Advanced Safeguards Measurement, Monitoring and Modelling Laboratory (AS3ML)

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ABSTRACT

Safeguarding declared nuclear facilities is a main duty of the nuclear safeguards inspectorates. Depending upon the amounts of nuclear materials present (and physical/chemical form), a certain inspection approach (and corresponding dedicated techniques and equipment) is developed. This approach will be very different for an item facility compared to a bulk-material handling process, whereby in each case we strive to a maximum efficiency and effectiveness of the safeguards system. Traditionally these safeguards measurements are executed with independent, safeguards approved, measurement equipment, complementary to the existing plant equipment and focusing on a variety of nuclear material diversion scenarios (and statistical considerations) The innovative aspect of the Advanced Safeguards Measurement, Monitoring and Modelling Laboratory, AS3ML, subject of this paper, is that it aims to complement the above approach by providing an alternative method to monitor the process of sensitive facilities such as Gas Centrifuge Enrichment and Nuclear Fuel Reprocessing plants. It endeavours thus to enhance the "traditional safeguards measures" by the focus on and analysis of (other) process parameters, which a priority each individually might not have a highly significant value, but which, taken all together, might allow to get a very good insight in the proper operation (thrust building measures) or alternatively to the deviations from the "theoretical" values of the behaviour of a facility. The AS3ML is thus conceived as an R&D location, test bed, demo facility and training centre for innovative safeguards approaches where researchers, inspectors (and operators) can conceive and analyse different approaches (including competing technologies) for safeguarding nuclear facilities. Techniques and approaches, not currently used in routine safeguards applications, will be discussed including a reference to a recent achievement for a fully new way of safeguarding a plutonium storage location which is presented elsewhere in this symposium.

1 – Rationale for an Advanced Safeguards Laboratory

For several decades NMAC (Nuclear Material Accountancy & Control) has been the cornerstone of nuclear safeguards. The main pillar of NMAC was mostly relying on nuclear measurements for the verification of operator's declared NM inventory; nuclear measurements, either destructive (DA) or Non-destructive (NDA), were then complemented by containment and surveillance measures (C/S) in order to guarantee the Continuity of Knowledge (maintaining in a long period the knowledge acquired during an inspection).

Since nearly 20 years, the implementation of safeguards has slowly moved away from classical NMAC towards the new approach of integrated safeguards. In addition to the verification of NM inventories, the IAEA inspectors have now the mandate to confirm the absence of clandestine activities having a potential proliferation risk. Information-based safeguards involve a broad possibility of collection of data from different sources, internal or external to the plant, and their correlation and analysis in order to confirm the conformity of the operations of the facility according to the declared activities and exclude the presence of undeclared activities.

These approaches require an increased use of monitoring techniques to automatically control nuclear activities in facilities such as reprocessing and to follow (tracking) processed nuclear materials. It can reduce requirements for inspector presence and increase safeguards effectiveness both in terms of timeliness and sensitivity. Monitoring involves the integration of data from a variety of sensors (pressure, neutron, gamma, cameras, weighing systems, barcode readers,…) to control activities involving material in transit or in process. The innovation lies mainly in having a high level of automated intelligence allowing the system to recognise anomaly in the behaviour by integrating the different types of data.

The collection and storage of these large amounts of data require also the development and validation of suitable databases apt to integrate all the data from the different types of sensors, time stamping them and reduce their volume as much as possible (by exclusion and compression algorithms) in order to avoid mass storage problems.

The analysis and interpretation of large amounts of process data in complex facilities requires also system modelling. A JRC software tool has been developed that continuously monitors nuclear material flows through a reprocessing plant. This JRC process monitoring tool aims at a verification of the consistency and coherency of plant operation with safeguards requirements. This allows timely comparison of the operational reports of the facility and the inspector's observations.

Integration of multi-sensors into complex systems introduces also the issue of data exchange and interoperability. Standardisation on data exchange formats will help in this integration process. .

The introduction and future expanded use in nuclear facilities of unattended instruments requires also reliable solutions concerning the remote and secure transmission of data from the facility to the inspectorate headquarter.

Following the above described trends, JRC-ITU-NUSEC felt the need to establish a new laboratory to be able to test and develop innovative integrated solutions for the implementation of safeguards in the different types of nuclear installations. The three main pillars that the new laboratory intends to put together are:

- **Measurement** of nuclear material that remains anyway the basic tool for NMAC
- **Monitoring** the operation of facilities through an extensive collection of data from multiple types of sensors
- **Modelling** the plant operations in order to be able to analyse the data collected by the monitoring system, compare to expected behaviours and derive conclusions on the appropriate operations of the plant according to declarations

The name of the new laboratory considers these three main aspects: Advanced Safeguards Measurement, Monitoring and Modelling Laboratory (**AS3ML**).

The goals that AS3ML wants to fulfil are:

- grouping the state of the art techniques / tools for advanced safeguards in almost all facilities of the current nuclear fuel cycle
- serving as platform for future developments of integrated safeguards concepts including advanced sensor and plant modelling, ambient intelligence, investigative approaches, remote control, and integrated data analysis
- paving the way for an increase in both safeguards efficiency and effectiveness

AS3ML aims to fulfil three main purposes:

- **Research & Development** on innovative techniques (sensors, tools and systems) for integrated safeguards applications
- **Demonstration** of integrated solutions for specific nuclear plants with full or reduced scale mock-ups
- **Training** of nuclear inspectors on these novel approaches

2 – AS3ML layout

AS3ML intends to cover (almost) the entire cycle of the nuclear fuel concentrating on the processes that constitute a major concern on proliferation risks and for which more efficient and effective techniques are required for nuclear safeguards:

- Uranium **enrichment** plants, in particular those based on gas centrifuges (GCEP)
- Fuel **fabrication** plants, in particular those for MOX fuels
- Nuclear **reactors**, with special attention to the spent fuel reactor pond
- **Reprocessing** plants
- Storage places for end products (e.g. PuO_2)
- Interim or final **storage** facilities for spent fuel and wastes

Following this concept the laboratory space (about 300 m2) has been conceived in modular way with areas dedicated to the different facilities. Figure 1 shows a preliminary layout of the laboratory and the different areas:

- GCEP test-bed facility for load cell monitoring systems
- Mini-Process area for small scale facility of liquid transfer in tanks of a reprocessing plant
- Interim/final storage area, indeed a test-bed of techniques for tracking of items within facilities
- Spent fuel pond area
- Simulation of the local inspector office and of the inspectorate headquarter to study and test remote data transmission issues

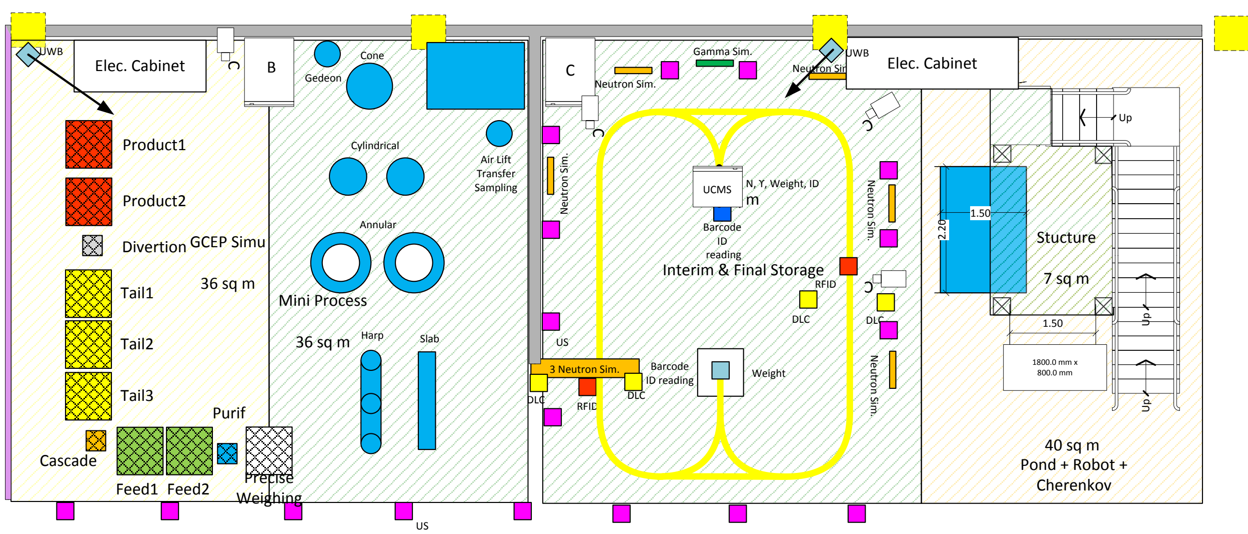

Figure 1 a – AS3ML layout

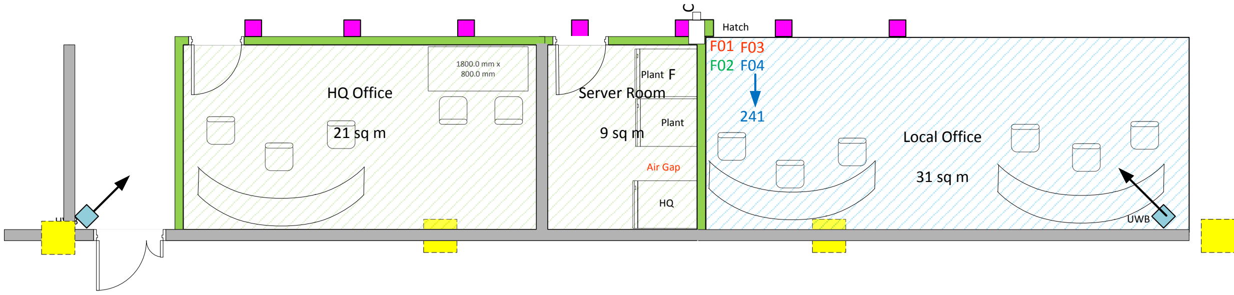

Figure 1 b – AS3ML layout

According to the type of facility, a variety of techniques that are currently applied or could be envisaged for future deployment have been selected to be integrated in AS3ML. The table in figure 2 provides a (non-exhaustive) list of the techniques that might be included in the laboratory.

	Technology	Gas centrifuge	Fuel Fabrication	Reactor (operation)	Temp Storage Spent Fuel Pond	Spent Fuel Reprocessing	Final Storage / PuO2 Store	Models for techniques / sensors
T1	Electronic seals			X	X	X		
T2	US Seals				X		X	
T3	RFID	X				X	X	X
T3'	Geo-location	X	X	X	X	X	X	
T4	Camera (2D/3D)	X	X	X	X	X	X	
T5	ID (OCR) of cans		(X)			X	X	X
T6	3DLVS	(X)		X		X	X	X
T7	Laser Contnm & ID	X	X			X	X	X
T8	Investigative Inspector	(X)		X		(X)	X	
T9	2D Laser Curtains/DLC			X	X	X		
T10	Balance (mass)	X	X			X		X
T11	Pressure (level, density)	(X)				X		X
T12	Temperature	(X)				X		X
T13	Neutron	X	X		X	X	X	X
T14	Gamma counting	X	X		X	X	X	X
T15	Gamma spectrum		X		X	X	X	X
T16	On-site lab (*)					X		
T17	Cherenkov radiation				X			
T18	Micro gravimetry						X	
T19	DA-Analytics (*)	X	X			X		
T20	Satellite imagery	X		X			X	X
T21	Remote data transmiss.	(X)	X	(X)	(X)	X	(X)	
T22	Process/Data Analysis	X	X	X	X	X	X	X
T23	Integrated Plant Model	(X)		X		(X)		

Figure 2 – Correspondence table of inspection techniques versus nuclear facilities

3 – The spent fuel pond area

Spent fuel ponds are the most sensitive part of nuclear power plants from a safeguards perspective and thus poses very specific needs. As in most other fields of safeguards there is a trend aiming at more efficient control systems. More efficiency means less exposure of personnel to radiation, better control, better integration with the facility procedures (and consequently a wider adoption and cooperation by operators). For this reason a dedicated area for techniques suitable for spent fuel ponds is foreseen in AS3ML with layout shown in figure 3. The facility integrates mainly items related to the underwater sealing and surveillance, since the spent fuel pond is an area of storage in the fuel life cycle. [1] The activities that are monitored by safeguards are mainly loading and unloading of stacks and movement of spent fuel bundles

[2]. These activities do not produce a continuous output. The main goal of safeguards in this case is to detect events that reveal undeclared activities.

Figure 3 – Layout of the pond area

The facility can be used also to test new technologies for safeguards. The ongoing research activities can be deployed and verified at an early stage, to test them from a functional point of view, but also to detect possible vulnerabilities.

Ongoing projects are:

- Ultrasonic seals
- Mixed ultrasonic-fiber optic seal for dry storage

Future projects are:

- Cherenkov effect simulation
- Remote-unattended verification of ultrasonic seals
- Laser curtain surface monitoring
- Automated verification of ultrasonic seals
- Sonar 3D underwater monitoring
- Tele-operation assistance

4 – The GCEP area

The layout of a Gas Centrifuge Enrichment Plant (GCEP) and the technologies typically applicable to safeguarding it are summarised in figure 4

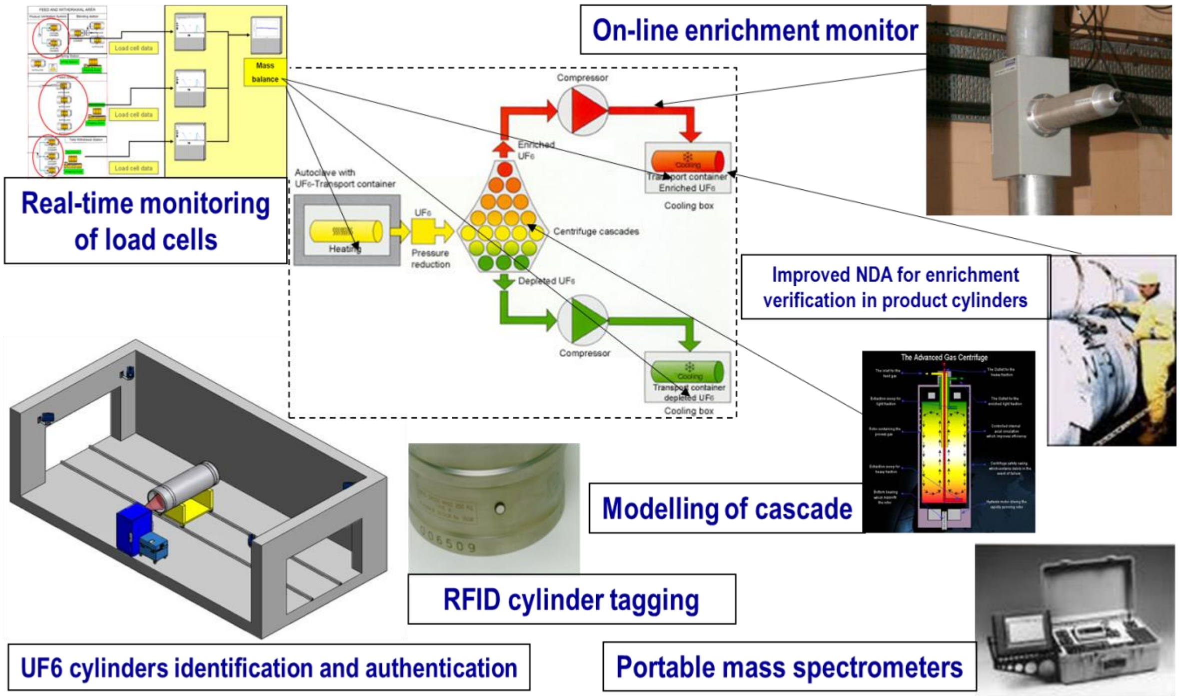

Figure 4 – Layout of a GCEP and related safeguards technologies

Among the main directions of evolution of safeguards technologies applicable to GCEPs we can certainly expect a few that will gain increased attention in the near future:

- Monitoring of the (feed, product and tail) load cells; coupled with
- Verification of plant operation through cascade/centrifuge modelling
- Tracking/identification/authentication of cylinders entering/exiting the facility
- Monitoring of activity through tracking of movements of the loading machine

All these are envisaged to be included in AS3ML.

The purpose of the GCEP test bed facility will be to demonstrate and support the implementation of the load cell monitoring technique to GCEP safeguards [3] through:

- Testing and optimization of the acquisition parameters
- Test and validation of the theoretical centrifuge/cascade model
- Analysis of transients
- Testing, validation and training on the analysis software
- Assess the capability to detect diversion scenarios

The facility will also be used for some model testing and corroborating.

AS3ML will also be used for demonstrating the well-known Laser Item Identification System (L2IS) and for the possible customization to different enrichment plants. Furthermore, it will be a platform for investigating the integration with other surveillance and tracking systems and with NDA systems for verifying the enrichment and mass of the cylinder content.

Apart from following the items containing nuclear material, an alternative method to monitor the operation in a nuclear facility could be the control of process equipment. One example is how indoor localization and identification could be used for tracking the transfer of UF_6 cylinders in GCEP, based for instance on ultrasound or radio-frequency.

5 – The mini-process area

Reprocessing plants (RP) are among the most sensitive ones in the nuclear fuel cycle and safeguards inspectorates have always invested large efforts to control them. JRC has an historical competence in supporting Euratom and IAEA inspections in reprocessing plants like La Hague, Sellafield and Rokkasho. In particular the Process Monitoring Laboratory (PML) is especially dedicated to the development and validation of techniques used to monitor and account solutions of nuclear material in RPs and to train inspectors [4[. The PML is equipped with full-scale vessels similar to those installed in RPs and is located in the same hall as AS3ML.

A demo and training area for simulation of processes in RPs is included in the AS3ML and will be equipped with reduced-scale vessels of different shapes. The layout is shown in figure 5.

Figure 5 – Layout of the mini-process area

The Mini-Process area is mainly intended to simulate the transfer of solutions containing nuclear material in reprocessing plants, to test the software used to monitor the process and train the inspectors in the review of data. This area will complement the equipment of PML providing a variety of smaller scale vessels of different shapes (cylindrical, conical, slab, annular, harp,…) connectable with a choice of transfer systems (pumps, gravity, syphon,…). Some R&D components associated to this is the development and validation of software for automated calibration of mass/volume measurement devices and for the tank calibration verification by continuous flow mode.

New measurement devices are foreseen to be developed using the latest technologies in term of industrial data acquisition and data transmission.

The monitoring software tool, called DAI (Data Analysis and Interpretation) has developed by JRC upon request of the EURATOM inspectorate and was initially specifically designed for process monitoring in RPs, even though its modularity and flexibility allows nowadays its use for monitoring most of the safeguards-relevant processes in all the nuclear facilities. This monitoring tool does more than just supervision: it interprets the signals and verifies the consistency and coherency with predefined criteria and without intervening in the process. These criteria are based on the design characteristics of the recipients and transfer mechanism.

6 – The interim/final storage area

The area called storage is indeed conceived to test techniques applicable to any kind of itemised facility, such as fabrication plants, nuclear material storages, reactors, interim storage of spent fuel, final repositories, waste deposits, etc. The area layout together with some preliminary list and disposition of equipment is shown in figure 6

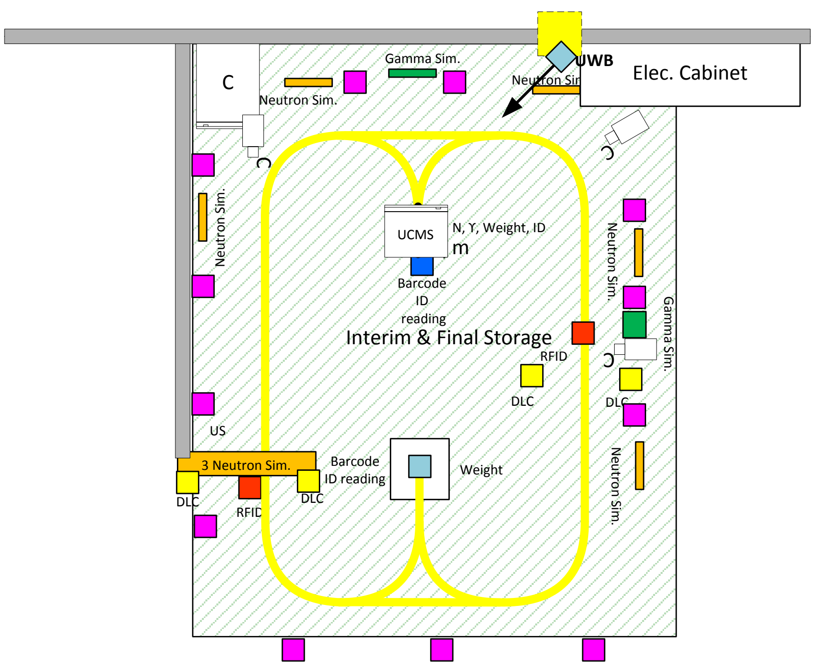

Figure 6 – Layout of the storage area

The storage area is going to be equipped with all the types of sensors that can be used to track and follow movements of items containing nuclear material in a plant. This might include (but not limited to):

- Simulated Radiation detectors (gamma and neutron)
- Surveillance equipment (cameras and lasers)
- Weighing systems
- Identification devices (bar-code readers, RFID,…)
- Localisation devices (UWB, ultrasound, ,…)
- Seals

The storage area will also integrate results of the innovative work on 2D and 3D cameras and advanced review software and the 3D Laser Verification System.

- 3D laser scanning for design information verification (DIV) and facility monitoring: 3D laser scanners are used to acquire as-built 3D models inside nuclear facilities with mm accuracy. The models are used i) to verify design information provided by the operators (DIV) or ii) to identify changes in the facility by comparing the current 3D model to previously acquired reference models (facility monitoring) [5], [6].
- 3D Containment and Surveillance techniques are also based on 3D measurements. The surface geometry at the time of verification is compared to a reference data set to verify that the surface has not been tampered. 3D containment can be applied on the container level (typically using triangulation-based scanning with high accuracy) or on facility level. [7]
- Laser-based identification and authentication techniques measure the surface geometry of nuclear containers with very high accuracy, thus creating a unique signature of the container. This 'fingerprint' is then used to uniquely identify the container. Examples include the L2IS for the identification of UF6 containers in enrichment facilities [8] and LMCV for the identification and authentication of dry storage containers [9].
- Current R&D activities include mobile 3D laser scanning, which allows the inspector to move while acquiring the 3D measurements and therefore to carry out the DIV and facility monitoring tasks described above more efficiently. Furthermore, it can be used for indoor localization in GPS-denied areas which can very valuable for example during Complementary Access visits [10], [11].

Since the use of real nuclear material is not foreseen within AS3ML, the signal of radiation detectors will have to be simulated. Neutron counter and gamma spectrometer surrogates are under development. They will be able to reproduce the signal of real instrumentation as a function of position and type of the simulated nuclear material.

An example of the type of work planned in this area can be derived from the work done for a Plutonium store in a reprocessing plant on the Sellafield site for DG ENER [12]. The plutonium storage serves to store PuO_2 containers received from reprocessing of spent fuel. It is divided in a temporary and a main store. Currently, the following procedure applies for the transfer of PuO_2 containers into the main storage:

- Main store can be accessed only in presence of a DG ENER inspector
- In the meantime, PuO_2 containers are introduced in channels between the main and the temporary stores
- Containers are retrieved in presence of the inspector and are manually measured with EURATOM instrumentation

An unattended monitoring system has been designed to improve the efficiency and effectiveness of safeguarding the plutonium storage, which makes integrated use of different measurement and surveillance devices:

- Double laser curtain to detect entry/exit events and to categorize items (forklift, trolley…) for direct review of relevant images
- To identify equipment pieces duly authorized to access the store
- Neutron portal monitor to distinct entries/exits of nuclear material
- Unattended Combined Measuring System combining a weighing device, neutron counter, gamma spectrometer and ID reader

7 – The local and remote inspector offices

Future safeguards will make use more and more of unattended monitoring systems coupled with remote data transmission, provided that secure data transmission is granted. In order to test the data communication tools and protocols and to demonstrate the functionalities of the remote monitoring software, AS3ML will host two offices that will act respectively as the Local Inspector Office at the facility and the Inspectorate Headquarters, see lower part of figure 1. The equipment of the office areas will basically consist on high-end servers for collection and storage of data from the different other areas of the AS3ML, workstations for data retrieval and analysis by the inspectors, large screens to project synoptic of the facilities

The main requirements for the data transmission systems include

- Flexibility in adding/removing devices to/from the data transmission system
- Monitors with Graphical User Interfaces (GUI) should allow to display the facility layout and verify the status of devices at the local office
- The Headquarters Office should allow to view the status of the process and access to a (limited) set of operator approved data
- Communication between facility and local office and between local and HQ offices should include authentication features
- Data communication between local and HQ offices shall have integrity strength to be managed by public internet (encryption)
- Communication protocols should be compatible with international standards and make use as much as possible of proven industrial tools

In addition to the capability to acquire data from devices and to analyse them through appropriate algorithms, remote monitoring of facility operations requires the functionalities enabling the inspectors to better understand the process and what is happening in the facility. This can be enhanced by developing suitable human interfaces with comprehensive and friendly pictorial representations of the facility and/or the process and of the devices that are used to monitor it. Among the goals of AS3ML, there are also the development, demonstration and user training on visualisation tools for efficient and effective monitoring.

8 – Outlook

The laboratory is currently under intensive construction. Some functionalities described above are already operational (like the spent fuel and part of the item facility). It is expected that the laboratory will be fully available for R&D, Demonstration and Testing after the summer 2015, i.e. about 1 year from now but we are already willing to start discussions with DG ENER and IAEA inspectorates and their technical support departments to examine their interests for future uses of the AS3ML.

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