IEC-based Neutron Generator for Security Inspection System

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Objects

- Explore the possibility of application of the cylindrical IEC with NAA methods for inspection systems through numerical calculations.

- Analysis of the physics of ion trapping and re-circulation in a cylindrical IEC intended for neutron-based inspection system (also see talk by Stubbers, et al.)
- cylindrical IEC is chosen to obtain a line source for broad area coverage

Outline

- Intro. of Neutron Activation Analysis: TNA, FNA and PFNA (Pulsed FNA)
- IEC device description
- Mathematic model and numerical calculation of neutron yields
- Schematic design of the security inspection system
- Conclusion and discussion
- Further work

Intro. of NAA

- Urgent need of more effective explosive detection system
- Main NAA methods:

TNA (Thermal neutron analysis)

(n, γ) Hydrogen, Chlorine, etc.

FNA (Fast neutron analysis)

(n, n'γ) Oxygen, Carbon, Nitrogen, Chlorine
Hydrogen, Phosphor, Sulfur, etc.

PFNA (Pulsed FNA) and time-of-flight

Reduce background "noise"

Provide localization Information

Comparisons (see. Table 1)

IEC Device Description

- History & development

  1. First proposed by Farnworth in 1950's
  2. Studied theoretically and experimentally by R.L. Hirsch in 1969
  3. Cylindrical IEC studied by T.J. Dolan (UI) in 1970
  4. Star-mode C-Device IEC developed by Fusion Group at UI in 1990's

- Description of spherical IEC and cylindrical IEC

SIEC (left) & CR-IEC (right)

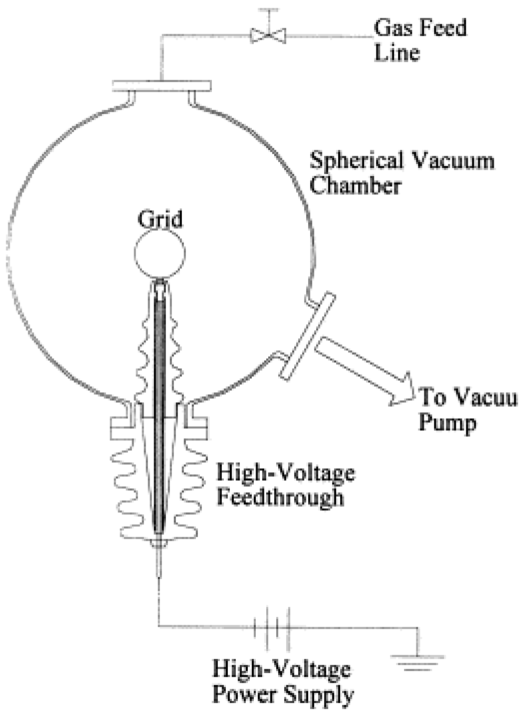

Fig. 1 Spherical IEC Device

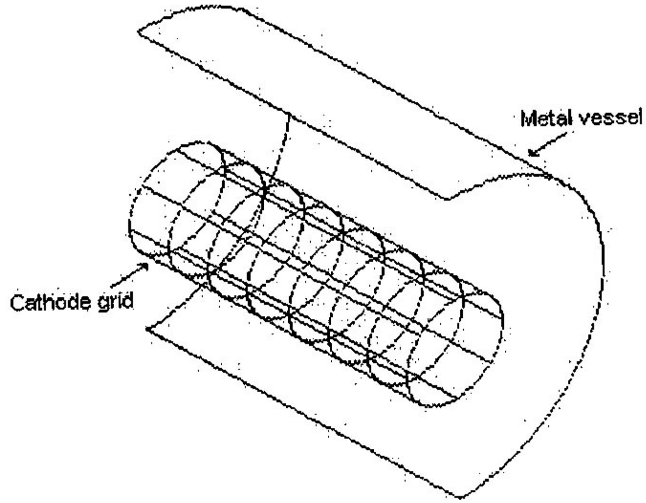

Fig. 2 Cylindrical IEC Device

IEC in neutron generating

- IEC device as a neutron generator:
  - simple configuration
  - easily switched on/off, and
  - reliably produces neutrons with minimum maintenance.
  - Data from prior studies:

  spherical IEC: ~10^8n/s (DD) and ~10^{10}n/s (DT) [1]

  cylindrical IEC: ~10^9n/s (DD) [2]

First-order Model of CR-IEC

- Poisson's Equation

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dV(r)}{dr}\right)=-\frac{e}{\varepsilon_0}[z_i n_i(r)-n_e(r)]$$

- Energy Conservation Equations (static at t=0)

$$\frac{1}{2}m_i v_i^2(r)+eV(r)=eU_i$$

$$\frac{1}{2}m_e v_e^2(r)-eV(r)=eU_e$$

- Ion/Electron Density (Collisonless)

$$n_e(r)=-\frac{I_e}{2\pi rle}\sqrt{\frac{m_e}{2e}}\frac{1}{\sqrt{U_e+V(r)}}$$

$$n_i(r)=\frac{I_i}{2\pi rle}\sqrt{\frac{m_i}{2e}}\frac{1}{\sqrt{U_i-V(r)}}$$

Numerical Methods

- Dimensionless Poisson's Equation

$$\frac{d}{dx}\left(x\frac{dy}{dx}\right)=K_1\left[\frac{\lambda}{\sqrt{k_2+y}}-\frac{1}{\sqrt{1-y)}}\right]$$

$$K_1=\frac{RI_i}{2\pi\varepsilon_0 l|U_i|^{3/2}}\sqrt{\frac{m_i}{2e}}$$

$$K_2=U_e/U_i; \qquad \lambda=\frac{|I_e|\sqrt{m_e}}{I_i\sqrt{m_i}}$$

The modified boundary conditions at the cathode grid

$$(1) \quad \frac{dy}{dx}\Big|_{x=1}=\int_0^1 K_1\left[\frac{\lambda}{\sqrt{k_2+y}}-\frac{1}{\sqrt{1-y)}}\right]dt$$

$$(2) \quad y\,|_{x=1}=1.$$

Numerical Methods (Cont.)

- Calculate the Potential and Ion Density:

$$V(r) -> n_i(r)$$

- Calculate the Neutron Yield Rate

$$N = \int n_i^2(\vec{r}) < \sigma \upsilon > d^3 \vec{r}$$

where < σ v > is the fusion rate parameter

Results

- Results from simplified calculation method (DD reaction)
  - **-80keV cathode voltage;**
  - **8-cm diameter and 100-cm length;**
  - **six 10-mA ion guns**

→

Neutron yield rate calculated ~10^5 n/s<< Hirsch measured (~10^9 n/s), probably due to different configurations and assumptions.

- Higher rate could be obtained by applying higher ion current.

Results (Cont.)

- Results from previous work at UI (using EIXL code) for an SIEC device show that even higher rates could be obtained if the core physics is optimized
- Possibilities include a deeper double potential well and control of electron/ion current ratio.

  - Double potential wells observed (See. Appendix A & Fig. 3)

  - Certain ratio of I_e/I_i and large angular momentum required

Results (Cont.)

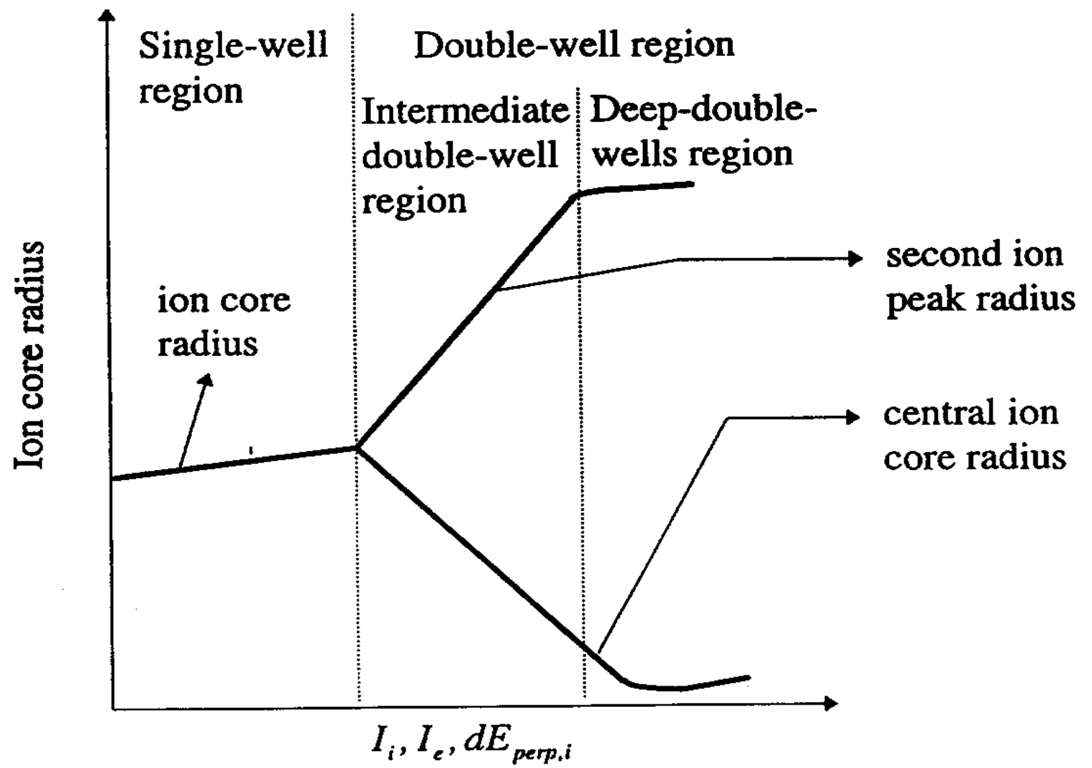

Fig.3 Schematic of the ion core radius separation (see Fig. A2)

Security Inspection System

- IEC allows unique use of an array of sources emitting 14 MeV, 2.45MeV neutrons and also x-rays.
- Array of neutron generators: CR-IEC
  Array of detectors: NaI(T1),etc
- Techniques: TNA, FNA & X-Ray
- Fuzzy logic control: optimize imaging quality and responding time, reduce "false" alarms (See Fig.4 & Appendix B)
- Possible pulsed FNA application

Schematic Layout

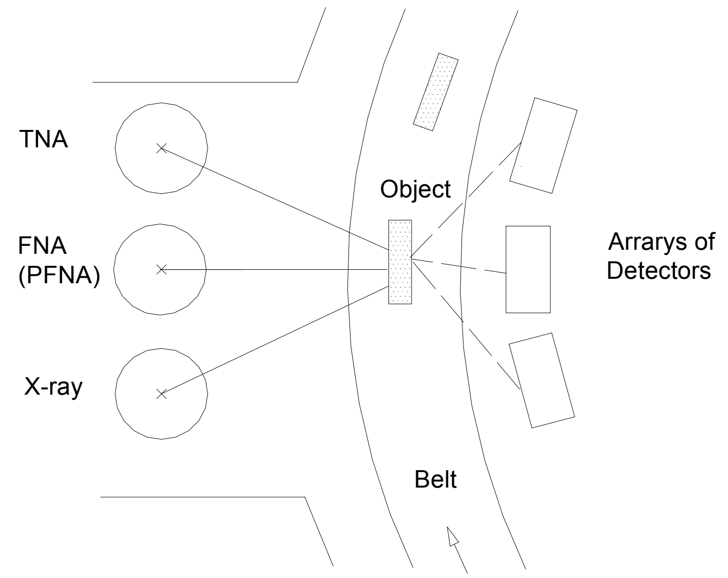

Fig.4 Schematic layout of Inspection System

Conclusion and Discussion

- Simple configuration, easy operation and reliable neutron production of IEC devices represent an attractive neutron source for NAA-based security inspection system

- A unique fuzzy logic system is recommended for combination of TNA/FNA and X-ray techniques to allow fast inspection while minimizing “false” alarms.

Further Work

a. Study the case of a certain angular momentum and solve Poisson-Vlasov equation to get better approximation results in CR-IEC device.

b. Study pulsed operation of the CR-IEC to exploit the potential of increasing neutron yields.

c. Study requirements on the parameters K1 and λ that are needed to avoid oscillation results from the nonlinear Poisson's equation with singularity.

Table 1 Comparison of the techniques

	TNA	FNA	X-Ray
Element identification			**Element density**
Nitrogen[a]	Low	**High**	
Carbon[b]	Very Low	**Very High**	
Oxygen[c]	NA	**High**	
Hydrogen[d]	**High**	High	
Chlorine[e]	**Very High**	High	
Phosphor[f]	NA	**High**	
Sulfur[g]	NA	**High**	
C/O Ratio	Low		

Table 1 (Cont.)

Background noise	High	Low with PFNA	NA
Imaging: geometry & localization information	Limited	PFNA provides depth information	High resolution
Source availability	Need thermalization	Directly	Directly
Application	Small suitcase	Suitcase to cargo	Suitcase to cargo; NA for plastics objects
Configuration	Complicated	Complicated	Simple
Operation & Maintenance Cost	High	High	Low

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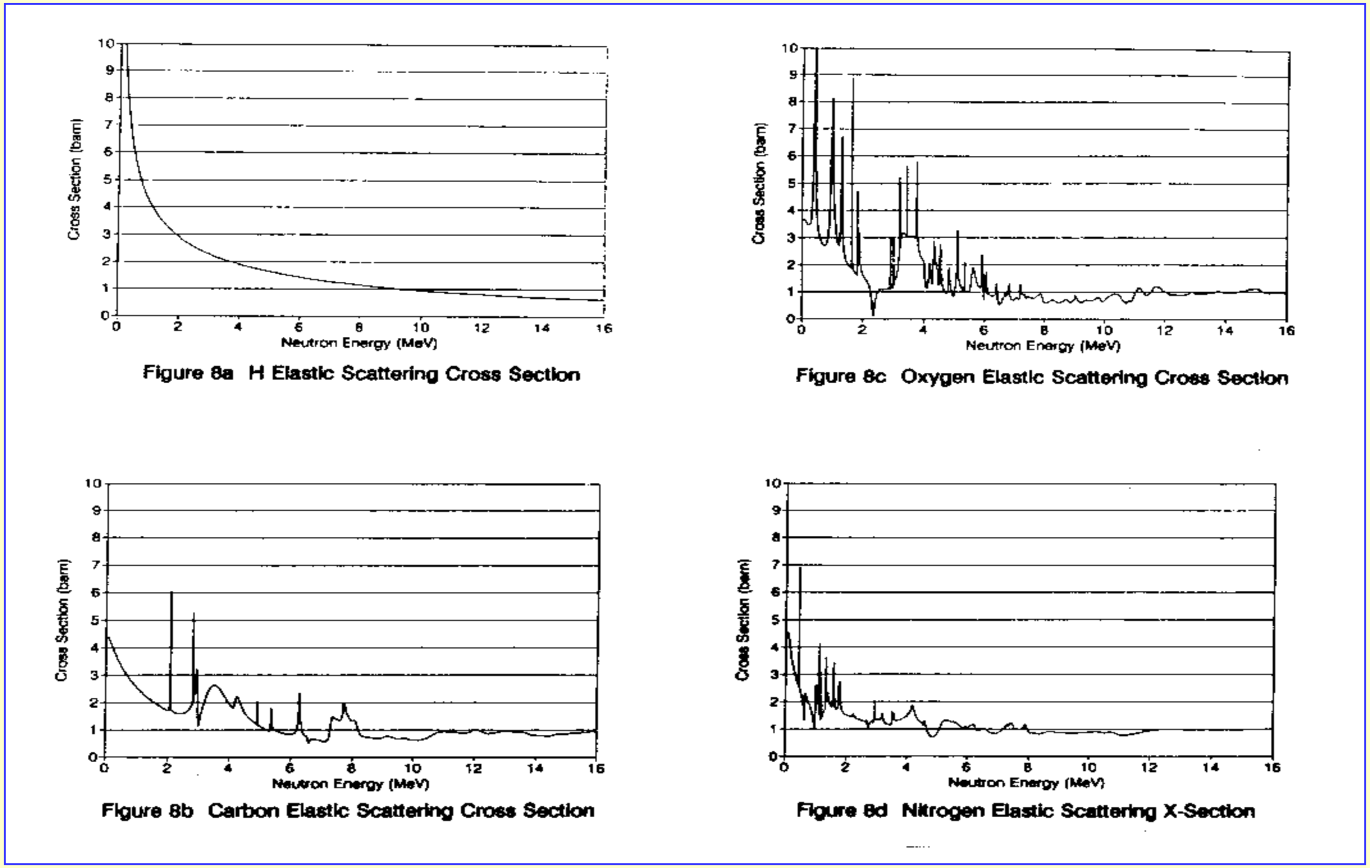
Elastic scattering cross sections of H, O, C, N (Tashi Gozani, 1992)



Inelastic scattering cross sections of H, O, C, N (Tashi Gozani, 1992)

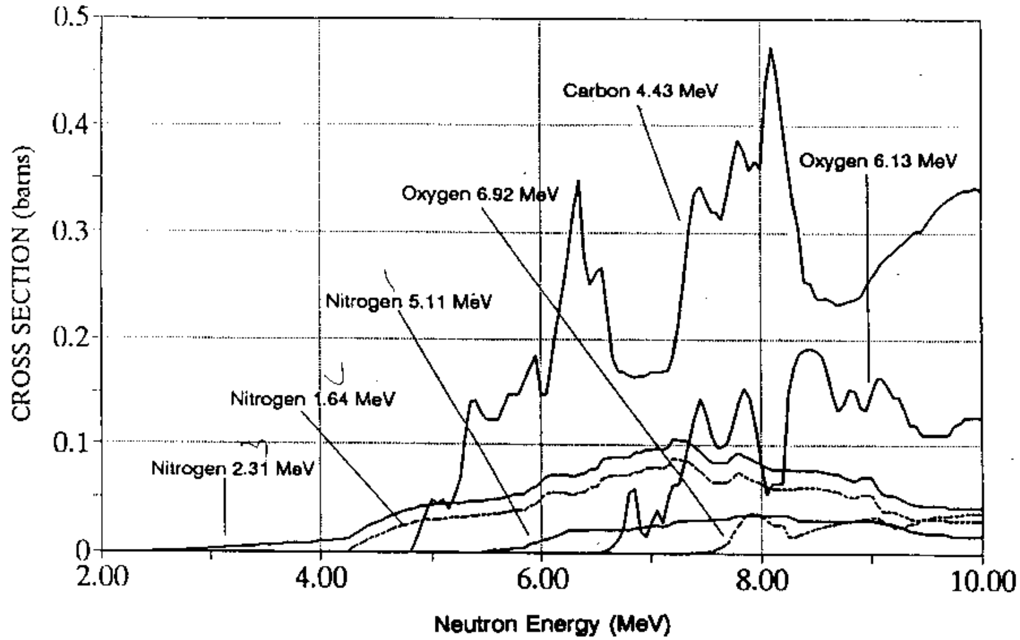


Figure 10 Gamma-Ray Production Cross-Sections Relevant to PFNA for Oxygen, Nitrogen and Carbon.

Appendix A: EIXL Calculation Results

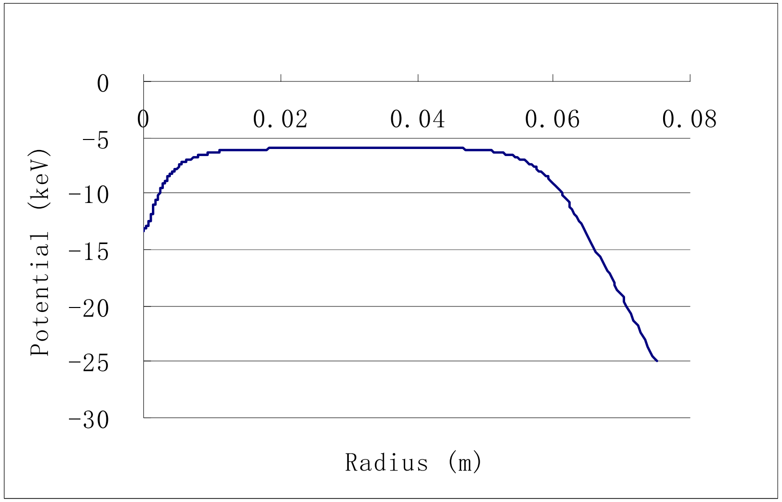


Fig. A1 Potential distribution along the radius

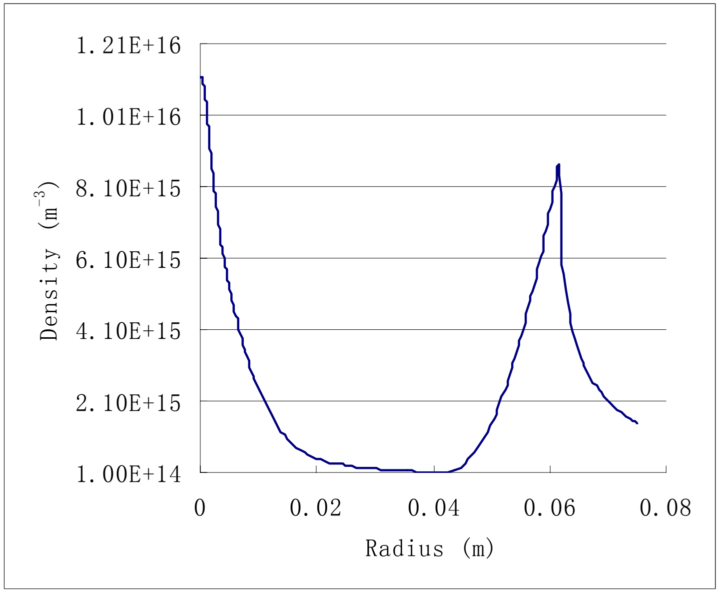
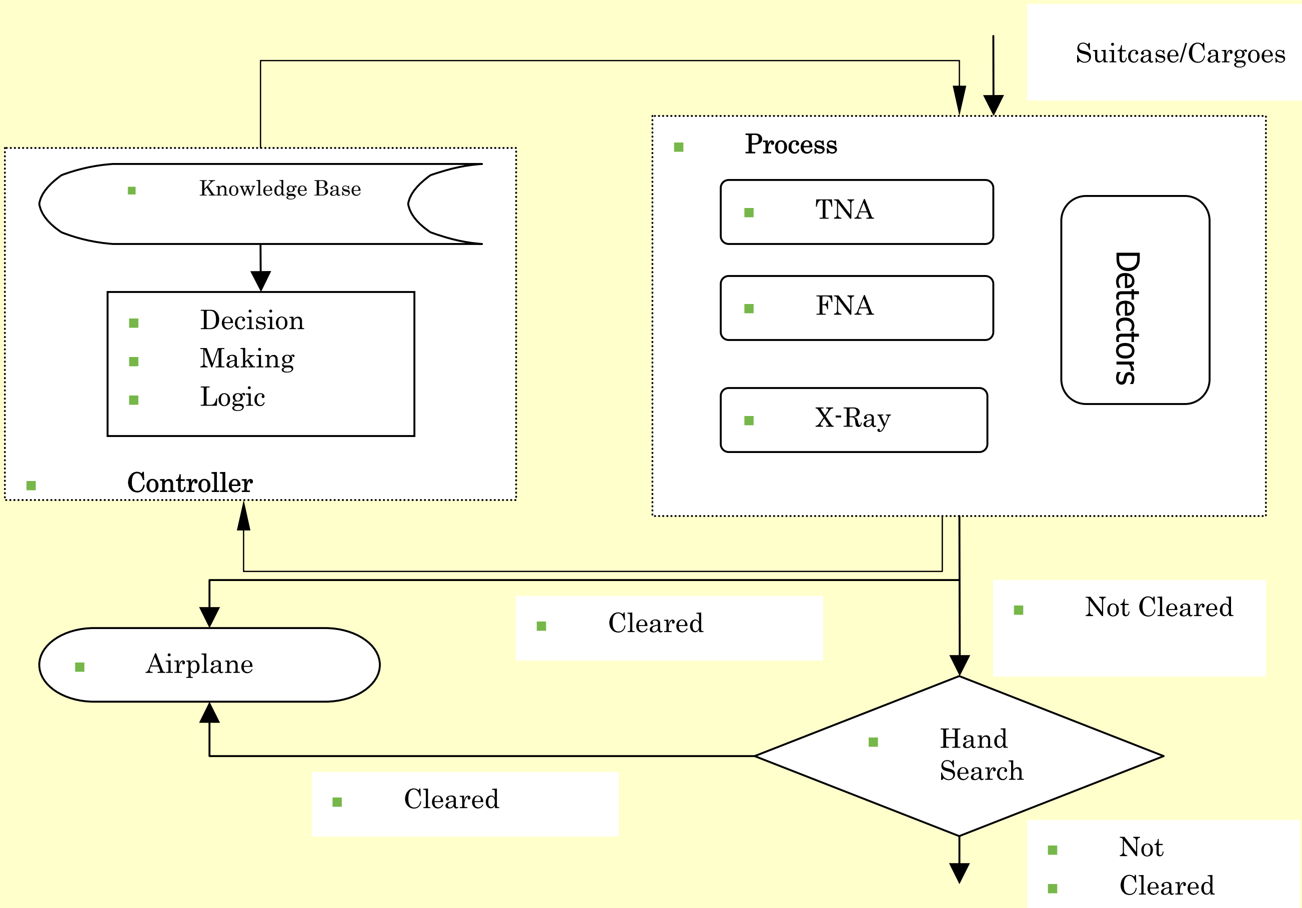


Fig. A2 Ion density distribution along the radius

Table 2 Parameters for EIXL calculation (High current case)

Cathode grid radius	0.075 m
Cathode grid potential	-25 kV
Total ion/electron current inside the grid	59 A/50 A
Ion/Electron injection energy:	19 keV/ 3 eV
Ion/electron energy spread	0.1 eV/ 3 eV
Ion/electron perpendicular energy spread	3 keV/ 3 eV
Recirculation factor	10

Appendix B: Fuzzy logic control



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Contents Difference

Elements	Explosive	Narcotics
C	low	high
H	low	high
N	high	low
O	high	low
C/O	low	high