TRT material budget

1 Overview

The amount of material in the Inner Detector affects the overall ATLAS performance in a significant way. Even though the impact of material at small radius on the performance is considered to be largest [5-1], particular care has been put into minimising the amount of material in the TRT detector, as described in the engineering part of the Inner Detector Technical Design Report [5-2] and as shown in Figure 1-1.

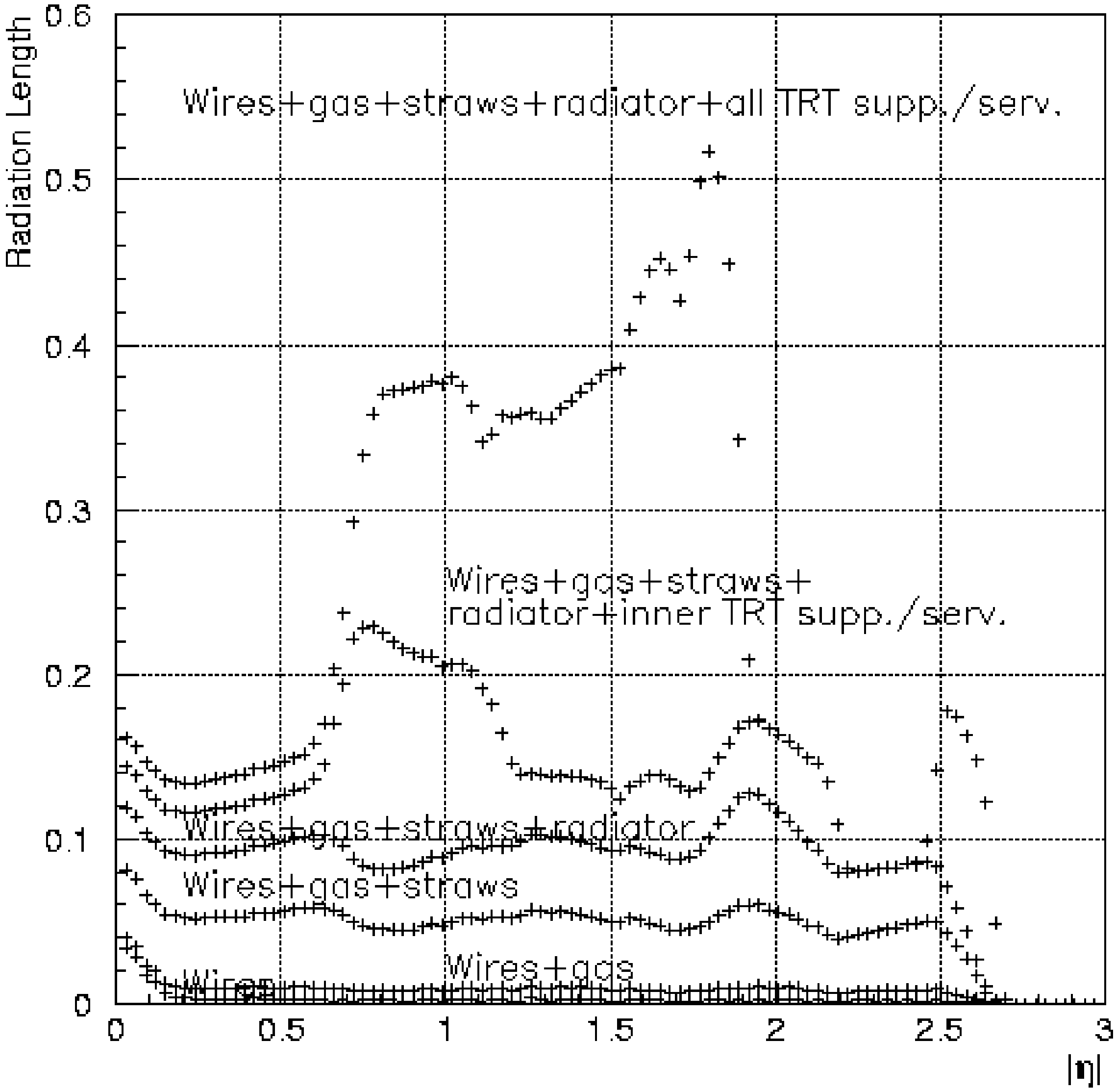

Figure 1-1 Cumulative distribution of TRT material (as presented in the TDR engineering estimates [5-2]) as a function of |η| (longitudinal vertex spread included).

Light-weight composite structures have been chosen for the mechanical support frames and the amount of metal has been kept at a minimum everywhere. In addition, the density of active detector elements (wires, gas, straws and radiator) has been chosen carefully, so as to maintain the total amount of active detector material to approximately 10% X_0 over the complete η-range. The abrupt increase of about 10% X_0 around η = 0.7 arises from the end-flange and services of the barrel TRT, and the significant additional increase at larger values of $|\eta|$, culminating at $|\eta|$ = 1.8, is concentrated at the outermost radius of the tracker volume and arises from the outer enclosure of the TRT end-cap wheels and, to a lesser extent from the accumulation of all TRT services (barrel and end-cap)

Figure 1-2 shows in the same way as for Figure 1-1, the cumulative distribution of the TRT material, but as obtained from the best present engineering estimates. Considerable work has been undertaken since the Inner Detector TDR to finalise the engineering design, in particular in terms of integration of services and electronics. This has resulted unavoidably in some increase of material at the outer radius. In the more sensitive part of the active volume, however, the changes are small, as described below.

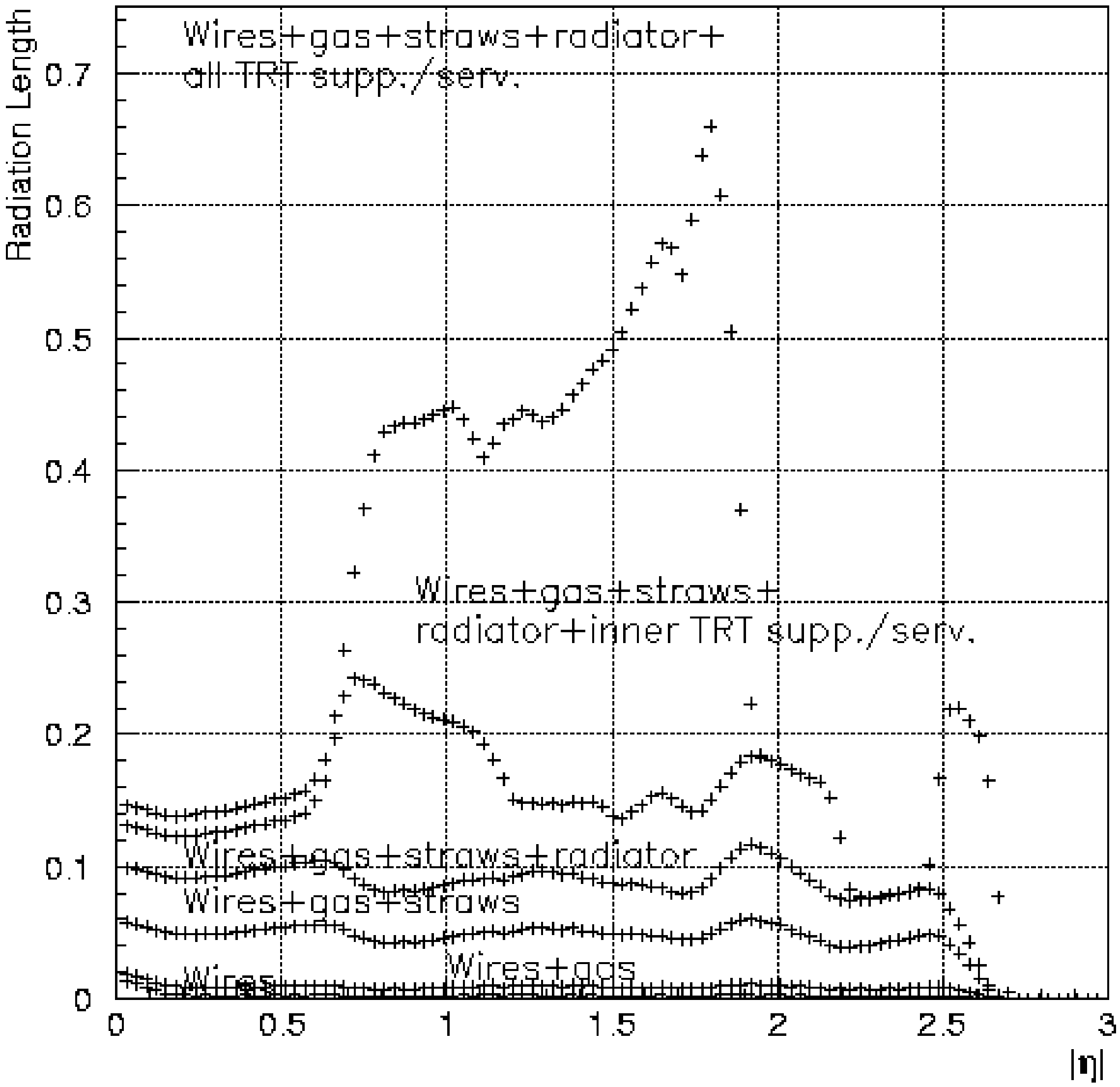

Figure 1-2 Cumulative distribution of TRT material (as obtained from best present engineering estimates) as a function of $|\eta|$ (longitudinal vertex spread included).

2 Description of TRT material changes

Table 2-1 Breakdown of the TRT material budget as a function of $|\eta|$ (longitudinal vertex spread included). The left-hand numbers shown for each value of $|\eta|$ represent the present best engineering estimate of the relevant material item, whereas the right-hand numbers represent the increase (or decrease) with respect to the numbers shown in the TDR.

	Radiation lengths in % X_0											
Pseudorapidity η	**0.0**		**0.6**		**0.9**		**1.2**		**1.78**		**2.2**	
Wires	1.3	*-2.1*	0.2	*+0.0*	0.2	*-0.1*	0.3	*+0.1*	0.3	*+0.0*	0.1	*-0.1*
Gas	0.6	*+0.0*	0.7	*+0.0*	0.6	*+0.0*	0.7	*+0.0*	0.7	*+0.0*	0.6	*+0.0*
Straw walls	3.9	*-0.1*	4.6	*-0.3*	3.6	*-0.1*	4.3	*-0.1*	4.3	*+0.1*	3.5	*-0.2*
Radiator	4.2	*+0.4*	4.9	*+0.5*	3.9	*-0.1*	4.2	*-0.3*	4.6	*-1.0*	3.5	*-0.3*
Barrel shells/cyl.	3.2	*+0.0*	3.5	*+0.3*	2.4	*+0.1*	0.1	*+0.1*				
Barrel end-flange and services			2.4	*+0.6*	10.7	*+0.5*	0.6	*-0.1*				
Inner end-cap enclosure							4.7	*+1.4*	5.8	*+1.8*		
Total: active volume	**13.1**	***-1.8***	**16.5**	***+1.2***	**21.6**	***+0.5***	**14.8**	***+1.1***	**16.0**	***+1.1***	**7.7**	***-0.5***
Outer end-cap enclosure					16.8	*+2.3*	20.8	*+2.7*	33.3	*+3.8*		
Outer services (barrel and end-cap)	1.5	*+0.2*	1.6	*-0.1*	5.4	*+3.5*	8.9	*+4.9*	11.5	*+5.8*		
Total: outer volume	**1.5**	***+0.2***	**1.6**	***-0.1***	**22.2**	***+5.8***	**29.7**	***+7.6***	**44.7**	***+9.5***		
Total: whole TRT	**14.6**	***-1.6***	**18.1**	***+1.1***	**43.8**	***+6.3***	**44.5**	***+8.7***	**60.8**	***+10.6***	**7.7**	***-0.5***
Uncertainty	±1.0		±1.0		±3.0		±3.0		±5.0		±1.0	

The TRT detector is presently in its final stages of engineering design and pre-production modules are (or will be very soon) under construction both for the barrel and the end-cap. In addition to the more global issues of integration, connectivity and validation through experimental measurements and system tests, considerable effort has been put into possible reductions of the material in the sensitive area and into minimising the increases due to items not yet foreseen at the time of the TDR. Table 2-1 shows the best present engineering estimates put into the detector description and based most often on existing components and prototypes. The values are displayed as percentages of a radiation length for six characteristic η-bins (of width 0.03) and are averaged over the spread of the longitudinal vertex. The left-hand numbers in each column represent the amount of material estimated for a given item and the right-hand numbers represent the increase (or decrease) with respect to the estimates shown in the TDR. Table 2-1 also shows two sub-totals for the TRT material, one for the so-called active volume which covers radii between 56 cm and 107 cm in the barrel and between 62 cm and 103 cm in the end-cap, the other for the so-called outer volume, which covers radii between the outer radius of the active volume and the position of the LAr barrel cryostat (radius of 115 cm). The uncertainties quoted in Table 2-1 correspond to the overall sum of the remaining uncertainties linked to final design and validation of certain technical solutions.

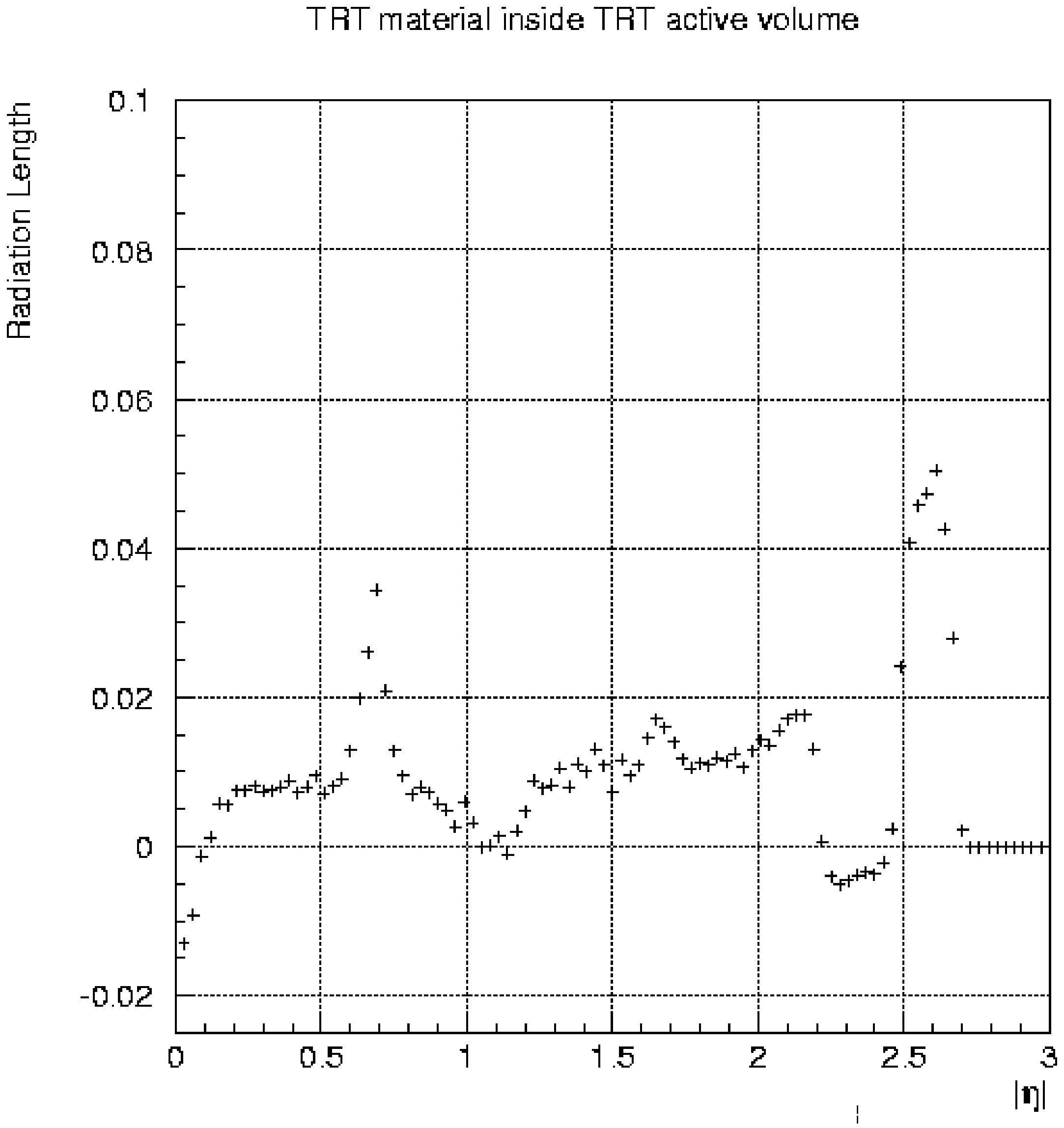

Figure 2-1 Distribution of the difference as a function of |η| (longitudinal vertex spread included) between the best present engineering estimates of the TRT material within the TRT active volume and those presented in the Inner Detector TDR.

As can be clearly seen from these sub-totals, the total material in the active volume has not changed much in either direction. This is better quantified in Figure 2-1, which shows the distribution of the increase (or decrease) of the TRT material in the TRT active volume as a function of |η| (see below for more details). On the other hand, the total material outside the TRT active volume, which is basically very close to the LAr barrel cryostat wall, has significantly increased, which is perhaps not surprising since this is the region where all the Inner Detector services have to be collected together, supported, and, specifically in the case of the TRT, connected to the end-cap wheels. As described below, this increase is due, in part to supports for services and connectivity details, which had not been included in the TDR, and in part to the more detailed and precise understanding of the layout of the outer enclosure of the TRT end-cap wheels. As illustrated more quantitatively in Figure 2-2, the maximum increase is almost 10% X_0 at $|\eta| \approx 1.8$.

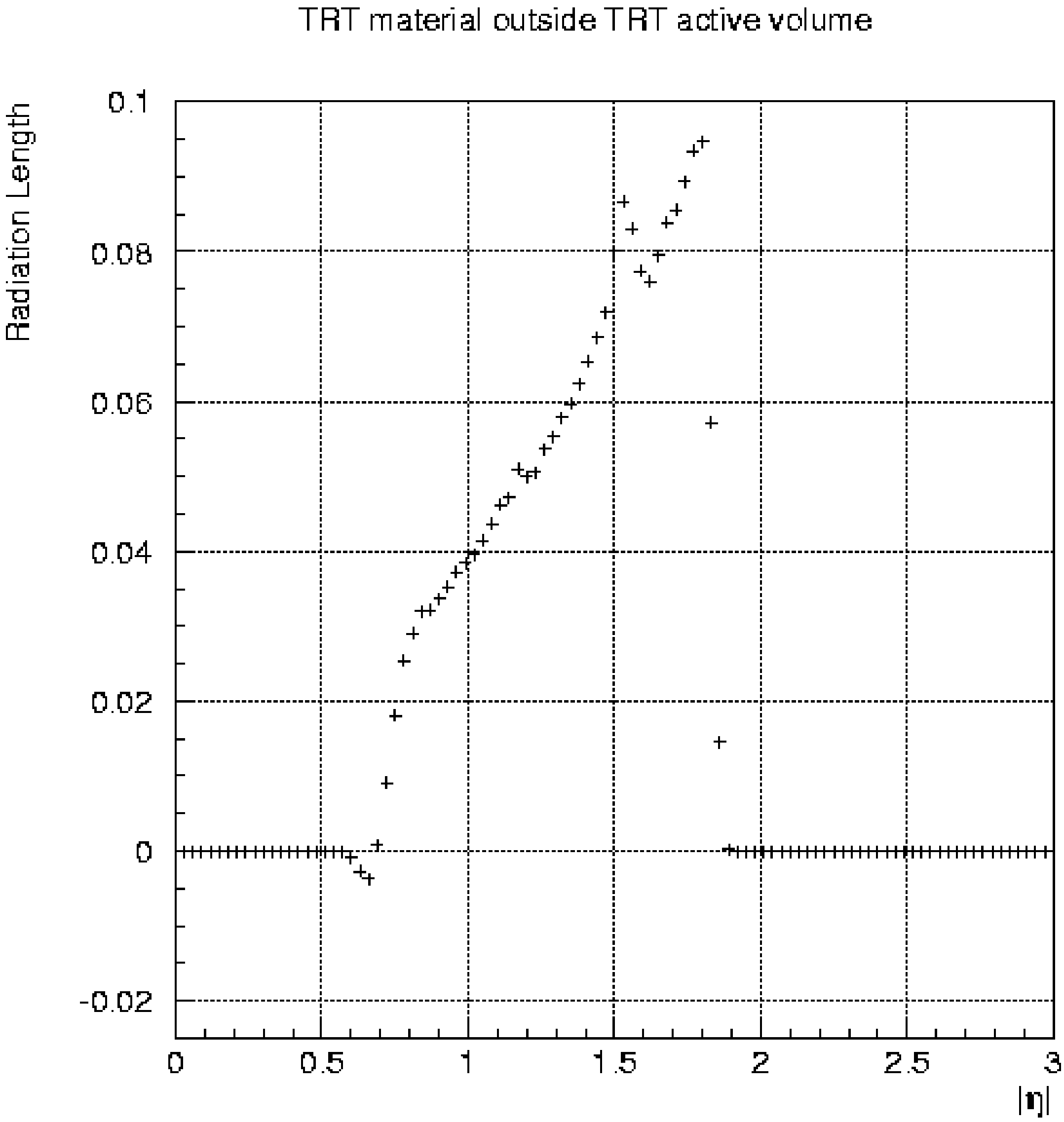

Figure 2-2 Distribution of the difference as a function of |η| (longitudinal vertex spread included) between the best present engineering estimates of the TRT material outside the TRT active volume and those presented in the Inner Detector TDR.

2.1 Changes within TRT active volume

The material within the TRT active volume can be divided into different functional categories, as illustrated in Figures 1-1 and 1-2 and described quantitatively in Table 2-1:

- the 30 μm diameter gold-plated tungsten wire, which amounts to a very small fraction of the total material of the active detector. However, in the barrel TRT, the wires are split in two in the middle and read out at both ends in order to reduce the single-channel occupancy. The wire-joints and wire-supports (twisters) used to achieve this appear as an average increase of 1.1% X_0 in the amount of material at $\eta = 0$ (the longitudinal vertex spread was included in the calculation of this increase). Thanks to a new and more aggressive design of these parts, a significant reduction of this contribution to the material (approximately a factor of 3) has been obtained (see Table 2-1);

- the ionisation gas (unchanged);
- the straws with their carbon-fibre reinforcement (essentially unchanged);
- the radiator (punched fibre mats in the barrel and thin foils in the end-cap). The amount of material due to the barrel radiator has slightly increased, since the diameter of the punched holes has been decreased from 5.2 mm to 4.8 mm to improve the electron identification performance, which is marginal at high luminosity in the barrel TRT. The amount of material due to the end-cap radiator has in contrast slightly decreased (the calculation is now based on existing polyproylene-foil industrially-produced radiator stacks);
- the carbon-fibre shells which define the barrel TRT modules (unchanged);
- the barrel end-flanges and services, which include all the components used to fix and position the straws and wires mechanically and to connect them electrically, the electronics (chips, boards, connectors, etc) and the cables and fluid pipes. The breakdown of these different components is presented in Table 2-2 and compared to the corresponding estimates at the time of the TDR. It should be noted that the length of the barrel straws has not yet been frozen, since it depends on the exact length of the SCT barrel detector. The length used for the estimates presented here is slightly shorter than the one used for the TDR and the effect of this change in length can be seen in Figure 2-1 in the region $0.6 < |\eta| < 1.2$. Two full-length barrel modules have been manufactured and tested in

Table 2-2 Breakdown of the material budget for the end-flanges and services of the barrel TRT. The left-hand numbers represent the present best engineering estimate of the relevant material item, whereas the right-hand numbers represent the increase (or decrease) with respect to the numbers shown in the TDR. The numbers are computed at normal incidence, i.e. at a fixed average radius of about 80 cm.

Material (per side)	**Radiation length in % X_0**	
Straw-fixation plate	0.94	*+0.22*
Gas	0.02	*-0.03*
Straw end-plugs	0.38	*+0.10*
Straw-fixation elements	0.27	*0*
Blocking capacitors	0.32	*-0.19*
Wire-connection plate (tension plate)	0.90	*-0.05*
Wire-fixation elements	0.76	*-0.43*
Electronics boards and connectors	2.13	*-0.28*
Fuses[a] and local HV connectors	0.17	*+0.17*
Barrel support structure (space frame)	0.55	*+0.14*
Services: cables, fluids, pipes, fittings, cooling hardware	1.37	*+0.27*
Manifolds (Al pipes + fluorinert liquid)	0.16 + 0.18 = 0.34	*+0.34*[b]
Total	**8.15**	***+0.26***
Uncertainty	±2.0	

a. Not accounted for in the TDR (see text)
b. Not accounted for in the TDR (see text)

beam since the TDR, and the design of the barrel modules is close to being finalised. As can be seen from Table 2-2, several of the components of the barrel end-flange have undergone significant reductions in material, but the net effect of the design progress since the TDR is nevertheless an small increase of 0.26% X_0, due mostly to engineering details in the area of cooling and of electrical services. The numbers in Table 2-2 still depend on certain assumptions about the final technical solutions which will be implemented once the barrel design is complete (this includes the front-end electronics and the barrel support structure). In particular, possible significant changes in the future could be:

a. an increase of the material due to electronics boards and connectors by 1.2% X_0, if a two-chip front-end electronics design has to be implemented rather than the preferred single-chip design;

b. an increase of the material due to the barrel support structure by 1.1% X0, if the deformations under load of a full-size prototype structure turn out to be significantly larger than foreseen by the present calculations (it should be noted here that the specifications for the deformation under load of the barrel support structure are defined by the barrel SCT and the pixel detectors);

c. a decrease of the material due to the straw-fixation and tension plates by 0.6% X_0, if the overall mechanical design of the barrel TRT and the assembly procedures are shown to be compatible with plates of only 1 mm thickness.

For all the above reasons, the uncertainty shown in Table 2-2 for the amount of material due to the barrel end-flange and services is still quoted to be around ±2% X_0;

- the inner end-cap enclosure, situated at a radius of 62 to 64 cm for the type-A and type-B wheels and of 46 to 48 cm for the type-C wheels. The breakdown of the material budget for this enclosure is shown in Table 2-3. This enclosure was foreseen to be based on a 1 mm thick C-fibre ring at the

Table 2-3 Breakdown of the material budget for the inner enclosure of the end-cap TRT. The left-hand numbers shown for each wheel type represent the present best engineering estimate of the relevant material item, whereas the right-hand numbers represent the increase (or decrease) with respect to the numbers shown in the TDR. The numbers are computed at normal incidence, i.e. at a fixed z for each wheel type.

	Radiation length in % X_0					
Wheel type	**A**		**B**		**C**	
Carbon fibre support ring (2 mm thick)	0.62	*+0.31*	0.68	*+0.34*	0.62	*+0.31*
Aluminised polyimide cover	0.30	*+0.04*	0.30	*+0.04*	0.30	*+0.04*
Gas (about 1.5 cm thick)	0.11	*+0.02*	0.11	*+0.02*	0.11	*+0.02*
Wire crimping pins	0.80	*+0.21*	0.40	*+0.11*	0.80	*+0.21*
Straw fixation rings	0.10	*0*	0.05	*0*	0.10	*0*
Straw end-plugs and moulded pieces	0.68	*+0.17*	0.34	*+0.08*	0.68	*+0.17*
Total[a]	**2.62**	***+0.76***	**1.89**	***+0.60***	**2.62**	***+0.76***
Uncertainty	±0.5		±0.5		±0.5	

a. cooling gas manifolds (three in total per side) have not been included here time of the TDR, but this thickness has been increased to 2 mm after a careful evaluation of the assembly steps and tooling required to implement a tension per straw sufficient to make sure that no straw is ever under compression once the detector is in place. This decision has been recently validated by prototyping of the precise tooling required for its implementation in the assembly of the first pre-production module. Given its position at the innermost radius of the end-cap TRT, this inner enclosure has been designed to be as lightweight as compatible with a safe mechanical design (thickness of carbon-fibre support ring, dimensions of plastic elements and, more importantly, of metallic crimping pins). As shown in Table 2-3, the final design values for several of these elements are higher than those of the TDR because of the conflicting engineering requirements for a robust and reproducible assembly procedure. It should be noted here that the total mass of the end-cap mechanical support structures can be expressed as approximately 1 g per straw (these CFRP structures are drilled with many thousands of precision holes).

2.2 Changes outside TRT active volume

- the outer end-cap enclosure (situated at a radius of 103 to 108 cm for all wheels), which, similarly to the barrel end-flange, comprises all components necessary to position and fix the straws and wires mechanically, the electronics, and the services. The breakdown of the individual components is shown in Table 2-4. The only significant change with respect to the TDR is an increase of 0.8% to 1.6% X_0 of the crimping pins which have been finally chosen as fully metallic rather than plastic/metal composites due to concerns about the long-term reliability of these crucial components for the wire fixation and the electrical signal connection. Table 2-4 does not explicitly include fittings for the gas and liquid cooling pipes (a small contribution since only a few pipes are foreseen per wheel), nor does it include the amount of material which might come from heat exchangers, which would have to be added (18 heat exchangers per side) if the present scheme for extracting the heat from the gas into the cooling liquid for the electronics were shown to be not viable.

Table 2-4 Breakdown of the material budget for the outer enclosure of the end-cap TRT. The left-hand numbers shown for each wheel type represent the present best engineering estimate of the relevant material item, whereas the right-hand numbers represent the increase (or decrease) with respect to the numbers shown in the TDR. The numbers are computed at normal incidence, i.e. at a fixed z for each wheel type.

	Radiation length in % X_0					
Wheel type	**A**		**B**		**C**	
Inner carbon support ring (4 mm thick)	1.08	*0*	1.28	*0*	1.18	*0*
Straw end-plugs and moulded pieces	1.16	*-0.02*	0.58	*-0.01*	0.86	*-0.03*
Gas	0.11	*-0.02*	0.113	*-0.03*	0.11	*-0.02*
Crimping pins	2.11	*+1.60*	1.06	*+0.81*	1.59	*+1.21*
Outer carbon support ring (4 mm thick)	1.34	*0*	1.41	*0*	1.37	*0*
Wire and HV connection board (active WEB)	1.86	*0*	1.45	*0*	1.65	*0*
Passive connection flange (passive WEB)	0.68	*0*	0.68	*0*	0.68	*0*
Fluid pipes (containing fluorinert liquid[a])	0.73	*+0.07*	0.73	*+0.07*	0.73	*+0.07*
Electronics boards and connectors	2.80	*0*	2.46	*0*	2.63	*0*
Total[b]	**11.87**	***+1.63***	**9.76**	***+0.84***	**10.80**	***+1.23***
Uncertainty	±1.5		±1.5		±1.5	

a. the corresponding values for the TDR were computed for water as coolant

b. fittings for the gas and liquid cooling pipes and possible heat exchangers have not been included (see text)

The tables organisation corresponds to one used in the TDR. Several entries has been added where appropriate. One table (TDR 12-4) has been suppressed since now we have no difference between ‘engineering’ and ‘simulation’ material budget. Table 1-1 is a MC result obtained from tables 1-2 through 1-4 with some numbers added from table 1-5. The ‘total’ in table 1-1 is a result of the summation in MC thus slight differences from direct summation in columns.

3 Details of changes

Changes:

Below in some detail are explained changes and deviations from TDR numbers. Not dealt with are the changes contained within quoted uncertainities.

1. wires at η=0, Table 2-1; the support and wire-break has been redesigned and redimensioned.

2. Radiators has been finally chosen and the X0 value come from detailed estimations.
3. Changes in the barrel-end flange. Present numbers are based on very advanced design and not on the approximation from small rather model than prototype. Significant contribution comes from present design of the FE-electronics. Two-chip solution requires much more printed boards thus connectors, pins etc - metallic objects which increase the material weight.
4. Outer enclosure of the end-cap wheels has no significant changes except for crimping pins. The design has been changed to ensure safe wire fixation and easier production
5. The changes in the inner enclosure are given by:
   a. increase by 100% of the thickness of the inner carbon-fibre ring due to engineering calculations
   b. longer crimping pins for safety of wire fixation
   c. redesigned straw end-plugs to facilitate production process
6. Changes in services and studied options are explained further. (see Table 3-1 as well)

Table 3-1 Breakdown of the material in services (barrel and end-cap) between squirrel cage and cryostat wall

Service	**Radiation length in % X_0**			
	Position			
	z = 830 cm,R = 1140 cm		*z = 3300 cm, R = 1140 cm*	
Fluid/gas services[a]	0.43	*-.13*	0.85	*+.07*
Cable services	0.96	*+.40*	4.0	*+1.93*
Cable services in **Al**	0.47	*-.14*	2.08	*0.0*
Connectors - 'PPF1[b]'			2.67 (z=840-3200)	*+2.67*
Cable trays[c] (plastic 2 mm)	0.2 (z=820-840)	*+.2*	0.52 (z=840-3200)	*+.52*
Squirrel cage[d]	0.0	*0*	1.55 (z=840-3200)	*+1.55*
Total as TDR baseline (Al)	**1.39 (*0.90*)**	***+0.28(-.27)***	**4.85 (*2.93*)**	***+2.0 (+.1)***
Total (Al)[e]	**1.59 (*1.1*)**	***+0.48 (-0.07)***	**6.92 *(5.00)***	***+4.07 (+2.15)***
Total - 'no PPF1' option (Al)	**1.59 (*1.1*)**	***+0.48 (-0.07)***	**9.59 *(7.67)***	***+6.74[f] (+4.82)***

a. Fluorinert in cooling system
b. Not shown before in TRT tables
c. Not shown before in TRT tables
d. Not shown before in TRT tables
e. Sums up the 'baseline solution' components (includes cable trays and squirrel cage)
f. Includes 'distributed' PPF1

4 Services

Table 3-1 contains not quoted before break-down of the materials contained in the services. TDR number did not contain two items: cable trays and squirrel cage which now are included. The only significant change in services was made in the low voltage cables area. (distribution in η of the material increase for services is shown on Figure 4-1). The crossections have been recalculated as well as the distribution ideology. The quoted change originates from very tough assumptions on voltage drops i.e. power dissipation in this cables (TRT works on the assumption of 'not-cooled' power supply cables). The power of the FE electronics is taken very conservatively (slightly more than TDR max.value), but based on the present estimates taken from prototyping. In the same table are quoted values for aluminium cables and this option is disscused later in the text.

At $830 < Z < 3300$ mm one should assume linear rise from 1.59 up to 6.92 %.

We have also studied some optional solutions for PPF1. Due to lack of free volume at the edge of cryostat as well as in the crack between Barrel and endcap LArg calorimeter we envisioned a solution where PPF1 at least for TRT electrical services is distributed all along TRT-endcap lentgh. Connections from such local patch panels to the PPF2 might be made by long pigtails if assembly and cabling scenario will permit. Proposed solution would allow for prefabrication of the cable trays carrying electrical services.

Figure 4-1 Increase of material in services.

Remarks:

- at the moment connectors at PPF1 are being dealt with and will be defined soon
- included in the services are cable trays and squirrel cage which were not there before
- Cooling services has been recalculated with the fluorinert as cooling medium.
- Radiation length value for row 'Connectors' assumes suppression of the electrical connectors on the PPF1 and distribution of this connectors all over given z-range. This option - is being studied but at the moment does not have approval from 'installation/maintenance' team.

4.1 Comments on aluminium option

We have studied an option for aluminium cables. This might have significant influence on the radiation length contribution from the cables due to very favourable ratio of the electrical conductivity to radiation length in comparison to copper (factor is about 4.0 keeping the same cable resistance) . However:

1. there is no aluminium miniature twisted pair signal cables on the market and contacted companies were not able to start development
2. about 30% of our copper is in the signal cables
3. point 1 applies to HV cables as well. Only shielding is possible to be produced from Al (and this is option adopted by TRT for HC cables)
4. aluminium cables for LV power lines of necessary quality are available on the market. Table 3-1 contains (in the brackets) values for radiation length where proper Al cables are adopted.

   However aluminium cables are:

i. more rigid and thus more difficult to lay-out and route (higher packing factor needed) which would increase areas needed for services.

ii. aluminium cable needs special connector to avoid corrosion in contact with copper/brass and allow non-soldered assembly. Reliability of the low-mass, miniature connectors is unknown.

iii. to avoid (partialy) problems enumerated in previous paragraphs pure aluminium cables are covered with either silver or copper-silver layers (microns thickness), however for multiwire conductors the fraction of silver can even reach 4 % of the conductor volume. This of course reduces the advantage of lower radiation length of aluminium (Z_{Ag} = 47, Z_{Cu} = 29). In addition the cut-out ends of the cables give still access to aluminium and probably would have to be covered with some sort of insulator or sealant.

iv. cost of the cables depends strongly on the quality of insulation (thin-normal, radiation hard - not rad.hard. etc.) but there is no substantial price difference between aluminium and copper cables (10-20 %) with the same specifications. However the price of equipping the cables with connectors is not defined since most of the firms have no experience. Without precise market survey expected cost increase can not be quoted.

v. the necessary cross-sections of Al cables must be higher by some 55 % having the same power dissipation on cables. It would mean increase of the already questioned TRT services area by about 16 %, from about 850 cm^2 to close to 1000 cm^2 .

5 References

5-1 D. Barberis et al., ATLAS Internal Note, INDET-No-188 (1997).

5-2 Inner Detector TDR, Vol. 2 (1997).