International Conference on Space Optics—ICSO 1997

Toulouse, France

2–4 December 1997

Edited by George Otrio

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International Conference on Space Optics — ICSO 1997, edited by Georges Otrio, Proc. of SPIE Vol. 10570, 1057026 · © 1997 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2326632

THE RESULTS OF THE THIN X-RAY MIRROR MODULE PRODUCTION FOR THE ESA XMM SPACECRAFT [1]*

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ABSTRACT - The High Throughput X-ray Spectroscopy Mission XMM is the second "Cornerstone" Project in the ESA Horizon 2000 Programme for Space Science. This observatory has at its heart three highly nested Wolter 1 grazing incidence X-ray telescopes which will provide a large collecting area (1475 cm^2 and 580 cm^2, each respectively at 1.5 keV and 8.0 keV). This optical system has a spatial resolution of about 16 arcsec and when coupled with reflection grating spectrometers and X-ray CCD cameras, it will provide a major advance in astrophysics by the end of the century

In this paper, we first present the design of the telescope and then describe the manufacturing and the integration processes of the telescope, with the emphasis on the production of the X-ray mirrors. Finally, the results achieved with the three Flight Models of the XMM telescope are presented with some prospective on the next generation of ultra thin X-ray mirrors

Key Words: *ESA, XMM spacecraft, X-ray optics, mirror production, advanced manufacturing, ultra thin mirror.*

1- INTRODUCTION

The X-ray Multi Mirror (XMM) spaceborn observatory (see figure 1), due for launch in August 1999 by an Ariane 5 launcher, has been designed to be a high throughput X-ray spectroscopy mission over a broad band of energies, ranging from 0.1 to 12 keV (as presented in references [1-11]). The payload most prominent elements are the three telescopes, developed under direct ESA contract by a consortium of several European firms led by Media Lario (Bosisio Parini - Italy), each of them having specific technical expertise for the design, the manufacturing and the assembly of the telescopes.

Figure 1. XMM spacecraft with view on the Mirror Support Platform and the three telescopes

The optics of each telescope (hereafter referred to as a Mirror Module (MM)) are made of 58 nested Wolter1 grazing incidence mirrors, chosen to maximise the effective collecting area. This calls for the manufacturing of a large number of very thin X-ray quality mirror shells. In the early 90s, a parallel development program was conducted using two potentially interesting technologies (as discussed in reference[2]): the CFRP epoxy replication,

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* This paper is an update of the one presented during the 48th Congress of the IAF 97 in Torino

successfully applied for Exosat and the nickel electroforming. The nickel electroforming was also successfully used for SAX. However, for XMM, the mirrors were too thick and the optical quality needed to be improved significantly.

In 1993, based on the X-ray testing of several individual mirrors, the nickel electroforming technology was selected for the production of the XMM's mirrors. Despite its lightness, the CFRP technology showed unstable X-ray performance under vacuum due to the roughness created by the "print through" of the carbon fibre matrix.

At that point in time, the production yield ratio of the nickel mirrors was not yet sufficient to start in good conditions the massive production (253 X-ray quality mirror shells representing in total more than 200 m^2 of high quality optical surface) needed for the Qualification Model and the four Flight Models Mirror Module (including one spare). Therefore, a special development programme was financed early in 1995 by the XMM Project to improve the quality of the production of the mirror shells in order to bring the nickel electroforming technology from an "art" to an industrial process. In parallel, under the guidance of Bureau Veritas, a Total Quality Management compliant with the ISO9000 standard was instored at Media Lario.
By February 96, this program had led to the manufacturing and the timely delivery of the full size Qualification Model of the XMM Mirror Module. After optical and environmental testing, this XMM Mirror Module was pronounced qualified in October 1996. The development of the mirror programme and the results of the Qualification Model of the Mirror Module are detailed in references [6,8].

In parallel to the development of the mirrors, the XMM Project team identified the need to develop a dedicated EUV vertical test facility for the verification of the performance of the mirrors. The implementation of this XMM test facility was contracted to Centre Spatial de Liège (Belgium).

2- MIRROR MODULE DESIGN DESCRIPTION

The optical concept of the XMM Mirror Module is shown in figure 2.

Focal length	7500 mm
Resolution in energy	**range (0.1-12 keV)**
Half Energy Width	16 arcsec
Full Width Half Max	8 arcsec
Effective area	1475 cm^2 (1.5 keV)
	580 cm^2 (8 keV)
Mirror diameter	
Outermost	700 mm
Innermost	306 mm
Mirror length	600 mm
Packing distance	1- 5 mm
Number of mirrors	58
Mirror Module mass	425 kg

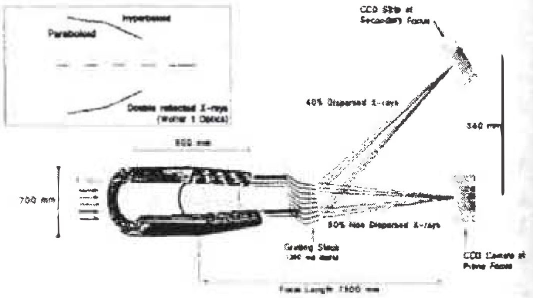


Figure 2. Optical design of the XMM Mirror Module with the grating assembly

The XMM Mirror Module is a grazing incidence telescope (Wolter 1 type) which is designed to operate in the X-ray energy range of 0.1-10 keV with a focal length of 7.5 metres and with a resolution of 16 arcsec. The grazing incidence angle of the X-rays ranges from 17 arcmin for the smallest mirror to 40 arcmin for the largest. A Mirror Module consists of 58 nested mirror shells bonded at one end on a spider (or spoke wheel) and their supporting structure.

Each mirror is a thin monolithic nickel shell which is shaped to a paraboloid surface in front and an hyperboloid surface at the rear for double reflection of the grazing X-rays. The 58 mirror shells, with diameters between 306 mm and 700 mm and a length of 600 mm, are mounted in a confocal and coaxial configuration. The reflective coating of the mirrors is 250 nm layer of high purity gold.

The thickness of the mirror shells ranges from 0.47 mm up to 1.07 mm proportional to their diameter. The mass of the smallest mirror is 2.35 kg and 12.30 kg for the largest one.

The mechanical design of the Mirror Module (MM) is shown in figure 3.

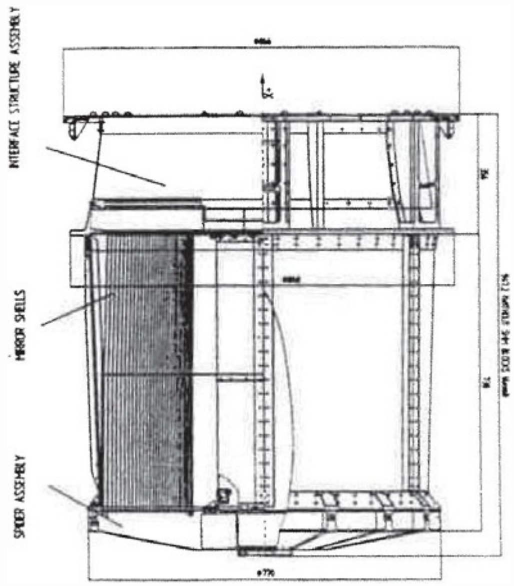


***Figure 3**: Mechanical design of the XMM Mirror Module*

The 58 mirror shells are glued at their entrance plane to the 16 spokes of a spider (spoke wheel) made out of Inconel. This material was chosen for its thermal expansion coefficient close to that of the electrolytic nickel of the mirrors. The spider is connected to the platform of the XMM spacecraft via an aluminium interface structure, called Mirror Interface Structure (MIS).

The Mirror Interface Structure also supports:

- a grating assembly with a mass of 60 kg, on the rear side of two out of three of the Mirror Modules
- the "electron deflector" (producing a tangential magnetic field), right behind the mirrors for diverting the "soft" electrons (with energy up to 50-100 keV) that otherwise will be seen as stray light on the detector.
- the X-ray baffle in front of the mirrors.

Heaters and thermistors, mounted on the spokes and the outer ring of the spider, are used for the thermal control of the Mirror Module at 20°C ± 2°C, with gradients not exceeding 2°C.

3- MANUFACTURING AND INTEGRATION PROCESS OF THE MIRRORS

The three XMM Mirror Modules, representing the heart of the XMM payload, were a major technological challenge to be completed in a short time.

The mirror shell manufacturing is based on a replication process (see figure 4) which transfers a gold layer deposited on the highly polished master mandrel to the electrolytic nickel shell which is electroformed on the gold layer.

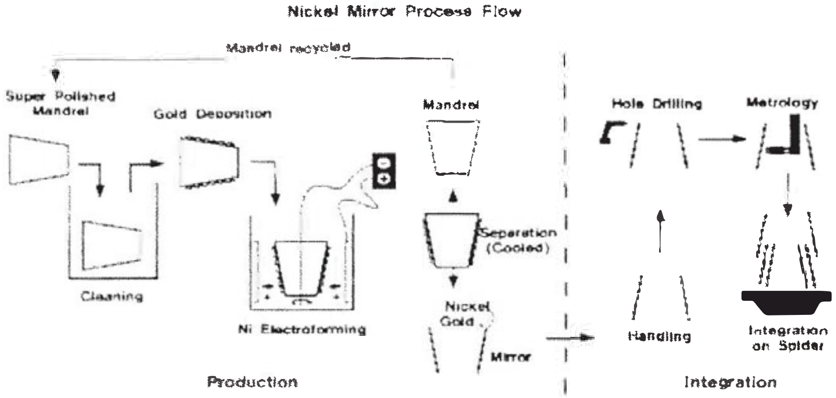


Figure 4: Mirror manufacturing and integration flow

The production of the required 58 master mandrels has been contracted to Carl Zeiss (Oberkochen - Germany). They are machined out of double conical aluminium blocks coated with Kanigen nickel and then lapped to the required paraboloid/hyperboloid shape and finally superpolished to a surface roughness better than 4 Å.

The most critical steps in the manufacturing of the Mirror Module are the production of the mirror shells and their integration on the spider. Indeed, the XMM mirrors are very "flimsy": their diameter to thickness ratio is in the order of 324, ten times larger than for SAX or JET X.
The mirror shell production is divided in the following steps:

- after verification of its surface roughness, the mandrel is thoroughly cleaned
- a reflective gold layer (thickness 2500 Å) is evaporated under vacuum onto the mandrel
- the gold plated mandrel is coated with nickel in an electroforming bath (nickel sulphamate) at a temperature of about 50°C
- the mirror and the mandrel are separated by using the difference of thermal expansion of the materials (aluminium for mandrel; nickel for mirror) and the difference of adhesion of the gold layer between the Kanigen nickel of the mandrel and the nickel of the mirror
- once separated, the mirror is carefully lifted with a highly accurate axial guidance system
- the optical quality of each mirror is assessed by geometry and micro roughness measurements.

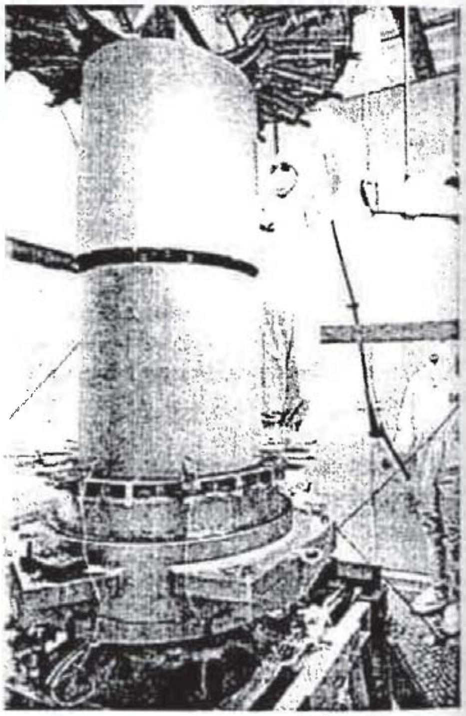


Figure 5: Mirror under integration in the Vertical Optical Bench

The mirror shell integration (see figure 5) is performed in a Vertical Optical Bench (VOB), working from the smallest to the largest mirror. This involves the following steps:

- each mirror shell is aligned at one end using an actively controlled suspension system
- the mirror position is laterally and vertically adjusted in the corresponding grooves in the spokes of the spider
- the mirror is bonded in the spider grooves with epoxy glue
- the optical performance is monitored and compared with that in free hanging conditions.

In order to fullfill the optical performance requirements, the following precautions are taken during the integration of the mirrors:

- the out-of roundness of each integrated mirror is not greater than 100 µm (amplitude of 2nd Fourier component)
- the mirror axis tilt is better than 30 arcsec
- the foci of the mirrors are within a circle of 100 µm diameter
- the paraboloid end of the mirrors are co-centered within 50 µm.

After the integration of the 58 mirrors, the Mirror Interface Structure is bolted on the spider.

Special cleanliness measures have been taken in order to maintain the high reflectivity. The molecular and the particulate cleanliness of the mirrors has to be maintained respectively at 2.10^{-7} g/cm^2 and 300 ppm until the end of the mission. Due to the affinity of hydrocarbons to gold and the criticality of the cleaning process, the mirrors are produced and integrated in class 100 rooms, equipped with charcoal filters.
The technological development and the management of the X-ray mirror programme have been detailed in references [3,6,8].

4- OPTICAL AND ENVIRONMENTAL TEST OF THE XMM MIRROR MODULE

4.1 Test programme

Since February 1997, after their delivery to ESA, the first three Flight Models of the XMM Mirror Module (see figure 6), are being optically, mechanically and thermally tested at various test centres in Europe, i.e. the Panter X-ray facility of the Max Planck Institute (MPE) at Neuried in Germany and the test centre of Centre Spatial de Liège (CSL) in Belgium.

The acceptance program includes the following tests:

- Extreme UltraViolet (EUV) optical and X-ray reflectivity tests at CSL
- vibration tests and thermal vacuum tests (with EUV optical and X-ray reflectivity tests in between for MM FM1) at CSL
- EUV optical and X-ray reflectivity tests at CSL
- X-ray optical tests at MPE.

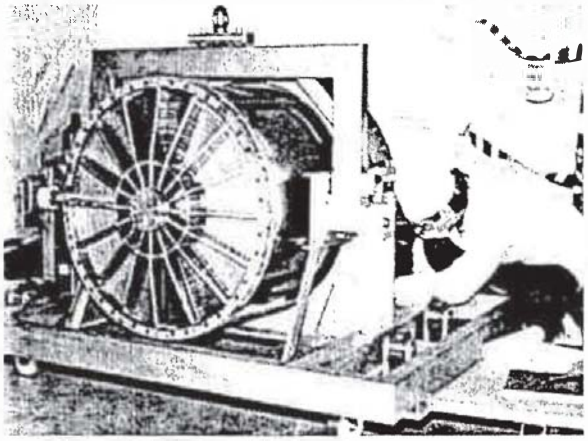


Figure 6: MM FM1 under final inspection at Media Lario

The purpose of these tests is to verify that each Flight Model of the Mirror Module is fulfilling the performance requirements after simulated environmental conditions which are at least as severe as the ones expected during the service life on XMM spacecraft.

The vibration tests were performed on the shaker of CSL. The Mirror Modules were subjected to sinusoidal and random vibration along the X, Y and Z axis at acceptance level (10 g axial and 6.7 g lateral). The thermal tests were carried out in the Focal 2 thermal vacuum test chamber of CSL. The Mirror Modules were subjected to three thermal cycles between -20°C and 40°C (about 60 hours per cycle).

4.2 Optical test facilities

The Max Planck Institute (MPE) X-ray test facility (Panter), which is operating under vacuum, consists of a source chamber and an instrument (detector) test chamber connected by a 130-metre long tube. The instrument chamber (13 metre long and 3.5 metre wide) is equipped with an optical bench on which the Mirror Module is mounted. The Flight Models of the XMM Mirror Module are tested in full illumination (horizontal X-ray beam with a source at 124 metres) at different X-ray energy levels between 0.1 keV and 10 keV, with two different detectors: a Position Sensitive Proportional Counter (PSPC) and a Charge Coupled Device (CCD).

In 1993, following several tests and analysis, the XMM Project had two major concerns related to the proper characterization of the optical performance of the mirrors:

- the effect of gravity on the very thin mirrors
- the impossibility to characterise the complete mirror surface with the available X-ray beam with a source at finite distance

A number of simulations by finite elements models and ray tracing of the effect of gravity on thin mirrors and on complete mirror module were conducted with the support of ESTEC Mechanical Department and BCV-Progetti (Milan - Italy). One conclusion was that the focal image of the mirrors could be significantly affected by their orientation during ground test. With the optical axis vertical, the difference in HEW resolution between zero gravity and ground test condition was limited to one arcsec. But with the optical axis horizontal, it was not possible to correlate to better than 2 or 3 arcsec the optical performance under zero gravity and ground test conditions. The uncertainty on the optical measurement with the mirror axis horizontal was further increased in the X-ray beam with a source at 124 m distance. Under these conditions, the first 30% of the paraboloid section of the mirrors is not refocused and any distortions in this area are just missed. Depending on the type of distortions present in the mirrors, the X-ray measurements under gravity could give better figure than the actual quality of the mirrors warrant.

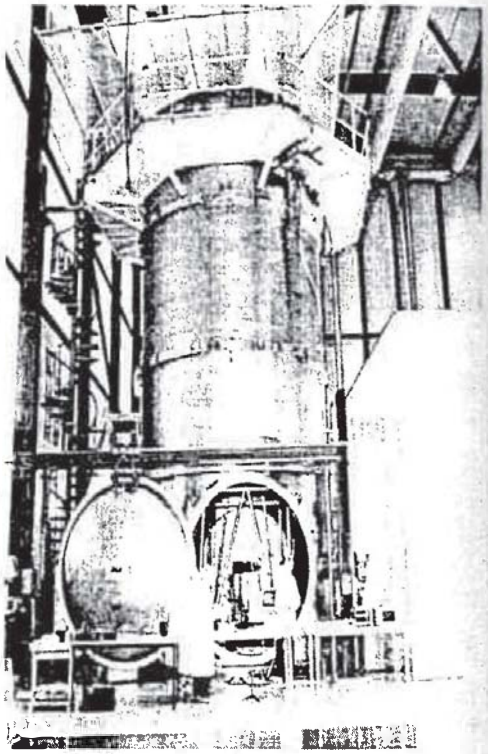


Figure 7: Focal-X facility at Centre Spatial de Liege

Therefore, in 1994, to complement the X-ray measurements to be done in MPE horizontal facility in Neuried, the XMM Project took the decision to finance and build a dedicated EUV vertical test facility (see figure 7).
Focal X is the EUV optical facility built at Centre Spatial de Liège, providing a vertical full aperture collimated EUV beam at 30 and 58 nm and two X-ray channels (pencil beam at 1.5 keV and 8 keV and a small collimated beam at 1.5 keV for reflectivity and scattering measurements). Detailed description of this facility are given in references [4,5].

4.3 EUV and X-ray test results at Centre Spatial de Liège

The image quality (Full Width Half Maximum (FWHM), Half Energy (HEW), 90% Encircled Energy (W90)) of the three Flight Models (FM) of the Mirror Module (MM), measured in EUV (58 nm) at CSL is summarised in table 1 and discussed below.

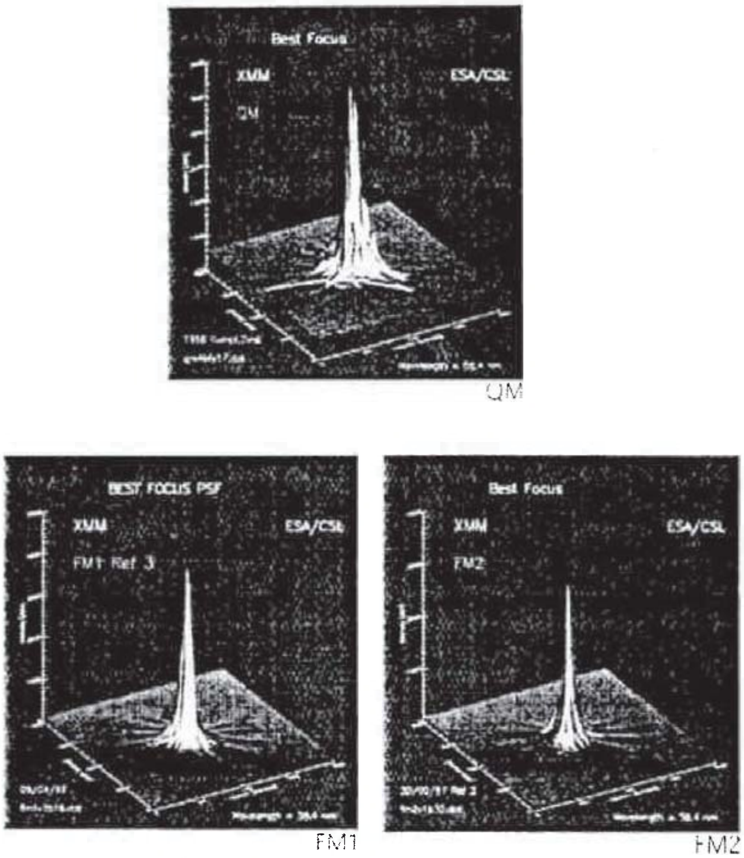
The EUV tests show no significant differences in the Encircled Energy Function (EEF) before and after environmental tests. The overall performance (see figure 8) in terms of resolution indicate consistent and important improvement compared to the MM QM:

- the cores of the Point Spread Function (PSF) are very sharp (no double peak as for the MM QM), especially MM FM3 with a FWHM of 5.9 arcsec
- the (HEW) resolutions are much better than for the MM QM (measured at 20 arcsec)
- the W90 has been improved compared to the MM QM, which was measured at 100 arcsec, due to improvement of the geometry of the edges of the mirrors.

	MM FM1		MM FM2		MM FM3	
Performance (58 nm)	**Pre-environment**	**Post-environment**	**Pre-environment**	**Post-environment**	**Pre-environment**	**Post-environment**
HEW at best focus (arcsec)	15.8	15.5	16.1	15.4	14.2	14
FWHM best focus (arcsec)	6.7	6.7	6.9	6.3	5.5	4.5
W90 at best focus (arcsec)	62	63	63.5	62	58	59
Best focus focal length (mm)	7495.2	7495.3	7495.1	7495.1	7496	7496
HEW at nominal focus (arcsec)	16.1	17.2	17.4	17.2	15.8	15.1
Effective area (cm^2)	1673	1555	1528	1556	1562	1523

***Table 1**: Image quality of the FM Mirror Module from CCD measurements at CSL*

The focal images of MM FM1 and FM2 (see figure 8) show a "triangular" shape, which comes from the distortion of some of the outer mirror shells (see also section 4.4). This distortion, responsible for a performance loss estimated to be in the order of one arcsec, has occurred during the integration of the Mirror Module. Indeed, several analyses have confirmed that the deformation of the outer mirrors is the result of the unevenness between the spider and the Mirror Interface Structure (MIS) (flatness of 15 - 25 µm instead of the specified 5 µm), aggravated by small deformations of the integration adaptor, on which the spider is mounted during the integration of the mirrors. This point was not identified for the MM QM as no large X-ray quality mirror could be integrated in that model. A shimming method was developed and tested, which has been successfully implemented on MM FM3. The optical resolution of MM FM2 has improved by 0.5 arcsec after the environmental testing, due to some relaxation of the mechanical stress at the MIS-spider interface. After the environmental testing, the mirrors recover somehow their original (non stressed) shape as it existed before the mounting of the MIS. The same happened also for MM FM1 but to a lesser extent.



QM

FM1

FM2

***Figure 8**: 3D view of the Point Spread Function of the QM, FM1 & FM2 MMs*

For the three MM FMs, the EUV effective area measurements (see table 1) show a systematic deficit of about 15 %, compared to the 'theory'. The measurement accuracy is about ± 3% (RMS). However the pencil beam X-ray test showed the X-ray reflectivity is within 5% from the 'theoretical' value at 1.5 keV and 8 keV.

The EUV effective area deficit is currently attributed to:

- non perfect geometry of the mirrors not taken into account in the 'theory'
- measurement inaccuracies
- lack of reliable information on gold reflectivity at 58 nm at grazing angle
- eventual contamination.

The good X-ray reflectivity during all the tests and the lack of effective area at 58 nm could be an indication of some molecular contamination, due to the high penetration of the X-ray at this energy level. This assumption is based on some studies conducted by the University of Berkeley (California - USA), confirming the extreme sensitivity of the reflectivity in EUV to hydrocarbons: a hydrocarbon layer of 0.5 nm could cause a 5% reflectivity loss at normal incidence in EUV (60 nm). However this cannot be transposed easily into reflectivity at grazing angle. The origin of any eventual contamination (mostly affecting EUV performance) is not yet identified despite many measurements.
All these results obtained at Centre Spatial de Liege are detailed in references.

4.4 X-ray test results at MPE

The image quality figures Full Width Half Maximum (FWHM), Half Energy Width (HEW), 90% Encircled Energy (W90)) of the first Flight Models, measured at Panter in April-July 97, are summarised in figure 9 and in table 2.

The X-ray results of the HEW and FWHM measurements give values almost identical to those obtained at CSL, within the measurement accuracy of the facility, which was not the case for the MM QM. This confirms that the efforts made on the mirror geometry, especially at the edges and at the intersection plane between the two sections, which are not "seen" at Panter due to its finite source distance, were successful.

The (corrected) values of the HEW obtained with the PSPC and those obtained with the CCD are overall in agreement, even at 8 keV where the corrections of the PSPC values start to be rather uncertain.

The values of the W90 measurements performed with the CCD are better than those obtained with the PSPC due to the limited size of the detector. The PSPC has a diameter of 38 mm, equivalent to a diameter of 980 arcsec in the focal plane, whereas the CCD has a size of 20 x 13 mm, which doesn't cover the wings of the PSF completely. As for the EUV tests, the improved W90 results, compared to MM QM, confirm that the improvements performed on the mirror edges (affecting 10% of the mirror surface) were successful

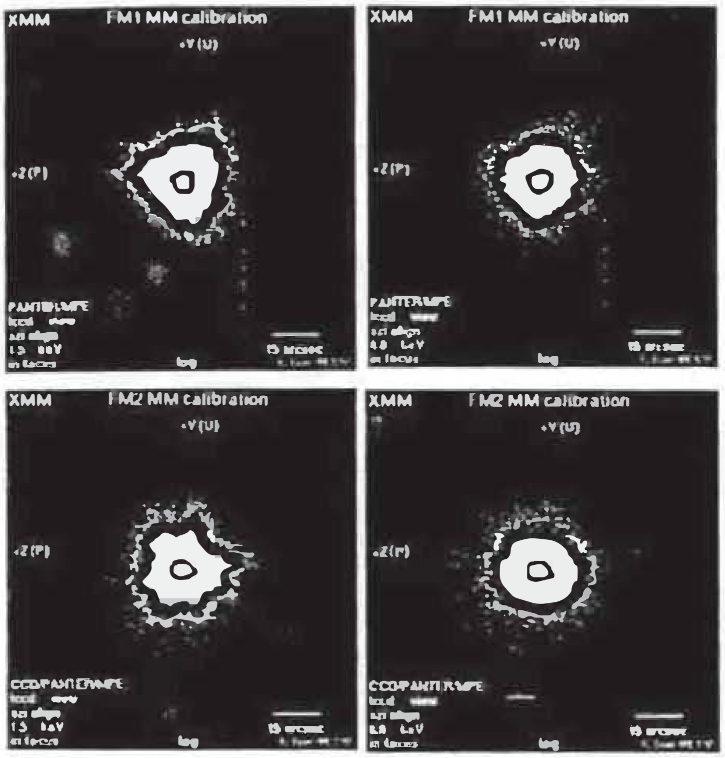


Figure 9: Close view on the focal image of the MM FM1 and FM2 at 1.5 and 8 keV Courtesy of Max Planck Institute (Neuried - Germany)

Performances at X-ray energy levels higher than 8 keV are slightly better than at 1.5 keV due to the better quality of the inner mirror shells. In figure 9, the triangular shape of the core of the focal image is no longer visible at high energies (above 4.5 keV), clearly confirming that the triangularisation is coming from the outer large size mirrors. The shadowing structures seen in the pictures are entirely due to the spider spokes. The images in figure 9 and the figures in table 3, show well that the power in the wing increases at energies between 0.9 keV and 6.4 keV while the central part does not change significantly. At the higher energies, the core and the wings get smaller, since the outer mirrors are no longer contributing, due to the finite source distance and the lower reflectivity of the large mirrors. In conclusion, the mirror scattering, which is expressed in W90 at high energies, is much better for MM FM1 and MM FM2 (180 arcsec) than for the MM QM, (measured at about 240 arcsec at 8 keV).

	FM1 with PSPC*		FM1 with CCD			FM2 with PSPC*		FM2 with CCD		
Energy	HEW	W90	HEW	FWHM	W90	HEW	W90	HEW	FWHM	W90
0.93 keV	-----	-----	15.3	9.1	53	-----	-----	15.0	6.5	51
1.5 keV	14.6	57	15.3	9.1	55	15.7	57	15.1	6.6	53
4.5 keV	16.9	117	15.6	9.1	65	19.9	139	15.8	7.3	60
6.4 keV	15.6	169	15.5	9.1	70	18.6	147	15.3	6.6	65
8.0 keV	13.2	161	14.7	9.1	72	15.8	182	14.8	6.6	64
9.9 keV	-----	-----	14.6	7.7	73	-----	-----	-----	-----	-----

Table 2: *X-ray image quality of the Flight Models of the Mirror Module at best focus (in arcsec)*
*(NB: *HEW data corrected by quadratical substraction of the intrinsic resolution of the PSPC at the corresponding energy)*

For the two first Flight Models, the effective area measured with full aperture illumination were systematically 10-15% lower (13% at 1.5 keV and 10% at 8.0 keV) than the 'theoretical' achievable value. Complementary tests at Panter on MM FM2, with a reduced beam aperture give a more reliable estimate of the effective area. The area is very close to the specified value as shown in table 3. The deficit observed in the full aperture test was not due to the reflectivity of the mirrors (see par 4.3), but to secondary shadowing due to the geometry of the Panter facility (finite source distance) with respect to the tight nesting of XMM mirrors.

	Effective area (cm^2) at 1.5 keV	**Effective area (cm^2) at 8 keV**
Measurement	1420	618
Theory	1534	619
Specification	1475	580

Table 3: *Effective area measurements at 1.5 and 8.0 keV (NB: theory using Henke (81-Zombeck (83) constants)*

5- PROSPECTIVE

From a scientific point of view, it is clear that the resolution of the mirrors is the most important parameter after collecting area. In view of the results of the first three Flight Models, of the knowledge gained and of the low cost of the production achieved, the XMM Project has decided to improve further the technology. Two extra Mirror Modules are now in production and the three best ones will be selected for flight in 1998.

The continuous effort spent on the production of the Flight Models of the XMM Mirror Modules and the systematic analysis of all the 400 mirrors produced so far has led to an improvement of the mirror quality, now largely determined by the performance of the mandrels (HEW= 4 to 5 arcsec).

Having produced the best mirrors from the available mandrels, Media Lario has carried out tests to reduce the shell thickness while maintaining high optical performance. The results of these activities are very promising and the feasibility of the production of good thin shells of 250 μm wall thickness at a diameter of 700 mm (i.e. one quarter of the thickness of a XMM mirror size 1 and 2) has been demonstrated, as shown in the table 4. The short "learning time"(3 months) needed to tune up the process in order obtain this results should be emphasized as well. These results demonstrate that the technology can comply with the requirements of the future X-ray missions in terms of optical performance and mass constraints.

Mirror thickness (μm)	Mirror mass (% of XMM mirror mass)	Mirror mass (g)	HEW (arcsec)
734	69.6	8302	6.5
700 *	67.9	8328	7.5
500 *	50.2	6152	7.4
300	28.5	3400	16.6
258	24.3	2900	16.5
286	27.1	3231	15.5
240	24.0	2865	9.4

Table 4: *700 mm diameter ultra thin mirror production (all mirrors size 2 with exception of the ones marked with * (size 1))*

6- CONCLUSIONS

The development of the XMM Mirror Modules is reaching completion. The continuous effort undertaken under the direct management of ESA to improve the quality of the mirrors has been successful:

- the optical quality of the mirrors is well below the specification and is kept constant, with a production yield now exceeding 90%
- the first two MM FMs have a resolution performance around 15-16 arcsec (HEW) at energies between 0.9 keV and 10 keV, values which are consistent with the 20 arcsec in-orbit requirement
- the third MM FM is under final X-ray testing at Panter and shows already good performance: a resolution (HEW) of 13.5 arcsec at 1.5 keV and 12.5 keV at 8.0 keV
- latest measurements on the MM QM with the EPIC p-n camera made at Panter, have also indicated that the Mirror Module is able to collect and focus sharply X-rays up to 17 keV (few cm^{-2}) with a resolution (HEW) around 15 arcsec
- the production and the testing of the Flight Models of the Mirror Module is going on as planned: the spare Flight Model will be delivered in March 98 for acceptance tests.

During the course of the development, several management novelties have been introduced by the XMM team. The introduction of pure ISO 9000 quality management has been instrumental to master a continuous improvement of the quality of the mirrors. With Media Lario and all subcontractors, the XMM team has operated a management by objectives instead of a classical management by procedures. This has been very useful to reduce the number of formal and less productive meetings in favour of cooperative working sessions down in the workshop if needed. Consequently the quantity of formal paper reporting was also reduced in favour of actual understanding of technical issues. This real understanding on both contractor and ESA side helped speeding up the decision process for the large investment needed up-front to improve the quality.

Today, we have now in Europe a very advanced understanding of the production of very good and very thin optics. Such thin optic can be of course used for future X-ray missions, but also for normal incidence optics such as thin flexible mirrors for adaptative optic systems, microwave high accuracy reflectors or cavities.

7- ACKNOWLEDGEMENT

The XMM Mirror Modules has been developed and manufactured entirely under ESA contract 10545 /93/NL/RE by Media Lario (Bosisio Parini - Lecco - Italy), as prime contractor with the support of:

- APCO (Vevey - Switzerland) for the manufacturing of the structural parts and the containers
- BCV-Progetti (Milan - Italy) for the optical and structural analysis
- Daimler Steyr Puch (Graz - Austria) for the manufacturing of the mirror storage containers
- Kayser Threde (Munich - Germany) for the mechanical design and the analysis.

The highly polished XMM mandrels were developed by Zeiss (Oberkochen - Germany) under ESA contract 10337/93/NL/MS.

All our congratulations go to the industrial team for their work, especially to Dr A. Valenzuela from Media Lario and A. Pugin and C. Jabaudon from APCO.
Members of the Telescope Advisory Group, Dr. B. Aschenbach and Dr. H. Bräuninger from the Max Planck Institute of Garching, Dr. P. de Korte from Space Research Organisation Netherlands of Utrecht and Dr. R. Willingale from University of Leicester as well as ESA personnel are thanked for their continuous support during this programme.
The involvement and the collaboration of the testing teams at the Max Planck Institute under the leadership of H.Bräuninger and at the Centre Spatial de Liège under the leadership of C. Jamar, with special mention of R. Egger, J.P. Tock, I. Domken and Y. Stockman is greatly acknowledged.

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