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Master Plate Production for the Tile Calorimeter Extended Barrel Modules*

By

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Approximately 41,000 master plates (Fig. 1) are required for the Extended Barrel Hadronic Calorimeter for the ATLAS experiment at the LHC. Early in the R&D program associated with the detector, it was recognized that the fabrication of these steel laminations was a significant issue, both in terms of the cost to produce these high precision formed plates, as well as the length of time required to produce all plates for the calorimeter. Two approaches were given serious consideration: laser cutting and die stamping. The Argonne group was a strong supporter of the latter approach and in late 1995 initiated an R&D program to demonstrate the feasibility and cost effectiveness of die stamping these plates by constructing a die and stamping approximately 2000 plates for use in construction of three full size prototype modules.[1] This was extremely successful and die stamping was selected by the group for production of these plates. When the prototype die was constructed it was matched to the calorimeter envelope at that time. This subsequently changed. However with some minor adjustments in the design envelope and a small compromise in terms of instrumented volume, it became possible to use this same die for the production of all master plates for the Tile Calorimeter.

Following an extensive series of discussions and an evaluation of the performance of the stamping presses available to our collaborators in Europe, it was decided to ship the US die to CERN for use in stamping master plates for the barrel section of the calorimeter. This was done under the supervision of CERN and JINR, Dubna, and carried out at the TATRA truck plant at Koprivinice, Czech Republic. It was a great success.[2] Approximately 41,000 plates were stamped and fully met specification. Moreover, the production time was significantly reduced by avoiding the need of constructing and then qualifying a second die for use in Europe. This also precluded small geometrical differences between the barrel and extended barrel plates (and therefore submodules) being an issue, with the result that standard submodules are fully exchangeable between the two types of module.

The master plates for the extended barrel modules were stamped using the US die in the same press at TATRA, Koprivinice, as was used for the barrel production. Prior to commencing production at the beginning of September 1998, the die was re-sharpened (though it was

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debatable whether this was absolutely necessary). Production was completed on December 18, 1998.

Stamping Quality Control Program

The identical quality control program as used for the barrel production was used for this production:

- for the initial setup 6 plates were stamped and measured on the 3-coordinate measuring machine and verified that the plates met the master plate specification
- every 30th plate was checked on the gauge plate
- every 600th plate was measured on the 3-coordinate measuring machine and the protocols faxed to Argonne for evaluation
- a vendor visit was made by at least one Argonne representative for each 10,000 plates stamped, as well as for the initial die validation and following re-sharpening (which was treated identically to the initial setup)

The protocol data were tracked using an Excel spreadsheet to record the deviation from nominal. We chose to restrict this tracking to those data we considered to be representative of the die performance and the most important dimensional parameters:

- longitudinal position of the source holes (Holes 1 through 11)
- the distance between inner and outer keys
- the full length of the master plate
- the inner and outer key widths, measured on top of the plate
- plate half widths at outer radius (A1/A2)
- plate half widths at inner radius (B1/B2)

Vendor Site Inspection

The tasks carried out as part of the site inspections depended on the stamping status.

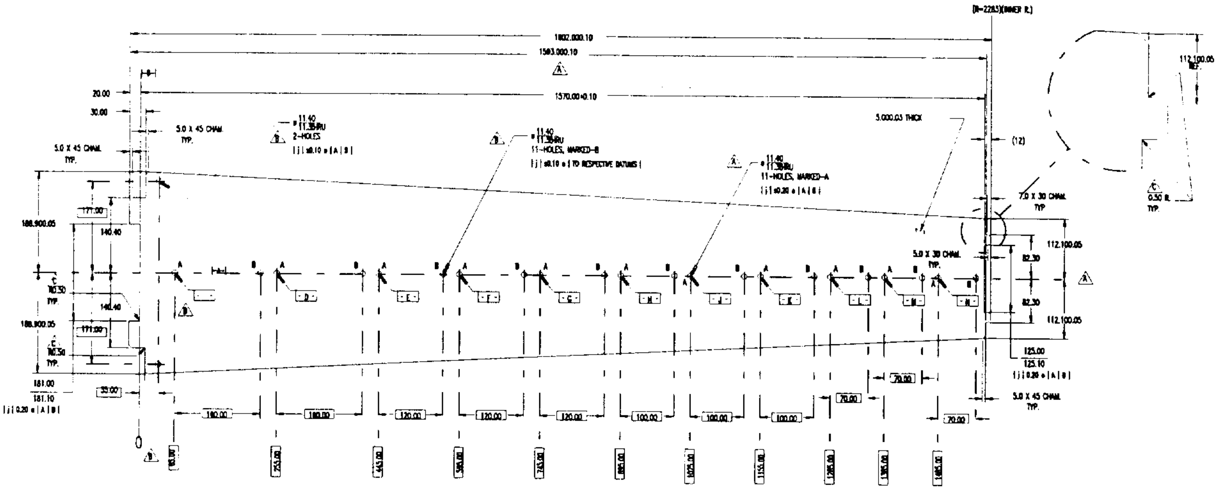

Figure 1. Master plate layout.

Die Certification - September 9, 1998

As part of the initial die certification, the die setup in the press was measured to confirm planarity. Six plates were stamped and measured on the 3-coordinate measuring system. The edges of these plates were visually inspected for burrs and edges defects and found to be acceptable. The protocol data were evaluated against the specification print used for the barrel production. All dimensional data met specification. However, it was clear that the general angular tolerance of +/- 0.5 degrees was needlessly tight (and failing) and the print was modified to relax this to 1.5 degrees.

Series Inspection at Approximately 12,600 Plates (protocols 7-28)

The first series inspection took place on October 14, 1998. The protocol data were reviewed with TATRA and accepted. The plate edges of the protocol plates were visually inspected and determined to be excellent. The outer radius key for top plates in all pallets of master plates, which were on hand at TATRA, were gauged using a precision bar (of dimension 180.9501/180.9491 mm) and determined to be fully within specification. This gauge bar itself was measured on the TATRA 3-coordinate measurement system to be 180.956mm.

1st Re-sharpening at Approximately 15,000 Plates

On October 22, between protocols 31 and 32, the data for source holes 7 through 11 fell out of specification and TATRA stopped production and notified Argonne. In addition, TATRA reported that the edge profiles were not as good as on earlier plates. Following discussion, as well as some additional stamping tests to check for any material effects, it was decided to re-sharpen the die and punches. On November 5, 1998, 6 plates were stamped for re-certification and found to meet specification and production re-started. The production represented by protocols 29 through 32 was accepted at this time.

Series Inspection at Approximately 21,500 Plates

The second series inspection took place on November 18. Plate edges were in excellent condition and no problems were apparent on the protocol data. Protocols 42 through 55 were accepted at this time.

Series Inspection at Approximately 31,000 Plates

The third series inspection took place on December 9, 1998. Plate edges were still in excellent condition. Protocols 56 through 85 were accepted at this time. Of these, however, protocols 65-79 are for test plates, which were stamped after a major deviation from specification was observed at protocol 64. The analysis of this data is discussed below. The conclusion is that this deviation was primarily due to temperature effects associated with storage of the master plate blanks in an unheated building. Once the blanks were allowed several days to come into thermal equilibrium with the press, the plates again fully fell within specification, and TATRA was instructed to pay careful attention to this issue for the remainder of the production.

Contract Completion

Master plate stamping was completed on December 18, 1998, with a total of 41,350 plates stamped, including an additional 130 plates as a precaution for plates damaged during shipping to the United States. Protocol data faxed to Argonne showed that dimensionally the plates fully met specification and therefore no closeout visit to TATRA was considered necessary.

Master plate shipping quantities are as follows.

6,100 plates to the University of Chicago
6,540 plates to the University of Illinois
10,110 plates to Argonne (inc. 3960 for the ITC)
18,600 plates to Barcelona

Shipping and Transportation Problems

Two (fortunately minor) problems were encountered during this production.

The first of these was with the blocking and bracing of pallets inside containers for shipment to the US. Early shipments to Chicago had a small number of pallets that shifted in transit. While discussions were in progress with TATRA concerning improvement of the packaging, 4 containers arrived at Argonne with seriously shifted loads (26 out of 56 pallets). TATRA was instructed to add additional bands to the pallets, both to secure the plates together and to secure the plates to the pallets. They were also given a more explicit description of what blocking and bracing was required to secure the pallets in the containers. This was successful and all subsequent deliveries arrived intact. The steel in the 26 broken pallets was re-stacked by hand, at which time the plates were checked for major damage. Although there were some minor scratches on a few hundred plates, they were not considered significant because they would be removed in the Timesaver process. Only 6 plates were rejected as unsalvageable (due to distortion).

The second problem was the weight of the container loads. These were heavier than allowed (both in Spain and in the US) due to an error in the plate weight (which was thought to be 16.5 Kg, though we are not sure exactly where this error crept in). This was corrected after about 4000 plates were sent to IFAE Barcelona (unfortunately giving the group there a storage problem.

Protocol Data Analysis

The protocol data was checked regularly throughout the course of the production run using the Excel database to identify trends. This is now the principal basis of the following analysis.

Outer and Inner Radius Keys

Perhaps the single most important feature of the master plate is the width of the inner and outer radius keys, which was measured both near the top surface of the plate and near the bottom surface of the plate (as defined by the direction of the stamping).

The distributions for the outer key are shown in Fig. 2 below, where the corresponding distributions for the barrel production are also presented. Plotted is the difference between the measured key width and nominal key width of 181.00mm (measured – nominal). The measured data are seen to fall generally well between the tolerance envelope of 181.00mm and 181.10mm. The few plates falling below the minimum width are not considered a serious problem.

The distributions are essentially identical for both barrel and extended barrel productions. The mean and rms of these distributions are shown in Table 1, where quantitatively one can judge that these distributions agree at the few microns level both in average and in spread.

The corresponding width distributions for the inner radius key are shown in Fig. 3 below. Plotted is the difference between the measured key width and the nominal key width of 125.00mm (measured – nominal).

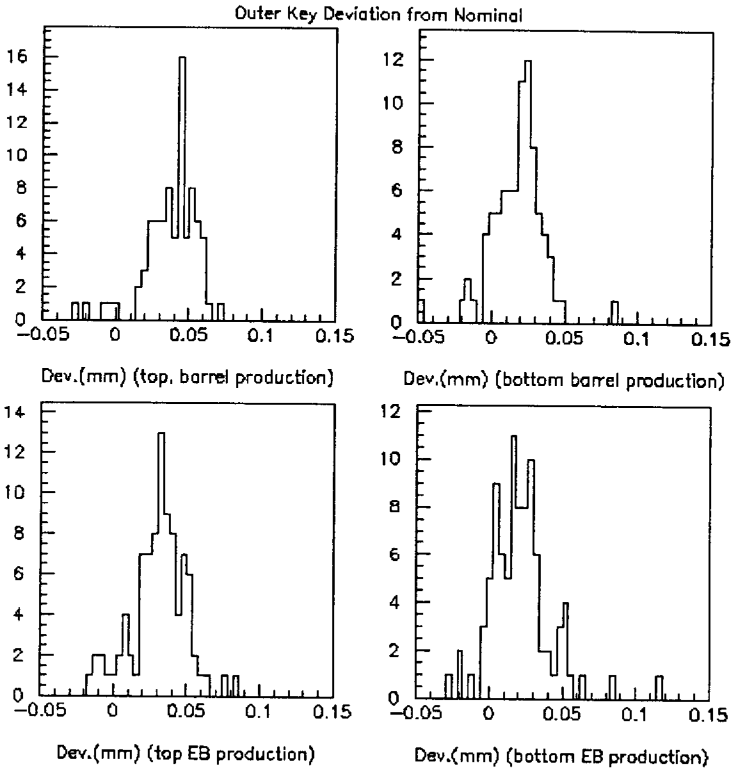

Figure 2. Outer key width difference from nominal (mm) for protocol measurements made for barrel and extended barrel productions. The nominal dimension is 181.000mm.

	Top Measurement		Bottom Measurement	
	Barrel	Ext. Barrel	Barrel	Ext. Barrel
Mean	181.038	181.031	181.018	181.021
Rms	0.018	0.018	0.017	0.021

Table 1. Outer radius key average width and rms (mm) for barrel and extended barrel productions.

As was the case for the outer radius key, the distributions are essentially identical though somewhat broader than was observed for the outer radius keys. It should also be noted that whereas the outer key width generally lays at the low end of its tolerance envelope, the inner radius key width is close to the upper end of its tolerance zone (125.00 to 125.10mm).

A more quantitative comparison can be made from Table 2 below, where the average and rms widths of the inner radius key measurement are shown. As was the case for the outer radius data, the data for the inner radius key also agree to a few microns for both production runs.

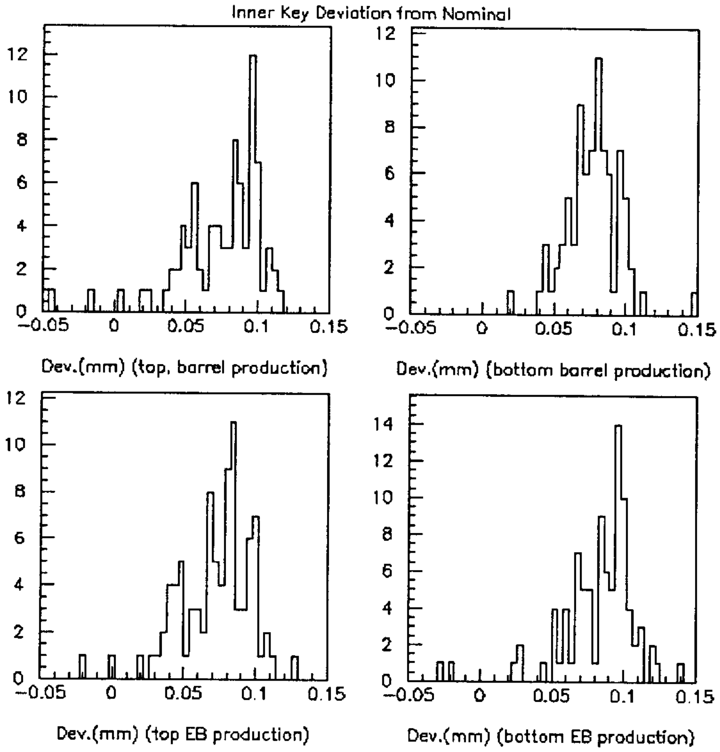

Figure 3. Inner key width difference from nominal (mm) for protocol measurements made for barrel and extended barrel productions. The nominal dimension is 125.000mm.

	Top Measurement		Bottom Measurement	
	Barrel	Ext. Barrel	Barrel	Ext. Barrel
Mean	125.074	125.072	125.077	125.082
Rms	0.028	0.025	0.018	0.026

Table 2. Inner radius key average width and rms (mm) for barrel and extended barrel productions.

Although the data do not indicate any time dependence, it is appropriate to confirm that this is the case, at least for the extended barrel production data that were entered into an Excel spreadsheet. The key widths as a function of protocol index are shown in Fig. 4 below. Apart from 3 oddball points, the data shows no non-uniformity. We suspect that burrs picked out by the measurement stylus cause the low widths to be measured and that the one very large width measurement occurred due to the stylus picking up the chamber at the tab on the plate. In any event, none are considered to be an issue for submodule assembly or the submodule envelope.

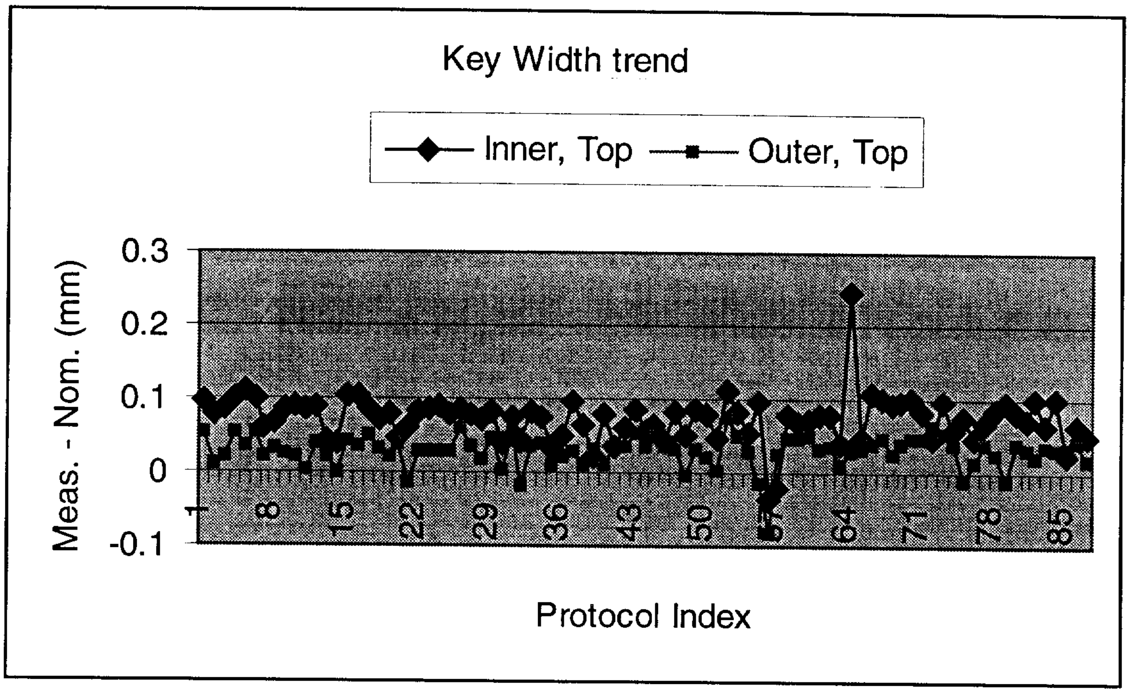

Figure 4. Inner and outer radius key width, deviation from nominal (mm), for the top set of measurements as a function of protocol index for the entire extended barrel production.

Hole Position

Monitoring of the source hole position in the protocol measurements became one of the more interesting areas of discussion during the course of the extended barrel production. Figure 5 shows the deviation of the measured source hole center position from its design value for holes 1 (at the outer radius), 6 (roughly at the middle of the plate), and 11 (at the inner radius) as a function of protocol index over the full production run. Generally, all deviations are within specification, which required them to be less than 0.1mm. However, three sets of data exhibit significant deviations from the specification: at index 26 (Protocol Number 32); at and around index 54 (Protocol Number 64); at index 84 (Protocol Number 96).

At Protocol 32, based on the barrel production experience at TATRA and the observation that the plates edges were becoming poorer, the die was re-sharpened (we attributed the deviation to die wear). At protocol 64, since we were extremely concerned that we would be perhaps reaching a limit with respect to the number of times that the die could be re-sharpened, we halted production for almost three weeks while evaluating the data. The deviation for hole 11 was the largest and that of hole 1 the smallest. Therefore, our suspicion was that temperature was playing a role in this deviation since some severe winter weather had passed through the area. The coefficient of thermal expansion of steel is approximately 10^{-5}/°C, which corresponds to about 0.015mm/°C for hole 11 and hence a relatively modest temperature difference (of say 10°C) could easily have this effect.

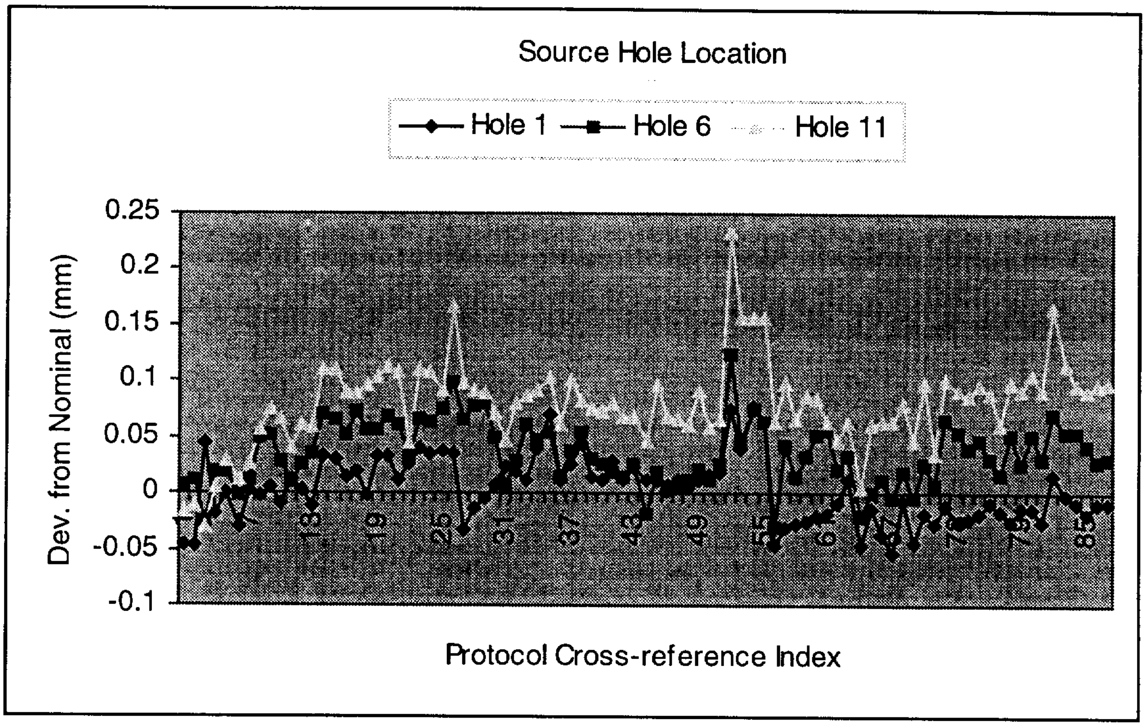

Figure 5. Hole location (deviation from nominal) for source holes 1, 6, and 11 as a function of protocol cross-reference index.

The position data were evaluated as a function of hole index for the four sections of data available at that time (protocol 7-35, protocols 42-63, protocols 64-69, and protocols 70-74). For completeness we now add a fifth section for protocols 75-102. The average hole position (deviation from nominal) as a function of hole location is shown in Fig. 6 for each of these sections. Even without the final section of data it is clear that the production series represented by Protocols 64-69 is fundamentally different from all others and has a trend suggestive of being caused by plate elongation. The conclusive evidence that the cause of this deviation is plate elongation is shown in Fig. 7, which shows the hole position deviations as a function of hole position along the plate for the data in Protocol 64. The linear dependence as a function of length shows clear evidence for plate elongation following stamping as would be the case if the plates were stored in a cold environment and not in thermal equilibrium with the die at the time of stamping (a temperature difference of only 12-14°C is all that would be necessary). Following this assessment at Argonne, TATRA was requested to move master plate blanks from an unheated storage location into the region of the press and held there for 7 days prior to stamping. Evidence that this corrected the problem is seen in Fig. 6, where the hole deviations for the final series of plates overlay all other series with the exception of those from Protocols 64-69.

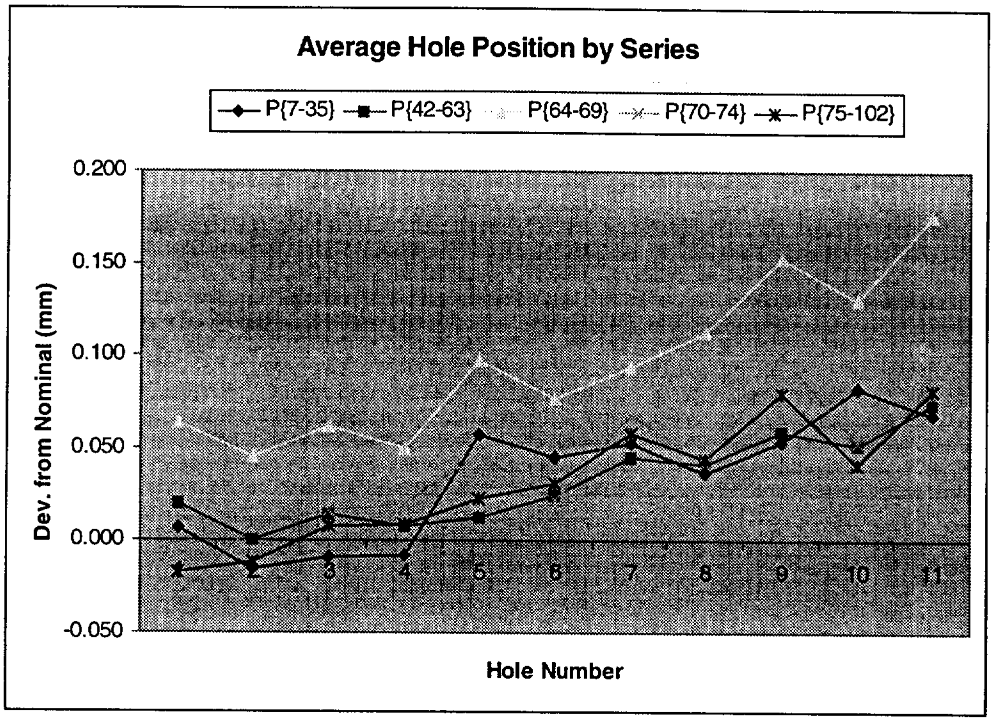

Figure 6. Average hole position, deviation from nominal, as a function of production protocol series.

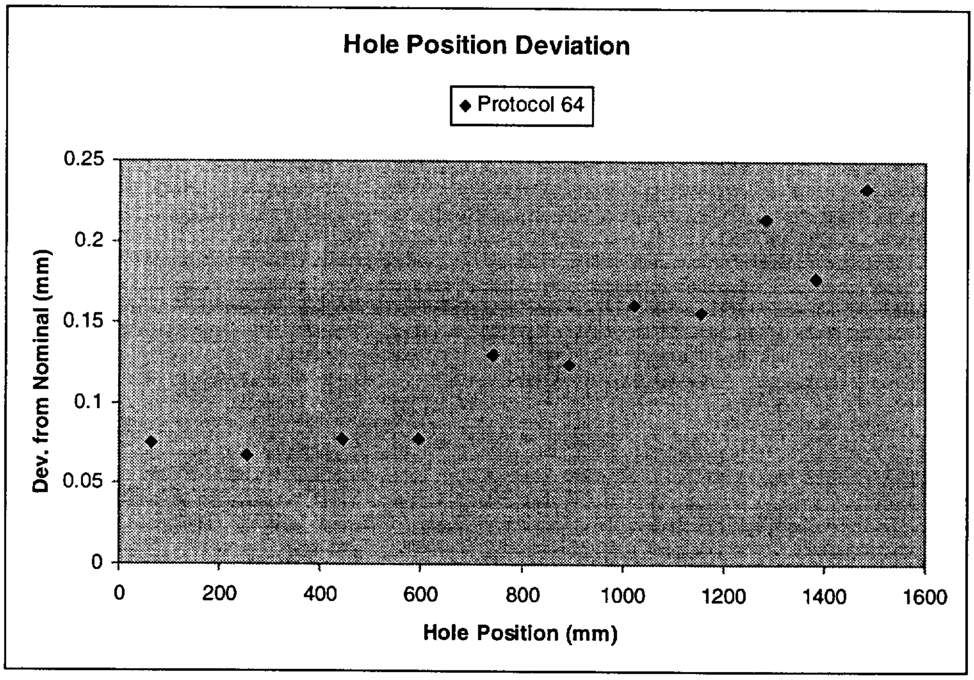

Figure 7. Hole position deviation as a function of hole position from outer radius end of master plate for protocol 64.

Following this evaluation of the data, we also re-visited the design tolerance envelope for scintillators and spacers. We decided that the scintillator design envelope would allow the source hole deviation to exceed 0.2mm without resulting in any assembly difficulties. TATRA was therefore instructed to report, but take no action, if hole location deviations exceeded 0.1mm but were below 0.2mm. Therefore, no action was taken for Protocol 96. With hindsight, it also seems likely that the deviation observed at Protocol 32 was also temperature related.

With the above explanation of glitches, it is appropriate to comment on the residual slope seen in Fig. 6. This could be simply explained by a few degree temperature difference between the operating temperature of the press and the measurement temperature in the measuring room. The measured slope suggests that this might be about 3°C. Of course this is only a guess at this stage and not that important, because all measurements fell within specification.

Finally, this analysis is a testament to the quality of the 3-coordinate computer measurement station and operators at the TATRA plant. Without such high quality data (a reproducibility better than 15 microns was estimated) none of this work would have been possible.

Plate Length, Key-to-Key

The story concerning the plate length is very similar to that of the hole locations (obviously) and, in fact, analysis of its behavior was used in the evaluation of the hole data and determination of temperature effects as the underlying cause. Figure 8 shows the key-to-key plate length versus protocol index for the extended barrel production. The glitches appear at exactly the same place as for the source holes (in particular for Protocol 64) and the distribution is entirely consistent with being uniform for all protocols outside 64-69, as is the case for the source holes. In any case, all measured points fell within the design specification of –0.2mm to +0.1mm from nominal.

Plate Radial Envelope

The plate half-width, measured relative to the center of the key at the inner and outer radius, was also monitored in the protocol data. The average half-width and the rms of the distribution is shown in Table 3 below (the nominal half-width at the outer radius is 188.900mm and at the inner radius 112.100mm). The data show that the plate is slightly more narrow at the inner radius than at the outer radius, though generally the data fall within specification (which allows –0.150mm below nominal). This is in reasonable agreement with the 0.80mm narrowing in half-width reported by the Dubna group monitoring the barrel production. Part of this minor change in the *as-built* dimension has already been accommodated by a small reduction in spacer plate radial width and the remaining deviations are well within the design tolerances.

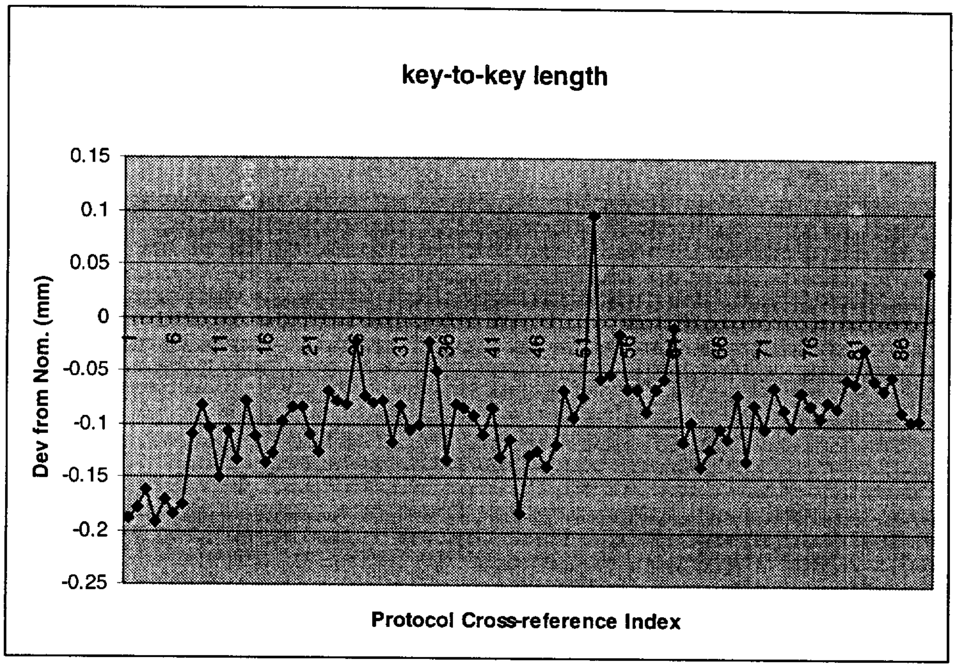

Figure 8. Key-to-key length, deviation from nominal, for all protocols covering the extended barrel production.

	Outer Radius Half Width		Inner Radius Half-Width	
	A1	A2	B1	B2
Mean	-0.117	0.022	-0.138	-0.108
Rms	0.038	0.032	0.032	0.033

Table 3. Plate average half-width difference from nominal and rms (mm) at outer radius (A1,A2) and inner radius (B1,B2).

Summary

This report documents the performance of the stamping die used for the production of the master plates for the extended barrel calorimeter modules. A corresponding summary has been written covering the barrel production,[2] for which the same die was used in the same press at the TATRA plant in Koprivinice, Czech Republic. Construction of this die began in late 1994. At that time there were some serious doubts raised within the Tile Calorimeter subsystem as to whether die stamping could meet the tight design tolerances required of the absorber plates, due to their size (roughly 50cm by 160cm) and thickness (5mm). In addition, there was a question as to whether die stamping could be carried out for an acceptable cost (in initial tooling and subsequent maintenance or even replacement due to wear and tear). The potential gains to be realized, relative to other possible fabrication approaches, were thought to be in the time required to complete production of 80,000 plates, piece reproducibility and costs associated with quality control. None of the serious doubts were an issue and die stamping resulted in the full complement of over 80,000 master plates being produced in under one calendar year with excellent reproducibility for a significantly lower cost than was estimated to be required for the other fabrication approaches that were considered. Quality control was quite straightforward once a good plan was worked out and the production at TATRA could be easily monitored from Argonne.

Acknowledgments

The construction of the die was carried out in the early days of US involvement in the LHC detector program using, in part, funds provided under the Argonne National Laboratory LDRD program. We wish to thank the Associate Laboratory Director at that time, Dr. F. Fradin for this support which allowed the High Energy Physics Division to contribute something unique to the ATLAS detector construction effort and now allows the Division to contribute to yet another major high energy physics calorimeter. The die itself was designed and constructed by Banner Tool & Die Co., Milwaukee, Wisconsin. Their belief was that this die, constructed as a proof-of-principal prototype would be capable of fabricating 80,000 pieces as would be required for the Tile Calorimeter. Their workmanship was outstanding and the data confirm their claim. We wish to thank and compliment them. We were also fortunate to have the opportunity to work with L. Adamcik from ZTS, Dubnica, and J. Suba and J. Kalisek from TATRA, Koprivinice, and would like to express our thanks for their contribution to the success of this work. Finally, we wish to thank the Tile Calorimeter Subsystem Leader, M. Nessi, for his support and assistance.

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