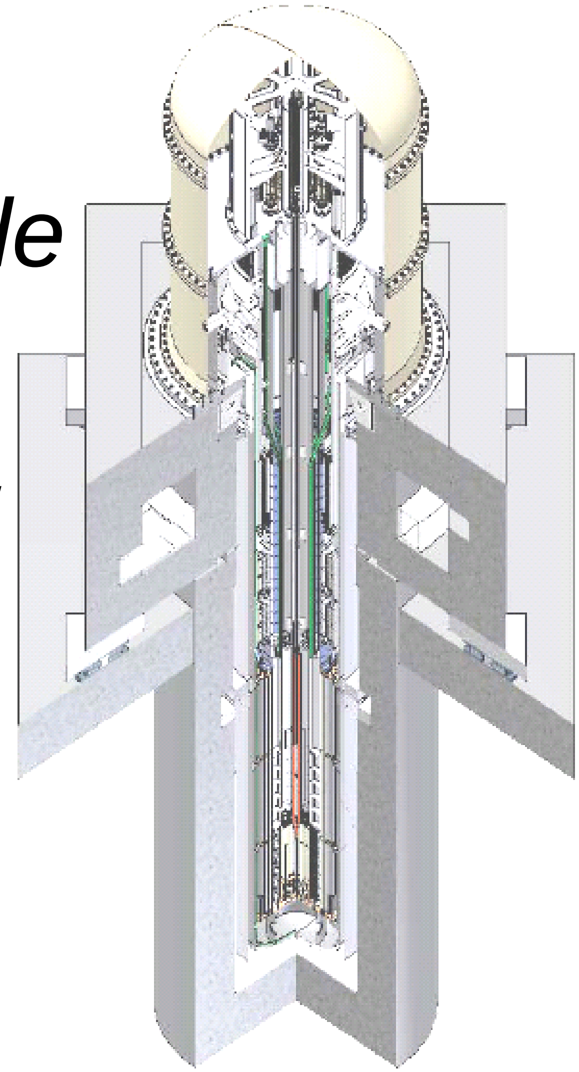
PSNE Control Number:PSN-2008-0622
Document Number:AFT-2008-000040rev.000(1)

4S Reactor
Super-Safe, Small and Simple



Third Pre-Application Review Meeting with NRC

May 21, 2008

CRIEPI · TOSHIBA Leading Innovation · Argonne National Laboratory · Westinghouse

Presentation Purpose

- Familiarize the NRC with the 4S safety design and regulatory conformance
- Obtain NRC feedback in areas related to 4S safety issues

Summary of First/Second Meeting

October 23, 2007 / February 21, 2008

- **High level overview**
  - Schedule and organization
  - Plant overview
- **Plant design parameters**
- **Main design features**
- **System design**
- **Long-life metallic fuel**

Near term action:

- One meeting left
- Series of technical reports to be issued for NRC review

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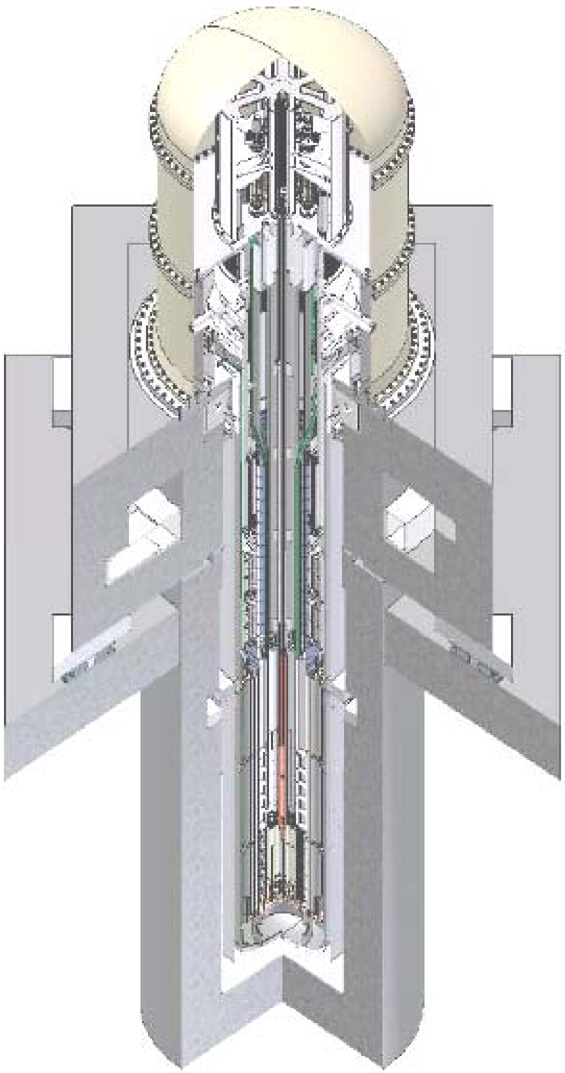
Presentation Overview

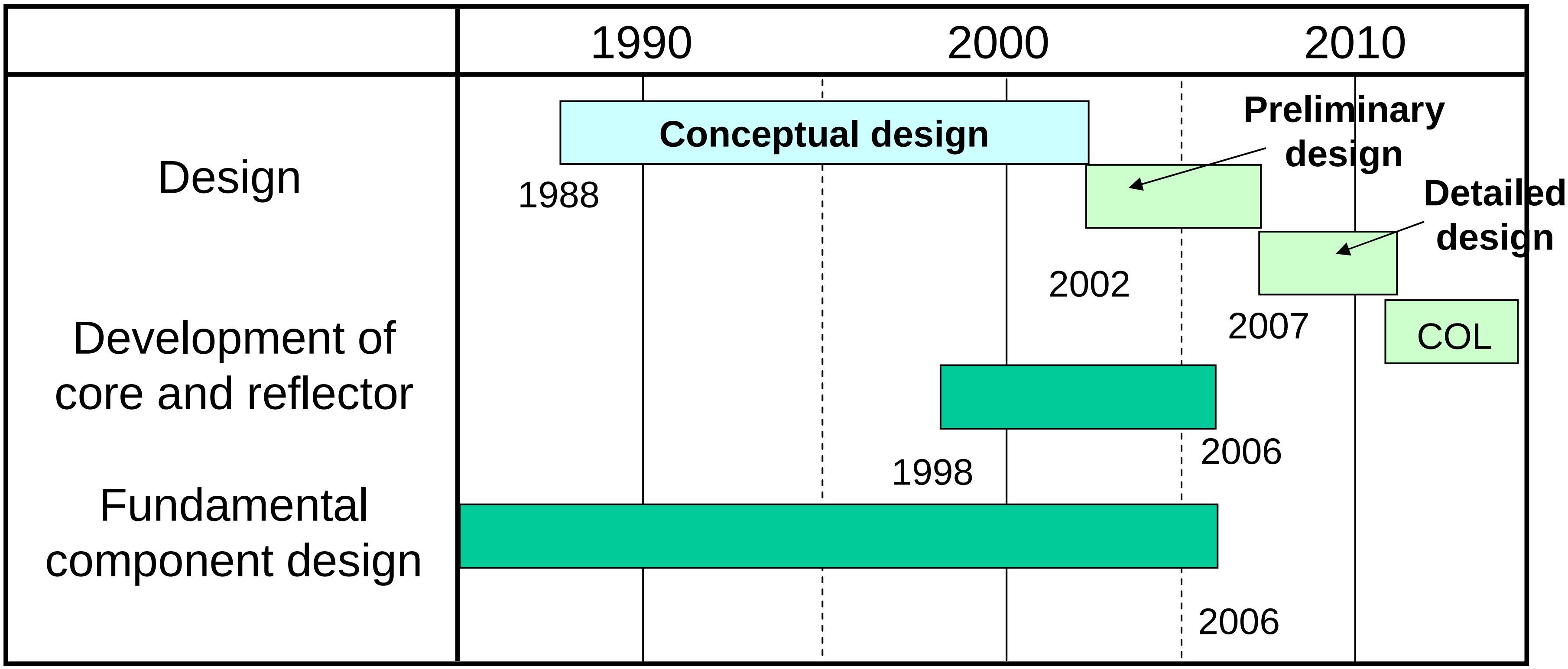
- Program Overview
- Basic Approach to Regulatory Conformance
- General/Principal Design Criteria (GDC, PDC)
- Design Conformance to 4S PDC
- Safety Criteria and Safety Analysis
- Enhancement of Safety Through Risk Reduction
- Applicability of Regulatory Guides
- Conclusions

Program Overview



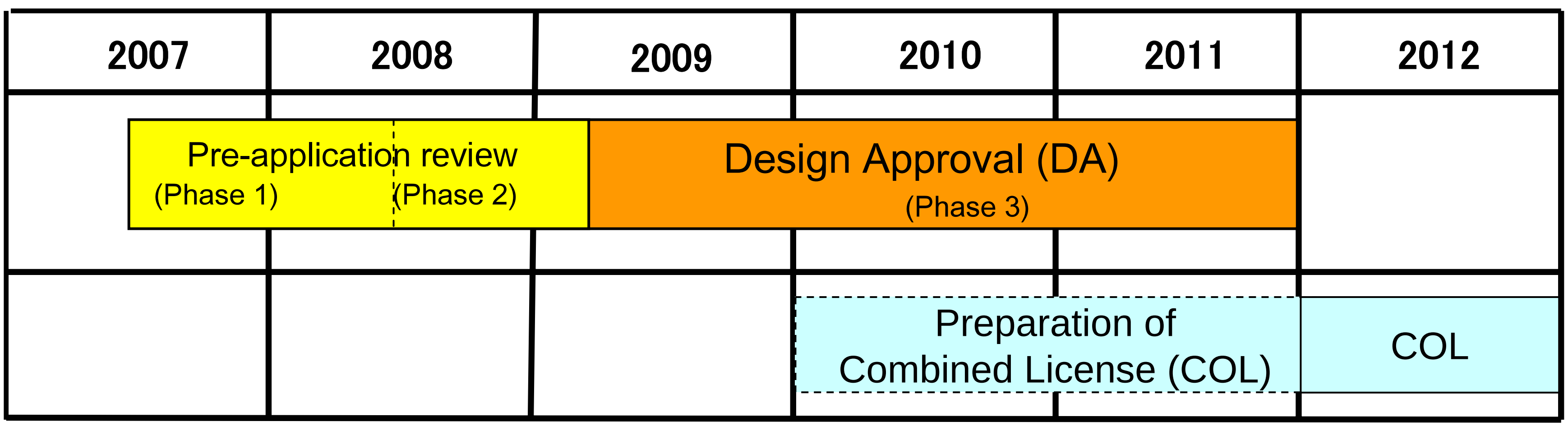
Current Status of 4S Design

- Preliminary design of reactor and heat transfer systems (HTS) is complete.
- Preliminary safety analysis is complete.
- Detailed design is in progress.



Proposed Licensing Approach

- **Submit Design Approval application in 2009**
  - **Phase 1:** Complete a series of meetings with NRC to identify issues to be addressed before Design Approval application
  - **Phase 2:** Submit technical reports and obtain NRC feedback to address the issues identified in Phase 1
  - **Phase 3:** Submit Design Approval application and obtain FSER
- **Toshiba expects a U.S. customer will submit a COL application referencing Design Approval.**



Phase 1 – Proposed Licensing Approach

	2007	2008		
	4Q	1Q	2Q	3Q
1st Meeting High level overview	▼			
2nd Meeting System design Long-life metallic fuel		▼		
3rd Meeting -Today Safety design and regulatory conformance			▼	
4th Meeting* PIRT review				▼

*) Subject to NRC concurrence

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Phase 2 – Proposed Licensing Approach

- **Schedule of technical reports for NRC review**

– Long-life metallic fuel • Analysis methodology • Fuel performance	June	2008
– Safety analysis • Analysis methodology • Safety analysis results	October	2008
– PIRT and test program	November	2008
– Seismic isolation	December	2008
– Responses to NRC questions	December	2008

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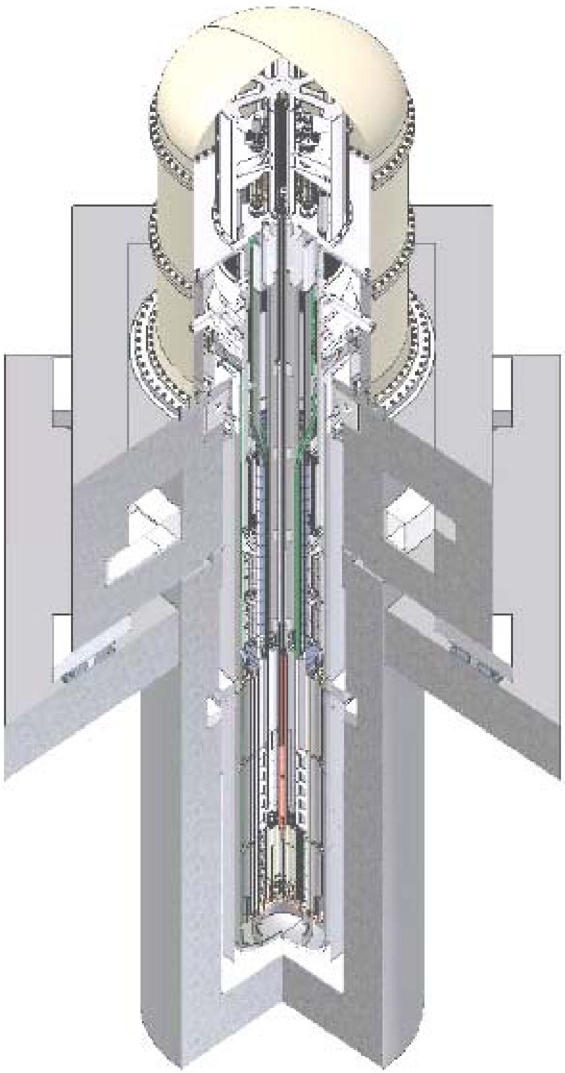
Basic Approach to Regulatory Conformance



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Developing 4S Principal Design Criteria

- **Approach**
  - Evaluate 10CFR50, Appendix A* applicability and completeness for 4S
  - Evaluate applicability of NRC-accepted LMR principal design criteria (ANSI/ANS-54.1**, CRBR PSER [NUREG-0968], and PRISM PSER [NUREG-1368]) for the 4S reactor
  - Evaluate applicability of NRC-accepted approaches for passive reactors and for regulatory treatment of non-safety systems that provide defense-in-depth to passive features
  - Use what is applicable, modify or replace what is not, and add new criteria as needed for 4S
- **Accomplishment**
  - Preliminary Principal Design Criteria for 4S completed

* General Design Criteria for Nuclear Power Plants

**General Safety Design Criteria for a Liquid Metal Reactor Nuclear Power Plant

Regulatory Basis of Safety Analysis

- **Approach**
  - Evaluate Standard Review Plan 15.0 (NUREG-0800*) for applicability to 4S
  - Use basic philosophy of event classification and analysis approach of NUREG-0800, modified for 4S
- **Accomplishments**
  - Acceptance criteria for 4S safety analysis developed
  - Safety analysis indicates large margins to acceptance criteria

* Standard Review Plan

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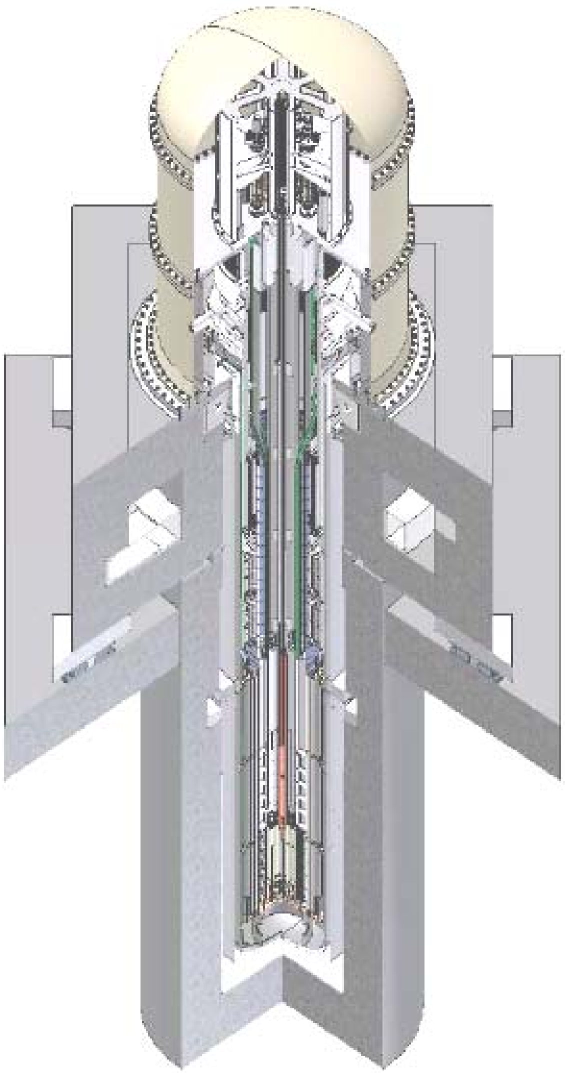
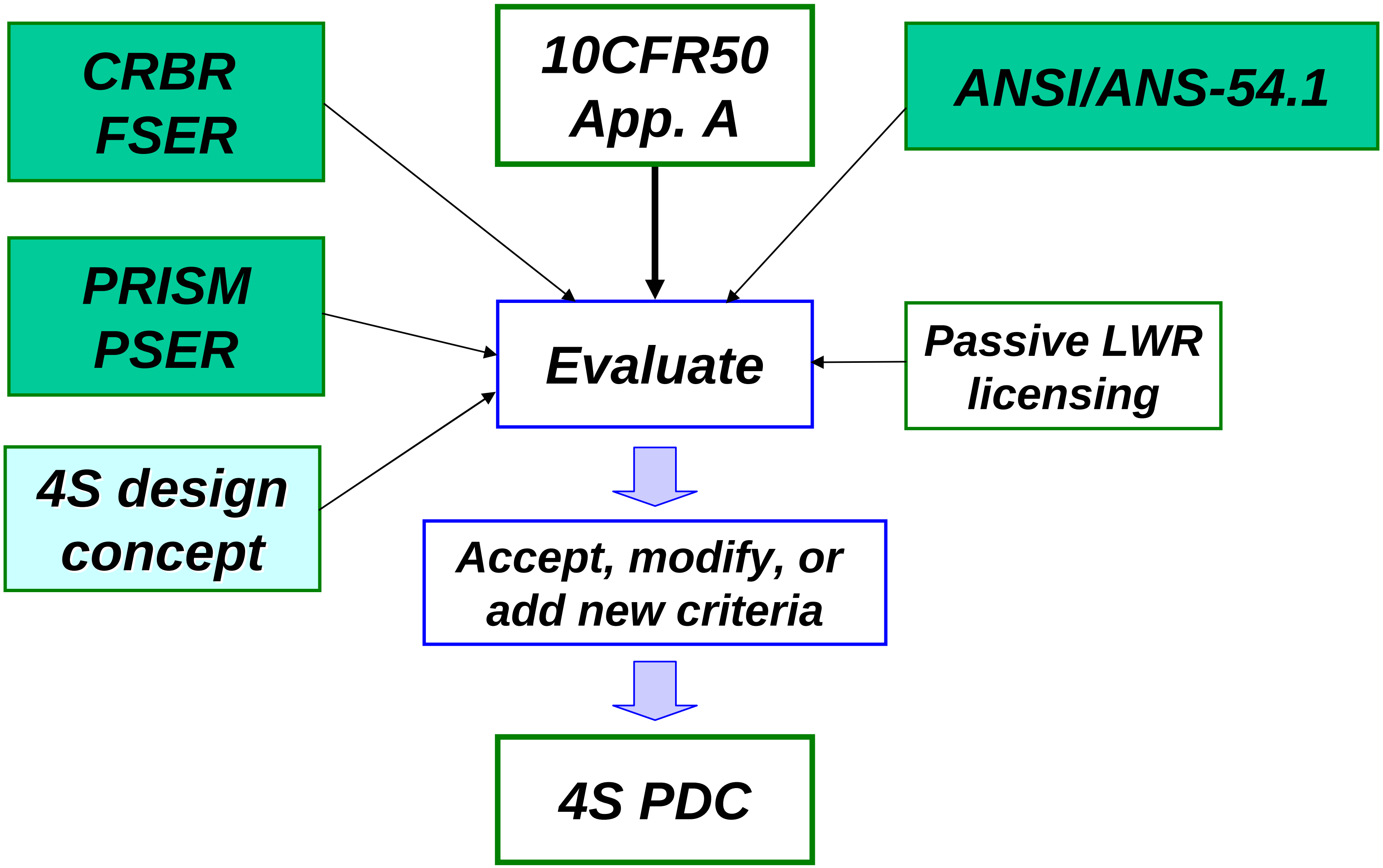
Applicable Regulatory Guides

- **Approach**
  - Regulatory Guides (RGs) categorized:
    - Inapplicable (e.g., strictly LWR)
    - Applicable (reactor type independent)
    - Partially applicable
    - Intent applicable
- **Accomplishment**
  - Exceptions to RGs identified and justified

General/Principal Design Criteria



Development of 4S PDC



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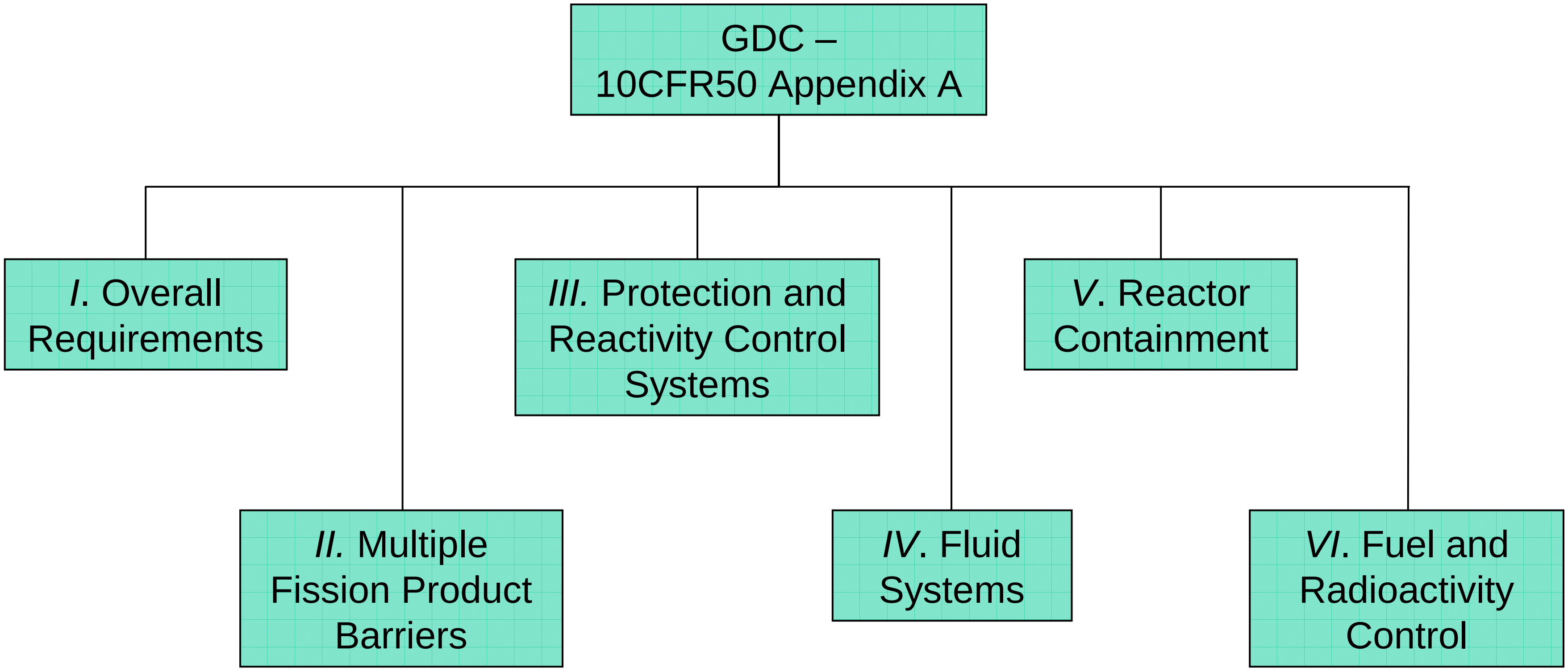
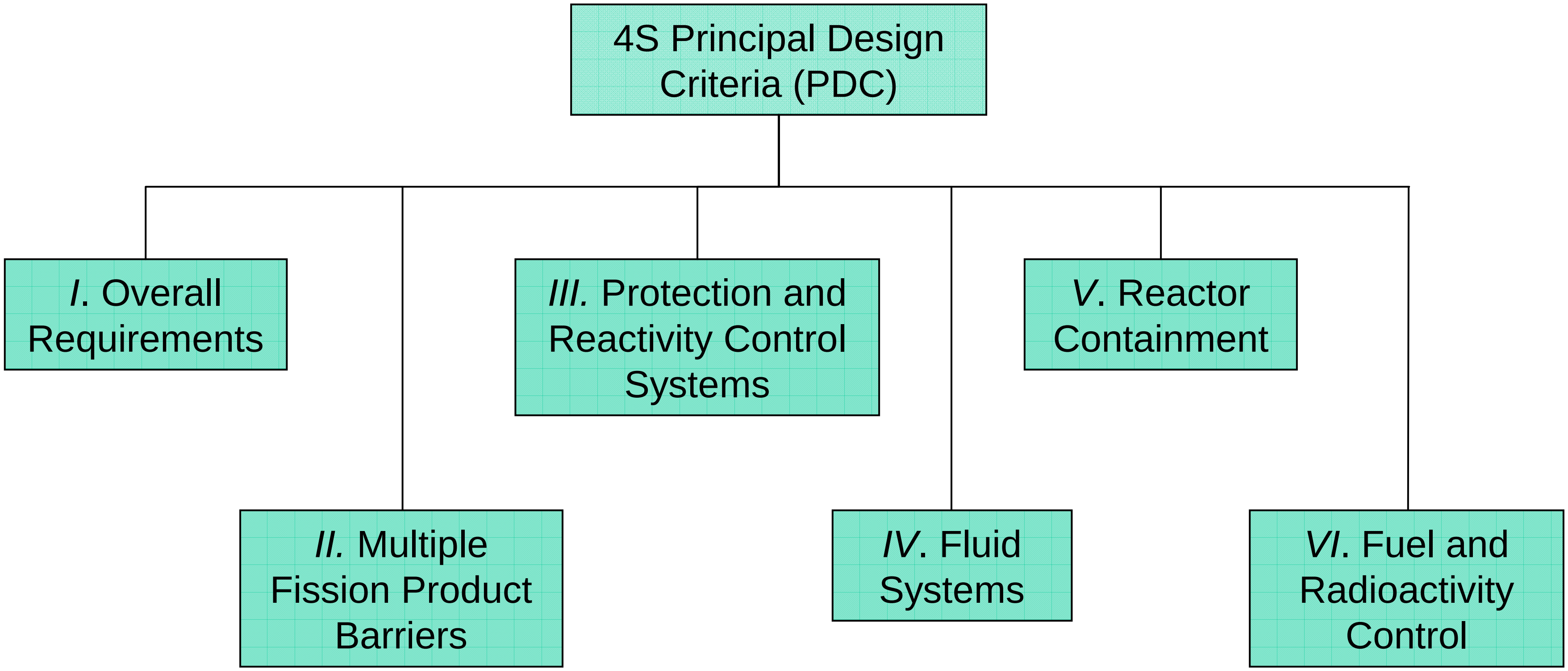
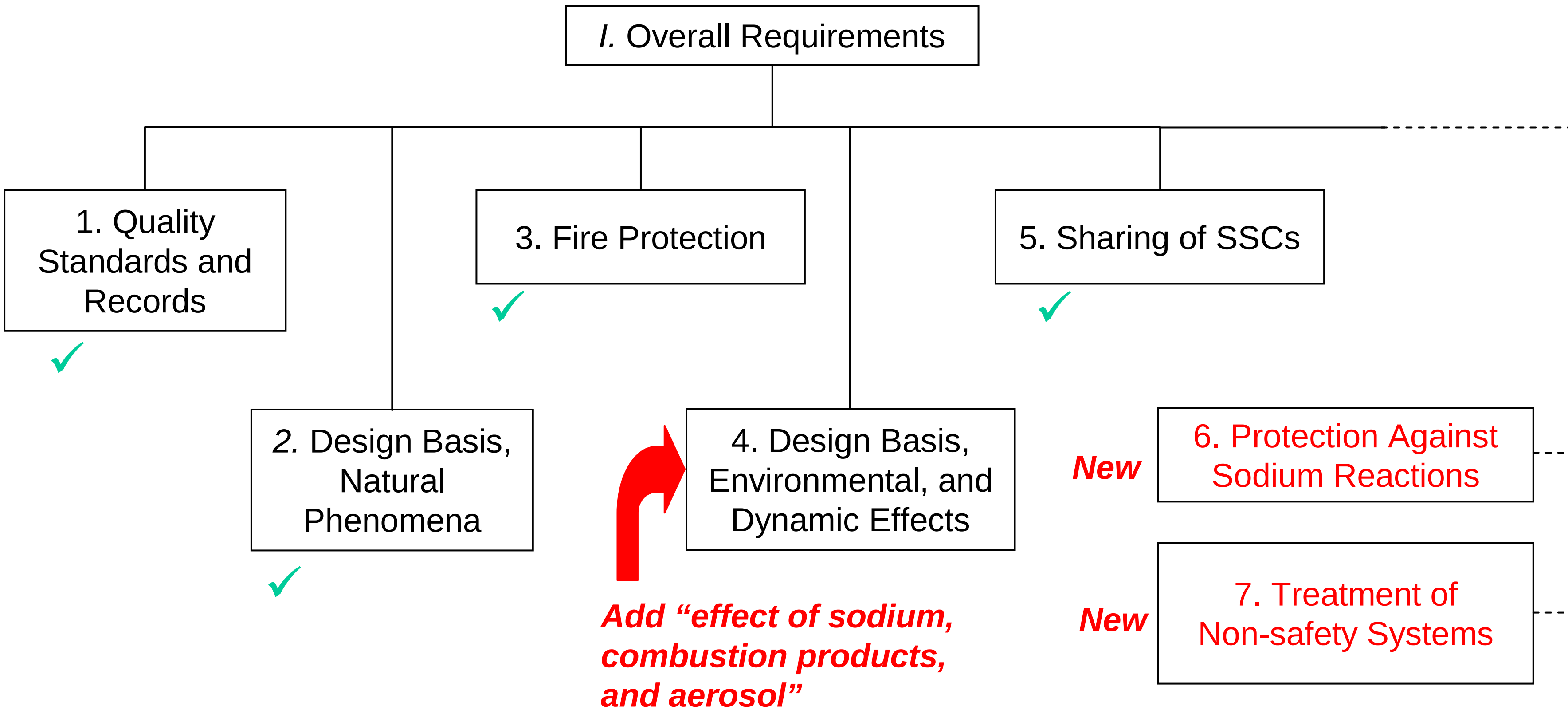
GDC Structure



4S PDC Structure



4S PDC – Changes from 10CFR50, Appendix A



4S PDC – Changes from 10CFR50, Appendix A (cont.)

II. Protection by Multiple Fission Product Barriers

Fuel Cladding

- ✓ 10. Reactor Design
- ✓ 11. Reactor Inherent Prevention
- ✓ 12. Suppression of Reactor Power Oscillations

Reactor Coolant Boundary

- 14. Reactor Coolant Boundary
- 15. Reactor Coolant System Design

Add sodium heating system to auxiliary systems

Containment

- ✓ 16. Containment Design

Change to accommodate non-safety EPS

Supporting Systems and Structures

- 13. I & C
- 17. Electric Power System (EPS)
- ✓ 18. EPS Inspection and Testing
- 19. Control Room

Add conditions from sodium reactions and accident conditions

4S PDC – Changes from 10CFR50, Appendix A (cont.)

III. Protection and Reactivity Control Systems

Protection Systems (PS)

- ✓ 20. PS Functions
- ✓ 21. Reliability and Testability
- ✓ 22. PS Independence
- 23. PS Failure Modes
- ✓ 24. Separation of PS and Control Systems
- 25. *PS Requirements for Reactivity Control Malfunction

Add "sodium and sodium reaction products" to adverse environment

Reactivity Control Systems

- 26. *Reactivity Control System Redundancy and Capability
- 27. *Combined Reactivity Control Systems Capability
- 28. * § Reactivity Limits

Protection and Reactivity Control Systems

- ✓ 29. Protection against Anticipated Operational Occurrences

** Change control rod to control element*

§ Change rod ejection and rod dropout to accidental control element motion

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4S PDC – Changes from 10CFR50, Appendix A (cont.)

IV. Fluid Systems

Assuring Adequate Core Coolant Inventory

30. Quality of Reactor Coolant Boundary (RCB)
31. Fracture Prevention of RCB
32. Inspection of RCB

33. Assurance of Adequate Coolant Inventory — ***Replace***

Core Heat Removal

34. Residual Heat Removal System (RHRS)
35. (ECCS, N/A)
36. Inspection of RHRS
37. Testing of RHRS

Containment Heat Removal

38. Containment Heat Removal System (CHRS)
39. Inspection of CHRS
40. Testing of CHRS

Containment Atmosphere Cleanup

41. Containment Atmosphere Cleanup System (CACS)
42. ✓ Inspection of CACS
43. ✓ Testing of CACS

Structures and Equipment Heat removal (S&EHR)

44. S&EHR System
45. Inspection of S&HER System
46. Testing of S&EHR System

New 47. Sodium Heating System

New 48. Reactor and Intermediate Coolant and Cover Gas Purity Control

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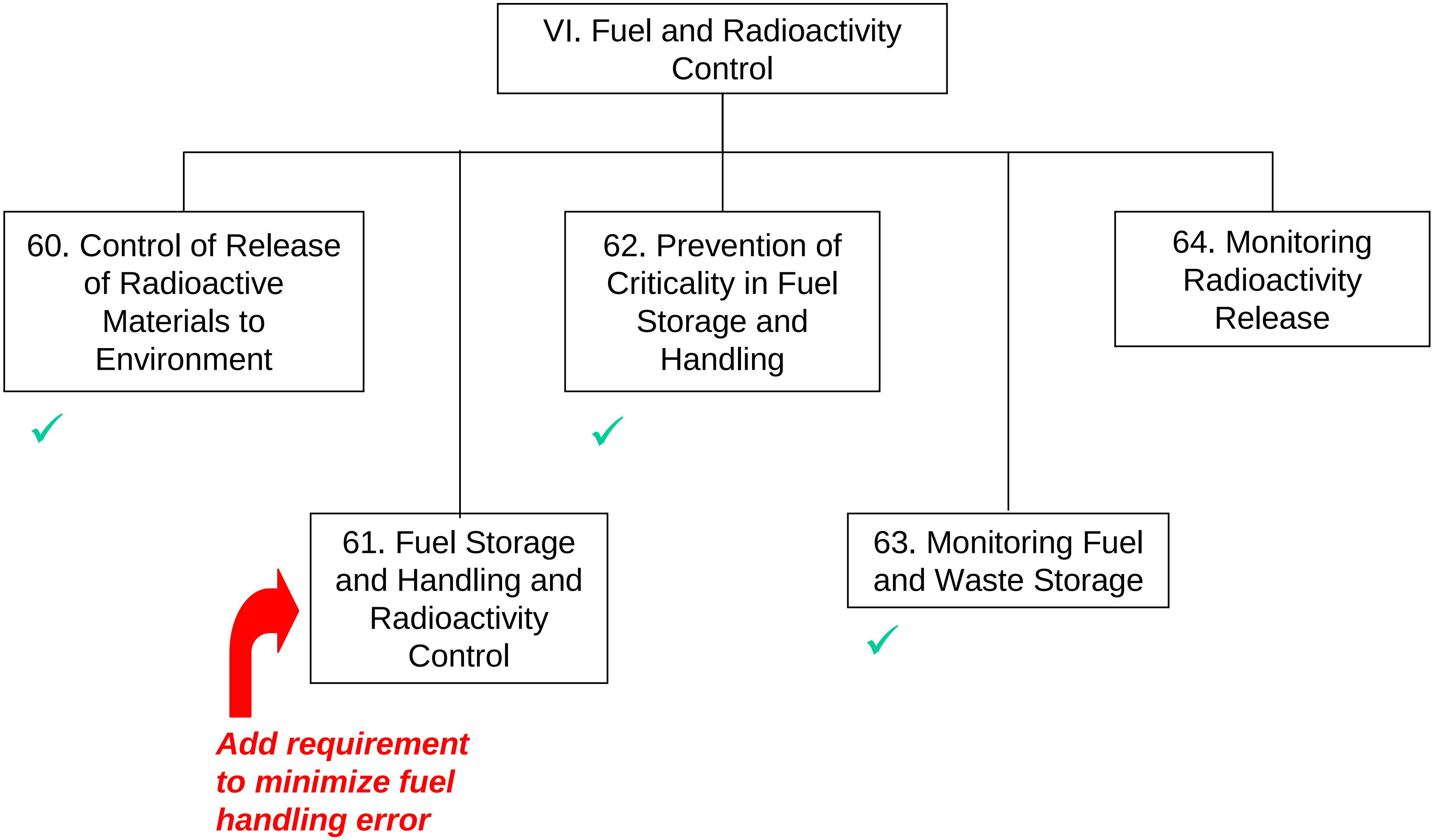
4S PDC – Changes from 10CFR50, Appendix A (cont.)

- *V.* Reactor Containment
  - 50. Containment Design Basis
  - 51. Fracture Prevention of Containment Boundary
  - 52. Capability for Containment Leakage Rate Testing ✓
  - 53. Provisions for Containment Testing and Inspection ✓
  - *Containment Penetrations*
    - ✓ 54. Piping Systems
    - 55. Reactor Coolant Boundary
  - *Containment Isolation*
    - ✓ 56. Primary Containment
    - 57. Isolation Valves

Use containment challenges appropriate for 4S (No LOCA or metal-water reaction)

4S PDC – Changes from 10CFR50, Appendix A (cont.)



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Preliminary 4S PDC Summary

Preliminary 4S PDC

I. Overall Requirements (PDC 1~7)

- 1 GDC (4) modified and 2 PDC (6 and 7) added

II. Protection by Multiple Fission Product Barriers (PDC 10~19)

- 5 GDC (13, 14, 15, 17, and 19) modified

III. Protection and Reactivity Control Systems (PDC 20~29)

- 5 GDC (23, 25, 26, 27, and 28) modified

IV. Fluid Systems (PDC 30~48)

- 14 GDC (30, 31, 32, 33, 34, 36, 37, 38, 39, 40, 41, 44, 45, and 46) modified, 1 GDC deleted (35), and 2 PDC (47 and 48) added

V. Reactor Containment (PDC 50~57)

- 4 GDC (50, 51, 55, and 57) modified

VI. Fuel and Radioactivity Control (PDC 60~64)

- 2 GDC (61 and 64) modified

Development of 4S PDC from GDC

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
I. Overall Requirements			
Environmental and dynamic effects design bases	**4**	Two changes	1) Add effects of sodium, combustion products and aerosol 2) Remove reference to LOCA
(Design of sodium systems [Protection against sodium reactions])	**6**	New criterion	Needed to address potential effects of sodium reactions
(Treatment of non-safety systems)	**7**	New criterion	Needed to allow for crediting of non-safety systems if appropriate

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
II. Protection by Multiple Fission Product Barriers			
Instrumentation and Control	**13**	One change	Replace “reactor coolant pressure boundary” by “reactor coolant boundary”
Reactor coolant pressure boundary	**14**	One change	See PDC 13
Reactor coolant system design	**15**	Two changes	1) Add sodium heating system to the list of auxiliary systems 2) See PDC 13

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
II. Protection by Multiple Fission Product Barriers (cont.)			
Electric power system	**17**	Major change	Change to allow use of non-safety ac power and power distribution if appropriate provided PDC 7 is applied
Control room	**19**	Three changes	1) Replace LOCA by "conditions from sodium reactions" 2) Change rem limits for whole body and thyroid to Sv and TEDE units for consistency with latest PDC 19 3) Change "cold shutdown" to "any coolant temperature lower than the hot shutdown"

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
III. Protection and Reactivity Control			
Protection system failure modes	**23**	Addition	Add sodium and sodium reaction products to the list of adverse environments
Protection system requirements for reactivity control malfunctions	**25**	Two changes	1) Remove "(not ejection or dropout)" 2) Change "rods" to "elements"
Reactivity control system redundancy and capability	**26**	Two changes	1) Delete "(including Xenon burnout)" 2) Change "rods" to "elements"
Combined reactivity control systems capability	**27**	Two changes	1) Delete "in conjunction with poison solution by the ECCS" 2) Change "rods" to "elements"

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
III. Protection and Reactivity Control (cont.)			
Reactivity limits	**28**	Several changes	1) Replace “Reactor coolant pressure boundary” by “Reactor coolant boundary” 2) Delete “rod ejection (unless prevented by positive means)” 3) Replace “rod dropout” by “accidental movement of control elements” 4) Replace “cold water addition” by “cold sodium addition”

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
IV. Fluid Systems			
Quality of reactor coolant pressure boundary	**30**	One change	See PDC 13
Fracture prevention of reactor coolant pressure boundary	**31**	Two changes	1) See PDC 13 2) Add effect of high temperature and sodium chemistry on material properties and stress.
Inspection of reactor coolant pressure boundary	**32**	One change	See PDC 13
Reactor coolant makeup	**33**	Inapplicable	Replace with ANSI/ANS-54.1, Criterion 3.4.1 (Assurance of adequate coolant inventory)
Residual heat removal	**34**	Several changes	Amend to include requirements for passive residual heat removal systems

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
IV. Fluid Systems (cont.)			
Emergency core cooling	**35**	ECCS Inapplicable	Delete
Inspection of emergency core cooling system	**36**	ECCS Inapplicable	Change to a PDC on "inspection and monitoring of residual heat removal system"
Testing of emergency core cooling system	**37**	ECCS Inapplicable	Change to a PDC on "testing of residual heat removal system"
Containment heat removal	**38**	Several changes	1) Amend to allow containment heat removal by passive means 2) Performance of non-safety active support system (if appropriate) must satisfy PDC 7

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
IV. Fluid Systems (cont.)			
Inspection of containment heat removal	**39**	Several changes	1) Change title to "Inspection and Monitoring of Containment Heat Removal System" 2) Add "and functional monitoring (for passive systems)"
Testing of containment heat removal	**40**	One change	Remove reference to water
Containment atmosphere cleanup	**41**	Two changes	1) Add sodium aerosol and reaction products as products of postulated accidents 2) Add sodium leakage, chemical reactions, and potential hydrogen generation from sodium-concrete interaction

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Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
IV. Fluid Systems (cont.)			
Cooling water	**44**	Two changes	1) Change title to "Structural and Equipment Cooling," and remove reference to water in the text 2) Add "as necessary" to allow for not having the system if not needed
Inspection of cooling water system	**45**	Two changes	1) Change title to "Structural and Equipment Cooling," and remove reference to water in the text 2) Delete "water"

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
IV. Fluid Systems (cont.)			
Testing of cooling water system	**46**	Two changes	1) Change title to "Structural and Equipment Cooling," and remove reference to water in the text 2) Delete "for reactor shutdown and for LOCA accidents"
(Sodium heating systems)	**47**	New criterion	Needed to address higher melting temperature of sodium coolant
(Reactor and intermediate coolant and cover gas purity)	**48**	New criterion	Needed to address measures to assure purity of cover gas and coolant

Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
V. Reactor Containment			
Containment design basis	**50**	Two changes	1) Replace LOCA by postulated accident 2) Replace "metal-water and other chemical reactions" by "fission products, potential sodium fire or aerosol formation, and exothermic chemical reactions"
Fracture prevention of containment pressure boundary	**51**	One change	Replace "ferritic" materials to "metallic" materials to broaden the application of the PDC
Reactor coolant pressure boundary penetrating containment	**55**	Two changes	1) See PDC 13 2) Add the reactor cover gas boundary as part of the primary coolant boundary
Closed systems isolation valves	**57**	Addition	Same as PDC 55

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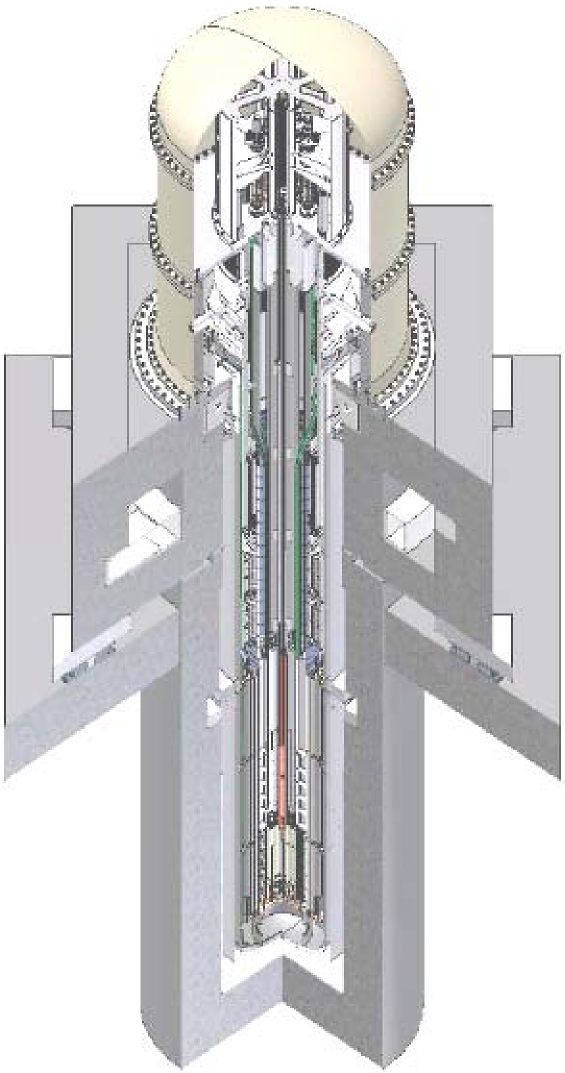
Development of 4S PDC from GDC (cont.)

GDC Title in 10CFR50 Appendix A	PDC No.	Applicability to 4S	Remarks
VI. Fuel and Radioactivity Control			
Fuel storage and handling and radioactivity control	**61**	Addition	Add statement to minimize potential for fuel handling error by design
Monitoring radioactivity release	**64**	One change	Remove reference to LOCA

Summary

- **Preliminary Principal Design Criteria for 4S (4S PDC) have been developed, using the General Design Criteria, with appropriate modifications to reflect the 4S design concept.**

Design Conformance to 4S Principal Design Criteria

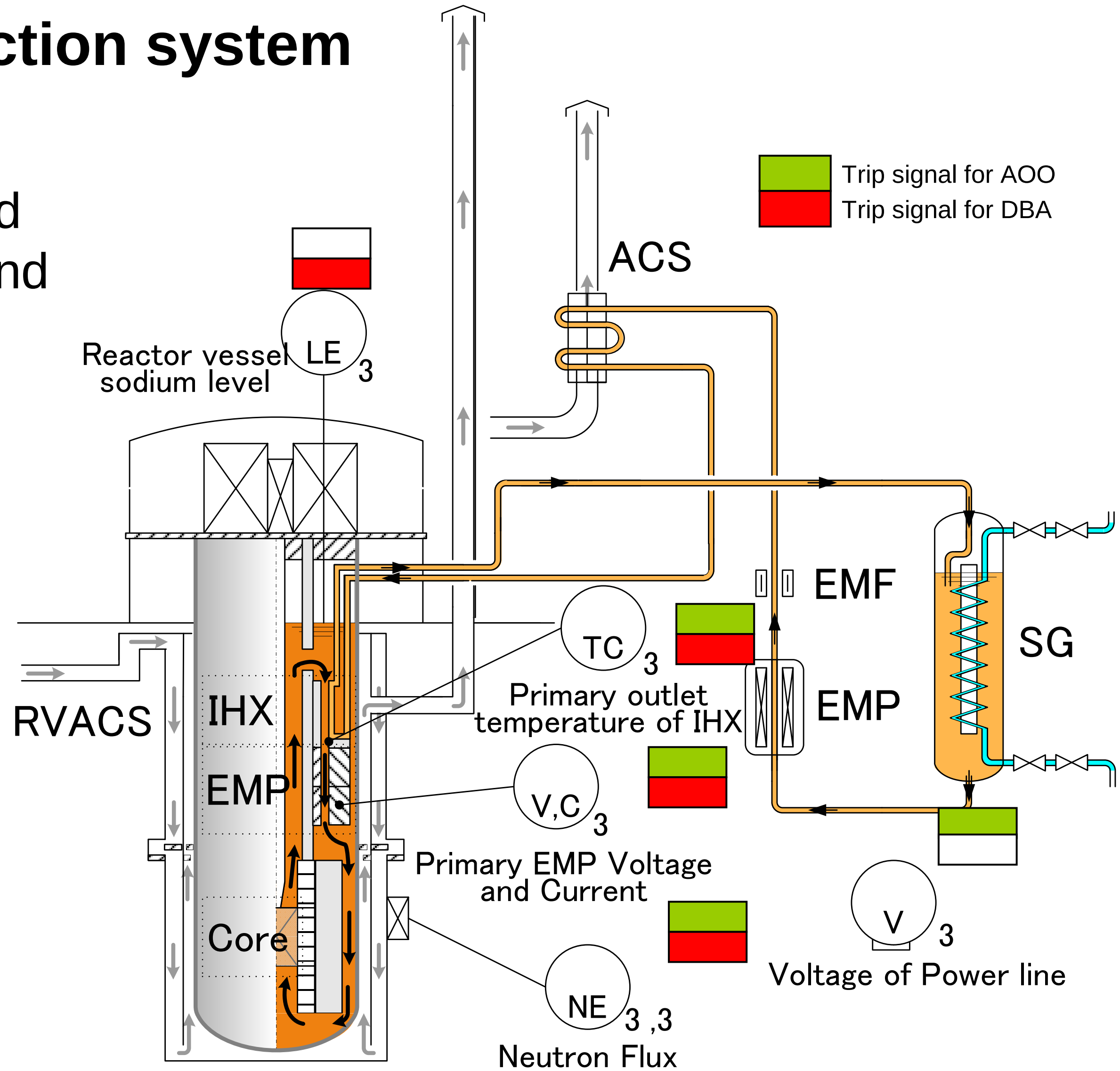


Example of Design Conformance to PDC

- **Reactor Protection and Reactivity Control Systems**
  - Protection system function (PDC 20)
  - Protection system reliability and testability (PDC 21)
  - Protection system independence (PDC 22)
  - Protection system failure modes (PDC 23)
  - Separation of protection and control systems (PDC 24)
  - Protection system requirements for reactivity control malfunctions (PDC 25)
  - Reactivity control system redundancy and capability (PDC 26)
  - Combined reactivity control system capability (PDC 27)
  - Reactivity limits (PDC 28)
  - Protection against anticipated operational occurrences (PDC 29)

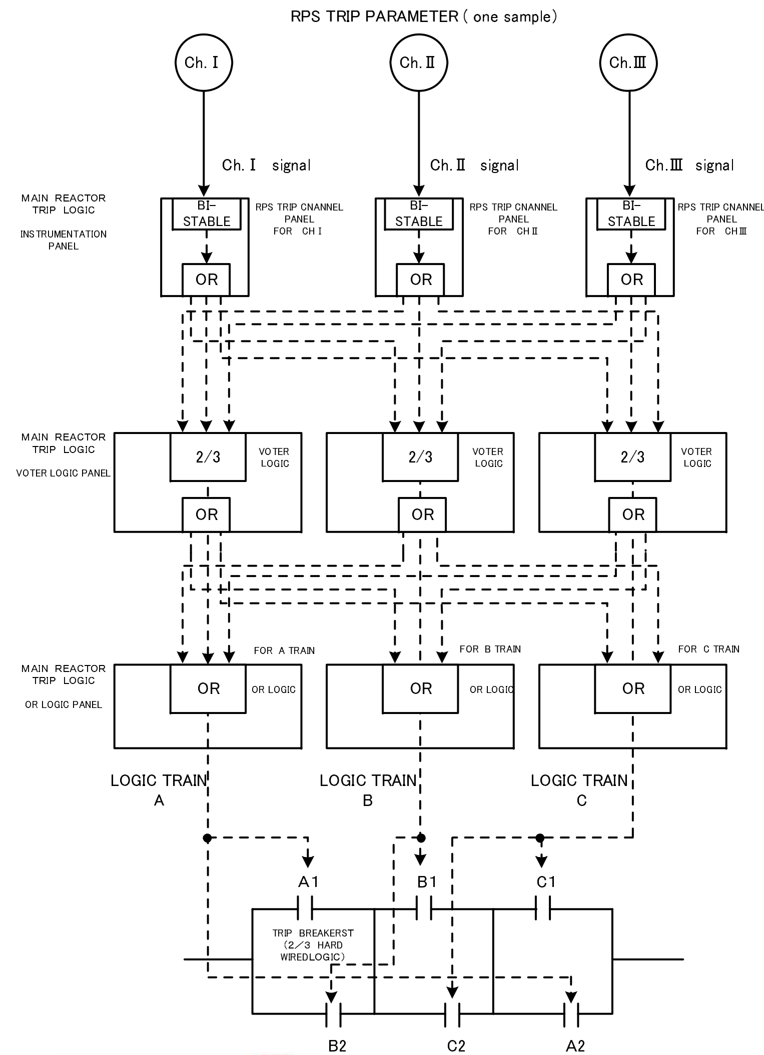
Design Conformance of RPS to 4S PDC 20

- **Criterion 20 Protection system functions**
  - Sense anticipated and accident conditions and initiate protection



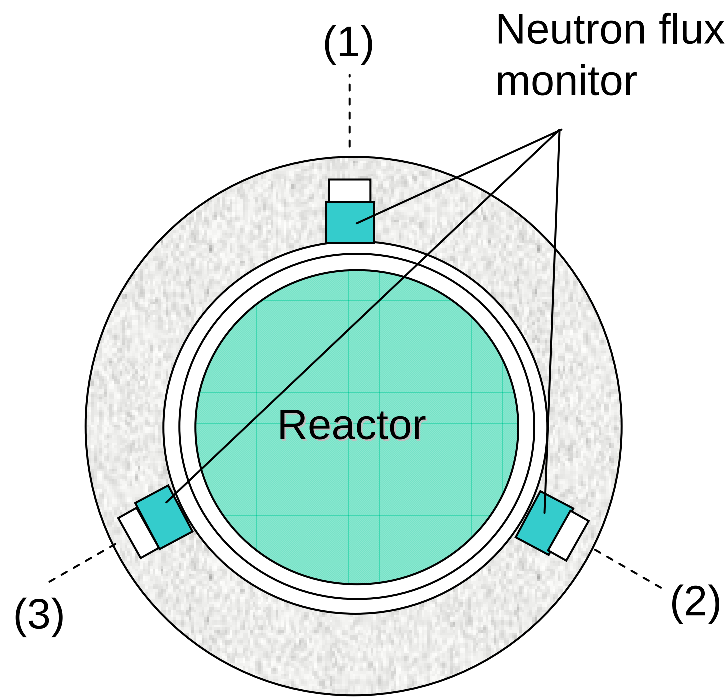
Design Conformance of RPS to 4S PDC 21

- **Criterion 21 Protection system reliability and testability**
  - Redundant and independent design
  - No single failure, results in loss of function
  - Periodic testing in operation



Design Conformance of RPS to 4S PDC 22

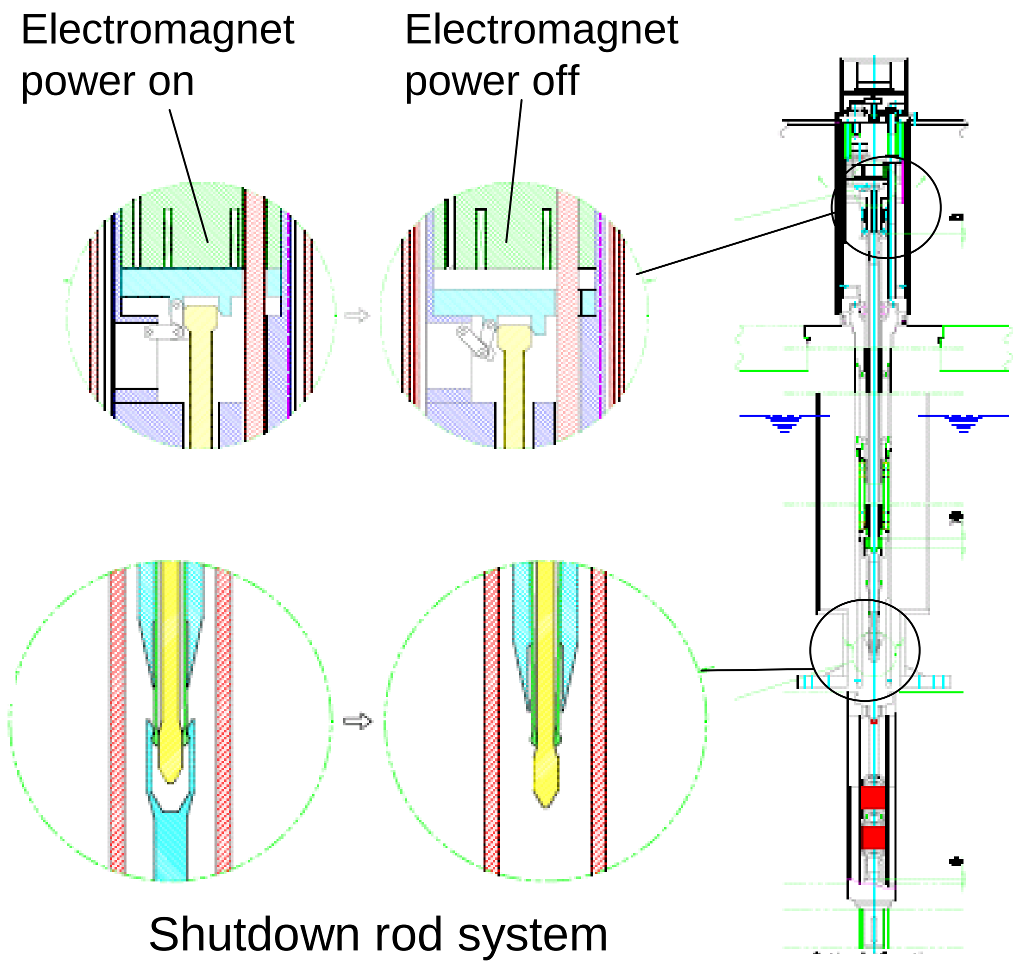
- **Criterion 22 Protection system independence**
  - Functional diversity
    - Separate main (reflector) and backup (shutdown rod) systems using different variables
  - Natural phenomena and postulated accident conditions do not result in loss of function
    - Physical separation



  - Detectors and channels
    - Physically separated
    - Power supplied by separate electric source

Design Conformance of RPS to 4S PDC 23

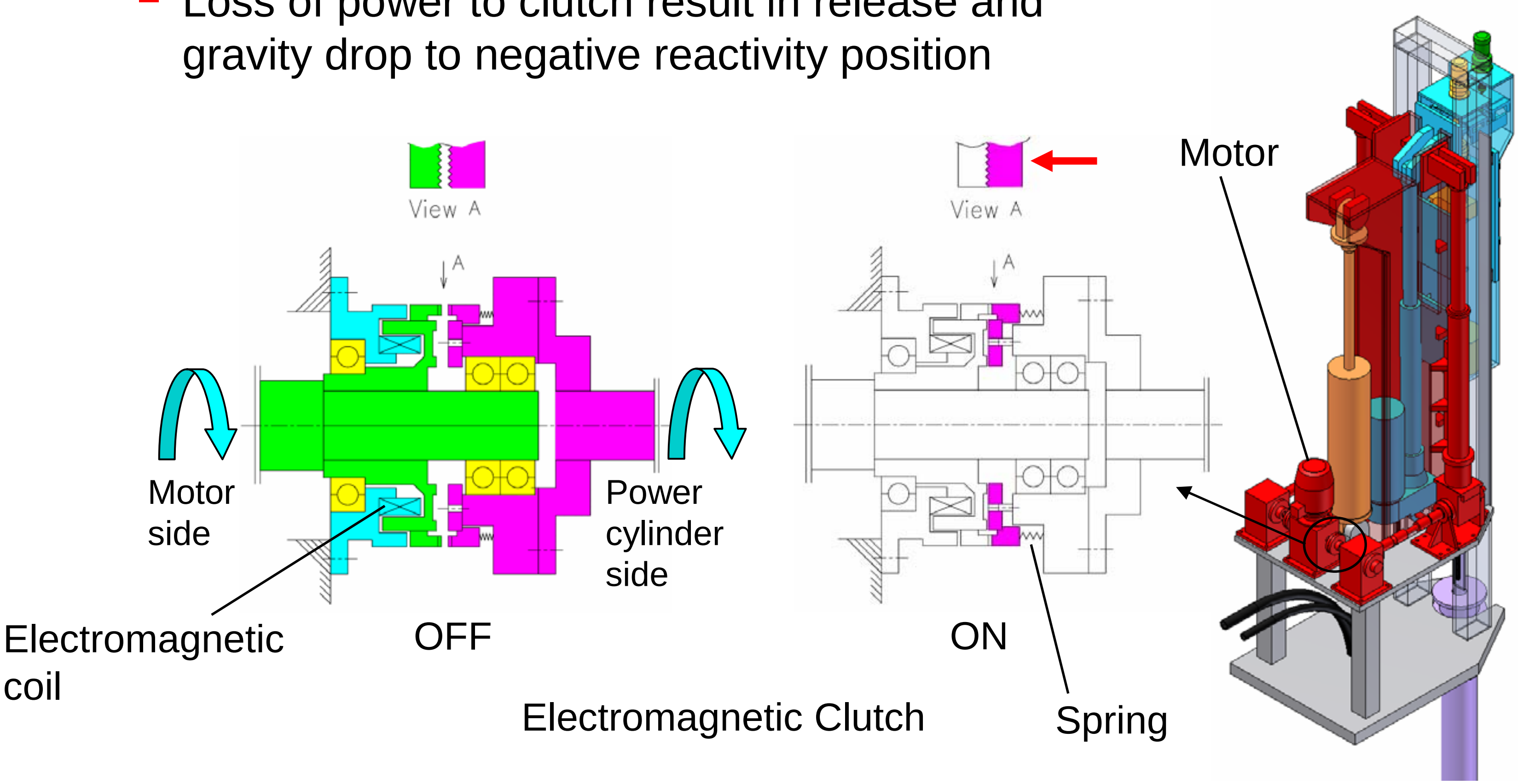
- **Criterion 23 Protection system failure modes**
  - Fail safe design
    - Shutdown rod system
      - Loss of power to electromagnet results in release and gravity insertion to negative reactivity position
      - Sealed against effects of adverse environment



Shutdown rod system

Design Conformance of RPS to 4S PDC 23 (cont.)

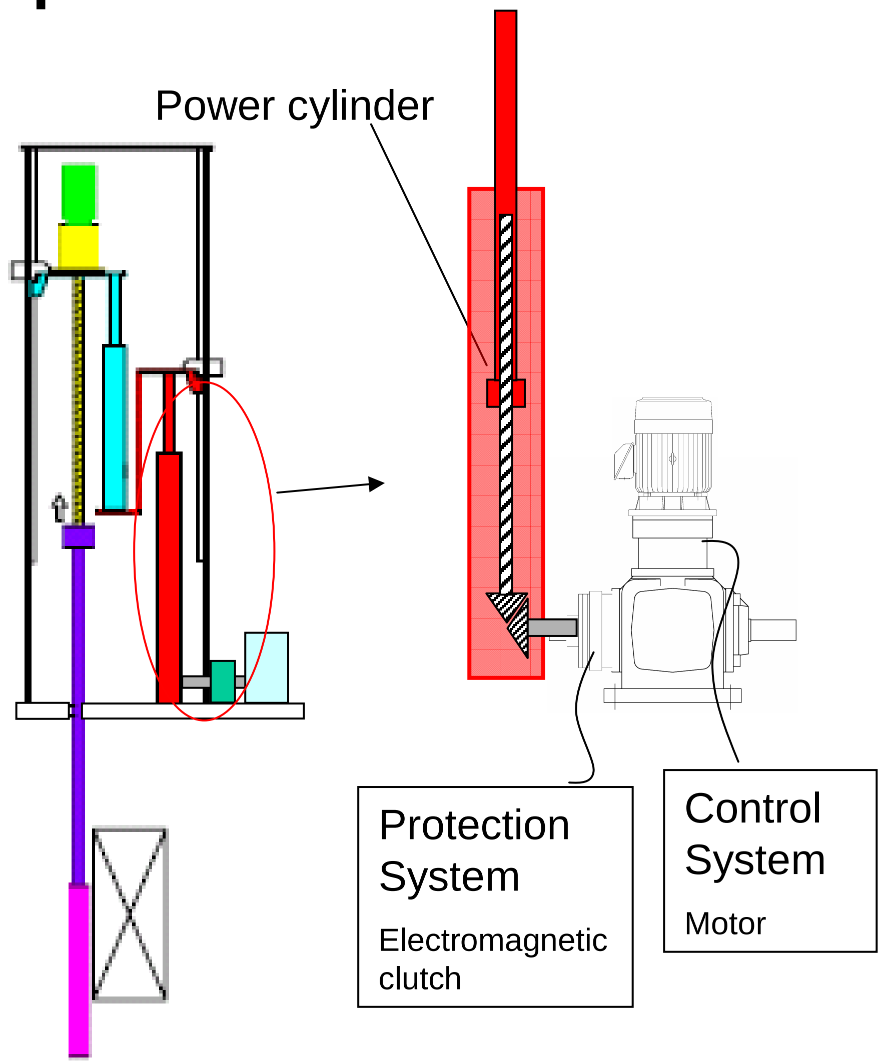
- **Criterion 23 Protection system failure modes (cont.)**
  - Fail safe design
    - Reflector drive system
      - Loss of power to clutch result in release and gravity drop to negative reactivity position



Electromagnetic Clutch

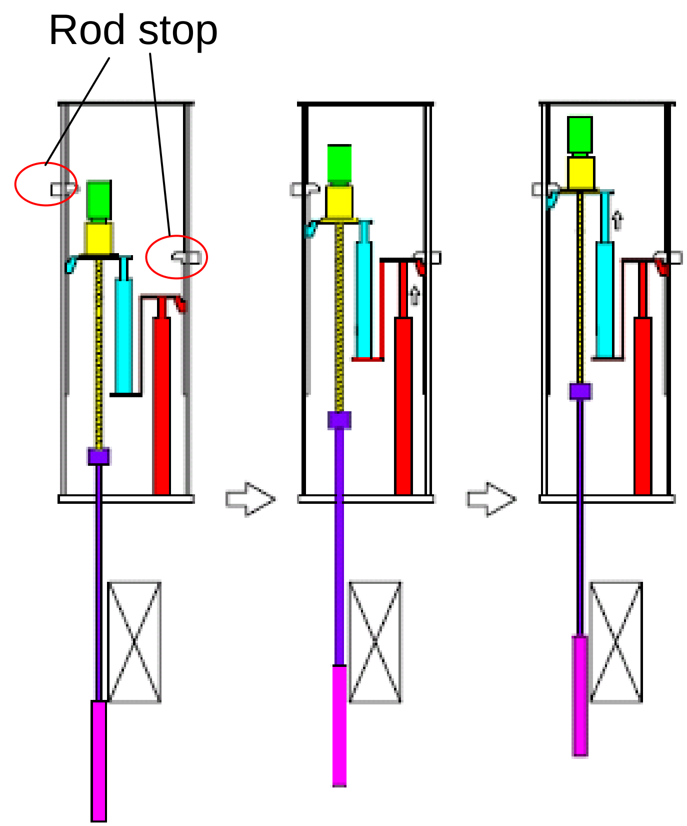
Design Conformance to 4S PDC 24

- **Criterion 24 Separation of protection and control systems**
  - The protection system is separated from the control system.
  - Interconnection is limited so that safety is not impaired.



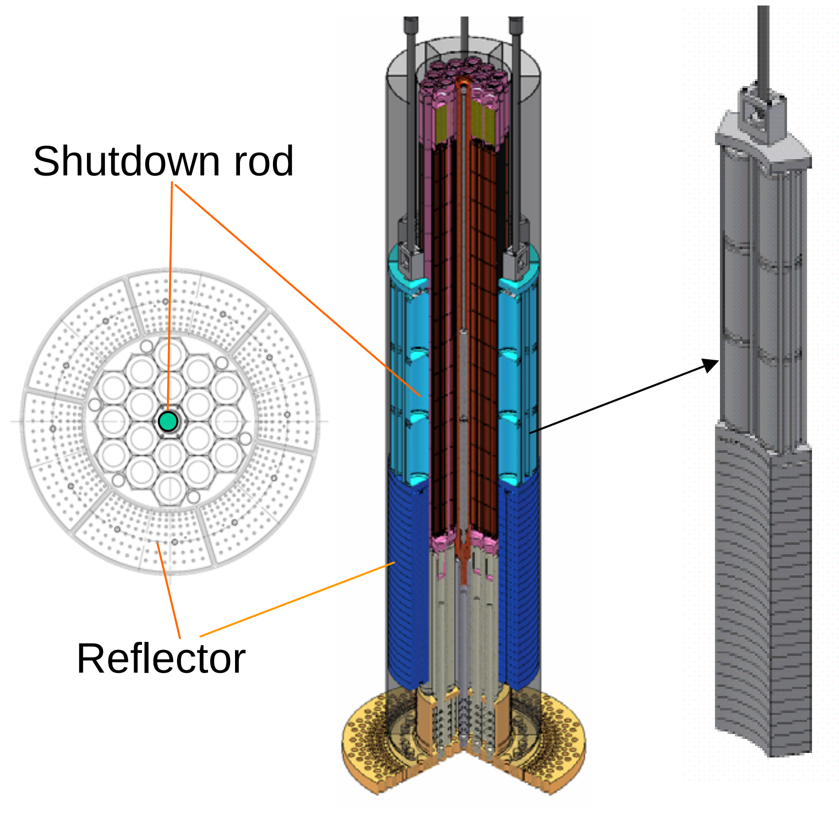
Design Conformance to 4S PDC 25

- **Criterion 25 Protection system requirements for reactivity control malfunctions**
  - Safe shutdown can be achieved with any single malfunction of the reactivity control systems, such as accidental movement of control elements.
    - Accidental reflector movement is restricted by mechanical rod stops.
    - Core achieves subcriticality using 5 of 6 reflector segments.



Design Conformance to 4S PDC 26

- **Criterion 26 Reactivity control system redundancy and capability**
  - 4S has two independent reactivity control systems of different design principles.
  - One of the systems with margin for stuck element.
  - Either of the systems is capable of holding cold shutdown.



Design Conformance to 4S PDC 27

- **Criterion 27 Combined reactivity control systems capability**
  - Combined capability of controlling reactivity change under accident conditions

Available Systems	Reflector	Shutdown Rod
Startup & normal shutdown	✓	✓
Burnup compensation	✓	-
Scram (gravity)	Δ *	Δ

✓ – Needed

Δ – Redundant and diverse

* - Provides one reflector stuck margin

- The reactor scrams and achieves cold shutdown with one reflector stuck.
- The reactor scrams and achieves cold shutdown with insertion of shutdown rod.

Design Conformance to 4S PDC 28

- **Criterion 28 Reactivity limits**
  - Designed with appropriate limits on the potential amount and rate of reactivity increase to avoid fuel melting with margin
  - Representative reactivity insertion initiators
    - Uncontrollable motion of reflector at full-power operation
    - Rapid motion of reflector at startup
    - Failure of a cavity can
    - Reactivity insertion by seismic event
    - Increase of primary coolant flow
    - Increase of intermediate coolant flow
    - Feedwater flow increase

Design Conformance to 4S PDC 29

- **Criterion 29 Protection against anticipated operational occurrences**
  - Designed to assure extremely high probability of accomplishing safety function in anticipated operational occurrence (AOO)
    - High quality equipment, diversity, and redundancy support high probability of accomplishing safety function in AOO.
    - Component testing is planned to prove design concept.

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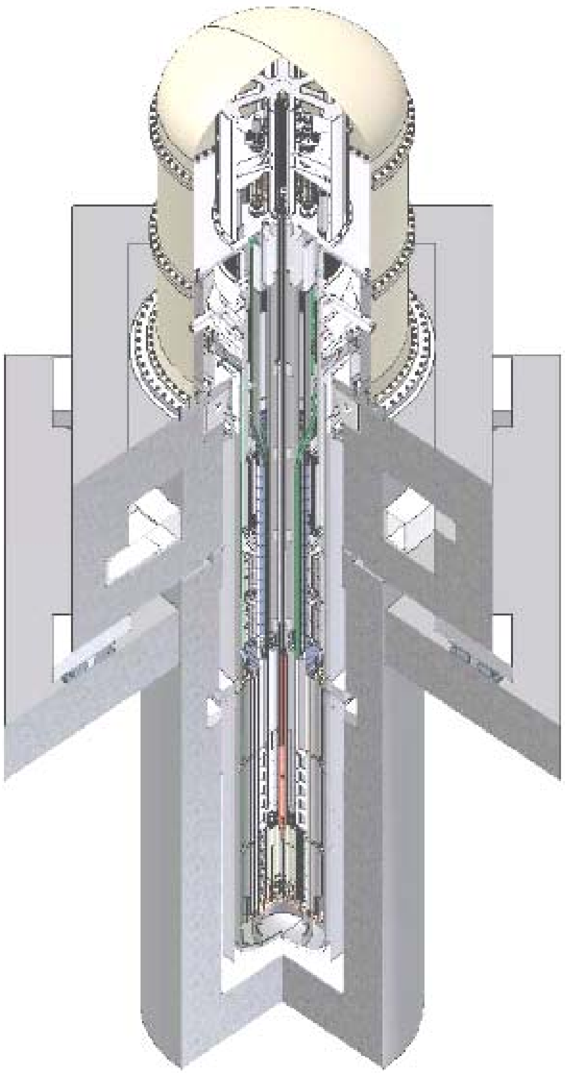
Safety Criteria and Safety Analysis



Safety Analysis Approach (1/2)

- **Application of contents of existing SRP**
  - Use basic philosophy and contents of Standard Review Plan (SRP: NUREG-0800), modify or replace for 4S
  - Categorize transients and accidents as indicated by SRP
  - Select anticipated operational occurrences (AOOs), and design-basis accidents (DBAs)
  - Consider anticipated transient without scram (ATWS) according to SRP
  - Develop acceptance criteria for AOO, DBA, and ATWS of 4S

Safety Analysis Approach (2/2)

- **Apply existing regulations regarding source term**
  - Source term analysis to evaluate validity of site suitability for 4S
    - Use basic philosophy and contents of 10CFR50.34* and10CFR52.47**

*Contents of construction permit and operating license applications; technical information

**Contents of applications; technical information

Anticipated Operational Occurrence

- **AOO**
  - *May occur one or more times during the life of the nuclear power unit (SRP 15.0)*
  - Consider single active failure of systems, structures, and components (SSCs)
    - *A single failure means an occurrence which results in the loss of capability of a component to perform its intended safety functions. Multiple failures resulting from a single occurrence are considered to be a single failure. Fluid and electric systems are considered to be designed against an assumed single failure if neither (1) a single failure of any active component (assuming passive components function properly) nor (2) a single failure of a passive component (assuming active components function properly), results in a loss of the capability of the system to perform its safety functions. (10CFR50, Appendix A)*

Design Basis Accident

- **DBA**
  - DBAs are *postulated accidents that are used to set design criteria and limits for the design and sizing of safety-related systems and components. (SRP 15.0)*
  - *Postulated accidents are unanticipated occurrences (i.e., they are postulated but not expected to occur during the life of the nuclear power plant). (SRP 15.0)*

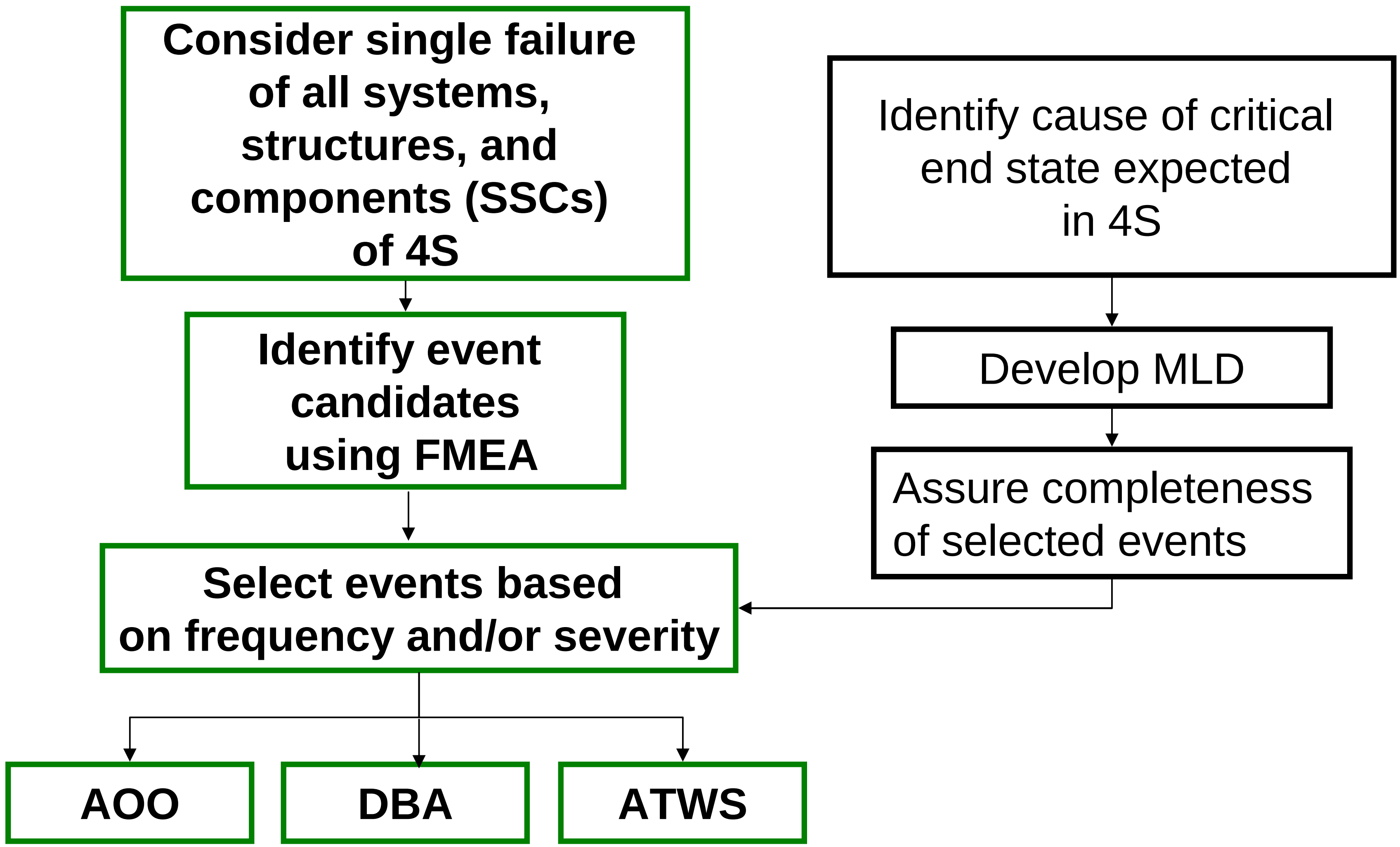
Anticipated Transient Without Scram

- **ATWS**
  - *Anticipated transients without scram (ATWS) are AOOs in which a reactor scram is demanded but fails to occur because of a common-mode failure in the reactor scram system. (SRP 15.0)*
  - *As such, they are beyond the design basis, and consequently, ATWS events are addressed separately (see SRP Section 15.8). (SRP 15.0)*

Selection Of AOOs and DBAs

- **Procedure**
  - Consider applicable operating experience
  - Consider single failure of SSCs
  - Perform Failure Mode and Effect Analysis (FMEA)
  - Identify transient and accident candidates for 4S
    - AOOs are selected within events which would occur one or more times during the plant life.
    - DBAs are selected to set design criteria and limits for the design and sizing of safety-related systems and components.
    - ATWS is selected within AOOs in which a reactor scram fails to occur
  - Use Master Logic Diagram (MLD) to assure the completeness of event selection

Selection of AOOs and DBAs (cont.)



Identify All SSCs

- **Reactor and core**
  - Core
  - Reactivity control and shutdown system
- **Reactor coolant system and connected systems**
  - Reactor vessel, shielding plug, guard vessel, and top dome
  - Reactor internal structure
  - Primary heat transport system
  - Intermediate heat transport system
  - Residual heat removal systems
    - Reactor vessel auxiliary cooling system (RVACS)
    - Intermediate residual auxiliary cooling system (IRACS)
- **Engineered safety features**
- **Instrumentation and control**
  - Reactor protection system
  - Safety-related instrumentation
- **Electrical power**
- **Auxiliary systems**
- **Steam and power conversion system**

FMEA Development for Each SSC

- **Example of FMEA development for reflector drive system**

Component	Function	Failure Mode	Causes of failure	Effect on safety	How to detect	Frequency	Category
Reflector	...	...	...	...	...	...	...
Cavity	Reactivity control	Sodium leaks into can	Environ-ment exceeds design condition	Decrease of reactivity control capability	Neutron flux level change	Low	DBA
Joint	...	...	...	...	...	...	...
Universal joint	...	...	...	...	...	...	...
Drive shaft	...	...	...	...	...	...	...
Reduction gear	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
Motor of burnup compensation system	Burnup loss compensation	Software failure	Human error	Increase of reactivity	Neutron flux level change	High	AOO
Rod position detection system	...	...	...	...	...	...	...
Power cylinder	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...

Example of Representative Events Selection

- **Positive reactivity insertion event**
  - Select event that will cause most severe effect, such as maximum positive reactivity and reactivity insertion rate
    - **AOOs**

SSCs	Failure mode
Motor of burnup compensation system	Software failure
Motor of power cylinder at startup	Software failure

- Reactivity insertion by uncontrollable motion of reflector at full-power operation
- Reactivity insertion by rapid motion of reflector at startup

    - **DBAs**

SSCs	Failure mode
Motor of power cylinder at startup	Failure of electrical parts
Cavity	Sodium leak-in

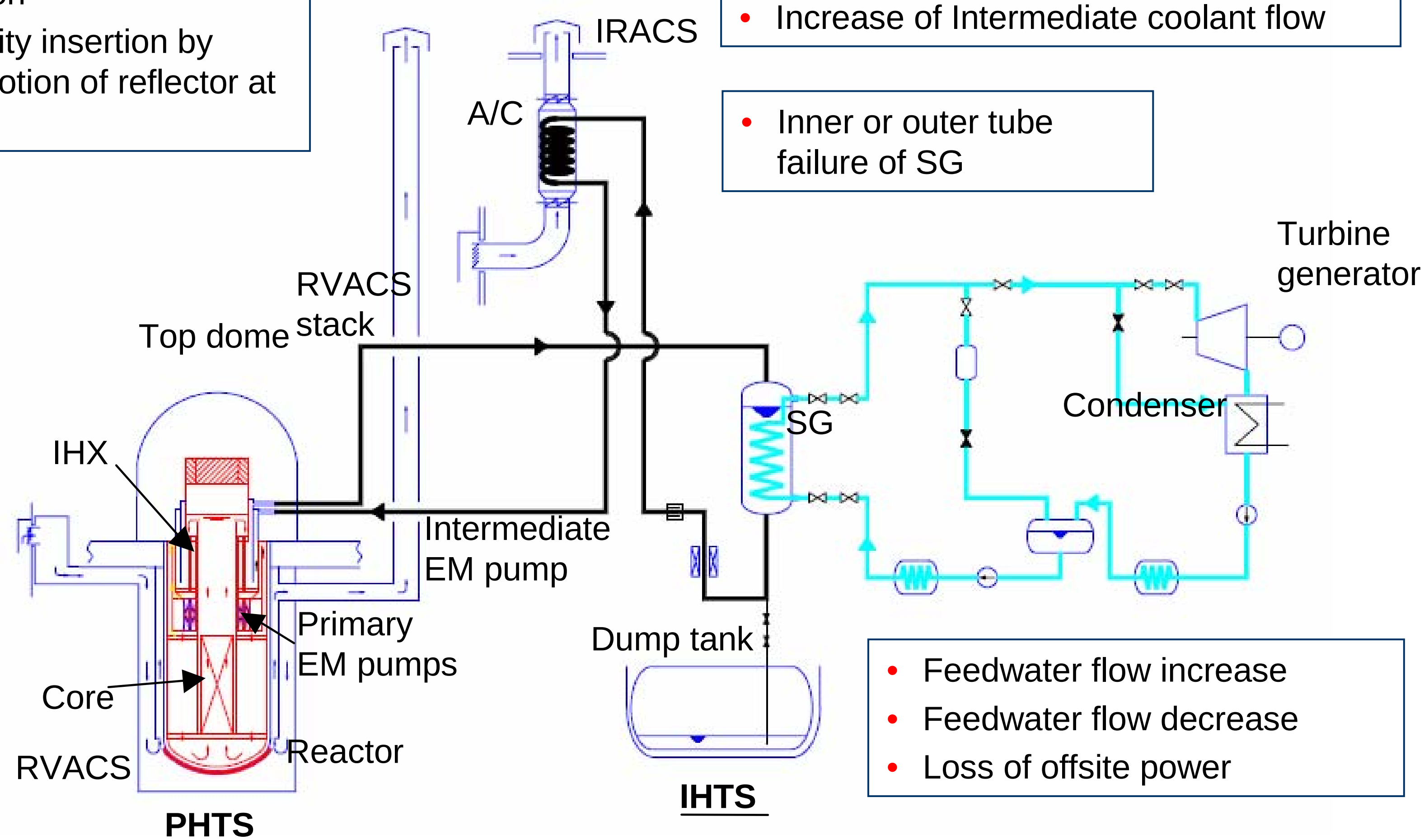
- Reactivity insertion by rapid motion of reflector at startup
- Failure of a cavity can

Representative AOOs

- Reactivity insertion by uncontrollable motion of reflector at full-power operation
- Reactivity insertion by rapid motion of reflector at startup

- Decrease of primary coolant flow
- Decrease of intermediate coolant flow
- Increase of primary coolant flow
- Increase of Intermediate coolant flow

- Inner or outer tube failure of SG

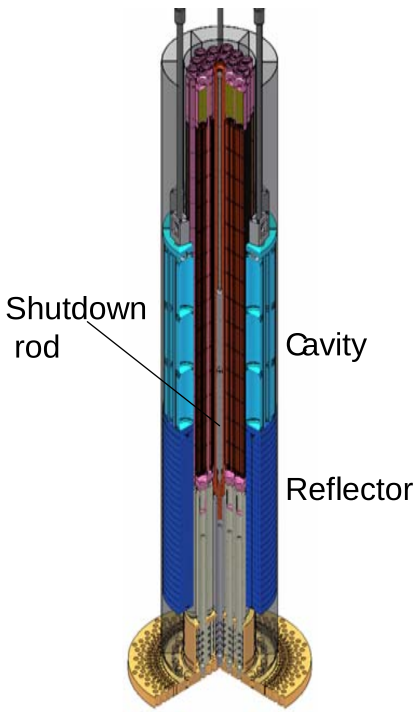


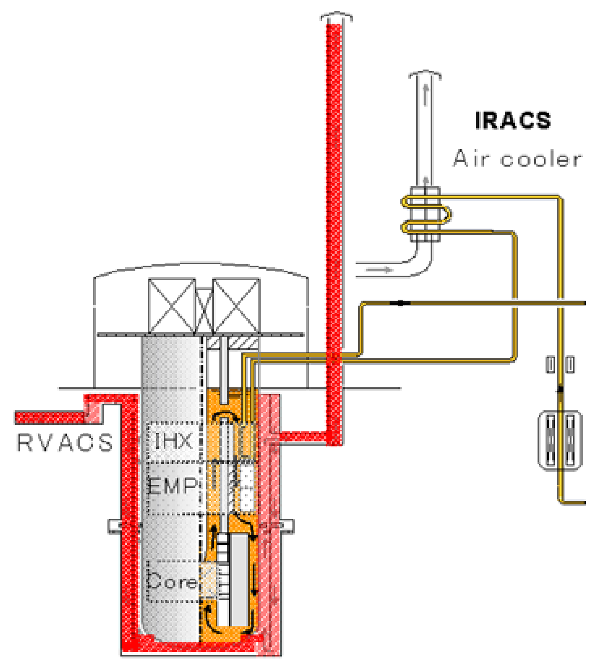
- Feedwater flow increase
- Feedwater flow decrease
- Loss of offsite power

Representative DBAs

- **DBAs for RPS**
  - Rapid motion of reflector at startup
  - Failure of a cavity can
  - Reactor vessel leakage
  - One primary EM pump failure

- **DBAs for RHRS**
  - Loss of onsite and offsite power
  - Sodium leakage from intermediate piping





Representative ATWS

- **Unprotected loss of flow**
  - Decrease of primary coolant flow without scram
  - Decrease of intermediate coolant flow without scram
  - Loss of offsite power without scram
- **Unprotected transient over power**
  - Reactivity insertion by uncontrollable motion of reflector at full-power operation without scram
  - Reactivity insertion by rapid motion of reflector at startup without scram

Development of Acceptance Criteria for 4S

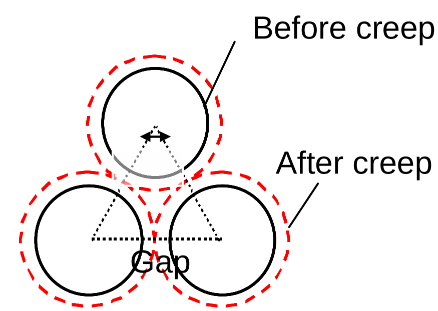
- **Define acceptance criteria**
  - **Desired characteristics of metrics**
    - Directly related to issue
    - Directly related to phenomena
    - Easily comprehended
    - Explicit
    - Verifiable by safety analysis
  - **To define acceptance criteria for 4S**
    - Return to regulatory requirements
      - Protect public health and safety
      - Limit fission product release
      - Limit fuel failure
    - Focus on
      - Integrity of primary coolant boundary
      - Integrity of fuel cladding and coolable geometry

Acceptance Criteria

Item	AOO	DBA	ATWS
Fuel cladding integrity and coolable geometry	No fuel melting $\sum_{i=1}^{M}\sum_{j=1}^{Ni}(CDF_{AOO})_{ij}+CDF_{DBA}\leq 0.1^{(1,2)}$ $\left(\sum_{i=1}^{M}\sum_{j=1}^{Ni}(\varepsilon_{AOO})_{ij}+\varepsilon_{DBA}\leq 8\%\right)$		$CDF_{ATWS}\leq 0.1$

(1) Cladding integrity is maintained with sufficient margin if total cumulative damage fraction (CDF) is below 0.1.

(2) Coolable geometry is assumed to be maintained if the gap between fuel claddings is bigger than cladding deformation due to creep strain. As creep strain is accumulated during every event, such as AOO, it is important to evaluate creep strain as the summation of strain increase at each event.
Creep strain is related to creep rupture time (CDF). For the pin pitch configuration, 8% of creep strain is allowed to maintain coolable geometry. Coolable geometry is satisfied when CDF is restricted 0.1 or less.



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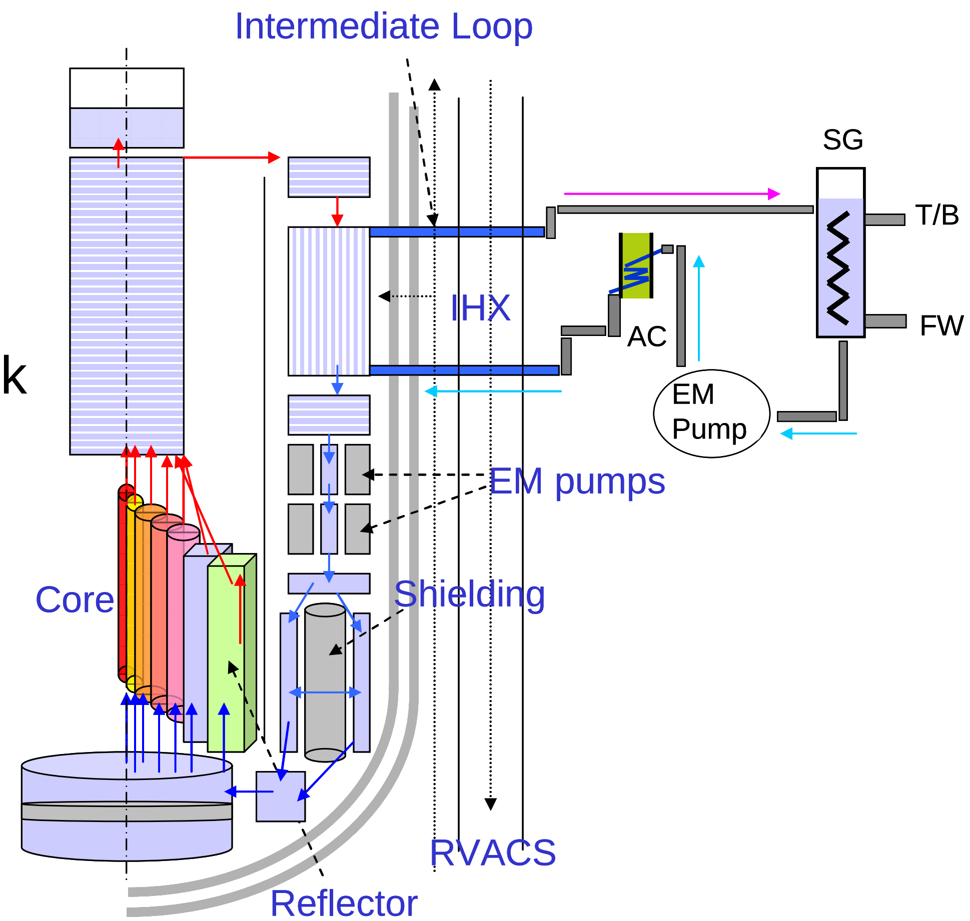
Analysis Methodology

- **Analysis code: ARGO**
- **Models**
  - Point kinetics
  - Spatial effect of reactivity feedback
  - Multiple channels in core
  - One-dimensional flow network



Degree of Conservatism

Attributes \ Analysis Event	AOO and DBA	ATWS
Reactivity feedback	Combination of minimum and maximum to obtain conservative value	Nominal and uncertainty (95/95）
Power and flow rate		
Material properties		
Plant parameters (pressure drop, halving time during coastdown, etc)		

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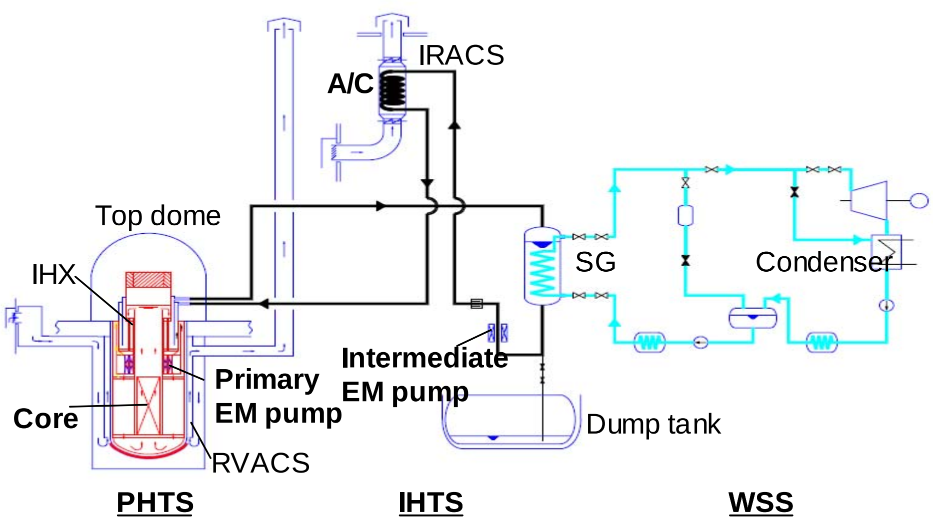
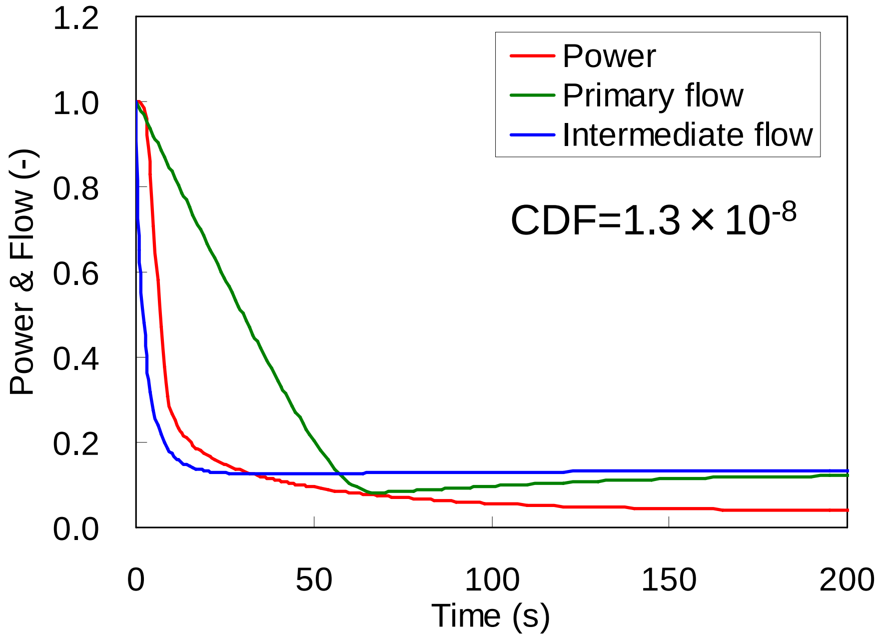
Analysis Results for AOO

- **Analysis results for loss of offsite power**
  - Primary, intermediate, and feedwater pumps trip
  - Detection of loss of offsite power
  - Reactor shutdown
  - Single air cooler damper closed (single failure criterion applied)

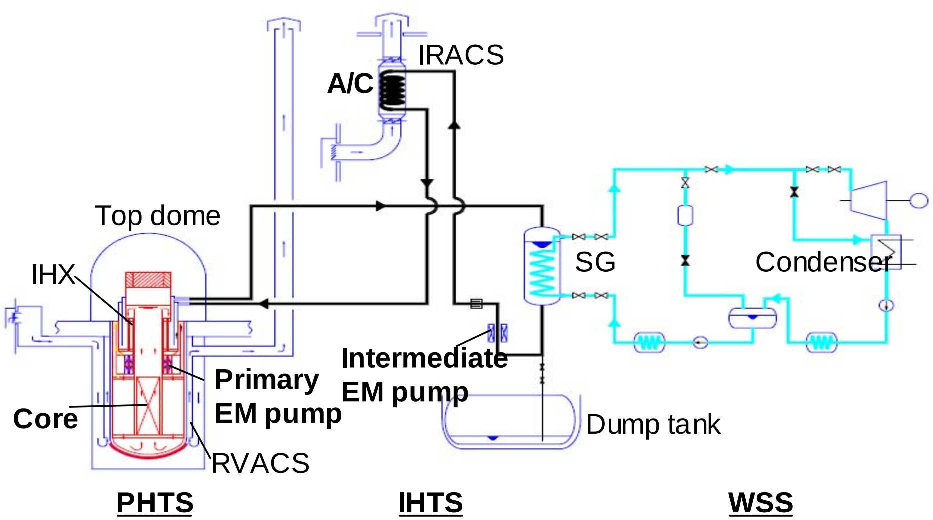


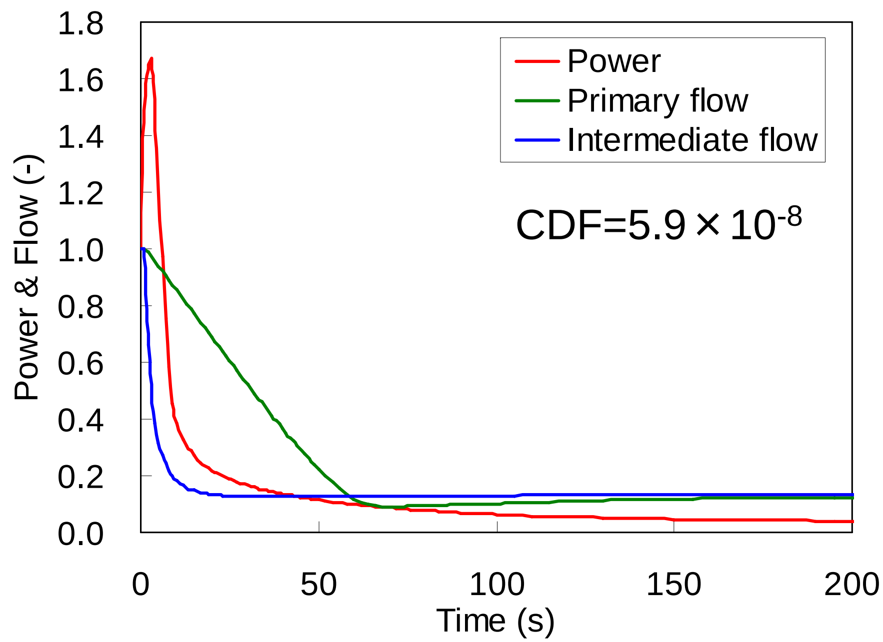


Reactor power, flow rate, and CDF

Analysis Results for DBA

- **Analysis results for failure of a cavity can**
  - Reactor power increase due to reactivity insertion
  - Detection of neutron flux increase
  - Reactor shutdown
  - Primary, intermediate, and feedwater pumps trip





Reactor power, flow rate, and CDF

Source Term Analysis

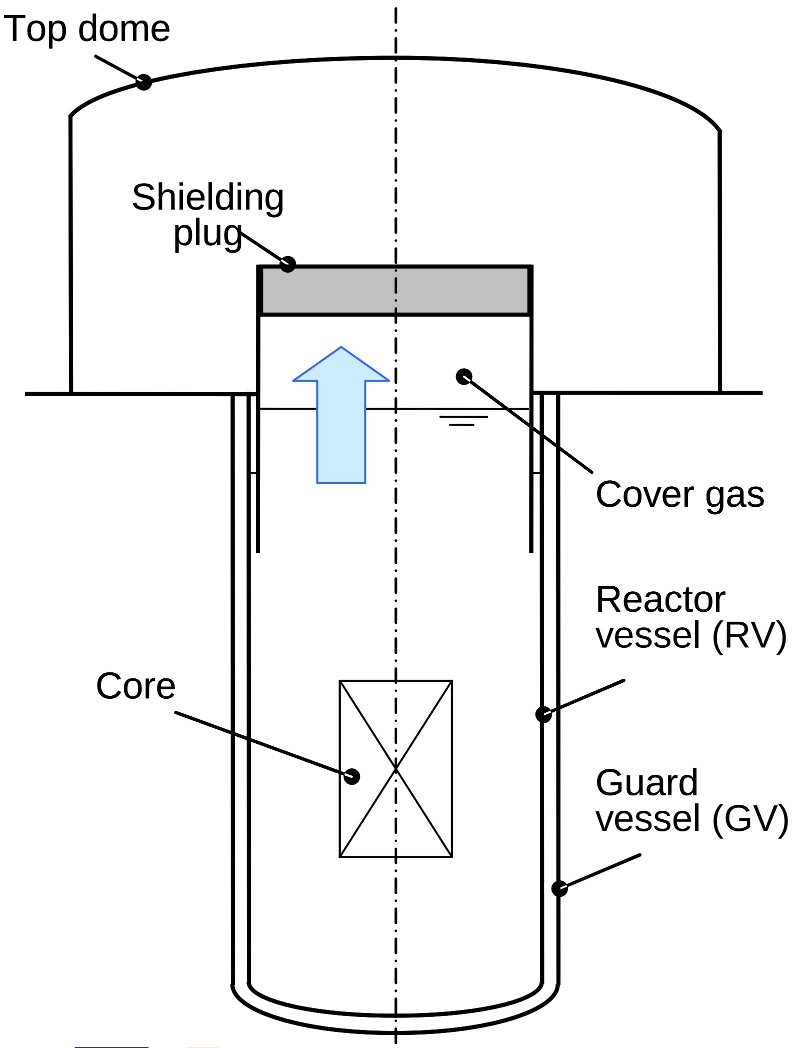
- Consider 4S safety features
- Define 4S source term to evaluate site suitability
- Perform source term analysis

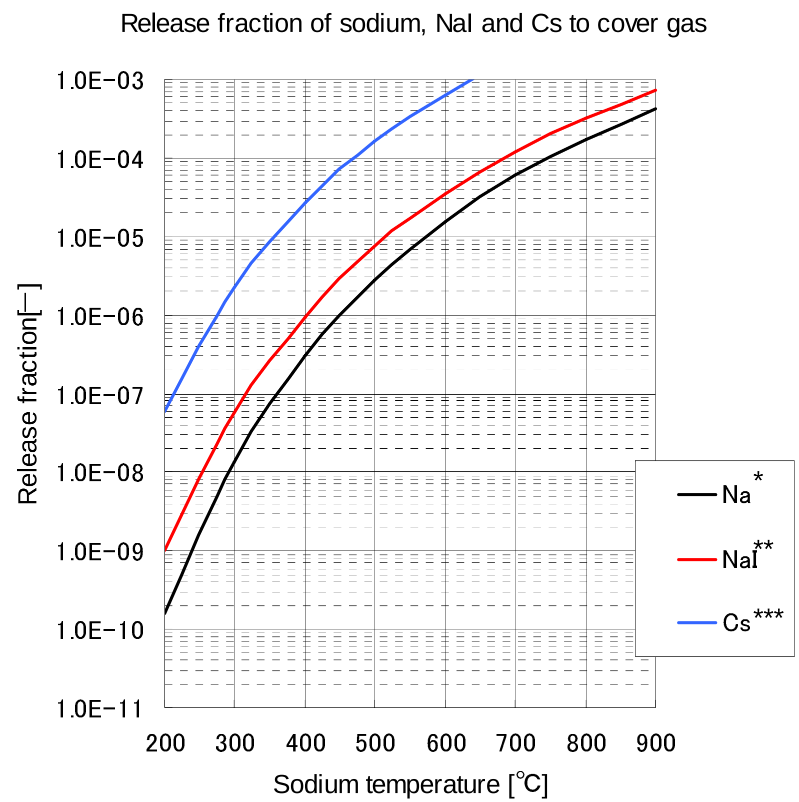
Safety Features of 4S

- **Source term reduction**
  - Low power results in low fission product inventory
  - Sodium affinity for fission products minimizes release
  - No significant release to containment due to absence of energetic and pressurization events
- **Radioactive release reduction**
  - Sealed reactor vessel and containment
  - Minimize penetrations and isolation valves
  - Threat to containment integrity is minimal due to absence of damaging phenomena (direct containment heating, steam explosion, hydrogen burning or detonation, missiles)

Sodium Affinity for Fission Products

- **Large FP retention capability of sodium**





*J.K.Fink et al.,"Thermophysical Properties of Sodium," ANL-CEN-RSD-1 (1971)

**C.G.Allan et al.," Solubility and Deposition Behavior of Sodium Bromide and Sodium Iodine in Sodium / Stainless Steel Systems," TRG Report 2458(D) (1973)

***B.D.Pollock et al.,"Vaporization of Fission Product from Sodium," ANL-7520 Part-1 (1968)

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4S Source Term Definition

- **4S source term**
  - Element groups
    - Radionuclide groups and the elements comprising each group are set as shown below in reference to RG 1.183 except for the following two points:
      - Uranium is not defined in RG 1.183. In this calculation, uranium is included in Cerium group
      - Coolant is added because of activation of sodium in this evaluation.

Noble gases: Xe, Kr
Halogens: I, Br,
Alkali Metals: Rb, Cs,
Tellurium Group: Te, Sb, Se
Barium, Strontium: Ba, Sr
Noble Metals: Ru, Rh, Pd, Mo, Tc, Co
Cerium group: Ce, Pu, Np, U
Lanthanides: La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Am, Cm
Coolant: Na

4S Source Term Definition (cont.)

- **4S source term (cont.)**

	4S Case (core inventory fraction released into primary sodium)	4S Case (core inventory fraction released into top dome)	LWR Case ("PWR core inventory fraction released into containment," RG 1.183)
Noble gases	1.0	1.0	1.0
Halogens	1.0	5×10^{-6}	0.4
Alkali metals	1.0	1×10^{-4}	0.3
Te group	1.0	3×10^{-6}	0.05
Ba, Sr	1.0	3×10^{-6}	0.02
Noble metals	0.001	3×10^{-9}	0.0025
Ce group	0.001	3×10^{-9}	0.0005
Lanthanides	0.001	3×10^{-9}	0.0002

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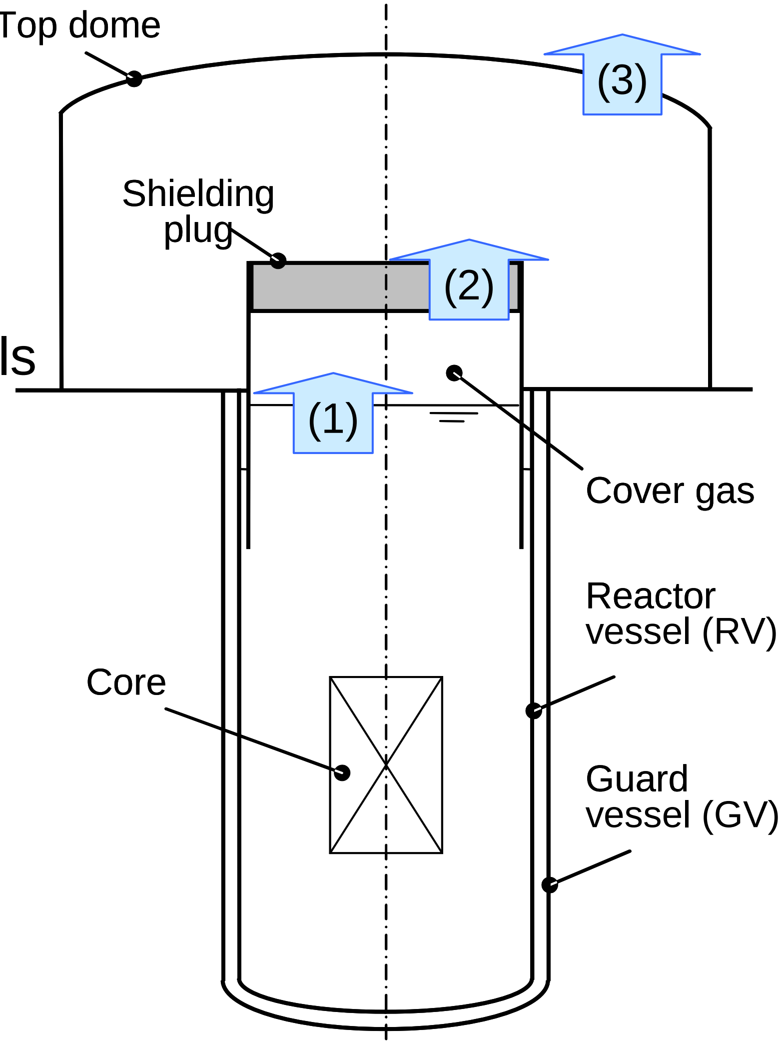
4S Source Term Definition (cont.)

- **Leak path for 4S source term analysis**
  - Sodium to cover gas (1)
    - Release fraction of noble gas to cover gas is 100%.
    - Release fraction of other materials is defined under chemical equilibrium between mass concentration in sodium and cover gas.
  - Cover gas to top dome (2)
    - Release rate is 0.1%/day.
  - Top dome to environment (3)
    - Release rate is 1%/day.



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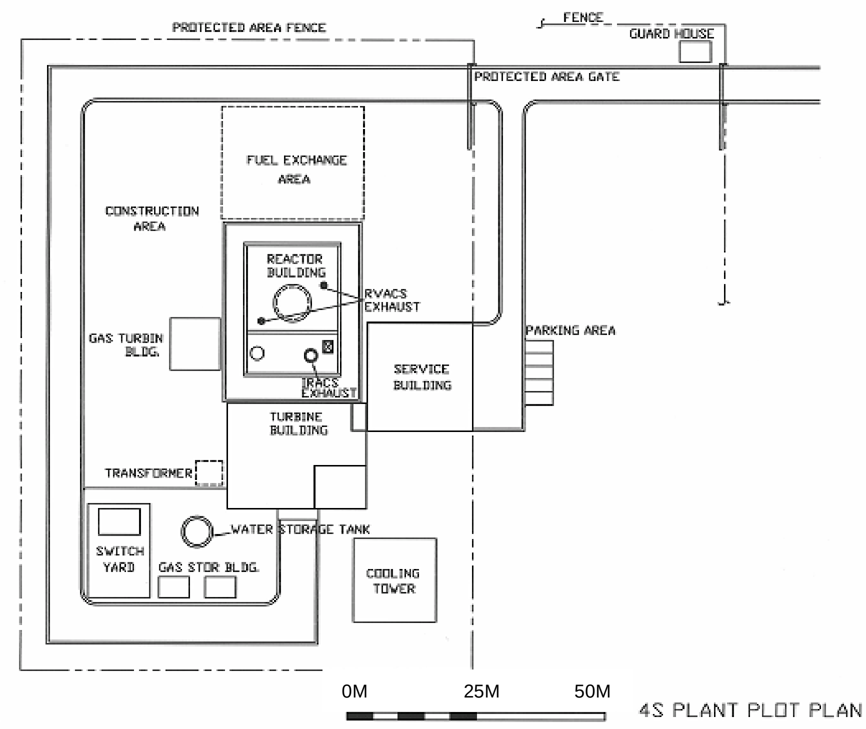
Analysis Results

- **Large margin to acceptance criteria of TEDE for site suitability**

Distance (m)	50
EAB (rem)	0.004
LPZ (rem)	0.2
Acceptance dose criteria (rem)	25

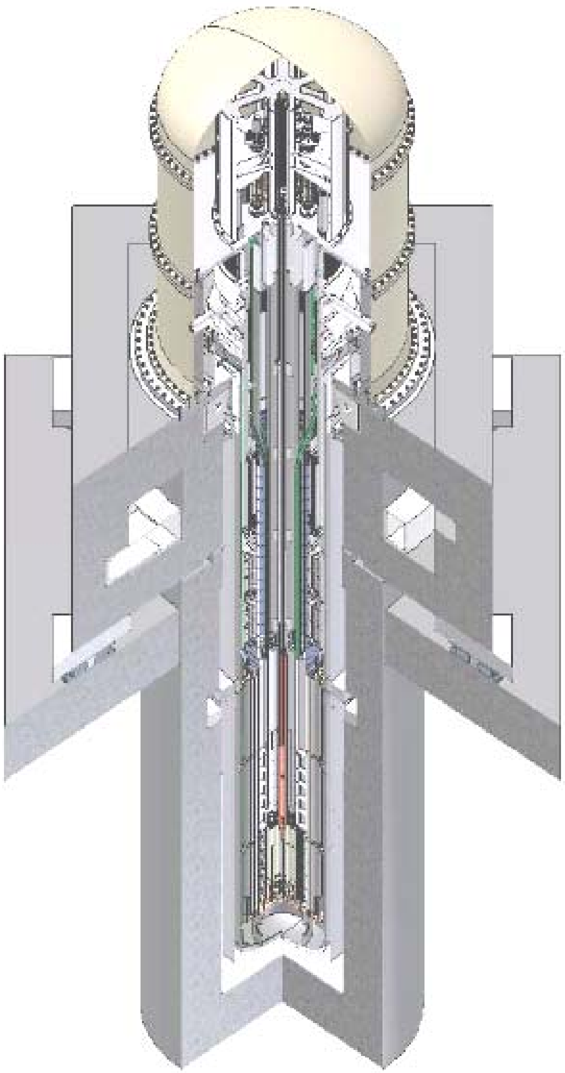
TEDE: Total equivalent dose
EAB: Exclusion area boundary
LPZ: Low population zone



Summary

- **Accomplishments**
  - Preliminary criteria for safety analysis for 4S developed
  - Accident analysis performed
  - Large margin against acceptance criteria for fuel integrity and coolable geometry confirmed
  - Large margin against acceptance criteria for dose for site suitability confirmed

Enhancement of Safety Through Risk Reduction



Measures Against Severe Core Damage

- **Safety design based on PDC**
- **Risk reduction by passive safety**
  - Metallic fuel
  - Negative feedback reactivity
  - Natural circulation
- **Risk reduction by evolutionary design**
  - No refueling
  - EM pump
  - Prevention by redundant flow path of inlet assembly module
  - Backup redundant and diverse system for residual heat removal system
  - Double-walled steam generator tube with leak detection
  - Backup support structure
  - Multiple redundant cavity cans

Measures against Severe Core Damage (cont.)

- 4S design excludes core damage for initiators previously identified by using passive safety and evolutional designs.

Initiators	Measures of Risk Reduction
ATWS (ref. NUREG-0968 App. A)	Metallic fuel, negative feedback reactivity, and low power density
Sudden LOF w/o S (ref. NUREG-1368)	Metallic fuel, negative feedback reactivity, low power density, and natural circulation
All CRs withdrawal w/o S (ref. NUREG-1368)	Redundant mechanical stops, very slow reactivity addition rate, and negative feedback reactivity
Fuel loading error (ref. NUREG-1368)	Similar enrichment level for both core regions

Measures against Severe Core Damage (cont.)

- 4S design excludes core damage for initiators previously identified by using passive safety and evolutional designs.

Initiators	Design for Risk Reduction
Inlet blockage of S/A (ref. NUREG-1368)	No refueling, EM pump, and prevention by redundant flow path of inlet module
Gas passage in the core	Negative void reactivity feedback
75% blockage of flow path of RVACS (ref. NUREG-1368)	Backup redundant and diverse system (IRACS and RVACS)

Measures against Severe Core Damage (cont.)

- 4S design excludes core damage for potential initiators by evolutionary designs.

Initiators	Design for Risk Reduction
Sodium water reaction	Double-walled steam generator tube with leak detection
Failure of core support structure	Backup structure

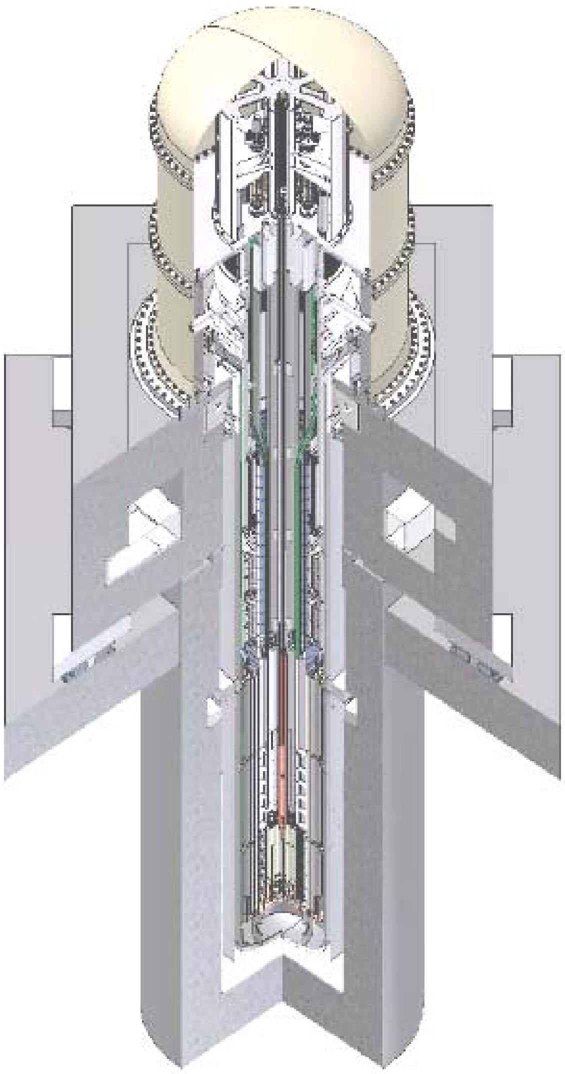
- New potential initiator in 4S reactor is excluded by redundancy of passive components.

Initiator	Design for Risk Reduction
Failure of cavity cans	Multiple redundant can

Summary

- **Exclude all sequences by passive safety and design measures against severe core damage**

Applicability of Regulatory Guides



Applicability of Regulatory Guides

- **Overview**
  - Regulatory Guide (RG) divisions evaluated for applicability
  - Criteria for determining applicability
  - Applicability rating
- **RG Applicability Examples**
- **RG Conclusions**

Overview

- **RG Divisions evaluated for applicability**

  Division 1: Power reactors
  Division 4: Environmental and siting
  Division 5: Materials and plant protection
  Division 8: Occupational health

- **Criteria for determining applicability**
  - Candidates for RG inapplicability
    - Withdrawn
    - Superseded
    - Not within Design Certification scope
    - Fuel cycle areas outside reactor site
    - LWR-specific
    - Material or item not applicable for 4S; e.g., concrete containment
  - Candidates for RG applicability
    - Related to applicable GDCs; e.g., design basis for protection against natural phenomena
    - Codes and Standards
    - Reactor type-independent; e.g., dose calculation

Overview (cont.)

- **Applicability rating**
  - Applicable: no exception
  - Partially applicable: exception to a portion of the RG; e.g., RG contains LWR-specific DBA and atmospheric dispersion formulae that are reactor-type independent
  - Intent applicable: RG uses LWR-specific items, but the intent of the RG is applicable to other reactor types; e.g., LWR radiation protection by radioactive release prevention
  - Not applicable
- **Examples**
  - Applicability of first 30 RGs and 2 referenced RGs of Division 1 are shown in following slides as examples.
  - Examples do not include RGs that have been:
    - Withdrawn (RG 1.2, 1.10, 1.15, 1.17, 1.18, and 1.19) or
    - Applicable without exception to the 4S reactor (RG 1.6, 1.11, 1.12, 1.21, 1.22, 1.23, and 1.30).

RG Applicability Examples

Guide No.	Title	Revision (Date)	Applica-bility	Remarks
1.1	Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal System Pumps (Safety Guide 1)	– (11/1970)	N	Replaced by RG 1.82 for for new reactors (Reference 1)
1.3	Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Boiling Water Reactors	2 (06/1974)	N	Should not be used for new reactors (Reference 1)
1.4	Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Pressurized Water Reactors	2 (06/1974)	N	Same as RG 1.3
1.5	Assumptions Used for Evaluating the Potential Radiological Consequences of a Steam Line Break Accident for Boiling Water Reactors (Safety Guide 5)	– (03/1971)	N	Superseded by RG 1.183 (Reference 2)

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RG Applicability Examples (cont.)

Guide No.	Title	Revision (Date)	Applica-bility	Remarks
1.7	Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident	3 (03/2007)	N	LWR-specific For LMR: no LOCA, hydrogen generation in reactor vessel not possible, containment inerted
1.8	Qualification and Training of Personnel for Nuclear Power Plants	3 (05/2000)	N (COL)	Not required for Design Certification (DC) application
1.9	Application and Testing of Safety-Related Diesel Generators in Nuclear Power Plants	4 (03/2007)	N	Diesel generators not safety related Requirements determined by RTNSS approach (Reference 3)

RG Applicability Examples (cont.)

Guide No.	Title	Revision Date	Applica-bility	Remarks
1.13	Spent Fuel Storage Facility Design Basis	2 (03/2007)	Intent	Some LWR-specific items not applicable to LMR RG 1.13 references: GDC 2 (no exception), GDC 4 (one exception), GDC 61 (one exception), and RG 1.26 (intent), RG 1.29 (intent), RG 1.76 (applicable), RG 1.52 (not applicable), RG 1.92 (applicable), and RG 1.115 (applicable)

RG Applicability Examples (cont.)

Guide No.	Title	Revision (Date)	Applica-bility	Remarks
1.14	Reactor Coolant Pump Flywheel Integrity	1 (08/1975)	N	PWR only
1.16	Reporting of Operating Information – Appendix A Technical Specifications (for Comment)	4 (08/1975)	N (COL)	Operating license application requirement
1.20	Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing	3 (03/2007)	Intent	LWR-specific components or prototypes
1.24	Assumptions Used for Evaluating the Potential Radiological Consequences of a Pressurized Water Reactor Radioactive Gas Storage Tank Failure (Safety Guide 24)	(03/1972)	N	PWR only

RG Applicability Examples (cont.)

Guide No.	Title	Revision (Date)	Applica-bility	Remarks
1.25	Assumptions Used for Evaluating the Potential Radiological Consequences of a Fuel Handling Accident in the Fuel Handling and Storage Facility for Boiling and Pressurized Water Reactors (Safety Guide 25)	– (03/1972)	N	Should not be used for new reactors (Reference 1)
1.26	Quality Group Classifications and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants	4 (03/2007)	Intent	LWR radioactive water and steam systems

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RG Applicability Examples (cont.)

Guide No.	Title	Revision (Date)	Applica-bility	Remarks
1.27	Ultimate Heat Sink for Nuclear Power Plants (for Comment)	2 (01/1076)	N	Water heat sinks only 4S reactor uses atmospheric air as heat sink for RVACS and IRACS
1.28	Quality Assurance Program requirements (Design and Construction)	3 (08/1985)	Partial	Covers design and construction phases Scope to be limited to design phase as defined by 10CFR52, Part B
1.29	Seismic Design Classification	3 (09/1978)	Intent	RG uses some LWR-specific items

RG Applicability Examples (cont.)

Guide No.	Title	Revision (Date)	Applica-bility	Remarks
1.82	Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident	3 (11/2003)	N	LWR only 4S reactor core remains covered with sodium and cooled passively without the need for ex-vessel coolant source
1.183	Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors	– (07/2000)	Partial	LWR specific DBAs and source terms Should replace with 4S reactor DBAs and source term

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RG Applicability Examples (cont.)

- **References:**

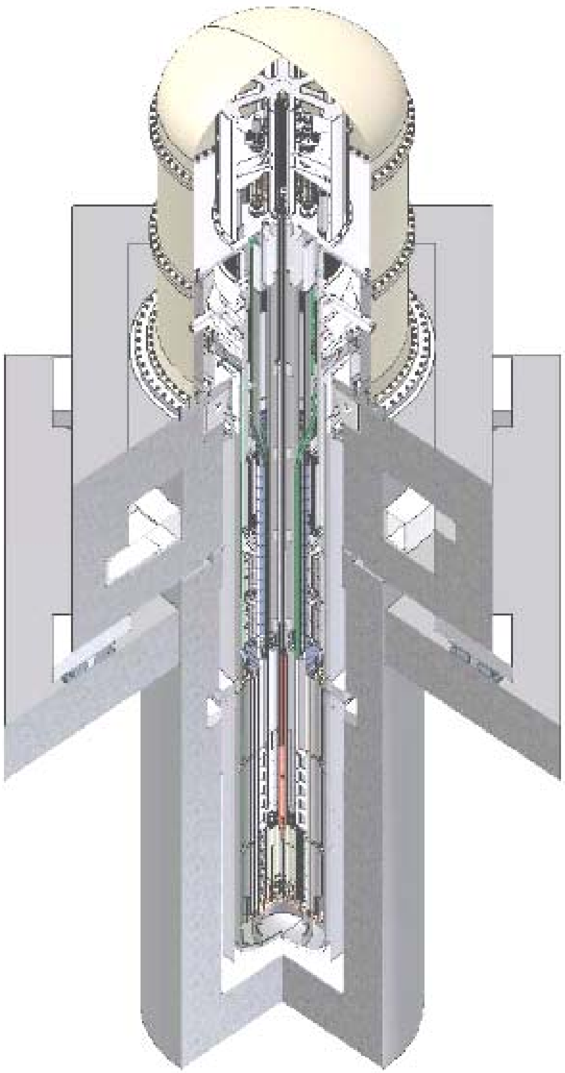
1. U.S. Nuclear Regulatory Commission, "Regulatory Guides to be Addressed for New Reactor Licensing," http://www.nrc.gov/reading-rm/doc-collections/reg-guides/status.pdf.
2. U.S. Nuclear Regulatory Commission, "Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Plants," Regulatory Guide 1.183, July 2000.
3. U.S. Nuclear Regulatory Commission, "Policy and Technical Issues Associated with the Regulatory Treatment of Non-Safety Systems in Passive Plant Design," SECY-94-084, March 28, 1994.

RG Conclusions

- 336 RGs of RG Divisions 1, 4, 5, and 8 have been evaluated for applicability to 4S.
- Applicability summary is as follows:

RG Division Number	Number of RGs	Withdrawn	Not Applicable	Applicable, Partially Applicable, Intent
1	209	27	57	125
4	20	3	15	2
5	68	24	33	11
8	39	5	29	5
Total	336	59	134	143

Conclusions



Conclusions

- **4S is a mature technology that is ready for commercialization.**
  - Preliminary systems design complete and detailed design in progress
  - Significant body of test data to support key components
  - Proven and tested fuel experience to support the 30-year core lifetime
- **4S U.S. licensing process has begun.**
  - Pre-application review meetings & topical reports
  - Target for FDA - 2011

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Phase 1 – Proposed Licensing Approach

	2007	2008		
	4Q	1Q	2Q	3Q
1st Meeting High level overview	▼			
2nd Meeting System design Long-life metallic fuel		▼		
3rd Meeting -Today Safety design and regulatory conformance			▼	
4th Meeting* PIRT review				▼

*) Subject to NRC concurrence

End