Southeastern Europe Tunnelling Conference (SETC-2025)
1-3 October 2025, Belgrade, Serbia

DOI: 10.5937/SETC25028T

Muon Tomography and its Application to Non-Invasive Tunnelling Investigations

Lee F. Thompson[a], Chris A. Steer[a]*

[a] Geoptic Infrastructure Investigations, South Warnborough, RG29 1SD, UK; lee.thompson@geoptic.co.uk, chris.steer@geoptic.co.uk

Abstract: Muon tomography is a novel technique that utilises highly-penetrating but free and abundantly-available natural radiation to image large-scale objects in a totally non-invasive and non- destructive way. This paper reports on the successful application of muon tomography to the imaging of railway tunnels on the UK rail network and outline a number of other applications that are relevant to the tunnelling industry. Specifically, the technique employed to image critical infrastructure using muon tomography technique is described. To place this work into context a brief summary of the recent and past applications the muon imaging method is also presented. Subsequently, there follows a more detailed description of a case study for the technique, specifically that of using muon tomography to image an Victorian era railway tunnel in the United Kingdom. This case study exemplifies the power of the muon tomography technique in that suspected hidden shafts are both identified and characterised in a totally non-invasive manner. There then follows a discussion of the methods involved in extracting visualisations of the tunnel overburden which includes examples of results from a UK railway tunnel. In conclusion, an outlook of potential future applications of muon tomography to the worldwide tunnelling sector is discussed.

Keywords: muon; imaging; non-invasive; tunnel; infrastructure

1. Introduction

Muon tomography exploits muons which are naturally-occurring and fundamental particles (which means that that cannot be broken down into smaller particles). Muons are created, in abundance, in the Earth's upper atmosphere as the result of high-energy particles from the Sun and other sources such as supernovae interacting with gas molecules - such as Nitrogen and Oxygen - in the atmosphere. Muons have properties similar to that of a heavy electron (they have approximately 200 times the mass of the electron) which results in them being highly-penetrating particles, capable, for example, of passing through tens to hundreds of metres of rock with ease.

The combination of muons being highly penetrating and the fact that muons have a high relative abundance (for example, at sea level there are 10,000 muons per square metre per minute), results in them being an ideal candidate to be used for the tomographic imaging of objects that would otherwise be difficult access.

The muon tomography method is completely analogous to that of a medical X-ray. In the case of an X-ray, the density information in an object of interest (for example, a bone in a patient's leg) is imaged when a beam of X-rays passes through the object and subsequently observed by a suitable ″detector” (usually an X-ray film) on the other side of the object. Muon tomography works in exactly the same way except that, in order to detect the muons, a muon-sensitive detection system is needed. It should be stressed that muon tomography is a non-invasive and non-destructive method - capable of returning vital information on the structural integrity of objects at a distance and without the need to interact with

*Corresponding author: lee.thompson@geoptic.co.uk (L.F. Thompson).

the object. Furthermore, just as an X-ray can diagnose issues that are otherwise hidden, muon tomography can identify features in, e.g. a tunnel overburden that would otherwise be invisible.

The parallels between muon tomographic imaging and X-ray imaging are useful to introduce the technique however there are a couple of important differences to note. First, in the case of muon tomography, the particles performing the imaging are free, unlike X-rays which have to be artificially produced. However since muon tomographic imaging relies on a flux of particles that comes from the sky then it is not possible to look down with this technique, muon detectors must be placed (ideally) underneath or to the side of the object(s) to be imaged.

The application of muon tomography to tunnelling is introduced below via a case study that took place on a disused railway tunnel in the UK which demonstrated, for the first time, the value of muon tomography in terms of providing essential and unique information to tunnel asset managers on live rail networks, as a consequence of this work, the technique has been successfully applied to the imaging of more than 20 historic Victorian rail tunnels within the UK. Within the context of tunnelling infrastructure other potential applications are documented in the conclusions section.

At this point it is worthwhile providing a short history of the technique's applications. The first documented use of muons in such applications took place in Australia in 1955 - just over 70 years ago - where the overburden in a tunnel system around a hydro-electric power station was measured. (George 1955). More recently muon tomography has been famously used to identify hidden chambers in the Great Pyramid (also known as "Khufu's pyramid") of Giza (Morishima et al. 2017). The presence of these voids was confirmed with the use of endoscopes in 2023. A summary of the broad range of applications of muon tomography has recently been published by the International Atomic Energy Authority (IAEA 2022). As an indication of the broad scope of the potential of muon tomography other recent applications of the technique within the tunnelling sector (Khaw et al, 2025), (Gebhart et al., 2023) and (Mao et al., 2023) are included in the references.

2. Methodology

2.1. Case study - Background

The muon tomography technique and its application to tunnels - which is of most interest to the SETC audience - is best introduced via a case study. The background to this case study is as follows. Much of the UK's railway infrastructure dates back to the Victorian era with an enormous increase in the UK rail network taking place between the 1850s and early 1900s. During this time significant numbers of bridges, tunnels and viaducts were built. In Victorian times the construction of railway tunnels commonly involved a number of additional vertical shafts being created along the length of the tunnel. These vertical shafts enabled the overall construction process to progress more rapidly. However, after the tunnel was completed what happened to these shafts varied greatly. In some cases the shafts were left open, in others they were bricked over in both the tunnel and on the surface, whereas some shafts have a combination of these approaches. In many cases any documentation regarding the location of hidden shafts is either incomplete or lost completely. In the present day, hidden shafts in particular are a concern to tunnel asset managers within the rail sector since they have potential for dramatic and unfortunate consequences, for example, in the early 1950s several houses near Manchester collapsed into an unknown hidden void, an incident that resulted in the loss of life.

Muon tomography is capable of locating areas of under-density (or, over-density) in an overburden and is thus well-suited to the identification of hidden shafts within rail tunnels. Furthermore, a more detailed tunnel survey with muon sensors is able to characterise any hidden shaft by locating its exact position and extent and also by returning valuable information on the opacity (effectively the integrated density along the column height above the tunnel) of any observed density deficit. Current methods used in the identification of voiding in ageing rail tunnels include invasive investigations, clearly a non-invasive method such as muon imaging is preferred over such techniques. Muon imaging is able to provide valuable information on the tunnel's condition, in certain cases this is used in parallel with other methods such as GPR, ERT and seismic to provide complementary information for the asset manager.

The technique is exemplified in the following case study which details a programme of work which took place on a disused Victorian-era rail tunnel in the UK and is particularly relevant to the tunnelling community as it clearly demonstrates that muon tomography is capable of accurately identifying hidden density changes in tunnel structures.

If required, long-term monitoring of railway tunnel infrastructure is also possible whereby density variations can be monitored to see if there are temporal changes in the density which could be correlated to, e.g. extreme rainfall events. In such cases, this would be evidence of water ingress being observed. Clearly such information is vital to tunnel asset managers.

2.2. Case study - Instrumentation

Figure 1 depicts a typical muon detection system that can be deployed directly onto a "Permaquip" link trolley (a manual propelled, stand- alone load-bearing rolling platform for use on-track) and rolled into a rail tunnel.

Fig. 1. Image of two planar muon systems deployed on railway tracks.

The detectors used in this measurement campaign are somewhat different to those used in some of the earlier studies discussed above and are designed specifically to be robust and to operate outside of the laboratory in what can be challenging environments. The system comprises a total of 5 Explorer 154116 cases for the detectors and a Explorer 5122 case for the control box. Inside each of the black, IP68-rated detector cases is an array of sheets or bars of a material called plastic scintillator. This results in an overall "field-of-view" for the instrument of typically 45 to 60 degrees along the direction of travel however this field-of-view is further subdivided into 12 sub-fields of view - a feature that is subsequently used in the analysis of the data (see Section 2.4 below). The control box carries a battery and all of the associated electronics to record the detected muon signals. When assembled the system measures 1629 mm x 1629 mm x 1300 mm and is able to operate for 40 off a single battery charge.

Plastic scintillator comprises a suitably transparent base material, usually polystyrene, which is impregnated, at the polymerisation stage, with small quantities of compounds called "fluors" which comprise benzene rings. When a muon passes through the scintillator the energy deposited by them causes the fluors to excite and de-excite, leading to a short-duration light flash which can be detected and recorded using devices called photosensors The time of the light flash is also recorded which can be used to further pin-point the trajectory information of the passing muon.

In the case of muon tomography, large area detectors work best as this maximises the statistics acquired in what is typically short duration data acquisition periods (access to rail tunnels on live lines is usually restricted to a few hours overnight). The instruments shown in Figure 1 above demonstrate the best compromise between surface area and robustness. However, for other tunnelling applications it is possible to configure bars of plastic scintillator into cylindrical detectors that can, for example, be deployed in a borehole. Other, smaller format planar detectors are suitable for longer duration data acquisition times such as those required to correlate overburden changes with rainfall events as discussed earlier.

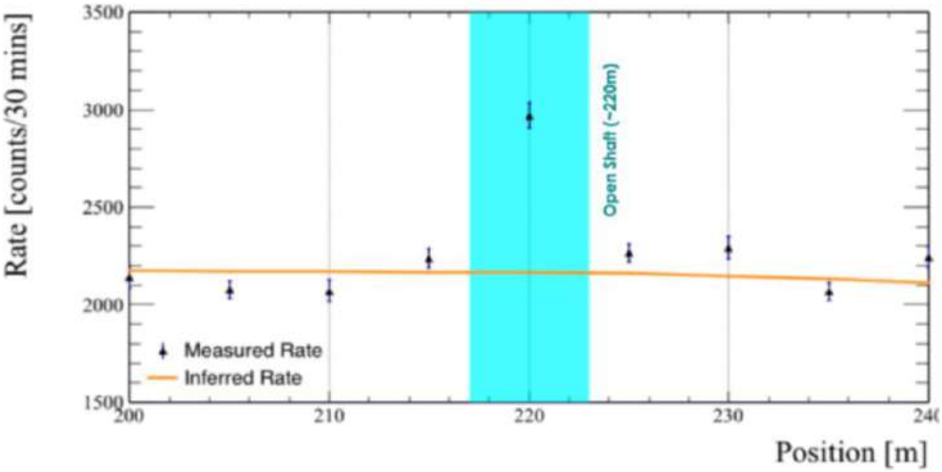

Fig. 2. Results of muon tomography scan of the Alfreton Old tunnel, observed data from muon instruments (points) and predicted data from digital twin assuming no hidden shafts (orange line).

2.3. Case study - Alfreton Old Tunnel

The world's first use of muon tomography in identifying and characterising hidden voids in railway tunnels was demonstrated at a disused railway tunnel located at Alfreton in Nottinghamshire, UK. This tunnel, known as "Alfreton Old Tunnel" has 3 shafts which are fully open to the surface and so this tunnel served as an ideal demonstrator for this particular application of muon tomography.

Muon sensors, as discussed in section 2.2 above, were deployed in the Alfreton Old Tunnel and a series of readings of the observed muon rate taken at regular 5 metre intervals along the tunnel. The observed muon rate was compared against that expected from prior desk studies using a digital twin of the tunnel. (A full report of the tunnel survey is published in (Thompson et al. 2020).

Figure 2 above shows the results of scanning the entire length of the tunnel at regular 5 metre intervals with 30 minutes of data-taking at each point. The "inferred rate" is that predicted, by the digital twin, to be seen in the muon instrumentation (via computer simulations) assuming the known geology (overburden depth and rock type) for the tunnel. The 3 open shafts (indicated by blue vertical lines) are clearly visible in the data as a highly significant excess of muons compared to that predicted by the digital twin in assuming no shaft (and hence more density and so fewer muons).

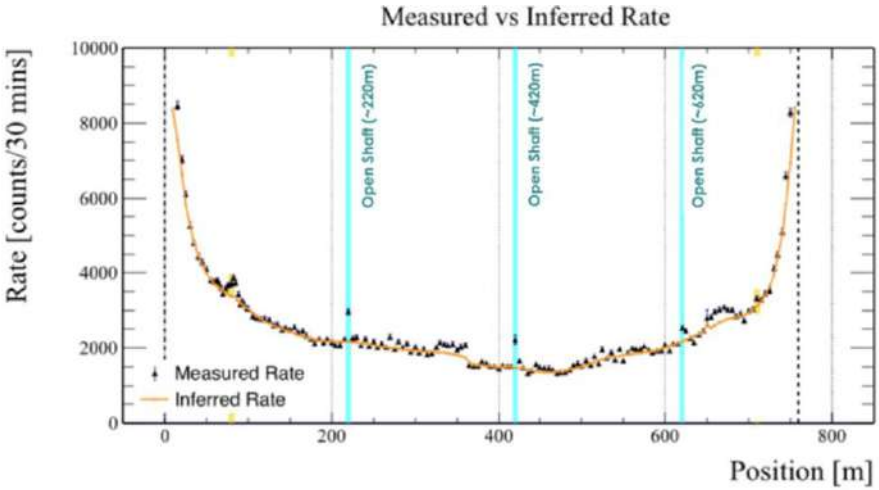

Fig. 3. Observed (points) and predicted (orange line) muon sensor system data observed around known open shaft

Fig. 3 shows a zoom-in of the data around 220 metres from the access portal. In this case the statistical significance of the open shaft observation is extremely high - 11 standard deviations. Figure 2 shows other features visible in the data: the discontinuity at approximately 350 metres was due to a system replacement and is understood, there is also some indication of an elevated muon rate around650-700 metres which may be the result of incorrect modelling of the overburden close to the tunnel portal. A further feature in the data of particular interest however is the deviation in the data around 80 metres, which is magnified in Fig. 4.

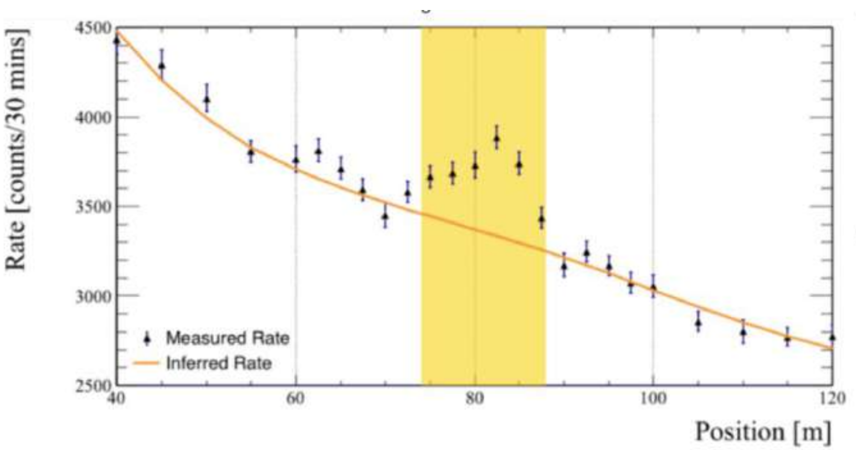

Fig. 4. Data from the suspected hidden shaft region.

The observed muon rate in this region demonstrates features that are indicative of a hidden shaft. Further discussions with the rail operator confirmed that there is a suspected hidden shaft in the area - information that wasn't available prior to the muon tomography survey.

A second stage of the Alfreton Old Tunnel field trial was subsequently carried out which demonstrates a further benefit of the use of muon tomography for this type of interrogation of civil infrastructures such as tunnels, namely that the technique is able to swiftly identify density anomalies of interest and, if required, can subsequently, with a more detailed survey, return additional characterisation data on the object of interest.

In the case of the Alfreton Old tunnel, the results from this second characterisation phase are included in Figure 5 which indicates that the hidden shaft is centred at the tunnel crown with a diameter of approximately 3.5 metres, the data also indicates that the overburden of the shaft is equivalent to 1 metre of standard density rock (5 metres of rock at 1 standard deviation), which suggests that the feature is highly likely to be a hidden shaft with minimal backfill material.

In addition to the identification and characterisation of features discussed above, muon tomography is also capable of performing longer-term monitoring of a region of interest. This could, for example, identify density changes in a region of interest and correlate them with, e.g. extreme rainfall events, in which case water ingress could be taking place.

2.4. Case study - Data Interpretation Techniques

Prior to any muon survey it is important to develop a complete-as-possible understanding of the geology and overburden that the muons will pass through. In general, such information may be a combination of, e.g., satellite, Lidar and additional topographic data. Where available, surface features such as houses, etc. are included in the "digital twin".

With the digital twin completed it is then necessary to estimate the expected muon flux through a specific sensor deployed at a point under the tunnel overburden. Here standard muon tracking software from the particle physics community is used such as GEANT (Agostinelli et al. 2003, Allison et al. 2006, Allison et al. 2016). Importantly this software samples the expected muon surface flux, as a function of energy. This process is important since high-energy muons are less plentiful but more penetrating.

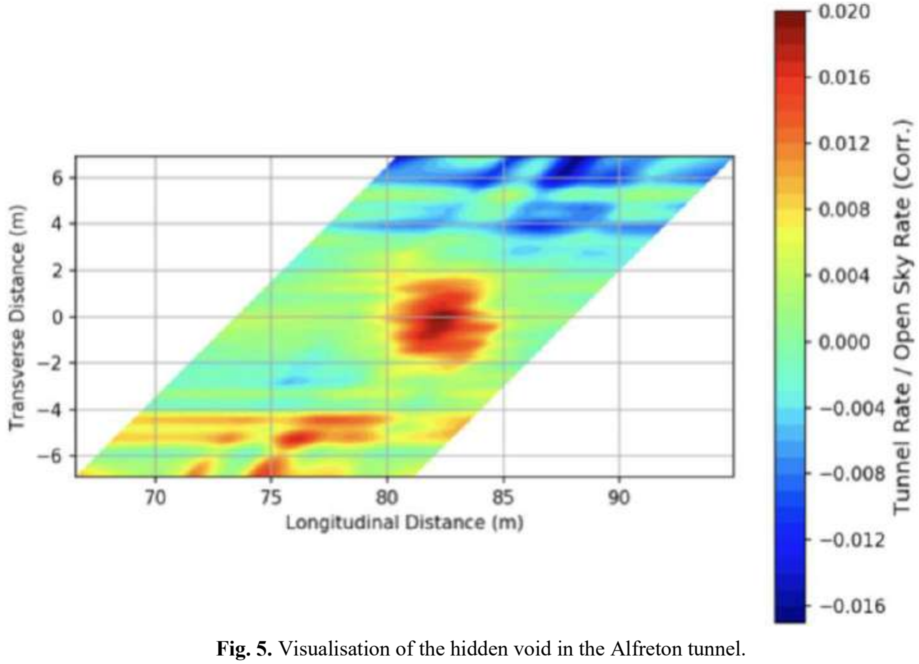

Fig. 5. Visualisation of the hidden void in the Alfreton tunnel.

With the digital twin complete it is then possible to compare the expected muon flux with the empirical data from a muon survey. As mentioned above, at each measurement the muon sensor has a particular field-of-view (depicted by the red V shapes in Figure 6 below). However, this field-of- view is subdivided enabling computer tomographic techniques to be applied which result in a 2D or 3D visualisation of the density changes, with respect to expectation, in the data.

An example of the 2D tomographic image that can be achieved through this technique is included in Figure 6 (note this is a 2D image of a different tunnel, not the Alfreton tunnel) where orange(red) colouration indicates medium(high) levels of under-density from the muon measurement compared with that expected assuming a solid overburden. In this particular case, evidence for several full-height hidden shafts can be seen.

In general, measurement times are largely dictated by the overburden of the tunnel. In the programme of work carried out in the UK following this initial study, data-taking campaigns have taken place in tunnels varying in depth typically between 30 metres and 80 metres. Given the large area instrumentation used for these surveys measurement times of typically between 10 and 60 minutes per point along the survey are required. The muon-sensitive instrumentation used in particular application is chosen to be compatible with the size of feature to be imaged in the rail tunnel surveys which is typically one the metre-scale. Other instrumentation exists which is capable of imaging down the centimetre scale.

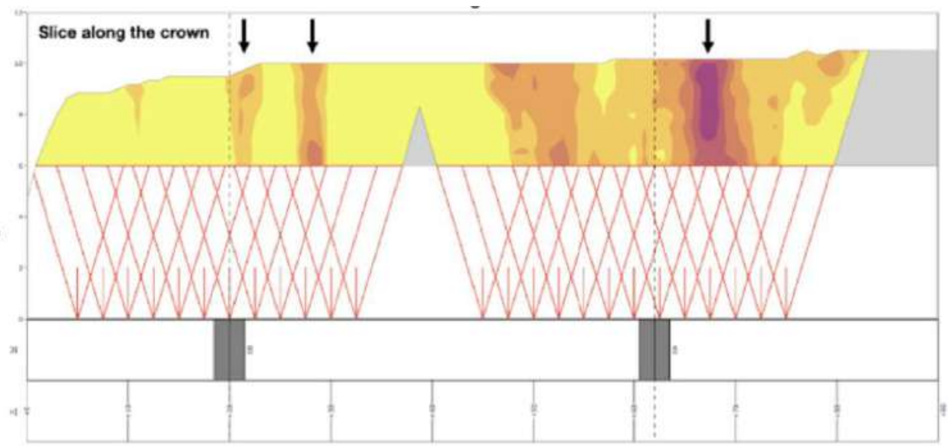

Fig. 6. 2D slice through a 3D tunnel overburden density reconstruction.

Other non-invasive techniques exist however, in the context of tunnel imaging Geoptic has not been party to any direct comparisons with the results delivered by, e.g. Electrical Resistivity Tomography (ERT), seismic or ground penetrating radar (GPR). Of note however is that in 2023 Geoptic completed a programme of work in Norway that measured the density change in the sub-surface as a result of an injection of CO2, in that case both muon instrumented and seismic techniques were co-deployed and both techniques returned the same result (Thompson et al., 2024).

3. Conclusion

This paper outlines the muon tomography technique and details its application to the identification and characterisation of hidden voiding in legacy rail infrastructure, specifically rail tunnels. A scan at 5 metre intervals through the area of interest with typically 30-60 minutes of data-taking per point (depends exactly on the depth of overburden of the tunnel) is sufficient to enable features such as hidden construction shafts and other areas of under-density (e.g. “cut and cover”) to be successfully identified. The programme of work as described above has led to muon tomography being embraced as a standard asset management tool for understanding the condition of Victorian era rail tunnels within the UK (to date around 20 tunnels have undergone scans using muon imaging). As highlighted above, an important aspect of this technique is the fact that this imaging takes place without any need for contact with the tunnel itself. However, clearly, this technique is not limited to hidden shaft identification and characterisation. Other tunnelling-related applications that are under consideration for muon imaging, for example, include possible geology "look ahead" for tunnel-boring machines, water ingress monitoring (since water ingress changes the density of the object of interest - something that muon imaging is directly sensitive to) and potential sinkhole avoidance by identifying undocumented lower density regions in urban environments. Density changes in other objects such as bridges and viaducts can also be identified - these applications, using smaller format, high resolution muon sensor systems, are currently being trialled.

In conclusion, muon tomography is a powerful non-invasive imaging technique capable of returning detail on density changes in an overburden without the need to make contact with the object of interest. As demonstrated in the case study, the technique is capable of both identifying and characterising otherwise invisible features behind the tunnel lining such as hidden shafts and voids in railway tunnels on the UK's rail network. Of particular note is that this technique has been adopted as a standard tool by tunnel asset managers on the UK's Network Rail infrastructure.

References

Agostinelli, S. et al., 2003. Geant4 - A Simulation Toolkit. *Nucl. Instrum. Meth. A* 506: 250-303

Allison, J. et al., 2016. Recent Developments in Geant4. *Nucl. Instrum. Meth. A* 835: 186-225

Allison, J. et al., 2006. Geant4 Developments and Applications. *IEEE Trans. Nucl. Sci.* 53: 270-278

Gebhart, L, et al., 2023. Muon tomography for detection of dynamic border tunnels. *Nucl. Instrum. Meth. A* 1053, 168383.

George, E.P., 1955. Cosmic Rays Measure Overburden of Tunnel. *Commonwealth Engineer* 42: 455-457

Khaw, K.S. et al., 2025. Non-Invasive Assessment of Sediment Accumulation Using Muography: A Pilot Run at the Shanghai Outer Ring Tunnel., 10.48550/arXiv.2504.00582.

Mao, X, et al., Muon radiography experiments on the subway overburden structure detection, https://arxiv.org/abs/2303.09819

Morishima, K. et al., 2017. Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons, *Nature* 552: 386–390

INTERNATIONAL ATOMIC ENERGY AGENCY, 2022. Muon Imaging: Present Status and Emerging Applications. IAEA TECDOC 2012

Thompson, L.F. et al., 2020. Muon tomography for railway tunnel imaging. *Phys. Rev. Research* 2: 023017

Thompson, L. et al., 2024. Muon Tomography - a Novel Imaging Technique for Monitoring the Carbon Capture and Storage Process. *European Association of Geoscientists and Engineers*, 2214-4609, 1-5.