Digital Camera Application in X-Ray Real Time Control of European Launcher's Solid Rocket Motors.

Elena TOSTI
AVIO Propulsione Aerospaziale, Colleferro (RM), Italy
Phone: +39 0697285835, Fax: +39 0697285893; E-mail: elena.tosti@aviogroup.com

Abstract

X-Ray real time control of Solid propellant Motors for the European launcher have been used since 1988. At the beginning of this application only analogue cameras where available and the required sensitivity needed the development of a customized camera. After 20 years of almost continuous usage the camera has had to be replaced due to the deterioration from X-Ray exposure extreme conditions. A new generation camera has been selected by considering two main requirements being actually possible by the state of art technology with respect the eighties: commercial available device and digital technology. Due to the extreme usage of the camera, tests have been performed in order to define if there was commercially available a such product or if again a customized camera was necessary for substitution of the old one. A high sensitivity EMCCD camera developed for low level emission with high spatial resolution and high frame rate has been considered how a potential substitute of the outdated and damaged camera. The comparison between results obtained from tests using the old analogue camera and the new digital camera shows that the new camera can replace the previous camera with all the advantages in terms of better performance coming from the digital sensor used and commercial availability of the device.

Keywords: X-Ray, radioscopy, Solid Rocket Motor, ICCD, EMCCD, digital, detector.

1. Introduction

In this paper the main information relevant to the activities finalised to the replacement of an obsolete radioscopy system used for X-Ray inspection of European launcher Solid Rocket Motor, are summarized. For clarity, a preliminary overview of the requirement submitted to the X-Ray radioscopy control of the motors is presented. On the basis of this requirement, tests finalized to the selection of a new system have been performed and the results are presented and discussed in this paper. The design of the new system is then presented and its final performance compared with the requirement.

2. X-Ray Inspection Methodology and Technical Requirement

The European launcher uses two solid propellant boosters each of them made of three segments (see Fig. 1): a forward segment SRM1 in which the igniter is installed, a central segment SRM2 and an afterwards segment SRM3 assembled with the nozzle. The three segments are built by AVIO Propulsione Aerospaziale and Regulus a Society operating in the Europe's Spaceport in France Guyane. In the Fig. 1 a section of the motor is shown and the main objects of the X-Ray inspection are highlighted. These objects are: propellant, thermal protection, liner and interfaces between them.

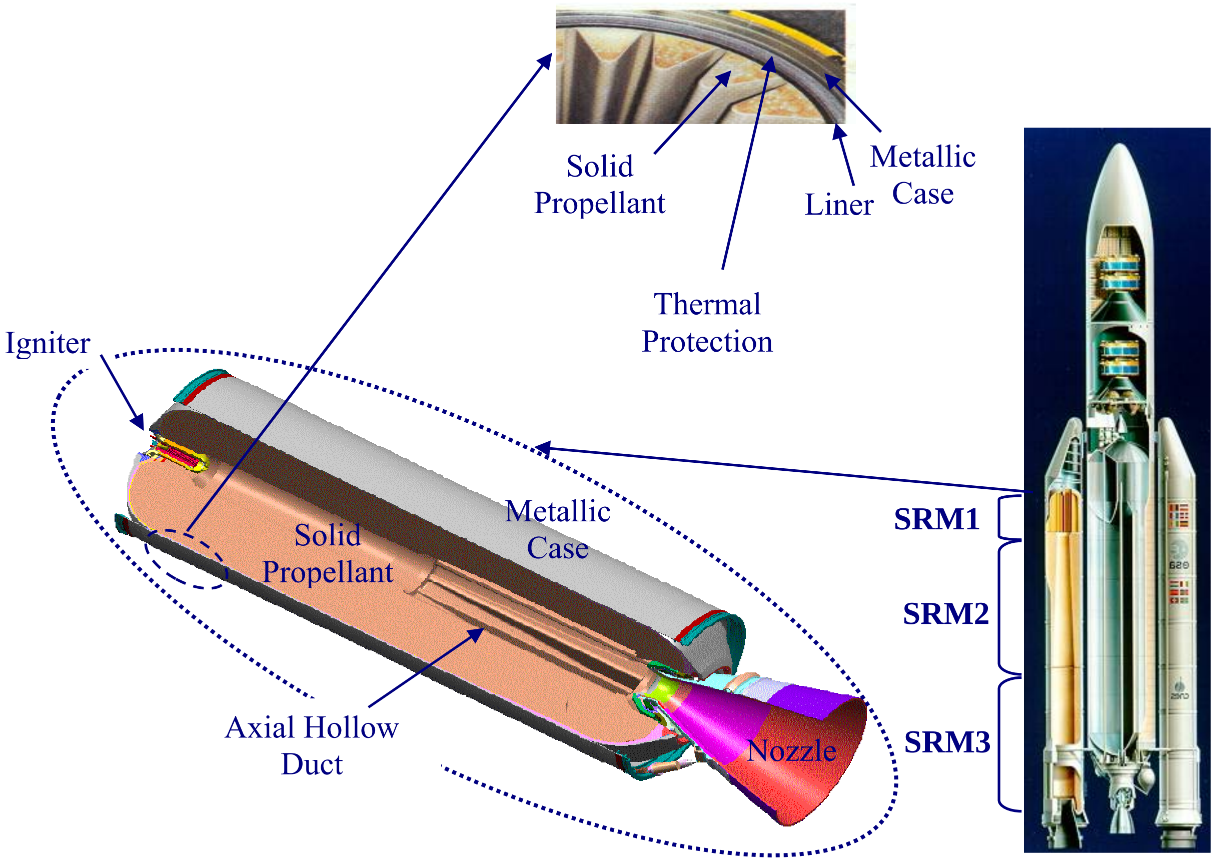


Figure 1 – Schematic of the European launcher.

After propellant loading, each segment is submitted to a radiographic inspection by means of a radioscopy system made of (see Fig 2): an optical camera generating the image from the collection of the visible photons emitted by a conversion screen on which the X-Ray beam releases its energy after the passage through the inspected object.

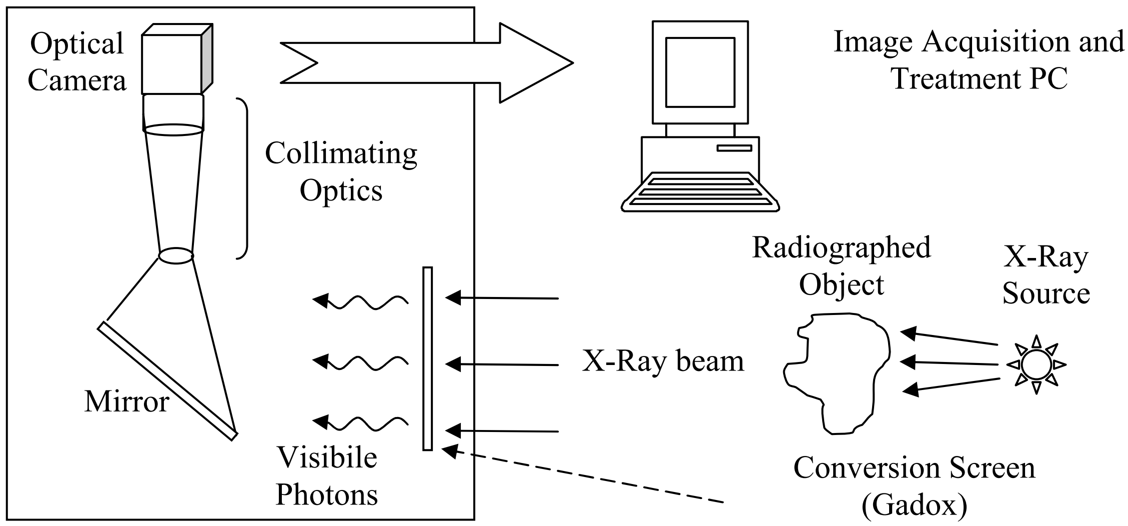


Figure 2 – Schematic of the radioscopy system.

The radiographic inspection on the motor has the purpose to check for: defects in the propellant (voids and cracks) and defects in the interfaces between case, thermal protection and propellant (debondings). Two radiographic techniques are used to inspect the presence of these defects: a single wall axial exposure with the radioscopy detector placed inside the inner hollow duct on the motor axis (see Fig. 1), allows for propellant inspection and a tangential exposure with the camera and the X-Ray source aligned tangentially to the motor external case is devoted to inspect the interfaces integrity. In order to have a 100% radiographic coverage the inspection is performed dynamically, that is: a real time radiographic image is obtained as the segment is continuously rotated.

Even if thermal protection and propellant are very low density materials, the large dimension of the motors (3 m in diameter) and the addition of stainless steel case, requires a very high energy X-Ray source. A dual energy source (9, 15 MeV) it is required to allow both axial and tangential control respectively. This high energy X-Ray source makes the definition of a radiographic image detector a big challenge mainly if a dynamic control is required. Among the three segments, SRM1 is the smallest, but most difficult from a radiographic inspection point of view. This because of the star shape of the propellant that generates a large radiographic latitude and a very fast change in thickness while the dynamic inspection is performed. All these considerations goes in the related technical requirements listed as follows.

- *High Sensitivity*: in a system using a luminescent screen the conversion efficiency is low (an absorption efficiency of about 20% is typical at the highest energies [1]) and a further reduction of the collected light transmitted by the optics to the camera, has to be considered due to the inevitable losses. In these conditions only a very sensitive device can achieve an image bright enough to obtain good radiographic performance. The lowest light level in the condition of the X-Ray control in object, is obtained at 15 MeV tangential control. In this case at least a sensitivity of 10^{-3} lux has been demonstrated as the minimum acceptable.
- *High Frame Rate*: an inspection in dynamic mode requires an high frame rate to provide a good real time radiographic image of the motor as it rotates. In addition, to reduce the apparent photon noise, it is also necessary to use a small number of frames (4 or 6) to generate a rolling average image. The use of slower frame rates, or more frames of integration will allow smaller defects to be missed by the operator. The frame rate has to be adequate to the rotation speed of the object. On the other hand the rotation speed has to produce the sensation of the motion to the operator in order to catch its attention and make more efficient the defect detection. A value of 25 f/s is typical in application similar to that in object.
- *Variable Gain*: due to the variable thickness of the propellant, the sensitivity of the camera needs to be adjusted dynamically during the rotation of the object. Also this “Gain Control” velocity has to be adequate to the rotation speed of the object.

In addition to these requirements, other conditions have to be imposed in order to define the camera to be installed in the new radioscopy system, namely: a field of view unchanged with respect to the old system and a final radiographic resolution equal to or better. Where possible a commercial camera would be preferred even if a customized solution may provide good performance. Finally, a complete automated sequence of the control and an operative mode of the accelerator oriented to an high economy in the total dose irradiated during the inspection, were required.

3. Performance Evaluation of Some Cameras Proposed for the Control

In this section a comparison among the most representative of the proposed cameras is presented with respect to the old camera considered as a baseline. The comparison is made both in terms of technical characteristic and performance from dedicated tests. Since technical considerations in this paper are not compromised if only acronyms indicating the cameras are used, any explicit reference to the manufacturer of each camera is avoided.

The following table summarizes the main technical performance of the cameras.

CAMERA	NUMBER OF PIXELS	SENSOR AREA [mm]	FRAME RATE [f/s]	MAX GAIN	ADC	SENSITIVITY (min light level at max Gain)	RESOLUTION
EMCCD Digital	1000(H) 1000(V)	8x8	30.1	$2 \cdot 10^3$	14 bit	(declared) 10^{-4} lux	342x342 mm
ICCD Analogue	768x575 (final monitor resolution)	Φ40	25	10	8 bit	(estimated) better than 10^{-3} lux	515x515 mm 30lp/mm 500-600 TV lines
Old Camera SIT Analogue	768x575 (final monitor resolution)	Φ40	25	10	8 bit	(estimated) better than 10^{-3} lux	515x515 mm 30lp/mm 500-600 TV lines

Table 1 – Performance of the proposed cameras

Acronyms:

EMCCD: Electron Multiplied CCD camera   ICCD: Intensified CCD camera

SIT: Silicon Intensified Tube

Feasibility tests were performed by simulating the low levels of light characterizing the X-Ray control in object. To simulate these conditions a filter and a variable iris was mounted on the camera input lens. Two iris openings were defined: one for 9 MeV propellant mass inspection and one for 15 MeV tangential inspection. Each iris opening was determined to provide comparable illumination equivalent to the gain and tube voltage of the baseline camera. This, both for the mass and for tangential control.

The performances of the cameras obtained during simulated tests were evaluated by means of fan gauge images and image analysis tools. At 9 MeV the expected highest resolution of the EMCCD camera is confirmed. The EMCCD camera also shows the highest contrast and the lowest noise. The ICCD camera shows similar performance with respect to the 25 year old SIT technology.

In Fig. 3 is shown, how an example, the "line profile" of the pattern 300 in the fan gauge (see. Fig. 4) obtained with the three cameras. The "line profile" of the two analogue cameras are similar, while in comparison the EMCCD camera shows the highest contrast performance.

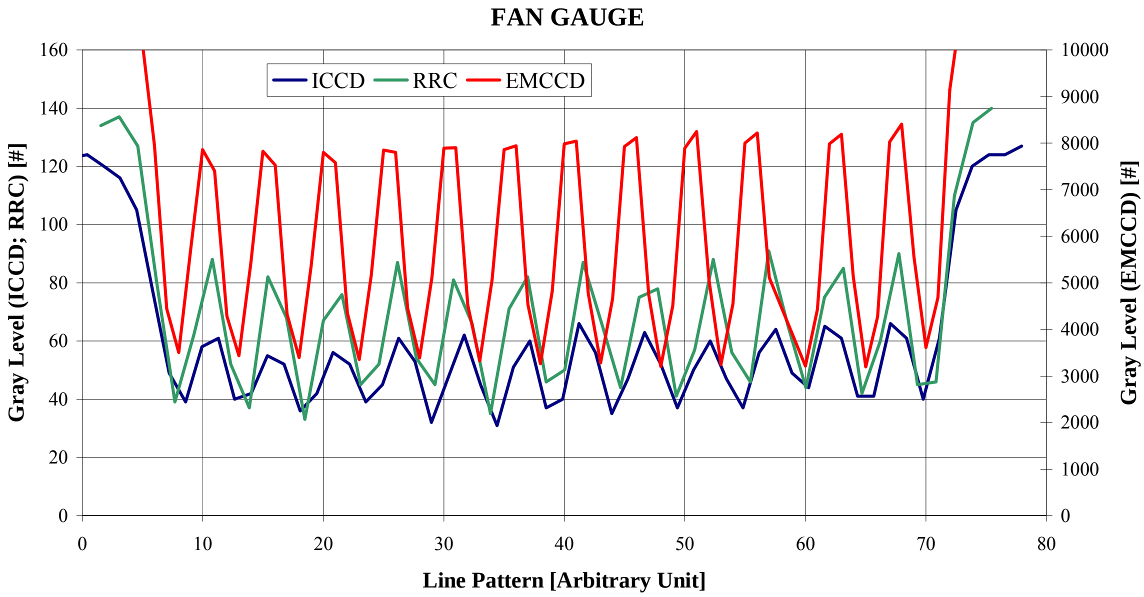


Figure 3 – Line Profiles obtained with the three cameras.

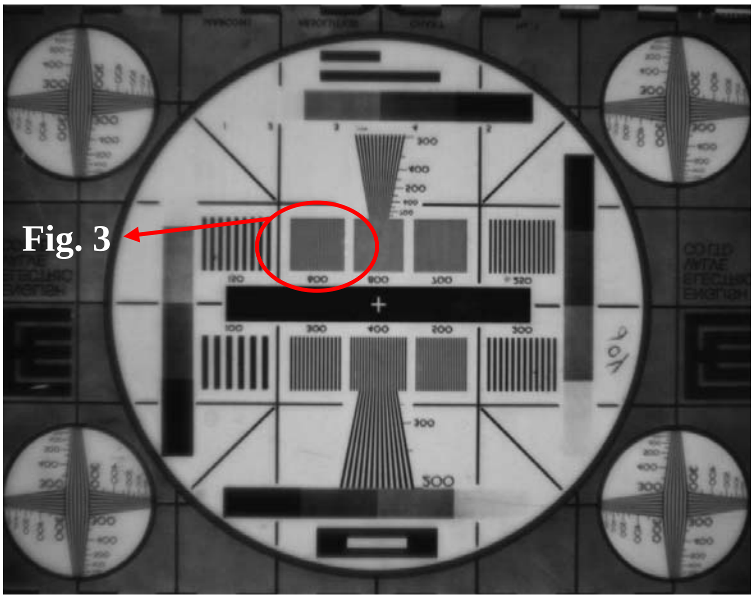


Figure 4 – Fan gauge. In the circle the line pattern used for the plots (see Fig. 3).

A similar trend was shown when 15 MeV inspection were simulated. The main difference with respect to the 9 MeV simulation tests was the high noise level. For this reason a real test at 15 MeV inspection was considered mandatory to define the final camera to be installed in the new radioscopy system. The results of the real test showed that the noise level could be reduced by a proper image treatment through frame integration, together with an adjustment of the gain to the highest values using the camera sensitivity suitable to compensate the low light level.

Trials performed by using the most extreme condition: 15 MeV X-Ray source energy, were performed by adapted shielding and S/W control of the camera. An SRM1 inert propellant loaded segment with artificial defects inside (a phantom used for the periodical re-qualification of the X-Ray inspection devices) were used as object. Even if tested in adapted conditions, the high sensitivity EMCCD camera passed the test. The obtained results are not included in this section, but the final performance of the camera will be presented in a dedicated paragraph.

4. Design of the System Using the Selected Digital Camera

Integration of a new camera in a existing plant means a complete reformulation of the interfaces. The main difficulties comes from: a) requirement to keep the number of the stations in the control unchanged, b) the large dimension of the X-Ray bay necessary for the Solid Rocket Motor control, c) the cable arrangement required when inspection is made in a single wall configuration and d) the high energy X-Ray source. The requirement a) mainly affects the overall dimensions of the camera and optics assembly, while b) and c) play an important role in defining the optimal engineering solution which allows suitable cable handling by considering the limit on cable length between devices and d) necessitates increased shielding for the EMCCD camera. The EMCCD (and the ICCD) are more susceptible to direct detection of primary and scattered X-Ray on the sensor than the original SIT camera. This radiation is both damaging to the CCD and produces visible artefacts on the real image. Consequently such devices need more shielding than the original SIT camera. Difficulties in defining a suitable engineering solution to meet these requirement are greatly enhanced when a digital camera is selected. In effect a digital camera (CCD device based) means: small chip area and then high focal length to maintain unchanged the field of view, expensive solutions for suitable cable handling system and remote camera control and a heavy shielding case for the camera.

In the Figs. 5 and 6 the new camera assembly is shown respectively in the tangential and axial control configuration. In the pictures, the high energy X-Ray linear accelerator, the Solid Rocket Motor SRM1 and the rotating support of the motor are also shown.

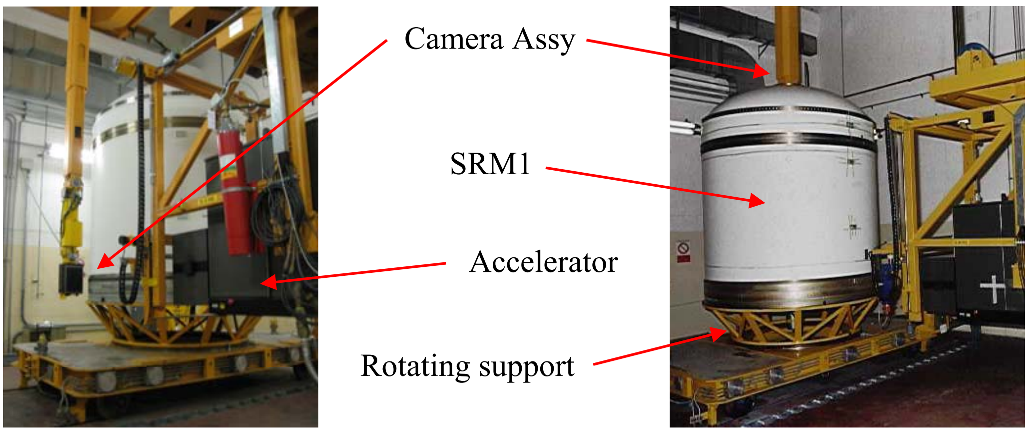


Figure 5 – Camera in Tangential Control

Figure 6 – Camera in Axial Control.

In the Figs. 7 (a) and 7 (b) the old camera assembly is shown respectively in a lateral and frontal view. The same is in Figs. 8 (a) and 8 (b) for the new camera assembly. In the pictures, the conversion screen and camera shielding subassembly is also shown.

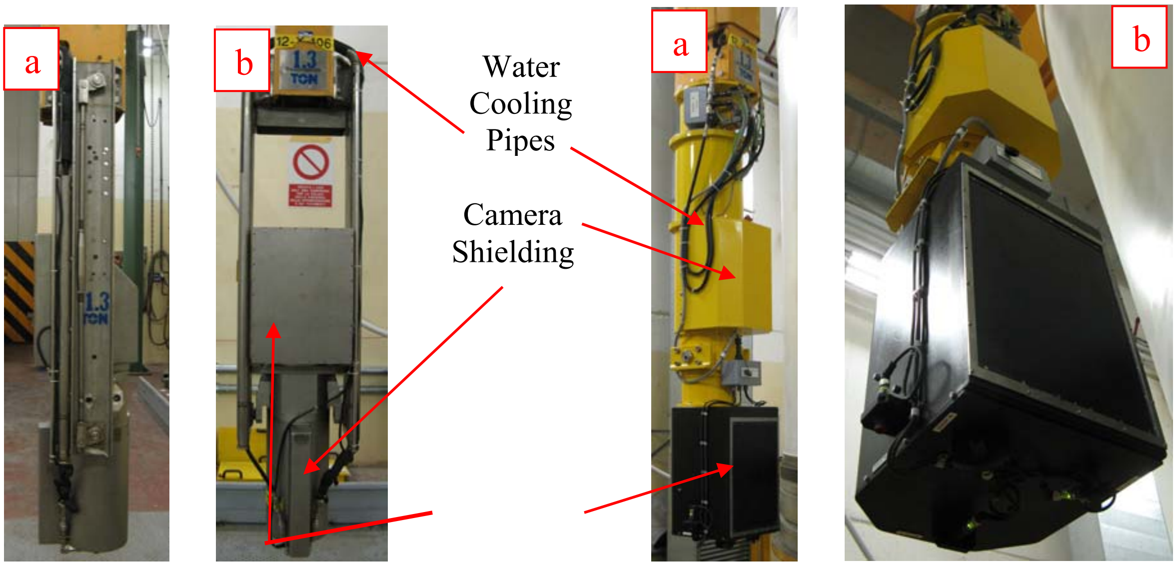


Figure 7 – Old camera assembly

Figure 8 – New camera assembly

The conversion screen used in the new camera assembly is a 300x400 mm screen and it is the same used in the old system. Both camera assemblies are provided of a water cooling circuit to reduce camera noise for overheating due to a long and continuous run time required in the control.

5. Final Performance of the System

Performance of the radioscopic system used for Solid Rocket Motor control, are evaluated through the capability to detect artificial defects inside an SRM1 phantom. These defects are defined on the basis of the acceptance specification relevant to a propellant loaded SRM1. Moreover, the quality of the radiographic image is evaluated by means of penetrameters placed on the thinnest and on the thickest part of the propellant channel. The acceptance condition for the new camera was to get at least the same performance of the old camera (before the deterioration). In Fig. 9 the performance of the old camera at the beginning of the qualification is shown respectively relevant to: (a) penetrameter in the thinnest propellant region, (b) penetrameter in the thickest propellant region and (c) 1 mm debonding in the between of thermal protection and propellant. In Fig. 10 the same details obtained with the new camera are shown.

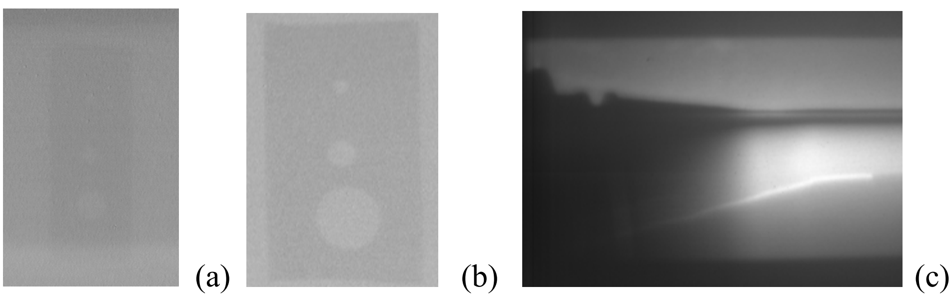
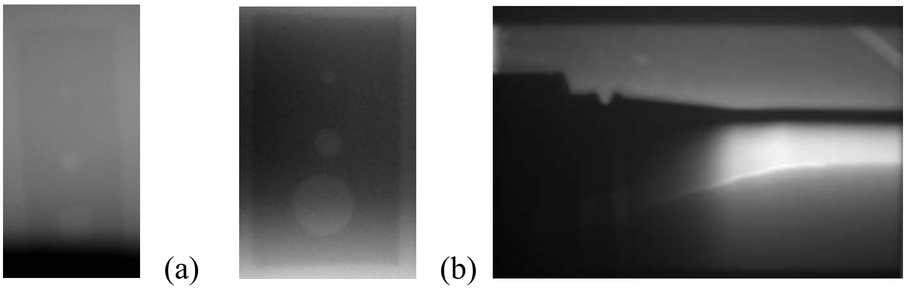


Figure 9 – Performance of the old camera at the beginning of the qualification [2]



(a) (b) (c)

Figure 10 – Performance of the new camera

The radiographic sensitivity evaluated through penetrameter is of 2-0.5T for both thin and thick penetrameter. The higher contrast of the new camera is confirmed at both energies 9 MeV and 15 MeV.

6. Advantages of the New Radioscopic System

Besides the better radiographic performances exhibited by the new camera, the new radioscopic system is compliant with other requirement that constitutes advantages much important on the industrial point of view: the shorter inspection time (a reduction of 50% has been experienced) and a lower total dose cumulated. While the former goes directly in the time reduction effort already initiated in AVIO in the field of the X-Ray control [3, 4], the latter gives indirectly a further contribution to the time reduction, since the lower total dose cumulated by the motor means less atomic activation and then shorter waiting time before handling of the motor. The optimization of operations comes from similar experiences [5, 6].

Acknowledgements

The author wishes to acknowledge Mr. Townsend N. J., Mr. Knight S., Mr. Drake S., Mr Allen M. and Mr. Aversa M. for their cooperation in defining the best solution and for the performed work to built and install the system.

References

[1] Technical Note from Varian.
[2] Townsend N. J. et al, “High Energy X-Ray for the A5 Programme”, 6° Congresso Nazionale dell’AIPnD, Milano, Italy, 1990.
[3] Tosti E. et al, “Controlli non Distruttivi su Componenti Aerospaziali mediante un Sistema di Radiografia Digitale”, 10° Congresso Nazionale dell’AIPnD, Ravenna, Italy, 1990.
[4] Tosti E., “Time Saving in the X.Ray Production Control by using ASD”, 9^{th} ECNDT, Berlin, Germany, 2006.
[5] Ramsey A.T., Dermody G.S., Handland R., Haig I.G., (2002), “Optimisation of X-Ray systems for industrial applications in CT and realtime inspection”, JRI 2002 Lyon, France, Nov 2002.
[6] Allen M., Ramsey A.T., Dermody G., (2005), “Industrial Computed Tomography Systems”, ASNT Digital Imaging VIII Conference, Mashantucket, CT, USA, July 2005.