Proliferation Sensitivity of Dual Use Equipment for Laser Isotope Separation

G. Janssens-Maenhout, J. Creemers*, J.F.A. Delbeke, S. Contini

Institute for the Protection and Security of the Citizen
Joint Research Centre, European Commission
Via Fermi, Ispra 21020 (VA) Italy
*Ghent University, Faculty of Engineering
E-mail: Greet.Maenhout@jrc.it

Abstract:

The international nuclear security is strengthened by explicit import/export control of dual-use equipment. This paper reports on a methodology applying Fault Tree Analysis (FTA) to enhance this control by detecting changes in import behaviour. The methodology is applied to the import of a combination of components that might be used for the construction of Laser Isotope Separation (LIS) plants.

The critical components that are necessary for the construction of a LIS plant are systematically described in a Tree structure. The Tree is analysed by the Fault Tree Analyser ASTRA developed in the safety domain. The fault tree can be analysed qualitatively or quantitatively. The qualitative analysis consists in determining the Minimal Cut Sets (MCS) and the Structural Components' Importance Indexes. In our application an MCS represents the minimum number of components categories needed to install a LIS plant. The quantitative analysis is possible when probabilities can be associated with the components. In our case the probability of a component is linked with the probability of importing the corresponding components class. As a first tentative the probability has been defined as the ratios of the financial value of critical components' export to one country to the financial value of the total export to all countries

The evolution in time of the Top Event probability is obtained by analyzing real data from five year periods, in seven subsequent time frames, starting with the period 1995-1999 towards the final period 2001-2005. This technique demonstrates the monitoring potential based on import statistics changes in behaviour of a country with regard to imported LIS components.

Advanced versions of this probabilistic method may provide customs services with a reduced watch dog list of sensitive components of LIS for a given country. It might also provide an effective tool that is of potential use for registering the capability of a country to setup LIS and for monitoring changes in import behaviour of this country with regard to LIS components.

Keywords: Laser Isotope Separation (AVLIS, MLIS), dual use, enrichment, Fault Tree (ASTRA), Combined Nomenclature (CN) Codes, non-proliferation

1. Introduction

Explicit import/export control of the equipment in the dual-use list (INFCIRC/254 part II) strengthens international security. However, in the field of Laser Isotope Separation (LIS) it is a challenge to detect nuclear technology transfer because of the small size of such plants and the steadily upgrading components [1, 2, 3]. Laser enrichment techniques are still under research [4, 5, 6, 7, 8] and as such the components under development have not made their way to the dual use list yet, even though the latter is periodically amended.

Many countries, that had initiated a LIS programme assessed that the Laser Isotope Separation (LIS) technique suffers from very low throughput and is therefore not competitive. The Separation of

Isotopes by Laser Excitation (SILEX) however has proven commercial viability. It is clear that the recent technical progress enhances the risk of successful laser enrichment programmes, and so the need for strengthened control.

LIS techniques (Atomic Vapour LIS (AVLIS), Molecular Obliteration LIS (MOLIS), Chemical Reaction by Isotope Selective Laser Activation (CRISLA) and Separation of Isotopes by Laser Assisted Retardation of Condensation (SILARC)) have separation factors that are considerably higher than current industrial techniques and are more energy efficient [9, 10]. A small number of separation units (a factor 10^2 smaller than in the case of centrifuges) is required to achieve high separation factors and therefore many traditional detection techniques are less effective for laser enrichment plants.

Current developments in up-scaling the technique seem promising. An industrial application of this technique might be a fact in the near future. Additional verification techniques, such as this study, that focus on the appropriate technical specifications of the different components could help in enhancing the estimation of a country's capability to construct a LIS plant.

2. Problem Statement

This work applied a probabilistic risk assessment approach to assess the possibility of establishing laser enrichment activities. The final goal is to develop a system that can give an early indication for detecting changes (in particular increases) in potential capabilities of establishing LIS plants. Given are import/export statistics for well-known countries (i, i+1, … i+k) to a country subject of our analysis with unknown production capacities regarding components useful for LIS. Figure 1 sketches the problem for a subject country X. The solid line arrows towards country X describe the import of components, of which some might be useful or specific for LIS. The dashed line arrows describe the bilateral relation back with the export of components from country X. The weight of the arrows represents the financial volume of the total transfer of components. Some special cases are:

- absence of solid line arrows: country X is impeded to import (e.g. embargo)
- absence of dashed line arrows: country X has no national production capacity developed for export
- the weight of the solid lines equals the weight of the dashed lines: country X is a transit country

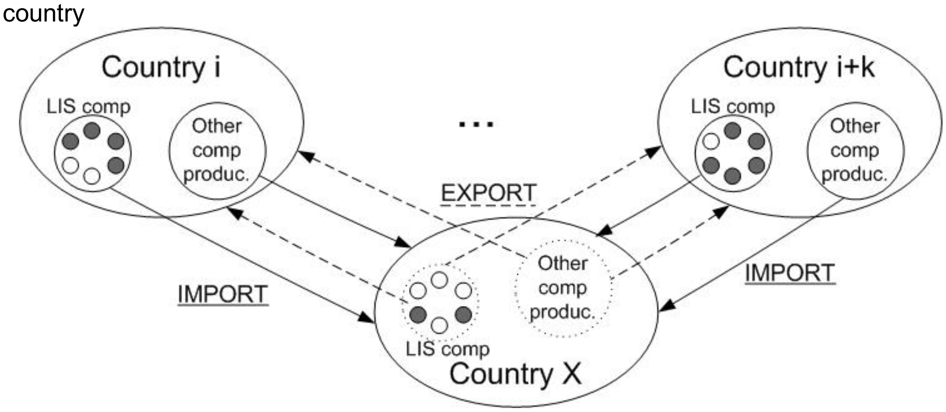

Figure 1: Schematics of the problem to extract useful data on LIS capability for a country based on import/export data.

The underlying assumption is that if the imported components are such that they form almost a complete set to construct a LIS, this import is with reasonable probability an indication of the will of the country to construct a LIS plant. However, the strong suspicion on potential LIS development needs then to be confirmed by the results of further investigations, with open source data, on e.g. the country's nuclear technology and uranium reserves, or data from illicit trafficking databases.

It is left up to the user (the inspector) to introduce a threshold of evidence above which an alarm is triggered. This threshold should represent the percentage of components present in the country to the total percentage of components needed to construct a LIS. (An example is represented in figure 1 by filling dark only the present components out of all necessary components.) Such threshold should take into account the minimal required size of a laser facility for isotope enrichment.

3. The Tree of the Laser Isotope Separation System

The Tree system of figure 2 has been constructed such that it incorporates the two laser techniques: Atomic Vapour LIS (AVLIS) and the Molecular LIS (MLIS, including MOLIS, CRISLA, SILARC). The necessary components that are required to construct a AVLIS or MLIS are determined from open literature. The AVLIS and MLIS can be developed in parallel and therefore are not mutually exclusive systems.

Both need a laser system with analysis instruments and optical equipment (A1). For the AVLIS option, an evaporation and collection system is operating under an electromagnetic field and at vacuum and hence all components of GAVLISDET are needed. For the MLIS options the slightly heated UF_6 gas needs to be compressed through a supersonic nozzle that is then cooled, hence all components of the GMLISDET are needed. The subdivision of a system in its components was repeated until the basic components are part of the internationally defined categories of components that are characterised with a Combined Nomenclature (CN) code index and used by the Customs in the EU. There are 21 basic events, named with the CN code.

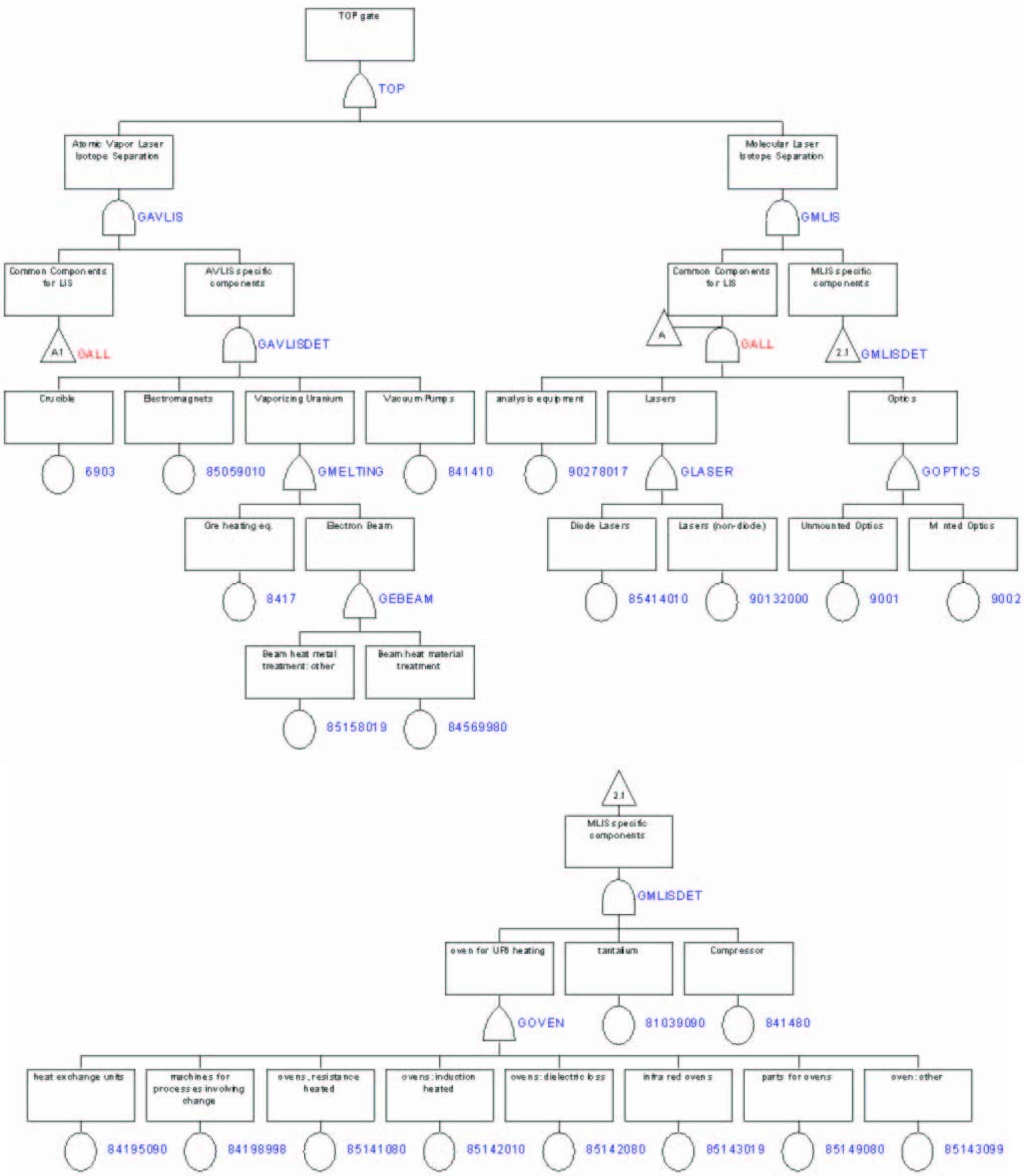

Figure 2: Fault Tree used for analysis

The analysis of the Tree determines the Minimal Cut Sets, defined as the smallest number of components necessary for the construction of a LIS plant. The tree in Figure contains 44 MCS, 12 of sixth order and 32 of seventh order. The structural importance of a component is related to the number and order of MCS in which it is contained.
The component category with highest structural importance was the analysis instruments for the laser system (CN 90278017). The list of the 15 component categories ranked in order of diminishing structural importance is given in Table 1. With this additional knowledge, the current list of dual use items might be upgraded with a ranking system for the most sensitive components common to LIS systems. It could also lead to a reduced watch dog list for a certain technique in a given country.

CN Code of basic event	***brief description***	***structural importance***[1]
90278017	Physical and chemical analysis instrumentation	18.63 %
81039090 841480	Articles of tantalum Air compressors of various types	12.47 %
9001 9002 85414010 90132000	Unmounted optical equipment (lenses, prisms, mirrors, etc.) Mounted optical elements (part of apparatus, fitting) Light emitting diodes Laser (excl. laser diodes)	6.21 %
6903 841410 85059010	Retorts, crucibles, nozzles, tubes, other refract. ceramic goods Vacuum pumps, diffusion pumps, cryo-pumps, adsorption pumps Electromagnets (not for medical use)	4.62 %
8417 84569980 85158019	Parts of electric industrial and lab furnaces and ovens Material removing machines (electron/ion beam, plasma arc) Electrical machine for hot spraying of metals or metal carbides	0.66 %
8514	Furnaces & ovens:electrical resistance, induction, dielectric loss, infrared	0.29 %
84195090 84198998	Heat exchanging units Device for treating materials (process based on temperature gradient)	0.05 %

Table 1: component categories with structural importance (The last column indicates the total contribution to Minimal Cut Sets in percentage)

4. Evaluation of Top Event Probability

4.1. Coupling of Import/export Statistical Data to the LIS Tree Components

To monitor a country's change in infrastructure and equipment with regard to laser enrichment requires a careful analysis of import/export statistics for that country and a good estimation of the internal production. For each imported category of components the total financial volume, as reported by the Customs in the import/export statistics is available. In this first approach neither the export statistics of the subject country nor the national production is evaluated. No number of components is available for the different categories, and so a direct relation for the probability of imported components is lacking.

In the example underneath the probability value for each imported dual use component is approached by the export fraction of a component for the LIS towards a subject country to the export of that component to all countries that are present in the database. More in particular, the cumulated export value of each LIS component from a predefined group of countries to this country over a certain period of time was divided by the sum of export of the subject component to all countries in this time period. More details can be found in [11].

[1] Total contribution in percentage

4.2. Methodology Applying Fault Tree Analysis

The example underneath is worked out using the Fault Tree Analysis (FTA) Technique. The Advanced Software Tool for Reliability Analysis (ASTRA), developed at the Joint Research Centre (JRC) of the European Commission [12] is used to analyse the Fault Tree. The analysis returns a value that can be interpreted as an indication that a state could be developing laser enrichment program with the imported components. The "Top Event" is defined as "the development of a laser enrichment programme with imported dual use components". The underlying events are not characterising "fault of a component" but "import of the dual-use component". Combined in the tree the probability to successfully acquire the necessary components is represented.

The ASTRA analyser yields the Top Event probability and its evolution in time due to the yearly changes in import of the dual-use components. These changes in import behaviour of the subject country compared to the other countries are then monitored in time with the cumulative distribution of all imported components. Biases that are caused by e.g. an economic crisis or an embargo become visible in these plots.

This approach is then used to register the relevant changes in capabilities of countries to construct a LIS plant. It is found that more significant results are obtained if the time periods are comparable with the duration of an economic cycle (5yr) and overlapping. The first analysis starts with data from the period 1995-1999 and subsequent five year periods are analyzed. Since this study is based on export data available from 1995 onwards the analysis was limited to seven time windows.

Obviously the availability of expertise in many scientific and engineering subjects is necessary to set up a LIS plant. Since the spread of knowledge and expertise cannot be measured using export data, it is not included in this first approach. One way of implementing such information is to monitor the scientific output in the subject area of the country's research centres, if it is published. The use of Expert Opinion based on open source information can be applied to define the probabilities of present knowledge and expertise.

4.3. Example of Monitoring Import Behaviour for Different Scenario's

To perform a quantitative analysis for different countries, three families of countries have been distinguished:

- The O family describes industrial well-developed countries with stable import/export. Countries with a Human Development Index (HDI) > 0.75 are allocated to this category.
- The A family describes a country of rapid economic growth, to which countries with $0.50 < HDI \leq 0.75$ are allocated.
- The B family describes very heterogeneous countries with slow economic growth, composed of countries with $HDI \leq 0.50$.

Based upon those families two storylines or scenarios are considered:

- The AB storyline applies to a country of family A with growing nuclear fuel cycle that could easily transform this cycle to a military one when surrounding conditions let it evolve to family B.
- The BA storyline applies to a country of family B with nuclear research an activity that abstains from its original military intentions, when evolving to family A.

Disposing of the export statistics for most CN codes from European to non-European countries a series of non-European countries have been selected to investigate their import behaviour in view of the above mentioned scenarios. These importing countries were divided into the above defined families O, A and B. Figure 3 presents the typical import behaviour for countries of each family. A relatively constant import behaviour over the short time period is clearly present. The order of the probability for the Top Event is very low due to the used financial volumes for the determination of the probability of basic imported components. Moreover this probability is closely related to the level of industrialisation and trade relations of the importing countries with the European exporting countries, which is for rather small countries with limited trade expected to be orders of magnitude lower compared to large countries with well-established economy. Other definitions of probabilities more appropriate for this type of analysis are under study.

Normalized Top Event Value
(Indicating capability of a country to acquire the necessary components for constructing LIS)

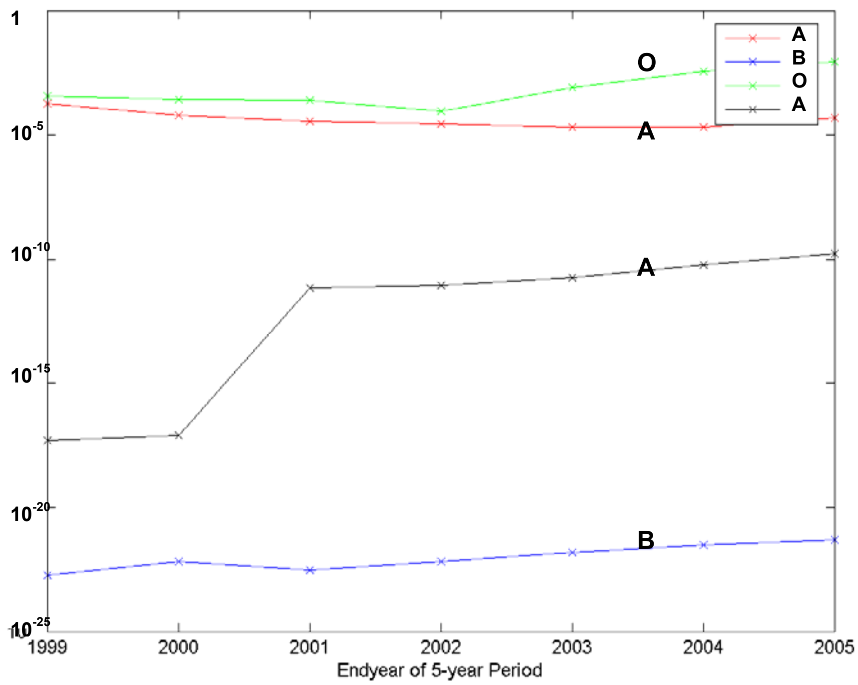

Figure 3: Monitoring of Import Behaviour (Normalised Top Event Value) over five year periods for countries of family A (Medium human development index (HDI)), B (low HDI), and O (high HDI)

For family A, the analysis was extended to a second country to illustrate the effect of significant increase in import behaviour, which was expected to have developed over the history a potential scenario. For that case a rising trend from 2001 onwards is clearly visible. More analysis of countries adhering to scenarios for countries of family A are performed, refining the group of countries. In addition one year time periods were applied to make abstraction of the existing infrastructures or equipment. These analyses show consistently a peak in 2001, which is supposed to be caused by a shift in economical dominance due to an economical crisis. This example illustrates also that the assumption of scenario AB should be used with precaution.

4.4 Criticality of imported components for a monitored country

The criticality index of a certain component expresses the relative variation of the Top Event probability caused by the relative variation of this component's probability. In the example here the Top Event probability refers to a financial budget with which components for potential use in LIS plants can be bought, which changes with the market prices. An actualisation of the total volume needed to buy the components of a LIS plant is needed to monitor the criticality index of a certain component in time.

Each variation in import behaviour of a country (as show in figure 3 for some countries) needs to be combined with an allocation of the change in imported components. In particular the typology of the imported components over time needs to be monitored, what is planned in a further study.

5. Conclusions and Perspective

It was proven beneficial to setup for a given proliferation sensitive system a Tree and to derive the minimal cut sets. This provides an identification of all components with structural importance for LIS construction. Depending on the ratio of present components in a subject country to the total number of necessary components a threshold could be set, that activates a flag of suspicion and launches additional investigations. With the components of structural importance the current list of dual use items could be upgraded with a ranking system for the most sensitive components common to LIS systems.

In a first example data from import/export statistics was coupled to the Tree and the Top Event was evaluated with the Fault Tree Analysis Technique. It was demonstrated that the method has the potential to indicate anomalies in import behaviour of dual use components of any kind for a given subject country. More info, in particular the number of imported components is needed to establish a more direct relation to the import/export data and the probabilities needed for the Tree.

Advanced versions of this probabilistic method may provide customs services with an effective tool that is of potential use for detecting anomalies in import behaviour of LIS or other sensitive technologies. Future research might compare the proposed FTA technique with alternatives such as Bayesian Networks.

6. Acknowledgements

The authors acknowledge Mrs. Versino and Mr. Mousty for their support in providing data and information used in this study.

7. References

[1] S.A. Erickson, "Nuclear proliferation using laser isotope separation - verification options", *Proc. of Symposium on International Safeguards: Verification and Nuclear Material Security*. LLNL, Oct. 2001.

[2] J. Boureston, "Laser enrichment: Separation anxiety", *Bulletin of the Atomic Scientists,* vol. **61**, No.2, pp.14-18, 2005

[3] B.M. Casper, "Laser enrichment a new path to proliferation", *Bulletin of the Atomic Scientists,* vol. **33**, No. 1, pp.28-41, 1977

[4] P. Parvin, B. Sajad, K. Silakhore, M. Hooshvar, and Z. Zamanipour, "Molecular laser isotope separation versus atomic vapor laser isotope separation"*, Progress in Nuclear Energy*, vol. **44**, No. 4, pp. 331–345, 2004.

[5] C. Schwab, A.J. Damião, A.B. Silveira, J.W. Neri, M.G. Destro, N.A.S. Rodrigues, and R. Riva, "Laser techniques applied to isotope separation of uranium"*, Progress in Nuclear Energy,* vol. **33**, No. 1, pp. 217–264, 1998.

[6] R. Ramakoteswara, Laser isotope separation of uranium*, Current Science*, vol. 85, no. 5, 2003.

[7] C.B. Moore et al, *"Alternative applications of Atomic Vapor Laser Isotope Separation technology",* Energy Engineering Board, Commission on Engineering and Technical Systems, National Research Council, USA, 1991.

[8] J.W. Eerkens, "Selected Papers on Laser Isotope Separation - Science and Technology"*, SPIE - The International Society for Optical Engineering,* 1995.

[9] S. Hargrove, "Laser technology follows in Lawrence's footsteps", *Science & Technology Review,* May 2000.

[10] R.J. Jensen et al., "Separating isotopes with lasers"*, Los Alamos Science,* vol. **3**, No. 1, 1982.

[11] J. Creemers, "*Proliferation Sensitivity of Dual Use Equipment for Laser Isotope Separation"*, Master degree thesis at the University Ghent, August 2006

[12] S. Contini, G.M. Cojazzi, G. de Cola, "On the Exact Analysis of Non-Coherent Fault Trees: The ASTRA Package", *Proc. of the 8th Int. Conference on Probabilistic Safety Assessment and Management (PSAM 8)*, New Orleans, USA, May 14-19, 2006.