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# Testing of the failure of a solid rocket propellant with tomography methods

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## Abstract

The paper presents the proposition of non destructive testing (NDT) of the rocket engine propellant rod. It presents the actual state of the research and perspectives of its continuation. In this research, capacitance tomography system was used. The method was compared with the radiological and radiometric methods. Experiments were done with the use of solid propellant with different pyrotechnic mass and artificial defects incorporated. Authors suggest a new method of differential tomography. ©2000 Elsevier Science S.A. All rights reserved.

*Keywords:* Non-destructive testing; Capacitance tomography; Duo-modal tomography; Differential tomography

## 1. Introduction

Developing rocket technology dynamically is gaining a growing position in the modern world, since it has a number of civil applications apart from military ones, (e.g. cosmic research, meteorology). For the assurance of the fulfilment of the mission and the security of people, diagnosis of the rocket's technical state, including the engine, is essential [9].

### 1.1. Propellant rod diagnosis

Solid rocket propellant is currently more often applied because of easier maintenance. Rocket engine work conditions, from which stable propulsive thrust and stable pressure is required, depend not only on the construction but on the propellant used. Specifically, these depend on the charge geometry and on the quality of the propellant mass internal structure, which means, on the kind and intensity of defects occurring in the propellant. Even the most accurately established and controlled technology process cannot assure a 100% defect-free production of the propellant charges. Not all the defects influence the combustion course. It depends on its dimensions, kind and location. These results show the necessity of controlling the production process [5,6], the post-production testing of the prepared product and control checking during the maintenance period.

### 1.2. Propellant rod technological defects

The technology of propellant charges has many similarities with the plastic technology. The main methods of propellant charge production are pressing and casting. The main factor rendering the technological process of the propellant charge difficult is the inadmissibility of the high temperature, which results in the incomplete fluidity of the moulded mass. As a consequence, a short shot form and residual air bubbles are produced.

Defects, such as delamination of the propellant mass parallel to the axis of the charge and inclusions of foreign, mainly metallic, materials, occur in the pressed rods. It is necessary to detect the following:

- delamination of the mass propellant of total surface from 250 mm$^2$ up;
- delamination of the length over 30 mm;
- delamination of the width from 3 mm upwards;
- inclusions with surface over 60 mm$^2$; and
- all mass cracking of the propellant.

Casting the final product is complex, as the combustible factor is usually a monomer (fluid) with the oxidising substance (solid propellant crystalline mass) which, when mixed together, is poured into the moulds in which polymerisation occurs. Solids added to the fluid are non-uniform in respect of the crystal dimensions and specific gravity, hence the following undesirable phenomenon occurs during the polymerisation process:

- separation of the thick crystals on the bottom from the fine ones on the top of the mould;

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- higher density substance separation from the lower density one; and
- higher concentration on the bottom of the mould and smaller on the top.

The following should be detected in the cast rods:

- single bubbles or their clusters with total surface from 200 $mm^2$ up.
- foreign matter inclusions with dimension higher than 5 $mm^2$; and
- all propellant mass cracking.

### 1.3. Propellant rod maintenance defect

Propellant rod maintenance is limited to their storage. The defects due to the storage conditions can be divided into two categories: mechanical and chemical.

The most common mechanical defects due to ageing are as follows:

- propellant mass cracking and spalling;
- propellant mass delamination; and
- deglutination of inhibitor layer.

Chemical defects that arise during the storage period are due to the reactions proceeding in the propellant mass. These reactions are accelerated by incorrect storage conditions. The most common defects of this kind are:

- increase of the water and volatile matter content (over 0.7%);
- decrease of the chemical durability;
- decrease of the constancy;
- decrease of the caloric value (combustion heat); and
- decreases in combustion velocity.

The influence of the kind of propellant (homogeneous or heterogeneous) on the defect formation should be underlined.

## 2. Propellant rod diagnostic state of art

Propellant rod testing can be divided into destructive and non-destructive. Destructive methods are applied periodically to the randomly chosen rods most often from the lots, which guarantee time of maintenance is over. Non-destructive methods are usually used for post-production control, which decides about the usefulness of a given lot for maintenance.

### 2.1. Destructive tests

Destructive tests are time consuming and require specialised testing equipment so they are very expensive. Usually they include:

- visual survey;
- water and volatile matter contents determination;
- density determination;
- calorific value determination;
- chemical durability determination;
- stability determination using mass decrement method; and
- linear combustion velocity determination.

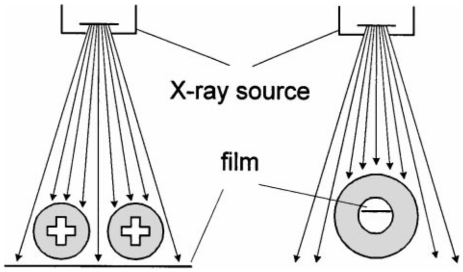


Fig. 1. Radiographic test of the powder rod through one and two walls.

### 2.2. Non-destructive tests

$X$ radiation ($\lambda = 10^{-4}$ up to 10 $\mu$m) or gamma radiation ($\lambda < 10^{-4}$ $\mu$m), are used in these methods, hence they too are expensive and time-consuming. They permit the detection of the majority of the mechanical defects, which presents the majority of defects of the post-productive stage. Radiographic and radiometric methods can be distinguished.

In order to detect and determine the defect using the radiographic method [1] in the tested rod, it is necessary to perform a number of the time-consuming operations (Fig. 1):

- preparation of the rod to exposition;
- exposition execution;
- irradiated-film photochemical processing; and
- radiogram interpretation.

Defect detectability exceeds technical requirements. This test requires very careful rod location against the film. Crashes are detected in the range of the 8° angle and minimal detectable crash is in the range 1–3 mm.

Radiometric method [2] of industrial product control consists of the measurement of the density of the gamma-radiation stream transmission through the tested product (Fig. 2). Application of this method for solid rocket propellant tests has been known for a long time, for example in the Allis Chalmers Company [7]. Experience shows that, with the radiometric method, it is possible to detect a crash 0.3–0.4 mm wide and 15–20 mm deep.

Tomography opens new perspectives in the propellant rod testing [4]. This method consists of obtaining slide images in different planes or instants on the basis of measurements in

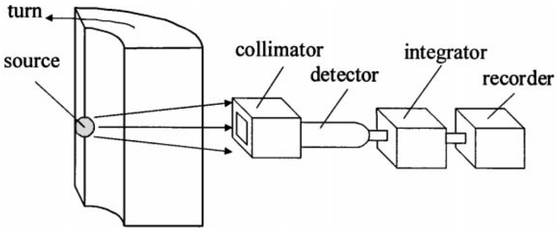


Fig. 2. Principle of radiometer function.

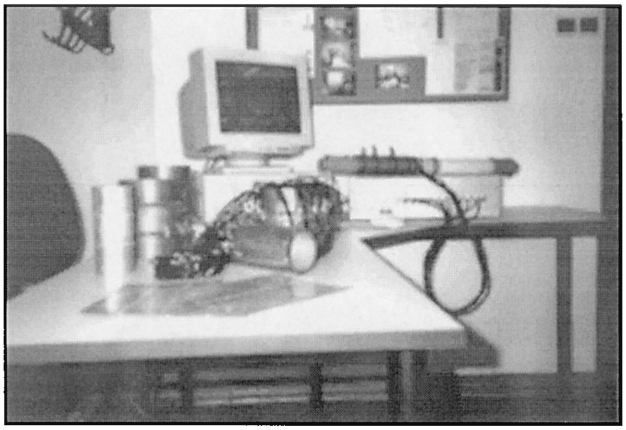


Fig. 3. Tomograph type PTL300 – TP-G.

perpendicular planes. These measurements are non-invasive and often done without contact with the product itself.

## 3. Sensors construction

In the laboratories of the Department of Maintenance and Technical Diagnostics at the Military University of Technology and in the Industrial Institute of Organic Chemistry in Warsaw, a series of experiments were conducted to confirm the usefulness of the process tomography in the diagnosis of rocket engine propellant rods. The PTL300–TP-G, developed at the University of Manchester Institute of Science and Technology, and produced by Process Tomography, was used in these tests. Two kinds of electrodes for testing rods of the different diameters were designed and made in Warsaw (Fig. 3).

### *3.1. Brass sensors*

These sensors are composed of 12 electrodes, ringside screens and inter-electrode screens (Fig. 4). Electrodes and screens are made of a 1-mm thick brass sheet, which assures the necessary rigidity of the construction and electrical conductivity. Connection to the measurement unit was made by concentric load RG174A type, 1300 mm long and by connectors SMB. Electrodes were earthed through a 1-MΩ resistance to discharge the electrodes between the measurement cycles.

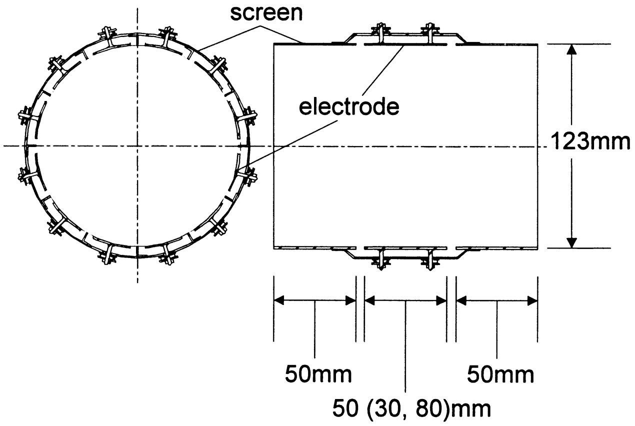


Fig. 4. Brass sensors.

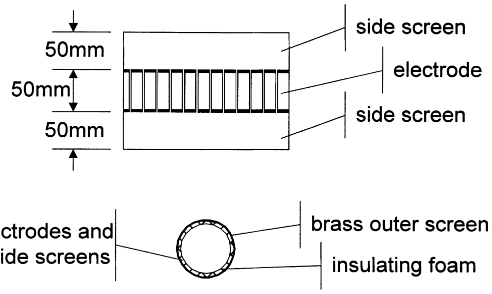


Fig. 5. Copper sensors.

Sensors for testing of a rod of 123-mm diameter, made of the heterogeneous (composed) propellant, were designed in three lengths (long — 80 mm, medium — 50 mm, and short — 30 mm).

### *3.2. Copper sensors*

The sensors, composed of 12 electrodes, ring side screens and inter-electrodes screens, were made of a flexible copper-clad laminate (0.15 mm thick, covered by the 0.05-mm thick copper layer) using standard photolithography and etching techniques (Fig. 5). The whole sensor, after coiling and soldering was encircled by antistatic insulating foam and a brass screen to ensure the necessary stiffness. Connection to the measurement unit was made by 1300 mm long concentric load RG174A type and by connectors SMB. Electrodes were earthed through a 1-MΩ resistance to discharge the electrodes between the measurement cycles. Also, 50 mm long sensors were designed for testing a rod of 67 mm diameter made of the homogenous propellant with inhibitor.

## 4. Experiments

Process tomography [3] opens up new perspectives for plastics mass products and, in particular, for propellant rod diagnosis [8]. The preliminary experiments confirmed that this application was correct.

### *4.1. Pattern rod testing*

The subject to test in the first stage was a rod made from the composed propellant, the basic components of which were:

- ammonium perchlorate;
- aluminium dust (about 10%); and
- polymer binder.

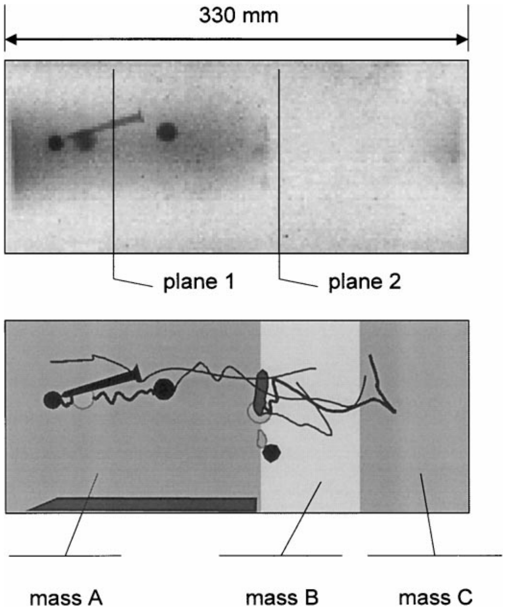


Fig. 6. X-ray picture and cross section of the tested rod.

The tomography calibration necessary for the test was done using the ‘pattern rod’ made of the same propellant (mass A), moulded without contamination and inclusions. The reliability of the ‘pattern rod’ was confirmed using the radiographic method.

The tested rod (Fig. 6) was contaminated with balls and plates of steel, lead, glass and Teflon, located in specific places. In addition, part of the rod was made of a material of a different composition (mass B).

Images were registered in two planes crossing through the different masses (Fig. 7). In plane 1, measurements were taken using short (30 mm) and long (80 mm) electrodes.

Areas of permittivity of lower and higher values than the propellant mass constant are sharply outlined in the images.

### 4.2. Heterogeneous rods testing

The propellant rods with ring cross section made of the heterogeneous mass were tested in the second stage. The results are shown in the Fig. 8. They were done on the one plane with electrodes of different lengths.

Measurements taken using the long electrodes are not accurate, because the capacitance values are averaging defects along the length of the electrodes. However, short electrodes caused difficulties in the interpretation of the results, because the electric fields are strongly non-linear. The length of the electrodes depends on the tested rod diameters. The possibility of the using a central electrode (Fig. 9) connected to the mass or a divided electrode was considered. It could increase accuracy, but requires a specialised reconstruction algorithm.

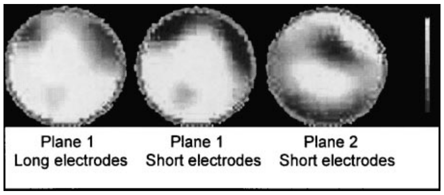


Fig. 7. Pattern rod tomograms.

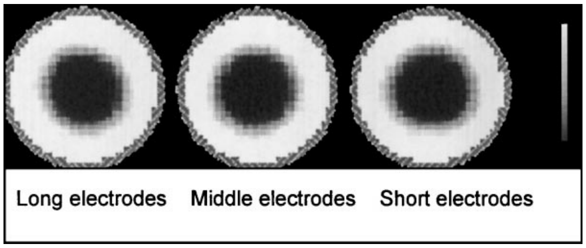


Fig. 8. Heterogeneous rod tomograms.

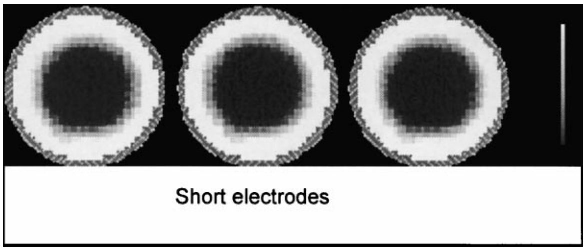


Fig. 9. Rod with central electrode (connected to the mass) tomograms.

### 4.3. Homogeneous rod testing

Copper electrodes were used for the next tests. Rods of 67 mm diameter, made of the homogeneous propellant with inhibitor, were used for the tests (Figs. 10 and 11). Tomograms allow confirmation of the chemical changes in the material and, especially, the increase in moisture content.

Deglutination of the inhibitor creates the next problem. In the case of inhibitor deglutination combustion takes place, not only on the front of the propellant rod, but along the deglutinated inhibitor as well. This phenomenon changes the engine parameters and can be dangerous. However, localisation of the inhibitor deglutination is difficult. The main difficulty is caused by the variable diameter of the tested rod.

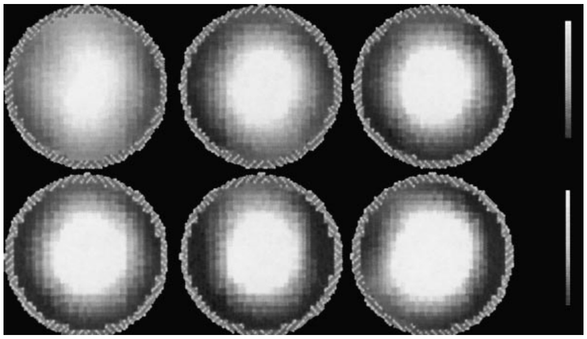


Fig. 10. Homogeneous model rod tomograms.

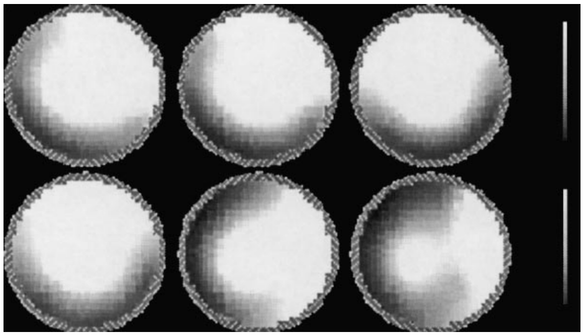
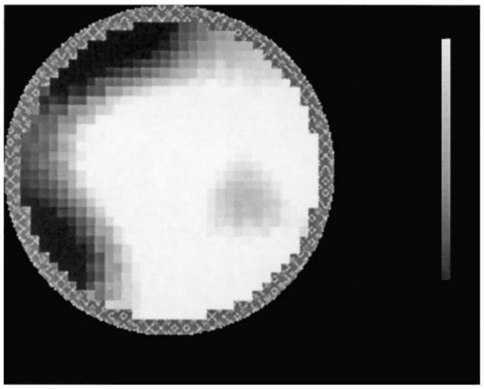


Fig. 11. Homogeneous rod with deglutinated inhibitor tomograms.

## 5. Image reconstruction and visualisation

A modified, linear back projection (LBP) algorithm [10] was applied for image reconstruction and the images obtained were presented in a black/white linear scale. To increase the tomograms readability, a multicolour scale using Microsoft Excel was proposed (Fig. 12). Assuming that only chemical changes occur, it is possible to assign adequately contrasting colours to particular kinds of changes.

Visualisation in the **Imgcon** program:



Visualisation in the **Microsoft Excel** program:

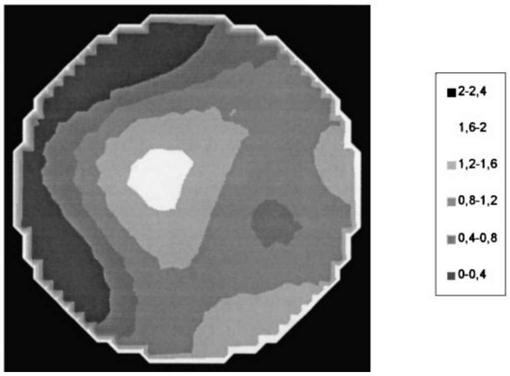


Fig. 12. Comparison of the visualisation manners.

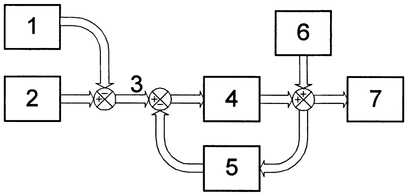


Fig. 13. Differential tomography scheme. 1, Standard specimen 28 measurements*; 2, test object vector of 28 measurements*; 3, difference vector (28); 4, linear back projection; 5 calculate 28 normalised difference vector values from image pixels; 6, previous difference image; and 7, latest difference image (* — normalised using series model).

To enable the assumption of only one kind of change, we proposed the application of duo-modal tomograph: capacitance — X-ray. X-ray tests distinguish foreign matter inclusion, cracking or delamination. It does not register the chemical changes observed by the capacitance tomography method well enough.

The next step is the vectorial presentation of the bit-map images. This allows the transmission of the images received in the test to quantify processing systems. The sequence of the successive tomographic images allows secondary-space reconstruction (3D). This reconstruction enables the evaluation of the adverse chemical or mechanical changes that took place in the volume.

Applying rough set methods, the operator can get information about the changes that took place in a volume $>$A mm$^3$ and $<$B mm$^3$.

## 6. Further research perspectives

In summary, the research conducted and experience acquired confirm that the tomographic methods are useful for the non-destructive testing of propellant rods for rocket engines.

Further research will concentrate on:

- optimisation of the electrodes dimensions;
- working out and testing of the specialised reconstruction algorithms;
- applying the neural network to the reconstruction;
- design of the capacitance — X-ray tomograph; and
- applying the software to vectorial presentation.

At present, the important direction of the research seems to be differential tomography (Fig. 13) which allows the object standard specimen to be taken into consideration on-line. It will permit the reduction of the influence of such factors as humidity, temperature and external magnetic field on the testing results. It will thus make it possible to conduct the research in the field and industrial conditions.

The authors hope that defectoscopic tomography, which combines process tomography methods with medical tomography requirements, will find its own place side-by-side with other methods in scientific and applied research.

## References

[1] J. Bonczyk, Badanie wad strukturalnych elementow stalych materialow miotajacych (Structural defects testing of the solid propellant materials) Problemy Techniki Uzbrojenia i Radiolokacji, Zeszyt 26, 1980, WITU, pp. 39–48.

[2] Z. Godlewski, J. Bonczyk, Kontrola radiometryczna stalych paliw rakietowych (Radiometric control of the solid rocket propellant) Problemy Techniki Uzbrojenia i Radiolokacji, Zeszyt 26, 1980, WITU, pp. 69–83.

[3] A. Pląskowski, M.S. Beck, R. Thorn, T. Dyakowski, Imaging Industrial Flows. Applications of Electrical Process Tomography, Institute of Physics Publishing, Bristol, 1995.

[4] A. Pląskowski, M.S. Beck, M. Byars, W. Pląskowski, Tomografia procesowa: zastosowania do wizualizacji, projektowania i sterowania procesami wielofazowymi (Process tomography application to multiphase processes visualisation, design and control) Referaty Konferencji AUTOMATION'97, Warszawa 1997, t.2, pp. 367–374.

[5] A. Pląskowski, K. Tomkiewicz, Metody tomografii w diagnozowaniu procesow przemyslowych (Tomography methods for industrial processes diagnosis) III Krajowa Konferencja Naukowo-Techniczna Diagnostyka Procesow Przemyslowych Referaty pp. 391–396, Jurata k/Gdanska, 7–10 September 1998.

[6] A. Pląskowski, K. Tomkiewicz, Produkcyjne diagnozowanie wyrobow z mas plastycznych (Industrial diagnosis of plastic mass products) III Krajowa Konferencja Naukowo-Techniczna Diagnostyka Procesow Przemyslowych Referaty pp. 369–374, Jurata k/Gdanska 7–10, September 1998.

[7] S.W. Rumiancew, Defektoskopia radiologiczna Radiological Defectoscopy) WNT, Warszawa, 1972.

[8] K. Tomkiewicz, A. Pląskowski, Metody tomografii procesowej w diagnozowaniu silnikow rakietowych (Process tomography methods for rocket engines diagnosis) Referaty Konferencji AUTOMATION'98, Warszawa 1998, pp. 223–232.

[9] K. Tomkiewicz, Rakieta jako obiekt diagnozowania Rocket as a diagnosis object) VI Konferencja Naukowa Sterowanie i regulacja w radiolokacji i obiektach latajacych, 1995, vol. 2, pp. 163–170.

[10] C.G. Xie, Review of Image Reconstruction Methods for Process Tomography Process, in: M.S. Beck, E. Campogrande, M. Morris, R.A. Williams, R.C. Waterfall (Eds.), Tomography — a Strategy for Industrial Exploitation, UMIST, 1993, pp. 115–119.