Container Inspection Utilizing 14 MeV Neutrons

Vladivoj Valkovic, Davorin Sudac, Karlo Nad, and Jasmina Obhodas

***Abstract*—A proposal for an autonomous and flexible ship container inspection system is presented. This could be accomplished by the incorporation of an inspection system on various container transportation devices (straddle carriers, yard gentry cranes, automated guided vehicles, trailers). The configuration is terminal specific and it should be defined by the container terminal operator. This enables that no part of the port operational area is used for inspection. The inspection scenario includes container transfer from ship to transportation device with the inspection unit mounted on it. The inspection is performed during actual container movement to the container location. A neutron generator without associated alpha particle detection is used. This allows the use of higher neutron intensities ($5 \times 10^9 - 10^{10}$ n/s in 4π). The inspected container is stationary in the "inspection position" on the transportation device while the "inspection unit" moves along its side. The following analytical methods will be used simultaneously: neutron radiography, X-ray radiography, neutron activation analysis, (n, γ) and (n,n'γ) reactions, neutron absorption. and scattering, X-ray backscattering. The neutron techniques will utilize "smart collimators" for neutrons and gamma rays, both emitted and detected. The inspected voxel is defined by the intersection of the neutron generator and the detectors solid angles. The container inspection protocol is based on identification of discrepancies between the cargo manifest, elemental "fingerprint" and radiography profiles. In addition, the information on container weight is obtained during the container transport and screening by measuring of density of material in the container.**

***Index Terms*—Activation analysis, container inspection, gamma ray spectra, neutron absorption, neutron scattering, neutrons, radiography, x-ray backscattering.**

I. Introduction

WHITHIN the framework of two EU projects (EURITRACK and ERITR@C) and one NATO project (SfP-980526), a technology of container inspection with a new neutron probe used as a secondary sensor has been developed for detailed inspection of the suspected container volume as determined by an X-ray system. A demonstration facility was constructed and mounted at the container terminal Brajdica, Port of Rijeka, Croatia. Some 150 containers have been inspected in combination with the Smith Heimann 300 unit.

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V. Valkovic was with the Ruder Boskovic Institute, Bijenicka c.54, 1000 Zagreb, Croatia. He is now at Kvinticka 62, Zagreb, Croatia (e-mail: valkovic@irb.hr).

D. Sudac, K. Nad, and J. Obhodas are with the Ruder Boskovic Institute, Bijenicka c.54, 1000 Zagreb, Croatia (e-mail: dsudac@irb.hr; nad@irb.hr; jobhodas@irb.hr).

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Following the implementation of the above mentioned projects, several disadvantages and imperfections of using tagged neutrons have been identified.

i) EURITRACK-like system requires a site area of $\sim 500m^2$ container terminal storage area. Loss of income to the Container terminal and Port of Rijeka during the implementation of EURITRACK and ERITR@C projects was estimated to 48,000 /year.
ii) No functional sensor (Smiths Heimann-Tagged neutron system) communication has been established.
iii) The neutron beam intensity has been limited to $\sim 10^7$ n/s in 4π requiring irradiations of suspected area/spot/voxel for 10 minutes since only a fraction of the neutron generator output was used with detection of associated alpha particles.
iv) Only small percentage of port leaving containers could be screened.
v) Questionable determination of the difficult to measure nitrogen signature and subsequent construction of C-N-O diagrams.

All mentioned disadvantages could be avoided by design, construction and building of an autonomous and flexible inspection system: Autonomous Ship Container Inspector System (ASCIS).

This could be accomplished by:

1. The incorporation of the inspection system on the container transportation devices (straddle carriers, yard gentry cranes automated guided vehicles, trailers–to be decided by container terminal operator). In this way, no part of the port operational area was used for inspection. The inspection scenario included container transfer from ship to transportation device with inspection unit mounted on it, and inspection during container movement to the container location (either to exit truck or terminal yard position).
2. Use of neutron generator without associated alpha particle detection. The area analyzed was determined by mounting the neutron generator inside shielding and collimator, defining a narrow fan beam of neutrons. This allows the use of higher neutron intensities ($5 \times 10^9 - 10^{10}$ n/s in 4π).
3. The inspected container was stationary in the "inspection position" on the transportation device while the "inspection unit" was moving along side with a speed of 12 m/min, resulting in ~ 1 min inspection time, T_i, for the whole container (2 TEU). The efforts were directed towards reduction of T_i to as low as possible value. A detached part of the "inspection unit" was mounted on the gentry crane spreader to detect radionuclides and SNM using fast neutron bombardment and detection of induced gamma and neutron radiation.

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4. It is proposed to design, construct and build a trailer inspection unit using the following analytical methods simultaneously: neutron radiography, X-ray radiography, neutron activation analysis, (n, γ) and (n,n'γ) reactions, neutron absorption, neutron backscattering, X-ray backscattering. Neutron based techniques take advantage of using "smart collimators" for neutrons, both emitted and detected. The inspected voxel was defined by the intersections of the neutron generator and detector solid angles.

In addition, the information on container weight was obtained during the container transport and foreseen screening. One of the essential parameter to be measured is the density of material in the container. Based on this measurement one should be able to evaluate the "average container density" and calculate its weight.

II. Concept and Approach

Radioactivity Measurements

Presently, there are several commercially available radiation detection unit mounted on the gantry crane which can detect eventual presence of radioactive materials inside the transported container by, so called, passive measurement [1]. VeriTainer's container crane mounted radiation detection and identification system, called the VeriSpreader, employs an advanced passive scanning technology (^{3}He neutron counter and NaI(Tl) γ spectrometer) and sophisticated identification algorithms to detect and identify gamma and neutron sources in shipping containers as they are loaded or discharged from a container ship. VeriTainer's prototype crane mounted solution (CMS) was in continuous operation at the Port of Oakland from April 2, 2007 through May, 2008 (13 months). It operated without mechanical failure or loss of sensitivity over the course of more than 47,000 container moves.

The detached component of the proposed inspection unit can be used as an additional screening unit providing a neutron source which might induce radioactivity especially on fissile materials and SNMs (U, Th and others), see Fig. 1. A potential candidate for the neutron generator is the so called "long neutron generator".

The proposed system will consist of a spreader bar for the container crane assembly, neutron generator, γ-radiation and neutron detectors and a computer capable of wireless (cloud) communication. The system will measure and analyze gamma-ray counts and energy spectra as well as neutron counts from the detectors in real time as the containers are loaded to, or unloaded from, the container ships. The primary purpose is to detect the presence of radioactivity especially of fissile materials and SNMs (U, Th and others) and alert the user of elevated gamma and neutron rates.

Inspection Unit

We assume that only a hybrid gamma ray / neutron system based not only on a typical fast neutron gamma radiography system will offer better detection capabilities. In the design of the inspection unit we considered incorporating the following analytical methods to be used simultaneously.

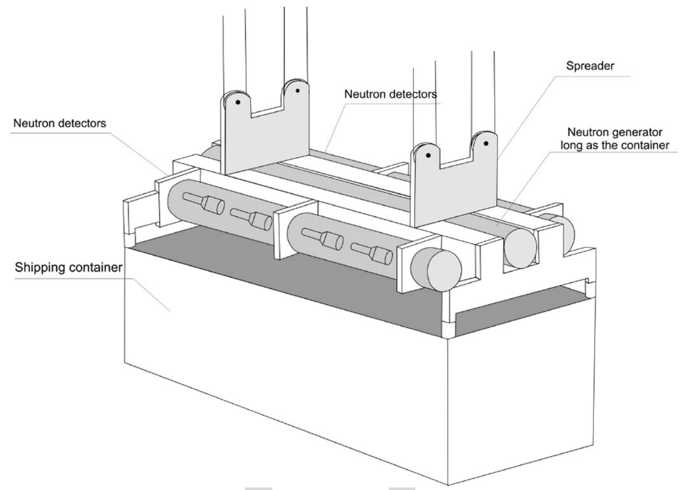

Fig. 1. Proposed inspection unit to be mounted on quay crane.

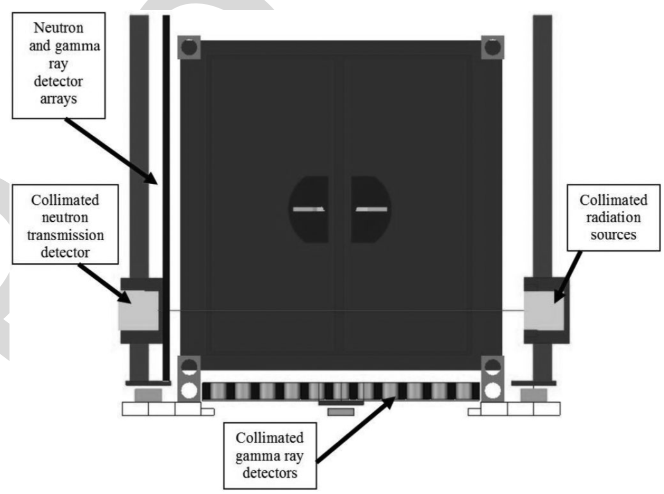

Fig. 2. Schematic presentation of U-shaped inspection unit; density determination by using neutron transmission measurement.

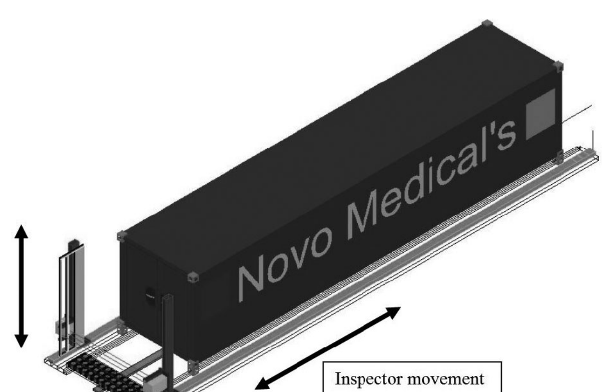

Fig. 3. U-shaped inspection unit slides on rails along side the inspected container.

- neutron radiography,
- gamma ray radiography,

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- neutron activation analysis, (n, γ) and (n,n'γ) reactions,
- neutron scattering and absorption.

The last two techniques will take the advantage of using "BM smart collimators" for neutrons, both emitted and detected.

There are several proposed radiography systems [2], [3]. The new system will be based on the AC6015XN air cargo scanner which has developed by CSIRO and Nuctech [4], because this is the most promising device. Comparison of the neutron and gamma-ray transmissions yields an R-value that can be used to discriminate between a wide range of organic and inorganic materials. However, although the fact that the AC6015XN is a triple beam device and there are 3 R-values the Australian scientists use only 2 R values. The third R value could offer extra and sometimes valuable information [5].

Attention was focused to the selection of the X-ray sources. We shall investigate which combination of the X-ray beams is the best among the typical energies 3, 4, 5, 6, 7, 8 or 9 MeV electron LINAC (linear accelerator), or some other values.

Smaller detectors, especially for the X-ray array will offer better inspection capabilities (5×5 mm CsI detectors–to be investigated). Also with smaller neutron detectors (e.g. 10×10 mm plastic detectors) we will "see" more details on the neutron radiography mode which represents a significant enhancement compared to the 20×20 mm detectors used today.

Regarding the neutron source, the only solution was the DT neutron generator because 14 MeV neutrons have relevant acceptable penetration capabilities. However, typical generators with a solid state targets have a short life times (typical 500-2000 hours), which makes associated alpha particle method inappropriate. Therefore, one should use the DT neutron generators using a plasma source. This provides for at least 25,000 hour of operational life.

The inspection unit is "U" shaped construction with three arms: right, bottom and left.

<u>Left arm</u> contains radiation units: neutron generator and X-ray source (6 MeV LINAC) inside shielding box, both having "smart collimators" in order to produce collimated beams.

<u>Bottom arm</u> will contained the battery of gamma detectors ($5'' \times 5''$ NaI or BGO, number, size and type to be determined). From our previous measurements [6] it is known that for the detection of 100 kg of explosive in iron matrix of density $0.2\ \mathrm{g/cm^3}$, 54485 s were needed with a neutron beam intensity of 10^7 n/s and by using two 3×3 NaI(Tl) gamma ray detectors inside a lead shielding thickness 5 cm. With the neutron beam intensity increased for three orders of magnitude this measuring time could be reduced to 54 s. By using a battery of thirteen 5" NaI detectors this could be reduced to some 3 s. This is only the rule of thumb estimate, the complete system performances will be assessed in the course of a future project.

<u>Right arm</u> contains the neutron detector array for neutron radiography containing probably some 700 neutron plastic detectors dimensions $20 \times 20 \times 75$ mm (to be determined); X-ray detector array of $10 \times 10 \times 50$ mm CsI(Tl) detectors (exact size, number and type to be determined). Both arrays will be stationary with respect to radiation sources and mounted inside appropriate shielding. This arm also has a beam transmission detector equipped with a smart collimator and n-γ separation circuit. The detector is at a fixed position with respect to neutron source at all times.

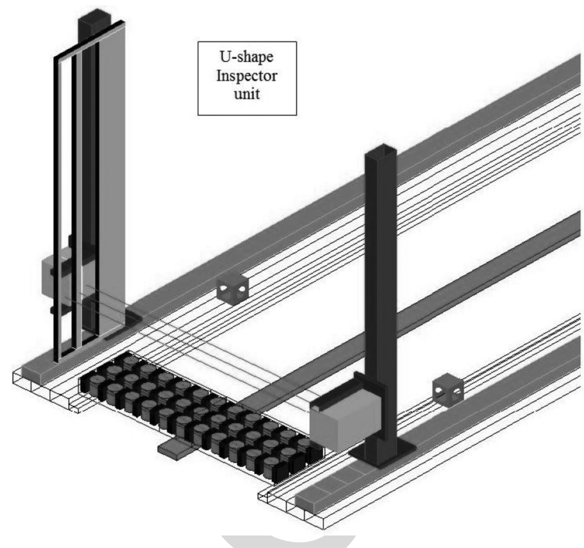

Fig. 4. Components of "U" shaped inspector: collimated radiation sources (neutrons and X-rays), collimated gamma-ray detectors (bottom), collimated neutron transmission detector, neutron and X-ray detector's arrays.

The size of the inspected voxel is defined by "smart collimators" in front of the detectors and neutron source. The construction of collimators will be based on the MNCP calculations and experiences of previous efforts as described in ref [7], [8]. With two gamma ray batteries in the bottom arm, 24 positions of inspection unit would be required to cover a 40" container length. If in addition 3 vertical positions are included, this will result in $3 \times 24 = 72$ scans, each lasting 3 s. It follows that the complete inspection can be done in 3–5 minutes. It should be mentioned that this estimation is valid for the detection of 100 kg of explosives (and other threat materials) in an iron matrix with a density of $0.2\ \mathrm{g/cm^3}$ or an organic matrix of density $0.1\ \mathrm{g/cm^3}$. Results for containers inspected in the Port of Rijeka, Croatia, indicated that the average container density was around $0.1\ \mathrm{g/cm^3}$, with organic type cargo represented by 62%, metallic with 15%. It follows that for containers with higher density cargo, the measurement time could be longer, which could be decided from the first evaluation of the container average density.

During the project implementation, considerations were made on the three variants of Inspection units: "U", "L" and "I" shaped, see Fig. 4, 8 and 9, respectively. We first start with "U" shaped Inspection unit because it can be realized with the applications of present day knowledge. In this case the Inspection unit is U-shaped so that the container can be brought inside it. The inspected container was stationary in the "gantry crane inspection position" while the "inspection unit" was moving along side with a speed of 1-2–m/min, resulting in $\sim$10 min inspection times for the whole container.

The chemical elements present in the investigated voxel were determined by measuring resulting gamma spectra by the 3 arrays, each containing 12 bottom placed gamma detectors

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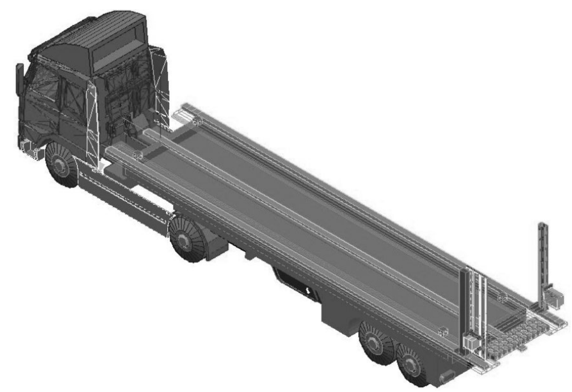

Fig. 5. “Inspector” mounted on the transport track.

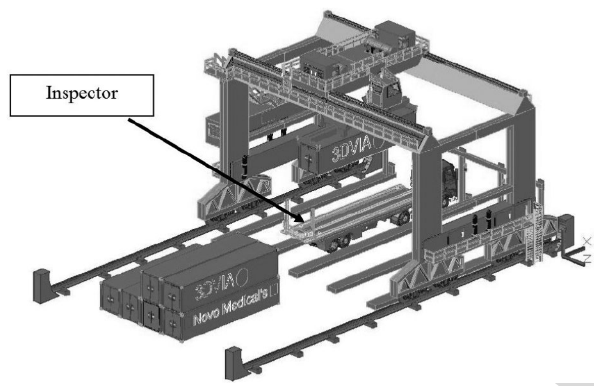

Fig. 6. Loading the container onto truck mounted inspection unit.

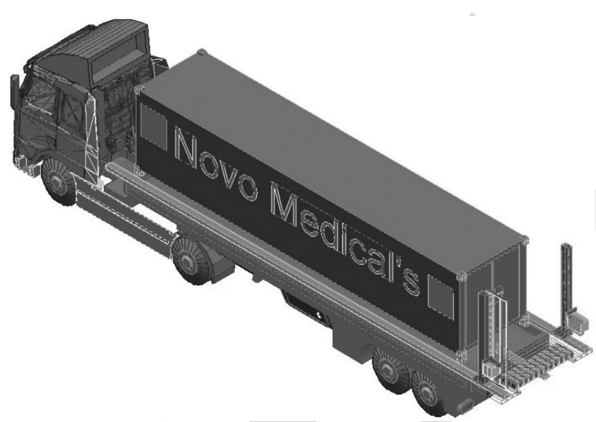

Fig. 7. On the way to the yard or any other transfer point.

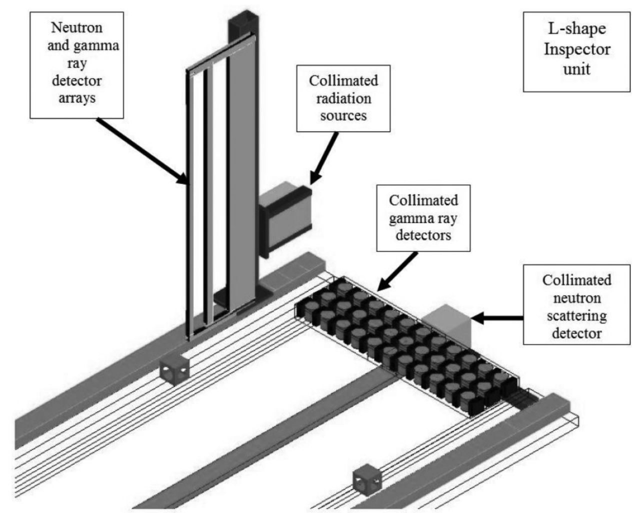

Fig. 8. Components of “L” shaped inspector: collimated radiation sources (neutrons and x-rays), collimated gamma ray detectors (bottom), collimated neutron transmission detector, neutron and x-ray detector’s arrays.

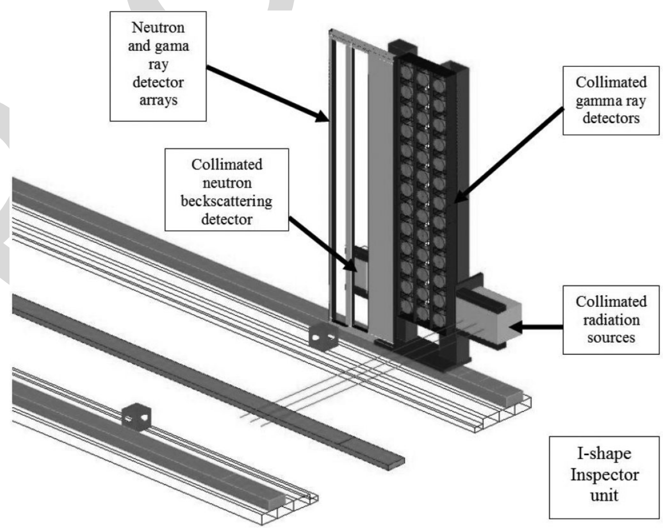

Fig. 9. Components of “I” shaped inspector: collimated radiation sources (neutrons and x-rays), collimated gamma ray detectors, collimated neutron transmission detector, neutron and x-ray detector’s arrays.

inside shielding and equipped with “smart collimators” for C, O (+ other elements) relative concentration determination.

Other parameters of components used are:

- Neutron beam intensity ($5 \times 10^9 - 10^{10}$ n/s in 4π) collimated using “smart collimators”.
- Neutron detector (transmission detector) collimated using “smart collimator”.
- Gamma source collimated–bremstrahlung source: 6 MeV LINAC (to be decided).
- Two source positions: bottom and top of the container or continuous up-down movement.
- Construction of C-O-rho(density) triangle diagrams for material identification, shown in Fig. 11 and 12.
- Sum triangle graph will be compared with individual γ-detector triangle graphs in data analysis process and cross checked with radiographs.

Until now, cargoes have been shipped based on declared container weights in booking information provided by shippers. Vessel storage plans and port operations are typically based on these pre-declared weights which can vary significantly from the actual mass of the cargo transported. The consequent risk to health and safety of seafarers and port operatives is clearly apparent [9]. Weighbridges located at the port gate are easy to implement, but present significant challenges in establishing the true tare weight of the vehicle and in differentiating the weights of multiple container loads. Within the port, reach stackers and fork-lift trucks provide a relatively low cost path for indirect weight measurement to be integrated into vehicle systems e.g. inferred from hydraulic pressure. However, this is

Fig. 10. 100 kg of Semtex1 explosive in an iron box $40 \times 40 \times 66$ cm^3 in volume (up) and 64.4 kg of paper in the same box (down).

likely to be of lower accuracy than direct measurement systems and it is questionable whether it would deliver full compliance with any genuinely robust regulation. Rubber-tired gantry cranes and straddle carriers provide a good opportunity for the implementation of direct weight measurement of individual containers with in the port environment but before final vessel loading operations. Such systems may offer a highly flexible solution with minimal disruption to existing port operations and container logistics.

The proposed Inspection unit will support one of the key recommendations, for the implementation of container weight verification technology, that container weight should be measured as close as possible to the point of lifting. In addition to enabling the verification of individual container weights, the proposed Inspection unit will also enable automatic estimation of centre of gravity; something that will be extremely useful in improving the safety of stacking operations.

III. Experience in Neutron Inspection of Containers

There are several different approaches in the use of fast neutrons for container cargo inspection. In addition to the use of continuous tagged neutron beam also pulsed neutron beam is used [10]. Also, the use of triangle graphs for threat material detection and identification has been extensively discussed by Maglich and coworkers [11]–[13].

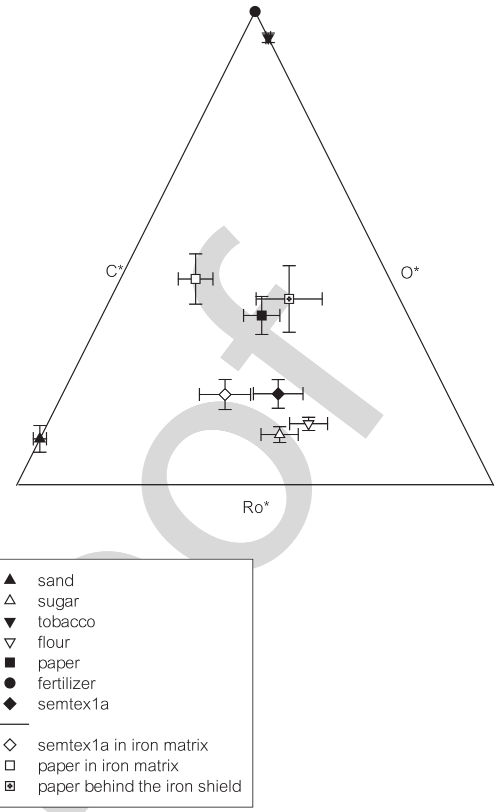

Fig. 11. Triangle diagram for various materials inside the empty container together with the paper and explosive semtex1a in iron matrix and paper behind the iron shield.

Let us present some of our experience of using C-O-ρ triangle graphs in identification of materials hidden inside container [14], [15]. The 14 MeV tagged neutron technique has been used to confirm the presence of the explosive Semtex#1a within the inspected container. Two $3'' \times 3''$ NaI(Tl) were put at the transmission position in the cone of the tagged neutrons beam. Each detector was shielded with a 5 cm thick lead brick [14]. Container around the target was filled with iron boxes of density $0.2\ \mathrm{g/cm^3}$.

We have also illustrated that various threat materials (including explosives) could be detected inside the container by measurement of three variables, C and O concentrations and the density of the investigated material [16]. Carbon and oxygen were detected, but not nitrogen. It can be shown that 100 kg of Semtex#1a can be detected in an iron matrix of density $0.2\ \mathrm{g/cm^3}$ by using the triangle graph like in Fig. 11.

The presence of an iron matrix around the target does not change the position of the material inside the triangle plot. It is, however, well known that an organic matrix would have a big influence on the neutron beam because of attenuation as well as termalization of fast neutrons. In order to demonstrate the usefulness of the neutron system, it was necessary to investigate if and how organic matrix changes the position of the signal of target material inside the triangle diagram.

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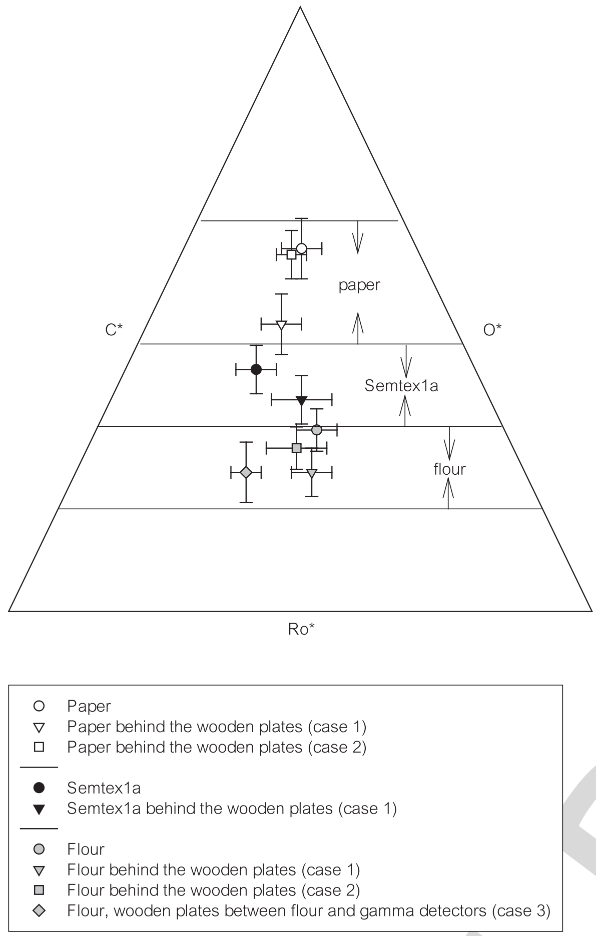

Fig. 12. Triangle diagram for the transmission detectors (taken from ref. 15).

The organic cargo was simulated with wooden plates (dry wood has formula $C_{22}H_{31}O_{12}$). Block made from wooden plates of 0.53 g/cm^3 density and thickness of about 27 cm was put in front of the target material in the first measurement and close to the container wall in the second measurements. The total thickness of this block was about 60 cm along the tagged neutron beam axis, which means that the effective density is about 0.25 g/cm^3 (because of the empty space between the wooden plates). However, the average density along the container was even less, around 0.1 g/cm^3.

Some of the experimental results are shown in the triangular diagram of Fig. 12, where the measured points are located in the three regions. The first region corresponds to the paper points. The second region corresponds to the semtex1a explosive and the third region belongs to the flour. Division is not rigid. Some overlap exists especially between semtex1a and flour. Generally, the effect of the wood plates is to lower down the position of the material in the diagram. It could be seen that the wooden plates which are far from the target (Case 2) have less influence on the target material position in the diagram than the wooden plates which are close to the target (Case 1 and Case 3). Even in the case where some overlap between the regions could be expected, the identification of the paper, semtex1a and flour is possible provided that the error on estimating the surrounding organic matrix density is not too large. By knowing

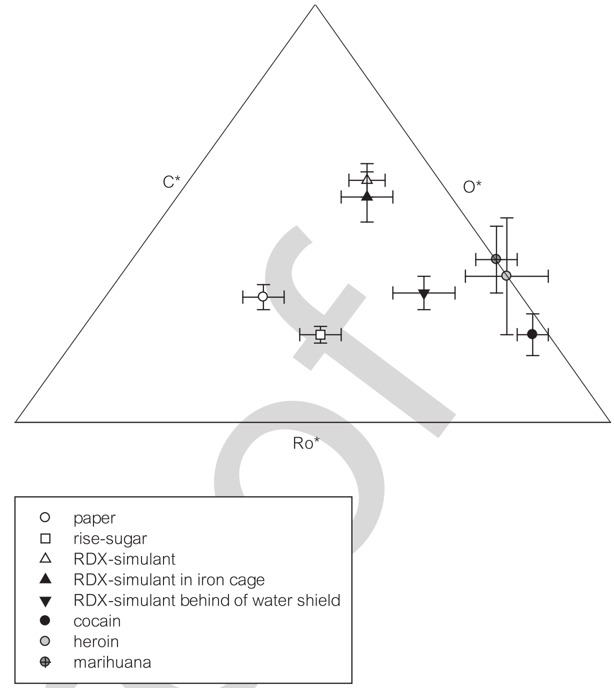

Fig. 13. Triangle diagram for the transmission detectors (taken from ref. [17]).

the matrix density and applying the appropriate calibration, it could be determined how much the position of the target inside the diagram is lowered down in comparison with the target case alone.

Axes in the figure are defined as:

$$Ro^* = \frac{\left(\frac{n'}{\bar{n}'}\right)^2}{\left(\frac{n'}{\bar{n}'}\right)^2 + \left(\frac{C}{\bar{C}}\right)^2 + \left(\frac{O}{\bar{O}}\right)^2},$$

$$C^* = \frac{\left(\frac{C}{\bar{C}}\right)^2}{\left(\frac{n'}{\bar{n}'}\right)^2 + \left(\frac{C}{\bar{C}}\right)^2 + \left(\frac{O}{\bar{O}}\right)^2},$$

$$O^* = \frac{\left(\frac{O}{\bar{O}}\right)^2}{\left(\frac{n'}{\bar{n}'}\right)^2 + \left(\frac{C}{\bar{C}}\right)^2 + \left(\frac{O}{\bar{O}}\right)^2}$$

where n' is the number of counts in the tagged neutron peak, C is the number of counts in the 4.44 MeV carbon peak, O is the number of counts in the 6.13 MeV oxygen peak and $\bar{n}'$, $\bar{C}$, $\bar{O}$ are average values.

Similar measurements were done during the Eritr@ck project with the EURITRACK system which was installed in the container terminal Brajdica, sea port Rijeka [17]. In that case RDX simulant was successfully detected, but also some drugs like cocaine, heroin and marihuana by using the triangle diagram, see Fig. 13.

IV. Radiation Safety

One important aspect of the neutron inspection portal to be clarified concerns the possible effects of irradiation on the goods inside the inspected container. Particular attention must be devoted to irradiation of foodstuff, but also pharmaceuticals and medical devices.

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The possible effect on the public health of irradiation with ionizing radiations of transported goods is twofold. The first effect concerns possible modifications of the properties of the irradiated materials, induced by the ionizing radiation. This problem is particularly relevant for foodstuff, the nutritional and organoleptic properties of which must not be altered or modified by any treatment. The second effect is connected to the possibility that the ionizing radiation might induce activation of nuclides of the irradiated products. This problem could be particularly relevant when the irradiation system makes use of neutrons, since it is unavoidable that some nuclei are converted to radioactive nuclides. This fact is particularly significant when the irradiated goods are foodstuff, pharmaceuticals or medical devices. Indeed, these particular type of goods when ingested, or kept in close proximity of the consumer, may deliver a dose to the individual [18].

In considering possible alteration of foodstuff nutritional and organoleptic properties, the following is of importance. For what concerns irradiation of foodstuff with X-ray for food preservation, the Directive 1999/2/EC of the European Parliament and of the Council of 22 February 1999 on the approximation of the laws of the Member States concerning foods and food ingredients treated with ionizing radiation, constitutes the reference norm in Europe, framework Directive (Official Journal of the European Communities, L 66 of 13.3.1999).

As previously mentioned, this Directive defines its own limits of application and shall not apply to: foodstuffs exposed to ionizing radiation generated by measuring or inspection devices, provided that the dose absorbed is not greater than 0.01 Gy, for inspection devices which utilize neutrons, and 0.5 Gy in other cases, at a maximum radiation energy level of 10 MeV in the case of X rays, 14 MeV in the case of neutrons and 5 MeV in other cases. Member States shall take all measures necessary to ensure that irradiated foodstuffs can be placed on the market only if they comply with the provisions of this Directive.

Therefore, irradiation with neutron beams of 14.1 MeV which cause an absorbed dose of less than 0.01 Gy can be considered safe for preservation of nutritional and organoleptic properties of foodstuff. Monte Carlo calculation using a modeling of particular installations by MCNP5 transport code [19], allows estimating the dose absorbed by different kinds of food and foodstuff in typical irradiation conditions.

V. Conclusion

The efforts in the implementation of this project proposal will result in an autonomous container inspector system which will allow high percentage inspection without interrupting container movement in the container terminal. The inspection will be effective in identifying the containers trying to smuggle humans, animals, explosive, drugs, miss-declared hazardous materials and other contraband items. The inspection procedure will not require any additional container terminal space and will be programmed together with other container terminal activities.

Container screening by novel methods should not be privilege of biggest EU sea-ports. The deployment of proposed technology, especially in small and medium size sea and river ports in Eastern and Southern parts of EU will protect whole EU from unexpected terrorist events, reduce the illegal traffic in humans, pets and animals, drugs and threat materials including radioactive elements and SNM.

The ports on inland European waterways should not be neglected in the EU port security network. If neglected, they will represent an ideal entry point to the pathways through the heart of EU and endanger many EU cities and large number of citizens.

Further development of the proposed system, especially in the variant "I" (see Fig. 9), when neutron/X-ray excitation and backscattering are used in one-side geometry, will yield to potential on-board applications. Such a need has been documented in several cases when intelligence sources indicated the ships carrying explosives in on-board containers. Any type of container examination on land is useless in this case if the intention is to explode the ship when in port.

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Container Inspection Utilizing 14 MeV Neutrons

Vladivoj Valkovic, Davorin Sudac, Karlo Nad, and Jasmina Obhodas

***Abstract*—A proposal for an autonomous and flexible ship container inspection system is presented. This could be accomplished by the incorporation of an inspection system on various container transportation devices (straddle carriers, yard gentry cranes, automated guided vehicles, trailers). The configuration is terminal specific and it should be defined by the container terminal operator. This enables that no part of the port operational area is used for inspection. The inspection scenario includes container transfer from ship to transportation device with the inspection unit mounted on it. The inspection is performed during actual container movement to the container location. A neutron generator without associated alpha particle detection is used. This allows the use of higher neutron intensities ($5 \times 10^9 - 10^{10}$ n/s in 4π). The inspected container is stationary in the "inspection position" on the transportation device while the "inspection unit" moves along its side. The following analytical methods will be used simultaneously: neutron radiography, X-ray radiography, neutron activation analysis, (n, γ) and (n,n'γ) reactions, neutron absorption. and scattering, X-ray backscattering. The neutron techniques will utilize "smart collimators" for neutrons and gamma rays, both emitted and detected. The inspected voxel is defined by the intersection of the neutron generator and the detectors solid angles. The container inspection protocol is based on identification of discrepancies between the cargo manifest, elemental "fingerprint" and radiography profiles. In addition, the information on container weight is obtained during the container transport and screening by measuring of density of material in the container.**

***Index Terms*—Activation analysis, container inspection, gamma ray spectra, neutron absorption, neutron scattering, neutrons, radiography, x-ray backscattering.**

I. Introduction

WHITHIN the framework of two EU projects (EURITRACK and ERITR@C) and one NATO project (SfP-980526), a technology of container inspection with a new neutron probe used as a secondary sensor has been developed for detailed inspection of the suspected container volume as determined by an X-ray system. A demonstration facility was constructed and mounted at the container terminal Brajdica, Port of Rijeka, Croatia. Some 150 containers have been inspected in combination with the Smith Heimann 300 unit.

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V. Valkovic was with the Ruder Boskovic Institute, Bijenicka c.54, 1000 Zagreb, Croatia. He is now at Kvinticka 62, Zagreb, Croatia (e-mail: valkovic@irb.hr).

D. Sudac, K. Nad, and J. Obhodas are with the Ruder Boskovic Institute, Bijenicka c.54, 1000 Zagreb, Croatia (e-mail: dsudac@irb.hr; nad@irb.hr; jobhodas@irb.hr).

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Following the implementation of the above mentioned projects, several disadvantages and imperfections of using tagged neutrons have been identified.

i) EURITRACK-like system requires a site area of $\sim 500 m^2$ container terminal storage area. Loss of income to the Container terminal and Port of Rijeka during the implementation of EURITRACK and ERITR@C projects was estimated to 48,000 /year.
ii) No functional sensor (Smiths Heimann-Tagged neutron system) communication has been established.
iii) The neutron beam intensity has been limited to $\sim 10^7$ n/s in 4π requiring irradiations of suspected area/spot/voxel for 10 minutes since only a fraction of the neutron generator output was used with detection of associated alpha particles.
iv) Only small percentage of port leaving containers could be screened.
v) Questionable determination of the difficult to measure nitrogen signature and subsequent construction of C-N-O diagrams.

All mentioned disadvantages could be avoided by design, construction and building of an autonomous and flexible inspection system: Autonomous Ship Container Inspector System (ASCIS).

This could be accomplished by:

1. The incorporation of the inspection system on the container transportation devices (straddle carriers, yard gentry cranes automated guided vehicles, trailers–to be decided by container terminal operator). In this way, no part of the port operational area was used for inspection. The inspection scenario included container transfer from ship to transportation device with inspection unit mounted on it, and inspection during container movement to the container location (either to exit truck or terminal yard position).
2. Use of neutron generator without associated alpha particle detection. The area analyzed was determined by mounting the neutron generator inside shielding and collimator, defining a narrow fan beam of neutrons. This allows the use of higher neutron intensities ($5 \times 10^9 - 10^{10}$ n/s in 4π).
3. The inspected container was stationary in the "inspection position" on the transportation device while the "inspection unit" was moving along side with a speed of 12 m/min, resulting in $\sim$1 min inspection time, T_i, for the whole container (2 TEU). The efforts were directed towards reduction of T_i to as low as possible value. A detached part of the "inspection unit" was mounted on the gentry crane spreader to detect radionuclides and SNM using fast neutron bombardment and detection of induced gamma and neutron radiation.

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4. It is proposed to design, construct and build a trailer inspection unit using the following analytical methods simultaneously: neutron radiography, X-ray radiography, neutron activation analysis, (n, γ) and (n,n'γ) reactions, neutron absorption, neutron backscattering, X-ray backscattering. Neutron based techniques take advantage of using "smart collimators" for neutrons, both emitted and detected. The inspected voxel was defined by the intersections of the neutron generator and detector solid angles.

In addition, the information on container weight was obtained during the container transport and foreseen screening. One of the essential parameter to be measured is the density of material in the container. Based on this measurement one should be able to evaluate the "average container density" and calculate its weight.

II. Concept and Approach

Radioactivity Measurements

Presently, there are several commercially available radiation detection unit mounted on the gantry crane which can detect eventual presence of radioactive materials inside the transported container by, so called, passive measurement [1]. VeriTainer's container crane mounted radiation detection and identification system, called the VeriSpreader, employs an advanced passive scanning technology (^{3}He neutron counter and NaI(Tl) γ spectrometer) and sophisticated identification algorithms to detect and identify gamma and neutron sources in shipping containers as they are loaded or discharged from a container ship. VeriTainer's prototype crane mounted solution (CMS) was in continuous operation at the Port of Oakland from April 2, 2007 through May, 2008 (13 months). It operated without mechanical failure or loss of sensitivity over the course of more than 47,000 container moves.

The detached component of the proposed inspection unit can be used as an additional screening unit providing a neutron source which might induce radioactivity especially on fissile materials and SNMs (U, Th and others), see Fig. 1. A potential candidate for the neutron generator is the so called "long neutron generator".

The proposed system will consist of a spreader bar for the container crane assembly, neutron generator, γ-radiation and neutron detectors and a computer capable of wireless (cloud) communication. The system will measure and analyze gamma-ray counts and energy spectra as well as neutron counts from the detectors in real time as the containers are loaded to, or unloaded from, the container ships. The primary purpose is to detect the presence of radioactivity especially of fissile materials and SNMs (U, Th and others) and alert the user of elevated gamma and neutron rates.

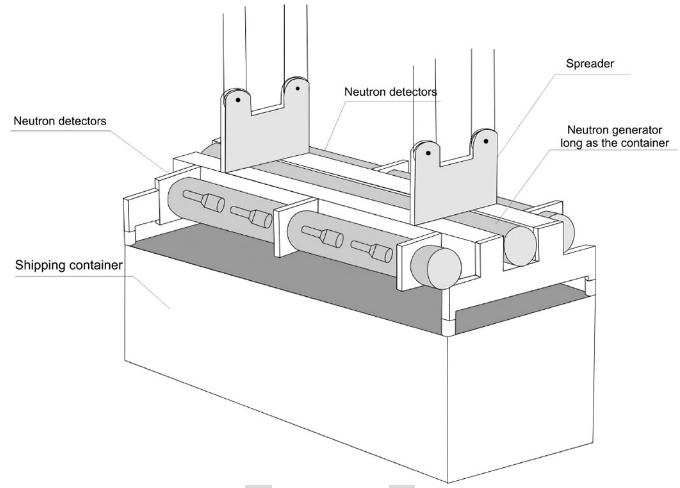

Fig. 1. Proposed inspection unit to be mounted on quay crane.

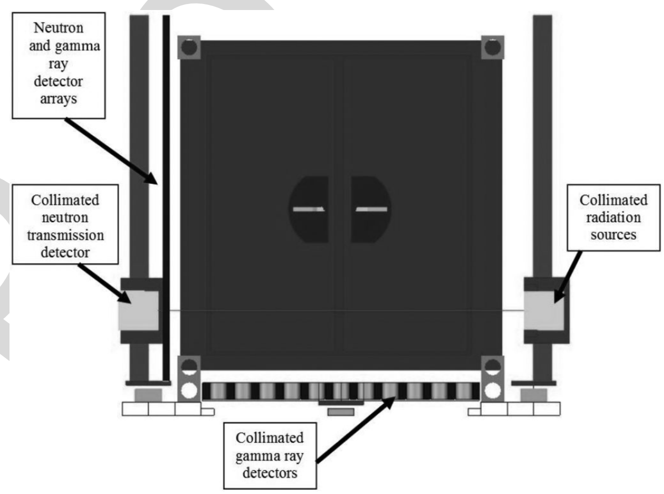

Fig. 2. Schematic presentation of U-shaped inspection unit; density determination by using neutron transmission measurement.

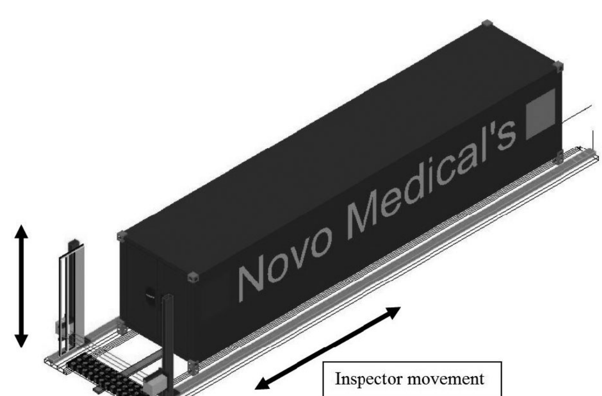

Fig. 3. U-shaped inspection unit slides on rails along side the inspected container.

Inspection Unit

We assume that only a hybrid gamma ray / neutron system based not only on a typical fast neutron gamma radiography system will offer better detection capabilities. In the design of the inspection unit we considered incorporating the following analytical methods to be used simultaneously.

- neutron radiography,
- gamma ray radiography,

- neutron activation analysis, (n, γ) and (n,n'γ) reactions,
- neutron scattering and absorption.

The last two techniques will take the advantage of using "BM smart collimators" for neutrons, both emitted and detected.

There are several proposed radiography systems [2], [3]. The new system will be based on the AC6015XN air cargo scanner which has developed by CSIRO and Nuctech [4], because this is the most promising device. Comparison of the neutron and gamma-ray transmissions yields an R-value that can be used to discriminate between a wide range of organic and inorganic materials. However, although the fact that the AC6015XN is a triple beam device and there are 3 R-values the Australian scientists use only 2 R values. The third R value could offer extra and sometimes valuable information [5].

Attention was focused to the selection of the X-ray sources. We shall investigate which combination of the X-ray beams is the best among the typical energies 3, 4, 5, 6, 7, 8 or 9 MeV electron LINAC (linear accelerator), or some other values.

Smaller detectors, especially for the X-ray array will offer better inspection capabilities (5×5 mm CsI detectors–to be investigated). Also with smaller neutron detectors (e.g. 10×10 mm plastic detectors) we will "see" more details on the neutron radiography mode which represents a significant enhancement compared to the 20×20 mm detectors used today.

Regarding the neutron source, the only solution was the DT neutron generator because 14 MeV neutrons have relevant acceptable penetration capabilities. However, typical generators with a solid state targets have a short life times (typical 500-2000 hours), which makes associated alpha particle method inappropriate. Therefore, one should use the DT neutron generators using a plasma source. This provides for at least 25,000 hour of operational life.

The inspection unit is "U" shaped construction with three arms: right, bottom and left.

Left arm contains radiation units: neutron generator and X-ray source (6 MeV LINAC) inside shielding box, both having "smart collimators" in order to produce collimated beams.

Bottom arm will contained the battery of gamma detectors ($5'' \times 5''$ NaI or BGO, number, size and type to be determined). From our previous measurements [6] it is known that for the detection of 100 kg of explosive in iron matrix of density $0.2\ \mathrm{g/cm^3}$, 54485 s were needed with a neutron beam intensity of 10^7 n/s and by using two 3×3 NaI(Tl) gamma ray detectors inside a lead shielding thickness 5 cm. With the neutron beam intensity increased for three orders of magnitude this measuring time could be reduced to 54 s. By using a battery of thirteen 5" NaI detectors this could be reduced to some 3 s. This is only the rule of thumb estimate, the complete system performances will be assessed in the course of a future project.

Right arm contains the neutron detector array for neutron radiography containing probably some 700 neutron plastic detectors dimensions $20 \times 20 \times 75$ mm (to be determined); X-ray detector array of $10 \times 10 \times 50$ mm CsI(Tl) detectors (exact size, number and type to be determined). Both arrays will be stationary with respect to radiation sources and mounted inside appropriate shielding. This arm also has a beam transmission detector equipped with a smart collimator and n-γ separation circuit. The detector is at a fixed position with respect to neutron source at all times.

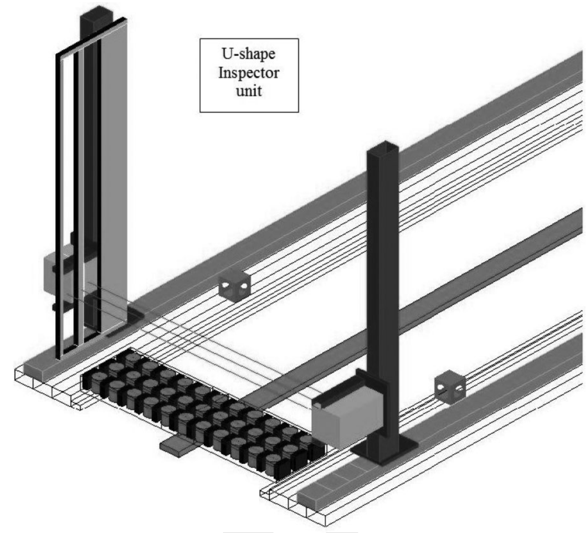

Fig. 4. Components of "U" shaped inspector: collimated radiation sources (neutrons and X-rays), collimated gamma-ray detectors (bottom), collimated neutron transmission detector, neutron and X-ray detector's arrays.

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The size of the inspected voxel is defined by "smart collimators" in front of the detectors and neutron source. The construction of collimators will be based on the MNCP calculations and experiences of previous efforts as described in ref [7], [8]. With two gamma ray batteries in the bottom arm, 24 positions of inspection unit would be required to cover a 40" container length. If in addition 3 vertical positions are included, this will result in $3 \times 24 = 72$ scans, each lasting 3 s. It follows that the complete inspection can be done in 3–5 minutes. It should be mentioned that this estimation is valid for the detection of 100 kg of explosives (and other threat materials) in an iron matrix with a density of $0.2\ \mathrm{g/cm^3}$ or an organic matrix of density $0.1\ \mathrm{g/cm^3}$. Results for containers inspected in the Port of Rijeka, Croatia, indicated that the average container density was around $0.1\ \mathrm{g/cm^3}$, with organic type cargo represented by 62%, metallic with 15%. It follows that for containers with higher density cargo, the measurement time could be longer, which could be decided from the first evaluation of the container average density.

During the project implementation, considerations were made on the three variants of Inspection units: "U", "L" and "I" shaped, see Fig. 4, 8 and 9, respectively. We first start with "U" shaped Inspection unit because it can be realized with the applications of present day knowledge. In this case the Inspection unit is U-shaped so that the container can be brought inside it. The inspected container was stationary in the "gantry crane inspection position" while the "inspection unit" was moving along side with a speed of 1-2–m/min, resulting in $\sim$10 min inspection times for the whole container.

The chemical elements present in the investigated voxel were determined by measuring resulting gamma spectra by the 3 arrays, each containing 12 bottom placed gamma detectors

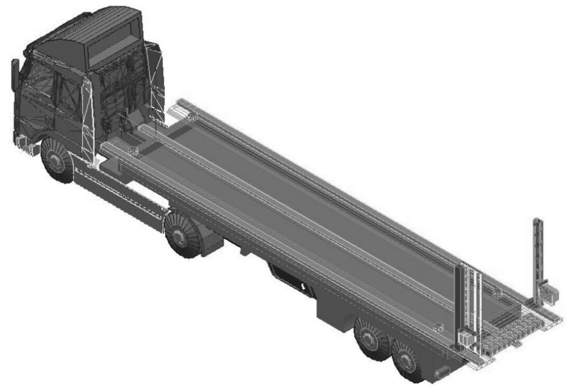

Fig. 5. “Inspector” mounted on the transport track.

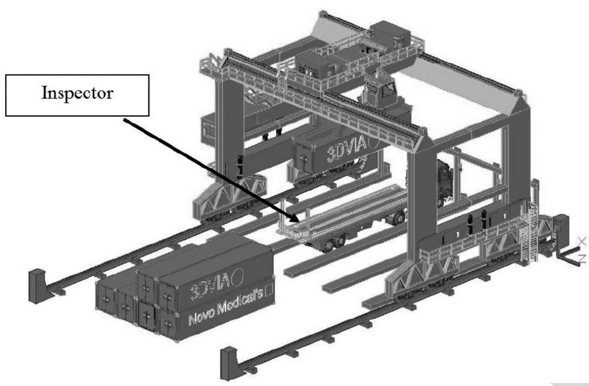

Fig. 6. Loading the container onto truck mounted inspection unit.

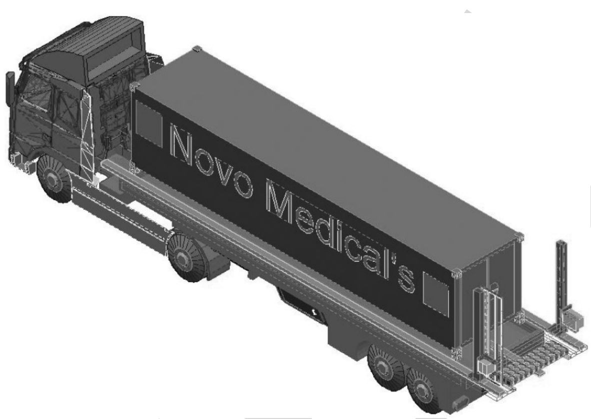

Fig. 7. On the way to the yard or any other transfer point.

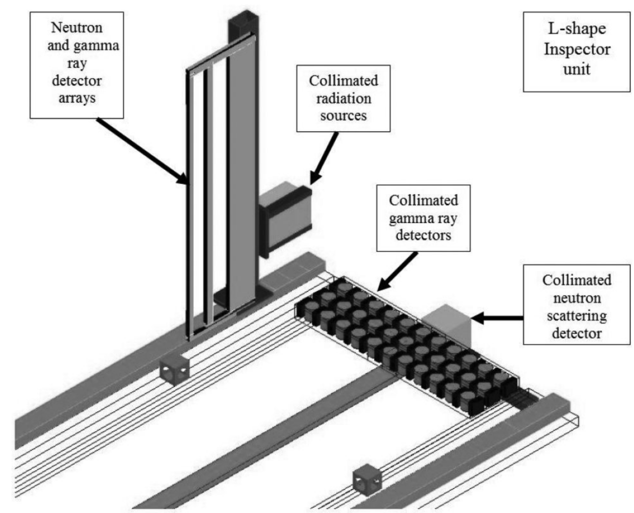

Fig. 8. Components of “L” shaped inspector: collimated radiation sources (neutrons and x-rays), collimated gamma ray detectors (bottom), collimated neutron transmission detector, neutron and x-ray detector’s arrays.

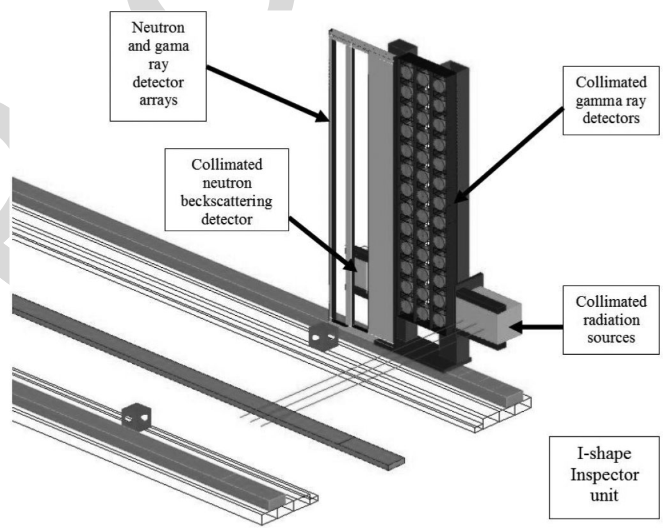

Fig. 9. Components of “I” shaped inspector: collimated radiation sources (neutrons and x-rays), collimated gamma ray detectors, collimated neutron transmission detector, neutron and x-ray detector’s arrays.

inside shielding and equipped with “smart collimators” for C, O (+ other elements) relative concentration determination.

Other parameters of components used are:

- Neutron beam intensity ($5 \times 10^9 - 10^{10}$ n/s in 4π) collimated using “smart collimators”.
- Neutron detector (transmission detector) collimated using “smart collimator”.
- Gamma source collimated–bremstrahlung source: 6 MeV LINAC (to be decided).
- Two source positions: bottom and top of the container or continuous up-down movement.
- Construction of C-O-rho(density) triangle diagrams for material identification, shown in Fig. 11 and 12.
- Sum triangle graph will be compared with individual γ-detector triangle graphs in data analysis process and cross checked with radiographs.

Until now, cargoes have been shipped based on declared container weights in booking information provided by shippers. Vessel storage plans and port operations are typically based on these pre-declared weights which can vary significantly from the actual mass of the cargo transported. The consequent risk to health and safety of seafarers and port operatives is clearly apparent [9]. Weighbridges located at the port gate are easy to implement, but present significant challenges in establishing the true tare weight of the vehicle and in differentiating the weights of multiple container loads. Within the port, reach stackers and fork-lift trucks provide a relatively low cost path for indirect weight measurement to be integrated into vehicle systems e.g. inferred from hydraulic pressure. However, this is

Fig. 10. 100 kg of Semtex1 explosive in an iron box $40 \times 40 \times 66$ cm^3 in volume (up) and 64.4 kg of paper in the same box (down).

likely to be of lower accuracy than direct measurement systems and it is questionable whether it would deliver full compliance with any genuinely robust regulation. Rubber-tired gantry cranes and straddle carriers provide a good opportunity for the implementation of direct weight measurement of individual containers with in the port environment but before final vessel loading operations. Such systems may offer a highly flexible solution with minimal disruption to existing port operations and container logistics.

The proposed Inspection unit will support one of the key recommendations, for the implementation of container weight verification technology, that container weight should be measured as close as possible to the point of lifting. In addition to enabling the verification of individual container weights, the proposed Inspection unit will also enable automatic estimation of centre of gravity; something that will be extremely useful in improving the safety of stacking operations.

III. Experience in Neutron Inspection of Containers

There are several different approaches in the use of fast neutrons for container cargo inspection. In addition to the use of

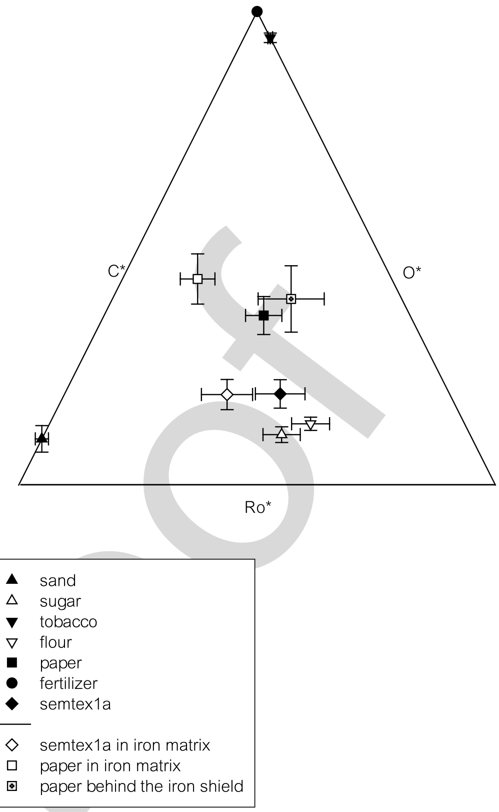

Fig. 11. Triangle diagram for various materials inside the empty container together with the paper and explosive semtex1a in iron matrix and paper behind the iron shield.

continuous tagged neutron beam also pulsed neutron beam is used [10]. Also, the use of triangle graphs for threat material detection and identification has been extensively discussed by Maglich and coworkers [11]–[13].

Let us present some of our experience of using C-O-ρ triangle graphs in identification of materials hidden inside container [14], [15]. The 14 MeV tagged neutron technique has been used to confirm the presence of the explosive Semtex#1a within the inspected container. Two $3'' \times 3''$ NaI(Tl) were put at the transmission position in the cone of the tagged neutrons beam. Each detector was shielded with a 5 cm thick lead brick [14]. Container around the target was filled with iron boxes of density $0.2\ \mathrm{g/cm^3}$.

We have also illustrated that various threat materials (including explosives) could be detected inside the container by measurement of three variables, C and O concentrations and the density of the investigated material [16]. Carbon and oxygen were detected, but not nitrogen. It can be shown that 100 kg of Semtex#1a can be detected in an iron matrix of density $0.2\ \mathrm{g/cm^3}$ by using the triangle graph like in Fig. 11.

The presence of an iron matrix around the target does not change the position of the material inside the triangle plot. It is, however, well known that an organic matrix would have a big influence on the neutron beam because of attenuation as well as termalization of fast neutrons. In order to demonstrate the usefulness of the neutron system, it was necessary to investigate if and how organic matrix changes the position of the signal of target material inside the triangle diagram.

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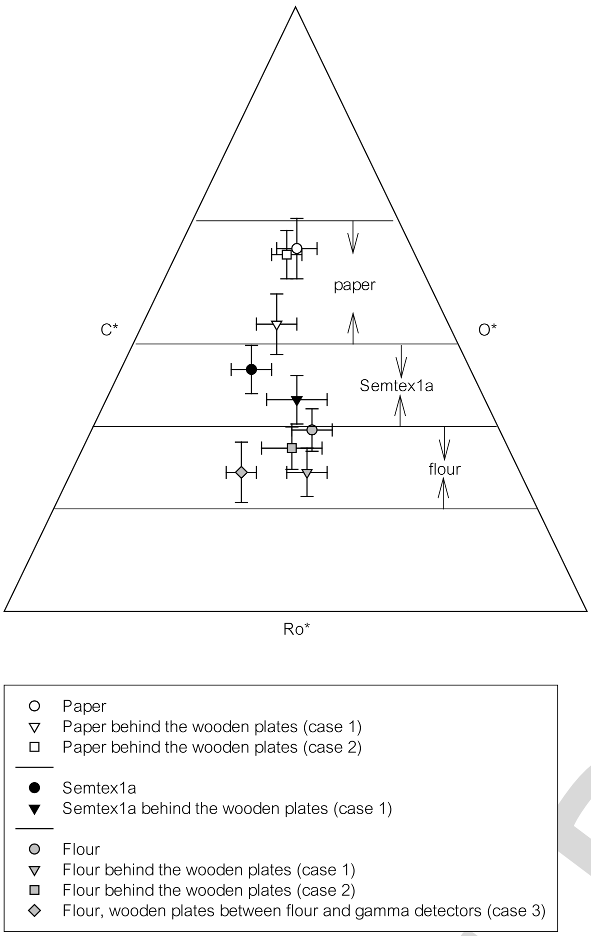

F12:1 Fig. 12. Triangle diagram for the transmission detectors (taken from ref. 15).

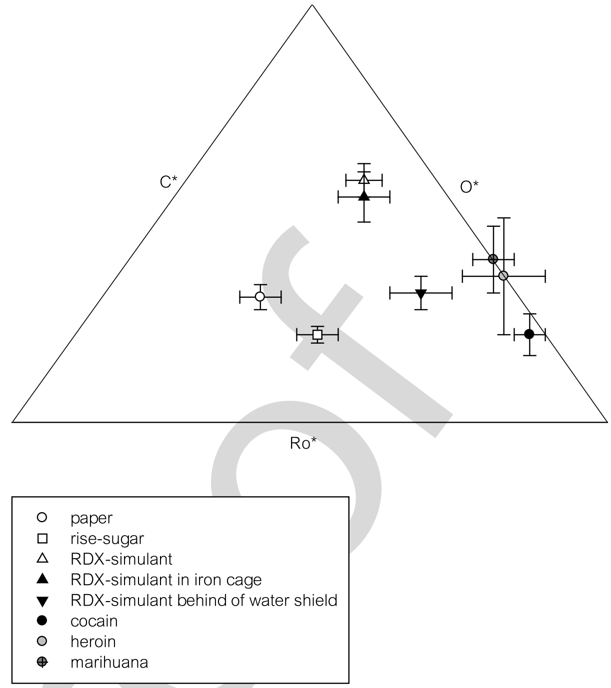

Fig. 13. Triangle diagram for the transmission detectors (taken from ref. [17]). F13:1

The organic cargo was simulated with wooden plates (dry wood has formula $C_{22}H_{31}O_{12}$). Block made from wooden plates of 0.53 g/cm^3 density and thickness of about 27 cm was put in front of the target material in the first measurement and close to the container wall in the second measurements. The total thickness of this block was about 60 cm along the tagged neutron beam axis, which means that the effective density is about 0.25 g/cm^3 (because of the empty space between the wooden plates). However, the average density along the container was even less, around 0.1 g/cm^3.

Some of the experimental results are shown in the triangular diagram of Fig. 12, where the measured points are located in the three regions. The first region corresponds to the paper points. The second region corresponds to the semtex1a explosive and the third region belongs to the flour. Division is not rigid. Some overlap exists especially between semtex1a and flour. Generally, the effect of the wood plates is to lower down the position of the material in the diagram. It could be seen that the wooden plates which are far from the target (Case 2) have less influence on the target material position in the diagram than the wooden plates which are close to the target (Case 1 and Case 3). Even in the case where some overlap between the regions could be expected, the identification of the paper, semtex1a and flour is possible provided that the error on estimating the surrounding organic matrix density is not too large. By knowing the matrix density and applying the appropriate calibration, it could be determined how much the position of the target inside the diagram is lowered down in comparison with the target case alone.

Axes in the figure are defined as:

$$Ro^* = \frac{\left(\frac{n'}{\bar{n}'}\right)^2}{\left(\frac{n'}{\bar{n}'}\right)^2 + \left(\frac{C}{\bar{C}}\right)^2 + \left(\frac{O}{\bar{O}}\right)^2},$$

$$C^* = \frac{\left(\frac{C}{\bar{C}}\right)^2}{\left(\frac{n'}{\bar{n}'}\right)^2 + \left(\frac{C}{\bar{C}}\right)^2 + \left(\frac{O}{\bar{O}}\right)^2},$$

$$O^* = \frac{\left(\frac{O}{\bar{O}}\right)^2}{\left(\frac{n'}{\bar{n}'}\right)^2 + \left(\frac{C}{\bar{C}}\right)^2 + \left(\frac{O}{\bar{O}}\right)^2}$$

where n' is the number of counts in the tagged neutron peak, C is the number of counts in the 4.44 MeV carbon peak, O is the number of counts in the 6.13 MeV oxygen peak and $\bar{n}'$, $\bar{C}$, $\bar{O}$ are average values.

Similar measurements were done during the Eritr@ck project with the EURITRACK system which was installed in the container terminal Brajdica, sea port Rijeka [17]. In that case RDX simulant was successfully detected, but also some drugs like cocaine, heroin and marihuana by using the triangle diagram, see Fig. 13.

IV. Radiation Safety

One important aspect of the neutron inspection portal to be clarified concerns the possible effects of irradiation on the goods inside the inspected container. Particular attention must be devoted to irradiation of foodstuff, but also pharmaceuticals and medical devices.

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The possible effect on the public health of irradiation with ionizing radiations of transported goods is twofold. The first effect concerns possible modifications of the properties of the irradiated materials, induced by the ionizing radiation. This problem is particularly relevant for foodstuff, the nutritional and organoleptic properties of which must not be altered or modified by any treatment. The second effect is connected to the possibility that the ionizing radiation might induce activation of nuclides of the irradiated products. This problem could be particularly relevant when the irradiation system makes use of neutrons, since it is unavoidable that some nuclei are converted to radioactive nuclides. This fact is particularly significant when the irradiated goods are foodstuff, pharmaceuticals or medical devices. Indeed, these particular type of goods when ingested, or kept in close proximity of the consumer, may deliver a dose to the individual [18].

In considering possible alteration of foodstuff nutritional and organoleptic properties, the following is of importance. For what concerns irradiation of foodstuff with X-ray for food preservation, the Directive 1999/2/EC of the European Parliament and of the Council of 22 February 1999 on the approximation of the laws of the Member States concerning foods and food ingredients treated with ionizing radiation, constitutes the reference norm in Europe, framework Directive (Official Journal of the European Communities, L 66 of 13.3.1999).

As previously mentioned, this Directive defines its own limits of application and shall not apply to: foodstuffs exposed to ionizing radiation generated by measuring or inspection devices, provided that the dose absorbed is not greater than 0.01 Gy, for inspection devices which utilize neutrons, and 0.5 Gy in other cases, at a maximum radiation energy level of 10 MeV in the case of X rays, 14 MeV in the case of neutrons and 5 MeV in other cases. Member States shall take all measures necessary to ensure that irradiated foodstuffs can be placed on the market only if they comply with the provisions of this Directive.

Therefore, irradiation with neutron beams of 14.1 MeV which cause an absorbed dose of less than 0.01 Gy can be considered safe for preservation of nutritional and organoleptic properties of foodstuff. Monte Carlo calculation using a modeling of particular installations by MCNP5 transport code [19], allows estimating the dose absorbed by different kinds of food and foodstuff in typical irradiation conditions.

V. Conclusion

The efforts in the implementation of this project proposal will result in an autonomous container inspector system which will allow high percentage inspection without interrupting container movement in the container terminal. The inspection will be effective in identifying the containers trying to smuggle humans, animals, explosive, drugs, miss-declared hazardous materials and other contraband items. The inspection procedure will not require any additional container terminal space and will be programmed together with other container terminal activities.

Container screening by novel methods should not be privilege of biggest EU sea-ports. The deployment of proposed technology, especially in small and medium size sea and river ports in Eastern and Southern parts of EU will protect whole EU from unexpected terrorist events, reduce the illegal traffic in humans, pets and animals, drugs and threat materials including radioactive elements and SNM.

The ports on inland European waterways should not be neglected in the EU port security network. If neglected, they will represent an ideal entry point to the pathways through the heart of EU and endanger many EU cities and large number of citizens.

Further development of the proposed system, especially in the variant "I" (see Fig. 9), when neutron/X-ray excitation and backscattering are used in one-side geometry, will yield to potential on-board applications. Such a need has been documented in several cases when intelligence sources indicated the ships carrying explosives in on-board containers. Any type of container examination on land is useless in this case if the intention is to explode the ship when in port.

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