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Proliferation Sensitivity of Dual Use Equipment for Laser Isotope Separation

by
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Abstract—**Under the non Proliferation treaty and the Additional Protocol of the International Atomic Energy Agency (IAEA), a set of safeguards measures exist to monitor the peaceful use of nuclear materials and nuclear technologies. The proliferation sensitivity of Laser Isotope Separation (LIS) is of concern, because the development of this technology is more easily concealed. This study proposes a way to apply Fault Tree Analysis (FTA) to detect changing capabilities of countries to construct a laser enrichment facility. Export data are converted to probabilities, by considering the fraction of export of certain items to this country, and inserted in a Fault Tree. ASTRA detects, by means of the Top Event probability, the Minimal Cut Sets (MCS) and the Criticality Index, a deviation in import behaviour of a given nation for sensitive components. The import statistics are monitored in an efficient way by evaluating the change in import of a combination of sensitive components and raise a flag when an anomality in the signal is detected.**

Keywords—**non-proliferation, AVLIS, MLIS, dual use, enrichment, ASTRA, CN codes, Laser Isotope Separation**

I. Introduction

Although the international nuclear security is strengthened by explicit import/export control of dual-use equipment it remains difficult to detect illegal nuclear technology transfer in the area of laser enrichment. Laser enrichment techniques are still under research and development and as such not directly declarable under NPT safeguards. Additional verification techniques that focus on the appropriate technical specifications of the different components could help in enhancing the estimation of a nation's capability to construct a laser isotope separation plant.

II. Methodology

This work applies probabilistic risk assessment in an alternative and innovative way for assessing the detection probability for potential laser enrichment activities. In particular, the developed technique aims to give an early indication to the inspector and may be a more effective approach for detecting potential establishments of laser isotope separation plants.

The technique is based on monitoring a nation's import behaviour over time and relates this to a change in infrastructure and equipment with regard to laser enrichment. Export data are then converted to component probabilities for use in a Fault Tree. The analysis returns a value that can be interpreted as a probability that a state could be developing a laser enrichment program with the imported components. The Advanced Software Tool for Reliability Analysis (ASTRA), developed at the Joint Research Center (JRC) of the European Commission is used to analyse the Fault Tree.

J. Creemers (UGent, Gent, Belgium) conducted this Masters' thesis research at the JRC-IPSC, Ispra, Italy. Promotor: G. Maenhout; Co-Promotor: A. Poucet

III. Fault Tree Construction

For each laser separation technique, the necessary components were determined from open literature. The different items are then grouped based on the Combined Nomenclature (CN) codes descriptions in import/export statistics reported by the Customs. The resulting groups of components are integrated in a Fault Tree, which is reconstructed case by case with the appropriate probability values, using Matlab programs.

IV. Using Export Data in FTA

Export data must be converted to probabilities that are then implemented in the Fault Tree. In our approach, the export value of all items for all countries is divided by the sum over all country categories. Five year periods are considered and the result is set as a value to the probability of that component. After analysis ASTRA detects with a Top Event probability all changes in import behaviour compared amongst countries and monitored in time. Whit this approach the relevant changes in capabilities of nations to construct a LIS plant are registered.

The evolution in time of the probability is obtained by analyzing data from five year periods. The first analysis starts with data from the period 1995-1999 and subsequent five year periods are analyzed. Since export data are only closely monitored from 1995 onwards, the analysis limited to seven time windows.

V. Country Analysis

A. First Analysis

Applying this technique to a series of nations results for most of them in constant Top Event values of which the height is closely related to the level of industrialisation and the trade relations with Europe, because the analysed data were European export values.

B. Five Year Periods

Some countries show a significant increase in Top Event value for the five year periods containing the year 2001. The type and amount of relevant items, exported from the EU to those non-EU countries changed in 2001 and remained several magnitudes larger from then onwards, as shown in figure 1. This change in behaviour was analysed in more detail with one year periods.

C. One Year Periods

Considering a one year time frame is too limited to get an overview on the infrastructure and equipment of a nation with regard to the capability in laser enrichment technology. However, applying the technique to one year periods can give an in-

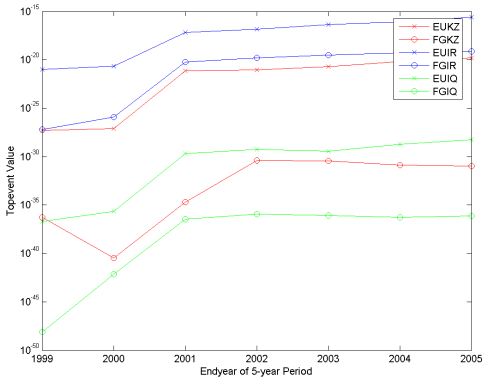

Fig. 1. Top Event value (using both export from France and Great Britain (FG) and whole EU): five year periods

dication of some trends. This analysis confirms the key position of the year 2001.

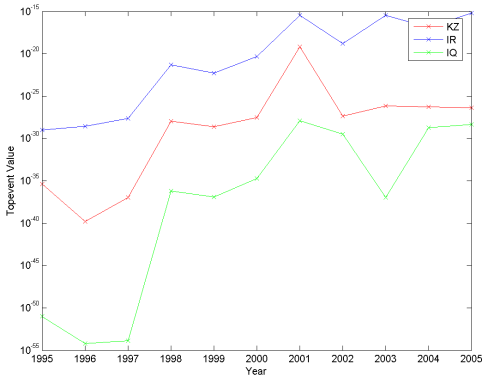

Fig. 2. Top Event value: one year periods

D. Importances

Changes in the importance of an item can help inspectors focus on those items with increased diversion risk. ASTRA can determine the critical and essential components by means of two indicators: the criticality index and the minimal cut sets.

For the total export to outside the EU, the criticality index remained fairly constant for all components, indicating little or no change in the European export behaviour. For the countries with deviating Top Event value evolutions however, also the criticality index differed significantly in time periods that contain the year 2001 from those before that.

VI. Improvements

Five year periods show a meaningful evolution and is a good estimate. The mainly monotonic Top Event evolution (mostly increase) impedes to draw global conclusions and the five year time frame conditions the analysis of the change in infrastructure and equipment with potential use for laser enrichment.

Other widths of time windows, and extension of the datasets from non-EU countries with the same details as available in this study for EU countries would result in a more precise Fault Tree

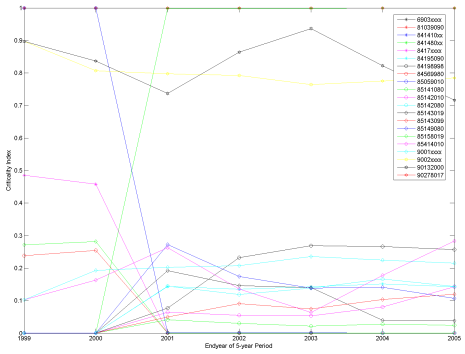

Fig. 3. Criticality index: evolution for all items, five year periods

and more reliable data. Moreover an additional study of the causes for increase/decrease in import behaviour, such as economical crisis, international conflicts etc. could enhance the interpretation of the results substantially. Finally it is needed to derive the critical minimum size for establishing LIS. Thereof a threshold could be set for a monitoring of the cumulative import distribution. This is required to establish a valuable early warning system for the inspectorate.

VII. Conclusion

The applied probabilistic technique has the potential for the inspector to indicate any anomaly in import behaviour, so that an effective monitoring for potential use of laser components and accessories for isotope separation can be launched. This technique might also serve the inspector as an analyzing tool for other sensitive technologies, such as centrifuge technology. The developed programs require only minor changes to work with other sets of items and Fault Trees.

Acknowledgments

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Preface

Under the Non-Proliferation Treaty and the Additional Protocol of the International Atomic Energy Agency (IAEA), a set of safeguards measures exist to monitor the peaceful use of nuclear materials and nuclear technologies. The proliferation sensitivity of Laser Isotope Separation in this frame deserves particular attention, because the development of this technology is more easily concealed.

This study proposes a way to apply Fault Tree Analysis (FTA) to detect changing capabilities of nations to construct a laser enrichment facility. Export data are converted to probabilities, by considering the fraction of export of certain components to this nation, and inserted in a Fault Tree. ASTRA returns the Top Event probabilities and the criticality indexes, of which the evolutions can give an early warning.

Keywords non-proliferation, AVLIS, MLIS, dual use, enrichment, ASTRA, CN codes, Laser Isotope Separation

Dutch Summary

Proliferatie-gevoeligheid van dual use laser-materiaal voor illegale isotopenscheiding

Onder het Non-proliferatie verdrag en het Additional Protocol, bestaat een hele reeks maatregelen om het misbruik van kernmaterialen en -technologieen voor militaire toepassingen te verhinderen. Deze maatregelen staan bekend als Nucleaire Safeguards en worden opgesteld door het Internationaal Atoom Energie Agentschap (IAEA) in samenspraak met de IAEA-lidstaat dat zich aan de controles onderwerpt.

Om de safeguards maatregelen te versterken worden landen aangespoord om naast hun traditionele safeguards overeenkomst een Additioneel Protocol te ondertekenen met extra safeguards maatregelen. De import en export van materiaal dat naast gebruik in niet nucleaire activiteiten tevens toepassingen kent in de nucleaire industrie is geregulariseerd. Deze zogenaamde dual-use componenten staan beschreven in INFCIRC/254 van het IAEA. INFCIRC/254 beschrijft onder andere de componenten die noodzakelijk geacht worden om een installatie voor uranium-verrijking te bouwen.

Aangezien verrijking door laser isotopen scheiding slechts kleine installaties vereist (84 verrijkingseenheden volstaan voor een commerciële installatie, terwijl bij centrifugetechnologie er tienduizenden nodig zijn) is het het moelijk om de illegale overdracht van nucleaire technologie te detecteren.

Bijkomende verificatietechnieken die op de geschikte technische specificaties en de specifieke combinatie van benodigde componenten focussen, stellen ons in staat om een betere afschatting te maken over de mogelijke status en voortgang van een laserverrijkingsprogramma.

Dit thesiswerk stelt een techniek voor om met behulp van de import- en exportgegevens de proliferatiegevoeligheid af te schatten. De techniek is gebaseerd op de tijdsevolutie van de export naar een welbepaald land en brengt op die manier de veranderingen in infrastructuur en apparatuur voor laserverrijking in kaart. Daartoe worden exportgegevens van dual-use componenten omgezet naar waarschijnlijkheden voor gebruik in een foutenboom. De ASTRA code, die voor de foutenboomanalyse gebruikt wordt, baseert zijn analyse op die waarschijnlijkheden.

De waarschijnlijkheid voor elke component wordt bepaald door de gecumuleerde export van alle items naar een bepaald land, te delen door deze gecumuleerde export voor alle landencategorien. De resulterende waarde wordt evenredig met de waarschijnlijkheid van dit individuele componenten voor een potentiele verrijkingsinstallatie beschouwd. De gegevens zijn beschikbaar vanaf 1995, omdat sinds dat jaar de exportgegevens door Euro-

stat vrijgegeven worden.

Om de relevante exportgegevens te selecteren is een lijst van alle vereiste componenten voor een laserverijkingsinstallatie (van het AVLIS of MLIS type) nodig. Gegevens uit open literatuur worden, voor elke laser isotopenscheidingstechniek, gegroepeerd volgens de gecombineerde nomenclatuur (CN) beschrijvingen in de import/export statistieken van de douane. De resulterende componentenverzamelingen worden geintegreerd in een foutenboom, die geval per geval door Matlab programma's gereconstrueerd wordt met de passende waarschijnlijkheden.

De foutenboomanalyse geeft een Top event waarde die kan geinterpreteerd worden als de mogelijkheid om een laserverrijkingsprogramma op te zetten met deze componenten. Deze probabilistische techniek wil in het bijzonder een vroege waarschuwing geven en zo een effectievere controle door de Safeguards inspecteurs mogelijk maken.

Na analyse van verschillende gegevensreeksen met vijfjarige tijdkaders, van 1995-1999 in 7 stappen tot 2001-2005, werd de Top-Event waarde geanalyseerd.

In de meeste gevallen blijft deze waarde constant en is haar grootte verwant met de industrialisatiegraad van het land. Bovendien zijn de waarden voor handelspartners van de Europese Unie systematisch hoger omdat de gegevens op Europese uitvoerwaarden gebaseerd zijn. Voor enkele landen veranderde de berekende waarde abrupt in 2001, door veranderingen in de hoeveelheid en de types van ingevoerde componenten. Een mogelijke oorzaak die gesuggereerd wordt is de algemene economische crisis van 2001 in vele exportlanden.

Naast een afschatting van het risico kan deze analysemethode ook gebruikt worden om die onderdelen te identificeren die momenteel belangrijk zijn voor de bouw van de laserverrijkingsinstallatie in het geanalyseerde land. Daartoe worden twee indicatoren gebruikt: de kritikaliteitsindex van de componenten en de Minimal Cut Sets van de combinatie aan componenten. De eerste indicator, de kritikaliteitsindex drukt de relatieve variatie uit van de Top-Event waarde door de relatieve variatie van de waarschijnlijkheid van de component. De relatieve verandering in kritikaliteitsindex-waarde gaat gepaard met de relatieve verandering in Top Event waarde voor dat land en volgt de verandering in handelsverhouding van dat land voor die componenten.

Voor de totale EU export, bleef de kritikaliteitindex vrij constant voor alle componenten, wat op weinig of geen verandering in het Europese handelsgedrag met betrekking tot zijn export wijst. De periodes van vijf jaar tonen een zinvolle evolutie en kunnen worden gebruikt voor een eerste beoordeling van het handelsgedrag met betrekking tot import in de beschikbare tijdsspanne van 1995 tot 2005. Het is niet mogelijk een volledig overzicht uit het monotone gedrag van de tijdsevolutie te verkrijgen. Daarom werden jaarlijke veranderingen rond een bepaald interessant effect (zoals het 2001-effect) geanalyseerd.

Een voortzetting van deze studie kan niet-Europese exportgegevens of verschillende tijdskaders bespreken. Verder kan ook een multidisciplinaire aanpak, waarbij ook economische aspecten geanalyseerd worden, bijdragen om de resultaten in een bredere context te analyseren. De voorgestelde techniek kan gebruikt worden voor de analyse van andere gevoelige technologieën, zoals gascentrifugetechnologie. De ontwikkelde programmas vereisen slechts minieme aanpassingen om te kunnen werken met andere reeksen van componenten.

Contents

List of abbreviations

α	total separation factor
α_1	enrichment factor
α_2	depletion factor
AR	Argentina
ASTRA	Advanced Software Tool for Reliability Analysis
AVLIS	Atomic Vapor Laser Isotope Separation
BE	Belgium
BR	Brazil
BWR	Boiling Water Reactor
CEA	Commissariat à l'Énergie Atomique
CN	Commodity Nomenclature
CVL	Copper Vapor Laser
COGEMA	Compagnie Générale des Matières Nucléaires (The Hague)
CRISLA	Chemical Reaction by Isotope Selective Laser Activation
CVL	Copper Vapor Laser
DE	Germany (Deutschland)
EG	Egypt
EMIS	Electromagnetic Isotope Separation
EU	European Union
F	Feed
FR	France
GB	Great Britain
HEU	Highly Enriched Uranium
Ic	Criticality Index
IN	India
INFCIRC	Information Circular (IAEA)
IQ	Iraq
IR	Iran
JRC	Joint Research Center
KMP	Key Measurement Point
KP or DPRK	The Democratic People's Republic of North Korea
KR	South Korea
KW	Kuwait
KZ	Kazakhstan
LLNL	Lawrence Livermore National Laboratory

LANL	Los Alamos National Laboratory
LWR	Light Water Reactor
MBA	Material Balance Area
MCS	Minimal Cut Set
MLIS	Molecular Laser Isotope Separation
MOLIS	Molecular Obliteration Laser Isotope Separation
MOPA	Master Oscillator Power Amplifier
MPA	Multi Photon Absorption
MPD	Multi Photon Dissociation
MUF	Material Unaccounted For
NL	the Netherlands
NMAC	Nuclear Material Accountancy and Control
NNWS	Non Nuclear Weapons States
NPT	Non-Proliferation Treaty
NWS	Nuclear Weapons State
P	Product
Pu	Plutonium
PWR	Pressurised Water Reactor
RGU	Reactor Grade Uranium
SILARC	Separation of Isotopes by Laser Assisted Retardation of Condensation
SILVA	Séparation isotopique par laser sur la vapeur atomique de l'uranium
T	Tails
U	Uranium
UF_6	uranium hexafluoride
QA	Qatar
RGU	Reactor Grade Uranium
SW	Separative Work
SWU	Separative Work Unit
UN	United Nations
UNSCOM	United Nations Special Commission
US	United States
USEC	United States Enrichment Company
VE	Venezuela
WGU	Weapon-Grade Uranium
X_F	abundance

Introduction

Background

During the Second World War, the USA invested significant amounts of resources in the Manhattan Project in order to develop large-scale isotope separation capabilities to produce enriched uranium for the manufacture of nuclear weapons. Obviously, laser enrichment was not yet an option, but the first photolysis of uranium hexafluoride (UF_6) was achieved during work on the Manhattan project using monochromatic lamps. Not this technique, but gaseous diffusion was withheld for large scale production in the following decades.

In the late 1970s, early 1980s, more efficient replacements were sought for the gaseous diffusion plants in Oak Ridge, Paducah and Portsmouth. Atomic Vapor Laser Isotope Separation (AVLIS) and Molecular Laser Isotope Separation (MLIS) were among the contestants, both funded by the US government and independently by Exxon. Exxon quit the pursuit for large scale laser enrichment in 1981, and in 1983, the US government decided to drop the MLIS project, developed at Los Alamos National Laboratory (LANL), focusing on the AVLIS program, managed by Lawrence Livermore National Laboratory (LLNL). Advances made in Laser Isotope Separation (LIS) research, prompted analysts, like Casper [1977] and Boureston and Ferguson [2005], to issue warnings about the proliferation sensitivity of these techniques.

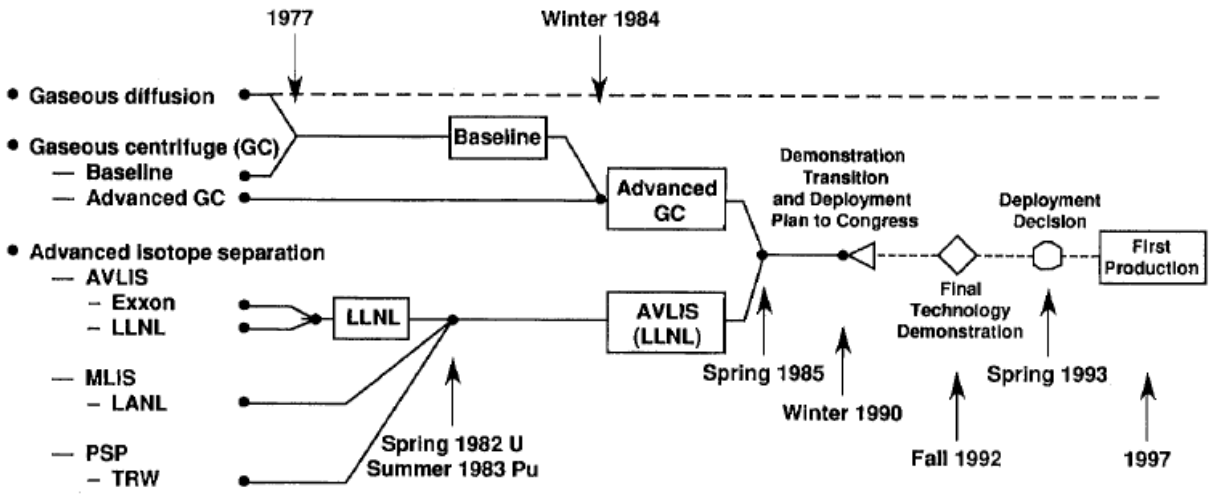

Figure 1: LIS in the USA: time line (Moore et al. [1991])

After spending about 1 billion US dollar on research, leading to some success in enriching plutonium and having some large scale hardware available, the development of uranium enrichment technology was transferred from LLNL to the United States Enrichment Company (USEC) in 1993 to be finalised. The expected costs turned out to be higher than anticipated, estimates for plant construction went beyond 2.5 billion dollar, so USEC decided to suspend AVLIS development.

U.S. interest in laser enrichment methods was not immediately gone with the ceased AVLIS program. In 1996, USEC invested in the Separation of Isotopes by Laser EXcitation (SILEX) technique being developed in Australia. The U.S. and Australian governments demonstrated further interest in the project on June 20, 2001, when they announced that they had officially classified the SILEX method. But USEC's interest in SILEX proved short-lived, and on April 30, 2003 it terminated SILEX funding. Silex Systems Ltd.,based in Australia, continued work and at the moment claims to have proven commercial viability. In May 2006, General Electric Company (GE), based in the USA, signed an exclusive commercialisation and license agreement with Silex Systems. In June 2006, GE received confirmation from the US government to proceed with certain preliminary activities contemplated in the SILEX Technology development project.

In 2004, France's Commissariat à l'Énergie Atomique (CEA) completed its research on laser-based uranium enrichment (SILVA[1] program). The research had been performed from the mid-1980's, co-financed by COGEMA[2] from 1993 to 2002 and an overview is given by Davis [2002]. The CEA completed construction of a pilot installation, Menphis, at Pierrelatte in early 2003. In November the CEA conducted a demonstration production run in the pilot, which produced more than 200 kg of uranium enriched to 2%-3% and a metric ton of depleted uranium. Menphis featured "a full-scale system integration of separator, atomic vapor production and laser." According to Patrice Bernard of the CEA, the CEA was so encouraged by the demonstration that it has begun looking into the implementation of the technology on a commercial scale, perhaps in twenty years. France's Court of Auditors (Cour des Comptes) has a less positive view of the Silva program. It charged in its report on public sector spending in 2003 that the CEA wasted money by keeping research on Silva going after the technology's lack of feasibility had become apparent. After COGEMA's decision to replace its Eurodif gaseous diffusion plant by centrifuge technology in 2007, the SILVA program was discontinued.

Not only the United States and France conducted research into Laser Isotope Separation (LIS). In October 2001, Japan brought its research effort into laser enrichment to an end. Brazil invested in a laser enrichment program for many years but eventually chose to build a commercial centrifuge plant. South Korea managed to enrich very small quantities of uranium and was reprimanded by the International Atomic Energy Agency (IAEA) for not reporting these uranium enrichment activities in a timely fashion as required by its Safeguards Agreement.

In total, more than 20 other nations have researched laser isotope separation techniques. A report by Boureston and Ferguson [2005] includes Argentina, Australia, Brazil, Britain, China, France, Germany, India, Iran, Iraq, Israel, Italy, Japan, the Netherlands,

[1]SILVA: Séparation isotopique par laser sur la vapeur atomique de l'uranium

[2]COGEMA: Compagnie Générale des Matières Nucléaires

Pakistan, Romania, Russia, South Africa, South Korea, Spain, Sweden, Switzerland, the United States and Yugoslavia.

Most of these nations have confined their LIS work to the laboratory. Britain, France and the United States have developed LIS programs that could move beyond the lab into the pre-industrial phase and ultimately into commercial production. Australia and Japan are also known to have invested significant resources in trying to build LIS uranium enrichment plants. Silex Systems Ltd, based in Australia, even went ahead to build a small scale pilot plant, intended to prove commercial viability.

Laser enrichment has long been regarded as too difficult for undeclared enrichment of uranium. The fact that Iraq abandoned laser enrichment in 1987 when it found the process beyond its technological means supports this assumption. But that was almost 20 years ago. Erickson [2001b] argues the technological and other barriers for nations in the middle economic rank will fall over the first half of the 21st century. Barely achievable technological goals may become routine decades later. In February 2003, International Atomic Energy Agency (IAEA) Director General Mohamed El-Baradei acknowledged the difficulties in detecting "these research and laboratory activities", but was confident that the IAEA's improved technological abilities would make it "highly unlikely" that an industrial scale LIS plant would go undetected. Dr Michael Philip Goldsworthy, Chief Executive Officer of Silex Systems Ltd., is even more reassuring, stating in a hearing by the Australian Standing Committee on Industry and Resources that "(...) if a clandestine or renegade government wants to build a bomb they (...) will not go for SILEX because it is too complex and too sophisticated".

Since Laser Isotope Separation involves technology more widely used than that of older methods, defining and enforcing effective export controls is more difficult. Moreover, the smaller size of the equipment and the smaller amount needed to construct an operational system facilitates undeclared import and export.

Objective

Although the international nuclear security is strengthened by explicit import/export control of dual-use equipment, published in IAEAs INFCIRC/254, it remains difficult to detect illegal nuclear technology transfer in the area of laser enrichment. Laser enrichment techniques are still under research and development and as such not directly declarable under the NPT safeguards. Focused verification techniques and control measures are needed to enhance the estimation of a nation's ability to establish a laser isotope separation plant.

Methodology

This thesis work applies the probabilistic risk assessment technique in an alternative and innovative way to assess the detection probability of laser enrichment activities. In particular this probabilistic technique is aimed to give an early warning to the inspector and so attain a more effective monitoring of potential establishments of laser isotope separation plants.

Chapter 1

Nuclear Safeguards

1.1 A History of Nuclear Safeguards

1.1.1 The Foundation of the International Atomic Energy Agency

With the discovery of nuclear fission in 1935, it was calculated that if a chain reaction could be controlled, one would have a tremendous source of power. Scientists began to speculate on the potential of nuclear power plants. But if the chain reaction were to occur in a violent, uncontrolled manner, one would have an atomic weapon. The latter would be demonstrated at the end of the Second World War when humanity was confronted with this horrendous development in warfare. The use of this nuclear weapon immediately resulted in the fear that the US's monopoly on nuclear weapons would soon end and that the proliferation of nuclear weapons technology would be a fact. Therefore, the US, the UK and Canada made a declaration in which they stated that the integration of a safeguards system would be a precondition for other states to have access to peaceful nuclear technology.

Following this statement the United States proposed a plan in which the promotion of nuclear energy was to be under the responsibility of the United Nations. This was the Baruch plan, named after the US delegate who presented it. The main objective of this plan was to assure that the nuclear knowledge would only be used in civil programs and not abused for military purposes. The US was prepared to hand over its atomic monopoly to a new UN Atomic Development Authority, which would be responsible for the international control of nuclear research and the elimination of nuclear weapons. The plan was not accepted since the former Soviet Union was developing its own nuclear weapons program which resulted in a successful test in 1949.

In December 1953 President Eisenhower held his famous "Atoms for Peace" speech before the general assembly of the United Nations. He tried -again- to promote the achievement of nuclear disarmament and the diffusion of peaceful nuclear technology. The success of this initiative led in 1956 to the decision to found an autonomous intergovernmental organization under the United Nations responsibility and in 1957 the International Atomic Energy Agency (IAEA) statutes were approved. The goal of this organization is to promote the use of nuclear technology for peaceful purposes and to ensure that no misuse of such technology could be performed. This is expressed in Article II and Article III of the

Statute of the IAEA:

Article II mentions the promotional function of the IAEA:

> The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose.

Article III mentions the controlling function of the IAEA -the so named Safeguards-

> The Agency is authorized: To establish and administer safeguards designed to ensure that special fissionable and other materials, services, equipment, facilities, and information made available by the Agency or at its request or under its supervision or control are not used in such a way as to further any military purpose; and to apply safeguards, at the request of the parties, to any bilateral or multilateral arrangement, or at the request of a State, to any of that State's activities in the field of atomic energy.

The Safeguards system is not to be confused with Safety and Security. Safety is related to the operation of civil nuclear installations, the transport of radioactive materials, the treatment and deposit of nuclear waste and the decommissioning of nuclear facilities, all this in order to protect the environment from any radioactive contamination.

1.1.2 The Establishment of a Safeguards System

Although the constitution of the IAEA was generally welcomed, it encountered two major problems in the following years: the implementation of the safeguards system and the political climate. The implementation of the safeguards system was achieved gradually by defining a set of rules for research reactors, followed by safeguards implementation for all sort of reactors, reprocessing facilities and fuel fabrication plants. By 1958, with the change in political climate -The Cold War- it was impossible for the IAEA to start her work at some main tasks. In the following years the increase in amounts of arsenals of nuclear weapons, or so-called vertical proliferation, was substantial.

Furthermore, Fisher [1997] mentions several events in the 1960s which proved that the horizontal proliferation could represent a real threat and that there was a need for Nuclear Arms Control: the Cuban missile crisis; the appearance in 1960 (France) and 1964 (The United Kingdom) of two additional Nuclear Weapons States; the proposals in NATO for a multilateral nuclear armed force; the discussions between French, German and Italian politicians suggesting that Germany and Italy might also acquire the bomb and rumors that Israel was about to do so. Those political events were accompanied with the construction of several research- and industrial reactors in states that were not yet in the possession of a nuclear weapon. In addition,, the construction of reactors in Pakistan and India deepened concern about a possible proliferation. All this led eventually to the Treaty on the Non Proliferation of Nuclear Weapons (NPT) in 1968, which entered into force in 1970.

1.1.3 The Non Proliferation Treaty and Classical Safeguards

The Treaty

The NPT is the only global non proliferation treaty, according to Carchon [1995], and is built around the following central ideas:

(i) The Non Nuclear Weapons States (NNWS) renounce nuclear weapons and therefore will not try to transfer, acquire or produce nuclear weapons.

(ii) The NWS will not provide any NNWS with the technology to produce nuclear weapons or give any help to acquire those weapons.

(iii) As a consequence of their willingness to put the fuel cycle under safeguards, the NNWS will gain access to nuclear equipment, material and technology developed for peaceful purposes.

(iv) All States will undertake negotiations toward nuclear disarmament.

To give effectiveness to the NPT, a complete set of Safeguards has been negotiated for the NNWS. Two Safeguards Agreements have been produced: one for the single States (INFCIRC/153) and the other for the regional state systems (e.g. EURATOM).

Classical Safeguards: INFCIRC/153

The document INFCIRC/153 is the basis for the Classical Safeguards and states:

> The Agreement should provide for the Agency's right and obligation to ensure that safeguards will be applied, in accordance with the terms of the Agreement, on all source or special fissionable material in all peaceful nuclear activities within the territory of the State, under its jurisdiction or carried out under its control anywhere, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices.

Each of these agreements, negotiated directly by the IAEA and the involved nation, needed additional Subsidiary Agreements that could describe in detail all the actions to be performed at each facility. Mainly, the Safeguards system based itself on the Nuclear Material Accountancy and Control (NMAC) performed in declared facilities and on declarations that the States have to submit regularly to the IAEA. The verifications of the declarations submitted by means of inspections could, via statistical analysis, find potential discrepancies on the inventories, indicators of possible nuclear proliferation. The inspections are designed in such a way that they can satisfy the Three Safeguards Goals:

- Significant Quantity
- Timeliness Detection
- Probability for False alarm and for Non Detection

Although the inspections were originally designed for the NNWS with time also NWS negotiated with the IAEA to allow inspections on the nuclear facilities involved in civil programs. Amongst the others, France and the UK, accepted the IAEA Safeguards system on selected facilities.

The EURATOM Treaty

The Euratom Treaty was signed between 6 member states of the European Union on 25 March 1957 and entered into force on 01 January 1958 (BENELUX, Germany, France and Italy). Those States were joined by Denmark, Ireland, United Kingdom (1973); Greece (1981); Spain and Portugal (1986); Austria, Finland and Sweden (1995). The enlargement of the European Union includes the obligation for the new member states to ratify the Euratom Treaty (Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia). Chapter VII of the Treaty deals with Safeguards and is built around three principles that can be found in Article 77 and Article 84: conformity, general control and territorial control.

Article 77 implies that the Euratom inspectors should verify the conformity of the effective use of nuclear material with the intended use. Furthermore Article 77 imposes a general control on all nuclear material within the territory of a member state. However, Article 84 explicitly excludes all inspections on non-civilian applications. Bril [2000] distinguishes within those principles three major differences with the IAEA inspections:

> The control by the Agency is a finality control, which intends to verify that the declared material is not used for any military purpose, moreover, the IAEA control is a partial control, only material obtained with the assistance of the Agency is under control, finally, the IAEA control is linked to the material itself and not to the territory.

Article 81 deals with the inspections on the nuclear materials and facilities and stipulates that the member state should fully cooperate with the inspectors in order to ensure compliance with the provisions of Article 77.

1.1.4 The Additional Protocol

The Iraqi Nuclear Program

In 1991 the IAEA's inspectors found clear evidence of a clandestine nuclear program in Iraq whose goal it was to produce HEU. To do so, Iraq made use of Electromagnetic Isotope Separation and gas centrifuge for enrichment. Further inspections made clear that Iraq possessed the knowledge to design and construct prototypes of Nuclear Weapons and was developing the explosive package for those devices. It was obvious that Iraq had violated the obligation, to which it was bound by the NPT, to declare all owned nuclear material. Resolution 687 of the UN Security Council gave the instructions to the IAEA to destroy all of Iraq's capability to proliferate. By mid 1998, the inspectors gave an overview of the Iraqi nuclear program in a special IAEA report (1998):

- Nothing indicated that Iraq was successful in its clandestine attempt in the 1970s and 1980s to produce nuclear weapons. However, some uncertainties surrounded the program's development and termination, including the extent of external assistance to the clandestine attempt.

- Iraq was near success in some areas, notably uranium enrichment. The areas included the production of highly enriched uranium through a physical process known as Electromagnetic Isotope Separation (EMIS); the production and pilot cascading of single-cylinder, sub-critical gas centrifuge machines; and the fabrication of the explosive package for a nuclear weapon.

- Nothing indicated that Iraq had produced more than a few grams of weapons-grade nuclear material through its indigenous enrichment processes, or that Iraq had secretly acquired weapons-usable material from external sources.

- All known weapons-usable nuclear material of any practical significance was removed from Iraq by February 1994; this included 208 spent fuel assemblies from research reactors.

- Left in Iraq was some safeguarded nuclear material at the Tuwaitha site. The bulk of material, some 1.8 tonnes, is low-enriched uranium; the rest includes several tonnes of natural and depleted uranium. All these stocks are verified and accounted for under IAEA safeguards.

- Though physical aspects of Iraq's program were eliminated, Iraq retained the practical knowledge acquired by its scientists and engineers about the production and processing of fissile material and the construction of a nuclear warhead.

On 31 October 1998 Iraq was not further prepared to cooperate with the United Nations Special Commission (UNSCOM) and therefore all the inspectors left Iraq.

The Democratic People's Republic of North Korea (DPRK)

The DPRK joined the NPT in 1985 (INFCIRC/403), but only in 1992 an agreement on the safeguards regime was reached. During the IAEA's inspections it became clear that the amount of verified material did not match with the declared material. In addition, a undeclared reprocessing facility had been discovered. The DPRK refused to allow access to those facilities, whereupon the IAEA concluded that The DPRK was violating its safeguards agreement and reported this to the United Nations Security Council. On 12 March 1993 the DPRK announced its withdrawal from the NPT but suspended the effectuation of this decision in June 1993. In 1994 the US negotiated with the DPRK and this resulted in an 'Agreed Framework'. The DPRK's graphite moderated reactors would be replaced with Light Water Reactors (LWR), an operation to be financed by the US. The spent fuel of a 5 MWe research reactor was to be disposed in a safe way but could, under no conditions be reprocessed in the DPRK. Furthermore, the US was willing to take steps to move toward 'full normalization of political and economical relations'. The DPRK, in return, promised to freeze further development of its nuclear facilities and give full co-operation to the IAEA's inspections.

The Additional Protocol

In 1993, in response to the failure of the IAEA to discover the secret nuclear weapons program of Iraq and The DPRK, the IAEA decided to undertake serous action to prevent this to happen again. The IAEA made efforts to strengthen the existing Safeguards system and this effort led to the creation of the Additional Protocol (INFCIRC/540), which was approved by the board of Governors on 15 May 1997. The essence of the Additional Protocol is twofold: an improved qualitative system and an improved accessibility to suspected facilities. In addition to the existing quantitative system, the improved qualitative system is aiming for an overall picture of a State's nuclear and nuclear-related activities (including nuclear related import and export) to check whether a State has declared all nuclear material and technology. Furthermore, The Additional Protocol entitles the IAEA to visit and inspect any facility -even the undeclared- of a State to get a clear view on the declared activities. Although the NPT States are not obliged to adopt the Additional Protocol, most of the NPT states did or are willing to do so. It might not be a big surprise that, although Libya (9 March 2004) and The Islamic Republic of Iran (December 2003) signed the Additional Protocol; they did not ratify it so far. The DPRK didn't sign any Additional Protocol at all.

The Conceptual Framework for Integrated Safeguards

At the March 2002 meeting of the Board of Governors the blueprint of the Conceptual Framework for Integrated Safeguards was presented. In establishing an 'Integrated Safeguards'- System, the IAEA aims for a combination of all safeguards measures under the Additional Protocol. The goal of these Integrated Safeguards is to reach an optimum in the efforts to prevent further proliferation. The renewed 'Facility Level Approach' will focus on:

- Timeliness Verification for irradiated fuel
- Unannounced Inspections
- Increased co-operation with State System of Accountancy and Control
- Use of surveillance

However, the real revolution of these Integrated Safeguards is the so-called 'State Level Approach'. The IAEA will combine the measures of the Additional Protocol (the improved accessibility) and the integrated safeguards for the State's nuclear facilities. These Integrated Safeguards will take into account the State's nuclear fuel cycle with the specific design of nuclear facilities and the development plans. This approach will lead to a 'tailor made safeguards system' for each individual State.

1.2 Technical Parameters and Inspections

1.2.1 The Three Safeguards Goals

Significant Quantity or Goal Quantity

The 'Significant Quantity' is the quantity of nuclear material that, if it was diverted, could be sufficient to manufacture a nuclear weapon. The significant quantity is not to be confused with the critical mass. The latter is the amount of fissile material needed to induce a chain reaction, while the significant quantity is the quantity which could lead to the critical mass if all the losses, due to the conversion processes, are taken into account. Amongst others, those processes could be reprocessing or separation of the desired isotopes.

Timeliness Detection

The detection of a diversion of a significant amount of material is not sufficient to prevent a State to produce a nuclear weapon. Time is an important parameter and the IAEA must be able to detect the diversion before the proliferator gets the time to manufacture a nuclear weapon. There can be a need to convert the material in order to make it Weapons Grade and to produce a finished weapon. The conversion time is defined as the time between the acquisition of the material and the finished nuclear device. The frequency of the inspections is determined by the conversion time.

Table 1.1: Significant Quantities

Material	**Significant Quantity (kg)**	**Safeguarded Element**
plutonium (Pu-238 ($\leq$ 80 %)	8 kg	Total Element
U-233	8 kg	Isotope
HEU (U-235 $\geq$ 20%)	25 kg	Isotope U-235
LEU (0.7% $\leq$ U-235 $\leq$ 20%)	75 kg	Isotope U-235
Natural U (U-235 $\approx$ 0.7%)	10t	Total Element
Depleted U (U-235 $\leq$ 0.7%)	20t	Total Element

Table 1.2: Estimated Material Conversion Times for finished Pu or U Components

Material	**Conversion Time**
Pu; HEU; U-233	7-10 days
PuO; Pu(NO3)4; other pure Pu components	1-3 weeks
HEU; U-233-oxide; other pure U components $\geq$ 20%	1-3 weeks
MOX, Other non-irradiated mixtures of Pu $\leq$ 20%	1-3 weeks
Pu, HEU or U-233 in scrap or other diluted mixtures	1-3 weeks
Pu, HEU, or U-233 in irradiated fuel assembly	1-3 months

Material	Conversion Time
Natural or depleted U or LEU (U-235, U-233)	12 months

The IAEA doesn't take the isotopic composition of plutonium into account once the Pu-238 concentration drops below 80%.This is due to the fact that all plutonium isotopes are fissionable with fast neutrons. The IAEA also makes a distinction between unirradiated plutonium and plutonium that is contained in irradiated fuel. The irradiated fuel contains strong β and γ emitters, which complicate the handling of the fuel and could disturb further chemical processing.

The Probability of False Alarm and Non-Detection

In order to be able to perform the measurements a Material Accountancy System is set up, which makes use of Material Balance Areas (MBA) and Key measurement Points.

Article 36(r) of The European Commission Regulation 3227/76 defines MBA as:

> 'Material Balance Area' means an area such that: (i) the quantity of nuclear material in each transfer into or out of each material balance area can be determined ;(ii) the physical inventory of nuclear material in each material balance area can be determined when necessary in accordance with specified procedures, in order that the material balance may be established.

The plant or installation, which is to be inspected, is divided into different MBA's. Within those MBA's key measure points are defined, where the measures are taken.

Article 36(q) of The European Commission Regulation 3227/76 defines KMP as:

> 'Key Measurement Point' means location where nuclear material appears in such a form that it may be measured to determine material flow or inventory. Key measurement points thus include, but are not limited to, inputs and outputs (including measured discards) and storages in material balance areas.

The verification of the material is a three-step process:

1. Counting of all batches and items
2. Qualitative checking
3. Quantitative verification[1]

[1]In some cases the IAEA uses seals to avoid the necessity of the quantitative re-verification. A seal can help to indicate that material was neither introduced nor removed from a container. At the same time, sealing provides a unique identity for the sealed container. Most IAEA seals are applied for extended periods of time, typically several months to years (Safeguards Techniques and Equipment, p36, IAEA, Vienna, Austria 2003)

Upon the possible diversion of material is concluded in the following way: the inspector compares the operator's statements, included in the Book of Inventory, with the results of his inspection verifications and is able to compute a value which is able to prove evidence of discrepancies between the two sets of measurements. This value is referred to as the Material Unaccounted For (MUF). Article 36 (s) of The European Commission Regulation 3227/76 defines MUF as:

> 'Material Unaccounted For' means the difference between physical inventory and book inventory

For a balance period, the interval between two time points of a so-called Physical Inventory taking of the nuclear facility, the MUF is computed as:

MUF = Beginning Inventory + Receipts - Shipments - Ending Inventory

In this balance equation, previous stock is compared with present stock, taking account of intervening receipts and shipments. Each term on the right hand side is the sum of the measured masses of the corresponding nuclear material. The measurement of any amount however, will incorporate the intrinsic measurement uncertainties of the methods being used to measure the material. If all the procedures related to accounting were carried out correctly, this material balance amount (MUF) should be just an accumulation of legitimate facility measurement errors. As a result, one important control procedure is to ensure that the MUF for any balance period is acceptably small whilst taking account of the legitimate measurement uncertainties of the nuclear material which have been processed. Deciding whether MUF is acceptable or not, is a problem of statistical inference. This is done by computing a standard deviation for the balance, and then judging the magnitude of MUF value relative to this standard deviation.

The statistical uncertainty due to stacking measurement errors can be modeled by a normal distribution around the measured MUF and the zero MUF expectation value. According to Miller [1990], the IAEA model contains three crucial statistical parameters:

- The standard deviation is set to 1% of throughput
- The detection probability must at least be 95%; this means that for an anomaly at least 95% of the zero curve area should not be overlapped by the actual MUF curve
- The false alarm probability must not exceed 5%, this means that for an alarm at least 95% of the actual curve area should not be overlapped by the expected zero curve

Both probabilities cut off the Gaussian curves at a 1.65 % (MUF) distance from the center to the right and the left respectively, in case of a positive MUF. Thus, the maximum MUF that will be tolerated becomes 3.3 % (MUF). If the MUF value is bigger than this threshold level, then the IAEA rejects the hypothesis that the real MUF is zero and investigates the possibility that diversion has occurred.

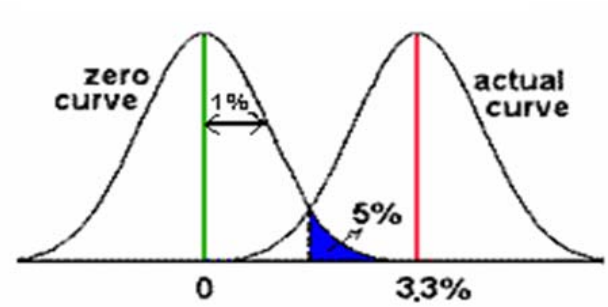

Figure 1.1: Gaussian Cut Off

1.2.2 Nuclear Material Accountancy and Control

The definition of nuclear material can be found in the IAEA safeguards Glossary (2001):

> Uranium, containing the mixture of isotopes occurring in nature; Uranium depleted in the isotope 235; Thorium; any of the forgoing in the form of metal, alloy, chemical compound or concentrate; any other material containing one or more of the forgoing in such concentrations as the Board of Governors shall from time to time determine. Pu-239; U-233; uranium enriched in the isotopes 233 or 235; any material containing one or more of the foregoing; and such other fissionable material as the Board of Governors shall from time to time determine.

Chapter 2

Laser Isotope Separation

2.1 Enrichment Process

2.1.1 Uranium

In its elemental form, uranium is a silvery-white metal. When divided in air, it ignites spontaneously and in its atomic vapor state it is highly corrosive to many materials. Most enrichment techniques, including MLIS, use uranium hexafluoride (UF_6), while atomic uranium is used for AVLIS. UF_6 is a colorless solid at room temperatures that sublimates at 56.5^oC. It is also highly corrosive to many metals and usually requires special nickel or aluminum alloys to contain it. These containers should also be extremely clean and free of leaks because UF_6 reacts strongly with water and many organic compounds, including oils and lubricants. Uranium is an α emitter, making radiological protection necessary.

2.1.2 Enriched uranium

Uranium, which is typically used in LWRs contains 3,5% to 5% of the fissile isotope U-235. Higher enrichment levels can in non nuclear weapon states only be obtained under undeclared activities in enrichment facilities.

In theory a nuclear explosive device can be constructed using Highly Enriched Uranium (HEU) with U-235 concentrations starting at 20% till 100%. With a higher concentration of U-235, a smaller quantity of uranium is needed to reach a critical mass and to construct a nuclear explosive device. The IAEA (2001) considers uranium as highly enriched when the U-235 concentration reaches 20% and classifies uranium as weapons grade material when the U-235 percentage is 93% or higher. The IAEA inspects HEU and LEU with the specific goal quantities as indicated in the tables 1.1 and 1.2 for significant quantity and timeliness

2.1.3 Separative Work

The enrichment of uranium is based on the isotopic separation of U-235 and mainly U-238[1]. U-235 and U-238 have the same chemical properties if they are in the ground state; therefore the separation techniques use the differences in physical properties of the two isotopes[2].

An isotope separation element divides a feed stream F with U-235 concentration X_F into two streams: the product stream, P, of enriched uranium with concentration X_P and a Tail stream, T, of depleted uranium with concentration X_T.

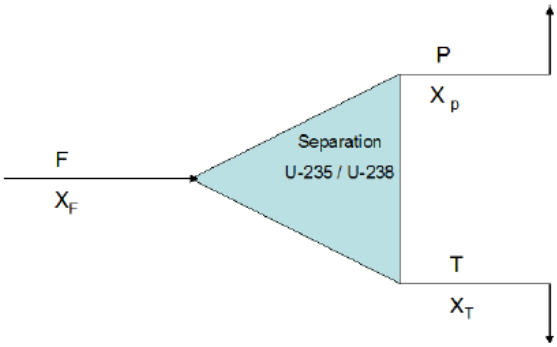

Figure 2.1: A separation unit

According to Matthieu [2004], the separation process is commonly described by three factors: the enrichment factor (α_1), the depletion factor (α_2) and the total separation factor ($\alpha = \alpha_1\alpha_2$). The enrichment factor, α_1, is defined as the relation between the isotopic ratios in the product and in the feed;

$$\alpha_1 = \frac{X_P(1 - X_F)}{X_F(1 - X_P)} \tag{2.1}$$

the depletion factor, α_2, as the relation between the isotopic ratios in the feed and in the tails;

$$\alpha_2 = \frac{X_F(1 - X_T)}{X_T(1 - X_F)} \tag{2.2}$$

and the separation factor, α, as the relation between the isotopic ratios in the product and in the tails.

$$\alpha = \frac{X_P(1 - X_T)}{X_T(1 - X_P)} = \alpha_1\alpha_2 \tag{2.3}$$

Usually the efficiency of a process is expressed by the separation factor. However, when dealing with very efficient methods like electromagnetic or laser enrichment the enrichment factor is used.

[1]Natural uranium also contains traces of U-234. Separation plants separate U-234 and U-235 from the heavier isotopes

[2]Contrary to the other enrichment techniques, which use mass difference, the laser separation technique makes use of the different quantum states of the isotopes

The separation factor expresses the degree of concentration or depletion achieved in one single separation element. To fully describe the separation process, the material flows F, P, T, their concentrations X_F, X_P, X_T, the total mass balance and the mass balance of the distinct isotopes are taken into account.

$$F = P + T \tag{2.4}$$

$$F.X_F = P.X_P + T.X_T \tag{2.5}$$

The work, needed to obtain a certain enrichment level, is calculated using the Separative Work (SW) expressed in Separative Work Unit (SWU). The SW represents the decrease in entropy, thus the increase in order, when dividing a mixture into two mixtures of different concentration. It has no quantifiable form, but calculates a value, which is proportional to the technical capacity and energy resources, needed for the separation of isotopes:

$$SW = P.V(X_P) + T.V(X_T) - F.V(X_F) \tag{2.6}$$

V represents the Value Function and is defined as (Matthieu [2004]):

$$V(x) = (2x - 1)ln(\frac{x}{1-x}) \tag{2.7}$$

The SW depends on 6 parameters:

$$SW = f(F, P, T, X_F, X_P, X_T) \tag{2.8}$$

The mass balances eliminate two of those six parameters. The remaining four parameters have to be specified as boundary to the set of two equations.

2.1.4 Enrichment Techniques

In the common industrial enrichment facilities two different techniques exist: gas diffusion and gas centrifuge (or ultracentrifuge). Gas diffusion is very energy demanding (2400 kWh/SWU) and gas diffusion facilities have large dimensions: 1 diffusion unit has typically a diameter larger than 1 m (URENCO, 2003). Those considerable volumes limit the enrichment grade in such facilities because of criticality safety.

Gas centrifuge units, on the other hand, can be built in a modular way and require only 40 kWh/SWU. Most centrifuges are based on the Zippe-G2 that consists of an aluminium rotor and has a capacity of 1.2 SWU/y although Albright and Hinderstein [2003] indicate a potential capacity increase of those centrifuges to about 2 SWU/y.[3] The enrichment is a stepwise process and the centrifuges or diffusion units are connected to each other in the so-called countercurrent cascades.

Apart from these two industrial techniques, Laser Isotopic Separation (LIS) has been investigated. This process makes use of the slight differences in the absorption spectra of the different isotopes to obtain an isotopic separation. Narrow band light sources make

[3]More recently, even values of 4 SWU/y are reported

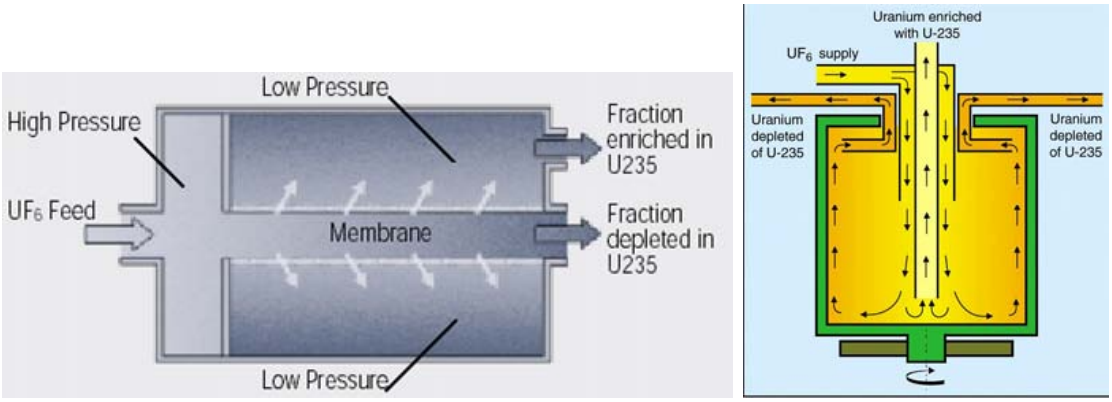

Figure 2.2: A gasdiffusor and a centrifuge

it possible to excite the isotopes selectively. The different uranium enrichment techniques are described below and compared in table 2.1, based on data from US Congress [1993], Eerkens [1995], Parvin et al. [2004] Schwab et al. [1998] and Erickson [2001a].

Table 2.1: Comparison of uranium enrichment techniques

	Diffusion	Centrifuge	Aerodynamic	Chemical	Electromagnetic	Laser
Separation Factor[4]	1.004-1.0045	1.2-1.5[5]	1.015-1.030	1.001-1.003	3-40	1.5-15 (200)
# stages for 90% HEU	3500-4000	40-90	540-1100	5000-16000	2-8	2-20
kWh/SWU	2500	60-200	3600-4000	150-600	200-30000	15-35
kW for 4000 SWU	1200	50-100	1800-2000	75-300	100-15000	low-125
Pilot plant[6] infrastructure cost ($/SWU)	5000	7000				250-725
Pilot plant product cost ($/SWU)	600	300				30-158
Industrial plant[7] infrastructure cost ($/SWU)	1000	1500				100-340
Industrial plant product cost ($/SWU)	120	100				20-87

[4]For electromagnetic and laser processes, estimates are for the enrichment factor, not the separation factor

[5]This separation range applies to modern centrifuges, older models went no higher than 1.026

[6]Pilot plant: 0.2MSWU/yr

[7]Industrial plant: 3 MSWU/yr

Thermal Diffusion

Thermal Diffusion has been abandoned as an enrichment technique since World War II, when it was used to produce the feed for Calutrons. The technique uses UF_6 in its liquid state contained in almost 15 meters high concentric tubes, cooled on the outside and heated on the inside. This causes the lighter isotope to slowly concentrate near the inner wall and rise, whereby it is removed.

Gaseous Diffusion

While not the most efficient technique, gaseous diffusion is still used for the production of most nuclear fuel by some main suppliers of enriched uranium, such as Eurodif or USEC. UF_6, gaseous in this case is forced through a suitable porous barrier, that preferentially passes the lighter isotope, as it travels on average a little faster and can therefore diffuse slightly more efficient through the barrier. The equipment is very energy intensive - the electricity consumption represents 75% of the total cost - and due to the low separation factor, an extensive cascade is necessary.

Gas Centrifuge

Centrifugal forces in rotating chambers cause lighter elements to concentrate near the center and heavier elements near the wall. In gas centrifuge plants, the heavier $^{238}UF_6$ is made to convect upwards from the wall, where it is "scooped out", leaving an enriched gas in the centrifuge. Enriching uranium, with its relatively small isotopic mass difference requires very fast rotation to obtain acceptable separation factors.

Aerodynamic Processes

The aerodynamic process also uses centrifugal forces, but not by spinning a chamber, but by forcing the gas through a curved nozzle or vortex. The heavier elements can then, like in gas centrifuge plants, be skimmed of.

Chemical Exchange Processes

Although isotopes of a single element are normally described as having the same chemical properties, this is not strictly true. In particular, reaction rates are very slightly affected by atomic mass. Lighter isotopes tend to react or evaporate more quickly than heavy isotopes, allowing them to be separated.

Electromagnetic Processes

Calutrons The electromagnetic technique works as follows. The isotopes are ionized, after which they are accelerated and deflected in an electro-magnetic field. Due to mass differences, the radius of this deflection differs (the higher the mass, the more inert and the bigger the radius). Since different isotopes have different mass, the isotopes are separated. This technology is known to be very efficient, but very energy consuming.

Ion Cyclotron Resonance Ion Cyclotron Resonance use the roughly 1% difference in frequency at which ions of the different isotopes orbit in a magnetic field. Precisely tuned radio waves selectively energize one isotope, making them orbit in larger spirals. Eventually they collide with collector plates at specific locations, leaving the other isotopes unaffected.

Plasma Centrifuge Separation In a toroidal rotating plasma, heavier isotopes tend to concentrate near the outer portion of the ring, where they can be removed. This method is probably the least developed EM technique, and it may use considerable amounts of energy and achieve low enrichment factors.

Laser Processes

In laser processes, precisely tuned lasers excite only one of the isotopes, after which it can be selectively separated. The energy consumption is approximately 1 to 2 orders of magnitude less than is the case with the main non-laser methods.

2.1.5 Influence of Initial Enrichment

Both Feed and SW are important parameters from a proliferation point of view. The necessary Feed determines the amount of nuclear material at the input for obtaining a certain product. The SW on the other hand is directly related to the number of separation units needed to obtain weapons grade material and to the energy demand. The difficulty to conceal an undeclared program, depends largely on the size or the energy demand. Laser techniques excel in both these qualities.

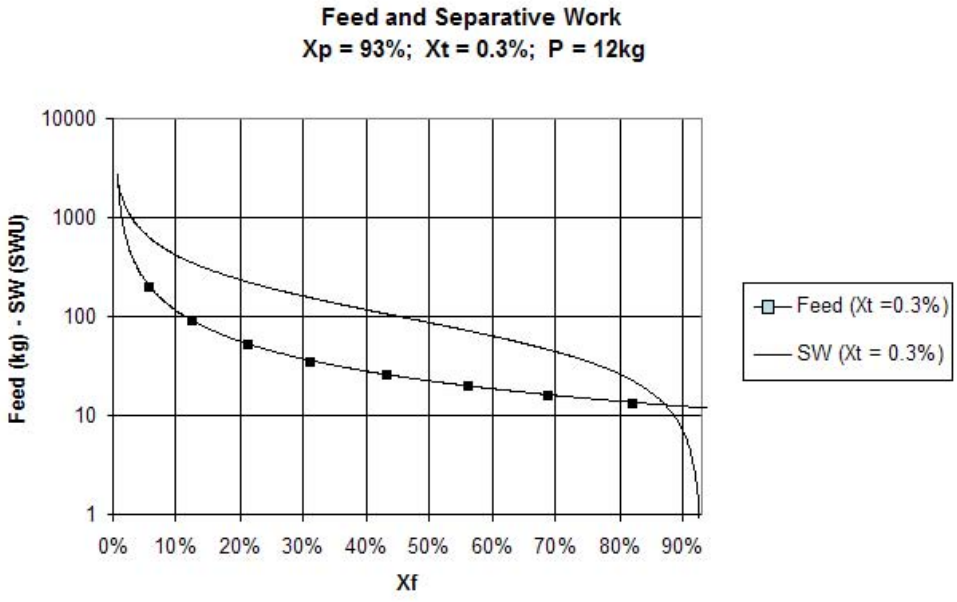

Figure 2.3: Feed and separative work

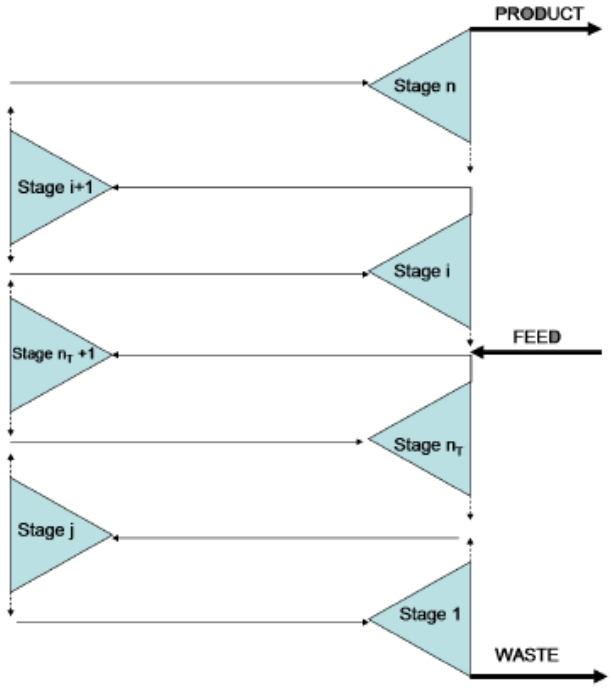

Figure 2.4: A cascade

2.2 Laser Enrichment

2.2.1 Isotope Shift

Laser enrichment is based on differing atomic structures. ^{238}U has three neutrons more than ^{235}U, giving it a different excitation spectrum. The energy required to excite an element, is given by the difference between the energy levels. Due to the change in the excitation spectrum, these excitation energies are slightly different. This difference is called the isotope shift. In figure 2.5, taken from Ramakoteswara [2003], the principle is graphically explained.

One way to excite an element from one energy level to another is to use photons with exactly this energy difference, thus with exactly the corresponding frequency[8]. A light source with a very narrow frequency band would be able to excite only ^{235}U and not ^{238}U. Lasers are, by design, monochromatic, and thus, in theory, emit only one frequency. In reality the frequency spectrum is narrow enough to use them for this kind of enrichment. Even though laser light is highly monochromatic, the challenge is to maintain one specific frequency over a long period of time at high power levels.

Uranium Isotope Shift

The mentioned isotope shift is also present in compounds with uranium, like uranium hexafluoride (UF_6). The other element in the compound, fluor, has only one stable isotope,^{19}F,

[8] $E = h \cdot \nu$

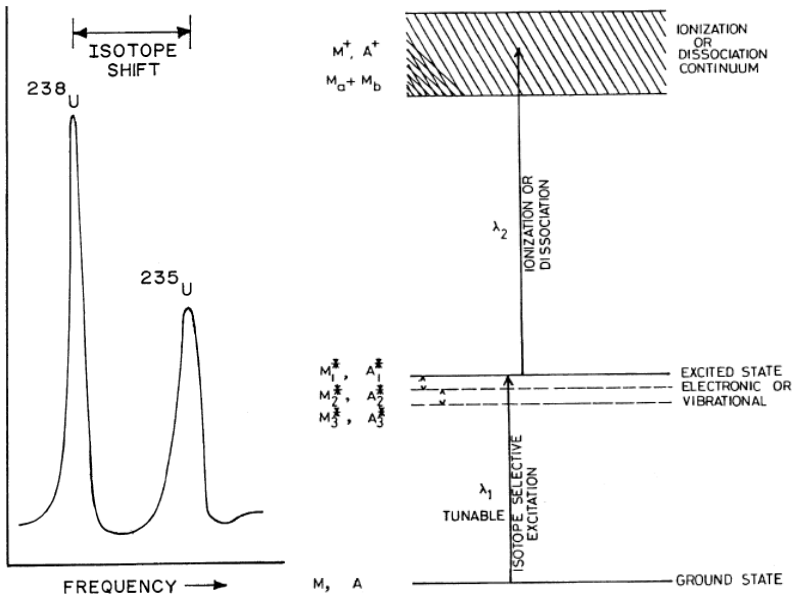

Figure 2.5: Basic principle of LIS: left: Isotope structure of the 436.2 nm line of uranium; right: A1, A2, A3 are three isotopes of A. M is a molecule containing A, and Ma and Mb are its dissociation products

of which the natural abundance is 100%. All isotope shifts are therefore due to the different uranium isotopes in the molecules.

The main division in laser enrichment techniques is: Atomic Vapor Laser Isotope Separation (AVLIS), which uses uranium metal vapor, and Molecular Laser Isotope Separation (MLIS), which uses molecules containing uranium. The latter actually covers a multitude of techniques, all using molecules.

The first step for all these processes is similar, exciting only the ^{235}U (or its compounds), using very precise laser light. After this, different techniques are used to separate only these excited molecules.

Because of its high separation factor, Laser Isotope Separation can be used to "mine the tails", or in other words to use extract the ^{235}U from the tails of other processes.

2.2.2 Atomic Vapor Laser Isotope Separation

Atomic Vapor Laser Isotope Separation (AVLIS) [9] is a process in which uranium metal is heated at low pressure beyond its sublimation point ($\approx$ 2800 K) to create a vapor flow. The vapor is then radiated with laser light, which selectively excites the ^{235}U to a certain level, after which it is radiated again, to ionize the atoms. This mixture is then guided through a electro-magnetic field, which separates the ionized ^{235}U atoms from the neutral ^{238}U atoms.

A major drawback for AVLIS is that it uses uranium metal, which is obtained by reduction of the oxide with Ca or Mg, a very energy consuming process. The production

[9] In France referred to as SILVA

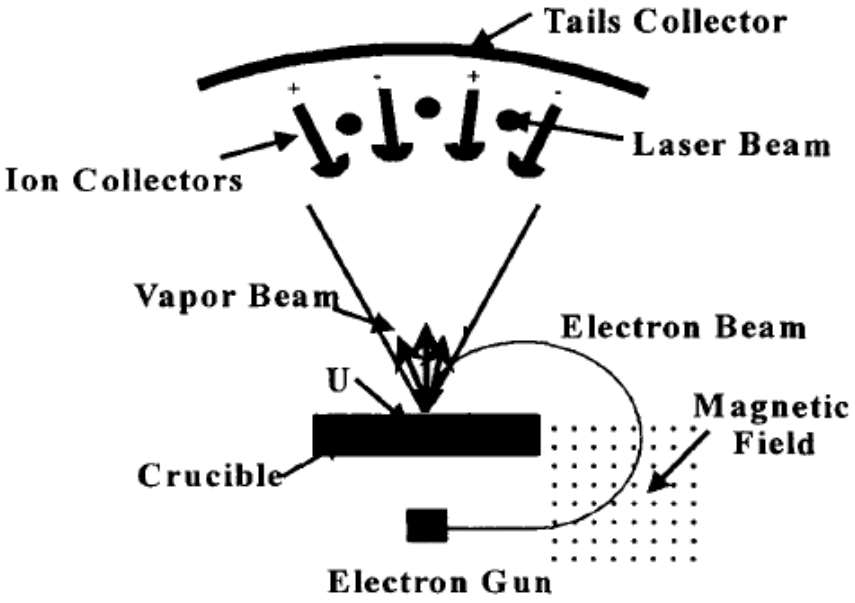

Figure 2.6: Overview of the AVLIS evaporation and collection system

of uranium hexafluoride (UF_6) requires far less energy.

Heating One way to heat the uranium metal is to simply heat the crucible containing the uranium using a resistor, often referred to as Joule heating. Unfortunately, there are few materials that do not react with the uranium at the high temperatures (2500 - 3000 K) involved. The reaction products contaminate the flow and have a bad effect on the process efficiency, since the laser light would irradiate the contaminants together with the uranium. A possible solution is cooling the crucible, but this requires enormous amounts of energy.

Therefore electron beams, which localize the heating on the free surface, are a better choice. High energy electrons, emitted from a high power electron source, are directed toward the uranium, which is consequently heated. The interface between crucible and uranium can even be maintained in solid state. Ionization of the uranium on electron impact should be avoided, since the ^{238}U would be ionized as well, decreasing selectivity. A pair of electrodes near the crucible can remove these ions from the stream. The metal vapor must be confined in a narrow region, in order to maximize the interaction with the laser beam, resulting in higher vapor densities. This can be obtained in two ways. One uses a linear electron beam, another a point electron beam, driven by a fast scanning system. For the latter, the convection energy is reduced and thus the efficiency enhanced, according to Couairon and Soubbaramayer [1992] with a factor between 10 and 35.

The location of the electron source is another important issue. Positioning in the "line of sight" of the hot and thus very corrosive uranium flow causes the electron source to interact with the uranium, reducing its efficiency. The electron source is therefore placed outside this "line of sight" and the electrons are guided toward the uranium in an electromagnetic field.

Electron beam heating is exhaustively covered by Ramakoteswara [2003] and Schwab et al. [1998].

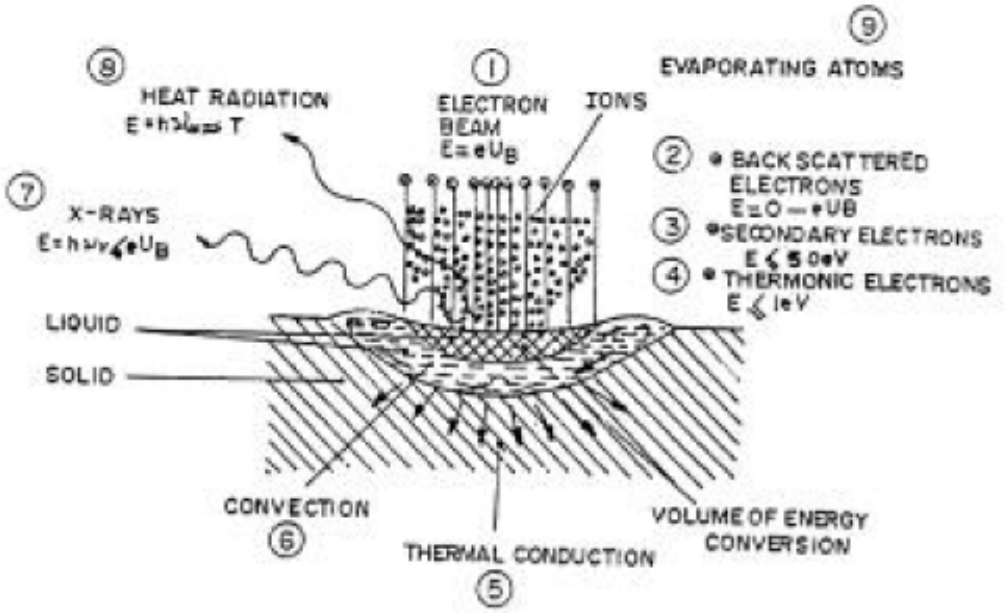

Figure 2.7: Electron beam heating: overview by Ramakoteswara [2003]

Another promising technique is the use of solenoids for local heating. By precisely calibrating them, the magnetic field can be focused in a way that electron movement heats up only the areas of interest. The major advantage is that the metal itself can still serve as crucible because of the very localised heating.

There is, according to Schwab et al. [1998], strong evidence that certain special uranium alloys show similar evaporation at lower temperatures than necessary in the case of pure uranium.

Ionization The ionization energy is approximately 6.194 eV (49957 cm^{-1}, 200.7 nm), so one step ionization of uranium is impossible with a single visible photon (1.8-3.1 eV, 400-700 nm). At least two steps are necessary, but, to improve selectivity, the ionization is frequently obtained in more than two steps. As we can see in figure 2.8, taken from Schwab et al. [1998], the excitation wavelengths are all around 600 nm, so in the visible light spectrum.

The laser light for each step is fine tuned for ^{235}U, making sure that its frequency doesn't correspond to a ^{238}U resonance. The shift in wavelength is of about the same order as the hyperfine structure, 5-10 GHz ($\approx$ 0.01 nm when considering a wavelength of 600 nm). More steps will reduce the number of ^{238}U that is excited along through line broadening phenomena (vibration effects...) and prevents the use of UV frequencies, which would considerably reduce the lifetime of the dyes used in the laser. However, every additional step will reduce the throughput or require the use of more powerful lasers. Only a fraction of the electrons in each level will be excited to the next level, the others will

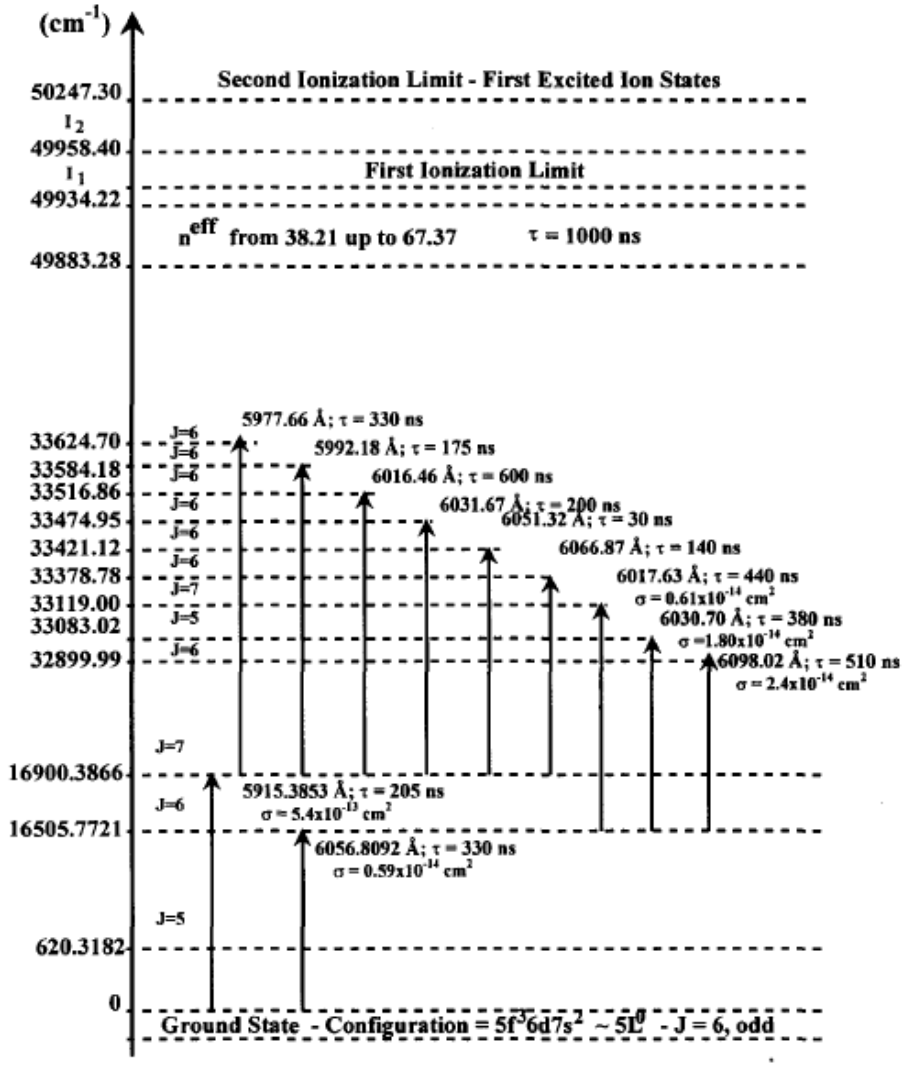

Figure 2.8: Two-photon absorption spectrum of uranium

have de-excited back to a lower level, before they could be excited to the next level. To have enough electrons in the level that leads to ionization, ever more electrons are needed in all previous steps. This means the laser that does the first excitement needs to be very powerful, and the more steps are used, the more power is needed. For a typical three step ionization, Parvin et al. [2004] reports the intensities of the lowest and intermediate exciting laser beams to be respectively about 100 and 10 times more than that of the highest exciting laser.

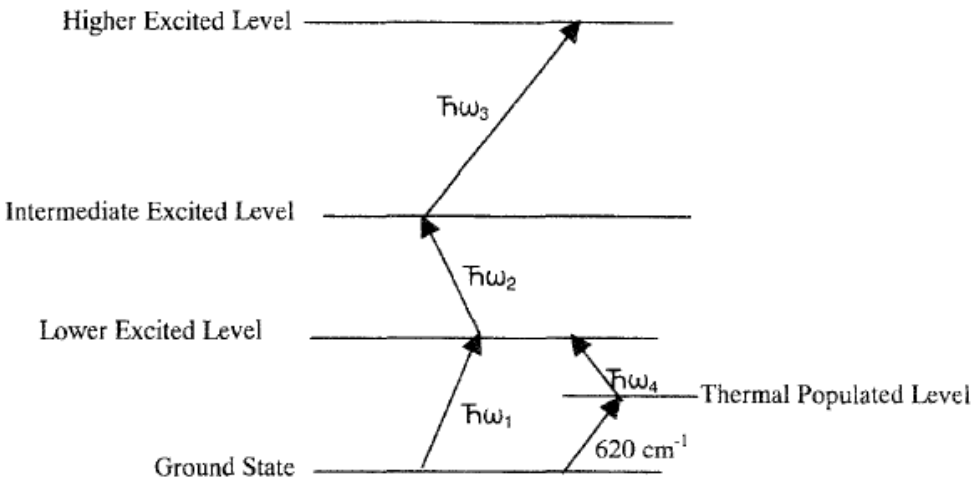

Figure 2.9: Diagram of three or four step ionisation

Another important aspect is thermal excitation. At the vaporization temperature ($\approx$ 2800 K) for metal uranium, Parvin et al. [2004] found 47% of the uranium atoms in the ground state, and 28% in an excited level with a shift of 620 cm^{-1} (=16.3 μm). Therefore, a four step excitation, including the thermal level, would be optimal (see figure 2.9, taken from Parvin et al. [2004]), since electrons in the thermal level would also be excited.

To obtain a suitable selection, Parvin et al. [2004] found that line widths should be around 0.001 - 0.0001 nm. To achieve this, complex optics are used, but the high power lasers produce a lot of heat in these, which causes thermal fluctuations.

Density A higher density improves the process speed. There is however an upper limit. Higher densities means more collisions, an effect which is amplified by the increase in collisional cross sections of both ^{235}U and ^{238}U with pressure. Charge may be transferred from ^{235}U to ^{238}U through collisions, ionising ^{238}U, causing it to be extracted along with the ^{235}U, reducing yield. Moreover, at higher densities, spectral broadening will decrease the photoionisation selectivity, because the laser will excite unwanted isotopes, whose shift is less pronounced. Maximum densities are reported by Schwab et al. [1998] to be around $10^{10} cm^{-3}$, since collisional effects begin to become relevant at this density.

Lasers Besides the obvious required laser properties, such as tunability, high intensity and coherence, the lasers must also possess a high repetition rate and short pulse durations.

The high repetition rate is necessary to illuminate all the atoms in the flux, while the pulse duration needs to be smaller than the particle collision time ($\approx 10^{-6}s$) and the radiative relaxation time of the intermediate state ($\approx 10^{-6}s$). An efficient process requires kW's of laser power. This can be achieved by a very powerful laser, or good amplification. Two types are often mentioned, the Nd:YAG pumped Ti:Al_2O_3 laser and the Copper Vapor Laser (CVL) pumped dye laser.

The higher the output of a certain laser, the more difficult it is to control spectral characteristics and beam quality. The low damage threshold of the optical components virtually forbids their use in high power systems. A solution consists of putting lasers in a Master Oscillator Power Amplifier (MOPA) configuration. In this configuration a low power generator, with good characteristics is amplified to reach the desired power, as shown in figure 2.10.

CVLs, dye lasers and cooling are commercially available, but custom made lasers can have very satisfying achievements. As a part of their research on AVLIS, Schwab et al. [1998] built several CVLs. Their CVLs show an efficiency of about 1%, power up to $100W$ and up to 10 kHz repitition rates. These lasers all have their specific power and cooling needs.

The laser is positioned in a way that its beam is perpendicular to the flow, avoiding a Doppler effect in the excitation frequencies, which would drastically decrease selectivity.

Extraction The ionized ^{235}U is deflected by an electromagnetic field, which leaves the neutral ^{238}U unaffected. This field should be strong enough and lead the ions to an extractor unreachable by the neutral ^{238}U. At high voltages and densities, plasma effects can occur, creating an internal field that cancels out the applied field.

To avoid this situation, when considering the design, the plasma and the electromagnetic configuration and geometry must be studied carefully.

Experiments by Schwab et al. [1998], show that this stage determines the efficiency. While photoionization is reported to have a selectivity of about 100 %, the process of ion extraction and collection produces a mixture with usually between 5% and 60 % of ^{235}U.

Container The containment of the interaction region should be able to withstand large underpressures, high temperatures and resist corrosion by the chemically active uranium vapor. High purity windows should be installed to allow the laser beam to enter. In some of their experiments, Schwab et al. [1998] mentions the use of Ar as buffer gas.

Efficiency The enrichment factor varies, depending on the source. Schwab et al. [1998] mention values between 7 and 200, which would allow one stage enrichment of uranium for nuclear reactors and the use of the tails of traditional processes as feed. Nations seeking to proliferate using laser technology would still require a multi-stage set-up. Some authors mention 100 % enrichment, but only in very low scale experiments.

Alternative Applications

AVLIS can be used for many different isotopes. There is a report prepared by the Committee on Alternative Applications of Atomic Vapor Laser Isotope Separation Technology

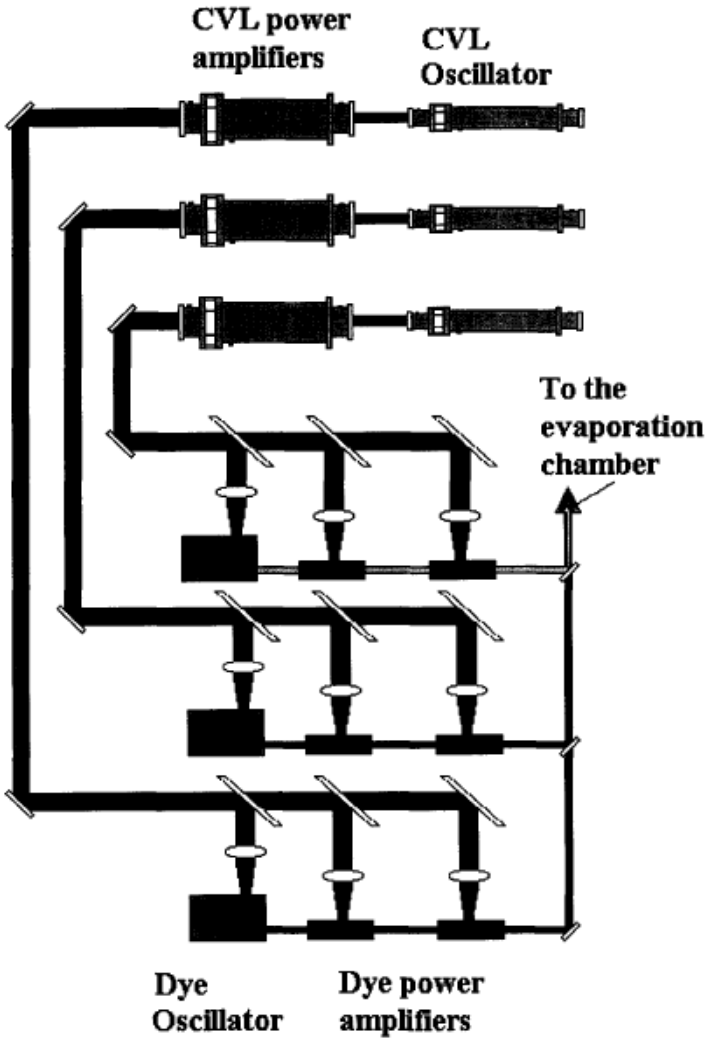

Figure 2.10: Simplified diagram of MOPA chain for AVLIS

that mentions separation of certain isotopes of zirconium (reactor cladding), hafnium (reactor cladding) and plutonium as possible applications, along with other non-nuclear applications. Moore et al. [1991] advises caution, because all proposed alternative AVLIS applications pose, to varying degrees, a proliferation risk. The production of isotopes of the metallic elements is of particular concern.

Parvin et al. [2004] mentions only three, shown in table 2.2.

Isotope	Ionization Energy	Laser Type
^{239}Pu	48601 cm^{-1}	Tunable Dye, $Ti:Al_2O_3$
^{235}U	49957 cm^{-1}	Tunable Dye, $Ti:Al_2O_3$
Zr	56056 cm^{-1}	XeCl, ring Dye

Table 2.2: List of some Isotopes that can be practically separated by AVLIS

Difficulties

Despite successes in low scale AVLIS, most research into commercialisation has been stopped. Many believe that AVLIS has no potential for large scale efficient enriched uranium production. This lead to the termination of some major projects.

A major problem in transferring this technology from lab to plant, is the extraction. In laboratories, an ingot in the crucible, the experiment is conducted, after which the system is opened and enriched uranium is extracted from its collector. This method is not suitable for continuous operation.

Parvin et al. [2004] mentions also:

- The need for laser beam synchronization, due to the short lifetime of excited atoms (order of ns). This exact timing leads to serious technical problems, especially in high power applications. An efficient process requires kWs of laser power.
- Uranium vapor is chemically active, and therefore a well designed irradiation cell or special coating is necessary to protect against chemical corrosion.
- As mentioned before, more steps require more energy in the upper excitation steps and a four step ionization is advised for good selectivity.
- The collisional cross section of uranium increases with pressure, causing more transferral of excitation energy from ^{235}U to ^{238}U. To obtain good selectivity, density should therefore be restricted.
- Laser spectrum line widths should be in the order of 0.001 - 0.0001 nm. The intracavity narrowing system, including a large number of gratings, etalons, beam expanders and prisms, is very sensitive to heat produced by the high power lasers, causing thermal fluctuations in the central frequency and line width.
- Maintenance of high vacuum to prevent a large background atom density

The low density allows the use of moderate laser power, but also limits the flow rate and consequently the yield, limiting the use of AVLIS in large scale enrichment facilities.

Successes

Moore et al. [1991] mention success in plutonium enrichment using AVLIS. Plant-scale hardware for plutonium (in 1984) and surrogate metals (in 1989) is said to have been developed at Lawrence Livermore National Laboratory (LLNL). Due to this effort process-ready equipment was, or still is, available at LLNL for the separation of selected metallic elements on a gram to kilogram scale. Later, a pilot plant, completed at LLNL in the fall of 1997, operated for more than one-and-a-half years, processing several thousand kilograms of uranium in a series of tests aimed at verifying component performance, operational lifetime, and economics. In September 1996 already, a 200 hours test was reported of processing 3 metric tons of uranium (Hargrove [2000]).

Figure 2.11: Pilot AVLIS facility at LLNL

Livermore physicist Bruce Warner, former LIS program leader, notes that USEC's decision to terminate the AVLIS program was no reflection on the strong advantages and technical capability of LIS. For example, the LIS process uses only 5 percent of the electricity consumed by existing gaseous diffusion plants, and LIS facilities would cost substantially less to build than those for other enrichment techniques such as centrifuge technology.

Despite the mentioned successes, no large-scale commercialization is foreseen so far, but with AVLIS it is feasible to produce Weapon-Grade Uranium (WGU). Moore et al. [1991] estimate that a 100 kg/yr-scale plant would require about 15 kW of copper vapor laser pump power. Hence, an array of a few hundred commercially available lasers would be needed. Erickson [2001b] describes the 1984 MARS demonstration at Lawrence Livermore National Laboratory (LLNL), with a throughput of a few kilograms of feedstock a day. A cascade of 50 to 120 of these machines would suffice to make 100 kg of Highly Enriched Uranium (HEU) a year.

According to Warner, it doesn't take much real estate to make a lot of product. The system is remarkably compact. A vacuum chamber holding one separator unit produces

output equivalent to that of several thousand of the best commercial centrifuges. A commercial LIS plant would use 84 enrichment units, compared to tens of thousands of centrifuge machines. This opens perspectives for underground facilities and the resulting detection difficulties.

Besides the USA, at least also France has demonstrated the production capability of tens of kilograms of Reactor Grade Uranium (RGU) using AVLIS. The costs of reinventing this technology are continuously dropping, because of the broader availability of knowledge and technology. While in 1984, the MARS facility, especially the development of the laser and electron beam heating, was an extraordinary achievement, nowadays it may be much easier to construct. Other means to obtain highly enriched uranium are still cheaper and easier than the laser approach, but this may not be true anymore in a near future.

2.2.3 Molecular Laser Isotope Separation

Most MLIS research has been conducted on UF_6, because of its high reward and its current status in the fuel cycle. Other molecules, like uranium tetraborohydride and dioxouranium (VI) tetrahydrofuran, have also been investigated, because of their absorption features in the $9.5 - 10.5\mu m$, where standard CO_2 lasers resonate on several lines. All Molecular Laser Isotope Separation (MLIS) techniques start off in a similar way. The gas containing the uranium is, as in AVLIS, first selectively excited to a certain energy level. A multitude of isotope separation techniques can then be applied to these excited molecules. Below a brief overview of 3 techniques is given. A more detailed description can be found in Parvin et al. [2004].

Cooling MLIS uses the molecule UF_6 and the isotope shift is much less than in uranium metal. At room temperature, thermal line broadening mechanisms (doppler, vibrational excitation...) cause an overlap in the photon absorption frequencies for ^{235}U and ^{238}U (see figure 2.12). Only a small fraction of the molecules are in their ground state. This causes selective excitation to be very inefficient at room temperature, making cooling necessary. Temperatures need to be below 200 K, according to Schwab et al. [1998] and are even lowered to 50 Kelvin. At the condensation temperature ($\approx$ 330 K), UF_6 has essentially no vapor pressure. This asks for alternative, nonequilibrium, fast cooling methods that prevent condensation of the supersaturated gas. In a laboratory setting liquid H_2 or N_2 cooling could be applied, but the flow in a pilot plant would require different techniques, such as adiabatic expansion nozzles.

Pressure Collisions could transfer energy from excited $^{235}UF_6$ molecules to $^{238}UF_6$ molecules, thereby reducing selectivity. To avoid these collisions, the partial pressure should be kept low enough.

Excitation Very precise laser light needs to be used. Schwab et al. [1998] describes the use of 16 μm lasers, resonant with the ν_3 vibration at 630 cm^{-1}. Due to the hyperfine structure in ^{235}U, we can find 21 lines, all with a 5-10 GHz frequency shift ($\approx$ 5-10 nm when considering a wavelength 16 μm). A multitude of excitation possibilities exist using

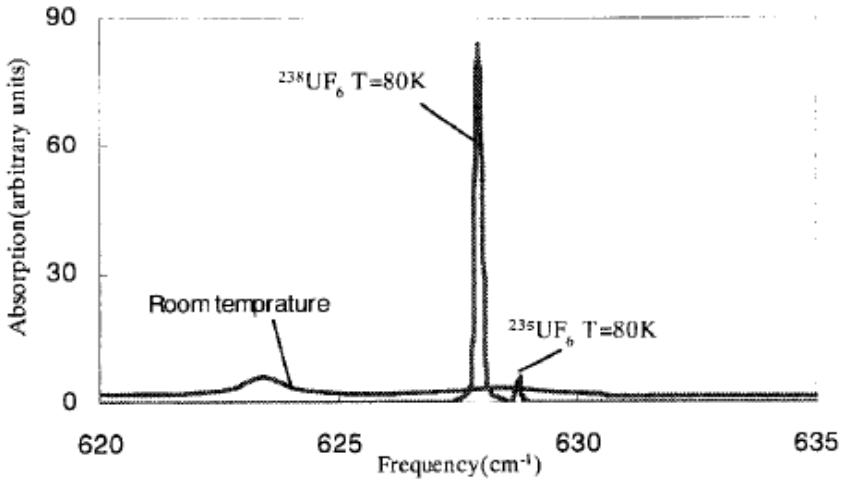

Figure 2.12: Photon absorption at room temperature and at 80 K

electronic, vibrational, rotational and other energy levels. A good overview of the different UF_6 absorption lines and the lasers used is given by Ramakoteswara [2003].

Molecular Obliteration Laser Isotope Separation

In Molecular Obliteration Laser Isotope Separation (MOLIS), the excited molecules are excited further into a dissociation. A possible method is the Multi Photon Dissociation (MPD). This name comes from the first step, the Multi Photon Absorption (MPA) into the vibrational quasi continuum. From here on single photon absorptions eventually lead to the continuum region where dissociation occurs. The MPD process is based on complex interactions between electronical and vibrational excitations. Since the cross section for MPA is obviously much smaller, depending on interaction with multiple photons, absorption is not only dependent on frequency, but on laser beam intensity as well. As demonstrated by Parvin et al. [2004] this leads to a threshold for laser intensity of a few MW/cm^2. A detailed description of the dissociation process can be found in Baranov et al. [1999].

Non MPD MOLIS methods are based on dissociation by consequent infrared IR lasers or a combination of a infrared and ultraviolet (UV) laser.

In both cases, the dissociated molecules react with each other and eventually precipitate, making it possible to extract the enriched substance.

Lasers Possibilities include 16 μm radiation produced by Raman conversion of 10 μm radiation from industrial CO_2 lasers, followed by photolysis by UV lasers or other combinations of IR and UV lasers. Most powerful standard CO_2 lasers used for cutting and welding do not fulfill the necessary requirements, but it is advised to check the laser properties of all exported CO_2 lasers and their possibilities for conversion.

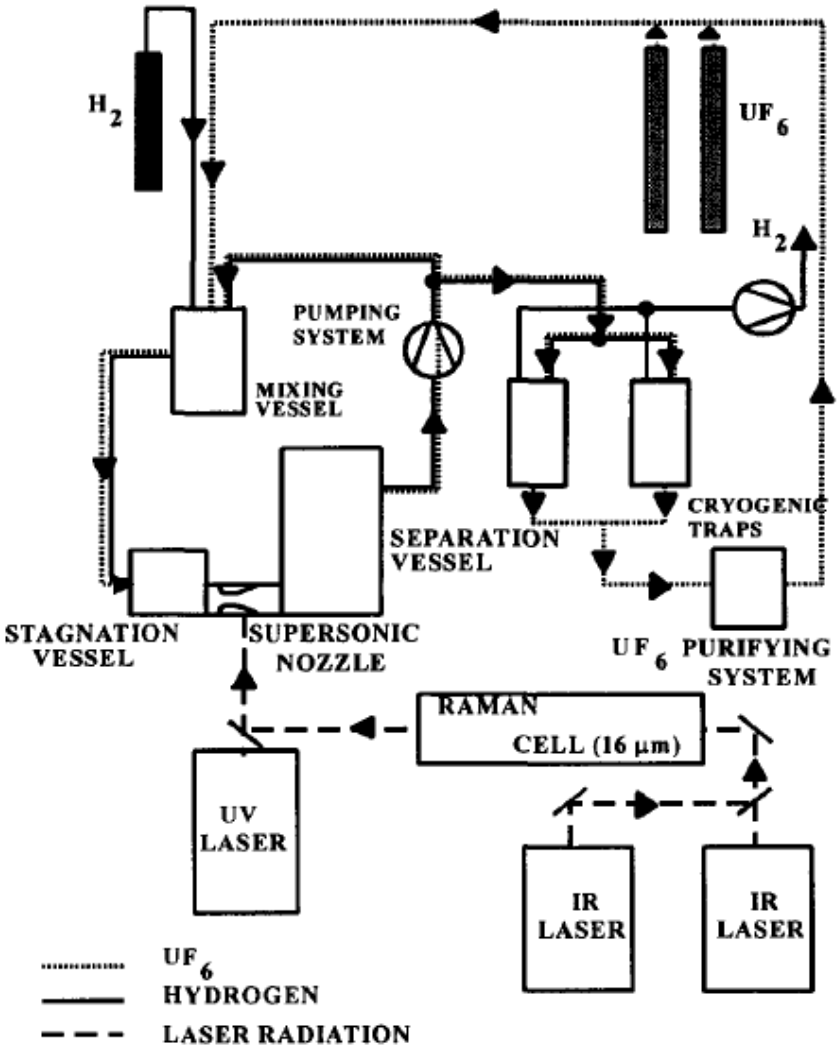

Figure 2.13: Setup for MLIS

Chemical Reaction by Isotope Selective Laser Activation

A closely related technique is Chemical Reaction by Isotope Selective Laser Activation (CRISLA). In this technique the molecule is similarly excited, but in stead of further photon absorption leading to dissociation, the acquired energy is used to initiate a chemical reaction with a certain threshold. Several chemicals, such as combinations of HCI, HBr, SiH_4, BrF_3, ClF_3, SF_4, N_2F_2 and CFCI=CFCl, can be used for this purpose. Chemical energy is cheaper than laser energy, making this method more efficient than MOLIS. The enriched compounds can consequently be extracted. Since only the excitation is done by laser power, the power broadening effect is reduced, improving selectivity. This technology relies heavily on gas filling systems and vacuum technology. Figure 2.14 represents a typical CRISLA set-up (taken from Parvin et al. [2004]).

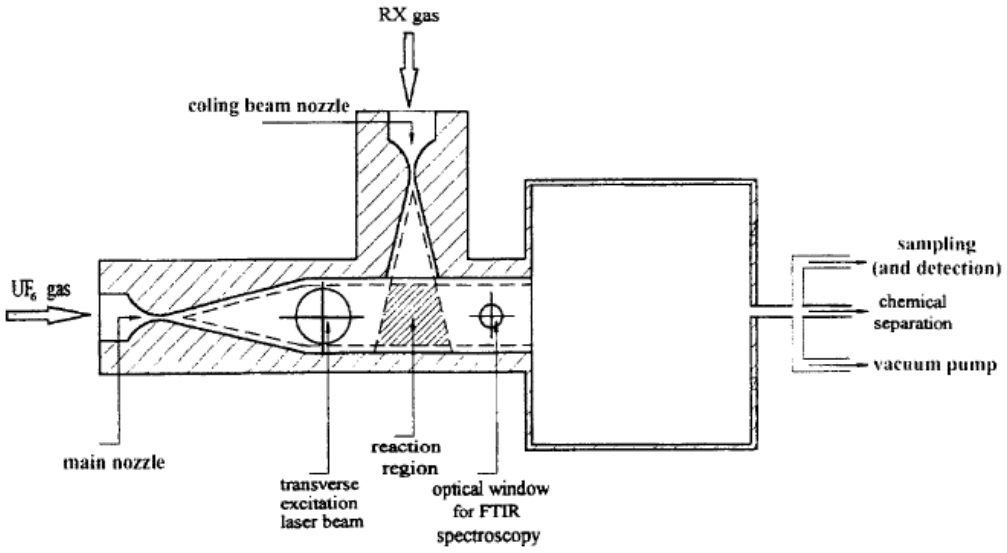

Figure 2.14: A typical CRISLA setup

Separation of Isotopes by Laser Assisted Retardation of Condensation

Separation of Isotopes by Laser Assisted Retardation of Condensation (SILARC) could be considered the opposite of last two techniques. Instead of forming enriched clusters through chemical reactions, SILARC creates depleted clusters. As in all MLIS techniques, a laser beam selectively excites the compounds containing ^{235}U after going through a nozzle. Excitation is known to delay cluster formation, and when the flow is supercooled together with a special carrier gas, the unexcited $^{238}UF_6$ will nucleate, while the excited $^{235}UF_6$ will be kept from freezing due to vibrational-vibrational and vibrational-translational transfers. The clusters are taken from the flow by a cluster trap (a stack of cooled zig-zag plates) or by injecting dust-scavenging particles that are subsequently removed by particle filters. The excited ^{235}U compounds manage to escape. The escaping gas is thus enriched in ^{235}U.

A typical SILARC apparatus is shown in figure 2.15 (taken from Parvin et al. [2004]).

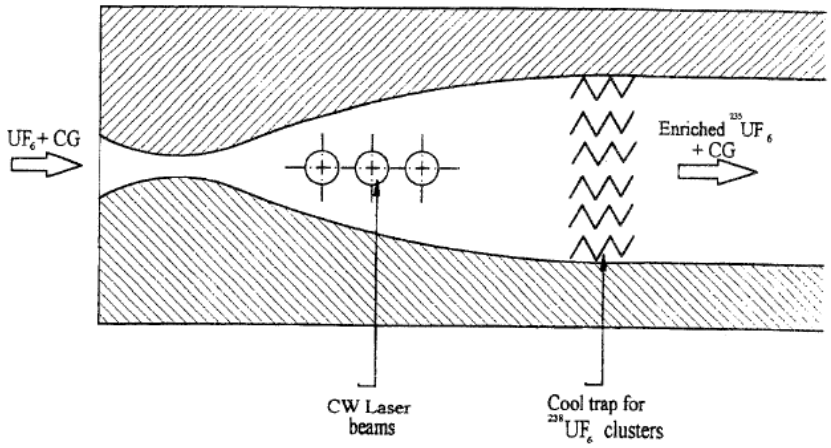

Figure 2.15: A typical SILARC apparatus

Alternative Applications

Currently Silex Systems Ltd. is doing research to apply MLIS to as many isotopes as possible. Besides their work on uranium, their main focus, there's also an effort to enrich silicium for the semiconductor industry and they are investigating other applications. In an announcement on their website, dating November 25 2004, they claim The SILEX Silicon Enrichment technology is fundamentally different to the SILEX Uranium Enrichment technology and can't be used for uranium enrichment in any way. The proliferation risk would therefore be minimal. Parvin et al. [2004] has an extensive listing of successes in MLIS enrichment, shown in table 2.3.

Table 2.3: List of some Isotopes that can be practically separated by MLIS

Isotope	Molecule	Technique	Laser Type
^{33}S, ^{34}S, ^{36}S	SF_6	MOLIS-IR, IR-IR, SILARC	CO_2
^{10}B, ^{11}B	BCl_3, $HClCHBCl_2$	MOLIS-IR	CO_2
^{13}C	CF_2HClCF_2Cl2, CF_3BrCF_3Cl	MOLIS-IR, IR-IR, Multi-IR	CO_2
^{81}Br	HBr	MOLIS IR-UV	HBr
^{29}Si, ^{30}Si	Si_2F_6	MOLIS IR	CO_2
^{13}C, ^{14}C	$COCl_2$	MOLIS-IR	CO_2
Tritium	CHF_3	MOLIS-IR, Multi-IR	CO_2

Successes

When talking about large scale MLIS, Silex Systems Ltd. cannot be ignored. While in the past funded by USEC, they have, during the past few years, continued research independently. Early 2006, a Direct Measurement program shows that their process can compete with other enrichment facilities. They are now cooperating with GE toward commercialising the technology. In comparison to mass-action separation like diffusion or centrifuge, processing costs would be three to ten times less, equipment footprints even a hundred times. This is attractive for organisations/nations that start enrichment activities.

Figure 2.16: Direct Measurement Laboratory at Silex Systems Ltd.

More details are not easily obtained, because most information is classified by both the Australian and American governments. Silex Systems Ltd. denies any proliferation risk associated with its technology.

2.2.4 Photochemical Technique for Monatomic Vapors

Traditionally, because of the large sums of money invested by governments, AVLIS has been the preferred atomic process. A variant, a sort of CRISLA for atomic vapors, is cited in Bokhan et al. [2003] as a good alternative. This technique, referred to as the photochemical technique, activates the metal vapor by excitation, after which it reacts with a chemical with a certain reaction threshold. The reaction product can then be extracted from the flow. An important advantage is that the concentration limit is about

Figure 2.17: Direct Measurement Laboratory at Silex Systems Ltd: Laser

$10^{13} cm^{-3}$, about three orders of magnitude higher then what is achievable with AVLIS. A higher yield can thus be obtained. It is hard to find out more about this technique's perspectives and properties due to a lack of open source information that discusses this technique.

2.2.5 Comparison

Although based on the same principle, AVLIS and MLIS are quite different. Table 2.4 gives an overview of the different techniques.

Table 2.4: Summary of LIS techniques

Technique	Excitation Process	Laser Type	Selectivity	Comments
AVLIS	Photo-Ionisation	Pulsed NIR, Visible, UV	High	Very low yield
MOLIS	Multi-Photon Dissociation	Pulsed	Low	Low yield
MOLIS	Photo-Dissociation	Pulsed IR-UV	Low	low yield, multistage
MOLIS	Photo-Dissociation	Pulsed IR-IR	Acceptable	Low yield

Table 2.4: Summary of LIS techniques

Technique	Excitation Process	Laser Type	Selectivity	Comments
CRISLA	Photo-Excitation	Continuous	Doubtful	Suitable buffers & co-reactants needed
SILARC	Photo-Excitation	Continuous or pulsed	Relatively High	promising

A brief comparison between AVLIS and MLIS, based on Parvin et al. [2004]:

- The dissociations energy of $^{235}UF_6$ (MLIS) is ≈ 3.87 eV, while it is larger than 6 eV for metal uranium (AVLIS).
- The absorption cross section of molecules (MLIS) is larger, increasing the separation efficiency.
- Even at low temperatures, the partial UF_6 (MLIS) pressure is higher than for metallic uranium (AVLIS), resulting in higher yield.
- Metallic uranium vapor (AVLIS) is extremely chemically active, but only in its vapor form.
- Focussing optics for MLIS do not have the same extreme requirements as the AVLIS optics, because of the broader line width ($\approx 0.2cm^{-1}$).
- Current enrichment techniques use UF_6 (MLIS), eliminating the need for a separate supply chain.
- Nuclear devices are made with metallic uranium, as used in AVLIS. Reducing uranium, as shown in figure 2.18 to its metallic form is very energy consuming. In MLIS only the product has to be reduced, while in AVLIS this has to be done for the entire feed.

2.3 Economics

In various sections of this report, it is claimed that Laser Isotope Separation for uranium enrichment, once commercialized, would be a lot cheaper and more efficient than the traditional enrichment techniques. A comparison, based on estimates by Hargrove [2000] and Silex Systems Ltd.:

- The AVLIS process process uses only 5% of the electricity consumed by existing gaseous diffusion plants.

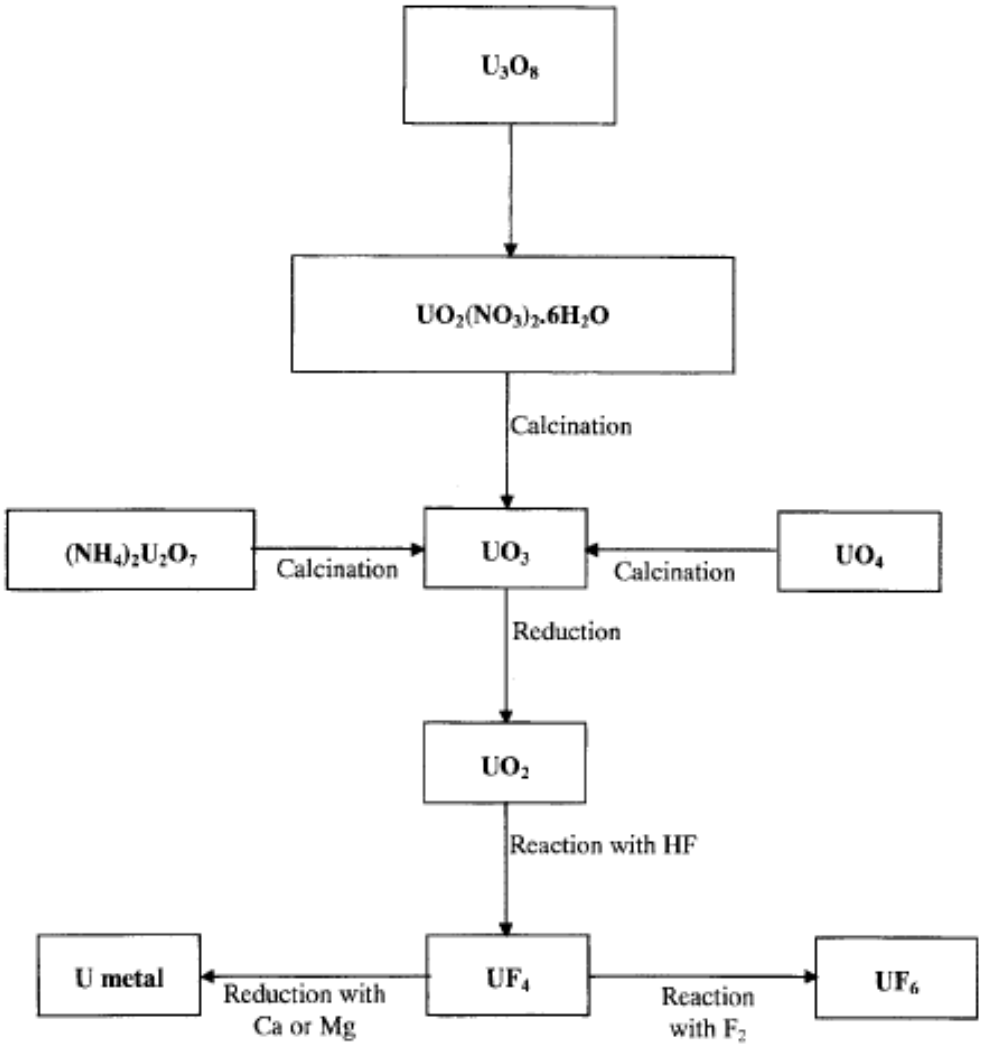

Figure 2.18: A typical scheme of processing stages of conversion of natural uranium

- 84 AVLIS units are the equivalent of 150,000 centrifuge machines.
- The required natural uranium feed would decrease by 30% if laser techniques were used in stead of the traditional enrichment techniques.
- An MLIS facility with 8.75 millions SWU per year was estimated in 1982 to cost about 1 billion dollars, with laser costs accounting for about half of this sum, five respectively six times lower than the estimated cost of a new gaseous diffusion respectively a gas centrifuge plant.
- The annual operating cost for a laser isotope separation facility was estimated to be about 100 million dollars, five times less than for a gaseous diffusion plant and almost two times less than for a gas centrifuge plant.
- Capital and operating costs for an LIS facility indicate a cost per SWU of about $30, while the current commercial cost for enriched uranium is about $80 per SWU.
- Enrichment factors for SILEX are between 2 and 20. They're about 1.004 and 1.25 for respectively diffusion and centrifuge.

Comparison Numbers from some other sources, such as Parvin et al. [2004], Schwab et al. [1998], Erickson [2001a], Eerkens [1995], are mentioned in table 2.6. The costs for a pilot plant take research costs into account. A proliferating nation will likely not have to reinvent all technology, so costs will be lower.

	Diffusion	Centrifuge	AVLIS	MOLIS	CRISLA / SILEX
Separation Factor	≈ 1.004	≈ 1.25	5-15	2-20	
# stages for 90% HEU	3500-4000	40-90	2-8	10-20	≈ 20
kWh/SWU	2500	50	40	30	20
Pilot plant (0.2 MSWU/yr) Cost (in $/SWU)	5000	7000	725	450	250
Product in pilot plant cost (in $/SWU)	600	300	158	75	30
Industrial plant cost (3 MSWU/yr) (in $/SWU)	1000	1500	340	180	100
Product in industrial plant cost (in $/SWU)	120	100	87	50	20

Table 2.6: Comparison between conventional and laser enrichment techniques

Even tails of other enrichment processes could be economically used as feed.

Chapter 3

Application of FTA to Proliferation Sensitivity

3.1 Fault Tree Analysis

3.1.1 Dual Use Items

Many of the components needed to build a laser enrichment facility are dual use items, which means that they can also be used in other industries. An increase in the export to a certain nation of these components therefore does not mean that this nation is trying to build a LIS plant. However, when a nation increases its import of all components used in a laser enrichment facility, there is bigger chance that these components are in fact used for such a facility. This study proposes a quantification of the combination of the import of these components using Fault Tree Analysis.

3.1.2 Fault Tree Analysis

In Fault Tree Analysis (FTA), an undesired effect is taken as the root (Top Event) of a tree of logic. Then, each situation that could cause that effect is added to the tree as a series of logic expressions. When fault trees are labeled with actual numbers about failure probabilities computer programs can calculate failure probabilities from fault trees.

The Tree is usually written out using conventional logic-gate symbols. A subtree that connects failure to the initiating events is called a cut set. The smallest cut set (least amount of triggers) is called the Minimal Cut Set.

ASTRA The Fault Tree Analysis (FTA) was done using the Advanced Software Tool for Reliability Analysis (ASTRA), developed at the Joint Research Center (JRC) of the European Commission.

3.1.3 Conversion of Export to FTA

Events in the fault tree are defined as the components needed for the construction of a laser enrichment plant. In section 3.3.3 import and export data are converted into a diversion

probability. The Top Event event then gives a probability that a nation is capable of building a Laser Enrichment Facility.

3.2 Components

3.2.1 Component Listings

In order to use export data, a list of components is essential. IAEA's INFCIRC/254 lists the items of which the export is strictly regulated. Part 1 has a section about laser enrichment and part 2 lists dual use items, of which we identified several as possible components of a laser enrichment facility. An overview of these components is given in appendix A.1.

Import and export data are categorised using Combined Nomenclature (CN) codes. Both the United Nations (UN) Commodity Trade (ComTrade) Statistics Database and Eurostat's External Trade Database use this format, which can be consulted on their websites. The latter was used for data extraction because of its more detailed division, but follow-up studies could integrate data from more nations. The entire database is checked for components that could be used in a laser enrichment facility, as identified in section 2.2.

The resulting components and their respective CN codes can be found in appendix A.3.

3.2.2 Uranium

The most essential requirement for uranium enrichment is obviously uranium. Uranium is already under strict safeguards, but some laser enrichment properties are cause for some extra concern. Not only is a tight control on all uranium the best way to prevent it to be diverted for use in nuclear weapons, but in case of laser enrichment, this diversion may sometimes be the only detectable activity. Hence, monitoring and supervision of uranium supply, use and transport should be maintained and improved.

As shown in table 2.6, the separation factor for laser enrichment is significantly higher than that of other techniques, making it easier to reduce the amount of ^{235}U in the tails. Compared to centrifuge or gaseous diffusion, Hargrove [2000] claims the laser process requires about 30 percent less natural uranium ore to produce a comparable amount of enriched product.

AVLIS uses metallic uranium, while MLIS uses molecular uranium compounds, mostly UF_6, because of its presence in the current fuel cycle. If samples in laser laboratories were to show either form, this could be a clue that they are experimenting with the corresponding laser enrichment technology. However, conversion from one type to another can be done, but is very energy consuming (the process is described in figure 2.18). This might also persuade some proliferators to prefer the MLIS process. UF_6 has some hazardous chemical properties, but most likely this will be of no concern to a proliferator.

This report assumes that uranium is readily available on site, so it is not integrated in the Fault Tree.

3.2.3 Lasers

AVLIS Most AVLIS experiments use Copper Vapor Laser (CVL) Pumped Dye Lasers. At present, these CVLs are part of high school science projects and undergraduate laboratory experiments, while Dye Lasers are readily available and very popular amongst hobbyists for their ease of construction and use. Solid state lasers, such as Nd:YAG pumped Ti:Al_2O_3 lasers, or free electron lasers are suitable alternatives.

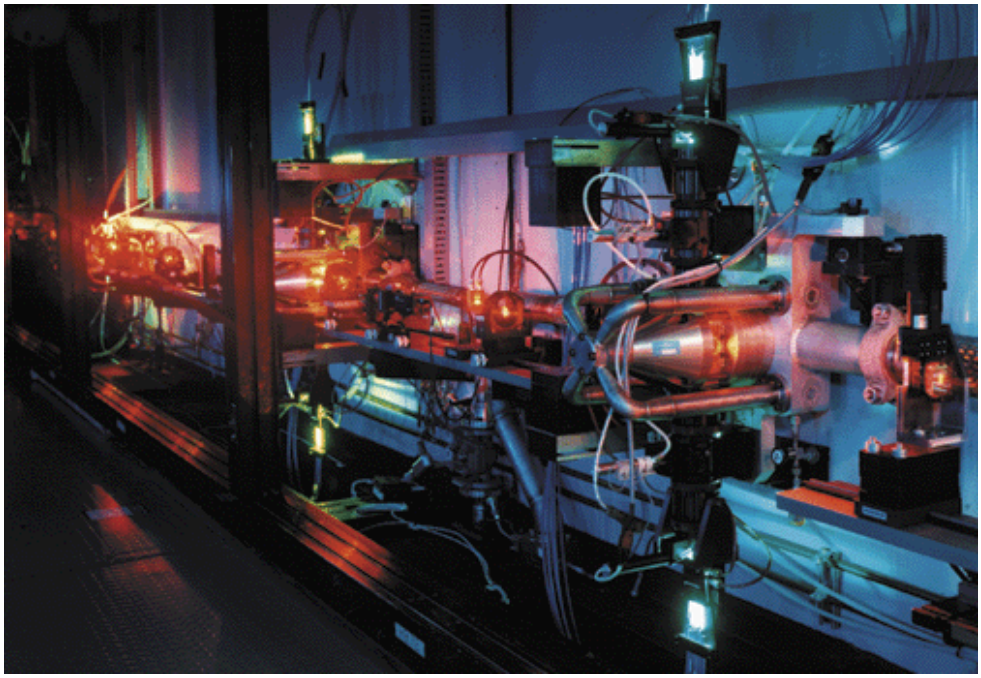

Figure 3.1: These dye lasers were used in the LLNL pilot AVLIS plant

MLIS For MLIS, usually CO_2 lasers are the preferred tool. Although they're not exactly the same as the ubiquitous CO_2 lasers used for cutting and welding, some modifications by qualified technicians might make them suitable.

Domestic construction A proliferating nation might also try to build the laser, instead of buying it abroad. Besides experts in the field of laser, which cannot be tracked using export data, the nation would also need access to components such as:

- Special Power Supplies
- Purification of the lasing media
- Tube-cooling devices
- Heat-resistant glass surfaces
- Laser pumping systems

Figure 3.2: Laser Laboratory at Silex Systems Ltd.

Export Control A possible route for proliferators is purchasing lasers with power levels slightly lower than the limit, to avoid export controls. The assembly of the facility would however be more difficult using these lasers, because of precise synchronisation and calibration requirements.

3.2.4 Electron Gun (AVLIS)

Although strictly speaking, electron gun heating is not necessary for AVLIS, other methods severely reduce efficiency. So unless a nation has uranium to spare, they will try to build or acquire a capable electron gun, possibly under the pretense of titanium recycling or medical applications.

3.2.5 Measurement equipment

The laser enrichment processes require stable narrow bandwidth laser light and quite some fine tuning. Hence, precise measurement equipment is essential. Most of this equipment can be used in various experiments, so it can be bought without raising to much suspicion. Nevertheless, should domestic be considered, required components include:

- Very fast circuitry
- Accurate spectrometers in the applied wavelength
- Power measuring devices

3.2.6 Knowledge and Expertise

With the diffusion of knowledge that is occurring in the related scientific and engineering areas, such as laser construction and set-up, a nation can acquire all the necessary knowledge by sending young scientists abroad to research the necessary topics. These scientists are able to use imported devices, and could produce for example the lasers and electron guns from available materials. Export control will cease to be a conclusive indicator of proliferation intentions. A covert program could possibly only be detected by analysing the research done by scientists and engineers returning to their home nation. Seemingly harmless research topics might, when combined, form a basis for the production of sensitive technologies.

Figure 3.3 gives an overview of the major disciplines encompassed by AVLIS technology.

Copper Lasers and Separators	Process Lasers	Computers, Networks and Controls
Laser/Separation Physics — Plasma physics — Optical saturation — Electromagnetic modeling — System diagnostics — Kinetics **High temperature materials** — Ceramics — Insulations — Refractory materials — Materials diagnostics **Pulsed power** — Switching power supplies — High average power switches — Magnetic compression — Immersion cooling — Circuit modeling **Thermal-mechanical engineering** — Radiative heat transfer — Thermal stress analysis — Integrated thermal/structural design **Vacuum technology**	**Tunable lasers** — Dye chemistry — Dye lasers — Solid state lasers — Kinetics — Photoexcitation and propagation physics — Fluid transport and control systems — Wavelength measurement and control **Optical systems** — Optical coatings — Optics fabrication — Integrated thermal/structural/optical design — Vibration isolation — Fiber optics — Laser beam control and diagnostics **Beam alignment** — Interferometry — Alignment systems — Wavefront control	**Distributed control systems** — Front end processors — Networking — Real-time databases — Computer graphics — Image processing — Safety interlock systems — Diagnostics and analysis **Computer operations and management** — CAD systems — Data analysis — Video and intercom systems — Computer system and network management — Personal computers

Figure 3.3: Major disciplines encompassed by AVLIS technology (taken from Moore et al. [1991])

An rough division of the different disciplines for AVLIS and MLIS is given in table 3.1.

Table 3.1: Disciplines encompassed by AVLIS and MLIS technology

AVLIS	MLIS
Laser science	
High temperature material science	Material science
Optics science	
Alignment and fine tuning	

AVLIS	MLIS
Vacuum technology	
	Flow Science
	Chemistry

Since the spread of knowledge and expertise cannot be measured using export data, it is not included in the Fault Tree. A similar technique based on scientific publications in relevant sectors could be a suitable addition to the technique proposed in this report.

3.2.7 Time Span

In this report a time span of five year is considered for evaluating the export to a certain nation. A time schedule estimated by Silex Systems Ltd., shown in figure 3.4 indicates a construction time of two years for a pilot plant. Purchases might however require some time before the construction phase, in particular in case of a hidden activity. Five years is possibly an overestimation and analyses with other time frames of respectively two, three and four years should be carried out. This has been omitted due to time constraints. However, the programs used for the analysis are flexible for other time spans to be considered.

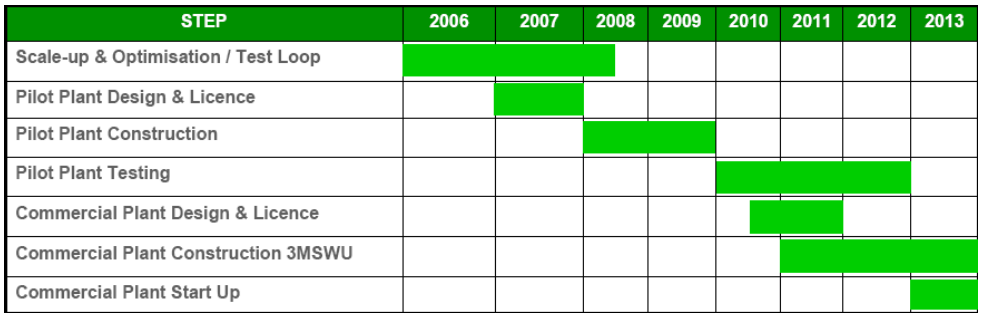

Figure 3.4: Time estimates by Silex Systems Ltd. for the deployment of their technology

3.3 Fault Tree Construction

3.3.1 Detailed Fault Tree

The Fault Tree, see appendix A.2, is constructed by top-down requirements analysis and is used for overview purposes and Minimal Cut Set (MCS) extraction. A Minimal Cut Set is the smallest set of triggers that needs to be true, to have a true Top Event.

The Top Event, laser enrichment, requires either AVLIS or MLIS, hence the OR gate. Because work on AVLIS does not exclude work on MLIS. they are not mutually exclusive events. Therefore, a simple non-exclusive OR gate suffices.

These techniques require certain components, which are all necessary, hence the AND gate. Some components can however be replaced by other components, so instead of a component an OR gate is used, to which these interchangeable components are connected.

MCS are a convenient means for establishing which components are essential, and what the minimum amount of components is.

3.3.2 CN code Fault Tree

In order to use export data in a Fault Tree, the CN codes need to be integrated. The reverse method, i.e. finding CN codes that can be used for a laser facility and integrating them in a Fault Tree, resulted in a tree that is used for analysis, as shown in figures 3.5 and 3.6.

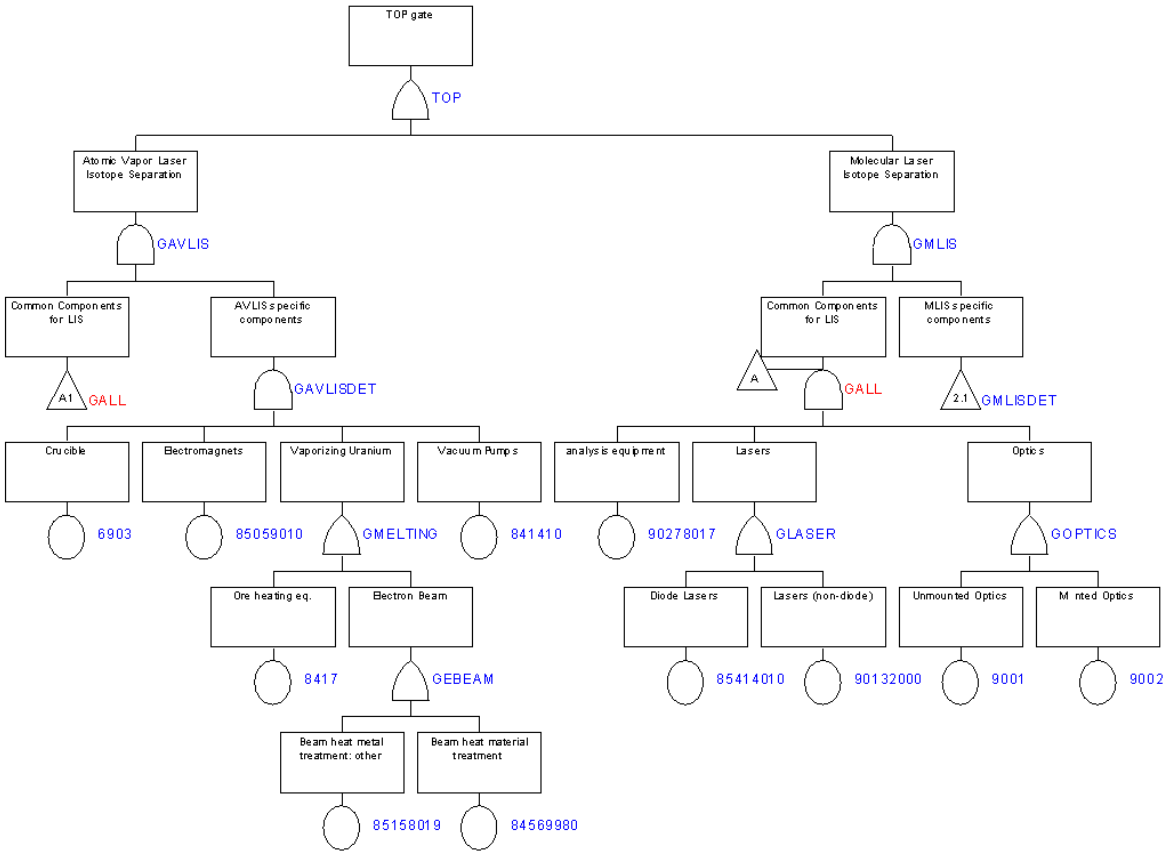

Figure 3.5: Fault Tree used for analysis

The used codes in the Fault Tree correspond with the CN codes. The Fault Tree also features a short description of each code. The Top gate is an OR gate, to which AVLIS and MLIS are connected. They both contain a technique specific gate and a common gate, connected to an AND gate. The CN codes are attached to their function. If more components (more CN codes) can be used for the same function, they are connected to an OR gate.

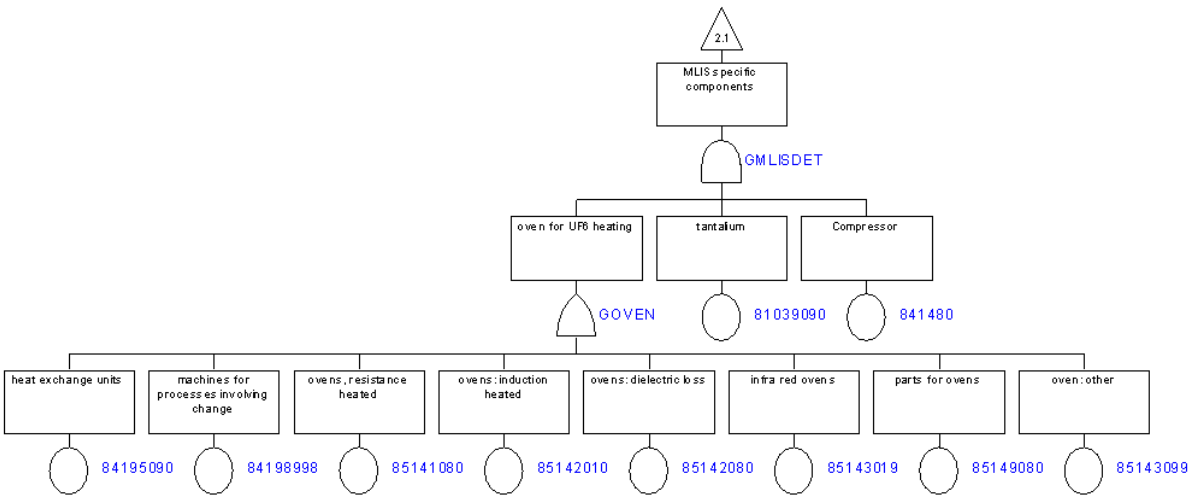

Figure 3.6: Fault Tree used for analysis (continued)

For some of the broader categories certain subcategories are omitted in the data extraction. For a full list refer to appendix A.3.

3.3.3 Assigning Probability Values

Extracting Export Data

The Eurostat website features a query option that allows extraction of import and export data from 1995 till the present. The big queries needed for analysis (export from the European Union (EU) and France and Great Britain, to all nations) require a login, in order to be put on a batch in the server. The result is a csv file with sets of country codes, CN codes, period (yearly) and Indicator Values in Euro.

Conversion to Probability

The starting point of the discussed technique is that the chance a nation can build a laser enrichment facility depends on the fraction of the export of a combination of components to that nation. Using the fault tree, the needed combination of components is worked out with the individual components. If a nation starts to import a series of components or if it suddenly increases the import of those components, then this might indicate that a new economic or scientific activity is started up. The steady continuation of imported components indicates the maintenance of the ongoing economic activities. A steady increase of imported components might indicate the expansion of the economic activities.

The import of components can be monitored either with the cumulative distribution of those components or with the time evolution over given time intervals. The distribution of imported components, cumulated in time can be used with a certain threshold for raising an alarm when the critical threshold for building an enrichment facility has been exceeded. However the threshold level is directly coupled to the false alarm probability, since those components can also be used for other activities.

With the time evolution of the imported components a strange behaviour in import can be seen, by distinghuising a sudden purchase from the normal growth in import. The time frame has to be chosen appropriately. A purchase over several years was anticipated and the construction time of a pilot plant over at least two years was considered. The length of the time frame was arbitrarily set to five years. This time is an overestimation but it was assumed to average out the time evolution signal that for time frames of consecutive single years was assumed to show a noisy behaviour. It was seen that the averaging was still indicating the trends, but as discussed in section 3.2.7, a more appropriate smaller time frame of 2, 3 or 4 years should be analysed.

The probability for each component was obtained as the ratio of the export of this component to the nation over the chosen five year time frame by the export of this component to all nation categories during the same five year period. This probability is an indication of the risk of diversion of that component during those five years in that nation. The resulting values of all these components are set as probabilities in the Fault Tree, and the resulting top event probability gives an indication of the risk a nation is equipped and able to potentially setup a new laser enrichment plant. These values are obviously higher for highly industrialised nations, but changes in the resulting value for a certain nation can also serve as an indication. For a more detailed analysis of the significance of the resulting top event probability, refer to section 4.1.

Calculating and Assigning Values

The ASTRA code requires an input file in the form of a ".tfx" file, in which the single probabilities for the different events are set. Making use of the Matlab[1] program, a code module, called "toastra.m", was developed to generate this ".tfx" file automatically, containing the Fault Tree and all necessary data for the different analyses with the five year time frame.

A variant code module, "toastra1.m", was also run in a second step for the analyses with the one year time frame. More details on the code module "toastra.m" can be found in appendix B.1.1.

Various cases for different nations have been run in batch mode, making use of the "makebatch.m", that calls the "formastra.m" module in a loop and that creates a batch file for ASTRA and delivers all necessary ".tfx" files to ASTRA with the "toastra.m" module. Refer to appendix B.1.2 for more details on this procedure.

Data Extraction and Plotting

For each Fault Tree, ASTRA creates an output file (.dpl). The large amount of output data were treated with a help tool, that consists of the code modules "fromastra.m" and "impfromastra.m" for extracting the results; and "topevents.m", "importances.m" and "countryanalysis.m" for displaying them.

Top Event Probability The Top Event probability is the main result of the Fault Tree analysis and will be discussed thoroughly in section 4.1. The programs "topevents.m",

[1]Matlab is a program and a high-level programming language, developed by The MathWorks, Inc.

"fromastra.m" and "countryanalysis.m" extract and plot these data in an automated way. Refer to appendix B.2.1, B.2.2 and B.2.3 for more information on these programs.

Importances The importance of the various components or events in the Fault Tree is also calculated in ASTRA. This importance or criticality index (Ic) of a certain component expresses the relative variation of the Top Event probability caused by the relative variation of this components probability. Roughly this means that if you modify the component's probability by x%, the variation of the probability of the top event is about Ic x%. The programs "impfromastra.m" and "importances.m", used for these calculations and its output, are described in appendix B.2.4 and B.2.5.

World Export Evolution The variation of the export over the considered time spans could be used to explain possible general increases or decreases in the Top Event Values. Another set of programs, "worldtotal.m" and "worldevolution.m" obtain and visualise these evolutions. They can be found in appendix B.2.6 and B.2.7. Some modifications in this program allowed its use for analysis of the components export evolution to individual nations.

France and Great Britain

It was considered interesting to check the Nuclear Weapons States (NWS) separately. That is why all relevant programs have a counterpart for France and Great Britain, noted with the letters frgb in front of the program name.

Chapter 4

Result Analysis

4.1 Nation Analysis

4.1.1 General Analysis

Focus

The object of this study is to find indicators for the covert construction of a laser enrichment facility. When looking at graphs of Fault Tree probabilities, some major differences between certain nations become apparent. Highly industrialised nations have a Top Event value that is several orders of magnitude larger than that of less industrialised nations. In this study it is assumed that the probability of diversion of certain series of components is proportional to the fraction of the world export to the investigated nation (as calculated in section 3.3.3). The probability that a highly industialised nation can covertly build a laser enrichment facility is, according to this study, higher than the probability for a less industrialised nation. This makes sense, since these nations could probably divert the necessary materials more easily, should they want to.

Therefore, this study focuses on anomalies in import behaviour and detects deviations from ordinary behaviour as present at most neighboring nations. If a nation suddenly has a much higher Top Event value, this would mean that its import of the combination of components necessary for a laser enrichment facility has increased, and thus also the probability that they could covertly construct such a facility. In the following sections, the Top Event values for some groups of nations are displayed.

As explained in section 3.3.3, the absolute minimum required, for which cumulative distributions and thresholds have to be introduced, was not part of the analysis in this thesis work.

Europe

In figure 4.1 the five year Top Event Values for some European nations are displayed. The values are relatively high, which can be expected due to the high level of industrialisation of these nations, and the fact that our data only considers export from European nations.

While high, the values remain relatively constant. Even if one of these nations was developing a covert laser enrichment facility during a certain period, distinguishing this

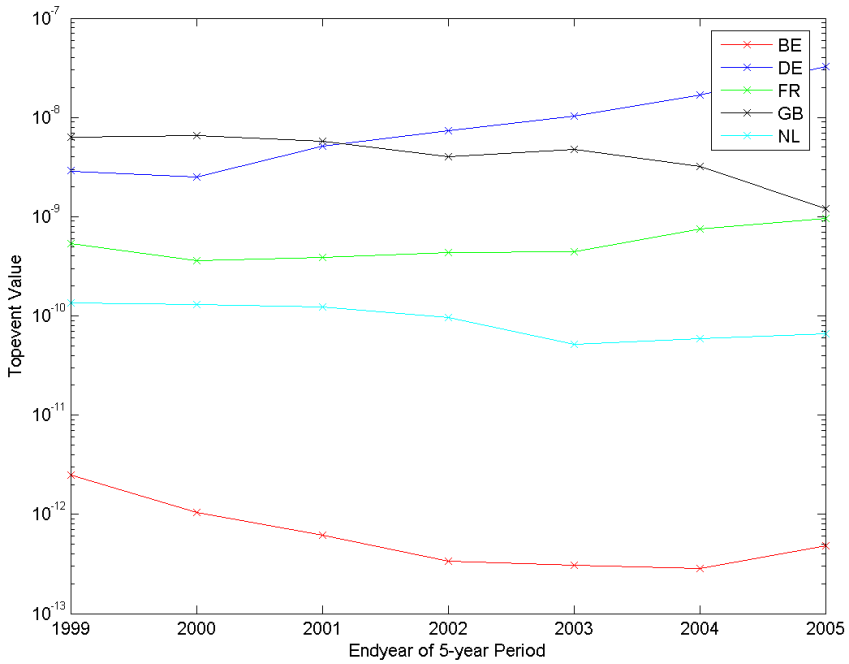

Figure 4.1: Top Event value evolution for Belgium (BE), Germany (DE), France (FR), Great Britain (GB) and The Netherlands (NL)

in figure 4.1 would probably be impossible, since the diversion possibility of the necessary components in these nations is, according to our study, constantly among the highest.

Total External Export and the United States

In figure 4.2 the Top Event Value evolution for export to all non-European nations and for export to the USA is displayed. A high and constant pattern is recognised.

Other Industrialised Western Nations

Figure 4.3, shows the evolution for some other industrialised western nations. The change does not exceed one order of magnitude.

Middle East

Figure 4.4 shows a fairly constant Top Event probability for the countries Egypt (EG), Saudi Arabia (SA), Syria (SY) and Qatar (QA). Iran (IR) and Iraq(IQ) display a sudden increase in the time period 1997-2001 versus 1996-2002, but no decrease after that. In section 4.1.2 this will be investigated in some more detail. The decrease of Kuwait's Top Event Value in the time period 1996-2000 versus 1995-1999 suggests an economical recession that can be due to the second Gulf war in Kuwait, of which the nation was still recovering.

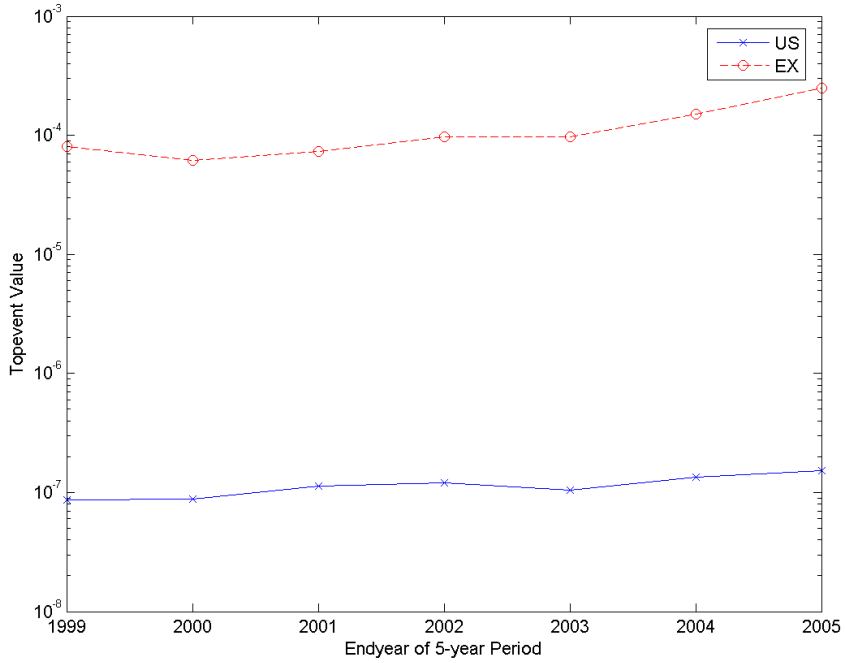

Figure 4.2: Top Event value evolution for all export to non-European nations (EX) and the USA (US)

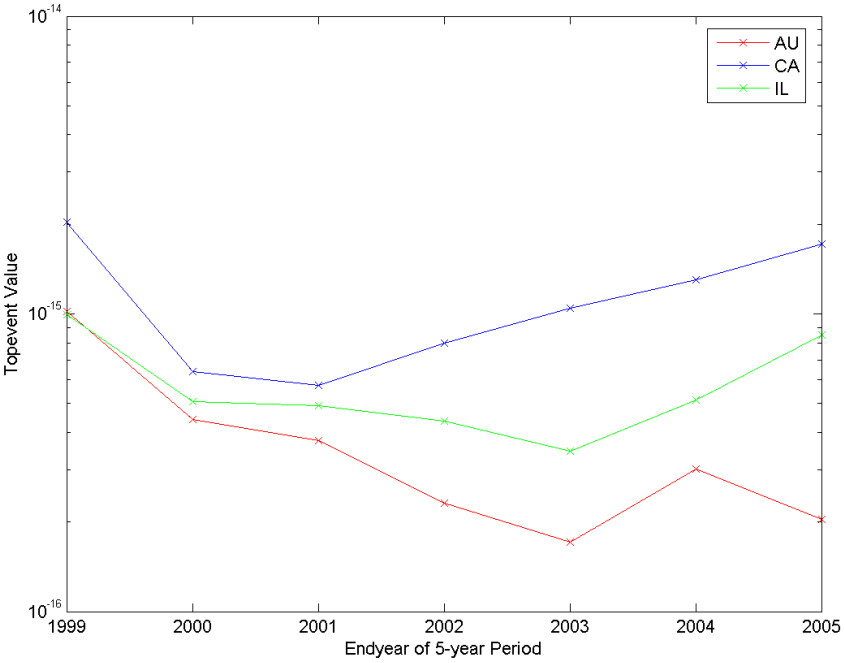

Figure 4.3: Top Event value evolution for Australia (AU), Canada (CA) and Israel (IL)

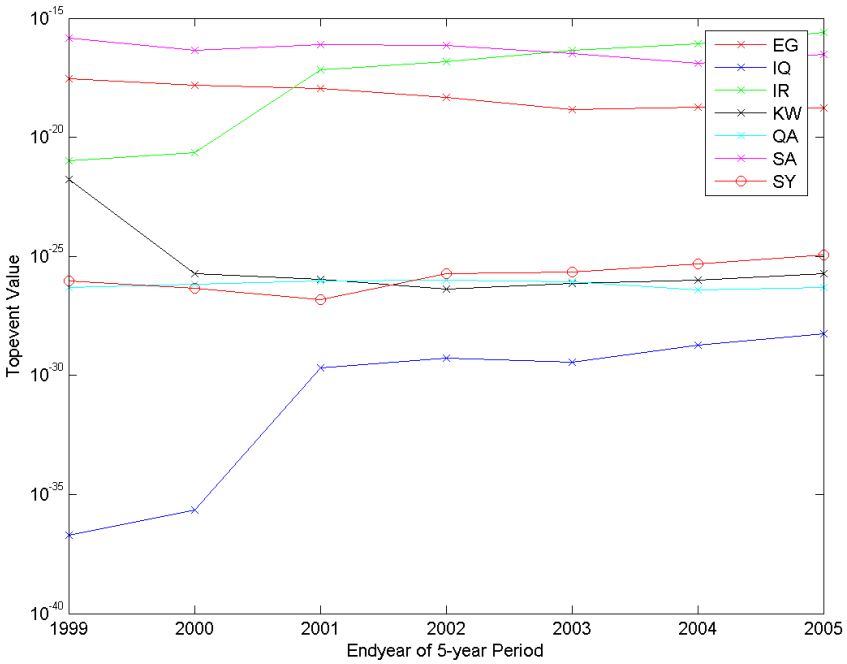

Figure 4.4: Top Event value evolution for Egypt (EG), Iraq (IQ), Iran (IR), Kuwait (KW), Qatar (QA), Saoudi Arabia (SA) and Syria (SY)

Asia

Figure 4.5 represents the time evolution for the Asian nations Kazakhstan (KZ), North Korea (KP), South Korea (KR) and India (IN). Except for Kazakhstan an almost constant Top Event probability is observed, indicating a steady state import, suggesting a stable related economy and trade.

Kazakhstan (KZ) seems to follow a similar pattern as Iran and Iraq, and will be discussed in section 4.1.2.

South America

In Figure 4.6 the Top Event value evolutions for some selected South American nations, Argentina (AR), Brazil (BR), and Venezuela (VE) are displayed. The time evolution show a fairly constant profile with a relative small decrease, in particular for Brazil in 2001. This might be related with an economic crisis around 2001 and disputes with the IMF and World Bank.

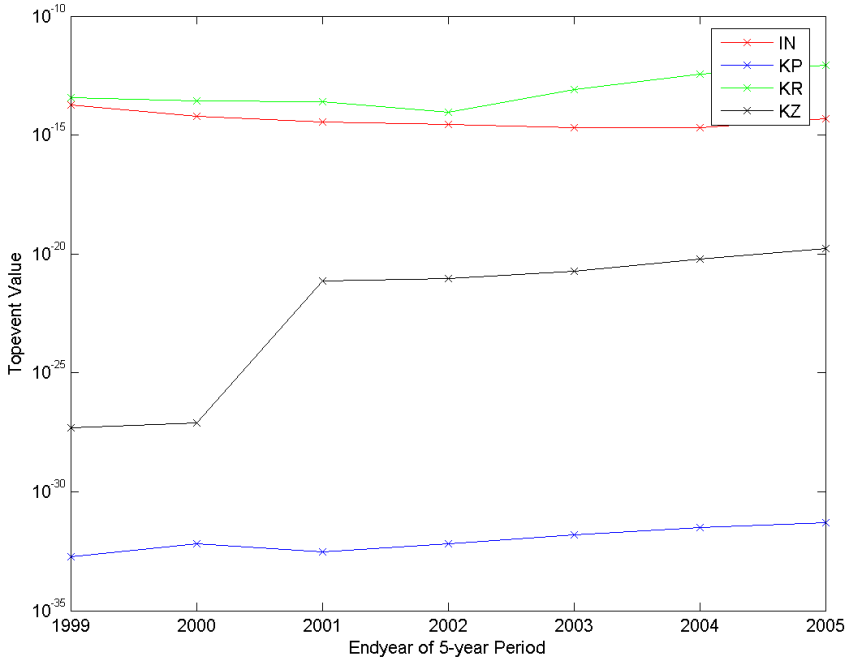

Figure 4.5: Top Event value evolution for India (IN), North Korea (KP), South Korea (KR) and Kazakhstan (KZ)

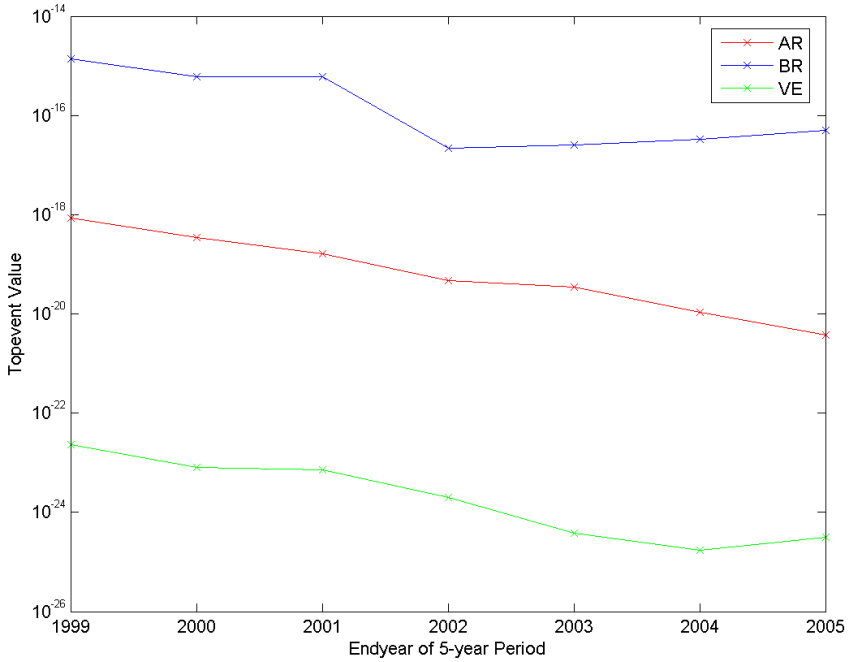

Figure 4.6: Top Event value evolution for Argentina (AR), Brazil (BR) and Venezuela (VE)

4.1.2 Detailed Analysis of Iran, Iraq and Kazakhstan

Five year period

In the previous figures 4.4 and 4.5, Iran (IR), Iraq (IQ), and Kazakhstan (KZ) show a sudden rise in import and are therefore selected for a more detailed analysis. In figure 4.7 the Top Event value due to export from the entire European Union (EU) is displayed along with export from only France and Great Britain, the Nuclear Weapons States, noted with the letters 'FG'. The trend is clearly visible in both cases.

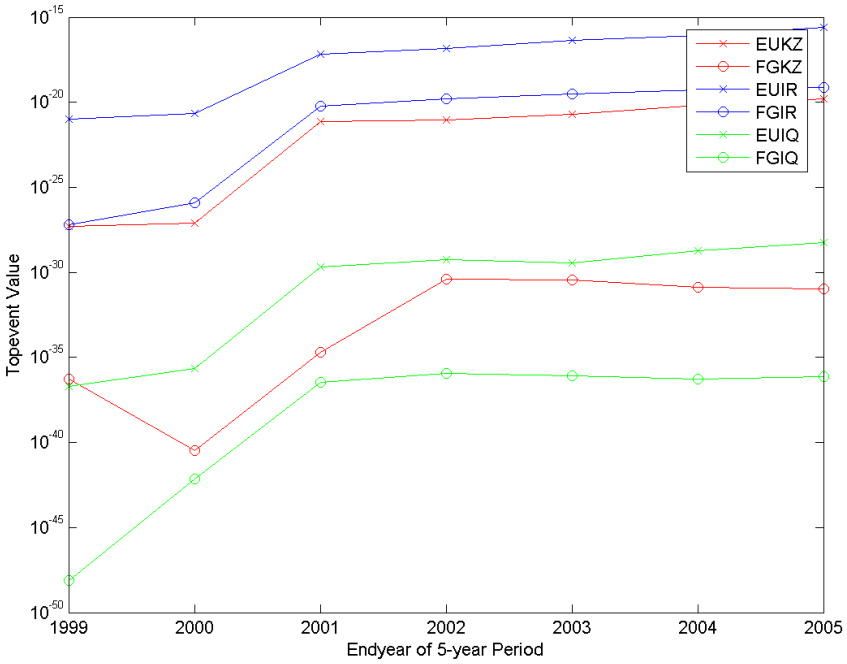

Figure 4.7: Top Event value (using both export from France and Great Britain (FG) and whole EU): evolution for Iran (IR), Iraq (IQ) and Kazakhstan (KZ), five year periods

All five year periods ending later than 2001 show a higher Top Event value, because of the substantial increment in 2001 on the almost constant import value for the other years, as schematically explained in figure 4.8. To indicate an anomaly in import for the combination of relevant components, it is desired to follow the behaviour with a smaller time frame. Using small consecutive time periods (e.g. of one year) that are not smoothed by taking an overlapping average are expected to show an increase and then a decrease, indicating clearly the event at a certain time.

One year period

Using a one year time period does not give reliable Top Event values, since it assumes the components for the facility were bought in one year, hence the much lower values. It is however a good way to discover peaks in activity.

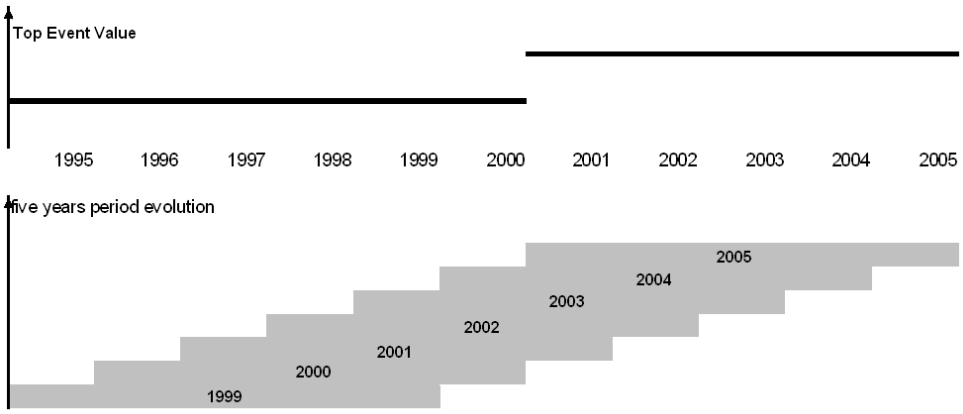

Figure 4.8: Representation of which five year periods contain the year 2001

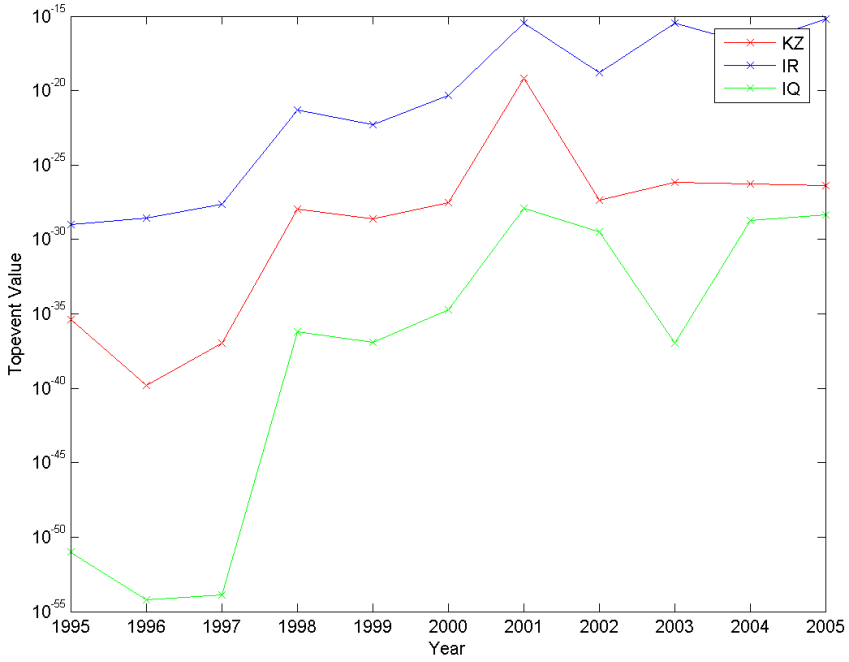

Figure 4.9: Top Event value evolution for Iran, Iraq and Kazakhstan, using one year periods

There is, as could be expected, a peak in 2001 and much lower values before 1997. Going from a one year period to a five year period is not simply adding the values up, since combinations can occur over more than one year, but the main points can be recognised.

The Iraqi war causes a distinct fall in the Iraqi Top Event Value. Its recovery could indicate the reconstruction of the industry that caused the original rise. The fact that this occurs under a different government does not exclude that the initial purpose of this industry was the diversion of components to a laser enrichment facility.

Components

In figures 4.10, 4.11 and 4.12, the relative evolution of all components in the Fault Tree is displayed for the respective nations. While there are some distinct peaks, these are not related to the peak in 1997-2001's Top Event Value, since they occur later in time. The description of the used codes can be found in table A.1 of appendix A.3.

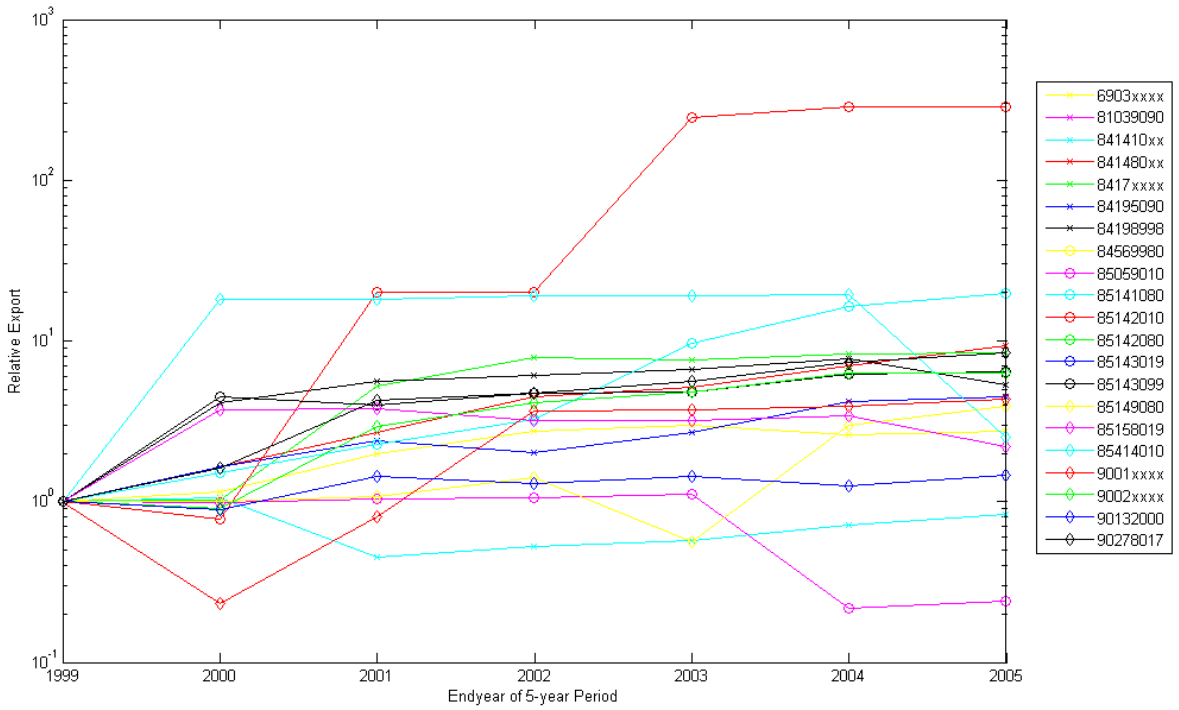

Figure 4.10: Export to Iran: evolution for all components, relative to the first five year period

A sudden increase does not have to occur simultaneously for all components. A change in import behaviour, preferring other components should trigger an early warning for the inspector. This is counted for in section 4.3.3 by considering a change in importance of the imported components.

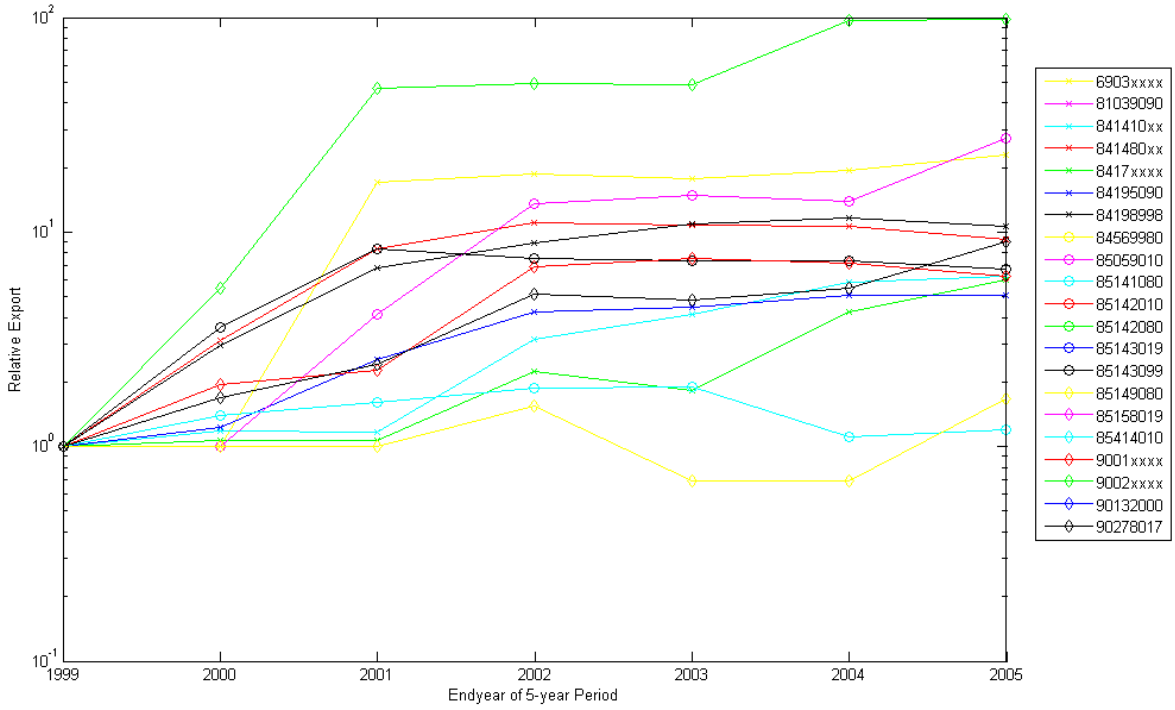

Figure 4.11: Export to Iraq: evolution for all components, relative to the first five year period

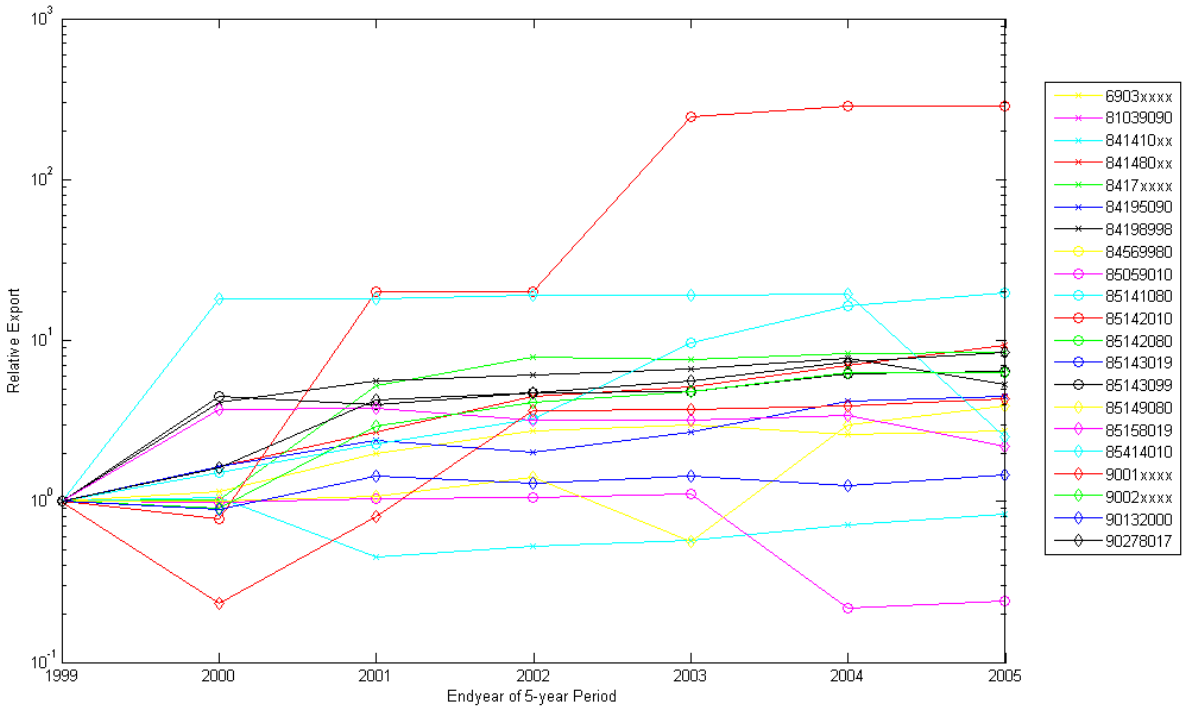

Figure 4.12: Export to Kazakhstan: evolution for all components, relative to the first five year period

4.2 Scenario Analysis

4.2.1 Crisis

Worldwide Economical Crisis

An economical crisis affects export and thus potentially the results. If the crisis is worldwide, than export to all nations drops, so also the cumulated export. The values used in this study are expressed in fractions of the total export, so if all decreases equally, nothing changes. However, an economical crisis could cause shifts in economical dominance, which would affect the Top Event values. These considerations could explain the behavior for some nations in the year 2001, when there was an economical crisis.

Regional Economical Crisis

When the economical crisis occurs in only one or a few nations, their fraction of total import decreases, affecting the Top Event value. The Top Event values for the exporting countries only change when the decrease in export to the affected countries cause a noticeable change in total export and when this decrease is not compensated by an increase to other importing countries.

Conflict

International conflicts can disrupt export to involved nations. Embargoes can be imposed or war could destroy the infrastructure of the nations. If embargoes are imposed on components in the Fault Tree, this has an effect on the Top Event value. War reduces export to the involved nations, except maybe of war related components, due to the destruction of normal industrial activity. The Top Event value decreases in these circumstances.

4.2.2 Laser Based Activities

If a nation starts a non-enrichment laser activity, the laser export to that nation increases. The Top Event value depends on this export, but also on the export of other components in the Tree to this nation. The Top Event value increases more if a nation imports larger quantities of the for enrichment required combinations of components. Changes in the Top Event values are therefore normal, making only larger changes a real indicator on which this study focuses.

4.3 Validation of Methodology

4.3.1 Top Event Probability

The Top Event value is the resulting probability due to a combination of event probabilities in the Fault Tree. The ease at which a nation can potentially divert a combination of components for undeclared use is considered proportional to the fraction of the world export of those components to this nation. This fraction is seen as a probability. The

resulting Top Event Value is considered to be a probabilistic indication of the ease at which this nation was able to acquire the components needed for constructing a laser enrichment facility. In this study, sudden changes are tracked, since they indicate a change in the possibilities for that nation. Sudden changes are more common in nations to which few components are exported, since small changes have large relative consequences. This technique is aimed to be an extra inspection tool that evaluates a selected combination of open source information.

4.3.2 World Export Evolution

The calculated probability is based on the fraction of the world export to a certain nation. This evens out effects of a global increase or decrease in demand for that component. To rule out all effects of variations for certain components, the export over all nation categories during five years periods is analysed and displayed in figure 4.13.

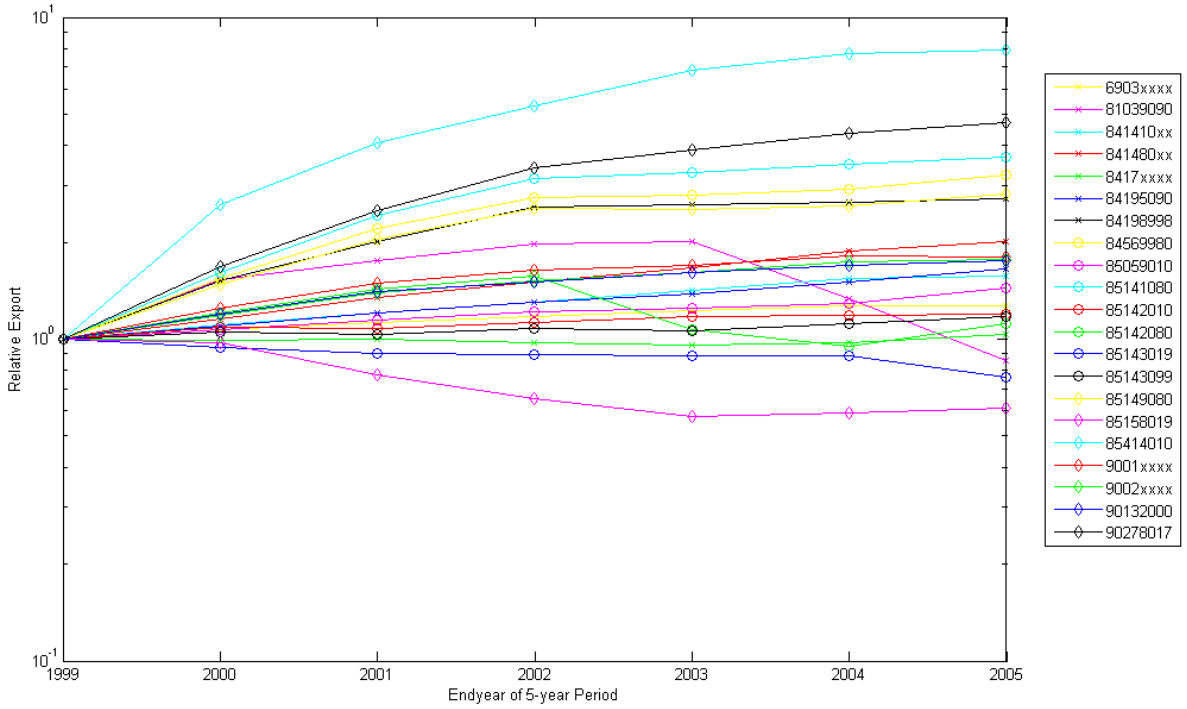

Figure 4.13: Total export: evolution for all components, relative to the first five year period

The changes in world-wide demand for the analysed components are showing a normal economic growth and are keeping the Top Event Value in the same order of magnitude. The changing world-wide demand for the analysed components does not distort the results.

4.3.3 Critical and Essential Components

In order to efficiently monitor the change in import behaviour of the components needed for laser enrichment, it is important to select a limited number of components that are most critical or essential. Both properties are derived by evaluating the criticality index of the various components and the Minimal Cut Sets (MCS) of the combination of components in the Fault Tree.

Criticality Index

The criticality index (Ic) of a certain component as defined in the ASTRA code expresses the relative variation of the Top Event probability caused by the relative variation of this components probability. The criticality index is higher for components that are more critical with an "AND" gate coupled in the Fault Tree. However more important is the change in criticality index for components that are coupled in the Fault Tree with an "OR" gate. If their criticality index change, this indicates that the nation tends to prefer another component/ technique. This might suggest that the activity with the components is changing in that nation.

In figure 4.14 the evolution of the importances for the export to outside the European Union is displayed. As expected for such a large group, there are no extreme evolutions, since this would require a change on a world scale.

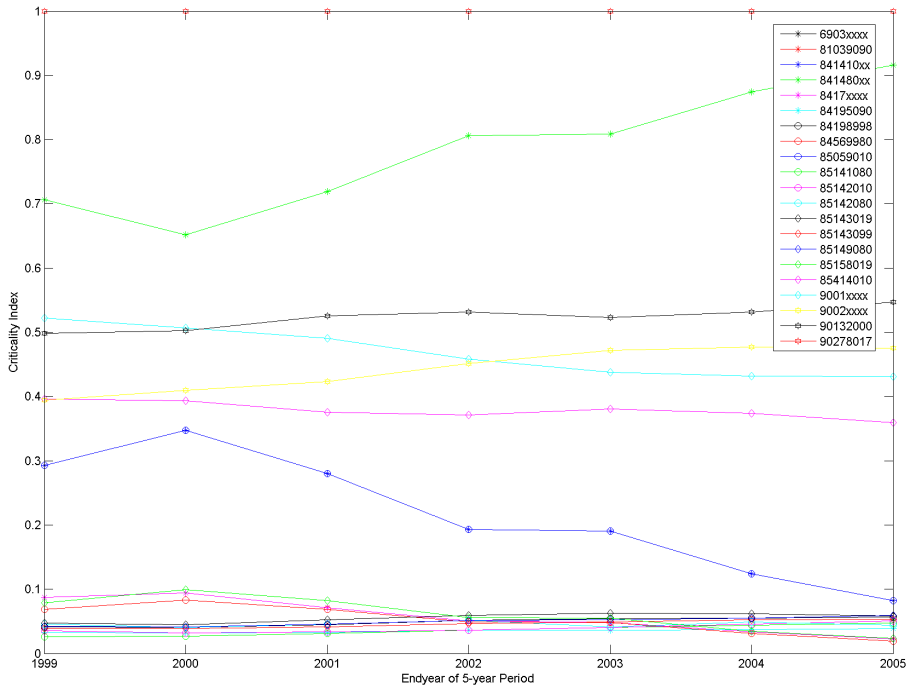

Figure 4.14: Criticality index for export outside the EU: evolution for all components

A sudden increase does not have to occur simultaneously for all components. A change

in import behavior can trigger abrupt changes in importances, as can be seen in figures 4.15, 4.16 and 4.17, that display the criticality index. Changes in the criticality index for a nation can be a guidance for inspectors.

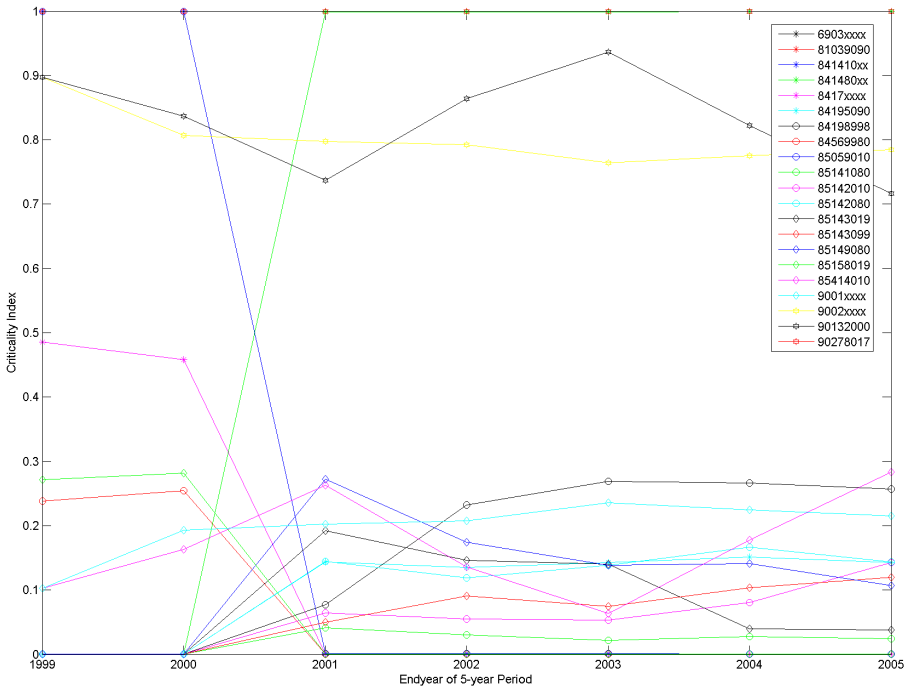

Figure 4.15: Criticality index for Iran: evolution for all components

Minimal Cut Sets

The criticality index depends greatly on the component's place in the Fault Tree. A component that is coupled in the Fault Tree with an "AND" gate has a higher criticality index than the same component at an "OR" gate to which more components are connected for an alternative possibility.

Exactly how "essential" a component is, is determined by extracting the Minimal Cut Sets (MCS). These MCS are the minimal combinations of basic events necessary for the top event to occur. The qualitative analysis (also called Logical Analysis) aims at determining the minimum system's failure modes, based on the by ASTRA suggested Binary Decision Diagrams approach. The order of a MCS is equal to the number of basic events that are part of the MCS. As indicated in table A.2 of appendix A.4 a total of 44 MCS were extracted for the Fault Tree used in the analysis.

Indicators

The minimal cut sets and criticality indexes indicate that component 90278017, analysis equipment, is most critical and essential. It is needed in all setups, but is also among

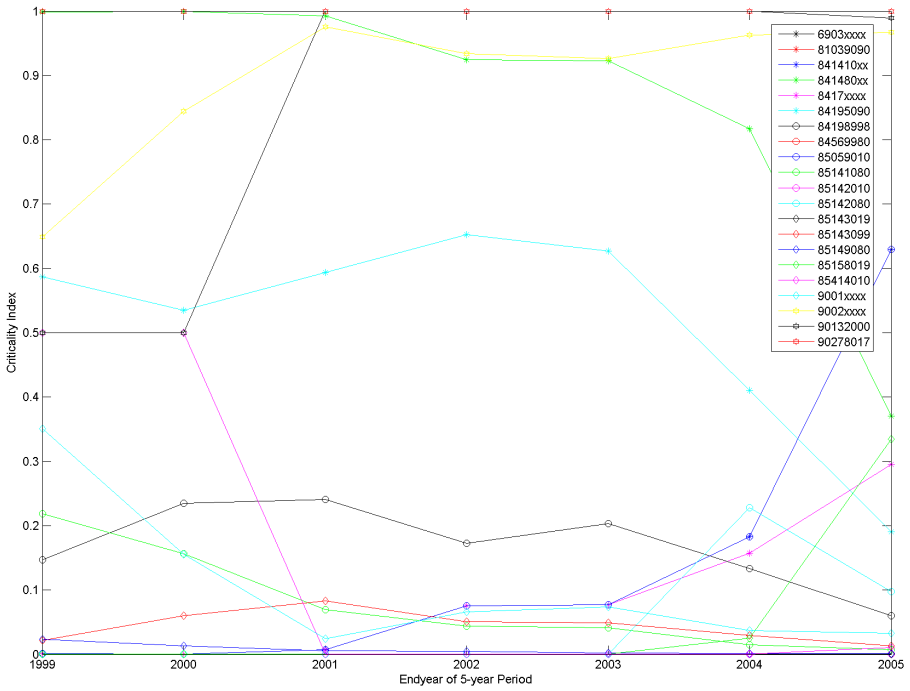

Figure 4.16: Criticality index for Iraq: evolution for all components

the most common components in the Fault Tree. Other components with high criticality indexes are, in order of criticality: compressors (841480), non-diode lasers (90132000), unmounted and mounted optics (9001 and 9002), diode lasers (85414010), compressors (841410) and electromagnets (85059010). Their occurance in the MCS in table A.2 of appendix A.4 confirms their relative necessities.

As for the Top Event probabilities, the relative change of the criticality index is an indicator, not the absolute value.

4.3.4 Comparison amongst Nations

The most conclusive evidence that abrupt changes in the Top Event value are indeed due to a change in capability to construct a laser enrichment facility is that this value remains constant for most nations, while it can be assumed that these nations are not all trying to build a covert laser enrichment facility.

The sudden changes in some nations can indicate an intention to divert the necessary components for a laser enrichment facility, but gives in no way an evidence of this hypothesis.

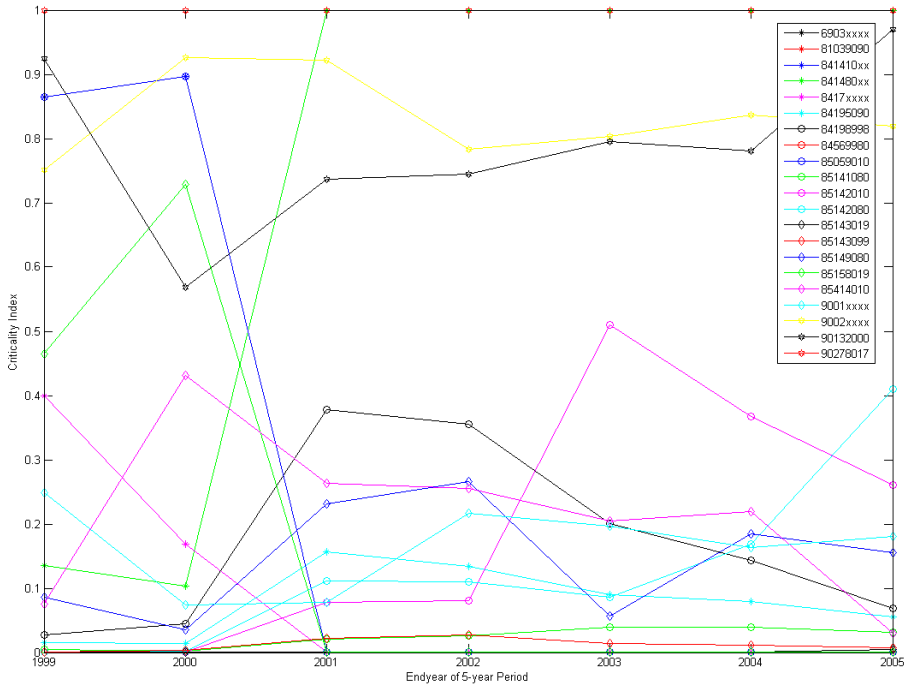

Figure 4.17: Criticality index for Kazakhstan: evolution for all components

Chapter 5

Conclusion

Under the Non-Proliferation Treaty and the Additional Protocol, a whole set of Safeguards Measures exists to prevent the misuse of nuclear materials and nuclear technologies for military applications. Laser Isotope Separation is of particular concern because of its small size and fewer components required, making it easier to conceal a facility.

This work proposes a technique for relating import/export data to proliferation sensitivity. Export data of dual-list components and accessories are converted to probabilities for use in a Fault Tree, after which the ASTRA code detects a deviation in import behaviour of a given nation for sensitive components. The import statistics are monitored in an efficient way by evaluating the change in import of a combination of sensitive components and raise a flag when an anomaly in the signal is detected. This study focuses on laser enrichment facilities but the technique can be applied to other proliferation sensitive industries, such as centrifuge technology. The developed programs require only minor changes to work with other sets of components and Fault Trees.

The relevant components for constructing a laser enrichment facility are determined from open literature. Those components are grouped based on their corresponding Combined Nomenclature (CN) codes descriptions in import/export statistics reported by the Customs. The resulting groups of components are integrated in a Fault Tree of which failure of the Top Event corresponds with all necessary components being imported.

The ASTRA code, which is used for Fault Tree Analysis bases its analysis on the probability of acquired components components. For proliferation sensitivity those probabilities are related to export data. The probability value is determined by dividing cumulated export values of all components for all nations by the sum over all nation categories. Data are available from 1995 on because since then export data are being monitored and released by Eurostat.

After analysis of five year time frames for different sets of data from the 1995-1999 period in 7 steps to the 2001-2005 period, ASTRA returns Top Event probabilities. The analysis of the time evolution of the probabilities for a given nation monitors each change in infrastructure that could be of potential use for laser enrichment.

In most of the cases, the analysis results in constant Top Event probabilities of which the value is closely related to the level of industrialisation. In addition, it is observed that the values that are associated with trade partners of the European Union are systematically higher because the imported data are based on European export values. The Top

Event value for some selected nations in the Middle East and Central Asia changed since 2001 with regard to the type and amount of imported components. To analyse the significant increment in import signal for those countries, an additional time evolution with consecutive years was analysed. The smaller time period of one year clearly indicated a peak in 2001, suggesting a temporary change in import behaviour. A hypothetical cause can be the general economical recession for most exporting countries and so a change in the world trade, but other causes are not excluded.

Another feature of this analysis tool is the determination of the critical and essential components with the ASTRA code. Both properties can be monitored by using two indicators: the criticality index (Ic) and the minimal cut sets (MCS).

The criticality index of a certain component expresses the relative variation of the Top Event probability caused by the relative variation of this components probability. The relative change in index value is a meaningful help to identify those components that are important for the construction of a laser enrichment plant in the analysed nation.

The second indicator, the Minimal Cut Sets (MCS) are the minimal combinations of basic events necessary for the top event to occur and lists the most essential components. The logic analysis of MCS indicates that the laser analysis equipment and the vacuum pumps are most critical. They are needed in all setups, but are also among the most common components in the Fault Tree.

For the total export to outside the EU, the criticality index remained fairly constant for all components, indicating few or no changes in the European export behavior. For the nations with a temporary anomaly in Top Event probability however, also the criticality index shows significant changes.

The probabilistic sensitivity analysis should be further extended, to investigate the influence of some parameters and the different factors that cause an anomaly. One arbitrarily chosen parameter is the width of the time frame, set initially to five years.

Five year periods show a meaningful evolution and can be used for a first assessment of the import behaviour in the available time span from 1995-2005. No complete overview can be obtained from the monotonic behaviour of the time evolution. It might be assumed that other widths of monitoring time frames, respectively two, three and four years, should be applied to derive the most appropriate time interval. In addition it would be opportune to obtain for non-EU countries the same export details as was available from the EU import/export statistics.

In order to account for the impact of different factors on the analysis, several scenarios should be worked out. The probabilistic assessment as such so far can not account for embargoes, countries independence, countries' development skills and economic crisis.

To make this technique functional as a valuable early warning system for inspectors, it is needed to monitor in parallel cumulative distribution of imported components and to introduce a threshold. The threshold value should result from a study on the minimal required size of a laser facility for enriching in a heavy isotope (U). The critical size of a laser enrichment activity is not investigated in this study but is specific for each laser technique separately, which complicates the derivation of a single minimum threshold. Moreover the threshold value may not lead with high probability to false alarms.

Appendices

Appendix A

Components Listings

A.1 IAEA

In revision 8, part 1 of Information Circular (INFCIRC) 254 of the International Atomic Energy Agency (IAEA), section 5.7 deals with laser enrichment:

- 5.7.1 Uranium vaporization system (AVLIS)
- 5.7.2 Liquid uranium metal handling systems (AVLIS)
- 5.7.3. Uranium metal 'product' and 'tails' collector assemblies (AVLIS)
- 5.7.4. Separator module housings (AVLIS)
- 5.7.5. Supersonic expansion nozzles (MLIS)
- 5.7.6. Uranium pentafluoride product collectors (MLIS)
- 5.7.7. UF6/carrier gas compressors (MLIS)
- 5.7.8. Rotary shaft seals (MLIS)
- 5.7.9. Fluorination systems (MLIS)
- 5.7.10. UF6 mass spectrometers/ion sources (MLIS)
- 5.7.11. Feed systems/product and tails withdrawal systems (MLIS)
- 5.7.12. UF6/carrier gas separation systems (MLIS)
- 5.7.13. Laser Systems (AVLIS, MLIS and CRISLA)

Part 2 of INFCIRC/254 (revision 7) contains the dual use items. Using section 2.2, the following components were identified as components of a laser enrichment facility:

- 1.B.4. Controlled atmosphere induction furnaces, and power supplies therefore

- 1.B.7. Vacuum or other controlled atmosphere metallurgical melting and casting furnaces and related equipment
- 2.A.1. Crucibles made of materials resistant to liquid actinide metals
- 2.C.6. Chlorine trifluoride
- 3.A.2. Lasers, laser amplifiers and oscillators
- 3.A.3. Valves
- 3.A.4. Superconducting solenoidal electromagnets
- 3.A.5 High-power direct current power supplies
- 3.A.6. High-voltage direct current power supplies
- 3.A.7. Pressure transducers
- 3.A.8. Vacuum pumps
- 4.A.3. Turboexpanders or turboexpander-compressor sets

A.2 Detailed Fault Tree

The following Fault Tree was constructed using data from section 2.2, and was used for Minimal Cut Set extraction and for overview purposes. It is too detailed for use with the broad export data categories in the CN codes.

A.3 CN Codes Descriptions

Table A.1 contains the description of CN codes used in the Fault Tree.

Table A.1: CN Codes Descriptions

CN code	Description
69031000	RETORTS, CRUCIBLES, MUFFLERS, NOZZLES, PLUGS, SUPPORTS, CUPELS, TUBES, PIPES, SHEATHS, RODS AND OTHER REFRACTORY CERAMIC GOODS, CONTAINING, BY WEIGHT, $\geq$ 50% GRAPHITE, OTHER CARBON OR A MIXTURE THEREOF (EXCL. REFRACTORY BRICKS, BLOCKS, TILES AND SIMILAR REFRACTORY CERAMIC CONSTRUCTIONAL GOODS)
69032010	RETORTS, CRUCIBLES, MUFFLERS, NOZZLES, PLUGS, SUPPORTS, CUPELS, TUBES, PIPES, SHEATHS, RODS AND OTHER REFRACTORY CERAMIC GOODS, CONTAINING, BY WEIGHT, $\leq$ 45% OF ALUMINA AND $\geq$ 50% OF SILICA (EXCL. REFRACTORY BRICKS, BLOCKS, TILES AND SIMILAR REFRACTORY CERAMIC CONSTRUCTIONAL GOODS)

Table A.1: CN Codes Descriptions

CN code	Description
69032090	RETORTS, CRUCIBLES, MUFFLERS, NOZZLES, PLUGS, SUPPORTS, CUPELS, TUBES, PIPES, SHEATHS, RODS AND OTHER REFRACTORY CERAMIC GOODS, CONTAINING, BY WEIGHT, $\geq$ 45% OF ALUMINA AND $\geq$ 50% OF SILICA (EXCL. REFRACTORY BRICKS, BLOCKS, TILES AND SIMILAR REFRACTORY CERAMIC CONSTRUCTIONAL GOODS)
69039010	RETORTS, CRUCIBLES, MUFFLERS, NOZZLES, PLUGS, SUPPORTS, CUPELS, TUBES, PIPES, SHEATHS, RODS AND OTHER REFRACTORY CERAMIC GOODS, CONTAINING, BY WEIGHT, $\geq$ 25 % BUT $=\leq$ 50% OF GRAPHITE OR OTHER FORMS OF CARBON OR OF A MIXTURE OF THESE PRODUCTS (EXCL. REFRACTORY BRICKS, BLOCKS, TILES AND SIMILAR REFRACTORY CERAMIC CONSTRUCTIONAL GOODS, AND THOSE CONTAINING $\geq$ 50 % BY WEIGHT OF ALUMINA ALONE OR MIXED WITH SILICA)
69039020	RETORTS, CRUCIBLES, MUFFLERS, NOZZLES, PLUGS, SUPPORTS, CUPELS, TUBES, PIPES, SHEATHS, RODS AND OTHER REFRACTORY CERAMIC GOODS, CONTAINING BY WEIGHT, SINGLY OR TOGETHER, $\leq$ 50% OF THE ELEMENTS MG, CA OR CR, EXPRESSED AS MGO, CAO OR CR2O3 (EXCL. REFRACTORY BRICKS, BLOCKS, TILES AND SIMILAR REFRACTORY CERAMIC CONSTRUCTIONAL GOODS)
69039080	RETORTS, CRUCIBLES, MUFFLERS, NOZZLES, PLUGS, SUPPORTS, CUPELS, TUBES, PIPES, SHEATHS, RODS AND OTHER REFRACTORY CERAMIC GOODS (EXCL. THOSE OF SILICEOUS FOSSIL MEALS OR OF SIMILAR SILICEOUS EARTHS, ARTICLES OF HEADING 6902, ARTICLES CONTAINING CARBON, ALUMINA, SILICA, OR THE ELEMENTS MG, CA OR CR OF SUBHEADING 6903.10.00 TO 6903.90.20)
69039090	RETORTS, CRUCIBLES, MUFFLERS, NOZZLES, PLUGS, SUPPORTS, CUPELS, TUBES, PIPES, SHEATHS, RODS AND OTHER REFRACTORY CERAMIC GOODS (EXCL. THOSE OF SILICEOUS FOSSIL MEALS OR SIMILAR SILICEOUS EARTHS, OF HEADING 6902, CONTAINING $\geq$ 25 % CARBON OR CONTAINING $\geq$ 50% BY WEIGHT OF ALUMINA OR A MIXTURE OR COMPOUND OF ALUMINA AND SILICA)
81039090	ARTICLES OF TANTALUM, N.E.S.
84141025	ROTARY PISTON VACUUM PUMPS, SLIDING VANE ROTARY PUMPS, MOLECULAR DRAG PUMPS AND ROOTS PUMPS

Table A.1: CN Codes Descriptions

CN code	Description
84141030	ROTARY PISTON VACUUM PUMPS, SLIDING VANE ROTARY PUMPS, MOLECULAR DRAG PUMPS AND ROOTS PUMPS (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.10.10)
84141050	DIFFUSION PUMPS, CRYOPUMPS AND ADSORPTION PUMPS (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.10.10)
84141080	VACUUM PUMPS (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.10.10, VACUUM PUMPS FOR USE IN SEMICONDUCTOR PRODUCTION, ROTARY PISTON VACUUM PUMPS, SLIDING VANE ROTARY PUMPS, MOLECULAR DRAG PUMPS AND ROOTS PUMPS, DIFFUSION PUMPS, CRYOPUMPS AND ADSORPTION PUMPS)
84141081	DIFFUSION PUMPS, CRYOPUMPS AND ADSORPTION PUMPS
84141089	VACUUM PUMPS (EXCL. VACUUM PUMPS FOR USE IN SEMICONDUCTOR PRODUCTION, ROTARY PISTON VACUUM PUMPS, SLIDING VANE ROTARY PUMPS, MOLECULAR DRAG PUMPS AND ROOTS PUMPS, DIFFUSION PUMPS, CRYOPUMPS AND ADSORPTION PUMPS)
84141090	VACUUM PUMPS (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING NO 8414.10-10, ROTARY PISTON VACUUM PUMPS, SLIDING VANE ROTARY PUMPS, MOLECULAR DRAG PUMPS AND ROOTS PUMPS, DIFFUSION PUMPS, CRYOPUMPS AND ADSORPTION PUMPS)
84148011	TURBOCOMPRESSORS, SINGLE-STAGE (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148019	TURBOCOMPRESSORS, MULTI-STAGE (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148021	TURBO-COMPRESSORS, SINGLE-STAGE (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148022	RECIPROCATING DISPLACEMENT COMPRESSORS, HAVING A GAUGE PRESSURE CAPACITY $\leq$ 15 BAR, GIVING A FLOW/H $\leq$ 60 M3 (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)

Table A.1: CN Codes Descriptions

CN code	Description
84148028	RECIPROCATING DISPLACEMENT COMPRESSORS, HAVING A GAUGE PRESSURE CAPACITY $\leq$ 15 BAR, GIVING A FLOW/H $\geq$ 60 M3 (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148029	TURBO-COMPRESSORS, MULTI-STAGE (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148031	RECIPROCATING DISPLACEMENT COMPRESSORS, HAVING A GAUGE PRESSURE CAPACITY $\leq$ 15 BAR, GIVING A FLOW/H $\leq$ 60 M3 (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148039	RECIPROCATING DISPLACEMENT COMPRESSORS, HAVING A GAUGE PRESSURE CAPACITY $\leq$ 15 BAR, GIVING A FLOW/H $\geq$ 60 M3 (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148041	RECIPROCATING DISPLACEMENT COMPRESSORS, HAVING A GAUGE PRESSURE CAPACITY $\geq$ 15 BAR, GIVING A FLOW/H $\leq$ 120 M3 (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148049	RECIPROCATING DISPLACEMENT COMPRESSORS, HAVING A GAUGE PRESSURE CAPACITY $\geq$ 15 BAR, GIVING A FLOW/H $\geq$ 120 M3 (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148051	RECIPROCATING DISPLACEMENT COMPRESSORS, HAVING A GAUGE PRESSURE CAPACITY $\geq$ 15 BAR, GIVING A FLOW/H $\leq$ 120 M3 (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)

Table A.1: CN Codes Descriptions

CN code	Description
84148059	RECIPROCATING DISPLACEMENT COMPRESSORS, HAVING A GAUGE PRESSURE CAPACITY $\geq$ 15 BAR, GIVING A FLOW/H $\geq$ 120 M3 (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148060	ROTARY DISPLACEMENT COMPRESSORS, SINGLE-SHAFT (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148071	SCREW COMPRESSORS, MULTI-SHAFT (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148073	ROTARY DISPLACEMENT COMPRESSORS, SINGLE-SHAFT (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148075	SCREW COMPRESSORS, MULTI-SHAFT (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT AND AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING)
84148078	ROTARY DISPLACEMENT COMPRESSORS, MULTI-SHAFT (EXCL. COMPRESSORS FOR REFRIGERATING EQUIPMENT, AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING AND SCREW COMPRESSORS)
84148079	ROTARY DISPLACEMENT COMPRESSORS, MULTI-SHAFT (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8414.80.10, COMPRESSORS FOR REFRIGERATING EQUIPMENT, AIR COMPRESSORS MOUNTED ON A WHEELED CHASSIS FOR TOWING AND SCREW COMPRESSORS)
84171000	INDUSTRIAL OR LABORATORY FURNACES AND OVENS, NON-ELECTRIC, FOR THE ROASTING, MELTING OR OTHER HEAT TREATMENT OF ORES, PYRITES OR METALS (EXCL. DRYING OVENS)
84179000	PARTS OF INDUSTRIAL OR LABORATORY FURNACES, NON-ELECTRIC, INCL. INCINERATORS, N.E.S.
84195090	HEAT EXCHANGE UNITS (EXCL. THOSE FOR CIVIL AIRCRAFT OF SUBHEADING 8419.50.10, INSTANTANEOUS HEATERS, STORAGE WATER HEATERS, BOILERS AND EQUIPMENT WITHOUT A SEPARATING WALL)

Table A.1: CN Codes Descriptions

CN code	Description
84198998	APPLIANCES AND DEVICES, WHETHER OR NOT ELECTRICALLY HEATED, FOR TREATING MATERIALS USING PROCESSES BASED ON TEMPERATURE CHANGE, N.E.S.
84569980	MACHINE TOOLS FOR WORKING ANY MATERIAL BY REMOVAL OF MATERIAL, OPERATED BY ELECTRO-CHEMICAL PROCESSES OR ELECTRON BEAM, ION BEAM OR PLASMA ARC PROCESSES (EXCL. FOR SOLDERING AND WELDING MACHINES, MATERIALS TESTING MACHINES, FOCUSED ION BEAM MILLING MACHINES FOR PRODUCING OR REPAIRING MASKS AND RETICLES FOR PATTERNS ON SEMICONDUCTOR DEVICES, MACHINE TOOLS FOR DRY-ETCHING PATTERNS ON SEMICONDUCTOR MATERIALS AND ON LCD SUBSTRATES, AND APPARATUS FOR STRIPPING OR CLEANING SEMICONDUCTOR WAFERS)
85059010	ELECTROMAGNETS (EXCL. MAGNETS FOR MEDICAL USE)
85141080	INDUSTRIAL AND LABORATORY FURNACES AND OVENS, RESISTANCE HEATED (OTHER THAN FOR THE MANUFACTURE OF SEMICONDUCTOR DEVICES ON SEMICONDUCTOR WAFERS, DRYING OVENS AND BAKING OVENS FOR BAKERIES, AND BISCUIT OVENS)
85142010	FURNACES AND OVENS FUNCTIONING BY INDUCTION
85142080	FURNACES AND OVENS FUNCTIONING BY DIELECTRIC LOSS (OTHER THAN FOR THE MANUFACTURE OF SEMICONDUCTOR DEVICES ON SEMICONDUCTOR WAFERS)
85143019	INFRA-RED OVENS (EXCL. DRY OVENS, DEVICES FOR HEATING ROOMS OR FLOORS OR FOR SIMILAR PURPOSES, AND FOR THE MANUFACTURE OF SEMICONDUCTOR DEVICES ON SEMICONDUCTOR WAFERS)
85143099	ELECTRIC INDUSTRIAL AND LABORATORY FURNACES AND OVENS (EXCL. RESISTANCE HEATED FURNACES AND OVENS WITH INDIRECT HEATING INDUCTION OVENS, OVENS WITH DIELECTRIC HEATING, INFRA-RED OVENS, DRY OVENS AND OVENS FOR THE MANUFACTURE OF SEMICONDUCTOR DEVICES ON SEMICONDUCTOR WAFERS)
85149080	PARTS OF ELECTRIC INDUSTRIAL OR LABORATORY FURNACES AND OVENS, INCL. OF THOSE FUNCTIONING BY INDUCTION OR DIELECTRIC LOSS, AND OF INDUSTRIAL OR LABORATORY EQUIPMENT FOR THE HEAT TREATMENT OF MATERIALS BY INDUCTION OR DIELECTRIC LOSS, N.E.S. (OTHER THAN FOR THE MANUFACTURE OF SEMICONDUCTOR DEVICES ON SEMICONDUCTOR WAFERS)

Table A.1: CN Codes Descriptions

CN code	Description
85158019	ELECTRICAL MACHINES AND APPARATUS FOR HOT SPRAYING OF METALS OR METAL CARBIDES (EXCL. METAL SPRAY GUNS SPECIFIED ELSEWHERE)
85414010	LIGHT EMITTING DIODES
90019000	LENSES, PRISMS, MIRRORS AND OTHER OPTICAL ELEMENTS, OF ANY MATERIAL, UNMOUNTED (EXCL. SUCH ELEMENTS OF GLASS NOT OPTICALLY WORKED, CONTACT LENSES AND SPECTACLE LENSES)
90019090	LENSES, PRISMS, MIRRORS AND OTHER OPTICAL ELEMENTS, OF ANY MATERIAL, UNMOUNTED (EXCL. FOR CIVIL AIRCRAFT, ELEMENTS OF GLASS NOT OPTICALLY WORKED, CONTACT LENSES AND SPECTACLE LENSES)
90029000	LENSES, PRISMS, MIRRORS AND OTHER OPTICAL ELEMENTS, MOUNTED, OF ANY MATERIAL, BEING PARTS OF OR FITTINGS FOR INSTRUMENTS OR APPARATUS (EXCL. OBJECTIVE LENSES FOR CAMERAS, PROJECTORS OR PHOTOGRAPHIC ENLARGERS OR REDUCERS, SUCH ELEMENTS OF GLASS NOT OPTICALLY WORKED, AND FILTERS)
90029090	LENSES, PRISMS, MIRRORS AND OTHER OPTICAL ELEMENTS, MOUNTED, OF ANY MATERIAL, FOR INSTRUMENTS OR APPARATUS (EXCL. FOR CIVIL AIRCRAFT OF SUBHEADING 9002.90.10, ELEMENTS OF GLASS NOT OPTICALLY WORKED, FILTERS AND OBJECTIVE LENSES)
90029099	LENSES, PRISMS, MIRRORS AND OTHER OPTICAL ELEMENTS, MOUNTED, OF ANY MATERIAL, FOR INSTRUMENTS OR APPARATUS (EXCL. FOR CIVIL AIRCRAFT, ELEMENTS OF GLASS NOT OPTICALLY WORKED, FILTERS AND OBJECTIVE LENSES)
90132000	LASERS (EXCL. LASER DIODES)
90278017	ELECTRONIC INSTRUMENTS AND APPARATUS FOR PHYSICAL OR CHEMICAL ANALYSIS OR FOR MEASURING VISCOSITY, POROSITY, EXPANSION, SURFACE TENSION OR THE LIKE, OR FOR MEASURING HEAT, SOUND OR LIGHT, N.E.S.

A.4 Minimal Cut Sets

Table A.2 contains the Minimal Cut Sets (MCS) of the Fault Tree used in the analysis.

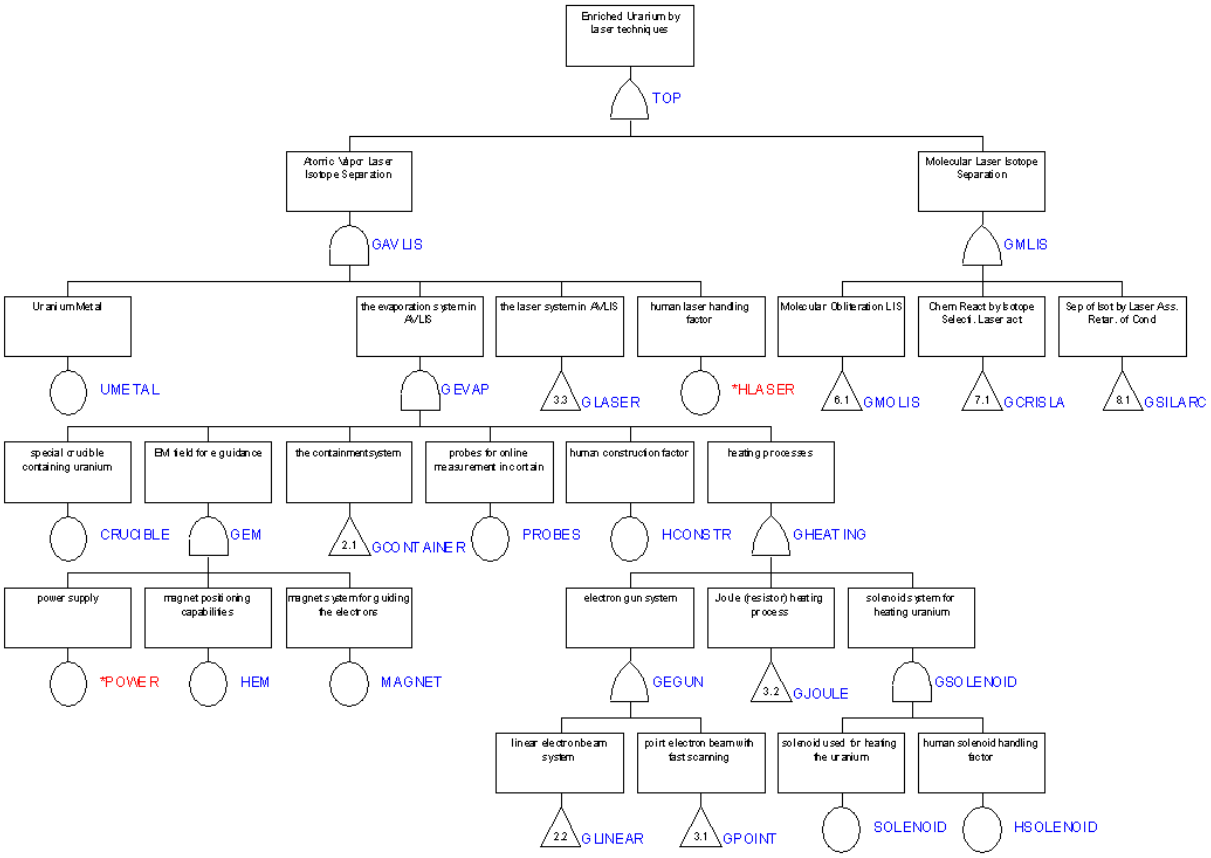

Figure A.1: Part 1 of the detailed fault tree

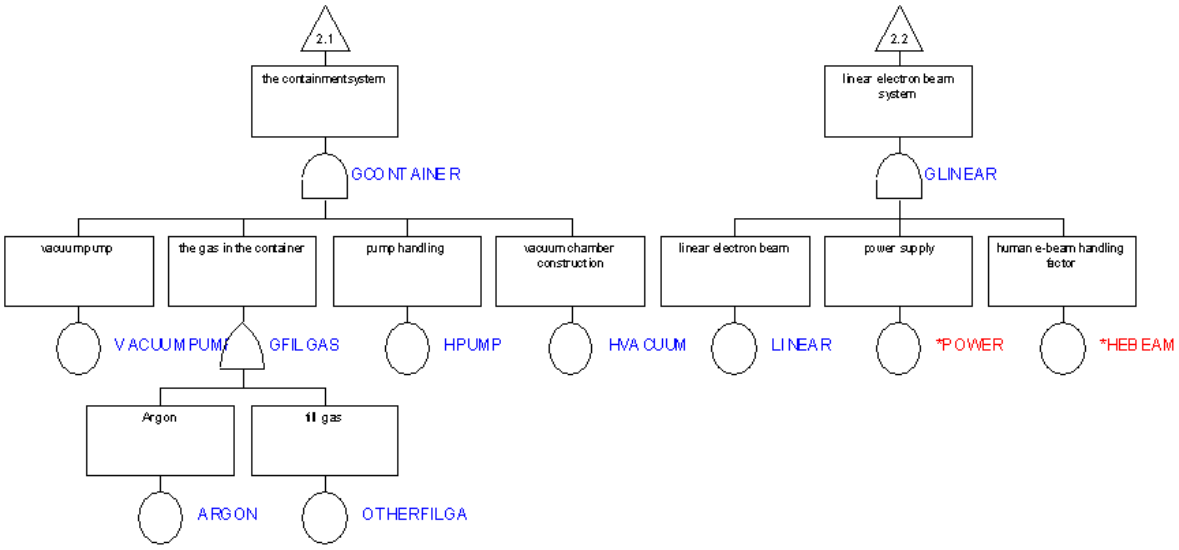

Figure A.2: Part 2 of the detailed fault tree

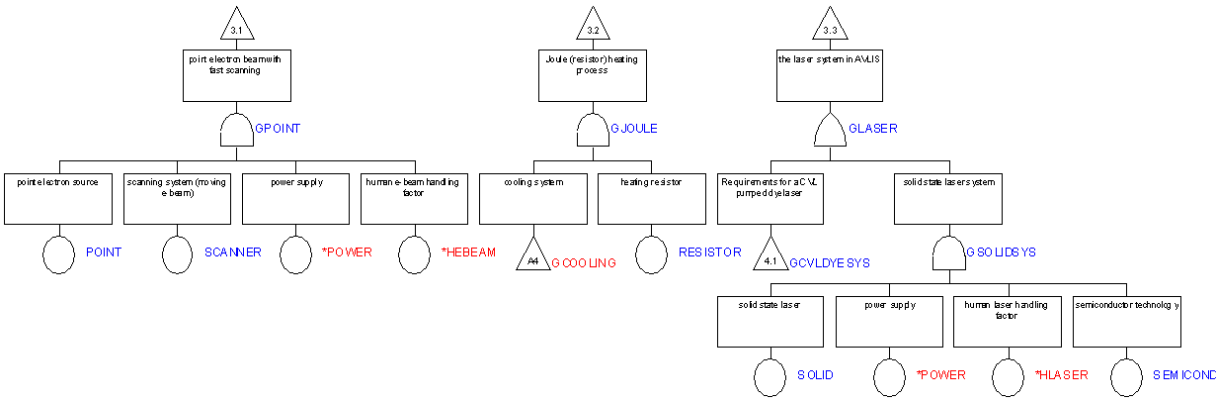

Figure A.3: Part 3 of the detailed fault tree

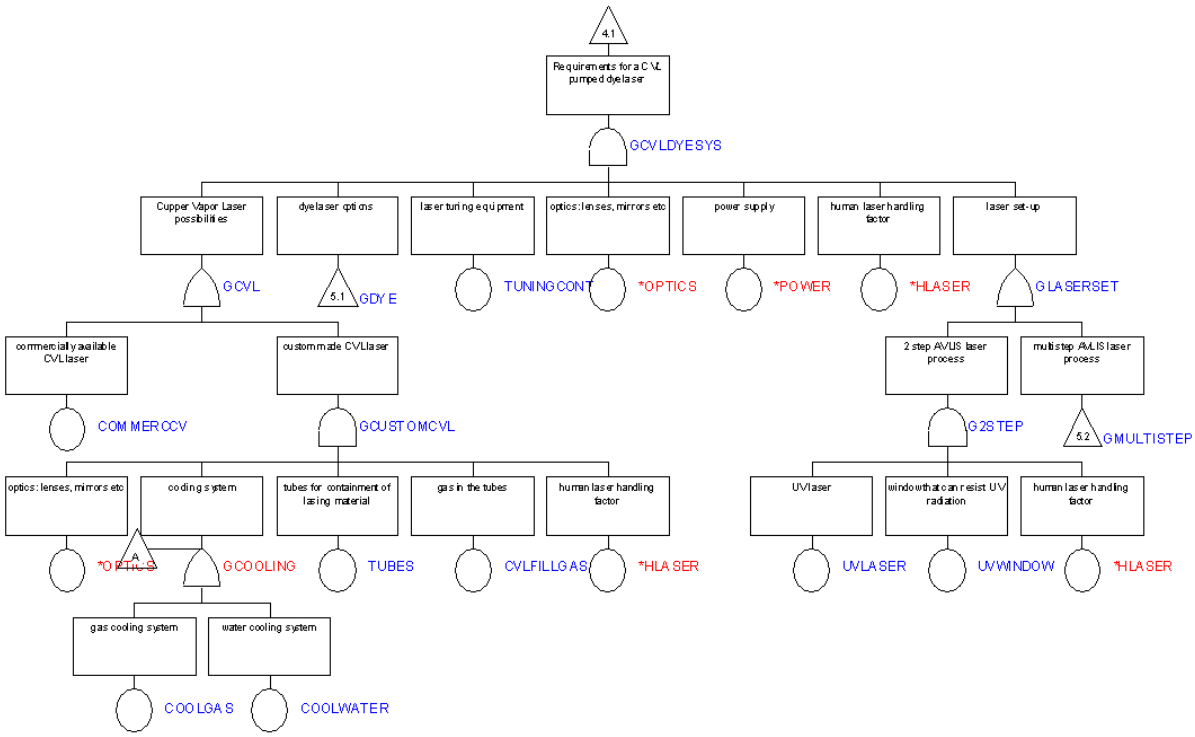

Figure A.4: Part 4 of the detailed fault tree

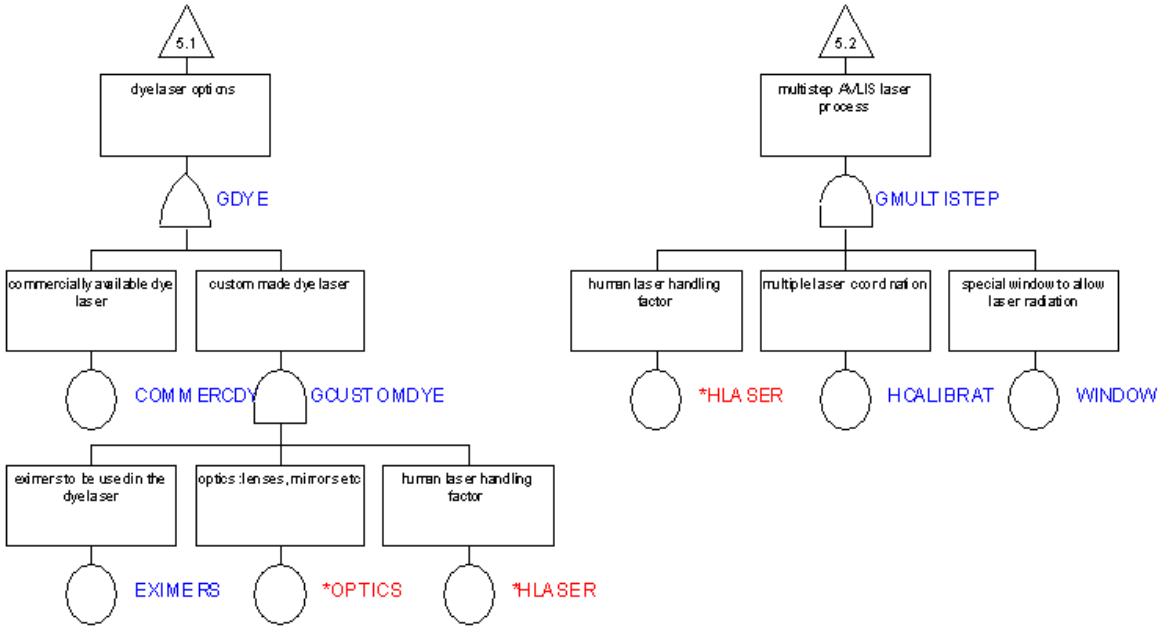

Figure A.5: Part 5 of the detailed fault tree

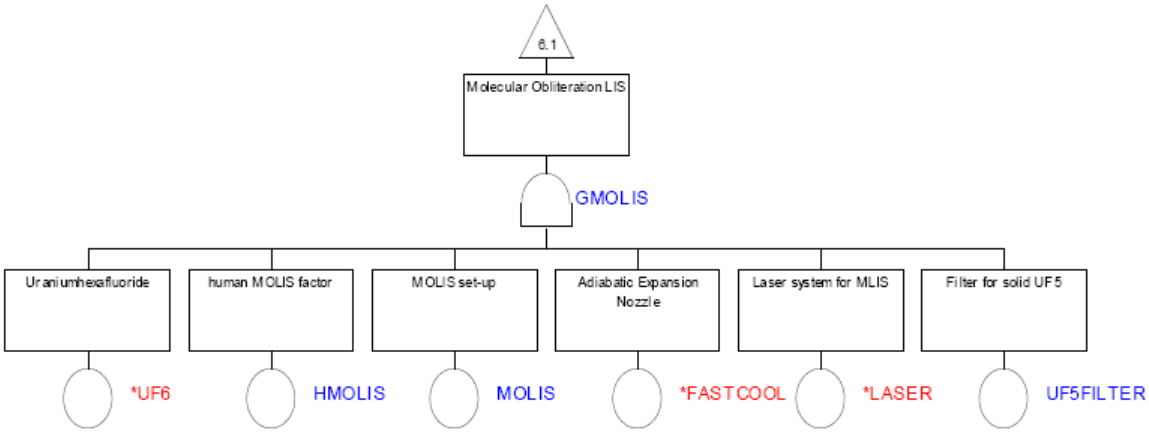

Figure A.6: Part 6 of the detailed fault tree

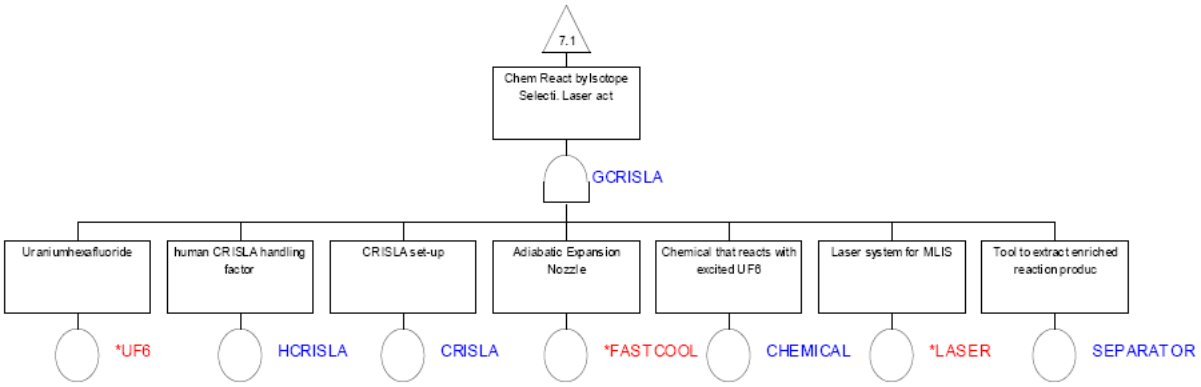

Figure A.7: Part 7 of the detailed fault tree

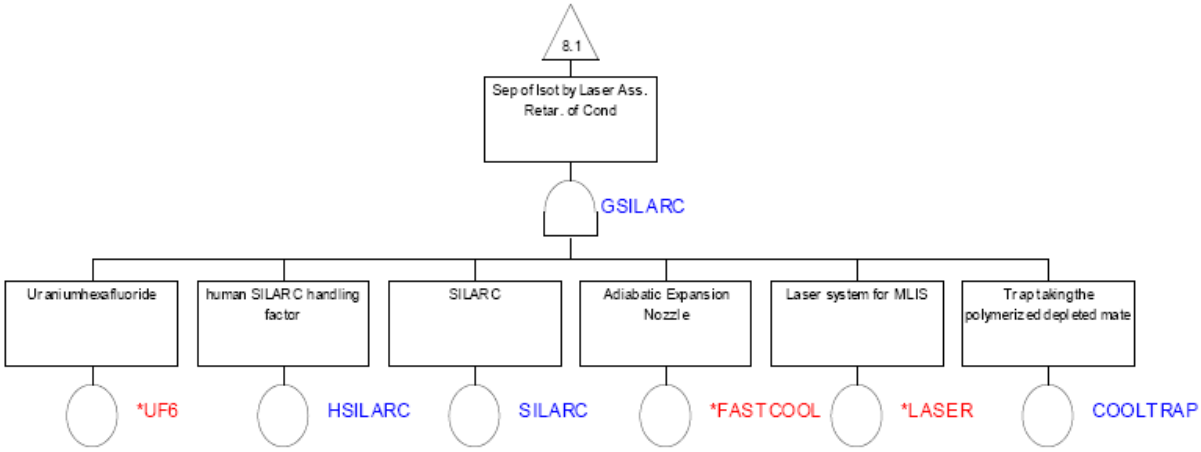

Figure A.8: Part 8 of the detailed fault tree

Table A.2: MCS of analysed Fault Tree

6903	841410	8417	85059010	9002	90132000	90278017
6903	841410	8417	85059010	9001	90132000	90278017
6903	841410	8417	85059010	85414010	9002	90278017
6903	841410	8417	85059010	85414010	9001	90278017
6903	841410	84569980	85059010	9002	90132000	90278017
6903	841410	84569980	85059010	9001	90132000	90278017
6903	841410	84569980	85059010	85414010	9002	90278017
6903	841410	84569980	85059010	85414010	9001	90278017
6903	841410	85059010	85158019	9002	90132000	90278017
6903	841410	85059010	85158019	9001	90132000	90278017
6903	841410	85059010	85158019	85414010	9002	90278017
6903	841410	85059010	85158019	85414010	9001	90278017
81039090	841480	85142080	9002	90132000	90278017	
81039090	841480	85142080	9001	90132000	90278017	
81039090	841480	85142080	85414010	9002	90278017	
81039090	841480	85142080	85414010	9001	90278017	
81039090	841480	85143099	9002	90132000	90278017	
81039090	841480	85143099	9001	90132000	90278017	
81039090	841480	85143099	85414010	9002	90278017	
81039090	841480	85143099	85414010	9001	90278017	
81039090	841480	84198998	9002	90132000	90278017	
81039090	841480	84198998	9001	90132000	90278017	
81039090	841480	84198998	85414010	9002	90278017	
81039090	841480	84198998	85414010	9001	90278017	
81039090	841480	85149080	9002	90132000	90278017	
81039090	841480	85149080	9001	90132000	90278017	
81039090	841480	85149080	85414010	9002	90278017	
81039090	841480	85149080	85414010	9001	90278017	
81039090	841480	84195090	9002	90132000	90278017	
81039090	841480	84195090	9001	90132000	90278017	
81039090	841480	84195090	85414010	9002	90278017	
81039090	841480	84195090	85414010	9001	90278017	
81039090	841480	85142010	9002	90132000	90278017	
81039090	841480	85142010	9001	90132000	90278017	
81039090	841480	85142010	85414010	9002	90278017	
81039090	841480	85142010	85414010	9001	90278017	
81039090	841480	85143019	9002	90132000	90278017	
81039090	841480	85143019	9001	90132000	90278017	
81039090	841480	85143019	85414010	9002	90278017	
81039090	841480	85143019	85414010	9001	90278017	
81039090	841480	85141080	9002	90132000	90278017	
81039090	841480	85141080	9001	90132000	90278017	
81039090	841480	85141080	85414010	9002	90278017	

Table A.2: MCS of analysed Fault Tree

81039090	841480	85141080	85414010	9001	90278017	

Appendix B

Matlab Programs

B.1 Creating Fault Trees

For the creation of the Fault Trees, two programs were created. They are listed below, with explanation in between the code.

B.1.1 toastra.m

```
function toastra(filename,beginyear,endyear,countrycode)
countryarray=importdata(filename);
country=countryarray.data;
countrycodearray=countryarray.textdata(:,1);
n=size(country,1);
```

In this part the function and its parameters are defined. The number of nations to be calculated is derived. “filename” contains all necessary data. “beginyear” is the first year of the period to be checked, “endyear” the last. “countrycode” is the code of the considered country, as used in the Eurostat database.

```
c6903=0;
c81039090=0;
c841410=0;
c841480=0;
c8417=0;
c84195090=0;
c84198998=0;
c84569980=0;
c85059010=0;
c85141080=0;
c85142010=0;
c85142080=0;
c85143019=0;
c85143099=0;
c85149080=0;
c85158019=0;
c85414010=0;
c9001=0;
c9002=0;
c90132000=0;
c90278017=0;

w6903=0;
w81039090=0;
w841410=0;
w841480=0;
w8417=0;
w84195090=0;
w84198998=0;
w84569980=0;
w85059010=0;
w85141080=0;
w85142010=0;
w85142080=0;
w85143019=0;
```

```
w85143099=0;
w85149080=0;
w85158019=0;
w85414010=0;
w9001=0;
w9002=0;
w90132000=0;
w90278017=0;
```

Here the variables that contain the total export of a component (noted with w) and export to an certain country (c) are initiated. Below all fields are checked and added to the corresponding variable.

```
for i=1:n
    j=i+1;
    string=char(countrycodearray(j,:));
    if strcmp(string,countrycode)
        if (country(i,1)¡69040000)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c6903=c6903+country(i,3);
            end
        elseif (country(i,1)==81039090)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c81039090=c81039090+country(i,3);
            end
        elseif (country(i,1)¡84141100)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c841410=c841410+country(i,3);
            end
        elseif (country(i,1)¡84148100)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c841480=c841480+country(i,3);
            end
        elseif (country(i,1)¡84180000)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c8417=c8417+country(i,3);
            end
        elseif (country(i,1)==84195090)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c84195090=c84195090+country(i,3);
            end
        elseif (country(i,1)==84198998)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c84198998=c84198998+country(i,3);
            end
        elseif (country(i,1)==84569980)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c84569980=c84569980+country(i,3);
            end
        elseif (country(i,1)==85059010)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85059010=c85059010+country(i,3);
            end
        elseif (country(i,1)==85141080)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85141080=c85141080+country(i,3);
            end
        elseif (country(i,1)==85142010)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85142010=c85142010+country(i,3);
            end
        elseif (country(i,1)==85142080)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85142080=c85142080+country(i,3);
            end
        elseif (country(i,1)==85143019)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85143019=c85143019+country(i,3);
            end
        elseif (country(i,1)==85143099)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85143099=c85143099+country(i,3);
            end
        elseif (country(i,1)==85149080)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85149080=c85149080+country(i,3);
            end
        elseif (country(i,1)==85158019)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85158019=c85158019+country(i,3);
            end
        elseif (country(i,1)==85414010)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                c85414010=c85414010+country(i,3);
            end
        elseif (country(i,1)¡90020000)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
```

```
            c9001=c9001+country(i,3);
        end
    elseif (country(i,1)¡90030000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            c9002=c9002+country(i,3);
        end
    elseif (country(i,1)==90132000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            c90132000=c90132000+country(i,3);
        end
    elseif (country(i,1)==90278017)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            c90278017=c90278017+country(i,3);
        end
    end
elseif strcmp(string,'SUM˙PARTNER')
    if (country(i,1)¡69040000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w6903=w6903+country(i,3);
        end
    elseif (country(i,1)==81039090)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w81039090=w81039090+country(i,3);
        end
    elseif (country(i,1)¡84141100)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w841410=w841410+country(i,3);
        end
    elseif (country(i,1)¡84148100)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w841480=w841480+country(i,3);
        end
    elseif (country(i,1)¡84180000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w8417=w8417+country(i,3);
        end
    elseif (country(i,1)==84195090)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w84195090=w84195090+country(i,3);
        end
    elseif (country(i,1)==84198998)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w84198998=w84198998+country(i,3);
        end
    elseif (country(i,1)==84569980)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w84569980=w84569980+country(i,3);
        end
    elseif (country(i,1)==85059010)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85059010=w85059010+country(i,3);
        end
    elseif (country(i,1)==85141080)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85141080=w85141080+country(i,3);
        end
    elseif (country(i,1)==85142010)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85142010=w85142010+country(i,3);
        end
    elseif (country(i,1)==85142080)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85142080=w85142080+country(i,3);
        end
    elseif (country(i,1)==85143019)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85143019=w85143019+country(i,3);
        end
    elseif (country(i,1)==85143099)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85143099=w85143099+country(i,3);
        end
    elseif (country(i,1)==85149080)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85149080=w85149080+country(i,3);
        end
    elseif (country(i,1)==85158019)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85158019=w85158019+country(i,3);
        end
    elseif (country(i,1)==85414010)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85414010=w85414010+country(i,3);
        end
    elseif (country(i,1)¡90020000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w9001=w9001+country(i,3);
        end
    elseif (country(i,1)¡90030000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w9002=w9002+country(i,3);
        end
```

```
        elseif (country(i,1)==90132000)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w90132000=w90132000+country(i,3);
            end
        elseif (country(i,1)==90278017)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w90278017=w90278017+country(i,3);
            end
        end
    end
end
```

Below a very low value is assigned to world values in case values are 0, to prevent dividing by zero. Since the export to a country is zero when the total export of the considered component is zero, this will not change the results.

```
if(w6903==0) w6903=1e-10; end
if(w81039090==0) w81039090=1e-10; end
if(w841410==0) w841410=1e-10; end
if(w841480==0) w841480=1e-10; end
if(w8417==0) w8417=1e-10; end
if(w84195090==0) w84195090=1e-10; end
if(w84198998==0) w84198998=1e-10; end
if(w84569980==0) w84569980=1e-10; end
if(w85059010==0) w85059010=1e-10; end
if(w85141080==0) w85141080=1e-10; end
if(w85142010==0) w85142010=1e-10; end
if(w85142080==0) w85142080=1e-10; end
if(w85143019==0) w85143019=1e-10; end
if(w85143099==0) w85143099=1e-10; end
if(w85149080==0) w85149080=1e-10; end
if(w85158019==0) w85158019=1e-10; end
if(w85414010==0) w85414010=1e-10; end
if(w9001==0) w9001=1e-10; end
if(w9002==0) w9002=1e-10; end
if(w90132000==0) w90132000=1e-10; end
if(w90278017==0) w90278017=1e-10; end
```

Below the value that is to be filled in as probability for the corresponding event is calculated.

```
qc6903=c6903/w6903;
qc81039090=c81039090/w81039090;
qc841410=c841410/w841410;
qc841480=c841480/w841480;
qc8417=c8417/w8417;
qc84195090=c84195090/w84195090;
qc84198998=c84198998/w84198998;
qc84569980=c84569980/w84569980;
qc85059010=c85059010/w85059010;
qc85141080=c85141080/w85141080;
qc85142010=c85142010/w85142010;
qc85142080=c85142080/w85142080;
qc85143019=c85143019/w85143019;
qc85143099=c85143099/w85143099;
qc85149080=c85149080/w85149080;
qc85158019=c85158019/w85158019;
qc85414010=c85414010/w85414010;
qc9001=c9001/w9001;
qc9002=c9002/w9002;
qc90132000=c90132000/w90132000;
qc90278017=c90278017/w90278017;
```

Since ASTRA can't work with zero probability, a very low value is assigned when probabilities were calculated to be zero.

```
if(qc6903==0) qc6903=1e-10; end
if(qc81039090==0) qc81039090=1e-10; end
if(qc841410==0) qc841410=1e-10; end
if(qc841480==0) qc841480=1e-10; end
if(qc8417==0) qc8417=1e-10; end
if(qc84195090==0) qc84195090=1e-10; end
if(qc84198998==0) qc84198998=1e-10; end
if(qc84569980==0) qc84569980=1e-10; end
if(qc85059010==0) qc85059010=1e-10; end
```

```
if(qc85141080==0) qc85141080=1e-10; end
if(qc85142010==0) qc85142010=1e-10; end
if(qc85142080==0) qc85142080=1e-10; end
if(qc85143019==0) qc85143019=1e-10; end
if(qc85143099==0) qc85143099=1e-10; end
if(qc85149080==0) qc85149080=1e-10; end
if(qc85158019==0) qc85158019=1e-10; end
if(qc85414010==0) qc85414010=1e-10; end
if(qc9001==0) qc9001=1e-10; end
if(qc9002==0) qc9002=1e-10; end
if(qc90132000==0) qc90132000=1e-10; end
if(qc90278017==0) qc90278017=1e-10; end
```

Below the .tfx file is created.

```
fid = fopen([countrycode,int2str(beginyear),int2str(endyear),'.tfx'],'w');
fprintf(fid,'laser enrichment export fault tree                                                    "n[EVENTS]"n6903       0.000000E+000
 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "Crucible" "n81039090    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000
  "tantalium" "n841410      0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "Vacuum Pumps" "n841480      0.000000E+000
   0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "Compressor" "n8417       0.000000E+000 0.000000E+000 %1.6E 0.000000E+000
    0.000000E+000 "Ore heating eq." "n84195090    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "heat exchange
     units" "n84198998    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "machines for processes involving
      change" "n84569980    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "Beam heat material treatment" "n85059010
       0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "Electromagnets" "n85141080    0.000000E+000 0.000000E+000 %1.6E
        0.000000E+000 0.000000E+000 "ovens, resistance heated" "n85142010    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000
         "ovens: induction heated" "n85142080    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "ovens: dielectric
          loss" "n85143019    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "infra red ovens" "n85143099    0.000000E+000
           0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "oven: other" "n85149080    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000
            0.000000E+000 "parts for ovens" "n85158019    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "Beam heat metal
             treatment: other" "n85414010    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "Diode Lasers" "n9001
              0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "Unmounted Optics" "n9002       0.000000E+000 0.000000E+000
               %1.6E 0.000000E+000 0.000000E+000 "M  nted Optics" "n90132000    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000
                0.000000E+000 "Lasers (non-diode)" "n90278017    0.000000E+000 0.000000E+000 %1.6E 0.000000E+000 0.000000E+000 "analysis
                 equipment" "n[GATES]"nTOP OR   GAVLIS      GMLIS      "TOP gate" "nGAVLIS AND  GALL       GAVLISDET  "Atomic Vapor Laser
                  Isotope Separation" "nGMLIS AND  GALL       GMLISDET   "Molecular Laser Isotope Separation" "nGALL AND  90278017
                   GLASER      GOPTICS    "Common Components for LIS" "nGAVLISDET AND  6903       85059010    GMELTING    841410
                    "AVLIS specific components" "nGMLISDET AND  GOVEN       81039090    841480     "MLIS specific components" "nGLASER OR
                     85414010    90132000   "Lasers" "nGMELTING OR   8417       GEBEAM     "Vaporizing Uranium" "nGOVEN OR   84195090
                      84198998    85141080    85142010    85142080    85143019    85149080    85143099   "oven for UF6 heating" "nGEBEAM
                       OR   85158019    84569980   "Electron Beam" "nGOPTICS OR   9001       9002
                    "Optics" "n$END"n',qc6903,qc81039090,qc841410,qc841480,qc8417,qc84195090,qc84198998,qc84569980,qc85059010,qc85141080,qc85142010,qc85142080
                          ,qc85143019,qc85143099,qc85149080,qc85158019,qc85414010,qc9001,qc9002,qc90132000,qc90278017);

fclose(fid);
tfxfile=[countrycode,int2str(beginyear),int2str(endyear),'.tfx'];
fid2=fopen([countrycode,int2str(beginyear),int2str(endyear),'.xml'],'w');
fprintf(fid2,'¡?xml version="1.0" encoding="utf-8" standalone="yes"?¿"n¡!--ASTRA-FTA Version 3 - ASBDDX input file--¿"n¡InputData¿"n
 ¡GeneralParameters¿"n       ¡TfxPath¿C:""Astra3""Workspaces""WS1""Joris""%s¡/TfxPath¿"n
  ¡DbxPath¿C:""Astra3""DB""eireda.mdb¡/DbxPath¿"n       ¡AnalysisType¿1¡/AnalysisType¿"n       ¡ITESize¿524287¡/ITESize¿"n
   ¡TraceLevel¿1¡/TraceLevel¿"n    ¡/GeneralParameters¿"n    ¡BDDAnalysis¿"n       ¡ApplyBC¿False¡/ApplyBC¿"n
    ¡ExactAnalysis¿True¡/ExactAnalysis¿"n       ¡ENFCalculation¿False¡/ENFCalculation¿"n       ¡MissionTime¿10000¡/MissionTime¿"n
      ¡Ordering¿asis¡/Ordering¿"n    ¡/BDDAnalysis¿"n    ¡TimeDependentAnalysis¿"n       ¡EnableTD¿False¡/EnableTD¿"n
       ¡ImportanceTP¿True¡/ImportanceTP¿"n       ¡TimePoints¿100¡/TimePoints¿"n    ¡/TimeDependentAnalysis¿"n
        ¡ImportanceMeasures¿"n       ¡ImpBIX¿True¡/ImpBIX¿"n       ¡ImpSTR¿False¡/ImpSTR¿"n       ¡ImpCRT¿True¡/ImpCRT¿"n
         ¡ImpRAW¿False¡/ImpRAW¿"n       ¡ImpRRW¿False¡/ImpRRW¿"n    ¡/ImportanceMeasures¿"n    ¡CutsetsAnalysis¿"n
          ¡EnableCutoff¿False¡/EnableCutoff¿"n ¡LogCutoff¿4¡/LogCutoff¿"n       ¡PrbCutoff¿0.0E+00¡/PrbCutoff¿"n
           ¡/CutsetsAnalysis¿"n¡/InputData¿',tfxfile);

fclose(fid2);
```

A variant for France and Great Britain, frgbtoastra.m, was created with some slight modifications.

B.1.2 makebatch.m

"makebatch.m" creates a batch file, "runastrabatch.bat", and a series of .tfx file, both for total export and export from France and Great Britain, using "toastra.m" and "frgbtoastra.m":

```
function makebatch(countrylist,beginyear,endyear,years)
countrynumbersize=size(countrylist);
countrynumber=countrynumbersize(1,1);
batchid = fopen('runastrabatch.bat','w');
yeardiff=endyear-beginyear-years+2;
```

Here the function and its parameters and some variables are defined, with "years" the number of years in one time period. The file "runastrabatch.bat" is created and is ready to be filled with the batch commands. Below, using the countrylist and the requested time periods, "toastra.m" and "frgbtoastra.m", are requested to create the desired .tfx files, after which a lines are added to the batch file that will run these Fault Trees in ASTRA.

```
for i = 1:countrynumber
    countryname = countrylist(i,:);
    for k = 1:yeardiff
        toastra('alles.txt',beginyear+k-1,beginyear+years-2+k,countryname)
        frgbtoastra('frgb.txt','alles.txt',beginyear+k-1,beginyear+years-2+k,countryname)
        fillin=['c:""astra3""asbddx.exe C:""Astra3""Workspaces""WS1""Joris""',countryname,int2str(beginyear+k-1),int2str(beginyear+years-2+k),'.xml"n
c:""astra3""asbddx.exe
C:""Astra3""Workspaces""WS1""Joris""frgb',countryname,int2str(beginyear+k-1),int2str(beginyear+years-2+k),'.xml"n'];
        fprintf(batchid,fillin);
    end
end
countryname = 'EU25˙EXTRA'
for k = 1:yeardiff
    toastra('alles.txt',beginyear+k-1,beginyear+years-2+k,countryname)
    frgbtoastra('frgb.txt','alles.txt',beginyear+k-1,beginyear+years-2+k,countryname)
   fillin=['c:""astra3""asbddx.exe C:""Astra3""Workspaces""WS1""Joris""',countryname,int2str(beginyear+k-1),int2str(beginyear+years-2+k),'.xml"nc:""astra3""asbddx.exe
 C:""Astra3""Workspaces""WS1""Joris""frgb',countryname,int2str(beginyear+k-1),
 int2str(beginyear+years-2+k),'.xml"n'];
    fprintf(batchid,fillin);
end
fclose(batchid);
```

B.2 Programs for Output

B.2.1 fromastra.m

The program "fromastra.m" extracts the Top Event unavailiability from the .dpl files:

```
function M = fromastra(countryname,beginyear,endyear,years)
yeardiff=endyear-beginyear-years+2;
M=[];
for i = 1:yeardiff
    filename=[countryname,int2str(beginyear-1+i),int2str(beginyear-2+i+years),'.dpl'];
    fid=fopen(filename);
    M(1,i)= beginyear-2+i+years;
    M(2,i)= cell2mat(textscan(fid,'%*s %*s %f',1,'headerlines',386));
    fclose(fid);
end
```

B.2.2 topevents.m

The program "topevents.m" uses "fromastra.m" to extract data from all necessary files to plot the evolution of the Top Event probability. The parameter "w" determines if the "EU25_EXTRA" countrycode needs to be considered. This special treatment was necessary because this code is longer than the standard two letters.

```
function topevents(countrylist,beginyear,endyear,years,colorvector,typevector,w)
countrynumbersize=size(countrylist);
countrynumber=countrynumbersize(1,1);
for i = 1:countrynumber
    countryname=countrylist(i,:);
    M = fromastra(countryname,beginyear,endyear,years);
    linespecs=['-',typevector(i),colorvector(i)];
    semilogy(M(1,:),M(2,:),linespecs);
    hold on;
end
if w==1
    M = fromastra('EU25˙EXTRA',beginyear,endyear,years);
    semilogy(M(1,:),M(2,:),'--or');
    countrylist(countrynumber+1,:)='EX';
end
legend(countrylist)
xlabel('Endyear of ',int2str(years),'-year Period');
ylabel('Topevent Value');
countries=[]
```

```
for n=1:countrynumber
    countries=[countries,countrylist(n,:)]
end
if w==1
    s1=['.“images“EUto',countries,'EX',int2str(years),'.fig'];
    s2=['.“images“EUto',countries,'EX',int2str(years),'.png'];
else
    s1=['.“images“EUto',countries,int2str(years),'.fig'];
    s2=['.“images“EUto',countries,int2str(years),'.png'];
end
saveas(gcf,s1)
saveas(gcf,s2)

hold off
```

B.2.3 countryanalysis.m

“frgbfromastra.m” and “frgbtopevents.m”, are the counterparts of “fromastra.m” and “topevents.m” for displaying Top Events probability, when only considering export from France and Great Britain. In order to have the information from both these sets of programs on one graph, another program was created, “countryanalysis.m”:

```
function countryanalysis(countrylist,beginyear,endyear,years)
colorvector=['r';'b';'g';'k';'c';'m'];
countrynumbersize=size(countrylist);
countrynumber=countrynumbersize(1,1);
legendlist=['     '];
for i = 1:countrynumber
    countryname=countrylist(i,:);
    M1 = fromastra(countryname,beginyear,endyear,years);
    linespecs=['-','x',colorvector(i)];
    semilogy(M1(1,:),M1(2,:),linespecs);
    hold on;
    M2 = frgbfromastra(countryname,beginyear,endyear,years);
    linespecs=['-','o',colorvector(i)];
    semilogy(M2(1,:),M2(2,:),linespecs);
    hold on;
    element1=['EU',countryname]
    element2=['FG',countryname]
    legendlist(2*i-1,:)=element1
    legendlist(2*i,:)=element2
end
countries=[]

for n=1:countrynumber
    countries=[countries,countrylist(n,:)]
end
legend(legendlist)
xlabel('Endyear of ',int2str(years),'-year Period');
ylabel('Topevent Value');
s1=['.“images“to',countries,int2str(years),'.fig'];
s2=['.“images“to',countries,int2str(years),'.png'];
saveas(gcf,s1)
saveas(gcf,s2)

hold off
```

B.2.4 impfromastra.m

“impfromastra.m”is similar to “fromastra.m”, but it extracts the importances, or criticality indexes, from the .dpl file, which require some changes since it must be able to return multiple values from separate lines in the .dpl file:

```
function M = impfromastra(countryname,beginyear,endyear,years)
yeardiff=endyear-beginyear-years+2;
M=[];
for i = 1:yeardiff
    for k = 1:21
        filename=[countryname,int2str(beginyear-1+i),int2str(beginyear-2+i+years),'.dpl'];
        fid=fopen(filename);
        M(1,(i-1)*21+k)= beginyear-2+i+years;
        v = cell2mat(textscan(fid,'%*f %f %*f %*f %*f %*f %*f %*f %f',1,'headerlines',327+2*k));
        M(2,(i-1)*21+k)= v(1);
        M(3,(i-1)*21+k)= v(2);
        fclose(fid);
    end
end
```

B.2.5 importances.m

"importances.m" uses "impfromastra.m" to obtain the importances, or criticality indexes, and displays their evolution for all components:

```
function importances(country,beginyear,endyear,years)
colorvector=['k';'r';'b';'g';'m';'c';'k';'r';'b';'g';'m';'c';
'k';'r';'b';'g';'m';'c';'y';'k';'r';'b';'g'];
typevector=['*';'*';'*';'*';'*';'*';'o';'o';'o';'o';'o';'o';
'd';'d';'d';'d';'d';'d';'h';'h';'h';'h';'h';'h'];
M = impfromastra(country,beginyear,endyear,years)
```

Above the function is initialised, along with some variables. "impfromastra" is called to return the importances, or criticality indexes. The format, year - component - criticality index, is not yet suitable for displaying using Matlab's plot function. It is converted below.

```
c6903=1;
c81039090=1;
c841410=1;
c841480=1;
c8417=1;
c84195090=1;
c84198998=1;
c84569980=1;
c85059010=1;
c85141080=1;
c85142010=1;
c85142080=1;
c85143019=1;
c85143099=1;
c85149080=1;
c85158019=1;
c85414010=1;
c9001=1;
c9002=1;
c90132000=1;
c90278017=1;

yeardiff=endyear-beginyear-years+2;

w6903 = zeros(yeardiff,2)
w81039090 = zeros(yeardiff,2);
w841410 = zeros(yeardiff,2);
w841480 = zeros(yeardiff,2);
w8417 = zeros(yeardiff,2);
w84195090 = zeros(yeardiff,2);
w84198998 = zeros(yeardiff,2);
w84569980 = zeros(yeardiff,2);
w85059010 = zeros(yeardiff,2);
w85141080 = zeros(yeardiff,2);
w85142010 = zeros(yeardiff,2);
w85142080 = zeros(yeardiff,2);
w85143019 = zeros(yeardiff,2);
w85143099 = zeros(yeardiff,2);
w85149080 = zeros(yeardiff,2);
w85158019 = zeros(yeardiff,2);
w85414010 = zeros(yeardiff,2);
w9001 = zeros(yeardiff,2);
w9002 = zeros(yeardiff,2);
w90132000 = zeros(yeardiff,2);
w90278017 = zeros(yeardiff,2);
```

The variables starting with c are indexes, while those starting with w are matrices that will contain the criticality index evolution for that component over the consecutive five year periods, but are here merely initialised. Below the matrix M will be checked line by line and put in the right w-variable.

```
iters = size(M)
iter = iters(2)


for i = 1:iter
    if M(2,i) == 85414010
        w85414010(c85414010,1)= M(1,i)
        w85414010(c85414010,2)= M(3,i)
        c85414010=c85414010+1;
    end
    if M(2,i) == 90132000
        w90132000(c90132000,1)= M(1,i)
```

```
    w90132000(c90132000,2)= M(3,i)
    c90132000=c90132000+1;
end
if M(2,i) == 9001
    w9001(c9001,1)= M(1,i)
    w9001(c9001,2)= M(3,i)
    c9001=c9001+1;
end
if M(2,i) == 9002
    w9002(c9002,1)= M(1,i);
    w9002(c9002,2)= M(3,i);
    c9002=c9002+1;
end
if M(2,i) == 90278017
    w90278017(c90278017,1)= M(1,i);
    w90278017(c90278017,2)= M(3,i);
    c90278017=c90278017+1;
end
if M(2,i) == 85143099
    w85143099(c85143099,1)= M(1,i);
    w85143099(c85143099,2)= M(3,i);
    c85143099=c85143099+1;
end
if M(2,i) == 85149080
    w85149080(c85149080,1)= M(1,i);
    w85149080(c85149080,2)= M(3,i);
    c85149080=c85149080+1;
end
if M(2,i) == 85143019
    w85143019(c85143019,1)= M(1,i);
    w85143019(c85143019,2)= M(3,i);
    c85143019=c85143019+1;
end
if M(2,i) == 85142080
    w85142080(c85142080,1)= M(1,i);
    w85142080(c85142080,2)= M(3,i);
    c85142080=c85142080+1;
end
if M(2,i) == 85142010
    w85142010(c85142010,1)= M(1,i);
    w85142010(c85142010,2)= M(3,i);
    c85142010=c85142010+1;
end
if M(2,i) == 85141080
    w85141080(c85141080,1)= M(1,i);
    w85141080(c85141080,2)= M(3,i);
    c85141080=c85141080+1;
end
if M(2,i) == 84198998
    w84198998(c84198998,1)= M(1,i);
    w84198998(c84198998,2)= M(3,i);
    c84198998=c84198998+1;
end
if M(2,i) == 84195090
    w84195090(c84195090,1)= M(1,i);
    w84195090(c84195090,2)= M(3,i);
    c84195090=c84195090+1;
end
if M(2,i) == 841480
    w841480(c841480,1)= M(1,i);
    w841480(c841480,2)= M(3,i);
    c841480=c841480+1;
end
if M(2,i) == 81039090
    w81039090(c81039090,1)= M(1,i);
    w81039090(c81039090,2)= M(3,i);
    c81039090=c81039090+1;
end
if M(2,i) == 84569980
    w84569980(c84569980,1)= M(1,i);
    w84569980(c84569980,2)= M(3,i);
    c84569980=c84569980+1;
end
if M(2,i) == 85158019
    w85158019(c85158019,1)= M(1,i);
    w85158019(c85158019,2)= M(3,i);
    c85158019=c85158019+1;
end
if M(2,i) == 8417
    w8417(c8417,1)= M(1,i);
    w8417(c8417,2)= M(3,i);
    c8417=c8417+1;
end
if M(2,i) == 841410
    w841410(c841410,1)= M(1,i);
    w841410(c841410,2)= M(3,i);
    c841410=c841410+1;
end
if M(2,i) == 85059010
    w85059010(c85059010,1)= M(1,i);
    w85059010(c85059010,2)= M(3,i);
    c85059010=c85059010+1;
```

```
    end
    if M(2,i) == 6903
        w6903(c6903,1)= M(1,i)
        w6903(c6903,2)= M(3,i)
        c6903=c6903+1
    end
end
```

The w-variables now contain the importances in a suitable format for plotting, which will be handled below:

```
n=1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w6903(:,1),w6903(:,2),linespecs);
hold on;
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w81039090(:,1),w81039090(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w841410(:,1),w841410(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w841480(:,1),w841480(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w8417(:,1),w8417(:,2),linespecs); n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w84195090(:,1),w84195090(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w84198998(:,1),w84198998(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w84569980(:,1),w84569980(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85059010(:,1),w85059010(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85141080(:,1),w85141080(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85142010(:,1),w85142010(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85142080(:,1),w85142080(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85143019(:,1),w85143019(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85143099(:,1),w85143099(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85149080(:,1),w85149080(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85158019(:,1),w85158019(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w85414010(:,1),w85414010(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w9001(:,1),w9001(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w9002(:,1),w9002(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w90132000(:,1),w90132000(:,2),linespecs);
n=n+1;
linespecs=['-',typevector(n),colorvector(n)];
plot(w90278017(:,1),w90278017(:,2),linespecs);
n=n+1;

componentlist = ['6903xxxx';'81039090';'841410xx';'841480xx';'8417xxxx';'84195090';'84198998';'84569980';
'85059010';'85141080';'85142010';'85142080';'85143019';'85143099';'85149080';'85158019';
'85414010';'9001xxxx';'9002xxxx';'90132000';'90278017']

xlabel(['Endyear of ',int2str(years),'-year Period']);
ylabel('Criticality Index');
legend(componentlist);

s1=['.\"images\"impEUto',country,int2str(years),'.fig'];
s2=['.\"images\"impEUto',country,int2str(years),'.png'];

saveas(gcf,s1)
saveas(gcf,s2)
```

```
hold off;
```

B.2.6 worldtotal.m

"worldtotal.m" uses the input file to find the value by which is divided in "toastra.m", being the total of export to all country categories, over the considered time period. This program can be easily adjusted to work for individual countries instead of the total export.

```
function M = worldtotal(filename,beginyear,endyear)
countryarray=importdata(filename);
country=countryarray.data;
countrycodearray=countryarray.textdata(:,1);
n=size(country,1);


w6903=0;
w81039090=0;
w841410=0;
w841480=0;
w8417=0;
w84195090=0;
w84198998=0;
w84569980=0;
w85059010=0;
w85141080=0;
w85142010=0;
w85142080=0;
w85143019=0;
w85143099=0;
w85149080=0;
w85158019=0;
w85414010=0;
w9001=0;
w9002=0;
w90132000=0;
w90278017=0;

for i=1:n
    j=i+1;
    string=char(countrycodearray(j,:));

    if strcmp(string,'SUM'PARTNER')
        if (country(i,1)¡69040000)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w6903=w6903+country(i,3);
            end
        elseif (country(i,1)==81039090)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w81039090=w81039090+country(i,3);
            end
        elseif (country(i,1)¡84141100)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w841410=w841410+country(i,3);
            end
        elseif (country(i,1)¡84148100)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w841480=w841480+country(i,3);
            end
        elseif (country(i,1)¡84180000)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w8417=w8417+country(i,3);
            end
        elseif (country(i,1)==84195090)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w84195090=w84195090+country(i,3);
            end
        elseif (country(i,1)==84198998)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w84198998=w84198998+country(i,3);
            end
        elseif (country(i,1)==84569980)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w84569980=w84569980+country(i,3);
            end
        elseif (country(i,1)==85059010)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w85059010=w85059010+country(i,3);
            end
        elseif (country(i,1)==85141080)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
                w85141080=w85141080+country(i,3);
            end
        elseif (country(i,1)==85142010)
            if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
```

```
            w85142010=w85142010+country(i,3);
        end
    elseif (country(i,1)==85142080)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85142080=w85142080+country(i,3);
        end
    elseif (country(i,1)==85143019)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85143019=w85143019+country(i,3);
        end
    elseif (country(i,1)==85143099)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85143099=w85143099+country(i,3);
        end
    elseif (country(i,1)==85149080)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85149080=w85149080+country(i,3);
        end
    elseif (country(i,1)==85158019)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85158019=w85158019+country(i,3);
        end
    elseif (country(i,1)==85414010)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w85414010=w85414010+country(i,3);
        end
    elseif (country(i,1)¡90020000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w9001=w9001+country(i,3);
        end
    elseif (country(i,1)¡90030000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w9002=w9002+country(i,3);
        end
    elseif (country(i,1)==90132000)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w90132000=w90132000+country(i,3);
        end
    elseif (country(i,1)==90278017)
        if ((beginyear*100¡country(i,2)) & (country(i,2)¡(endyear+1)*100))
            w90278017=w90278017+country(i,3);
        end
    end
  end
end

M = [w6903;w81039090;w841410;w841480;w8417;w84195090;w84198998;w84569980;
w85059010;w85141080;w85142010;w85142080;w85143019;w85143099;w85149080;w85158019;
w85414010;w9001;w9002;w90132000;w90278017]
```

B.2.7 worldevolution.m

"worldevolution.m" plots the evolution of the data obtained in "worldtotal.m". This is the evolution of the value by which is divided in "toastra.m". This program can be easily adjusted to work for individual countries instead of the total export.

```
function worldevolution(beginyear,endyear,years)
colorvector=['y';'m';'c';'r';'g';'b';'k';'y';'m';'c';'r';'g';'b';'k';
'y';'m';'c';'r';'g';'b';'k';'y';'m';'c';'r';'g';'b';'k';'y';'m';'c';
'r';'g';'b';'k';'y';'m';'c';'r';'g';'b';'k']
typevector=['x';'x';'x';'x';'x';'x';'x';'o';'o';'o';'o';'o';'o';'o';
'd';'d';'d';'d';'d';'d';'d']
componentlist =
['6903xxxx';'81039090';'841410xx';'841480xx';'8417xxxx';'84195090';'84198998';'84569980';
'85059010';'85141080';'85142010';'85142080';'85143019';'85143099';'85149080';'85158019';
'85414010';'9001xxxx';'9002xxxx';'90132000';'90278017']
yeardiff=endyear-beginyear-years+2;
M=[]
for i = 1:yeardiff
    M(:,i)=worldtotal('alles.txt',beginyear+i-1,beginyear+years-2+i)
end
l=size(M)
ll=l(1)
```

If the following piece of code is uncommented, the relative evolution will be plotted.

```
% G=M(:,1)
% for k = 1:yeardiff
%     for m = 1:ll
%     M(m,k)=M(m,k)/G(m)
%     end
% end
```

```
for n = 1:ll
    linetype=['-',typevector(n),colorvector(n)];
    plot(beginyear+years-1:endyear,M(n,:),linetype)
    hold on;
end
xlabel(['Endyear of ',int2str(years),'-year Period']);
ylabel('Relative Export');
%ylabel('Export Value');
legend(componentlist);
s1=['.“images“worldevolution',int2str(years),'.fig'];
s2=['.“images“worldevolution',int2str(years),'.png'];

saveas(gcf,s1)
saveas(gcf,s2)

hold off;
```

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