Strategy for solving barrel TRT wire-joint problem

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Abstract
This document outlines the plan for addressing and solving the barrel TRT wire-joint failure observed in irradiation tests performed in fall 2001. A brief description of the problem is presented, the ongoing work to solve it is described, and a set of decision deadlines and actions are outlined. The impact on the schedule and cost are discussed together with the proposed request for the release of US management contingency funds in FY02 and FY03 for the completion of the construction of the barrel TRT modules.

1 Introduction
The TRT barrel consists of 96 modules with a total of 52,544 straws. The signal wires are electrically separated end-to-end inside the straws by glass capillaries that form what is called the glass wire-joint. This glass wire-joint had been identified as a sensitive component early on. Radiation hardness in terms of integral dose had been confirmed, and an irradiation validation within an operational straw had been completed up to an accumulated charge of about 5 C/cm, albeit under operating conditions somewhat different from those expected at the LHC (very high instantaneous dose rate with a narrow beam and very high gas flow and gas gain). However, during the fall 2001, in the early stages of a more thorough irradiation validation test at Duke University, it was discovered that the glass capillary was rapidly eroding under irradiation in the baseline Xe/CO2/CF4 active gas mixture (see Section 4). The result was immediately verified in a series of separate tests. It is very dependent on the water content, but occurs at some level even with very low water content. At the end of October 2001, the decision was taken to pause glass wire-joint manufacturing at Duke University, as well as wire-stringing at Duke and Indiana Universities, while seeking a solution to this problem.

Two approaches to solving the problem were adopted. One was to look for replacement materials and a new design for a wire-joint. The other approach was to investigate an alternate gas mixture, such as binary Xe/CO2, since it is very likely that CF4 in conjunction with water is the source of the glass erosion. Alternate wire-joint construction and testing at Duke, Hampton and Indiana Universities began almost immediately. Work is going on at all three sites to evaluate several alternate wire-joint implementations in the standard gas mixture at high and low dose rates and to study the existing glass joints in a binary gas mixture. The details of the wire-joint development work and validation status are given below (see Section 2).
While this work is ongoing, the US Barrel TRT management has adjusted the work-flow to avoid "standing-army" expenses and to avoid laying off trained technicians. Increased rates of module production have been instituted at both Duke and Indiana Universities. Modules are only carried through the mechanical stages prior to stringing, which constitutes about half of the total module assembly time.

The proposed plan is to achieve a sufficiently large accumulated charge (2 C/cm) to make a minimum-risk decision in March on the new wire-joint solution. If this decision is accepted by US ATLAS, accelerated development of production tooling will begin. By May 2002, the irradiation testing should have reached a level of about 4 C/cm for larger statistics of the chosen wire-joint (including production-grade samples), and the TRT community is confident that, at that time, it will be in a position to request authorisation from US ATLAS to begin actual stringing and to commit US management contingency funds for the second half of 2002.

A work-schedule has been developed that shows the June transition to wire-stringing occurring as mechanical assembly ramps down. Hampton University has been equipped to become a wire-stringing site, once straw production has been completed. With this increased stringing capability, the entire module assembly can be completed by the middle of 2003, with no significant perturbation to the original barrel TRT schedule nor to the overall Inner Detector schedule. However, there will be additional costs for irradiation testing, prototyping, tooling for new wire-joints, and establishment and running of an additional stringing site. In addition, there are several months of additional work with respect to the previous schedule at all sites, in order to cope with the de-stringing and re-stringing of the approximately 20% of already strung wires.

A new Estimate of cost to Completion, ETC02, was completed at the end of 2001, and has been submitted to DOE. This indicated an overall increase in project costs of about 120 k$ and 174 k$ in management contingency (see Section 3 for details). US-TRT soon needs to request management contingency for the construction of the final 30% of the modules. As stated above, a first installment will be required by May 2002, when their assembly would begin. Stringing would begin in June 2002, subject to a successful completion of the milestones indicated above and described in more detail below.

The non-US part of the TRT community has been concentrating since last fall on characterising a possible binary gas mixture within the scope of the much wider issue of the overall TRT gas system: Section 4 summarises the status to-date and explains the difficulty of abandoning the well-established baseline active gas as a resolution of the barrel wire-joint problem. In the meantime, binary gas studies are ongoing at Duke and Indiana as part of wire-joint testing.

Finally, Section 5 summarises the conclusions which have been drawn to-date by the TRT community and the proposal on how to solve this problem with minimal impact to the overall ATLAS project in terms of performance and schedule, and with hopefully an acceptable impact on the US ATLAS schedule and funding.

2 Alternate wire-joint solutions under investigation

2.1 Production of alternate wire-joints

There are currently three wire-joint solutions under investigation at Duke, Hampton and Indiana Universities. These three were selected as the most promising from nine that were initially considered.
2.1.1 Encapsulated glass

An encapsulated glass wire-joint is being investigated at Duke University. This approach exploits the known excellent properties of the glass-wire bond and eliminates erosion by sealing the glass surface with a polyester heat-shrink tube. In addition, the tube is sealed with Stycast 1266 epoxy resin. A wire-joint of this type is shown in Figure 1. This method of protecting the glass joint has the benefit of using the existing tooling setups for glass wire-joints and the supply of several thousand glass joints already produced. Details of the construction technique are given in [1].

Production considerations

Production consists of two steps. The first is to produce a glass wire-joint, as was done previously. The second is a hand-operation for the encapsulation and glueing. Each joint would be visually inspected. It is estimated that the production rate could approach 70-100 per day per station. With an extra shift added each day, 260 wire joints/day or 5200/month could be constructed. The total time needed to procure and commission the tooling is estimated to be one to two months.

Production of about 70,000 wire-joints is therefore estimated to require 266 working days. The production costs are estimated to be 203k$ for this solution and the total cost for the project is estimated to be 350k$ (see Table 1).

Risks

The principal risk with this type of wire-joint is the possible failure of the protective shield covering the glass joint. If the shield fails in operation, the glass joints could be destroyed. Other than a visual inspection, it is not possible to verify gas tightness at production time. Radiation tests on production wire-joints are required to validate the process.

2.1.2 PEEK

A wire-joint made entirely of PEEK plastic is being designed and prototyped at Indiana University. PEEK is a highly radiation-resistant material, and one of the materials already used in the barrel TRT modules for gas-service lines and connectors. It is also thought to be resistant to the type of attack that the glass wire-joint suffered. This seems to be supported by initial studies, but more extensive irradiation tests are required. The bond to the signal wire at either end of the PEEK joint is made by locally heating the wire which melts the PEEK and forms the bond. The resulting PEEK joint is shown in Figure 2. A number of techniques for heating the
wire are under investigation (resistive and laser heating have been used to-date). Details of the construction technique are given in [2].

Production

Production could in principle proceed with tooling that is quite similar to the existing glass-joint stations. The same positioning jigs, visual alignment, and video capture could be used. Depending on the type of heating used, the production times could be similar, since it would be a individual operator hand-operation. Laser-induced melting of the wire-joint could be more rapid than the present gas-heating system, however, the resistive-heating method might be slower. The tooling requirements for insertion of the signal wires into the Peek tubing are more demanding. The estimated production rate is about 5760 joints/month with two stations and 12-hour shifts.

Production of about 70,000 wire-joints is therefore estimated to require 250 working days. The production costs are estimated to be 178 k$ for this solution and the total cost for the project is estimated to be 313k$ (see Table 1).

Risks

The major risks with this type of wire-joint are elongation, mechanical failure or wire slippage. There has not been the long-term experience with this material that has been accumulated with glass. Mechanical tests for creep and for slippage or elongation under irradiation conditions are planned.

2.1.3 Polyimide/epoxy wire-joint

A wire-joint made of polyimide tubing and epoxy resin is being designed and prototyped at Hampton University. The wire-joint is shown in Figure 3. Polyimide is a highly radiation-resistant material and the epoxy (Stycast 1266) is one of the validated glues, which is already being used in the barrel TRT modules. Both the polyimide material and epoxy resins in general are believed to be resistant to the type of attack suffered by the glass wire-joints. This seems to be supported by initial studies, but more extensive irradiation tests are required. The joints are made of a 6-mm diameter polyimide tube filled with Stycast 1266 epoxy resin. Wires are inserted into each end and the epoxy allowed to harden. Each wire has a small knot at the end, which becomes embedded in the epoxy and provides additional assurance that the wire will not slip. These knots are easily made and similar knots are routinely used during assembly of the modules. Details of the construction technique are given in [3].

Production

Production could, in principle, proceed with quite simple tooling. The production station involves mostly hand tools, a glue dispenser, and various fixtures, along with a microscope camera for inspecting the joints. The expected cost is about 5 k$ per station. The estimated production rate is about 5760 joints/month with three stations and 8-hour shifts.

Production of about 70,000 wire-joints is therefore estimated to require 250 working days. The production costs are estimated to be 127 k$ for this solution and the total cost for the project is estimated to be 249 k$ (see Table 1).
Risks

The major risk with this type of joint is elongation of the polyimide/epoxy, cracking of the epoxy, or de-bonding of the epoxy from the polyimide tube. Wire slippage is not considered likely, thanks to the mechanical knot, but this will be validated through mechanical tests. There has not been the long-term experience with this material that has been accumulated with glass. Mechanical tests for elongation, creep, slippage and/or breakage of the epoxy under irradiation conditions are underway.

2.2 Validation tests

2.2.1 Mechanical tests

The principal mechanical test of the wire-joints monitors wire slippage, creep or breakage. This can be broken into three phases: static tests in the lab, monitoring in an irradiation environment, and monitoring in the straw during irradiation. For the monitoring under irradiation, over-tension will be applied to some wires. Any wire-joint candidate is considered viable for further consideration, only if it holds tension up to the wire breaking point and all three types under investigation have shown this strength. The wires are pre-tested at 100 g before they are strung at a nominal 60 g tension in the test setups. The crucial monitoring during irradiation will be done with intermittent tension tests. While only tests on production-grade wire-joints are truly valid, a growing number of wire-joints will be maintained under tension in the laboratories for long-term observation (see [4] for details).

2.2.2 Irradiation

A crucial validation measurement for each of the wire-joint types is operation in a straw under high irradiation. The straws on the inner part of the barrel module will operate with a current of about 0.1 \( \mu A/cm \) at the LHC design luminosity. During the operational life-time of the ATLAS detector at the LHC, the expected total accumulated charge could be as high as 10 C/cm, including a safety factor of 1.5. Validation tests under irradiation must approach this number. It is also important to do the wire-joint testing over the full length of the wire with the same gas (including contaminants such as water) and at the same flow-rates, which will be used during operation. However, in order to complete the tests in a reasonable amount of time, one must obviously run at considerably higher currents, at least a factor of 10 or 20.

Any of the new wire-joint technologies presently under study will have to pass all the irradiation tests with very stringent specifications: at each step of accumulated charge (2 C/cm for March 2002, 4 C/cm for May 2002 and 10 C/cm for August 2002), none of the samples examined should display any significant sign of damage of any sort, when examined under a microscope.

A 46-straw test-stand has been developed by Duke University and is presently in operation with several wire-joint types. This test module has two isolated gas volumes, which allows for joint testing of Xe/CO\(_2\)/CF\(_4\) and Xe/CO\(_2\) at several gas-gain settings. The straws are irradiated using ten Sr sources, and currents as high as 0.4 \( \mu A/cm \) can be sustained. The wire-joint validation will be done with a water content of the active gas kept below 300 ppm. Details of the test setup and of its operation are shown in [5].

A copy of this test module is being readied for operation at Indiana University. The test module will be irradiated with an X-ray source and should allow full irradiation with currents as high as 1 \( \mu A/cm \). The validation tests in this module will be done with a higher water content of the active gas of about 1000
ppm, which corresponds to the upper limit of the specification for the operation of the TRT within the overall ATLAS Inner Detector environmental conditions.

Timescales

The tests at Duke University are presently under way with two types of joints, encapsulated glass and Peek. Polyimide/epoxy joints will be added shortly. At the present current draw, the wire-joints will achieve an accumulated charge above 2 C/cm by the end of March 2002.

At Indiana University, the test setup is being strung with all three types of joints, and is being prepared for insertion in a new X-ray cabinet, which is nearing completion. The water-content monitoring and adjustment has been tested on a smaller test chamber. It should be possible to achieve an accumulated charge above 2 C/cm by the end of March 2002 for this test chamber also.

Associated costs

In addition to the test setup costs, which were approximately 30 k$ at Duke University and 30 k$ at Indiana University, there is the added cost of Xenon for these tests, which is approximately 5$ per litre. The estimated consumption cost is about 1.5 k$ per month at each site. There is also a modest overhead for monitoring and data-taking. These costs are summarised in Table 1.

3 Proposed strategy for completion of construction

3.1 Decision dates

There are several natural decision dates that arise from the validation procedures. The first is a decision date for the selection of the prime wire-joint candidate. This decision can be made when the irradiation has shown that all joints under test are unaffected for an accumulated charge of about 2 C/m (see [5] and Section 2.2.2). In addition to examining the results of the mechanical and irradiation tests, the wire-joint production scheme will be reviewed. It must be capable of supporting module-stringing rates, which will meet the proposed module completion schedule, and it must be within the ETC02 budget. With the present test schedules this decision can be reached before the end of March. March 25th 2002 is selected as the latest date for this decision, which will trigger the construction of the production tooling for the chosen wire-joint. It is expected that the design, and perhaps some of the production tooling, will have already been completed during prototype testing. If by this deadline date none of the wire joints meet the specifications as discussed above, then it would be necessary to pursue the change to a binary gas without CF4.

The second critical decision date is the approval of wire-stringing commencement. If a new wire joint had been chosen in March, this approval will be contingent on mechanical tests of production wire-joints, and successful irradiation validation of these wire-joints, including production-grade samples, up to about 4C/cm. The readiness and validation of the wire-joint production setup will also be reviewed (see [4] and Section 2.2.1). The production tooling and irradiation times are consistent with such a decision in May 2002. It is therefore proposed that this decision be made at the TRT Steering group meeting at Hampton University on May 24th. It is expected that wire-joint production will be sufficiently advanced that wire-stringing can begin by the middle or end of June. If a decision had been taken to pursue a binary gas, then the details of the irradiation tests that have been underway at CERN, Duke, and Indiana would be reviewed and a target date for recommencement of stringing with glass wire-joints could be set, consistent with the constraints for cost and schedule.
3.2 Plan for work before stringing resumes

After the decision to pause the glass wire-joint production and wire-stringing at Duke and Indiana Universities, a plan was created for avoiding "standing-army" costs and moderating the impact on the overall barrel TRT schedule by increasing the assembly rates for the mechanical construction modules. This schedule is shown in the attached Line of Balance (LOB) plots in Figures 4 (all sites), 5 (Duke University) and 6 (Indiana University). Mechanical assembly includes shell machining, radiator insertion, HV-plate insertion, straw insertion, gluing operations and mounting of the tension plate. It also includes testing and verification of alignment, HV stand-off tests, and leak-testing of the straw/HV-plate boundary. These operations constitute about 65% of the total assembly time.

This change required readjustment of the module component flows, many of which are centered at Hampton University, most critically the straw assembly and HV-plate/tension-plate assembly. Reinforced straw production in Russia has been accelerated further and future deliveries are expected to support the higher straw assembly rates required since November 2001. HV-plate construction from the supplier has increased and is able to support the new schedule. One adjustment was made at Hampton University, by moving the radiator-preparation operation to Indiana University. This helped Hampton University maintain a higher straw-assembly rate with the same work force, and supplied work for one technician at Indiana University. An additional assembly cell has been created at Indiana University and rates for type-1 and type-3 module mechanical assembly have increased.

Table 1 shows a detailed breakdown of the project and labour costs associated with the implementation of the new wire-joint solution. Clearly, the costs incurred by the various solutions considered at present are somewhat different and will enter as a parameter in the final choice, assuming several solutions would be technically validated by the March 2002 deadline.

Figure 4 Plan for barrel TRT module construction (all sites).

Table 1 shows a detailed breakdown of the project and labour costs associated with the implementation of the new wire-joint solution. Clearly, the costs incurred by the various solutions considered at present are somewhat different and will enter as a parameter in the final choice, assuming several solutions would be technically validated by the March 2002 deadline.
3.3 Plan for work after stringing resumes

The LOB plots discussed above show the schedule, for the case when stringing begins in June 2002. There will be three stringing sites, the existing sites at Duke and Indiana Universities, plus a new site at Hampton University (see Figure 7). Wire-stringing rates, which have been previously achieved at Duke and Indiana Universities, have also been assumed for Hampton University. By the end of FY02, the construction work at all three sites will consist almost entirely of wire-stringing. The schedule indicates that the stringing of 32 modules of each type will be completed in May 2003.

3.4 Impact on schedule and costs

The plan for solving the wire-joint problem presented above has a number of important features. While the overall module assembly schedule is lengthened by several months, there is very little impact on the overall TRT schedule nor on the installation dates. The modules will be shipped to CERN, where they will be acceptance-tested and prepared for assembly into the barrel Inner Detector space-frame. The duration of this acceptance-testing period will increase as the ATLAS schedule most likely slips later this year, so the amount of float in the overall schedule will no doubt increase.

The shift in schedule has however resulted in increased costs. In ETC01, a project budget, which would cover the construction of 70% of the modules. Project money for assembly labour and supervision was only budgeted up that point. After that point the assembly labour costs were, if approved, to come from

Figure 5 Plan for barrel TRT module construction (Duke University).
management contingency, and, in FY03, all assembly operations, which are almost exclusively wire-stringing, were to be covered by management contingency. At that time of the calculation of ETC01
it was estimated that 798 k$ in management contingency for production labour would be needed to finish the assembly of all modules. This was split into two parts: 600 k$ for finishing 32 modules, plus 198 k$ as lower-priority funding for completion of all spares.

In the ETC02 which was calculated in December, 2001, project costs increased by $120K, due to the estimates for wire joint development, and tooling costs. The required management contingency was 175 k$ in FY02 (needed in May, 2002) and 600 k$ in FY03, amounting to a total of 735 k$ for 96 modules. These numbers are shown in Tables 2. The Barrel TRT management is acutely aware of these projected cost increases. Search for cost savings and possible rebudgeting for FY02 and FY03 are presently under active review.

To better understand the cost of delaying a decision, the monthly operating costs have been calculated. The monthly operating costs for the TRT Barrel can be broken into two major areas, a) assembly operations, i.e. the four technicians at each of the three sites and supplies, and b) supervision and

<table>
<thead>
<tr>
<th>Wire-joint option</th>
<th>Encapsulated</th>
<th>PEEK</th>
<th>Polyimide/epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing (Duke/Indiana)</td>
<td>70k$</td>
<td>13 k$</td>
<td>2 k$</td>
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<td>R&amp;D costs before production</td>
<td>27k$</td>
<td>28k$</td>
<td>15 k$</td>
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<td>Time to 100% production rate</td>
<td>Four months</td>
<td>Two months</td>
<td>Two months</td>
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<tr>
<td>Time per wire-joint (minutes)</td>
<td>5</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Total number of stations</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Total number of technicians</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Shift duration (hours)</td>
<td>12</td>
<td>8</td>
<td>8</td>
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<tr>
<td>Wire-joints produced per month</td>
<td>5760</td>
<td>5486</td>
<td>5760</td>
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<td>Time needed (person-months)</td>
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<td>50</td>
<td>36</td>
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<tr>
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<td>30k</td>
<td>35k</td>
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<tr>
<td>Labour costs</td>
<td>203k$</td>
<td>178 k$</td>
<td>127 k$</td>
</tr>
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<td>Total cost for wire-joint</td>
<td>350 k$</td>
<td>313 k$</td>
<td>249 k$</td>
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<table>
<thead>
<tr>
<th>Year</th>
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<th>Management contingency</th>
<th>Total contingency requested</th>
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<tr>
<td>FY02</td>
<td>120</td>
<td>174</td>
<td>294</td>
</tr>
<tr>
<td>FY03</td>
<td>0</td>
<td>610</td>
<td>610</td>
</tr>
<tr>
<td>Total</td>
<td>120</td>
<td>784</td>
<td>904</td>
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</table>

Table 1 Wire-joint production parameters and costs (for about 70,000 wire-joints).

Table 2 Contingency needed for completing the barrel TRT module construction (in k$).
4 Choice of active gas

The difficult operating conditions expected at the LHC and the specific characteristics of transition radiation detectors have imposed strong restrictions on the choice of straw gas:

- the gas must be a Xenon(Xe)-based mixture, with the maximum Xe-concentration compatible with safe and reliable operation at the LHC, thereby providing efficient absorption of X-rays;
- the gas must also be as fast as possible, thereby minimising pile-up in time, which consists of signals deposited by particles produced in interactions occurring before or after the bunch crossing of interest. The gas mixture must therefore contain as large as possible a concentration of CF$_4$ (which is the fastest possible choice for the TRT straws);
- the gas must also guarantee stable operation of the straws over a sufficient high-voltage range, for a large integrated charge per centimetre of wire (typically 4C/cm, but in some cases up to a maximum of 10 C/cm including a safety factor of 1.5), for very high fluxes of particles crossing the straws (typically 200 kHz/cm), and for wire offsets of up to 400 µm, defined by the tolerances on the mechanical construction of the components and on the mechanical assembly of these components into modules and wheels.

Among the various possible mixtures, which might satisfy these requirements, the fastest one was found to be Xe/CF$_4$. However, such mixtures are known to be rather prone to discharges and therefore do not guarantee stable operation over long periods of time. As a consequence, ternary mixtures were investigated, and Xe/CF$_4$/CO$_2$ was found to provide very stable operation without sparking up to very high gas gains.

The maximal Xe-concentration cannot be much above 70%, since higher Xe-concentrations lead to unstable operation of the straws. Lower Xe-concentrations would obviously degrade significantly the transition radiation performance (see below). The straw gas mixture was finally chosen about ten years ago to be 70% Xe + 20% CF$_4$ + 10% CO$_2$. A dedicated programme of eight years of studies of the basic performance of straws operating with this gas mixture and of ageing and material validation measurements has been carried out since then, and the results to-date have demonstrated that the TRT straw system will operate robustly for more than ten years at the LHC.

### Table 3 Monthly cost for TRT Barrel (in k$).

<table>
<thead>
<tr>
<th>Year</th>
<th>Monthly costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly technicians &amp; supplies</td>
<td>48</td>
</tr>
<tr>
<td>Supervision and engineering</td>
<td>42</td>
</tr>
<tr>
<td>Total</td>
<td></td>
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</table>
A final validation of the TRT detector operating as a system within a closed-loop gas system has not yet been achieved however and is the subject of ongoing active R&D in Russia and at CERN. The remaining significant source of concern is linked to fluorine-containing active species, which, in a similar way with what has happened with the glass wire-joint of the barrel TRT modules, may reach concentrations such that they could be the source of significant damage to the overall system. It is not expected that these studies will be completed for quite some time still, but, in the event that they might demonstrate insurmountable problems, a binary gas is being actively investigated as a fallback solution. There is only one possible choice for this fallback gas mixture, namely Xe/CO₂.

The properties of this binary gas mixture are described below and compared to those of the baseline ternary gas mixture. A short summary of this section explains why the choice of a binary gas cannot be considered on any short-term timescale as a solution to the problem of the barrel TRT glass wire-joint.

4.1 TRT performance issues

The performance impact of a change of the active gas mixture can be divided into two basic areas, namely the signal collection time, which is directly related to the straw hit probability or occupancy (and thereby to the drift-time measurement efficiency and accuracy), and the amount of Xenon gas, which is directly related to the transition-radiation (TR) performance.

4.1.1 Signal collection time

This parameter is very critical, since the TRT can only provide robust performance at the LHC if the straws operate at counting rates below 20 MHz and if the drift-time measurement efficiency is maintained above 50% for the highest counting rates (innermost-radius barrel straws and large-z end-cap straws).

Calculations (using the MAGBOLTZ program) and direct measurements (performed in October 2001 in the test-beam without magnetic field) have been used to assess as precisely as possible the signal collection time in Xe/CO₂ binary mixtures as a function of the Xe-concentration. The calculations show that, for the nominal gas-gain of 2.5 \times 10^4, the fastest Xe/CO₂ binary mixture is for a Xe-concentration of 65%. Both the calculations and the measurements show that this fastest binary mixture is 5 ns slower than the baseline ternary mixture in terms of signal collection time. For a magnetic field of 2 T, the signal collection time is expected to increase from 42 ns for the baseline mixture to 47 ns for the fastest binary mixture.

The implication on the performance of the TRT would be a direct increase of the occupancy by about 10% for a fixed-width hit validation gate (chosen to be 12.5 ns for the baseline zero-suppression scheme). The efficiency for valid hits would be also reduced somewhat (a few %) in the case of the binary gas mixture. The overall impact on the TRT performance in terms of level-2 trigger, pattern recognition and momentum resolution would have to be evaluated through detailed simulations to fully quantify the impact of a change of gas on the performance. This impact, although significant, would most likely not be considered as a show-stopper, in the case of a changeover to 65% Xe + 35% CO₂.

4.1.2 TR-performance

Reducing the Xe-concentration results in a direct degradation of the TR-performance in terms of electron/pion separation power at a fixed electron efficiency. This degradation would be small (less than 20%) for the changeover considered above (65% Xe + 35% CO₂), but would become unacceptably large
(a factor of 2-3), if one were to consider more stable binary mixtures (e.g. 50% Xe + 50% CO₂), as discussed in Section 4.4.

4.2 **Impact on front-end electronics and high-rate operation**

The highest-priority issue to be studied was whether any difference observed between the signal shape from the straw for the two gas mixtures would imply a change in the shaping of the front-end electronics. The shape of the ion tail was found to be the same to better than a few % for both gas mixtures. The fast electron component was measured to be 5% smaller in the case of the binary gas mixture, but this is well within the 20% margin allowed for this parameter by the front-end electronics design. The design of the ASDBLR analogue front-end chip for the TRT is therefore insensitive to the choice of gas mixture.

Direct measurements in the October 2001 test-beam period have shown that the high-rate performance of a straw connected to the ASDBLR chip shows no difference between the two gas mixtures up to at least counting rates of 11 MHz.

4.3 **Gas gain and streamers**

The difference in gas-gain between the two mixtures is very small for a given operational voltage. Both mixtures are therefore compatible with the presently foreseen high-voltage system design. In addition, the binary gas mixture displays an even smaller fraction of self-limited streamer discharges (below 10⁻⁴) than the baseline ternary gas mixture (about 5 10⁻³).

4.4 **Operational stability (discharges and sparking)**

The issue of operational stability was originally the key motivation to choose a ternary gas mixture, and it is therefore not surprising that it is in this area that the drawbacks of the choice of a binary gas mixture appear to be the most severe (the performance degradation itself could be considered tolerable if one had no other choice, as discussed in Section 4.1).

When increasing the gas gain above that considered for TRT operation, namely above the range 2.5 10⁴ to 4 10⁴, which corresponds to an operational high-voltage range between 1530 V and 1570 V, the behaviour of the straw is very different in both gas mixtures:

- in the ternary gas mixture, the straw goes into glow-discharge mode as the high voltage is raised and continues operating in this regime until sparking and breakdown occur about 150 V higher;
- in the binary gas mixture, in contrast, there is no glow-discharge regime and the straw switches brutally from normal operation to sparking and breakdown as the high-voltage is raised.

The breakdown voltage decreases rapidly for large wire offsets with respect to the centre of the straw. Table 4 shows a comparison between the observed breakdown voltages for the ternary gas mixture (these are independent of the presence or not of irradiation and of the type of irradiation) and for the binary gas mixture as a function of wire offset. The specification for the wire offset is that all channels with a wire offset above 400 μm will be disconnected from high-voltage (more than 95% of the channels have been observed to have a wire offset below 300 μm to-date). For the binary gas mixture, the breakdown voltage depends strongly on the presence or not of irradiation and on the type of irradiation (the breakdown voltage observed for α-particles was even 20-30 V lower than that quoted for X-rays in Table 4). The values quoted here vary by 10-20 V depending on the wire chosen for the measurement.
In summary, the difference in operational stability expected between the two gas mixtures can be evaluated by comparing the high-voltage difference between the upper edge of the operational range (namely 1570 V) considered for the TRT at the LHC and the lower edge of the range of breakdown voltages observed during direct measurements as a function of various parameters, the most prominent of which is the wire offset. The resulting minimum high-voltage differences are:

- 280 V for the baseline ternary gas mixture;
- 65 V for a possible fallback binary gas mixture.

The importance of operating with the utmost possible robustness a 420,000-channel system under the harsh conditions prevailing at the LHC cannot be over-emphasised. The extremely reduced plateau for operational stability of binary mixture, with perhaps tolerable (but yet to be demonstrated) degradation of the physics performance, sets a very high threshold on changing the overall active gas mixture for the TRT, especially if motivated only by the failure of a single component in the system. The operational stability of a binary mixture would be increased by increasing the amount of CO₂ to e.g. 50%, if the need arose, but the performance impact on the TRT detector would become very significant and such a decision would have to be taken ATLAS-wide.

### 4.5 Ageing properties

The binary gas mixture is expected to be less chemically aggressive than the ternary one, but this has yet to be demonstrated through the whole range of ageing measurements needed to validate any gas mixture for operation at the LHC. This programme of work has only just begun and no decision to move to a new gas mixture could be taken until this work is completed.

It should be pointed out here that the CF₄ component of the TRT active gas does have some beneficial features (etching of deposits, operational stability, etc.), which cannot be overlooked, when considering seriously the possibility of removing it from the baseline mixture: all the material validation studies performed to-date would have to be repeated to a large extent and this work has been the subject of many person-years of effort in the recent past.

### 4.6 Summary and conclusions

Since the timescale for completing the validation work for the binary gas mixture is quite long, typically more than one year, and not well defined because of its coupling to the final choice of components for the gas system, it has been clear from the very moment the problem with the glass joint appeared that a new wire-joint was needed. It is very likely that any wire-joint validated in the ternary gas mixture will survive
the more benign binary gas mixture, and it is also hoped that the glass wire-joint itself will have been at least partially validated for the binary gas mixture by May 2002.

In summary, it has been shown in this section that many of the properties of a binary gas are very similar to those of the baseline ternary gas mixture. The performance impact of moving to a binary gas with 65% Xenon could be considered to be tolerable even if it is significant. The impact on the operational stability of the straws with their expected range of wire offsets is however considered to be sufficiently severe, that no change of gas mixture can be seriously considered before all technical options for a replacement wire-joint are exhausted.

5 Summary

At the end of October 2001, large-scale irradiation tests of the baseline glass wire-joint for the barrel TRT modules showed that it was seriously eroded in operating conditions similar to those expected at the LHC (irradiation along the full length of the straw, nominal flow of the baseline active gas mixture and water content at the 1000 ppm level). Since then, several types of replacement wire-joints have been developed and are being mechanically tested and exposed to high accumulated charge under irradiation. The TRT community (US barrel teams, TRT project management and Russian gas and straw operation experts) is confident that one or several of the alternate wire-joints under investigation will be demonstrated to meet all the specifications for robust operation of the barrel TRT modules at the LHC.

To this end, the TRT community requests the release of US management contingency funds to the barrel TRT project, under the conditions that two milestones be met successfully:

1. by March 25, an alternate wire-joint should be selected among the three technical possibilities, based first on it surviving the ~2 C/cm accumulated charge until that time in the irradiation setups at Duke and Indiana Universities, and second on production-grade samples of this wire-joint passing all the required mechanical tests. If no wire joint can be chosen, it would be necessary to pursue a change to binary gas.

2. by May 25, the production tooling and process should be commissioned and production-grade samples of the new wire-joint should have successfully accumulated a charge of 4 C/cm and passed a series of long-term accelerated mechanical tests.

During this transition period, workloads at all three US assembly sites have been adjusted and personnel has been reduced. The rate of module mechanical assembly has been increased, Hampton University has been equipped and trained for wire-stringing, and provisions have been made for resuming stringing at all three sites by June 2002. A detailed schedule has been worked out, assuming conservative wire-stringing rates and real-time performance of mechanical assembly, leading to a realistic goal of completing all 96 barrel TRT modules by May 2003. This schedule is fully compatible with the present overall TRT and ATLAS Inner Detector schedules.

The US project costs have however increased by about 120 k$ (testing and tooling for new wire-joint), and the management contingency costs have increased by about 175 k$ to a total of 730 k$ (new stringing site at Hampton University and delay in the schedule for completion of construction). The barrel TRT project therefore requests authorisation from US ATLAS for FY02 management contingency funds from May 2002, at which point mechanical assembly will begin for the final 30% of the 96 barrel modules. The release of these funds (174 k$) should be subject to the successful completion of the milestones described above. The remaining management contingency funds (610 k$) are only needed in FY03 and can therefore be released at a later date.
## References

1. Encapsulated glass wire-joint
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3. Polyimide-epoxy wire-joint
4. Mechanical validation tests of new wire-joints
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