Detection of buried landmines and hidden explosives using neutron, X-ray and gamma-ray probes

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It is estimated that more than 110 million active mines are a permanent threat in some 70 countries, resulting in about 2000 casualties per month, most of them being civilians. The anti-personnel mines (APM) and anti-tank mines (ATM) found in several affected countries are mostly buried, non-metallic or with minimum metal content; the most dangerous types are PROM_1, MRUD, PMR_3, and TMR_P6.

Using the classical technologies (metal detector, dogs, prodding) finding, localizing and identifying the landmines is a time consuming, expensive and extremely dangerous procedure. In addition, it will take a long time to de-mine the affected countries, mainly because the same tedious procedure has to be applied to all areas suspected to be contaminated with landmines. Mined areas are generally close to the battlefields, being consequently heavily infested by metal pieces from the explosions of different ordnances (explosion of an ordnance can result in more than 1000 small metal fragments). The presence of metal clutter produces a large number of false alarms in the metal detectors (MD) commonly used in de-mining. As a consequence, there is a need for a technological breakthrough in this field to solve definitively the land-mine problem.

Moreover, the threat of terrorist use of explosive devices and chemical, biological or radioactive agents has become realistic since the SARIN attack in the Tokyo subway system on March 20, 1995 and after the tragic events of September 11, 2001. The possibility of further terrorist actions against civil population is one of the most important issues on the international political agenda. An often evoked scenario implies the use of the so-called "dirty bomb": a sizeable quantity of radioactive material detonated by conventional explosive and dispersed in the environment. The illicit trafficking of explosives and fissile material through conventional commercial networks (air, maritime and terrestrial) represents therefore a real challenge to civil security for future years. Manual and visual inspection of large commercial payloads at terrestrial borders (trucks), seaports (containers) and airports (check-in luggage) would not be a viable solution both from efficiency considerations and for legal reasons. It is mandatory to realise standoff integrated inspection systems of cargo by means of imaging and analytical methods based on a sound technology to identify threat materials.

X-ray or gamma-ray based imaging is the only technique which enables a direct view of objects embedded or buried in soil. State of the art systems can give good precision density measurements with high-resolution three-dimensional images. The observed shapes and mechanical structure of detected objects may help to identify a particular mine type or at least to distinguish a mine from other buried objects such as metal scrap. Metal can be distinguished further by the available gross information about the elemental content of the inspected item (low Z vs. high Z discrimination).Two recent examples of systems under investigation are discussed below.

Mine detection with neutrons

The key to distinguishing explosives from benign materials is, as for the detection of buried landmines, the use of the elemental analysis. Only neutron interrogation offers the possibility of measuring the elemental density of most elements in materials independent of their particular structure.

The use of neutron-induced reactions for non-destructive bulk elemental analysis is well documented. All neutrons, in particular fast neutrons, are well suited to explore large volume samples because of their high penetration in bulk material.

Nuclear techniques hinge on the fact that the explosives contain hydrogen, carbon, nitrogen, and oxygen in variable concentrations (for example, elementary compositions of some common explosives are: TNT - $C_7H_5N_3O_6$; RDX - $C_3H_6N_6O_6$; pentrite - $O_{12}N_4C_5H_8$; hexogen - $O_8N_8C_4H_8$; ammonium nitrite - $O_3N_2H_4$). The problem of explosive identification can be thus reduced to the problem of identification of light elements. Furthermore, the measurements of concentration ratios, especially carbon to oxygen and carbon to nitrogen, are very effective in discriminating explosives from the medium in which they are buried or hidden.

▲ Fig. 1: Test of the thermal neutron sensor prototype in the laboratory

Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn:2005403

We present three different neutron based techniques for applications to the landmine detection and cargo inspections. The first is based on the so-called Thermal Neutron Analysis where fast neutrons from a radioactive source are thermalized in a moderator and then sent onto the inspected area where they are eventually captured by the elements that characterize the investigated volume [1]. In this technique the search is for an anomalous concentration of nitrogen that is characteristic of most explosives. The second is based on the Neutron Backscattering Technique where fast neutrons from a radioactive source are sent directly onto the investigated area and the flux of thermal or epithermal neutrons scattered backward is proportional to the inverse atomic number of the elements contained in the inspected volume. In this way materials with a high hydrogen content (such as the explosive in a landmine and the plastic case as well) are detected if the background has an average higher atomic number [2]. The third is the so-called Associated Particle Technique where one produces neutrons by the d + t reaction that yields a neutron of 14 MeV and an alpha particle of 3.5 MeV energy emitted back-to-back in the center of mass of the compound system. The possibility of detecting with high efficiency the α particles allows a determination of the direction and the time of production of the associated neutrons. In this way one can direct a beam of "tagged" neutrons onto the area to be investigated and measure the characteristic gamma radiation originating from the neutron induced reactions on several elements highly reducing the "environmental" background [3].

Thermal Neutron Analysis

A picture of a thermal neutron sensor prototype, as assembled for laboratory tests is shown in Fig. 1. A ^{252}Cf neutron source (1.10^7 neutron/s) in a spherical lead shield (inner radius 1.5 cm, outer radius 4.5 cm) is housed in a high density polyethylene cylinder of 28 cm diameter and 26.5 cm height. The stand-off distance of the sensor is about 20 cm from a sand box with 1 m^3 volume. The moderator geometry is selected after an experimental study devoted to the optimisation of the thermal neutron flux in the soil. It is certainly mandatory to increase the thermal neutron flux at the typical depth where landmine are buried, i.e. up to 20 cm, the moderation capability of the bare soil being too low to allow measurements of the neutron capture reaction on nitrogen nuclei in realistic time. Four large scintillation detectors serve in this set-up to detect the characteristic gamma rays. The relative detection probability of chemicals containing nitrogen was determined as a function of the burial depth and of the soil moisture to investigate the capability of the method in different conditions (i.e. depth and soil moisture).

Results demonstrate that it is still possible to detect a sample of about 800 g of the explosive simulant Melamine even in the presence of relatively high soil moisture (up to about 20 % in weight). The increase of the burial depth causes a sizeable decrease of the signal from the explosive simulant due to the solid angle effects. In the measurements shown here the stand-off distance is about 20 cm (see Fig.1). In this condition, the presence of a buried object can be identified up to burial depths of about 15 cm. For deeper burial depths, the signal-to-noise ratio for Melamine samples up to about 2 Kg makes the detection very difficult.

About 20 minutes measurement time is needed for a Melamine sample at a depth of 15 cm in order to distinguish the explosive from the background. This suggests the use of such a sensor only for Anti Tank Mines. In the case of a common ATM, such as the TMA3, the TNT charge is about 6 kg. Considering a source of 2×10^7 neutrons/s and increasing the number of detectors from 4 to 8, the confirmation time for such a mine buried up to 15 cm would be less than 2 minutes, making realistic the use of such sensor.

Neutron Backscattering

The principle of the technique is very simple: when a fast neutron source (such as ^{252}Cf) is used to irradiate the soil, the yield of thermalized, backward scattered neutrons depends on the hydrogen content of the irradiated volume. Therefore, to confirm the presence of the mine, a Neutron Backscattering (NB) sensor will verify the presence of anomalous hydrogen concentration in the target point, previously identified by using, for instance, a common tool such as the MD. From an operational point of view, it is mandatory to have a unique hand-held system that integrates a NB probe inside a MD.

One possible Neutron Backscattering detector design makes use of a large area (20 x 20 cm^2) Multi-Wire Proportional Counter (MWPC) as a neutron detector. The detector consists basically of 3 parallel electrodes: a plane of wires as anode and the two cathodes coated with a 3 μm thick B_4C layer, 97% enriched in ^{10}B. The anode wires are grouped to obtain 10 independent portions having an area of 2 x 20 cm^2. In this system, the efficiency for low energy neutrons is determined by the conversion via the $^{10}B(n,\alpha)$ reaction which is estimated to be about 16% .The detector electrodes are light (700 g) and have been specifically designed to minimize the metal content, so that the performance of a standard MD is not lowered when it is integrated with the NB sensor. Laboratory tests with the NB sensor working in stand-alone mode, in a configuration where the MWPC electrodes are enclosed in a gas-tight, sealed G-10 box operated at atmospheric pressure with a mixture of Ar (85%) and CO_2 (15%) show that a steady gas charge will allow operation during an 8 hours shift without showing a significant deterioration of the signal size.

An example of a portable system realized by the group of Prof. Carel W.E.Van Eijk of Delft University (The Netherlands) is shown in fig. 2.

▲ Fig. 2: Portable Neutron backscatter system in operation

Associated Particle Technique

In the last few years a prototype of the Tagged Neutron Inspection System (TNIS) was developed using tagged beams of 14 MeV neutrons with suitably defined beam profile, produced by the d+t reaction. Recent studies on this technique point to the development of a portable sealed neutron generator with the neutron-tagging detector embedded into the system.

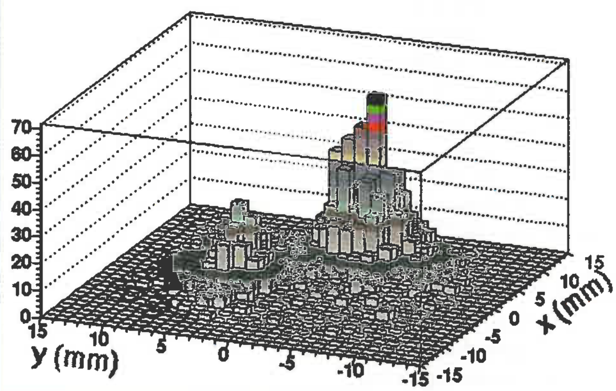
A possible design for the alpha-particle detector for this application has been tested at the Neutron Generator Laboratory of the Ruder Boskovic Institute (IRB) in Zagreb, Croatia. The experimental system now in operation at the IRB contains a neutron tagging detector made of a 40 mm diameter, 0.5 mm thick YAP:Ce scintillator placed inside the reaction chamber at approximately 5.5 cm from the target, 90° with respect to the beam direction and at an azimuthal angle of 45°.

As a test to measure the effectiveness of the method on the signal-to-noise ratio a graphite sample of 5x5x5 cm^3 located at about 90 cm from the source of neutrons is used. The detection of the 4.4 MeV gamma rays emitted by the ^{12}C first excited level populated by neutron inelastic scattering by means of a 4 inch x 4 inch NaI scintillation detector is used to determine the improvement of the spectrum quality. The results of the irradiations are shown in fig. 3: on the left-hand side is shown the gamma-ray spectrum detected without requiring a strict coincidence between the alpha particle and the associated neutron hitting the sample. One can see a peak between 5 and 6 MeV due to neutrons hitting directly the NaI counter, and the 4.4 MeV and "first escape" peaks associated to the decay of ^{12}C in the sample. On the right-hand side is shown the same spectrum but with a strict condition on the alpha-gamma coincidence time.

One can notice a dramatic improvement of the signal-to-noise ratio due to both the "geometrical" and "timing" related reduction of the background contribution. Such improvement can be of up to two orders of magnitude in the case of a pure mono-elemental sample.

Another important property of a system based on fast neutron elemental analysis is the "granularity" of the tagging system that determines the number of neutron beams that can be produced and their maximum transversal dimension. In other words the position resolution of the alpha particle tagging system determines the "imaging" properties of the associated neutron beams.

With the use of two small (5x5x5 cm^3) graphite samples placed at about 6 cm distance from each other on a plane at 90 cm from the neutron source, the usual gamma-ray line at 4.4 MeV is used to confirm that a neutron has hit one of the two samples. The "image" of such a double-sample system as determined in the associated alpha-particle detector is shown in fig. 4 below.



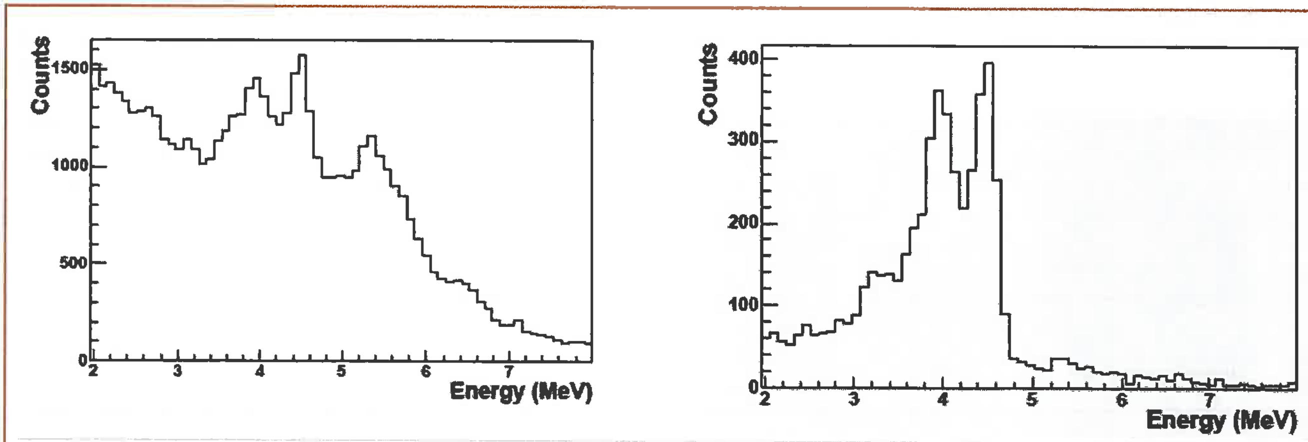
▲ Fig. 4: Position resolution demonstrated with two graphite samples 6 cm apart.

The distribution of hits on the 40 mm diameter YAP:Ce alpha counter is determined in this case by the "centre-of-gravity" method of the signal amplitudes recorded by a multi-anode photomultiplier tube. One can see in the figure the capability of one such system to create an "image" of a given element (in this case ^{12}C). Extending the method to different elements or mapping directly the elemental ratio one can envisage obtaining a "chemical map" of the area under investigation.

Mine detection with photons

As discussed earlier, neutron activation may cause gamma rays with characteristic energies to be emitted by land mine constituents. The second, rather promising approach to employing photons in the landmine detection process is photon scattering. Compton scattering is dominant in most materials at photon energies below several hundred keV. In this process, photons collide incoherently with the atomic electrons, thereby loosing part of their energy. The scattering probability is dependent on the electron density, and consequently the mass density, of the medium. Therefore, Compton scattering can provide a density map, which can be used as an indicator that an anomaly falls in the range of explosive materials.

The intensity of photons scattered by an object embedded in soil is proportional to i) the intensity of the photons emitted from a source towards the object, ii) the attenuation of the photons before they scatter, iii) the probability of scattering in the back direction and iv) the attenuation of the photons as they pass back out of the object and traverse the soil on the way to the photon detector.



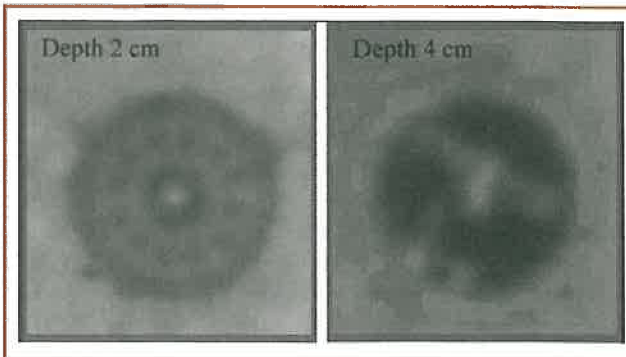
▲ Fig. 3: Neutron activation spectrum without (left) and with (right) alpha particle coincidence (see text).

Sources of photons can be either high power x-ray generators capable of producing x-rays ranging in energy up to 300 keV and more, or gamma sources containing radioactive isotopes such as ^{137}Cs or ^{22}Na. The photons emitted in the direction of the soil and the objects therein are partly removed by side-scattering or absorption in the material. Back-scattered photons travelling towards the detector are again partly removed by further scattering or absorption. Organic material and in particular explosives are characterized by a low effective atomic number, resulting in a high scattering probability and low absorption probability. Dense, metallic material on the other hand readily absorbs low energy photons (x-rays), while for higher energy gamma-rays the remaining Compton scatter probability together with the high density may yield a stronger backscatter signal compared to organics and soil. The combination of density and atomic number can therefore be characteristic for explosives, metal debris or other material.

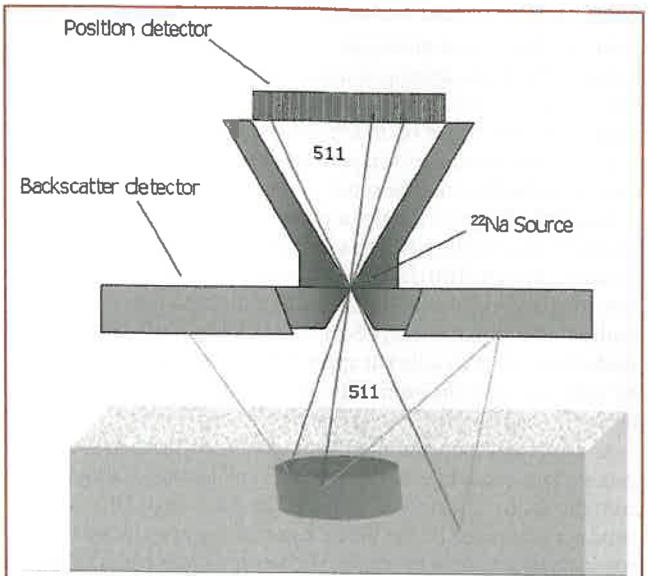
The photon backscatter techniques aim at mapping the effective atomic number and the density of a given soil area. An image of the backscatter distribution may thus reveal irregularities in the soil enabling one to distinguish metallic clutter from land mines by geometry and scatter probability. Generally a position resolution of 2 mm to 4 mm is sufficient for the identification of APMs, whereas for ATMs 1 cm may still be adequate.

In conventional systems collimation of the employed x-ray or gamma-ray beam and its scanning movement is required to map a suspicious surface area. Appropriate beam geometry is achieved by means of a suitably shaped channel in a dense and heavy absorbing material such as lead or tungsten alloys. Good image resolution generally requires a small beam profile, thus the usable fraction of radiation emitted by the photon source is often very small in the range of 0.001 to 1 percent. Rather high source activity is required to obtain the necessary radiation dose at each scanning position in a short time span. Otherwise the total time to generate an image would be impractically long.

Devices can for instance be mounted on a remote-controlled vehicle, with only the detectors suspended over the minefield by a cantilever arm. To produce an undistorted image the speed of the vehicle would need to be either regulated or accounted for. The backscatter system might be applied as the second stage of a two-stage process in which the first stage identifies suspect objects, and backscatter imaging verifies each threat. For example, a metal detector and a neutron detection system could be used in the first stage.



▲ Fig. 5: X-ray images of a buried PPM-2 APM.



▲ Fig. 6: Principle of the annihilation radiation imaging method.

X-ray imaging

X-ray imaging is a mature technology with the advantage of very high image contrasts and good position resolution. In contrast to transmission technologies such as radiography a backscatter image normally is obtained pixel by pixel. A scanning mechanism for a pencil-like x-ray beam is used to generate images. The attenuation of low energy x-rays in soil and explosives is tremendous. Depending on the soil composition and density the total probability for an x-ray to penetrate through the soil to a mine, be backscattered by the mine material and to travel through the soil back into the detector may be of the order 10^{-8} at 10 cm mine depth. Therefore the highest possible x-ray energies and intensities are required to achieve good contrast in a reasonable scanning time.

An example is the prototype scanner ComScan450 developed by the company YXLON to detect land mines (W. Niemann et al., YXLON International X-Ray GmbH, Hamburg [4]). All the components of the system are mounted on a trailer. A high flux 450 kV x-ray tube and a multi-channel x-ray detector system are the major components. The largest and heaviest part of the system is the power generator for the x-ray tube.

ComScan450 has been in use on military test sites several times. Tests were made at varying soil conditions such as humus, sand, gravel etc. Tests were also made with varying conditions of vegetation and of wetness. In the following example in fig. 5 images of a buried PPM-2 APM are shown. The diameter of the mine is approximately 12 cm, layers are shown at depths of 2 cm and 4 cm, respectively. In the first layer, structures of the top lid are clearly visible. No non-mine object in the soil (such as stones, sand, vegetation) would reveal structures like this.

Backscatter imaging with gamma rays

Recently a novel backscatter imaging technique has been introduced, which uses the source of gamma rays very effectively by avoiding any collimation. Therefore the required source activity can be several orders of magnitude below conventional systems. Fig. 6 illustrates the principle of the new method. A point-like ^{22}Na positron source emits pairs of 511 keV positron annihilation gamma rays directed 180° to each other. One gamma ray may be registered in the Position gamma detector. The active detection area of this detector defines the beam shape of the correlated 511 keV gamma rays intended to probe the object to be examined. Its spatial resolution determines the image resolution. The Backscatter gamma detector detects gamma rays scattered from the object. The backscatter probability depends on the amount, density and element composition of the object. To distinguish between gamma rays belonging to the probing beam and other gamma rays emitted by the source or by other natural or artificial radiation sources, time coincidence of the signals of both detectors is demanded.

Currently a detection system is being developed at GSI Darmstadt by its technology transfer partner company GFE mbH, aiming particularly at the detection of land mines in soil. It incorporates a ^{22}Na source of 10 MBq activity in a massive tungsten alloy shielding. The position detector has nine position sensitive LYSO scintillator block elements. The elements form a shell segment covering a solid angle of about 5% of 4π. Each element is coupled to a position sensitive photomultiplier which, together with the subsequent electronics circuitry, produces x and y position as well as time information for each gamma ray detected.

The Backscatter detector consists of 8 plastic detector elements read out by three photomultiplier tubes each, forming a 5 cm thick disc with ca. 50 cm outer diameter and a rectangular centre hole. The 511 keV gamma rays emitted by the source illuminate the object of inspection through this hole. If a 511 keV gamma ray is detected at a certain position of the Position detector its 180° counterpart may be scattered off an object in front of the set-up. For a given range of scattering angles this scattered gamma ray may be detected in the Backscatter detector and generates a coincidence trigger. An image of the matter distribution in the field of view –defined by the active area of the Position detector and the source to matter distance– is obtained by incrementing an image data array in the data acquisition computer.

Fig. 7 shows as an example the image of a metal object and of a small candle of 5 cm diameter in sandy soil. The enhanced backscatter probability of the metal allows it to be discriminated from the candle with its reduced probability, which resembles the scattering behaviour of a plastic mine with 511 keV gamma rays. Depending on the soil type and the volume of the mine the layer thickness that can be penetrated is 10 to 40 cm.

The presented imaging device may help to verify mines found e.g. by metal detectors and may considerably speed-up the clearing of mine fields by avoiding time consuming treatment on harmless metal objects. Moreover, for APM detection in shallow depths a handheld system may be realized since the efficient use of the gamma source with this new method allows for low activity and, hence, lightweight protective shielding.

The novel methods employing neutron and gamma ray probes for mine detection reveal very promising results in the laboratory and in field trials. Therefore we believe that instruments based on these techniques may soon become available to detect land mines in a much safer way and much faster compared to current approaches.

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Dr. Jürgen Gerl is physicist specialized in experimental nuclear structure research. Besides pure science he was always interested in the development of novel instrumentation and its application for "practical" purposes outside science.

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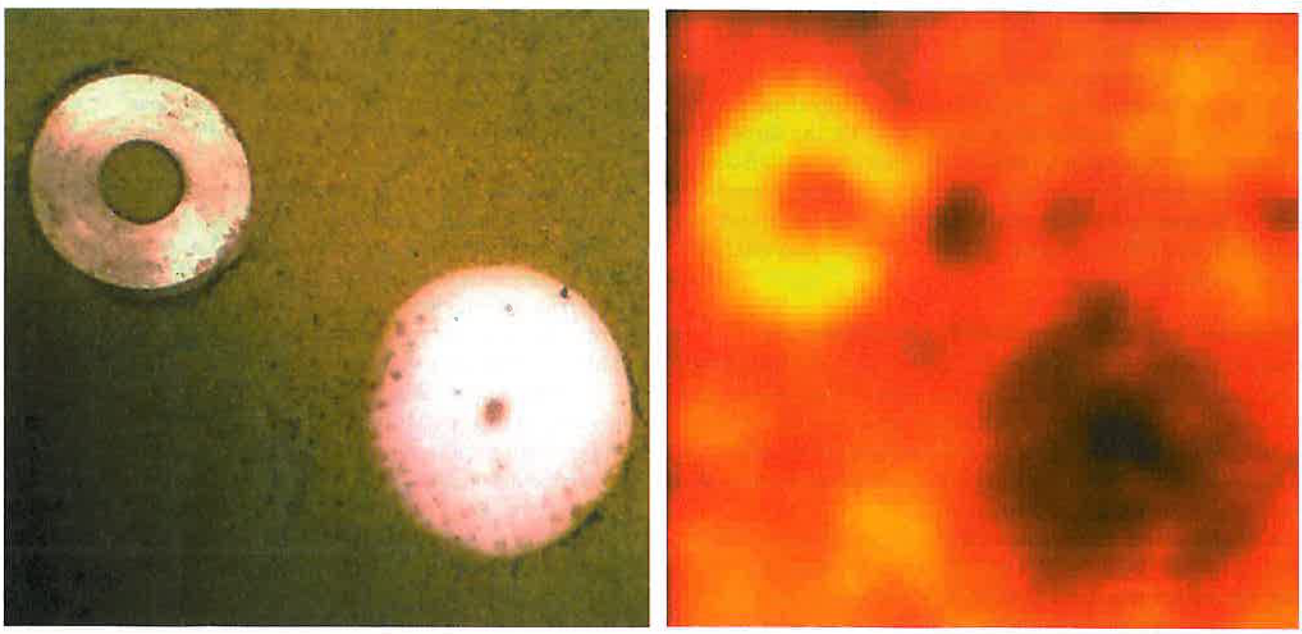

▲ Fig. 7: Image of a metal object and a candle.