Air Cargo Inspection using Pulsed Fast Neutron Analysis

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Abstract. A powerful tool for air cargo inspection exists at the George Bush Intercontinental Airport in Houston, Texas USA that utilizes the Pulsed Fast Neutron Analysis (PFNA) technology. Funded by the Transportation Safety Administration (TSA) under the United States Department of Homeland Security (DHS), a system has been developed to detect explosives at the threat levels of interest to aviation security in a wide range of cargoes. The system utilizes a tandem Van de Graaff accelerator operating at 3.5 MHz that produces pulses of deuterons with a FWHM of 1.5 ns. Neutrons of several nanosecond duration are created through the d,D reaction at an energy of around 8.5 MeV with a deuteron beam intensity of up to 140 micro-A. A neutron collimator near the deuteron gas target produces a neutron beam spot 9-cm wide by variable (typical) 12-cm tall at the center of the container. This neutron beam oscillates vertically by moving a collimator. Translational motion of the air cargo is provided by a constant-velocity conveyor system. The inspection volume is surrounded by a large array of 15.25-cm diameter right cylindrical NaI detectors to collect the gamma-rays from the neutron inelastic scattering reactions occurring within the volume. Using the time-of-flight technique to determine the position in the container in which the neutron inelastic scattering reactions occur, the data acquisition system and the image reconstruction engine produce a three dimensional image of the cargo contents. The images have a typical volume element granularity of 6.3-cm wide x 6.3-cm wide x 8-cm deep. The latest signature measurements from the 4.44-MeV gamma ray from carbon, the 6.13-MeV gamma ray from oxygen, and the 1.63-MeV, 2.31-MeV, and 5.55-MeV gamma rays from nitrogen of threat and non-threat material, as well as images demonstrating the capabilities of this unique inspection tool, will be presented.

1. Introduction

The Implementing Recommendations of the United States 9/11 Commission Act of 2007 mandates the DHS to establish a system to physically screen 50 percent of cargo transported on passenger aircraft by February 2009 and 100 percent of such cargo by August 2010. DHS TSA has funded a number of technology development initiatives over the past several years. One such development is the PFNA system located at the George Bush Houston Intercontinental Airport. At this site, a fully functional system was built; including, a Van de Graff based neutron production system, an air cargo container transport system, and a data acquisition and imaging reconstruction engine to produce three dimensional elemental images of air cargo container contents for automated explosive detection.

The PFNA screening approach is vastly different than the technologies currently used today [1]. Instead of making alarm decisions based on a positive identification of explosive material particulates or by radiographic images, PFNA measures the elemental composition of the cargo contents by detecting gamma-rays following inelastic neutron reactions.

The PFNA air cargo screening system provides detection capability not currently available to the cargo screening community today. Rapiscan Systems (and its precedents (Ancore Corporation and SAIC Advanced Nucleonics Division) have been developing the Pulsed Fast Neutron Analysis (PFNA) technology over the last decade from the initial conceptual framework started a decade before [2][3][4][5]. The present system designed for air cargo inspection is currently ready for its final calibration and tests.

2. Technical Approach

The PFNA system creates a three dimensional elemental composition image of the cargo container's contents and the three dimensional position of a potential threat utilizing a neutron time-of-flight (TOF) and gamma-ray energy spectral measurement of the entire cargo container's entire volume. An overview schematic of the principles involved is shown in Fig. 1. By utilizing the energy and time information from the gamma-rays detected and the position information of the vertical and horizontal motion systems, the PFNA system imaging software reconstructs a three dimensional elemental image of the container's contents.

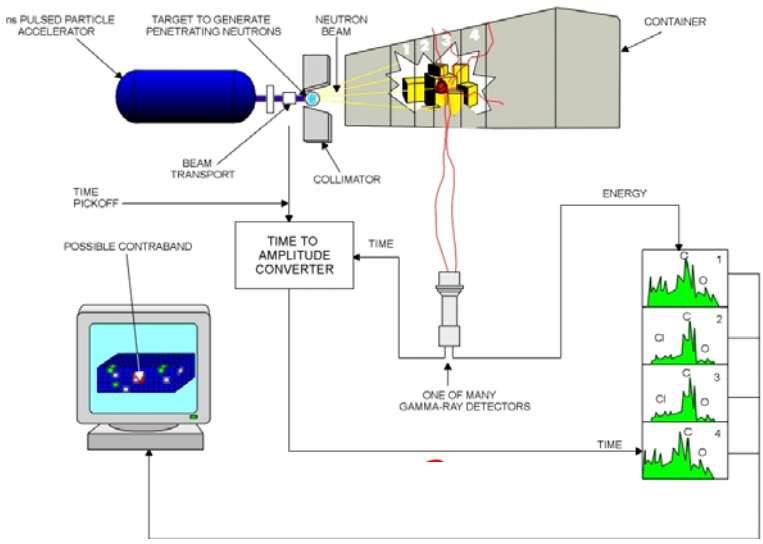

Fig. 1. Schematic depicting the principles of PFNA used to produce an elemental image of the inspected object.

The PFNA neutron production system produces neutrons using a deuteron (d) beam striking a deuterium (D) gas target. The neutrons (n) are produced by the reaction $d+D \rightarrow {}^{3}He+n$. The desired neutron beam energy for the PFNA system is around 8.5 MeV which requires an average deuteron energy of 5.3 MeV. Because the deuterium gas target requires a thin entrance window the actual beam energy required to allow for energy losses in the window is roughly 7 MeV. The choice of neutron's energy is dictated by its penetrability into the cargo, which is determined by the total neutron interaction cross sections. The neutron interaction with material can take different forms; including, elastic scattering (n,n), inelastic scattering (n,n'), radiative capture or absorption (n,γ), and fission (n,f). For producing useful threat detection gamma-ray signatures, the inelastic reaction is the primary one of interest. This reaction occurs when a neutron bombards an elemental nucleus and leaves the latter in an excited state. The nucleus lying in the excited state decays by emitting a gamma-ray. The cross section for this reaction is denoted by the symbol σ_i. The cross-section is a strong function of the bombarding neutron energy as can be seen by the cross-section curves in Fig. 2. The figure shows the cross section to excite the three primary nitrogen gamma-rays (2.31, 1.63, and 5.11 MeV), the 6.13-MeV oxygen gamma-ray, and the 4.44-MeV carbon gamma-ray.

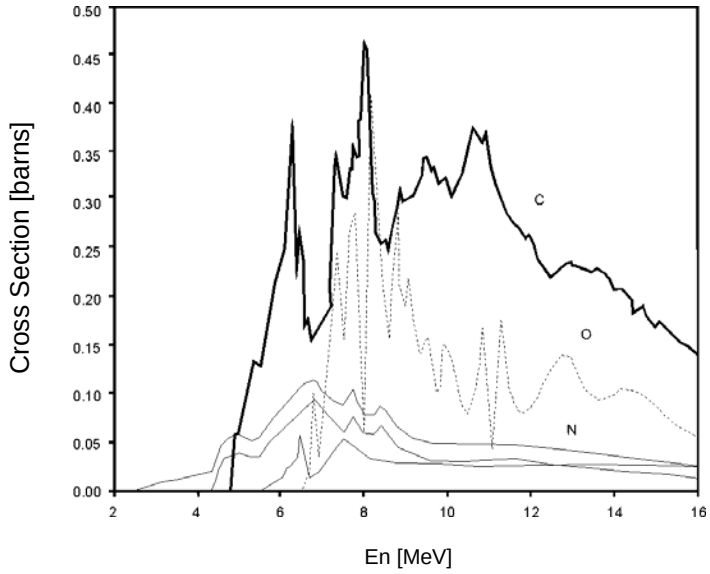

Fig. 2. The inelastic scattering cross section for N (exciting 3 nuclear levels), C, and O

In order to utilize the TOF technique, the PFNA system requires pulsed neutron beams with MHz repetition rates and nanosecond pulse widths. These requirements in turn require the deuteron beam to have the same pulsing characteristics. The Houston PFNA system pulses at 3.5 MHz and has a deuteron beam pulse width of about 1.5-ns full-width at half-maximum (FWHM). The deuteron beam is produced by a small tandem Van de Graaff system manufactured by National Electrostatics Corporation (NEC). It is a 4-MV machine but is operated at 3.5 MV. A plan view of the neutron production system is shown in Fig. 3. The key components are numbered:

1. Ion source
2. Low energy beam line with chopper and buncher
3. Model 12 SDH Pelletron accelerator (4.0 MV)
4. Cooling and drying system
5. SF_6 gas transfer system
6. Electrostatic quadrupole triplet lens
7. High energy beam line components

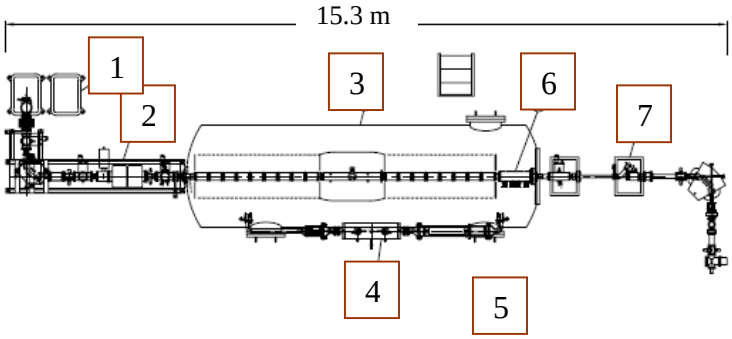

Fig. 3. PFNA neutron production system

The deuteron beam starts at the ion source (at 1). The source produces a DC beam of negative deuteron ions (d– ions). The source output is capable of delivering up to 800 μA. The source is maintained at positive high voltage and is isolated from the rest of the beam line with insulators. The beam is accelerated to 100 keV and passes through a 90-degree bending magnet. In the low energy beam line it is chopped and bunched (at 2) to produce a nanosecond pulsed beam. The chopping and bunching reduces the beam current to roughly 140 μA. The beam then enters the Pelletron (3) and is accelerated toward the central terminal section in the center of the Pelletron. If the Pelletron is operating at a typical operating voltage of 3.5 MV, the beam energy at this point is 3.6 MeV. The beam then is stripped of its 2 electrons in an argon-filled gas stripper. The resulting d+ ions then accelerate (repelled by the positive charge) to the end of the Pelletron. The beam exits the Pelletron at 7.1 MeV and passes through the quadrupole triplet lens (6) where it is focused. The beam then enters the high energy beam line (7) and undergoes another right angle bend. At the end of the high energy beam line, it strikes the deuterium filled gas and creates neutrons. The beam line past the right angle bend is mounted on the scan arm. The scan arm can cause the 90 degree beam line to move up and down by rotating it about the Pelletron axis. This allows the neutron beam to be pointed. Apertures are distributed throughout the beam path to protect sensitive accelerator and target components from the strong ion beam used in this accelerator. The critical performance parameters of the neutron production systems are summarized in Table I.

Table I: NEUTRON PRODUCTION SYSTEM PERFORMANCE SPECIFICATIONS

Parameter	**Specification**
Beam Intensity	140 micro-A
Neutron Energy	8.5 MeV
Pulsing Frequency	3.5 MHz
Deuteron Pulse Width	1.5 ns
Target Thickness	4.5 cm
Target Pressure	608 kPa
Beam X width at container center	9 cm
Beam Y width at container center	12 cm

The PFNA detector system consists of two different detector types which serve different purposes. The 15.25-cm diameter right cylindrical NaI detectors are used to detect the characteristic signature gamma-rays of materials in the container. The detector size is selected to achieve the highest full energy peak intensity, highest peak to Compton ratio and eliminate to a large extent the second escape peak (thus simplifying the gamma spectrum). The detectors are grouped in eight large arrays that effectively form a ring around the container on both sides of the inspection plane (see Fig. 4). Organic plastic scintillator detectors are used in the radiography detector array. These detectors are 2.54-cm diameter and 15.25-cm long. They are placed in line with the beam on the far side of the inspection tunnel. They detect neutrons and gamma-rays which emanate from the neutron production target on the scan arm. Since the neutrons and gamma-rays travel at 4.5 cm/ns and 30 cm/ns, respectively, the two species form two groups which are separated by about 100 ns in time by the time they reach the radiography detectors. This allows the radiography detectors to form separate neutron and gamma radiographic images of the cargo (also known as “Dual Species Radiography”). These images are used to improve the determination of elemental densities in the PFNA image reconstruction.

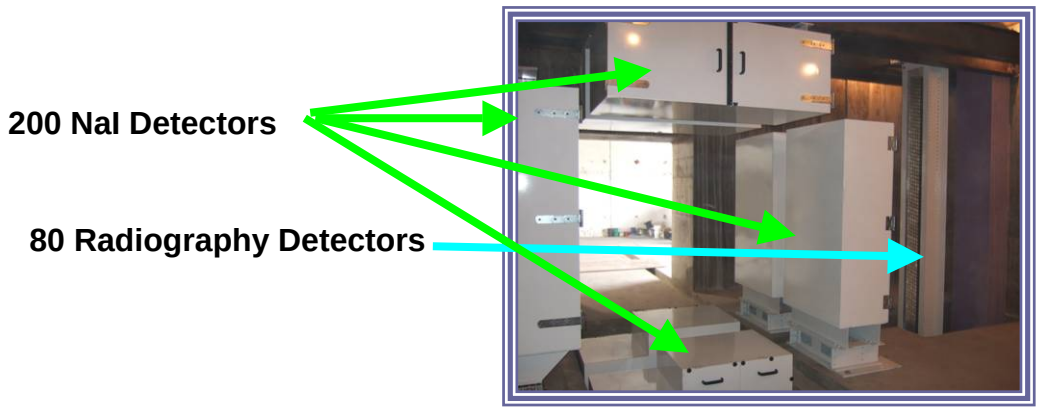

Fig. 4. A photograph of the PFNA detector array of NaI detectors and plastic scintillator radiography detectors

When a probing neutron interacts with one of the nuclei of interest by transferring kinetic energy to it, the nucleus lies at an excited state. De-excitation occurs by gamma-ray emission. The gamma-rays are detected by the system detectors. The resulting gamma-ray spectra show distinct shapes with peaks and valleys in different energy regions depending on the specific gamma-rays emitted through the de-excitation process. The primary gamma-ray spectra of interest for PFNA for explosives are from C, O, and N. Typical NaI detector gamma-ray spectra for these elements are shown in Fig. 5. The unique gamma-rays emitted from each element are evident by observing their spectral shapes. Carbon has a photopeak at 4.44 MeV from the 1st excited state to the ground state transition of ^{12}C. Oxygen has a photopeak at 6.13 MeV from the 2nd excited state to ground state transition in ^{16}O, and 3.85 MeV, 3.69 MeV, and 3.09 MeV from the 3rd, 2nd, and 1st excited states to ground state transitions in ^{13}C populated by the (n,α) reaction of ^{16}O. Nitrogen has photopeaks from $^{14}N(n,n'\gamma)$ at 5.11 MeV from the 4th excited state to ground state transition, 2.31 MeV from the 1st excited state to ground state transition, and 1.63 MeV from the 2nd excited state to 1st excited state transition.

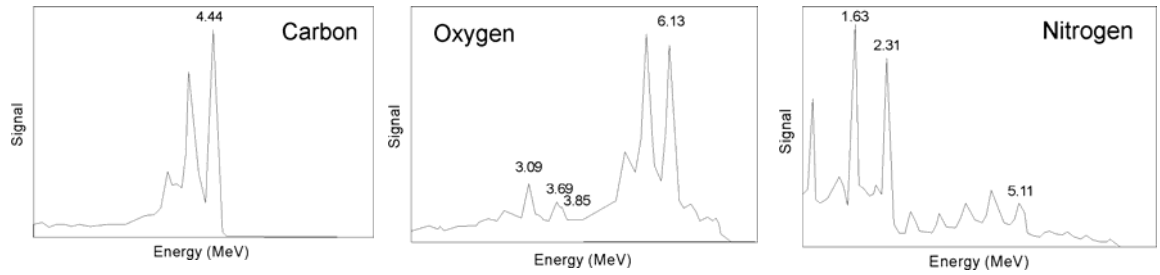

Fig. 5. Gamma-ray spectra from ^{12}C, ^{16}O, and ^{14}N non-elastic neutron scattering

In principle, the gamma-ray spectra from individual elements give an indication as to the defining spectral features that manifest themselves during an inspection. However in practice, a PFNA system will encounter a wide range of materials during inspections that are combinations of various elements. Fig. 6 displays the spectrum produced from irradiating a trinitrotoluene (TNT) threat with the PFNA neutron beam. The prominent peaks are of N, C, and O. The actual N, O, C weight percentage for TNT is 19%, 42%, and 37%. The balance consists of H.

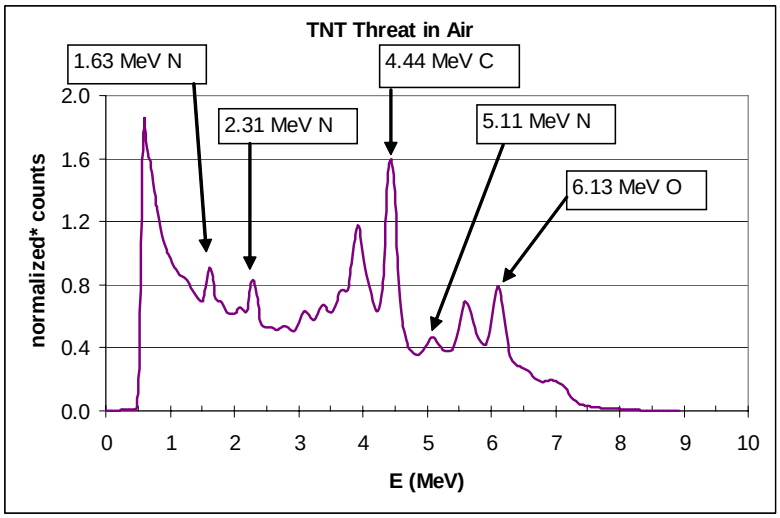

Fig. 6. Inelastic gamma-ray spectrum of a TNT threat

In addition to the gamma-ray energy information, the TOF information for each gamma-ray is determined by measuring its arrival time relative to the production of the neutron pulse. The TOF is calculated by starting a time to amplitude converter (TAC) when the neutron is produced (by the (d,D) reaction), by detecting when the deuteron beam passes into the deuterium gas target. A stop signal is created when the gamma-ray is detected by the gamma-ray detector. The time between the start and the stop signals is the TOF. This quantity is a summation of the neutron flight time to the reaction point and the short gamma-ray flight time to the detector. The two dimensional data acquisition system histograms the gamma-ray energies detected for each 1-ns time bin following the TAC start signal. A typical 2-D spectrum of an explosive simulant is shown in Fig. 7. The horizontal axis is the gamma-ray energy with increasing energy going right. The vertical axis is the TOF with increasing TOF going down. Since this histogram contains binned information in both time and energy, windows can be placed around limited sections of the time and energy data to create both energy and time spectra. Looking at the 2-D histogram in Fig. 7, a window of time can be chosen around the explosive sample to produce the gamma-ray energy spectrum produced by it. This spectrum is shown towards the right side of Fig. 7. Note the gamma-ray peaks from C, O, and N are all present for this C4 explosive simulant. The energy spectra for two different time windows are shown on the right side of Fig. 7. The top spectrum is attributed to the time uncorrelated background (TUB), since it is produced by nuclear reactions irrespective of the beam neutron time profile. This spectrum is produced by thermal capture reactions and activation reactions instead of inelastic scattering reactions that offer PFNA its unique signatures. Note that the primary peak shown in the TUB is the H 2.22-MeV peak from the thermal neutron absorption reaction.

Similarly, a window can be placed around a limited section of the energy axis to display the time spectrum for that energy region. The time spectrum at the bottom of Fig. 7 shows the time spectrum produced by choosing an energy window around the O 6.1-MeV gamma-ray photopeak. This spectrum shows quickly where the high concentration of oxygen is present in the inspection area. As expected, there is a high concentration at the C4 simulant position.

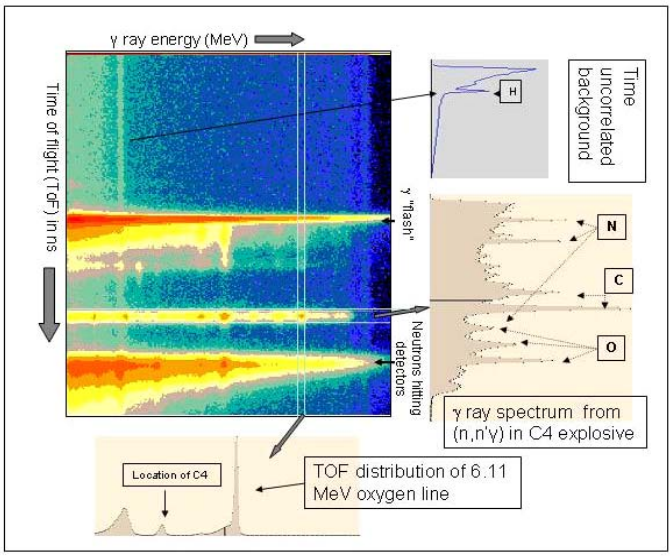

Fig. 7. Two dimensional DAS histogram of gamma-ray energy and gamma-ray detection time

The principles covered above are used to determine the elemental composition of the inspected object along the neutron beam path. In order to determine the elemental composition of the contents of an entire air cargo container, the neutron beam must be directed to beam paths that intersect with the entire volume of the container. This step is accomplished by moving the container on a conveyor at a predetermined speed and by swinging the scan arm vertically. The former allows spatial resolution in the container motion direction (x-direction). The latter allows for spatial resolution in height (y-direction). The neutron/gamma-ray TOF allows for spatial resolution in the neutron beam direction (z-direction).

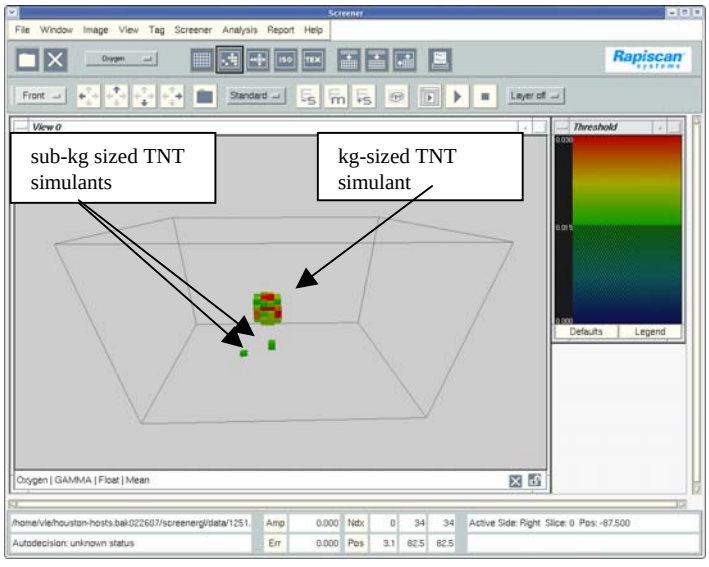

Fig. 8. An oxygen image 3-D view of LD3 containing TNT stimulant

The image reconstruction routine divides the container into many volume elements called voxels. Each voxel contains information about the elemental composition of the container that

overlaps its spatial position. The various elemental images of the container are utilized by the decision algorithm routines to determine voxels that have elemental compositions similar to the threat material. If an alarm is present, this final algorithm displays the threat type to the user as a 3-D rendering of contiguous voxels with position information (in rectilinear coordinates x, y, and z) as shown in Fig. 8. This figure shows an oxygen threshold image of three TNT simulants hidden in boxes inside an air cargo container. The image was produced by only displaying voxels that simply exceeded a threshold signal of oxygen.

3. Conclusion

The PFNA technology is unique in that it provides three-dimensional information about the elemental composition and thus the material composition of the inspected item. This feature is particularly important when attempting to detect sub-kilogram sized threats in a range of different cargoes. Unlike an x-ray system, which can only find unusual densities in an object, PFNA can automatically find materials that are different in elemental composition from the benign materials used to conceal them. Examples are the detection of explosives, narcotics, hazardous chemicals (including flammables or those forbidden for transportation), chemical weapons, nuclear materials and others concealed in the goods of ordinary commerce. Throughout its development, PFNA has been considered primarily for security applications and drug interdiction. However, PFNA is a multipurpose device that has a potential use for cargo manifest verification as well, to detect the smuggling of illegal material or taxable items. Development studies undertaken in the last ten years have shown that PFNA is a feasible technology for several applications. Although the specific performance metrics cannot be revealed because it is sensitive security information, the latest air cargo system results show that high PD and low PFA can be achieved for air cargo over an international cargo distribution. As for throughput, an average can be derived from the feedback received from Continental Airlines Cargo [6] at George Bush Houston Intercontinental Airport. They claim that the cargo mix should fall somewhere between the low to low/medium density category (around 5-10% dense cargoes such as paper and organic matter) because of the large quantity of computer components and flowers shipped. The average throughput with a cargo distribution such as this is expected to be between 9-12 LD3 containers per hour.

4. References

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