NEUTRON AND X-RAY IMAGING OF THE 'BLACK BOXES' FOR THE ANCIENT CHARM PROJECT

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Abstract

The Ancient Charm project binds together archaeologists and neutron scientists. Their shared goal is a development of new neutron-based imaging techniques for non-destructive investigation of valuable archaeological objects, while the objects are treated with the highest precautions. One of the tasks of the Ancient Charm project was an analysis of test objects – so called 'Black Boxes' prepared by the archaeologist for the initial development phase of the new neutron-imaging techniques. Since such a development is a challenging task, we decided to use well established imaging methods first: With the help of the neutron resp. X-ray radiography and tomography, we were able to find out and define the shapes and forms of the unknown objects inside of the black boxes. Provided with these pieces of information, the new neutron imaging methods can be positioned to the spots of interest within the black boxes and make the measurements. The overview of the neutron and X-ray radiography and tomography of the black boxes is presented in this article.

Kivonat

Az Ancient Charm projekt összeköti a régészeket és a neutronokkal foglalkozó természettudományos szakembereket. Együtt törekszenek új, neutron alapú képalkotási technikák kifejlesztésére értékes régészeti tárgyak roncsolásmentes vizsgálata céljából. A kutatások során a tárgyakat a legnagyobb elővigyázatossággal kezeljük Vizsgálatukat megelőzően próbatesteket, úgynevezett fekete dobozokat ('Black Boxes') vizsgálunk, amelyeket a régészek tervei szerint készítettek a vizsgálati módszerek lehetőségeinek kipróbálására. Elsőként a jól ismert és már hagyományosnak tekinthető képalkotási technikákat használtunk a tárgyak belsejének felderítésére, mégpedig röntgen és neutron tomográfiát. Ezek segítségével észlelhető és meghatározható a fekete dobozok belsejében rejlő ismeretlen elemek körvonala és formái. Ezekre az ismeretekre alapozva eredményesen alkalmazhatók az új neutron analitikai módszerek, mert a fekete dobozon belül pontosan lehet pozícionálni a vizsgálandó területeket. A cikkben a röntgen- és neutron tomográfia rövid összefoglalását és a kísérletsorozatban elért eredményeinket mutatjuk be.

KEYWORDS: NEUTRON BASED IMAGING ANALYSIS, TOMOGRAPHY

KULCSSZAVAK: NEUTRON ALAPÚ KÉPALKOTÁSI TECHNIKÁK, TOMOGRÁFIA

Introduction

The aim of the ANCIENT CHARM project is a development and usage of the new neutron-based imaging techniques with a focus in the non-destructive analysis of valuable cultural heritage objects. The length of the EU6 projects is three years, starting January 2006 (Gorini et al., 2006). Very nice introduction to the Ancient Charm topic was written in this journal by Zs. Kasztovszky et al. (2006a). The new neutron techniques should provide a set of 3-D information (position sensitive information) on the elemental and phase composition of the selected archaeological objects of interest. As a result of the investigations with neutrons, archaeologists should obtain a complementary set of information, which can help them to solve typical questions about the production of the particular object: when, where and from which material it was made, manufacturing technique, and other potential questions of interest.

The new methods for the 3-D neutron analysis are being developed from well established methods and they are called: Prompt Gamma-Ray Activation Imaging combined with Neutron Tomography (PGAI/NT) (Zs. Kasztovszky et al., 2006b); Neutron Resonance Capture Imaging (NRCI) (Postma et al., 2006) and Neutron Diffraction Imaging (NDI) (Kockelmann et al., 2006).

Black Boxes

For testing purposes during the development phase of the new methods, the archaeologists prepared some testing objects: replicas of the real objects and the black boxes. These closed metal cubes were made of 1.2 mm thick iron plates (by Hungarian National Museum, Dúzs 2008) and of 1.0 mm aluminium plates (by University of Bonn, Kirfel 2008) and contained objects of various shapes, forms and elemental composition. Care was taken to choose characteristic materials and elements, which are representative to the composition of the real archaeological objects.

Figure 1. - Picture of one iron (left) and one aluminium (right) black box.

The task was to recognise the elemental composition and the rest-strain of the inner objects by the new methods. The well established methods of neutron resp. X-ray radiography and tomography were used to visualise the inner content of the black boxes and to help with targeting the coordinates of the interesting spots for the new 3-D neutron techniques.

The Hungarian iron black box dimensions are 4 cm × 4 cm × 4 cm and they are named H-I - H-IX. The Bonn aluminium black box dimensions are 5 cm × 5 cm × 5 cm and are named D-I – D-XI. The iron black boxes were closed by gluing the iron covers with an epoxy resin.

This material contains lots of hydrogen and is therefore not transparent for neutrons, which influences the quality of the neutron tomography and radiography result at those parts. An example photo of one iron and one aluminium black box is presented in **Figure 1.**

Neutron and X-ray radiography and tomography

The radiography with neutron beam or with X-ray beam (Röntgen ray) is based on transmission of the beam through the object. The transmitted image provides 2-D information about the content of the object according to how much of the beam is absorbed, scattered and transmitted through different parts and materials of the object. The gained 2-D image gives us some information about the shape and materials. Neutron and X-rays penetrate the materials by different physical ways, so the information given by those radiographs is complementary (neutrons and X-rays have different transmission coefficients for different elements). For example, X-rays penetrate easy through organic materials (like hydrogen, carbon) and are transmitted with more difficulty by heavy metals (e.g. gold, lead). By neutrons, their transmission coefficients vary randomly among elements: e.g. lead and aluminium are transparent for neutrons and hydrogen or cadmium are opaque for them. For both neutrons and X-rays the transmission of the beam intensity is exponentially decreasing with the given thickness of the material, which the beam has to pass through.

Table 1 - Parameters of the neutron radiography and tomography of the black boxes

Date	*13^{th} - 14^{th} of September 2006*
Neutron beam	thermal + cold neutron flux ~ $2.5 \cdot 10^7$ n/cm^2 s
L/D ratio	800
Radiography of black boxes	H-I - IX
	D-II, V, VII, VIII, IX and X
Tomography of black boxes	H-I, II, III, IV, V, VI, VII and IX
	D-II, V, VII, VIII, IX and X
Dimensions of 1 black box	~ 520 x 520 x 520 voxels (Al black box)
Resolution (voxel size)	~ 0.1 × 0.1 × 0.1 mm
Number of projections	400
Irradiation time / projection	7 s
CCD camera	16 bit, 2048 x 2048 pixels
Data reconstruction software	'All In One' Reconstruction tool, based on IDL software (IDL, 2007)

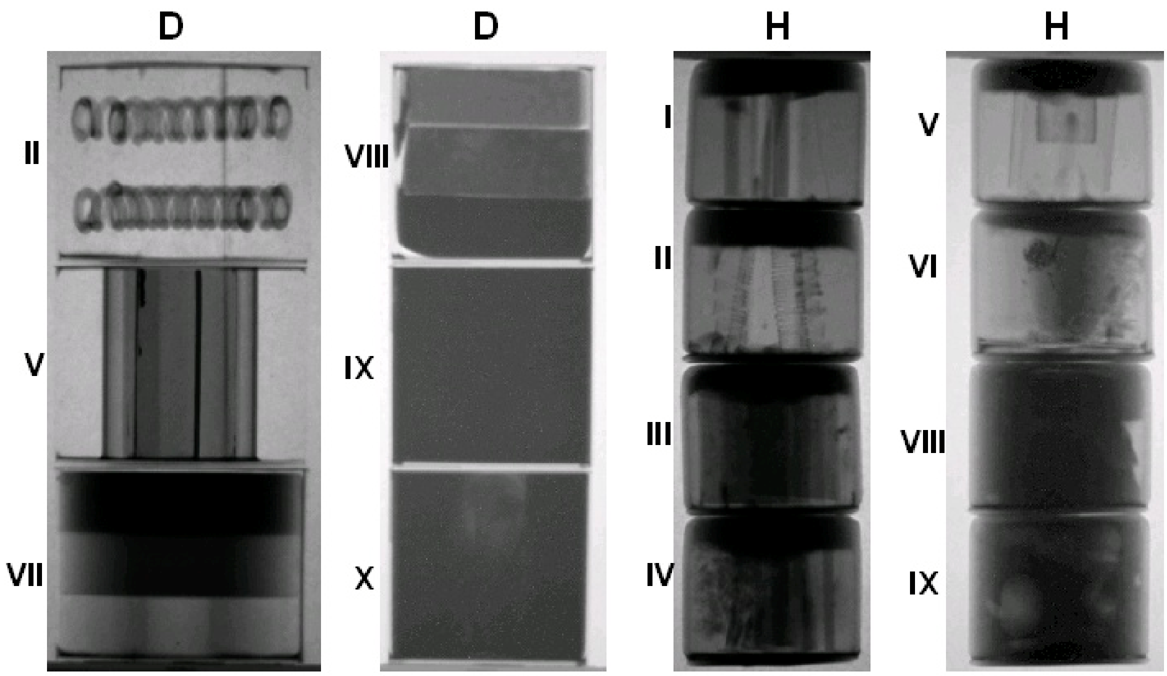

Figure 2 - Neutron radiographs of selected black boxes measured at ANTARES

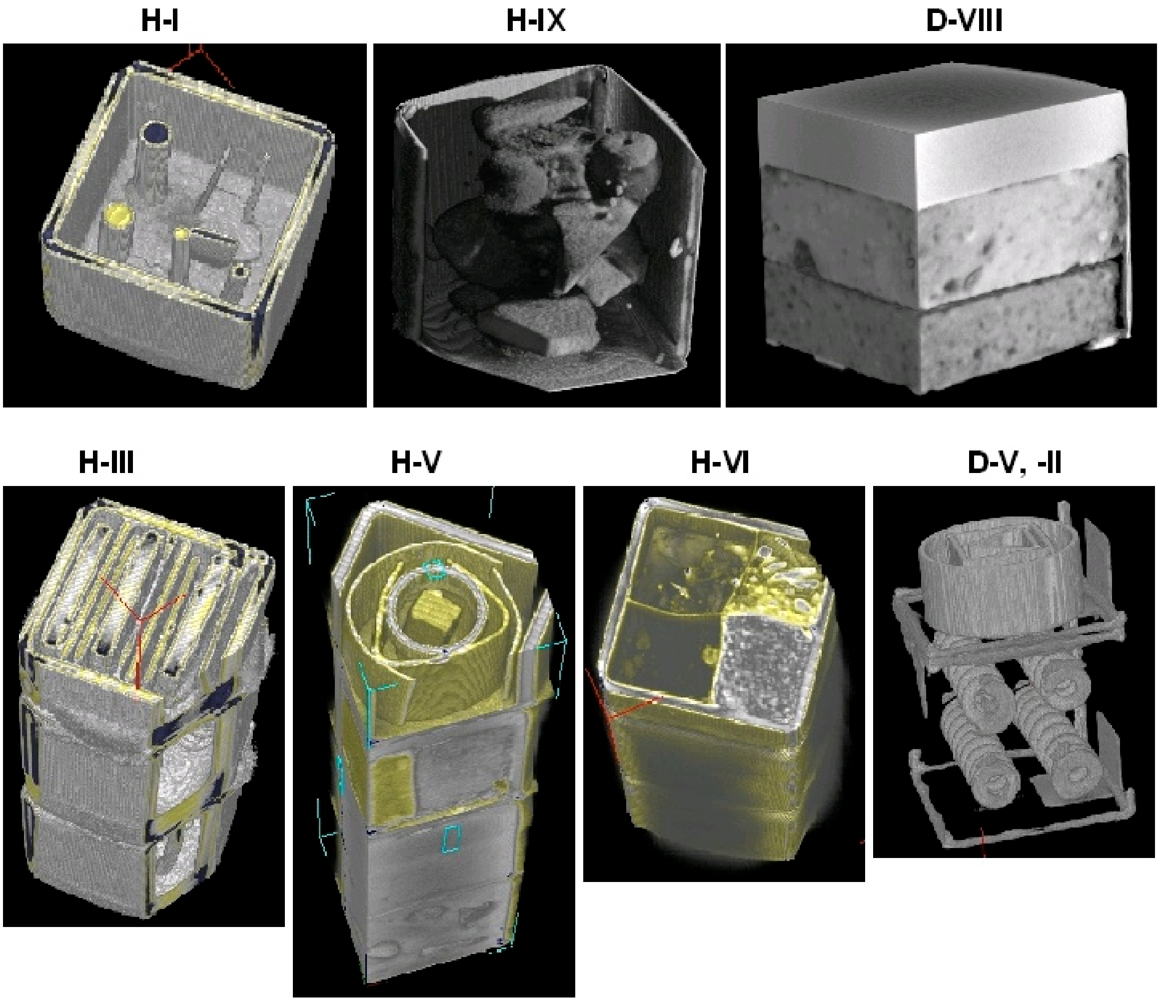

Figure 3. - Selected neutron tomographs of the black boxes measured at ANTARES

Table 2 - Parameters of the X-ray radiography and tomography of the black boxes

Date	*1st - 3rd of August 2006*
X-ray cone beam + 3 mm thick Cu filter	average energy ~ 80keV; maximum energy ~ 160keV
L/D Ratio	> 10000
Radiography of black boxes	H-I, II, III, IV, V, VI, VIII and IX D-II, IV, V, VI, VII, VIII, IX and X
Tomography of black boxes	H-VI, VIII and IX D-VIII and X
Dimensions of 1 black box	~ 600 x 600 x 600 voxels (Al black box)
Resolution (voxel size)	0.07 × 0.07 × 0.07 mm
Number of projections	500
Irradiation time / projection	10 s
CCD Camera/Image Intensifier	12 bit, 1024 x 1280 pixels
Data reconstruction software	OCTOPUS (Xraylab, 2007)

The tomography of the objects is actually based on producing a set of many radiographs of the object while rotating the sample around its vertical axis through about 400 equally spaced positions within 360°. Having these 2-D images (called projections) and making some corrections on them (like normalisation, correction for noise signal, white spot filter) filtered back-projection (or other reconstruction algorithms) is performed on them. The result is a 3-D image of the object, which can be sliced in different views by suitable visualisation software. Very nice introduction to the tomography with X-rays and neutron was published by Kardjilov & Moreno, (2006).

Experimental

Neutron Imaging

The neutron radiography and tomography of the black boxes were performed in cooperation with the ANTARES group (Antares, 2007) at the research reactor FRM II (FRM II, 2007). The analysis of the data was also done by the group itself. The parameters for the neutron radiography and tomography are presented in **Table 1**. Radiographs of some selected black boxes are shown in **Figure 2** and tomographs of other selected black boxes are shown in **Figure 3**. For the visualisation of the tomography images, VGStudio Max 1.2 (Volumegraphics, 2007) was used.

X-Ray Imaging

The X-ray radiography and tomography with selected black boxes were performed at the Centre for X-ray Tomography at the Ghent University (UGCT, 2007) in cooperation with the group of Prof. Dr. Luc Van Hoorebeke. Parameters presented in **Table 2** summarise the conditions of the measurements. Radiographs of some selected black boxes are shown in **Figure 4** and tomographs of other selected black boxes are shown in **Figure 5**.

Discussion and conclusion

The neutron and X-ray tomography brought some light into the black boxes. The tomography method gives information about the shape and form of objects. Although this information is not sufficient to determine the elemental composition of the objects inside of the black boxes, it is good enough to resolve some different materials (e.g. according to the colour pattern in Fig. 5, black box H-IX or Fig. 3, black box H-I). Neutron tomography is generally more convenient for any material mixtures (and metals) with close atomic numbers, where X-rays have very similar transmission coefficients (transmission coefficients of X-rays decrease with increasing atomic number). For objects containing organic materials and metals, X-rays may show better the inner structures and shapes. Having many scattering materials like Hydrogen, neutrons cannot penetrate such objects and those are not suitable for the neutron tomography. X-rays are useless for objects covered e.g. with lead walls. By using neutrons, the activation of the objects during the measurement must be taken into account and accordingly the cooling down time. This is mostly important for samples containing e.g. Silver, Cobalt, Zinc or Antimony.

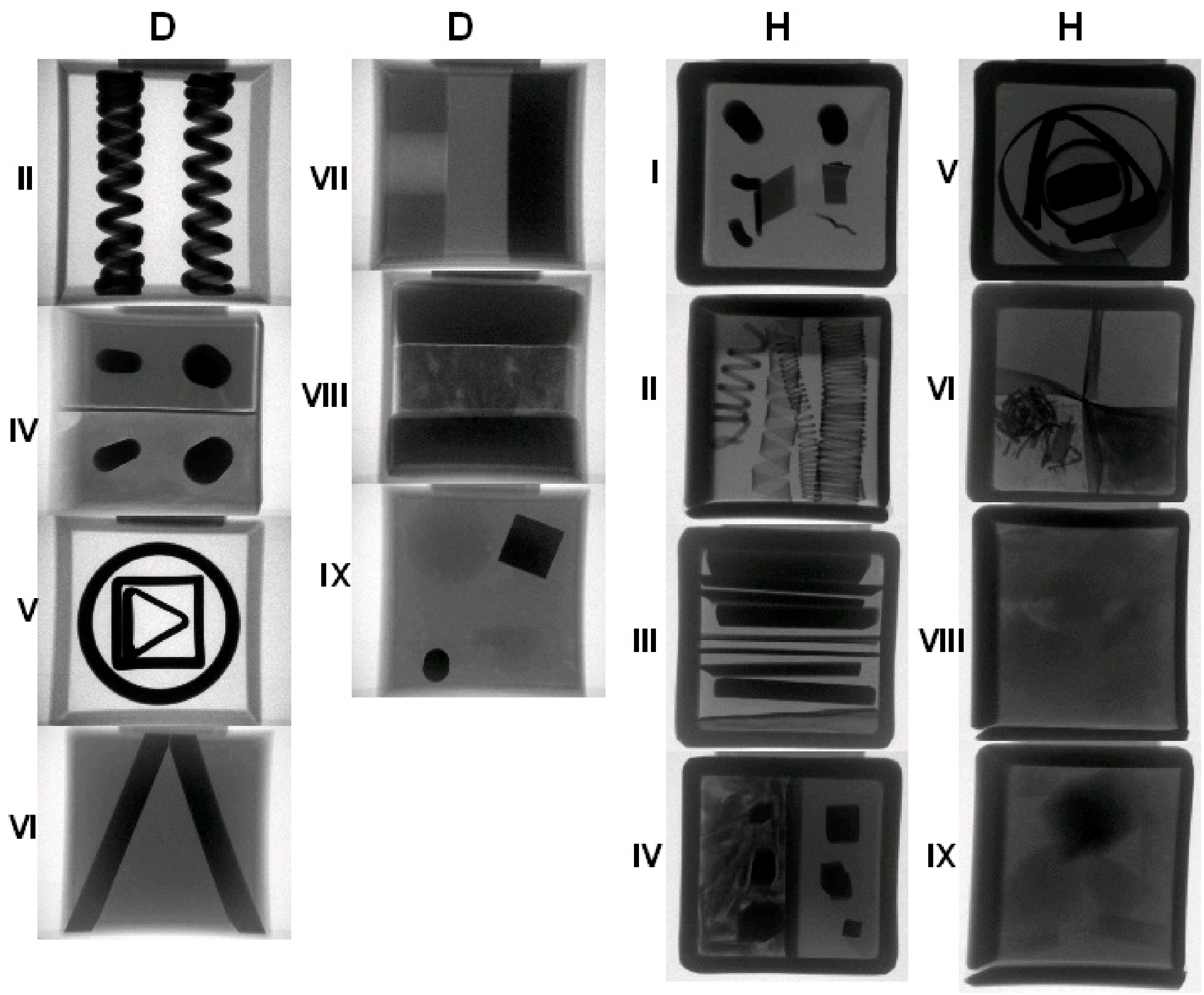

Figure 4 - X-ray radiographs of some selected black boxes measured in Gent

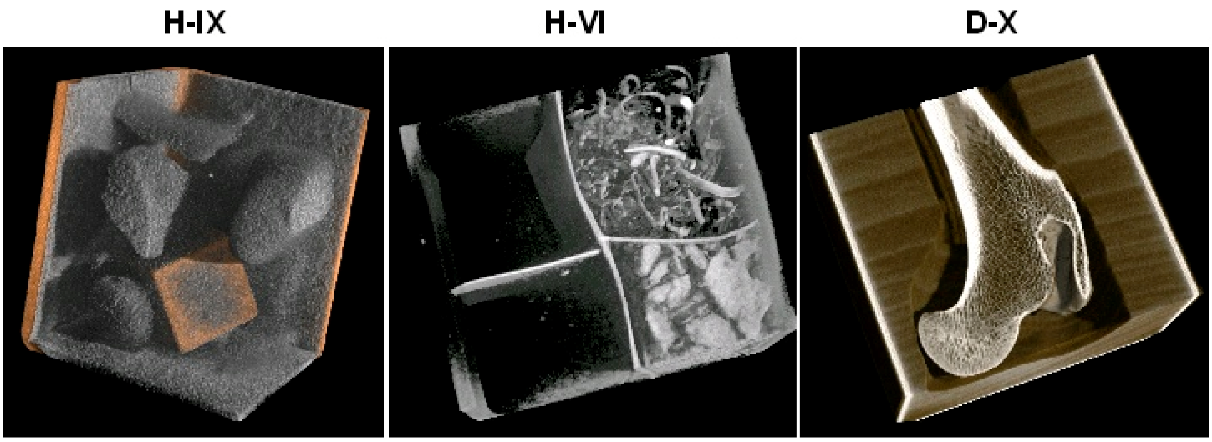

Figure 5 - Selected X-ray tomographs of some black boxes measured in Gent

More information to the black boxes and to the alignment of the neutron tomography to the X-ray tomography and so combining their results can be found in publication by Kudejova et al. (2007).

Using this 3D information about the shapes inside of the black boxes, the particular parts of them were measured at different experimental places to test the new methods like e.g. PGAI. The results of those measurements were presented at the 'Black box meeting' in Sárospatak, Hungary. The results of the measurement were afterwards compared to the real composition of the black boxes.

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More tomography and radiography pictures can be found on this webpage: http://www.ikp.uni-koeln.de/~petra/AC/