Tunable Diode Laser Spectroscopy in International Safeguards

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ABSTRACT

The International Atomic Energy Agency (IAEA) implements nuclear verification measures to verify the correctness and completeness of declarations made by States about their civil nuclear energy programs. In order to answer to specific verification objectives, measures are selected carefully and Integrated Safeguards (IS) is the current target of the IAEA to achieve the most effective and efficient combination of all safeguards measures.

IAEA inspectors are using a broad range of instrumentation (attended, unattended, or remote) that is constantly upgraded and enhanced as advanced technologies emerge. Further, the IAEA investigates novel verification and detection tools for safeguards activities. Recently, the applicability of Tunable Diode Laser Spectroscopy (TDLS) based system toward the detection of materials involved in nuclear fuel cycle processes has been investigated. TDLS is appealing for safeguards for two reasons: 1) non-invasiveness and 2) in-situ analysis with real-time data processing.

The paper will outline the various envisioned applications of TDLS in different fields of potential use. It will describe the operation of a Working Group established by the IAEA for TDLS-based systems and discuss three possible fields of use with their related challenges and opportunities. Recommendations on how to best conduct the necessary R&D and system integration will conclude the paper.

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1. INTRODUCTION

One important mission of the International Atomic Energy Agency (IAEA) is the verification that Non-Proliferation Treaty (NPT) signatory states are in compliance with their safeguards agreements to exclusively use nuclear energy for peaceful purposes. Initially, such efforts aimed at the correctness of information about declared nuclear materials and facilities, and mainly included materials accountancy, materials composition measurements, and containment verification (traditional safeguards measures). With the implementation of the Additional Protocol, the IAEA is further tasked to verify the completeness of declarations to ensure that safeguarded countries do not pursue covert nuclear weapons programs using undeclared nuclear materials and installations.

In the center of the IAEA's verification regime stand inspectors that visit both declared and undeclared facilities to conduct safeguards inspections. Undeclared facilities can be entered on a short-notice basis to conduct Complementary Access (CA) inspections. Inspectors are supported by a wide variety of instruments both portable for measurements, containment integrity verification, or sample taking (attended) as well as fixedly installed at safeguarded facilities to gather and securely store relevant information during the inspector absence (unattended). Some unattended instruments even automatically upload data directly to IAEA Headquarters (remote monitoring). Integrated Safeguards (IS), which depicts the most effective and efficient application of all safeguards measures, is the main driver for the evolution of new safeguards concepts [1].

The IAEA constantly evaluates its suite of instrumentation and investigates new techniques for the use in safeguards. Such efforts are driven both by the potential of enhanced capabilities, reliability, and quality of new technologies and the need to keep ahead of the adversary who might use technology advances to defeat older systems. One such technique that is currently investigated for safeguards applications is Tunable Diode Laser Spectroscopy (TDLS).

The following paper will outline the broad range of existing or emerging IAEA needs that can be met with TDLS-based systems, both for traditional safeguards and the detection of undeclared materials and activities. It will then introduce a Working Group specifically implemented to plan and execute a technology roadmap for development projects to make TDLS instrumentation available for safeguards. Next, a sample development project already initiated will be described. Considerations on how to best involve various stakeholders (e.g., the IAEA, developers, manufacturers, and funding agencies) will conclude the paper.

2. TDLS IN INTERNATIONAL SAFEGUARDS

TDLS-based systems can be configured to detect the presence of certain molecules in gas samples by shining a laser tuned to a specific spectral region (where the molecules of interest has a strong spectral absorption) through the sample and analyzing the resulting spectra. Such systems have already been designed for an array of molecules, ranging from ethanol to methane. For safeguards applications, TDLS-based instrumentation is of interest because molecules of interest would be present in ambient air samples and would have strong spectral absorption in areas of the spectrum where other molecules contained in regular air have specifically low absorption (i.e., absorption bands located in the low and mid-infrared).

To this point, promising research has been conducted with certain molecules with different isotopes that are either a direct result or an immediate byproduct of processes involved in the nuclear fuel cycle. More specifically, of safeguards interests are molecules like UF_6, HF, HDO, HTO, (among others) as well as the measurement of the enrichment level of UF_6, all of which play a role in multiple processes throughout the nuclear fuel cycle (See Figure 1).

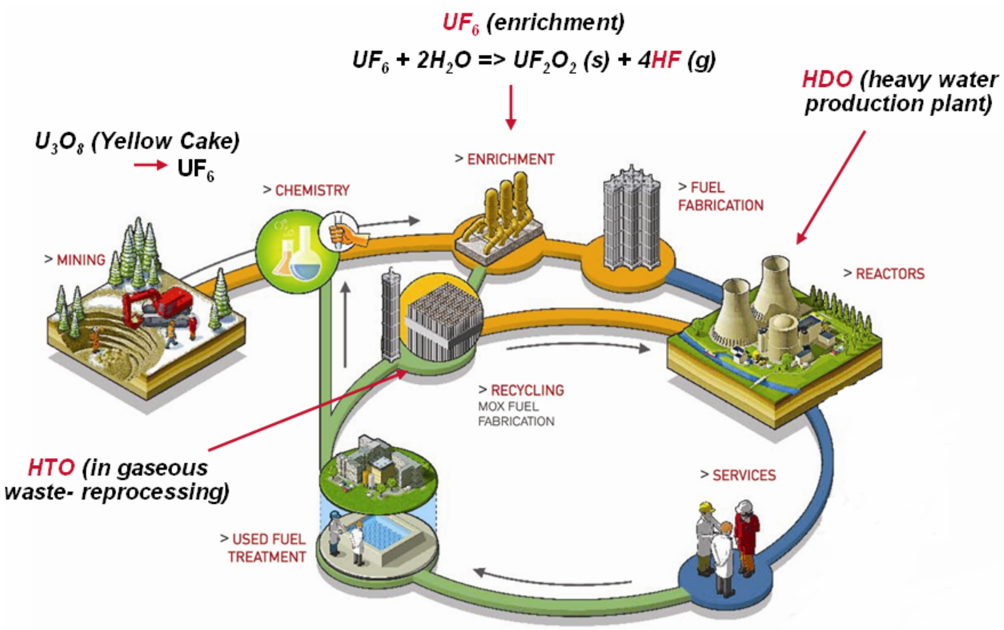

Figure 1: Some molecules of Interest in the Nuclear Fuel Cycle

A strong indicator for the presence of a nuclear process is Uranium Hexafluoride (UF_6) as it is a product of nuclear fuel production and used in various enrichment processes. UF_6 molecules that are released into ambient air, even in minute quantities, react with their atmosphere water, resulting in Hydrogen Fluoride (HF) as a byproduct. The detection, even at low level of HF, could be used for the detection and the localization of undeclared activities involving UF_6. Other molecules that exist throughout the fuel cycle and are of interest for safeguards are Hydrogen Deuterium Oxygen (HDO) as it is a moderator for nuclear reactors and it is involved in the production of Hydrogen Tritium Oxygen (HTO). HTO itself can be found in the gaseous waste of nuclear power stations and can potentially be used for a reactor boosted nuclear weapon.

The detection of such molecules can support safeguards measures in two ways. Their presence can first be an indication of nuclear processes where none should exist (undeclared activities), and second, provide additional information about the nature of declared nuclear processes. The main advantage of TDLS is that such systems can provide non-invasive measurement results with real-time or near real-time data processing, thus avoiding costly and time-consuming swipe sample taking, handling and shipment, as well as destructive analysis methods.

Of specific interest is the measurement of the isotopic composition of UF_6 as its enrichment level is an indicator for the potential use of the fuel. UF_6 is the only gaseous form of uranium and used throughout the nuclear industry to separate the ^{235}U isotope from the ^{238}U isotope using various enrichment methods. The percentage to which the uranium is enriched in its ^{235}U content represents the potential use for the generated fuel; relatively low enriched uranium (LEU) is used for the production of fuel elements for civil power reactors while relatively highly enriched uranium (HEU) can be used for the production of a nuclear weapon.

While the mere presence of UF_6, regardless of its enrichment, can give significant clues about the existence of undeclared nuclear programs, the IAEA also has to verify the uranium enrichment in declared facilities as the same installations can be used to produce both LEU and HEU. The current safeguards approach uses swipe samples and destructive analysis by mass spectrometry. Thus, TDLS could provide a time and effort saving alternative.

Overall, three fields of applications for TDLS-based systems can be envisioned for safeguards use. The first group consists of portable instruments inspectors can carry into the field to take air samples and conduct measurements to detect traces of certain molecules such as HF and UF_6. The results of such an analysis can give clues about the presence of undeclared nuclear activities and complement information the IAEA has gathered about a safeguarded country or a specific location using other information sources, such as other environmental sampling methods, satellite imagery, open source analysis, or wide area monitoring.

The second application is a portable instrument for the on-site, non-destructive analysis of UF_6 samples taken at declared nuclear facilities to verify the enrichment level of the produced material. This method could complement or replace the current destructive analysis process and give near real-time measurement results that could be used by the inspectors to draw safeguards conclusions in a timely manner. It should be noted that such an instrument is not only of interest to the safeguards community; but operators of enrichment facilities might be interested in a similar instrument to complement their own quality assurance tests using destructive analysis and mass spectrometry.

Finally, a third application could be a continuous enrichment monitor permanently installed at the facility in an unattended mode and integrated into the enrichment process to continually measure the enrichment level of the UF_6 production. Such an instrument would have to include all the necessary features for unattended or remote equipment, such as the authentication of generated data, protection of the electronics using secure, tamper-indicating enclosures, etc.

All three applications pose unique technical challenges to researchers and developers. Attended instruments need to be portable, battery powered, rugged for field use, and easy to operate. They need to complement and, under certain circumstances, be capable of interacting with other instrumentation the inspector carries into the field. Unattended instrumentation requires the development of TDLS systems based on laser techniques that operate at room temperature or with non-liquid nitrogen cooling detectors as continuous unattended operation with liquid nitrogen cooling would not be feasible.

In addition, other technical challenges lie in the requirement for the high accuracy needed for the measurement of the isotopic ratio of UF_6 molecules, as the system needs to be at least as effective as the current measurement methods to represent a viable alternative (for example in unattended mode the accuracy should be better than 3% relative of the measured enrichment). Finally, the issue of prototype testing has to be carefully addressed as there is no current baseline test procedure available to interpret the results obtained by TDLS-based instruments in such applications.

Overall, the third application would be the most difficult to implement since its implementation not only faces the technical challenges of unattended equipment, but also implies changes to the existing infrastructure of existing facilities which might have undesired consequences for the operation of the plant. Also, certain parameters of the production feed of the plant are considered confidential by plant operators and could potentially be measured by a TDLS-based system, adding a confidentiality factor to the picture. The challenges surrounding this application are not only of a technical nature but are impacted by political and procedural concerns, making its realization so much more difficult.

3. THE TDLS WORKING GROUP FOR IAEA SAFEGUARDS

When the IAEA investigates a new technology field that has never been applied towards safeguards, it falls into its Novel Technology program. Within this program, the Agency investigates new technological development as well as solutions developed for other markets with regards to their applicability to existing and emerging needs of the safeguards community. In early 2006, the IAEA dedicated a Novel Technology Workshop to the field of laser spectrometry to identify potential additions to safeguards measures and to define technology roadmaps for how to realize new instrumentation [2]. An international group of invited experts in the field of laser spectrometry discussed with IAEA staff members and inspectors the capabilities of various techniques and identified a list of tasks for the development of TDLS based and other systems.

The first task item was the creation of the Working Group to further study possible TDLS-based safeguards applications and to better coordinate future instrument developments. The Working Group for the Implementation of TDLS for IAEA Safeguards started its work by assembling members actively involved in the research and development of TDLS-based components and instrumentation, commercialization of safeguards equipment, and technical support for safeguards inspectors. The Working Group meets on a regular basis to review the progress of projects on an as-needed basis and oversees the project progress, defines milestones, accepts deliverables, and reviews the requirements for new TDLS applications.

4. SAMPLE TDLS-BASED DEVELOPMENT PROJECT

The first application selected for the implementation for safeguards use falls into the first category mentioned above – a portable detector to be carried into the field by an inspector to analyze ambient air samples both inside and in the vicinity of selected facilities during complementary access inspections. The molecule under investigation is Hydrogen Fluoride (HF). HF is an indicator for potential, undeclared production of UF_6 of any enrichment level as UF_6 that leaks into ambient air reacts with its hydrogen in accordance with the following formula:

$$UF_6 + 2H_2O \rightarrow UF_2O_2\,(s) + 4HF$$

The presence of HF – once detected in an air sample – is a signature of interest for the IAEA, but not necessarily conclusive evidence for a covert nuclear program as other industrial processes, such as the production of aluminum generate HF. It is, however, an indicator that might lead to further investigation by the IAEA or that might complement other safeguards relevant information gathered through other methods.

In a framework of international partners, under the project management of the IAEA, conducted the baseline research and development for the HF detector, identified and built the necessary components, and completed the design into a portable backpack version. Picture one shows the prototype unit.

Picture 1: Portable HF Detector

The trace HF molecule concentration detector determines molecule content by its resonance absorption. A diode laser with a working wavelength (close to 1.29 μm) that coincides with the molecular absorption band is used as a light source; a S. M. Chernin [3] multipass optical cell is used for improving the sensitivity. The detector consists of an analytical and a reference channel, both connected to the diode laser. Figure 2 below shows the general schematic of the detector. The diode laser module interrogates both channels; the resulting spectra are sent via an interface to a conventional notebook for analysis. First tests show the limit of detection of the instrument to be around 1 part per billion. The detection sensitivity would need to be better than 0.5 ppb.

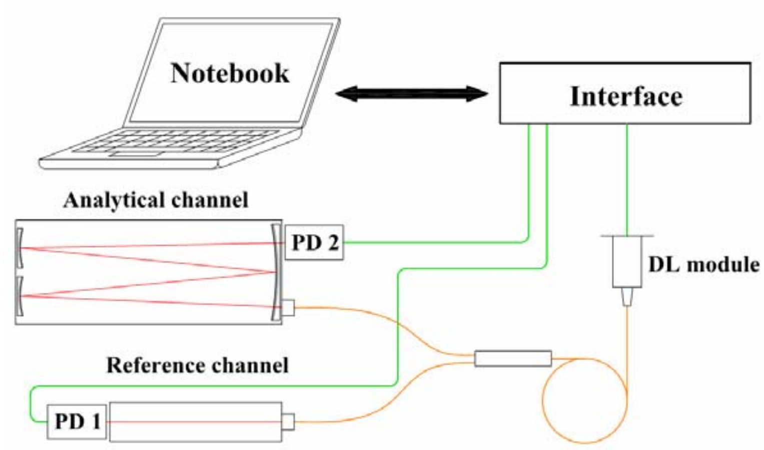

Figure 2: Trace HF molecule concentration detector general schematic

The greatest challenges impacting the design for the HF detector were the mechanical design, as the size and weight had to be supported by an IAEA inspector of average strength and build, in addition to the technical specifications formulated by the IAEA and the TDLS Working Group. Since this was the first instrument of this type for safeguards purposes, the final requirements could only be formulated once the first testing results were available. This in turn forced the designers to change the component to achieve the desired precision. Also, the generation of baseline reference values needs to be completed in field tests at real facilities to understand the value of the quantitative analysis of presence of HF gas in the atmosphere at enrichment facilities and other installations where HF might be present. These tests are currently on-going, using the prototype unit delivered to the IAEA. Their results will help to further refine the design of the HF detector and give a better understanding of the user requirements for other TDLS-based systems.

5. CONCLUSIONS

TDLS-based instrumentation can be used extensively for international safeguards applications. The detection of undeclared activities and inspections on a short- or no-notice basis will gain more and more importance for evaluating NPT Member States as a whole and will help channel inspection resources to the appropriate locations. At the same time, increasing the effectiveness and efficiency where traditional safeguards measures can be applied helps the IAEA to find the right balance of verification efforts on an international level.

To bring on-going and planned projects on TDLS-based instruments for safeguards to a successful conclusion and into the hands of inspectors, the efforts of the TDLS Working Group need the continued support of existing partners and sponsors, as well as the involvement of other potential contributors. The involvement of Member States Support Programs (MSSPs) that donate funding, expertise, and task management services to the IAEA on an extra budgetary basis, needs to be fostered and expanded. Currently, the German Support Program is sponsoring the development for a laser diode tuned to the specific spectral range of UF_6 as a key component for the design of a UF_6 detector. The involvement of other support programs in a similar manner will be essential to the success of such development efforts.

Furthermore, the expertise of research and development institutions currently not involved in a TDLS project but with insight into baseline physics research, as well as operators of nuclear facilities where TDLS-based systems would be used, should be drawn upon to tune the requirements of the instrumentation and to allow for testing and calibration under real conditions. This is work in progress, and existing and potential partners are lined up to make TDLS-based solutions available for the non-proliferation community in the near future.

REFERENCES

1. The IAEA Safeguards Glossary, 2001 Edition, International Nuclear Verification Series No. 3, Vienna 2002, or http://www.iaea.org/About/index.html.

2. Technical Meeting on Application of Laser Spectrometry Techniques in IAEA Safeguards, STR-352, 28 August-1 September 2006, Vienna, Austria.

3. S. M. Chernin, E. G. Barskaya: Optical Multipass Matrix Systems. Appl. Opt. 30, 51-58 (1991).