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Determination of 'Decommissioned for Safeguards Purposes' of the Post-Accident Facilities at Fukushima Dai-ichi

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Abstract

The status of a post-operational facility being *decommissioned for safeguards purposes* is determined in part by the designated essential equipment for that facility either being removed or rendered inoperable. Inherent in that determination is the ability of the IAEA to visit the essential equipment in the facility to observe its status. It is not possible to visit many of the essential equipment locations at the post-accident facilities on the Fukushima Dai-ichi site due to the radiological conditions. This paper examines the methodology by which these facilities can be considered decommissioned for safeguards purposes without full access to the essential equipment, by taking a holistic approach to the equipment systems required for the operation of a reactor.

Introduction

The International Atomic Energy Agency (IAEA) safeguards measures that apply to a facility depend on the *Facility life cycle* phase, with different measures applied during the different phases. The determination by the IAEA of which phase a facility is in is therefore an important component of the safeguards approach for that facility, particularly for the *post-operational phases* as key measures such as *Inspections* and *Design Information Verification* are no longer applied when the facility reaches the appropriate phase. Generally, the definitions of the life cycle phases are such that the determination of the phase is straightforward; for example, a facility that is not in operation and being decommissioned moves from the *shut-down* phase to the *closed-down* phase when all the nuclear material has been removed from the facility. The complete removal of the nuclear material can be verified by the IAEA through inspection.

It has been recognized that the final phase change, from the closed-down phase to the *decommissioned for safeguards purposes* phase, is less straightforward for the IAEA to determine, as this requires an assessment of the removal of any functionality of the facility related to nuclear material. The IAEA Department of Safeguards has recently produced guidance [1] on the application of safeguards at facilities during the post-operational phases, which contains a methodology for determining whether a facility has been decommissioned for safeguard purposes. The determination has two major components: verification by the IAEA that nuclear material is no longer present at the facility; and a determination that that the equipment essential for the operation of the facility has either been removed or rendered inoperable.[1]

An issue arises when considering the decommissioning of facilities at which accidents have occurred ('post-accident facilities'), as access to *essential equipment (EE)*, as defined in the *Essential Equipment List* (EEL)[2] may be restricted by the radiological or other safety-related conditions at the facility or on the site. These facilities may be functionally inoperable and undergoing decommissioning, but, without access, inspectors cannot meet the requirements of Ref. [1].

This became apparent when considering the decommissioning of the post-accident facilities on the Fukushima Dai-ichi site. A case in point is the Unit 4 reactor on the site, for which the IAEA has verified that all the nuclear material has been removed (closed-down phase) and is being decommissioned. However, not all the EE is accessible. A methodology for the determination of the status of decommissioned for safeguards purposes for Unit 4 is presented here.

Fukushima Dai-ichi Reactor Unit 4

Unit 4 is a 760 MWe boiling water reactor (BWR), with a Mark I containment design. At the time of the earthquake in March 2011, it was undergoing maintenance, and the core was empty, with all core fuel unloaded to the spent fuel pond (SFP), which also contained a large number of spent fuel and fresh fuel assemblies. Following the tsunami, the reactor hall was badly damaged by an explosion caused by hydrogen generated at the neighbouring Unit 3 reactor.

The damage to the building caused by the explosion left no working infrastructure with which to recover the fuel assemblies from the SFP. In response, the facility operator Tokyo Electric Power Company (TEPCO) built a new free-standing cover over Unit 4 that incorporated fuel handling equipment for the transfer of the fuel assemblies from the SFP to a cask. The cask was then used to move the fuel assemblies to the common spent fuel storage (CSFS) facility on the site. These transfers commenced in November 2013 and by the end of 2014 all fuel assemblies had been removed from Unit 4 and stored in the CSFS, where they have been reverified by the IAEA [2].

The declared nuclear material inventory in Unit 4 is zero, and therefore the facility can be considered to be in the closed-down phase.

Determination of Decommissioned for Safeguards Purposes

In order that a facility may be designated as in the decommissioned for safeguards purposes phase, the methodology given in Ref. [1] requires that the IAEA make a determination that sufficient equipment from the facility’s EEL has either been removed or disabled such that the equipment is “rendered inoperable,” and that the facility cannot be returned to operation, with rendered inoperable defined as “not used to store and can no longer handle, process or utilize nuclear material.” Implicit in this assessment is a determination that the equipment is permanently disabled, with Reference 1 stating that, as a practical matter, inoperability means that “equipment cannot be repaired and returned to use in any facility.”

Note that, in addition to the EEL items, Ref. [1] also requires the facility’s “residual structures” be removed or rendered inoperable. A feature of some post-accident facilities like Unit 4 is that the residual structures, such as the reactor building and turbine hall, may have been damaged in the accident but remain in place, as removing the structures could release radioactivity to the environment. It is difficult for the IAEA to independently judge the inoperable status of an accident-damaged structure from a safeguards perspective. It is therefore considered that the requirement of Ref. [1] to assess a facility’s residual structures may not be applicable for post-accident facilities.

Successful determination of the decommissioned status results in a reduction in the verification burden at the facility for both the State and the IAEA. For a State with an Additional Protocol in force, complementary access to the decommissioned facility remains an option for the IAEA.

BWR Essential Equipment List

The Department of Safeguards has defined a generic EEL for light water reactors, which was developed based on an assessment by independent experts. The light water reactor EEL is applicable to all light water reactor types, and includes the BWRs and pressurized water reactors (PWRs) in use in Japan. As this is a generic EEL, it does not describe the specific equipment for an individual facility as declared in the *Design Information Questionnaire* (DIQ).[3] This has presented an issue for the reactor operators in Japan when considering the decommissioning of power reactors, as a list of the specific EE for the reactor is required so that the DIQ can be updated as equipment is removed. In response, the Japanese power reactor operators proposed a specific EEL for the BWRs and PWRs in Japan, which was reviewed by the IAEA and adopted. Table 1, at the end of this paper, presents the generic EEL for light water reactors, and the specific EEL adopted for Japan's BWRs, including Unit 4. A schematic diagram of the EE of Unit 4 is shown in Figure 1.

Note that, for Unit 4, some of the pre-accident EE was damaged in the accident, and the infrastructure erected for the recovery operations has led to the installation of new EE (for example a new gantry crane, and refuelling platform) that has replaced the damaged equipment.

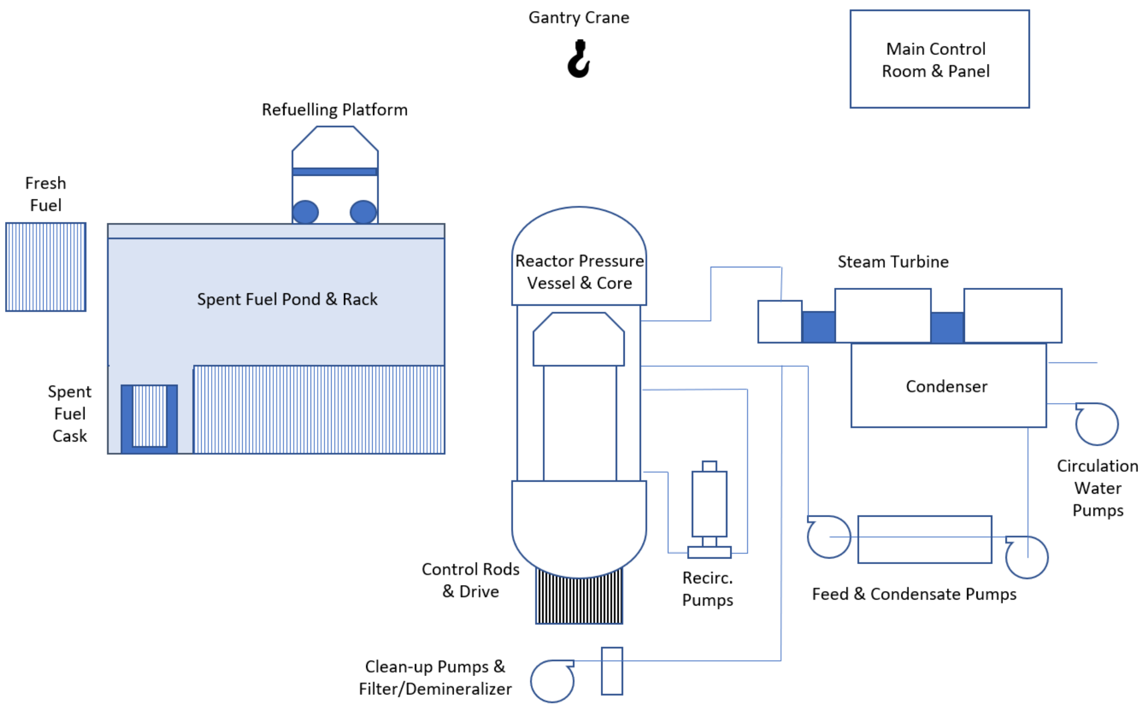

FIG. 1. Schematic Diagram of the Essential Equipment in Fukushima Dai-ichi Reactor Unit 4.

Group Essential Equipment for BWR reactor into systems.

The standard procedure for the assessment of the items on the EEL for a facility is to consider the status of each EE item separately, and to assess the operability of the facility based on the status of all the EE items; i.e., the facility is considered decommissioned if all[4] the EE is removed or rendered inoperable. This approach has the advantage of being the most complete, as it considers all the possible ways that a facility may operate (handle, process or utilize nuclear material). It also allows for the fact that nuclear facilities may retain functions important to the *acquisition path analysis* (APA)[5] whilst not being able to fulfill the original function of the facility. This is particularly true for facilities that process nuclear material; for example, a fuel fabrication plant may retain the EE to process nuclear material to produce sintered pellets, whilst removing the EE required to produce a fuel assembly. The APA would then consider the production of pellets and transfer to another facility at which fuel assemblies could be made.

From a safeguards perspective, the only processing of nuclear material in a power reactor is the irradiation of fresh fuel to spent fuel; the nuclear material in the fuel is utilized to produce heat. The EE items either directly support this process (e.g., reactor pressure vessel components) or are indirectly supporting (e.g., fuel handling and storage equipment). In general, in order to process or utilize nuclear material, a reactor facility requires the entire EE in the facility to be in an operational condition. This recognition allowed a refinement to the standard procedure to be developed for post-accident reactor facilities, in which the status of *functional systems* of EE are considered rather than each EE item alone.

The EEL for Unit 4 was analysed, and the EE grouped into the following functional systems:

- Reactor Pressure Vessel
- Fresh Fuel / Fresh Fuel handling
- Instrumentation and Control
- Coolant Circulation
- Heat removal
- Irradiated fuel handling

In addition to the systems required for utilizing nuclear material, the EE groups include the functional systems for the handling of nuclear material (i.e., fresh & spent fuel assemblies). The specific EE associated with the Unit 4 functional systems are shown in Table 2, at the end of this paper. Note that some items appear in more than one group.

Assessment of the Operability of the Functional Systems

By grouping the EE into functional systems, the status of the functional systems can be assessed using *Design Information Verification* (DIV), even if not all the EE items are available.[6] If the DIV finds that one or more EE items belonging to a functional system are removed, or rendered inoperable such they are permanently disabled, an assessment of the EE functional system will be performed that could conclude that the functional system as a whole is inoperable, and that the reactor cannot operate. This would remove concerns about the facility's potential misuse while such a state is maintained. This assessment should be continuously monitorable and be based on easily detectable changes, i.e., thorough implementation of routine IAEA safeguards measures such as complementary access and satellite imagery analysis. Focusing on EE functional systems is the central difference for the approach being suggested for post-accident facilities versus that outlined in Ref. [1].

In order to aid the assessment of the EE functional systems, it was decided to use standardized assessment language for the conclusion of the DIV for each functional system, with each judged to be:

- Operable – the system shows little or no evidence of inoperability, or is known to have operated in the post-accident period.
- Showing evidence of inoperability – the condition of the observed EE in the system provide evidence that the system may not be able to operate. Can be qualified as being 'strong' or 'weak' evidence as necessary.
- Inoperable – Firm evidence of inoperability, such as restraints on operation, unrepairable damage or removal of EE.
- Not assessed – if a judgement could not be made, for example if there was insufficient evidence seen during the DIV.

The use of standardized assessment language permits a uniform application across different facilities. As discussed above, for reactors, a single functional system assessed as inoperable is sufficient to show that the reactor cannot operate, provided that state is maintained. If there are no functional systems assessed as inoperable, the assessment will need to consider those systems that are assessed as 'showing evidence of inoperability', and a judgement made on a case-by-case basis of the cumulative impact of the evidence across several functional systems on the overall operability of the facility.

Design Information Verification

DIV was performed at Unit 4 in February 2023 by a team of IAEA inspectors, accompanied by State inspectors from the Japan Safeguards Office (JSGO) and TEPCO operators. Prior to the visit, the IAEA reviewed the EEL, and selected equipment to which access was expected to be possible. This excluded equipment that was located in the main reactor building, such as the primary loop recirculation pumps, due to access constraints resulting from the accident. The list of candidate equipment was shared with JSGO and TEPCO, and TEPCO were asked to provide information on the accessibility of the equipment. The resulting list of accessible EE is shown in Table 2.

The visit was carefully planned with the cooperation of all parties, in order to minimize the dose accrued by the visit team. TEPCO provided dose rate maps of the areas to be visited, and the routes through the facility areas and the length of time to be spent in each area agreed in advance.

During the DIV, standard activities were performed, with visual observations, photograph taking, GPS coordinate taking and dose rate measurements made.

DIV Findings for each Functional System

Reactor Pressure Vessel

As Unit 4 was in an outage at the time of the accident, the Reactor Pressure Vessel Head (RPVH) had been removed, and was being stored in its laydown position in the Reactor Hall. After the accident, the location of the RPVH on the floor of the damaged reactor hall was verified by the IAEA during DIV in 2012. Since then, the RPVH has been lifted down from the reactor hall prior to the installation of the new cover. During the February 2023 DIV, the RPVH was observed stored at a location on the site away from Unit 4.

The original gantry crane was damaged in the hydrogen explosion, and later removed. The newly installed cover has a new gantry crane, with a capacity sufficient to lift the RPVH. However, during the DIV, it was observed that the range of the gantry crane is limited by the design of the cover – the cover is designed such that the roof in the core region is significantly lower than in the rest of the reactor hall. The DIV confirmed that the gantry crane cannot pass over the reactor well, and the RPVH cannot be lifted into position in the reactor well given these constraints. The DIV therefore confirmed that the Reactor Pressure Vessel is **inoperable**, provided the installed cover remains in place.

Fresh Fuel / Fresh Fuel Handling

Unit 4 does not contain any fresh fuel, as it has been removed and is currently stored elsewhere on site. The new cover has a refuelling platform installed, which replaced the original damaged refuelling platform, and was used during the recovery operations to transfer the stored fresh and spent fuel assemblies from the SFP to the cask for removal from the facility. The design of the cover does not permit the new refuelling platform to pass over the core; however, an additional working platform has been installed to service the core region, and this could potentially be used to load fuel into the core. The Fresh Fuel / Fresh Fuel Handling system is therefore considered to be **operable**.

Instrumentation and Control

The Unit 4 main control room was visited and it was found to be intact, with all control panels and switches still in place. However, without power to the systems, the Instrumentation and Control system **could not be assessed**.

Coolant Circulation

The primary loop recirculation pump, clean up water pump and clean up water filter demineralizer are inaccessible as they are located in the Reactor Building, and could not be assessed.

The condensate pump and condensate booster pump, which are located on the basement floor of the turbine building, were inaccessible, partly due to high dose rate measured at access points, and reportedly due to water ingress.

Unit 4 has two Reactor Feed Water Pumps. Pump A was observed during the DIV to be in a dismantled state with the rotor removed. The surface of the rotor appeared corroded. The access to Pump B was restricted due to stored equipment, but its general condition appeared to be poor.

The observations during the DIV provided **strong evidence of inoperability** of the Coolant Circulation system.

Heat Removal

The high-pressure and low-pressure turbines were found to be still in place, but with the high-pressure turbine in a state of dismantlement, with the turbine blades removed, and stored adjacent to the turbines. The gantry crane in the turbine hall is still in place, but its working condition could not be assessed. It is possible that the turbine blades could be replaced at short notice. However, assuming the major components remain viable, returning the turbines to a state of full operability would require a major overhaul to ensure proper rotor balancing, sealing and bearings, etc. As such, the DIV assessment was that there was evidence of the inoperability of the turbines.

At the time of the tsunami, the circulation water pump was located on the sea front. It was observed during the DIV not to be in place, and evidence from reviewing satellite images taken in the immediate days following the earthquake suggest that it was destroyed by the tsunami. The Unit 4 circulation water pump is therefore inoperable. The location is accessible, and new infrastructure and equipment is being installed in the area, so it is possible that another pump could be installed. However, the DIV assessment was that there is evidence of the inoperability of the circulation water pump system.

The observations during the DIV provided **evidence of inoperability** of the Heat Removal system.

Irradiated Fuel Handling

The gantry crane, spent fuel pond and racks was found to be in position, and they are known to be **operable** as they were used to transfer the spent fuel from Unit 4.

DIV Summary and Conclusions

In summary, the DIV assessment of the operability of the Unit 4 EEL functional systems was as follows:

- Reactor Pressure Vessel — Inoperable
- Fresh Fuel / Fresh Fuel handling — Operable
- Instrumentation and Control — Not assessed
- Coolant Circulation — Strong evidence of inoperability
- Heat removal — Evidence of inoperability
- Irradiated fuel handling — Operable

Given the inoperability of the Reactor Pressure Vessel, it is clear that Unit 4 is not capable in its current state to utilize nuclear material to produce power, i.e., Unit 4 cannot function as a reactor. This removes any concerns regarding the possibility of misuse of the reactor. However, as Unit 4 retains the functions associated with the handling and storage of nuclear fuel it cannot overall be classified as decommissioned for safeguards purposes.

Considering this assessment, Unit 4 could be reclassified from a reactor to a storage facility (as allowed for in Ref. [1]), albeit with zero inventory, which would allow streamlining of the safeguards approach for the facility, reducing the burden on the IAEA and the facility operator. In addition, this would reduce the DIV requirement, such that only the storage areas were required to be visited in future, which would provide safety benefits.

It is noted that the assessment of inoperability of the Reactor Pressure Vessel is determined based upon the structure of the installed cover, and the IAEA will continue to monitor, through measures such as complementary access on the site and satellite imagery analysis, that the installed cover remains in place and is not modified.

Extension of the methodology to the other Post-Accident Reactor Units

The methodology developed for Unit 4 can be applied to other post-accident reactors that are in the closed-down phase. However, some post-accident reactor facilities still maintain a nuclear material inventory, which is possibly inaccessible for verification at the time of the assessment. The Fukushima Dai-ichi reactor Units 1, 2 and 3 fall into this category, as the partial core melting that occurred in these units resulted in fuel debris material in the cores that cannot yet be accessed and retrieved. While the same sort of determinations about the presence and operability of the EE can be made with this methodology, the move to a closed-down or decommissioned for safeguards purposes status is not possible due to the presence of nuclear material.

The IAEA has performed similar DIV activities at the Unit 3 reactor on the site. While achieving a closed-down or decommissioned status is likely a very long way away, verification of the EE and independent determination that the facility can no longer perform any of the functions of a reactor can allow the eventual reclassification of the facility from a power reactor to something more appropriate. It is expected that the core debris retrieval efforts will involve the installation of new EE for the handling and removal of the nuclear material. It is also expected that new removal routes will be opened up as the retrieval process advances. The type of design information relevant to safeguards will change accordingly.

The storage, retrieval and any attendant processing of nuclear material from the damaged cores will involve EE distinct from that required for a reactor. The most appropriate facility classification and the types of EE for the Fukushima Dai-ichi Units 1, 2 and 3 will be considered as the safeguards approach for the retrieval operations of the core debris material is developed.

Conclusions

The IAEA Department of Safeguards has developed a methodology for determining the status of a post-operational facility as being decommissioned for safeguards purposes. Inherent in that determination is the ability of the IAEA to access the EE in the facility to observe its status. However, for post-accident facilities, such as the damaged reactors on the Fukushima Dai-ichi site, it is not always possible to have access to all the EE in the facility. In response, the methodology has been adapted by grouping the EE into functional systems and the operability of the EE functional systems is assessed during DIV, rather than each EE item. This holistic approach potentially allows the determination of decommissioned for safeguards purpose status to be made without full access to every defined EE item in the facility.

DIV was performed at Unit 4 in order to assess the EE functional systems. This assessment concluded that, due to the inoperability of the Reactor Pressure Vessel functional system, the facility can no longer support the process of fuel irradiation. However, the functional systems that relate to the handling and storage of nuclear material were assessed to be operable. Therefore, the overall conclusion is that the facility cannot be classified as decommissioned for safeguards purposes; however, this would allow the facility to be considered as a closed-down, zero-inventory, storage facility, enabling simplification of the safeguards approach.

The methodology can also be applied to the damaged reactor Units 1, 2 and 3 on the Fukushima Dai-ichi site, although as these facilities maintain a nuclear material inventory in the form of core debris material, they cannot be considered as in the closed-down phase. The methodology instead can be used to determine the appropriate facility type classification for these units.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, International Safeguards Guidelines for the Post-Operational Phases of Nuclear Facilities and Locations Outside Facilities, STR-396, IAEA, Vienna.

[2] MURRAY, M., PERSIN, J., HORTON, G., NAKAJIMA, S., KABUKI, T., OYAMA. K., 'Responding to evolving safeguards challenges at Fukushima Dai-ichi' INMM & ESARDA Joint Virtual Meeting (Proc. Annual Meeting 2021), INMM, 2021.

TABLE 1. ESSENTIAL EQUIPMENT LIST FOR JAPAN BWR

Generic Light Water Reactor Essential Equipment List		**Detailed Equipment in Japan BWR**
Process	**Equipment**	
Pressure containment	Reactor Pressure Vessel	Reactor pressure vessel （including reactor core shroud）
Fuel	Fuel pins, normally zirconium alloy tubes loaded with sintered UO2 and potentially some MOX pellets, assembled as fuel assemblies.	Fuel assembly
Moderator and primary coolant	Light water	Reactor Pressure Vessel
Coolant	Main and auxiliary cooling water systems (intake)	Reactor feed water pump Condensate pump Condensate booster pump
Coolant circulation	Pumps	Primary loop recirculation pump Reactor feed water pump Condensate pump Condensate booster pump
	Primary coolant treatment plant	Reactor clean up water pump Clean up water filter Demineralizer
Reactivity Control	Control rods/assemblies (indium/cadmium and silver alloy or boron carbide)	Control rod Control rod drive
	Borated water	Not applicable
Instrumentation and control	Control room; neutron flux, power, temperature, flow and pressure monitors.	Control panel at Main Control Room （Monitors of neutron flux, power, temperature, flow and reactor pressure）
Heat removal for producing electricity	Steam generator	Not applicable
	Steam driven turbines and condenser	Steam turbines （High Pressure, Low Pressure) Condenser
	Cooling towers, water reservoirs	Circulation water pump
Refuelling	Refuelling machines	Refuelling platform
Irradiation fuel handling/storage	High integrity cranes	Gantry crane (Operating Floor)
	Large pools of water	Spent fuel rack Spent fuel storage pool
	Irradiated fuel casks/castors	Spent fuel cask

TABLE 2. UNIT 4 FUNCTIONAL SYSTEMS

Functional System	**Essential Equipment**	**Location in Unit 4**	**Accessible for DIV**
Reactor Pressure Vessel	Reactor pressure vessel （including reactor core shroud） Gantry Crane	Reactor Hall	Yes
Fresh Fuel / Fresh Fuel handling	Fuel assembly Refuelling platform	Reactor Hall	Yes
Instrumentation and Control	Control panel at Main Control Room (Monitors of neutron flux, power, temperature, flow and reactor pressure）	Service Building	Yes
	Control rod Control rod drive	Reactor Building	No
Coolant Circulation	Reactor feed water pump	Turbine Hall	Yes
	Condensate pump Condensate booster pump	Turbine Hall	No
	Primary loop recirculation pump Reactor clean up water pump Clean up water filter Demineralizer	Reactor Building	Yes
Heat removal	Steam turbine （HP, LP)	Turbine Hall	Yes
	Condenser	Turbine Hall	No
	Circulation water pump	Seaside Yard	Yes
Irradiated fuel handling	Gantry crane Spent fuel rack Spent fuel storage pool Spent fuel cask*	Reactor Hall	Yes

* Spent fuel casks are stored on the site in the CSFS facility and are accessible for DIV.

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[1] There is also acknowledgment of the role of Complementary Access under an Additional Protocol in determining the ongoing status.
[2] The *Essential Equipment List* for a facility is a list of equipment, systems and structures essential for the operation of the facility.
[3] A document submitted to the IAEA by States to provide information on the design of a facility in accordance with the requirements of a comprehensive safeguards agreement.
[4] Or most sufficient; Ref. [1] allows some flexibility on the level of removal required.
[5] An acquisition path analysis is a structured method used to analyze the plausible paths by which, from a technical point of view, nuclear material suitable for proscribed purposes could be acquired.
[6] DIV are activities carried out by the IAEA at a facility to verify the correctness and completeness of the design information provided by the State.