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Title: DOE/NSA Perspective Safeguard by Design: GEN III/III+ Light Water Reactors and Beyond

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Abstract

DOE/NNSA Perspective Safeguard by Design: GEN III/III+ Light Water Reactors and Beyond

An overview of key issues relevant to safeguards by design (SBD) for GEN III/IV nuclear reactors is provided. Lessons learned from construction of typical GEN III+ water reactors with respect to SBD are highlighted. Details of SBD for safeguards guidance development for GEN III/III+ light water reactors are developed and reported. This paper also identifies technical challenges to extend SBD including proliferation resistance methodologies to other GEN III/III+ reactors (except HWRs) and GEN IV reactors because of their immaturity in designs.

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DOE/NNSA Perspective Safeguard by Design:

GEN III/III+ Light Water Reactors and Beyond

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December 15, 2010

Outline

- Introduction
- Lessons Learned
- IAEA Safeguards Objectives
- SBD for GEN III/III+ LWRs
  - Impact on Current Safeguards Regimes
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    - Area-specific Guidance
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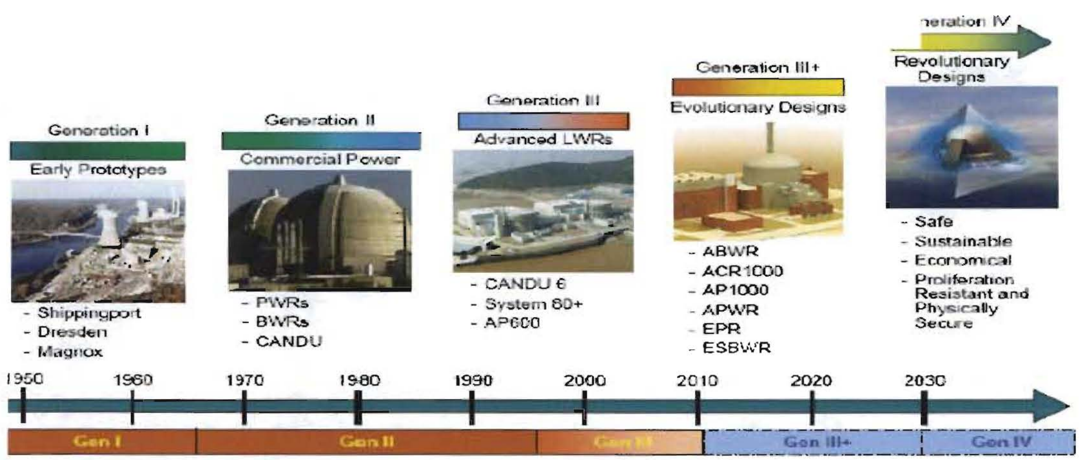
- Challenges Ahead
- Conclusions

Introduction

Safeguards by Design (SBD): An incorporation of safeguards requirements early in the design phase of a new nuclear facility to minimize plant life-cycle costs by averting potential plant retrofits after construction and operation of the plant.

Generations of Nuclear Energy:



Characteristics of GEN III/IV Reactors

- GEN III/III+ Reactors (LWRs, HWRs, HTGRs, FBRs)
  - Economical: less fuel cost (~5-7%) uranium/MWh, >35% thermal efficiency (for example, LWRs)
  - Safer: 100-1000 below NRC's core melt and large release frequencies
  - Extended reactor life: from 40 to 60 years
- GEN IV Reactors (Thermal and Fast Reactors)
  - At various theoretical design stages (deployable by 2030)
  - Further improvement in performance, nuclear safety, proliferation resistance
  - Reduction in waste generation, natural resource utilization
  - Saving in cost to build and operate

Future Outlook of Nuclear Power

- Projected nuclear power capacity, grows from 400 GWe to 1000 -1500 GWe by 2050.
- Total of 32 GEN III/III+ LWRs are under considerations in U.S.
    - 14 Advanced Passive (AP1000), 7 European PWR (EPR), 4 Advanced BWR (ABWR), 2 Advanced PWR (APWR), 1 Economic and Simplified BWR (ESBWR), 4 TBD
    - 4 early site permits issued by NRC
    - 10 GWe projected by 2020, 64 GWe by 2030

Lessons Learned

- Olkiluoto 3 (GEN III+ EPR) in Finland
  - Camera locations readjusted in reactor building and in fuel building
  - Need penetrations for safeguards instrumentation cables
  - Fuel identification and transfer routes difficult to be under continuous C/S, acceptable solutions discussed.
  - Additional design for safeguards instrumentation, unexpected costs, delay etc.
  - Early involvement by safeguards authorities is desired
  - Safeguardability and proliferation resistance should be added to the design requirements
  - All stakeholders should be addressed for safety, security, and safeguards precautions before national licensing
- SBD was implemented at ACR-1000 based on Proliferation Resistance and Physical Protection (PR&PP) methodology, diversion pathways identified and addressed in design phases.

Olkiluoto 3 in 2009

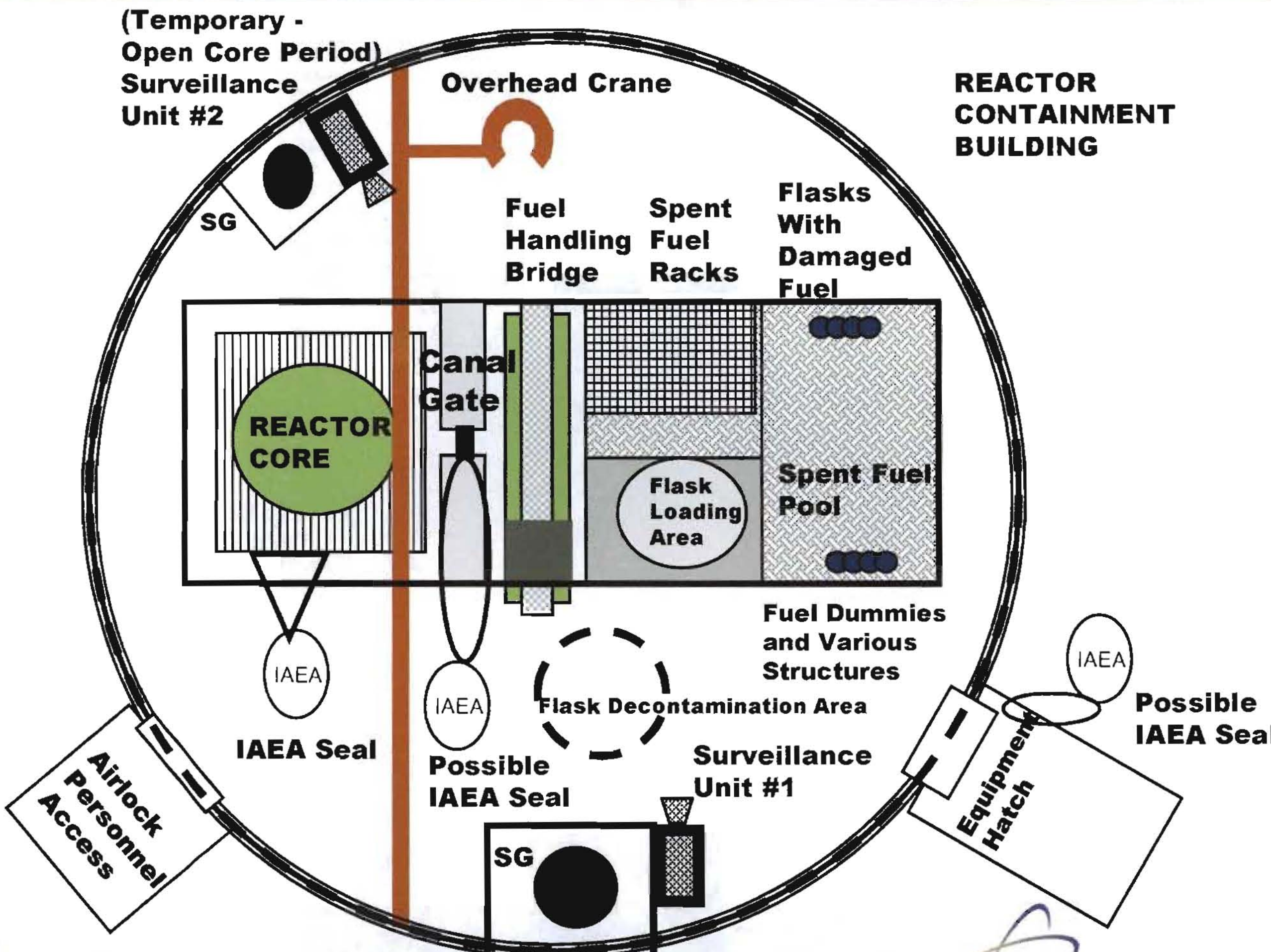
Representative GEN III/III+ LWRs

Reactor	Supplier	GEN	MW(e)	Enrichment	Burn-Up (GWd/T)	Fueling Interval	MOX Capability	Life (YR)	NRC Design Certification
ABWR (Advanced BWR)	GE, Hitachi, Toshiba	III	1350	1.7-3.2% initial, 4.2% reload	45	35% for 2 yr-cycle	Yes	60	1997
AP600 (Advanced Passive)	Westinghouse	III	600	1.9% (Region 1) 2.8% (Region II) 3.7% (Region III)	65	18 months	Yes	60	1999
APR 1400	Korean Advanced PWR (US System 80+)	III	1450	5%	55	18 months	Yes	60	2012 (to apply)
VVER-1000 (PWR)	OKBM Gidropress	III	1000	2.4-4.4%	47	1 yr	Yes	35	na
ESBWR (Economic and Simplified)	GE Hitachi	III+	1520	4.20%	50	20% for 1 yr, 42% for 2 yrs	Yes	60	2010-2011 (expected)
AP1000	Westinghouse	III+	1000	2.35% (Region 1) 3.4% (Region II) 4.45% (Region III)	65	2 yr	Yes	60	2005
EPR (European PWR)	Areva	III+	1650	up to 5%	65	2 yr	Yes	60	2004

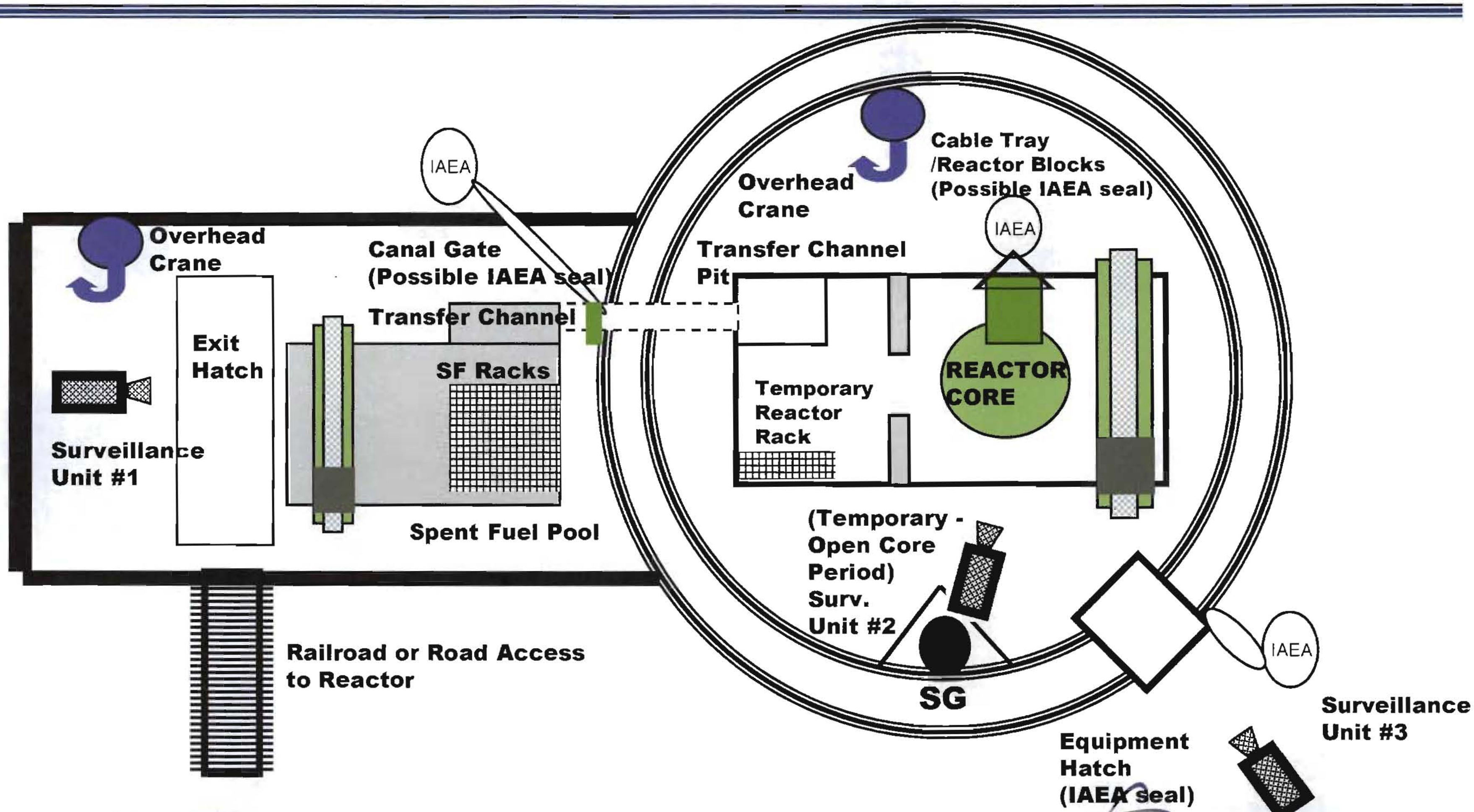
IAEA Safeguards Objectives

Material Category	Fuel Types	Amount of SQ	Timeliness Goal
Unirradiated Direct-Use	HEU Fresh Fuel	U-235 = 25 kg	1 Month
	MOX Fresh Fuel	Pu = 8 kg	
	Fresh Fuel	U-233 = 8 kg	
Irradiated Direct-Use	Core Fuel, Spent Fuel	Pu = 8 kg	3 Months
	Core Fuel, Spent Fuel	U-233 = 8 kg	
Unirradiated Indirect-Use	LEU Fresh Fuel	U-235 = 75 kg	1 Year
	Th Fresh Fuel	Th = 20 T	
Unrecorded Production		Pu = 8 kg	1 Year
		U-233 = 8 kg	

LWR Layout - Type I Reactor Design



LWR Layout - Type II Reactor Design



Safeguards Concerns at LWRs

- LEU Fresh Fuel Diversion
  - Source of LEU for enrichment
  - Pu production in reactor
- MOX Fresh Fuel Diversion
  - Source of unirradiated Pu
- Spent Fuel Diversion
  - Source of Pu by diversion of
    - Entire fuel assemblies
    - Individual fuel pins
- Unreported Pu Production
  - Source of Pu produced in fertile targets in PWR guide tubes or Burnable Poison Rods (BPR)

Diversion and Concealment Activities

Diversion	Method	Timing
LEU FF Diversion	Substitution of dummy element for actual element	After FF receipt verification - prior to Core Loading
MOX FF Diversion	Substitution of dummy element for actual element	Prior to Core Loading
SF Assembly Diversion	Substitution of dummy element for actual element	From Reactor Core, SF Pool, or SF transfer cask
SF Pin Diversion	Substitution of dummy pin for actual pin	From SF Pool or SF transfer cask
Unreported Pu Production	Insertion of fertile item in reactor for irradiation -In CF – (PWR Guide Tubes or BPR)	From SF Pool or SF transfer cask

GEN III/III+ LWRs: Safeguards Perspective

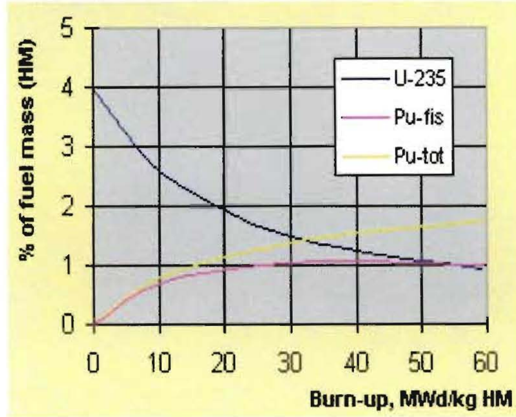
- All GEN III/III+ LWRs are designed for LEU and MOX fuels
- U-235 enrichment: ranging from 1.7 to 5 %*
- Fuel burn-up ranges from 45 to 65 GWd/T*
- Refueling cycle ranges from 12-24 months*

* Design of International Reactor Innovation Secure (IRIS) PWR deviates from the above:

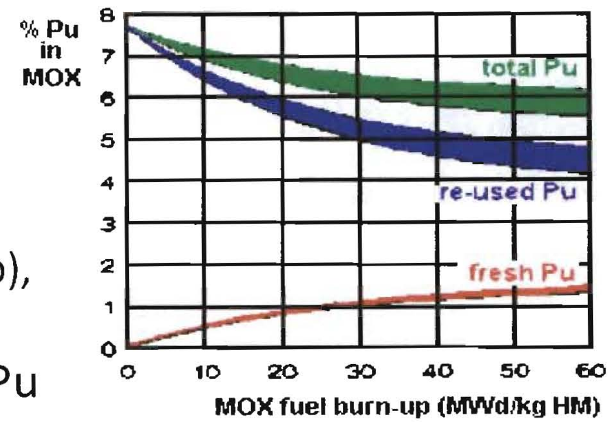
- Enrichment: 5% (initial), 10% (ultimate)
- Burn-up: 60-80 GWD/T
- Refueling cycle: 3-3.5 years (initial), 10 years (ultimate)

GEN III/III+ LWRs: Significant Quantities

- **75 kg of U-235 in LEU Fuel**
  - For 4% initial U-235 enrichment, ~5 fresh fuel assemblies contain 1 SQ, ~15 spent fuel assemblies (at burn-up of 40 GWd/T) contain 1 SQ.
  - For 10% initial enrichment, 2-3 fresh fuel assemblies contain 1 SQ.



- **8 kg of Pu in MOX Fuel**
  - Fresh Fuel
    - For 8% Pu, 1 fuel assembly contains ~30 kg Pu
  - Spent Fuel
    - For 5-6 % Pu (at burn-up of 60 GWd/T burn-up), one fuel assembly contains ~20 kg
  - One MOX fuel assembly has more than 1 SQ Pu



GEN III/III+ LWRs: Impact on Current Safeguards Regimes

- Fresh and spent MOX fuels that EACH fuel assembly contains >1 SQ Pu
  - Requiring additional safeguards procedures
- Gen III LEU SF with higher burn-ups than Gen II LEU SF
  - Gen III LEU SF Contains more Pu than LEU SF from GEN II LWRs
- Increase in time between refueling and SF pool cooling time
  - Impacts physical inventory verification schedule and or SG approach
- Fabrication of MOX fuel requires more Pu production
  - Impacts safeguards process on spent fuel reprocessing
    - More SF transports
    - More reprocessing facilities and/or Pu throughput
    - More separated Pu and/or stored Pu

SBD Initiatives and Key Guidance Documents

- IAEA Technical Reports Series No. 392, "Design to Facilitate Implementation of Safeguards at Future Water Cooled Nuclear Power Plants," 1998
- Safeguards Guidance Document for Designers of Commercial Nuclear Facilities: International Nuclear Safeguards Requirements and Practices fro High Temperature Gas Reactors (Pebble Fuel HTGRs), INL, 2010
- Safeguards by Design: Safeguards Guidance for GEN III/III+ Light Water Reactors, LANL, 2010

GEN III/III+ LWRs: General Guidance in Safeguards Design

- Material transport paths
  - Minimum access points
  - Adequate illumination
  - Continuity of knowledge
  - Containment and surveillance
  - Maximize joint-use equipment

- Safeguards inspection activities
  - Minimum impact on plant operations
    - Integration of operation, safety, security, safeguards
    - Joint-use equipment
    - Remote and automated systems
    - Data processing and communications
  - Safe (ALARA)
  - Expeditious
  - Continuous

GEN III/III+ LWRs:
General Guidance in Safeguards Design (cont)

A. Data Information Collection and Transmission

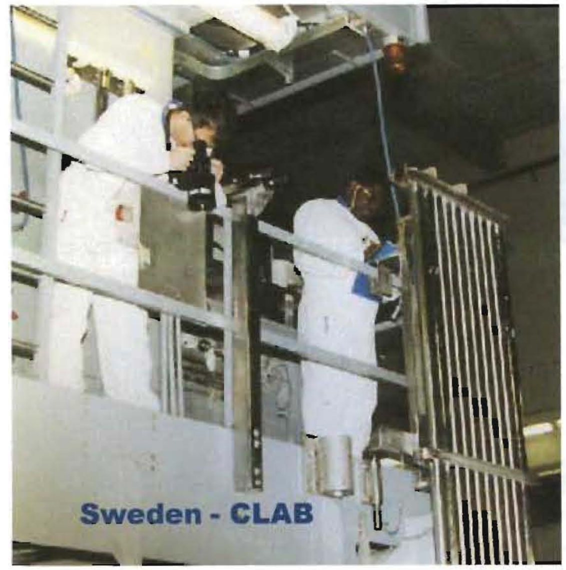
- Penetrations for data transfer lines
- Network connections at measurement sites
  - Tamper resistant
  - Digitizing equipment
  - Centralized data recording, analysis, and processing
  - Remote and offsite transmission

Collection, Conversion, and Transmission of Inspection Data

GEN III/III+ LWRs: General Guidance in Safeguards Design (cont)

B. Identifiers for Fuel Assemblies and Fuel Rods

- Water clarity and readability
  - Readable from above in the fresh fuel storage area, the spent fuel pool, and in the reactor core
- Temper resistant
  - Hard to remove or change without detection
  - Legible throughout irradiation and storage.



Tracking, Accounting, and Control of Fuel Assemblies

GEN III/III+ LWRs: General Guidance in Safeguards Design (cont)

C. Containment and Surveillance

C.1 Sealing Systems – Means of Demonstrating Secure Containment

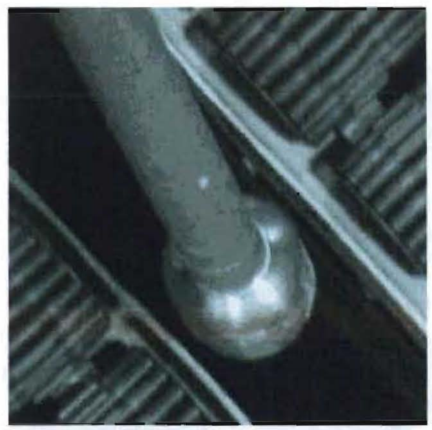
- Secure (no passage of a fuel item)
- Temper resistant
- Shock resistant (for example, mechanical and radiation)
- Accessible

C.2. Optical Surveillance

- Continuity of surveillance
  - Power supply
  - Operational versatility

GEN III/III+ LWRs:
Area-Specific Safeguards Design Guidance

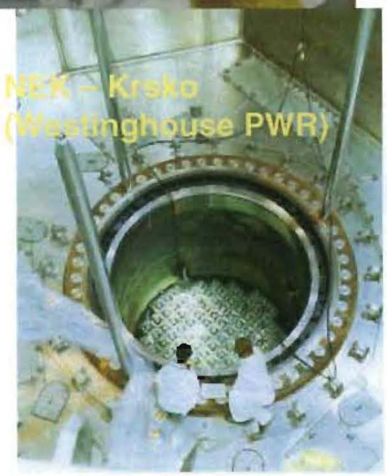
- Fresh Fuel Receiving and Storage Areas
  - Minimize openings in the building structure with suitable arrangements that allow for sealing and/or surveillance of these openings
  - Design storage area that ensures CoK
  - Provide adequate space and illumination between assemblies



Detects 186 keV gamma peak from U-235 in gamma spectrum

GEN III/III+ LWRs: Area-Specific Safeguards Design Guidance (cont)

- Fuel Loading and Unloading
  - Mount surveillance equipment to view tops of fuel assemblies
  - Design an indexing mechanism on refueling machine to identify location of each assembly
  - Provide sealing for canal gate to indicate fuel movement
- Reactor Core
  - Design a sealing system for the nuclear material located in reactor core
  - Integrate surveillance equipment for viewing reactor vessel operations
  - Incorporate underwater illuminations
  - Ensure water clarity for confirming fuel identifiers



GEN III/III+ LWRs: Area-Specific Safeguards Design Guidance (cont)

- Spent Fuel Storage and Shipping Areas
  - Select light sources that its spectrum does not overlap the characteristics of Cerenkov viewing device
  - Configure single-layer storage rack for top viewing of identifiers, if practical
  - Minimize number of openings with suitable arrangements that allow for sealing and/or surveillance of these openings
  - Provide water clarity for visual inspection of stored fuel assemblies with evidence of Cerenkov glow from the assemblies
  - Provide mechanisms to facilitate annual physical inventory verification, for example, minimizing spent fuel movement for NDA verification

Detects Cs-137 660 keV gamma peak in SF gamma spectrum

GEN III/III+ LWRs:
MOX-Specific Safeguards Guidance

Fresh MOX Fuel

- Minimize fresh fuel storage time at the power plant,
- Provide adequate space for the use of NDA equipment,
- Provide a means for easily sealing the fuel within dry storage.
- Provide for the installation of underwater surveillance camera(s) that cover the MOX fuel.

Spent MOX Fuel

- For purposes of safeguards, the designers should treat the MOX SF the same as LEU SF, both fuels contain plutonium and uranium. The IAEA considers them irradiated direct-use material with 3-month timeliness.

Challenges Ahead

- To what extent that one should develop and include "improvements" of current proliferation resistance methodology (e.g., PR&PP) in the SBD process?
  - The presence of intelligent adversaries
  - The changing threat over time
  - The presence of evolving and adaptive defensive strategies
  - The difficulty of estimating the effectiveness of measures that may not yet have been deployed, or in some cases, may not even have been developed
  - The need for information protection and classification
- How to develop and deploy an advanced and integral nuclear material tracking system from fuel enrichment, fabrication, transport, power generation in reactor core, storage, to shipment?
- What metrics does one use to measure effectiveness of SBD, or what is the value added of SBD?
  - Life cycle cost
  - Safeguardability enhancement (quantitative, qualitative etc)
  - IAEA inspection time and effort

Conclusions

- Safeguards guidance for GEN III/III+ light water reactors was developed based on
  - IAEA safeguards objectives, requirements, reactor designers.
  - Lessons learned from IAEA inspection experts (now residing at Los Alamos) in nuclear power installations.
  - Specific design features to the GEN III/III+ LWRs (e.g., high burn-ups, MOX fuel, cooling time)
- NNSA's SBD for HTGR provides safeguards guidance for GEN IV designers
- Lessons learned (from EPR and ACR) need to be addressed as early as practical
- Periodic update of advanced technologies is required
  - Material verification
  - Data processing and analysis
  - Communications

BACKUP Slides

GEN III/III+ Nuclear Power Reactors

LWRs	Reactor	Supplier	GEN	MW(e)	Enrichment	Burn-Up (GWd/t)	Fueling Interval	MOX Capability	Life (YR)	NRC Design Certification
	ABWR	GE, Hitachi, Toshiba	III	1350	1.7-3.2% initial, 4.2% reload	45	35% for 2 yr-clycle	Yes	60	1997
	ABWR1700					70	18 months	Yes		
	System 80+ (APR-1400)	KEPCO	III	1450	5%	60	18 months	Yes	60	2012 (to apply)
	AP600 (Advanced Passive)	Westinghouse	III	600	1.9% (Region 1) 2.8% (Region II) 3.7% (Region III)	65	18 months	Yes	60	1999
	APWR-Japan	Mitrubishi		1538		55, then 62				
	ESBWR (Economic and Simplified)	GE Hitachi	III+	1520	4.20%	50	20% for 1 yr, 42% for 2 yrs	Yes	60	2010-2011 (expected)
	SWR 1000 (BWR)			1250					60	
	APWR-US			1700			2 yr			2012 (expected)
	AP1000	Westinghouse	III+	1000	2.35% (Region 1) 3.4% (Region II) 4.45% (Region III)	65	2 yr	Yes	60	2005
	IRIS (International Reactor Innovation and Secure)	Westinghouse	III+	100-335	initial: 5%, ultimate: 10%	60 then 80	3-3.5 yr, ultimate: 10 yr	Yes		

GEN III/III+ Nuclear Power Reactors (cont)

LWRs	Reactor	Supplier	GEN	MW(e)	Enrichment	Burn-Up (GWd/t)	Fueling Interval	MOX Capability	Life (YR)	NRC Design Certification
	Atmea1	Areva + Mitsubishi					1-2 yr	Yes	60	
	APR+		III+	1550						
	EPR (Erupean PWR)	Areva	III+	1650	up to 5%	65	2 yr	Yes	60	2004
	US-EPR (Evolutionary)									2012 (expected)
	VVER-1000	OKBM Gidropress	III	1000	2.4-4.4 %	47	1 yr	Yes	35	na
	VVER-1200, 1500	OKBM Gidropress	III+	1200, 1500	2.4-4.4 %	50-60	3 yr	Yes	50	
	VBER-300	OKBM Gidropress	III	300	2.4-4.4 %			Yes	60	

GEN III/III+ Nuclear Power Reactors (cont)

HWRs	Reactor	Supplier	GEN	MW(e)	Enrichment	Burn-Up (GWd/t)	Fueling Interval	MOX Capability	Life (YR)	NRC Design Certification
	Enhanced CANDU-6 (EC-6)	AECL	III	750					60	
	CANDU-9	AECL		925-1300	natural U, sightly enriched U, PWR spent fuel, thorium			Yes		1997
	Advanced Candu Reactor (ACR)	AECL	III+	700-1000	natural U, sightly enriched U (1.5-2.0%), PWR spent fuel, thorium		3	Yes	60	na
	AHWR (boiling light water colled, heavy water moderated)	India		300	Inner: 12 pins Th-U with 3% U-233: Intermediate: 18 pins Th-U233 with 3.75% U-233; Outer: 24 pins Th-Pu-239 with 3.25% Pu	24	113 fuel clusters (1/4 core) /yr, 2 yrs cooling time, 1/2 yr inventory of frresh fuel	Yes	100	na
	AHWR-LEU (boiling light water cooled, heavy water moderated)	India	III+	300	12 pins Th-U with 3.555% U-235, 18 pins Th-U with 4.345% U-235, 24 pins Th-U with 4.444% U-235 (pins with 18%, 22%, and 22.5% LEUO2 enriched to 19.5% U-235)	64	113 fuel clusters (1/4 core) /yr, 2 yrs cooling time, 1/2 yr inventory of frresh fuel (to be verified)	Yes		na

GEN III/III+ Nuclear Power Reactors (cont)

HTGR	Reactor	Supplier	GEN	MW(e)	Enrichment	Burn-Up (GWd/t)	Fueling Interval	MOX Capability	Life (YR)	NRC Design Certification
	HTR-PM	Tsinghua, China		105	9%	80			60	
	Pebble Bed Modular Reactor (PBMR)	Eskom-Mitsubishi	III+	165	4-5%	80	2.3	Yes	40	
	GT-MHR (Gas Turbine - Modular Helium Reator)	GA		285		100		Yes		

FBR	Reactor	Supplier	GEN	MW(e)	Enrichment	Burn-Up (GWd/t)	Fueling Interval	MOX Capability	Life (YR)	NRC Design Certification
	PRISM (Power Reactor Innovative Small Module)	GE-Hitachi	III+	311	U-Pu metal	150	2 yr, 1/3 core1	Yes		
	FBR	India		500	U-Pu carbide					
	JSFR	Japan		500-1500	U-Pu oxide					
	BN-800	Russia			U-Pu nitride, metal			Yes		
	BREST FBR	Russia		300						

Sources: EPRI (Program on Technology Innovation: Integrated Generation Technology Options), Wikepedia, World Nuclear Association, Cokinos (BNL)...