Product Assurance on the XMM Project

J.P. van Dooren
XMM Project, ESA Directorate for Scientific Programmes,
ESTEC, Noordwijk, The Netherlands

Product Assurance has both a preventative and a corrective role in terms of quality control in a spacecraft project. This article summarises how it was approached within the XMM project, what unforeseen problems were encountered, and what lessons can be learned from our experience.

Product Assurance Management

The main elements of Product Assurance (PA) management are manpower, requirements, information flow, configuration control, risk and reviews.

In the case of XMM, ESA project manpower for PA was limited to 1 PA manager and 1 PA engineer. The Prime Contractor provided 1 PA manager and 5 PA engineers and technicians. Each of the subcontractors has at least 1 PA staff member assigned to the project, and each experimenter has at least 1 PA engineer on their team. Functional support has been provided by ESTEC.

The XMM PA requirements are based on the ESA PSS-01 series of Product Assurance and Safety Standards, tailored to XMM needs. They are applicable to the entire spacecraft, with the exception of X-ray mandrel and mirror production and the instruments (OM, RGS, EPIC and RAD). For the mirror production at Medialario (I), ISO-9000 certification was obtained. The facility was built practically from scratch and several Quality Assurance (QA) and other procedures needed to be written.

Dornier, the Prime Contractor for the XMM spacecraft, expanded the ESA PA requirements into their own ‘PA Requirements for Subcontractors’, which specify the details of XMM PA management for their subcontractors. ESOC organised a new QA structure, following the ISO-9000 standard, and obtained ISO certification. PSS-05-0 is applicable to software.

XMM documents and correspondence have nearly all been generated, stored, transmitted and received electronically. Minutes of meetings are still mostly written by hand. Besides local PC storage, central storage is provided in the form of a Document Management System (DMS) that is accessible via the ESA Intranet. The DMS stores and provides access to faxes, E-mail, reports, technical notes, drawings, etc. Many documents are still faxed, but the E-mail portion is growing. The possibility to attach just about any word-processed text, database file, Non-Conformance Report (NCR) form, scanned photograph or graph, scanned hand-written minutes, etc. to an E-mail message, and the expedient transmission make this technique far superior to faxing. Large documents are sent under the Internet FTP protocol. DMS documents can be searched with keywords. Some discipline is therefore needed from the authors in formulating the title and the abstract. XMM still keeps a paper file, both at ESTEC and at the Prime Contractor, as a backup. Many documents (XMM User Manual, system NCRs) are copied and distributed on CD-ROM.

Some lessons can be learned from the XMM information-handling experience. The use of electronic mail (E-mail, FTP) should be maximised and fax and paper mail must be minimised. Hand-written minutes of Materials Review Board (MRB) meetings should be replaced by electronic text using portable PCs. Teleconferences and video-conferencing (over the Web) should be encouraged. Sub-contractors must be requested to provide their NCRs directly in electronic format. Hand-written notes and drawings must be scanned and electronically linked to the NCR database. Digital photography and videotaping should be encouraged for Mandatory/Key Inspection Point (MIP/KIP) or configuration inspections. All review documents should be on CD-ROM and on the Project Internet web site, with the necessary access limitations, encryption and password protection.

The PSS-01-11 requirements are applicable to Configuration Management (CM). In general,

Figure 1. The Reaction Control System fault tree (loss of human life)

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Loss of Life
caused by
    or ------explosion in contained pressurized environment
    |       caused by
    |           or ------contamination
    |           or ------hot spot
    |           or ------overheating due to jammed closed valve
    |           or ------material incompatibility
    |           or ------other causes
    |
    or ------fire in non-contained ambient environment
    |       caused by
    |           or ------erroneous, un-coordinated thruster operation
    |           |       caused by
    |           |           or ------procedural error
    |           |           or ------other causes
    |           |
    |           or ------loss of containment --- ----AND---  --------------ignition
    |           |       caused by                                        caused by
    |           |           or ------rupture                                 or ------static discharge
    |           |           |       caused by                                or ------electric switch spark
    |           |           |           or ------collision                   or ------lightning induced current
    |           |           |           or ------pressure peak               or ------other causes
    |           |           |           |       caused by
    |           |           |           |           or ------wrong temperature
    |           |           |           |           or ------wrong loading
    |           |           |           |           |       caused by
    |           |           |           |           |           or ------ procedural error
    |           |           |           |           |           or ------GSE pressure regulator failure
    |           |           |           |           |           or ------human error
    |           |           |           |           |           or ------other causes
    |           |           |           |           or ------other causes
    |           |           |           or ------other causes
    |           |           |
    |           |           or ------leak
    |           |           |       caused by
    |           |           |           or ------spacecraft  (see RCSFTR0.WK4)
    |           |           |           or ------GSE
    |           |           |           or ------other causes
    |           |           |
    |           |           or ------spillage
    |           |           |       caused by
    |           |           |           or ------human errror
    |           |           |           or ------wrong procedure
    |           |           |           or ------other causes
    |           |           |
    |           |           or ------other causes
    |           |
    |           |
    |           or ------other causes
    |
    or ------poisoning
    |       caused by
    |           or ------loss of containment  (see above)
    |           or ------contaminated wastes in supply and waste containers
    |           or ------other causes
    |
    or ------other causes
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CM worked quite well on XMM, although some problems were encountered with software CM, because the many software designers used their own design tools and the interfaces and design methods were insufficiently standardised.

Some lessons can be learnt from our experiences here too. Configuration inspections should be included during MIP and Delivery Review Boards. Standards for software CM should be imposed on all software sub-contractors, including operations and experiments. Interface standards must be defined early in the design phase, and software transferability should be carefully tested. Standards for satellite databases must be imposed on all contributors, including the experimenters.

sense, FTA provides a clearer relationship between cause and effect. It encompasses not only hardware effects, but also software, processes, procedures, and everything that could cause a failure when done incorrectly. The XMM project used FTA extensively to analyse the causes of important non-conformances.

XMM had to deal with a number of non-conformances, as chronicled in Figure 2. Minor NCRs were handled at local level, while major ones involved the Prime Contractor, with the ESA PA and specialised project engineers maintaining an overview and taking action whenever necessary. This delegation of quality handling has resulted in very efficient and fast NCR processing. All NCRs that are still open, relating mainly to operations software and database issues, will probably be closed before the Flight Acceptance Review. Waivers have been handled by a Configuration Control Board (CCB), both at the Prime Contractor and at ESA. This approach has prevented ‘creeping design changes’.

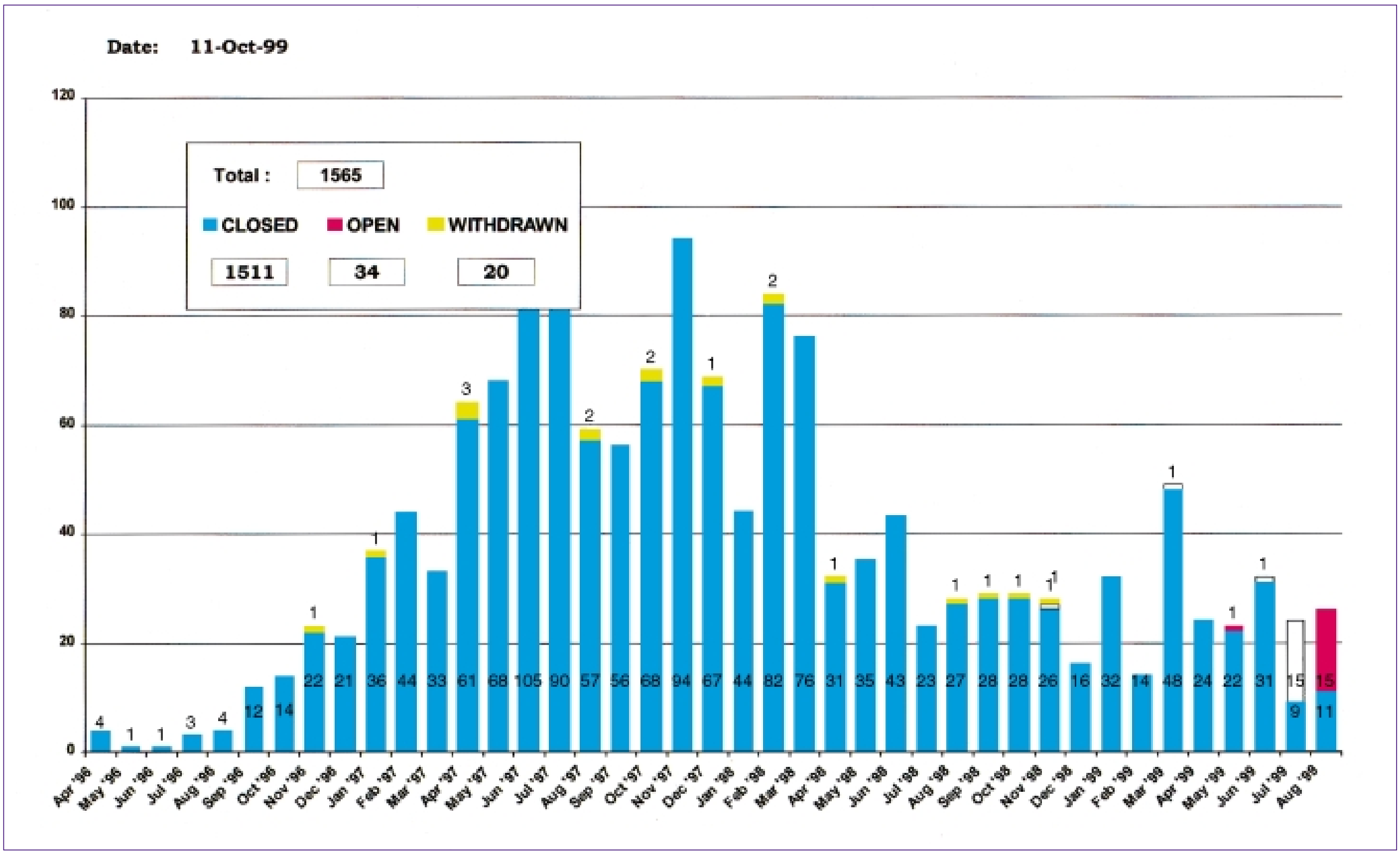

Figure 2. History of major XMM non-conformances

The flow of NCR data could have been improved by requesting subcontractors to write their NCRs directly in database format and E-mail them (within the required 24 hours) to the Prime Contractor and to ESA. ESOC opted for consequent database processing of NCRs and their system is working excellently.

Formal risk management was not an XMM requirement, but an XMM Safety Review was held that achieved roughly the same result. This review used Fault-Tree Analysis (FTA), starting from an overall ‘loss of mission’, down to the general system functions. Every function was further divided into subfunctions, and into causes that could lead to a subsystem failure which could lead in turn to the loss of the mission. The Reaction Control System fault tree is shown as an example (Fig. 1).

FTA uses a ‘top-down’ approach, whereas Failure Mode Effects and Criticality Analysis (FMECA) follows a ‘bottom-up’ method. In this

EEE Parts Procurement

As is customary at ESA, PA runs the procurement of electronic, electrical and electro-mechanical (EEE) parts. The reason for this is that testing and quality control is the most important aspect of parts procurement. IGG of Fareham (UK) was selected as the Co-ordinated Parts Procurement Agent for both the XMM and Integral spacecraft in early 1995. They collected the parts' orders from all users, combined them, proposed alternate choices to reduce the number of types, ordered the parts from the manufacturers, performed inspections and functional and parametric tests, and dispatched the parts, with the appropriate number of spares, to the users. Parts known to be radiation-hard above 100 krad were not total-dose-tested again, those between 20 and 100 krad were radiation tested (three pieces per lot), and parts that did not withstand a total dose of 20 krad could not be used. A few waivers were accepted for parts violating this requirement, but which are sufficiently shielded to achieve a low total dose.

Decisions were made during a monthly Parts Co-ordination Board (PCB) meeting at IGG. Most parts were bought against SCC specifications, some against MIL-STD class S, and some against JANTX that were upgraded. The total volume of EEE parts bought by IGG (XMM and Integral) was about 730 000 pieces, divided over 2686 ‘line items’ (different parts). Their quality was controlled through 592 NCRs, which were all closed. 21 NCRs resulted in lot rejection. The main problems encountered were radiation sensitivity, logic IC delivery, and the general quality of some parts.

A major problem occurred with ASICs (VCA and VCM SOS) from one manufacturer, which are used in the Command and Data Management Unit (CDMU) data channel. Parts were rejected because of excessive leakage currents. We discovered that these parts accumulated an electrostatic charge during burn-in, because of some floating pins due to bad contacts. The charges could be removed by a bake-out, which removed the leakage currents. The lot was eventually accepted and the parts caused no further problems.

Materials and Processes Engineering

The XMM Project has pioneered the use of several materials and processes for novel applications. Because of their criticality, they were subjected to rigorous qualification tests.

For the telescope tube, cyanate ester prepreg. mats have been used instead of the better-known epoxy mats. The cyanate CFRP has better mechanical properties and much lower outgassing than epoxy. In order to achieve the specified cleanliness requirements inside the tube, an aluminium vapour barrier was necessary to prevent outgassing towards the inside. The internal surface had to be black for stray-light suppression, and smooth to minimise the effective surface to which contamination molecules could adhere. Both requirements were satisfied with the selection of black Kapton as the innermost layer. It has similar optical absorption characteristics to rough black paint, such as Electrodag 501, but it is very smooth and shiny, which is actually an advantage for stray-light suppression.

A ray of stray light is reflected from the Kapton surface in a specular pattern, whereas from the black paint it reflects in a spherical pattern. This means that for the black Kapton, the telescope tube is only filled with stray light after several reflections, and from the paint in only one. Since at every reflection about 95% of the stray light is absorbed, the suppression is more effective for black Kapton than for black paint, despite or rather thanks to its shiny appearance. It is also slightly conductive. From a cleanliness point of view, the Kapton also proved to be vastly superior to any other inner lining. One important problem was the adherence to the aluminium vapour barrier foil. Several adhesives were evaluated for adhesive strength and low outgassing. Problems with air bubbles occurred during structural and thermal model manufacture. A large air bubble was discovered in the flight-model tube just before the final integration of both tube halves. It was decided not to repair it, but to deflate it by drilling three small holes into it from the outside, without puncturing the inner liners.

The mirror production processes revealed many interesting problems, all of which were successfully solved. The mirror mandrels at one time suffered from a high density of pores. This was caused by an inadequate choice of material (cast aluminium versus forged), which was sensitive to micro-corrosion. This caused tiny pits on the surface on which nickel was deposited. From these pits, pores started to grow around hydrogen bubbles that were not readily removed by the electrolyte flow. A change of material eliminated this problem. Initially, a great deal of effort went into the process of mirror separation from the mandrel. Many small improvements eventually resulted in a mirror shell and module quality well within specification.

An unexpected group of materials and process problems showed up with adhesives. The cells on the spacecraft’s solar panels are protected against ultraviolet light and micrometeorites by cover glasses. These are covered with a conductive layer of Indium Tin Oxide (ITO), to prevent electrostatic charging. The ITO is electrically connected with the neighbouring cells' ITO with a dot of conductive RTV silicone rubber. To prevent a short-circuit to the solar cell, a layer of non-conductive RTV is applied first. It turned out to be very difficult to get a low resistance from the ITO layers to ground. Eventually, we settled for a resistance of better than 2 MOhm, which was shown to be more than adequate to remove any charges induced by radiation-belt electrons or protons.

A similar problem occurred with the Optical Solar Reflectors (OSRs), small mirrors that are glued to a Sun-facing surface to keep it cool. They are also covered with a thin layer of conductive ITO to prevent electrostatic charging, on the top and on the sides. The electrical contact with the spacecraft structure, which is the ‘ground’, is made via conductive RTV at the metallised back, which is connected to the ITO layer at the top through the sides. The main difficulty is making the RTV sufficiently conductive, by adding silver powder. In our case, it did not work. A solution needed to be found by grounding the ITO from the top. Several conductive adhesives were applied on test samples, thermally cycled and tested. The best results were obtained with Electrodag 501, applied at the OSR edges, because it was discovered that the ITO did not extend into the mirror corners.

Another adhesive problem occurred with heaters inside the p-n camera, which see severe thermal cycling. The solution was to mechanically clamp the heater strips to the structure, and not to rely on adhesive strength at all. Yet another adhesive problem showed up with the Delrin stand-offs used to keep the Multi-Layer Insulation (MLI) thermal blankets at a few centimetres distance from the tube, to minimise damage from possible micro-meteoroid impacts. Many stand-offs separated from the tube at the acrylic glue-to-Delrin interface. They were perforated and an epoxy glue was applied that protruded through the holes in the feet, creating a kind of rivet effect. This improvement successfully passed thermal-vacuum and acoustic testing.

An important lesson to be learned from our experience with adhesive problems is that thorough training, and possibly certification, is needed for technicians working with adhesives, to the same degree as with hand-soldering and other vital skills. This is a task for the specialist ESTEC laboratories.

A serious problem occurred during electrical testing (SVT-1): the CDMU showed bootstrap oading errors in some parts of the memory, on both redundant units. Suspect memory chips were removed and tested at ESTEC, but proved fault-free. The most likely cause was one or more open circuits in the multi-layer printed-circuit boards (PCBs). These were sent to ESTEC’s laboratories for cross-sectioning. Two open-circuited ‘vias’ (plated-through holes) were discovered, which explained the failures (Fig. 3). More than fifty vias were cross-sectioned at ESTEC and at the PCB manufacturer, without discovering any further opens. The root cause of the problem was traced back to the manufacturing process. During the cleaning of PCBs with very fine vias, the procedure called for a powerful vibrator to be switched on, in order to remove any air bubbles from the holes. This had been forgotten for the XMM and Integral flight boards, which were in the same lot. For the spare-board lot, the vibrator had been switched on. These boards were thermally cycled to simulate the reflow soldering process, and thoroughly visually inspected, and they were fine. The boards were completely assembled, environmentally tested, and passed without problem. They have been used since then and passed acoustic testing without a glitch.

During X-ray testing of the propellant tanks, a handling error caused deformation of a titanium

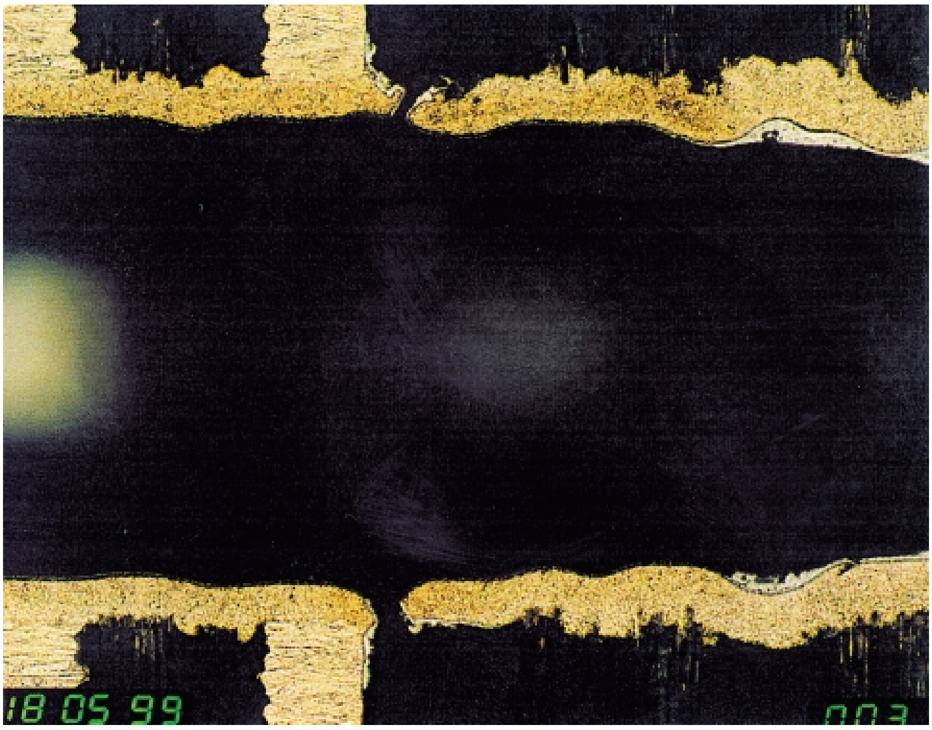

Figure 3. Detail of a via (plated-through) hole from a failed area, showing the gap in the barrel copper

tube. Since it happened very close to the tank inlet fixture, it was impossible to weld. The manufacturer proposed to use a ‘Cryofit’ memory metal shrink sleeve, which is used extensively on fighter aircraft, where it is subjected to high stress, and on some NASA spacecraft. We decided to perform a series of evaluation tests on it, namely vibration, thermal-cycling, and static-bending and torsion-load testing until failure. The devices turned out to be very robust and it was very difficult to cause a leak under high mechanical stress. We declared it qualified for the repair. ESTEC is currently engaged in a qualification programme for this repair technique’s general use.

Cleanliness

The cleanliness requirements for XMM are very strict, with a maximum of 200 ppm at end-of-life for particulate contamination, and $2x10^{-7}$ g/cm^2 for molecular contamination. These requirements apply inside the telescope tube, which is a Class-100 environment, to the mirrors and to the experiments. The rest of the spacecraft is a Class-100 000 environment, at the level of a normal Assembly, Integration and Verification (AIV) Clean Room.

In the design phase, these stringent requirements were taken into account by making the mirror modules, the telescope tube, and the experiments separately closed units, with their own doors and purging devices. The tube and mirror modules had to be always closed, except for relatively brief moments during optical testing. Special mirrors are used for alignment, so that the mirror module did not need to be opened for this purpose. The mirror modules, telescope tube and optical monitor were continuously purged with pure nitrogen or synthetic air. The EPIC MOS and p-n cameras were evacuated, whilst the RGS cameras were pressurised with nitrogen.

The telescope tube is sealed from CFRP outgassing towards the inside by a continuous aluminium foil, acting as a vapour barrier. For stray-light suppression, the inner surface needs to be black. It also needs to be super-clean. Both requirements were satisfied by choosing a black kapton foil, 25 micron thick, as the innermost layer, glued to the aluminium foil with low-outgassing adhesive. The kapton foil could be cleaned, but this was never necessary thanks to the above-mentioned contamination prevention measures.

Overall cleanliness conditions were kept under control through a detailed measurement programme. AIV room particulate cleanliness was continuously measured with fixed particle counters. The ESTEC and Dornier Clean Rooms have an elaborate air-conditioning system with electrostatic and high-efficiency particulate air filters. A mobile counter was set up next to the satellite. Particle fall-out mirrors (PFOs) were installed before each important test phase and evaluated for particle count. Molecular witness plates were also regularly used.

Tape lifts were taken from inside the telescope tube and sometimes on the outside. Wipe tests were performed on the inside of the tube to measure molecular contamination. For both the structural and thermal model and for the flight model, the measurement results were always well within specification, proving that our contamination prevention programme worked. After thermal-vacuum testing in the Large Space Simulator (LSS) at ESTEC, tape-lifts measured 50 ppm average inside the tube. Wipe tests measured $<0.1x10^{-7}$ g/cm^2.

The most serious cleanliness problem occurred with the EPIC p-n camera’s flight model. Noisy signals were read from part of the 4-inch wafer CCD, which is not passivated. At first, it was believed that a coronal discharge due to ice formation was responsible, caused by insufficient vacuum during cooling down. We used the fault-tree technique to identify all possible (imaginable) causes of failure, and possible contamination was listed a number of times. The ESTEC quality-control laboratories tried to provoke such a discharge by cooling test CCDs down in weak vacuum conditions, but that proved to be impossible. Tape lifts had been taken from the flight-spare camera, and a large number of metallic and non-metallic particles were identified with a Scanning Electron Microscope (SEM) (Fig. 4). The failure symptoms were very closely reproduced by randomly shedding metallic particles of different sizes and shapes over the (uncoated) rear side of the CCD.

The lessons learned regarding cleanliness, mainly during the structural and thermal model campaign, can be summarised as follows:

– Keep all sensitive surfaces closed and enclosed volumes purged as long as possible.
– Use all existing techniques for measuring particulate and molecular contamination extensively throughout the programme, and take immediate action if cleanliness deteriorates.
– Test contamination-control procedures during the structural and thermal model programme.
– Perform regular cleanliness inspections involving the materials laboratory.
– Coat or passivate vulnerable surfaces.

Quartz crystal monitors had been installed on the mirror modules to measure molecular contamination, but they turned out to be unreliable.

Radiation

Like every space project, XMM has an extensive radiation-control programme. The space radiation environment was estimated by ESTEC experts, and summarised as a total dose curve versus shielding thickness. Dornier (D) performed a sector analysis, in which the expected total dose was estimated for every electronic unit, assuming a certain amount of shielding from the spacecraft. Every unit designer did his own sector analysis, taking the spacecraft's and his own unit's shielding into account. He provided a list in which the total dose seen during the satellite's ten-year orbital lifetime by every electronic part was listed.

The Central Parts Procurement Agent (IGG) conducted total dose testing, with the standard cobalt-60 test, on those parts that were known to be sensitive to less than 100 krad. Parts sensitive to less than 20 krad were, in principle, rejected. Late in the project, a controversy emerged regarding the radiation hardness of 3C91 opto-couplers. Several laboratories had irradiated these parts with protons, and this showed that they were degrading much faster than with the standard cobalt-60 test. We started a thorough analysis effort on all circuits where this device was used. Monte-Carlo simulation was used to assess what the real failure rate would be, using the actual measured Current Transfer Ratios (CTRs) for the procured parts, as measured by IGG, the actual shielding thickness for the unit, realistic assumptions for the other parameters, and a statistic of the CTRs after proton irradiation versus shielding thickness. The results indicate that in some worst cases on some circuits there may be a problem after several years in orbit. We decided that the risk was small enough to leave the circuits as they were, and to fly them as is. In the critical circuits (FDCE, ACC, PDU) a very large amount of de-rating had been applied, reducing the failure risk almost to zero.

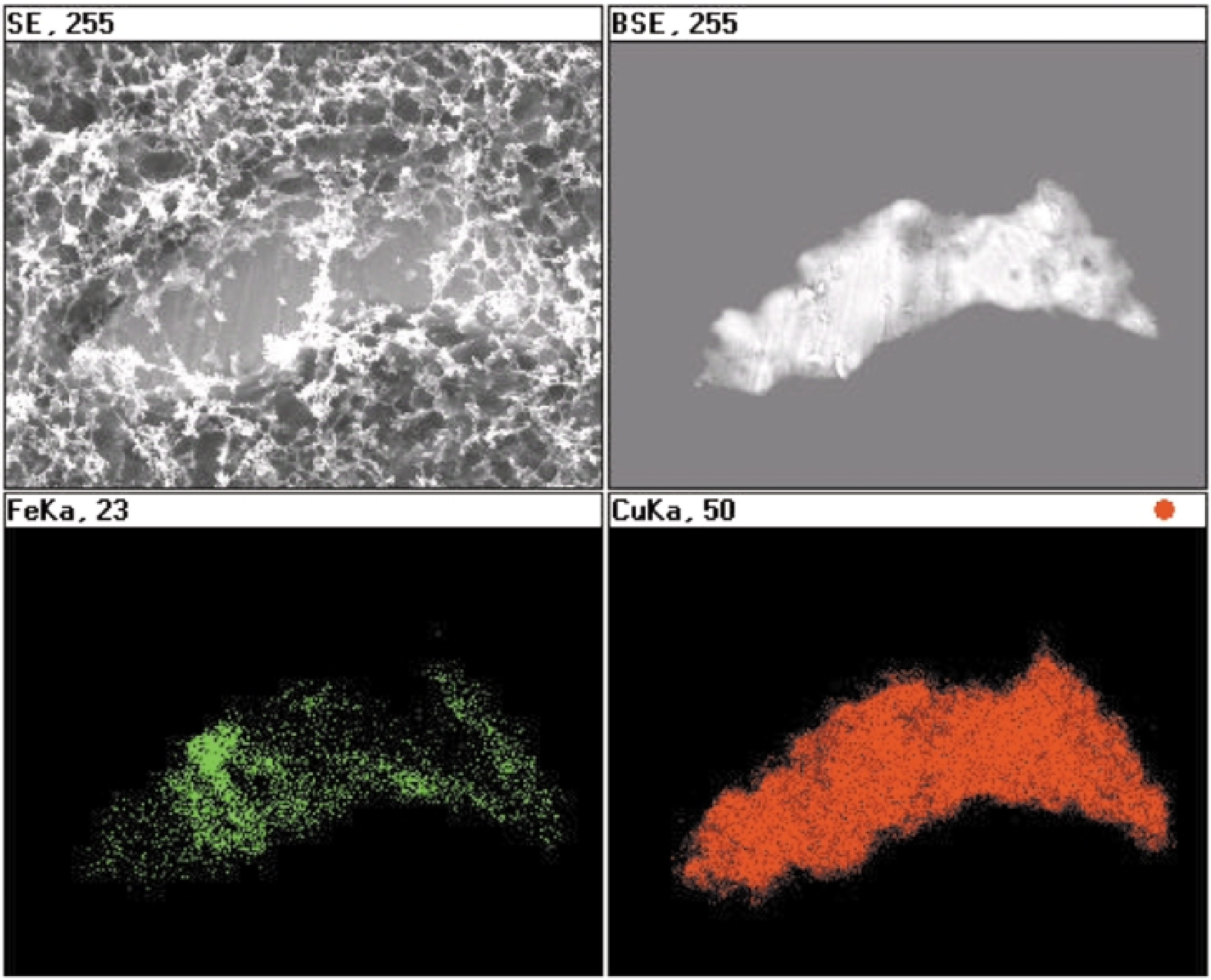

Figure 4. SEM images of a contaminant particle in XMM's p-n camera

Much effort has been spent to evaluate the sensitivity to Single Event Upsets (SEUs) of a number of XMM's components. The driving factor behind this effort was the temporary loss of the SOHO spacecraft in 1998. A number of phenomena had been recorded before contact was lost that could be explained by SEUs in several circuits. We had already carried out a number of SEU tests on parts used in the (non-redundant) FDCE unit. Test circuits were built and the tests themselves were carried out by Hirex at the University of Louvain-la-Neuve (B) on their synchrotron facility.

The devices under test are irradiated with diverse species of ions, corresponding to energy levels of 1 to more than 100 MeV. The electrical transients in the circuit are counted and recorded. By repeating the test at several energy levels, an upset rate against energy curve is obtained. From this graph, a threshold energy is derived at which the part starts to get upset, and a 'cross-section', which is a measure of the upset rate at threshold. A mathematical convolution of this graph with the distribution function of heavy-ion particles in orbit versus their energies yields the expected upset rate for the tested part in orbit.

Several parts turned out to be quite sensitive. If they were in a critical circuit, performing a critical function, we decided to modify the circuit to make it more immune to SEUs. This can be readily done by slowing the circuit down with RC low-pass filters. The XMM team has in fact done some pioneering work in the field of SEU immune design, which now needs to be expanded into a standard procedure and made available to all projects.

Software

The XMM software requirements are according to ESA PSS-05-0 and ESA PSS-01-21, tailored to project needs. Flight software was validated by an independent contractor. A large number of Non-Conformance Reports were written on Electrical Ground-Support Equipmant (EGSE) software. Problems were encountered due to weak configuration control, and too little standardisation of development tools.

RAMS

Reliability block diagrams and FMECAs were made at system level and at unit level, and also for the complete Attitude and Orbit Control Subsystem (AOCS). A reliability budget was not required for XMM. Reliability analysis is most useful in the initial design phase (Phase-A) of a project, when the overall architecture and concepts are defined. If it is done later, it becomes too much of an academic exercise. Fault-tree analysis was used extensively throughout the project, both for failure analysis and design reviews. Safety is limited to compliance with launch-safety (CSG) requirements.

Ground operations

ESOC started a programme in 1998 to gain ISO-9000 certification for the Centre, which is about to be finalised. The XMM project has benefitted from this effort, by co-operating to set up a non-conformance management procedure, which is working very well. Doubtless, XMM will also benefit from this quality awareness during its operation in orbit.

Conclusions

Product Assurance has proved to be a vital discipline for the XMM project. Important progress was made in materials engineering, especially regarding telescope tube and mirror materials.

EEE parts procurement was well within schedule and cost, and is a guarantee of quality. Hundreds of parts' problems were solved accurately and expediently. The XMM safety review, using top-down Fault-Tree Analysis, was a novel approach to design assurance. Cleanliness control was rigorously enforced, with outstanding results. ESA PA assistance to Experimenters was greatly appreciated, although somewhat late. Important efforts were made in Single-Event Upset analysis and prevention. The ESOC ISO-9000 certification process was very helpful in improving quality assurance for the ground operations for XMM.

Acknowledgements

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