Joint ICTP-IAEA Nuclear Safety Institute Workshop

Assessment of Major Systems - Reactor Core

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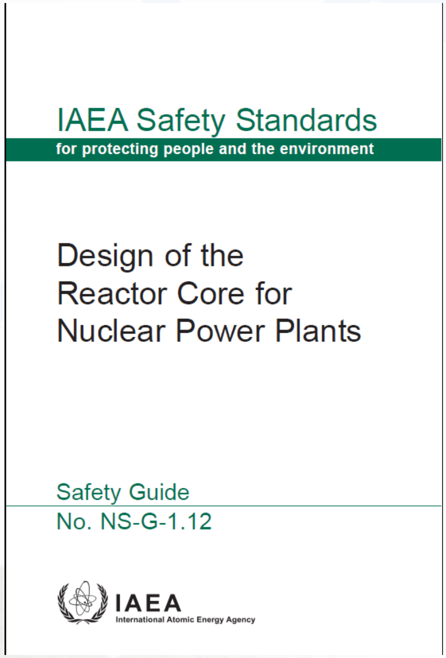
October 2015

OUTLINE

Lecture on LWRs based on the IAEA Safety Guide NS-G-1.12

- **General Safety Considerations in Design**
- **Specific Safety Considerations in Design**
- **Qualification and Testing**
- **Quality Assurance in Design**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Design of the
Reactor Core for
Nuclear Power Plants

Safety Guide
No. NS-G-1.12

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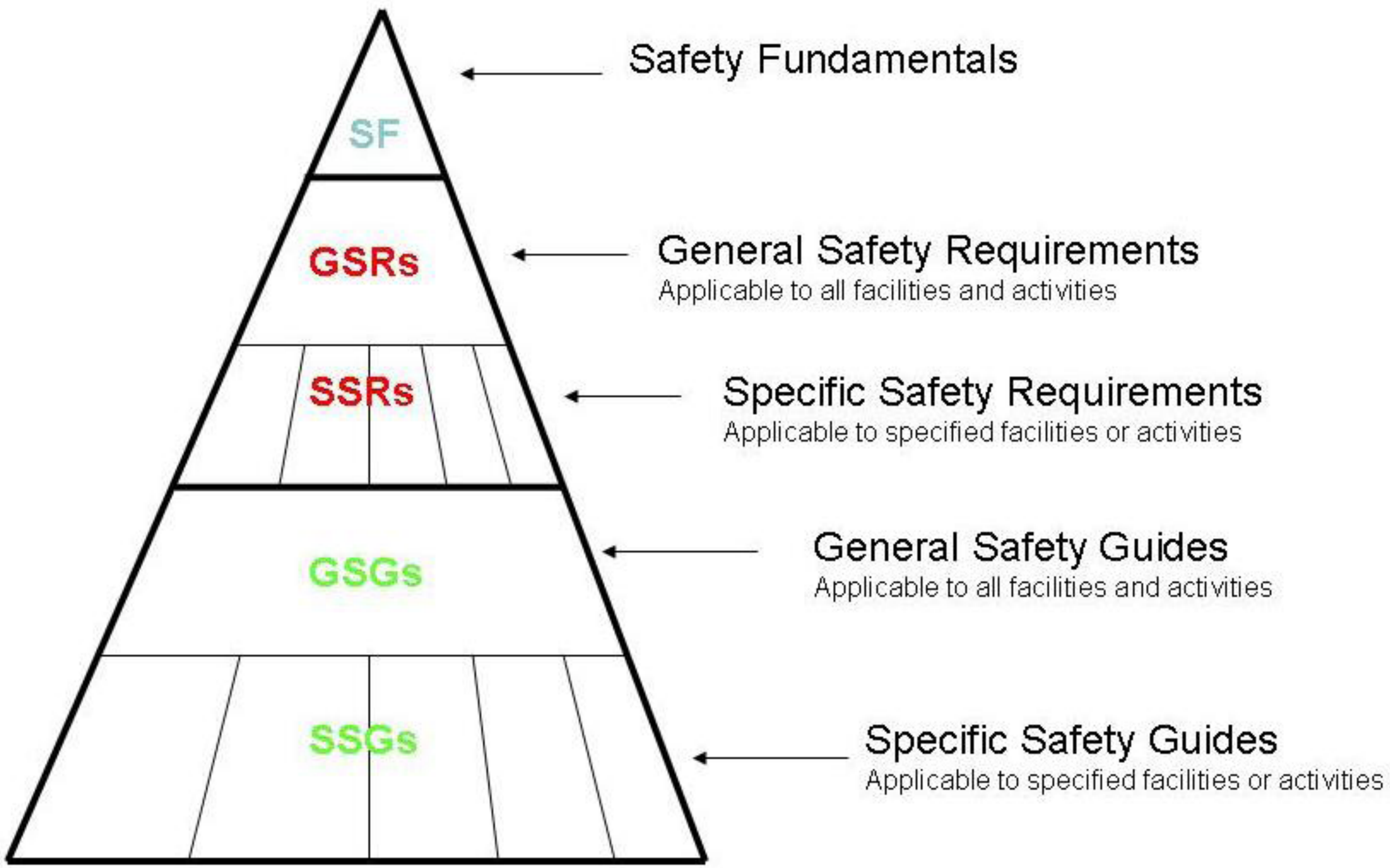
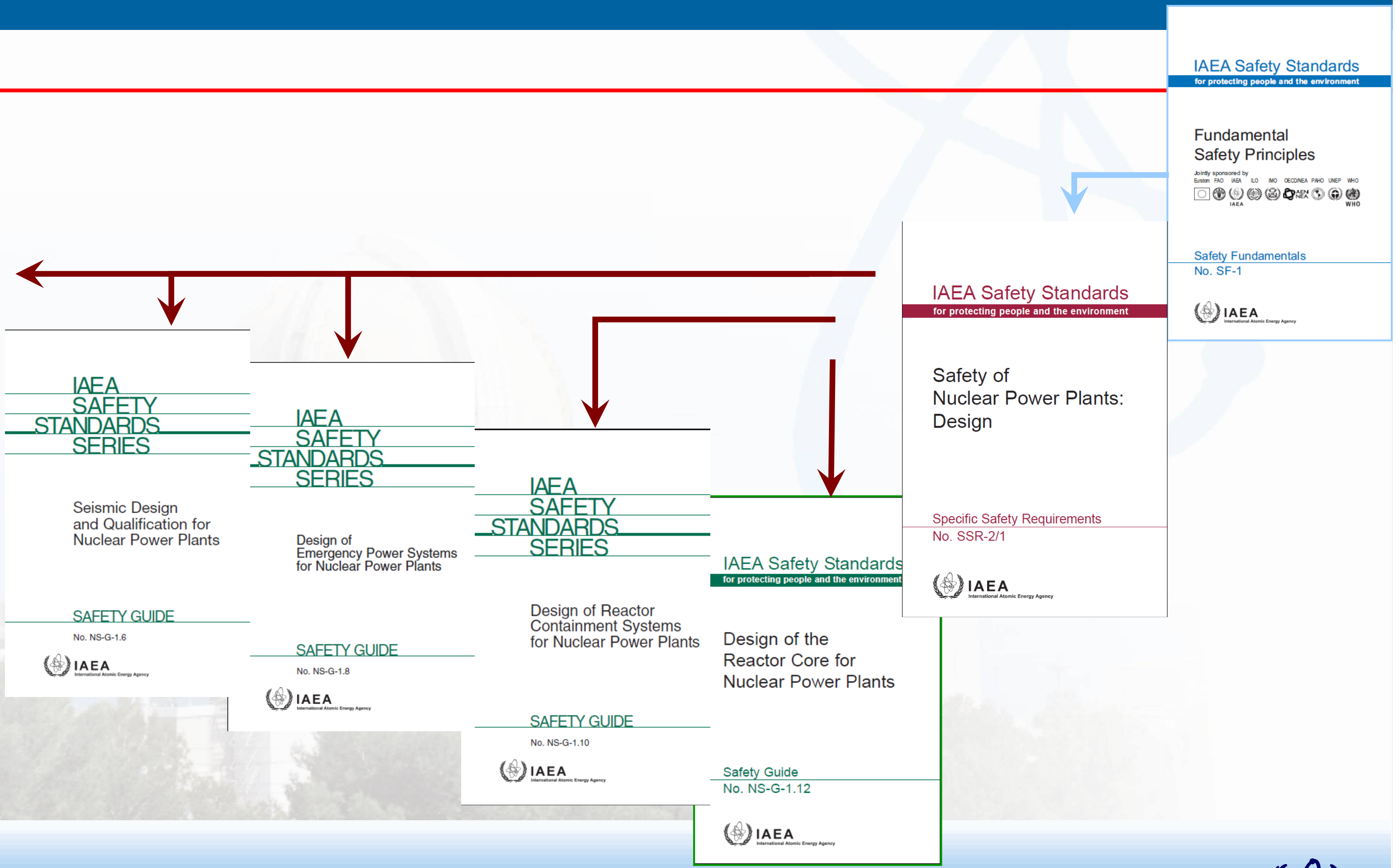
NEW LONG TERM STRUCTURE OF THE SAFETY STANDARDS



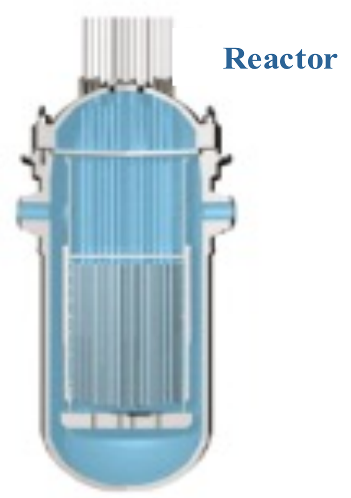
SAFETY STANDARDS RELATED TO SSR 2-1



MAIN SAFETY FUNCTIONS

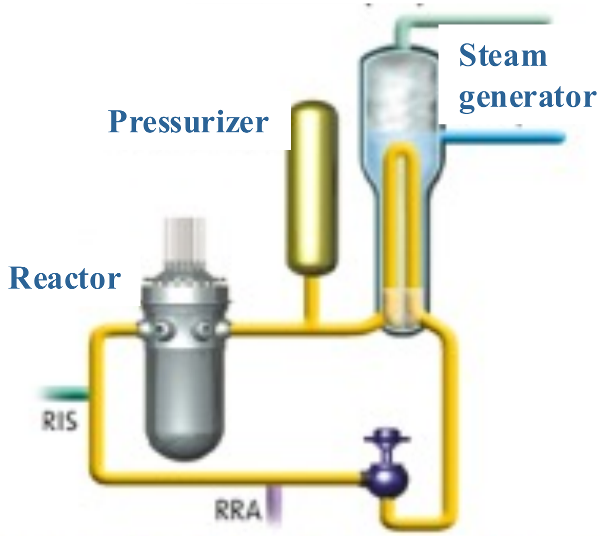
Control of reactivity

- Control rods
- Boron concentration



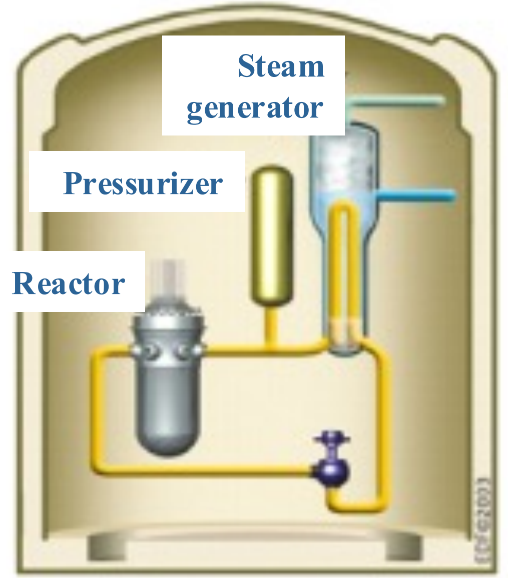
Cooling of the core

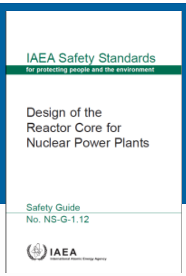
- Steam generators
- RHR
- Safety injection
- …



Confinement of radioactive materials

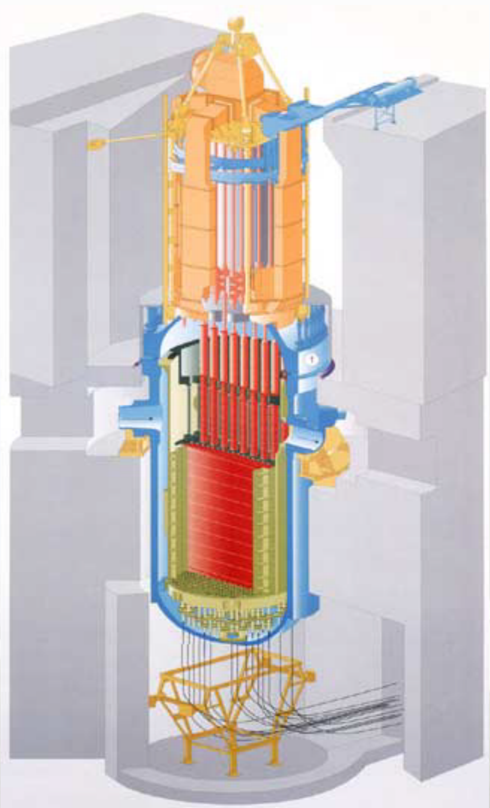
- Fuel cladding
- Primary cooling system
- Containment



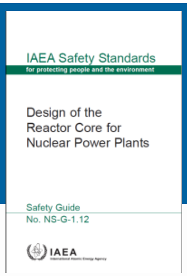


GENERAL SAFETY CONSIDERATIONS IN DESIGN

➢ **WHICH ARE THE MAIN THREE "DISCIPLINS" INVOLVED IN CORE DESIGN?**



- **Neutronic Design**
- **Thermal-Hydraulic Design**
- **Mechanical Design**
- **Safety Classification Aspects of Core Design *(for the record*)**



➢ Neutronic Design

- **Design of the core intrinsically stable:**
  - ✓ feedback characteristics of the core rapidly compensate for an increase in reactivity (neutronics vs. thermal-hydraulics)
  - ✓ capability of the control and shutdown systems to actuate for all operational states and Design Basis Accidents (DBAs)
  - ✓ Speed and reliability are important (e.g. Control Rod drop time, Fuel Assembly Bowing etc.)

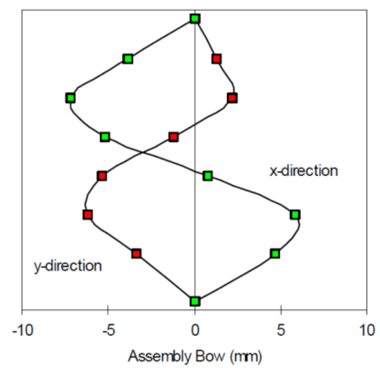


FIG. 3. Ringhals 4 – Example of S-shaped assembly bow.

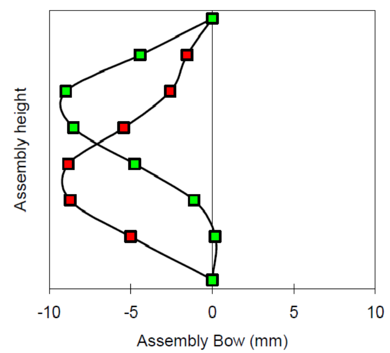
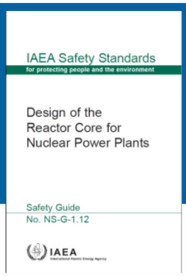


FIG. 4. Ringhals 3 - Example of C-shaped assembly bow.

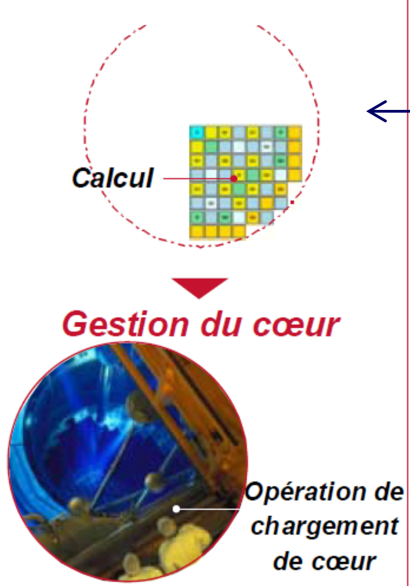


GENERAL SAFETY CONSIDERATIONS IN DESIGN

➢ Thermal-Hydraulic

- **Design limits set up with sufficient margins in operational states to keep the fuel failure rate limited in DBAs**
  - ✓ maximum heat generation rate
  - ✓ minimum critical power ratio (BWR) ≈ Departure of Nuclear Boiling (PWR)
  - ✓ peak fuel temperature and peak cladding temperature

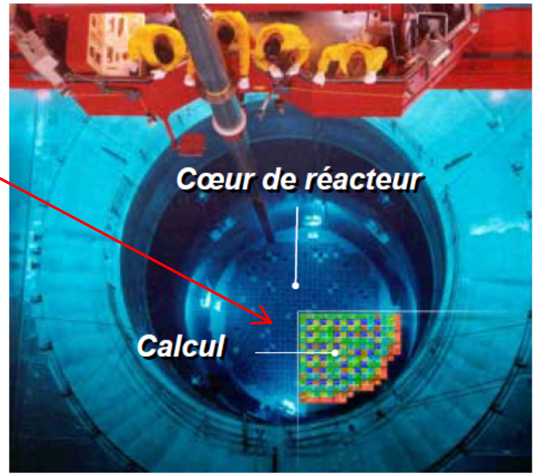
PWR

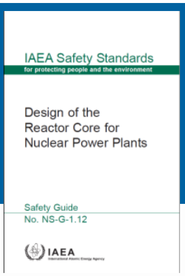


Core Calculation

Core fuel management

BWR





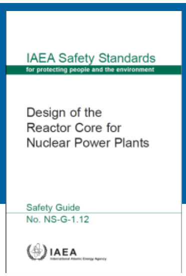
GENERAL SAFETY CONSIDERATIONS IN DESIGN

- **Thermal-Hydraulic (cont'd)**

  - **Suitable means of instrumentation and control so that parameters indicative of the core conditions can be monitored and adjusted safely to ensure that the design limits are not exceeded for all operational states, (including refuelling)**

    - ✓ **Rate of coolant flow**
    - ✓ **Coolant temperature**
    - ✓ **Neutron flux**

  - **Suitable instrumentation for monitoring is required to be provided for assessing the status of the core and associated features under accident conditions**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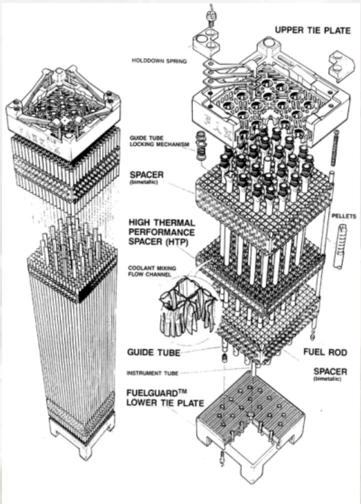
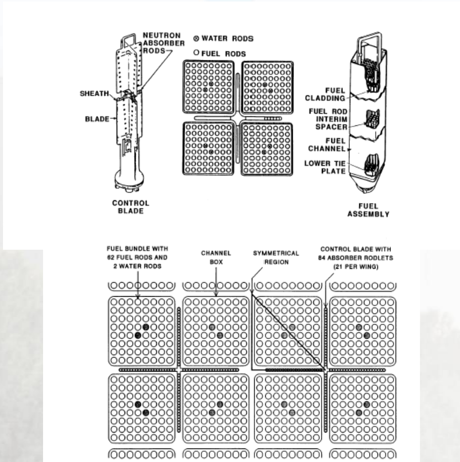
GENERAL SAFETY CONSIDERATIONS IN DESIGN

➢ Mechanical design (fuel assemblies)

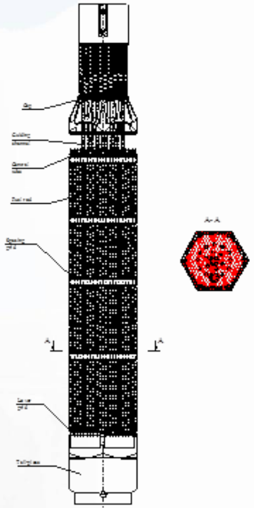
- **Leak tight cladding for all operational states throughout its lifetime (1st barrier)**
  - ✓ **effects of temperature, pressure, irradiation, fission products, static and dynamic mechanical loads, including seismic loads, flow induced vibration and changes in the chemical characteristics of the constituent materials.**



PWR



BWR



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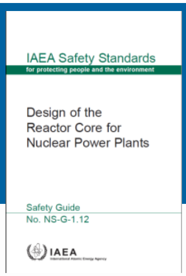
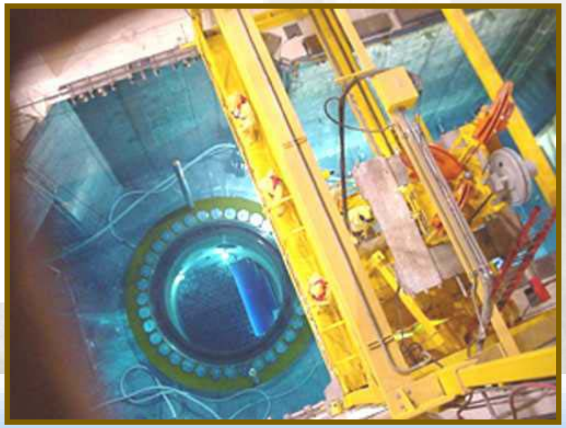
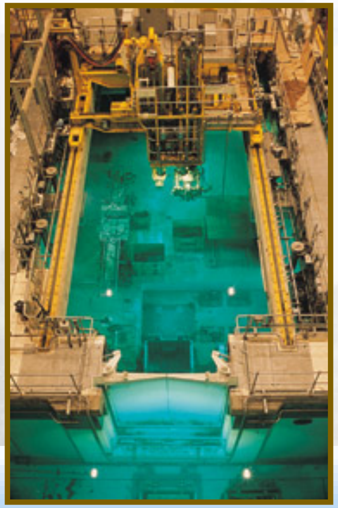


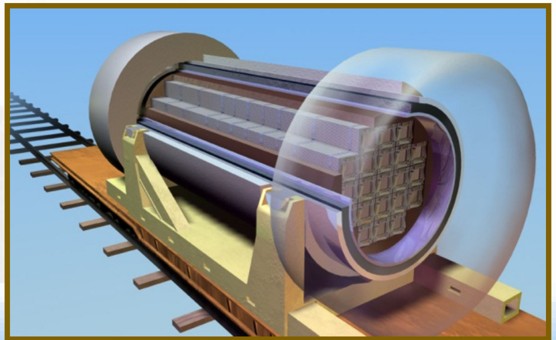
GENERAL SAFETY CONSIDERATIONS IN DESIGN

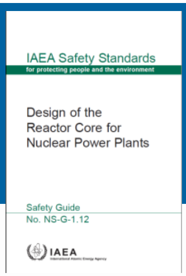
- **Mechanical design (Handling)**
  - **Means to ensure safe handling to be provided**
    - ✓ Fuel assemblies,
    - ✓ Control and Shutdown devices
    - ✓ Core Support Structure

    to ensure integrity in transport, storage, installation and refuelling operations









GENERAL SAFETY CONSIDERATIONS IN DESIGN

➢ Mechanical design (Core and Associated Components)

- **Structural Integrity ensured in NO and DBAs**
  - ✓ Control of reactivity (shutdown system)
  - ✓ Coolability to avoid flow blockage (e.g. loose of spare parts)
  - ✓ Static and Dynamic loads, including thermal stress to be considered

- **Design compatible with effects of irradiation and chemical and physical processes**
  - ✓ Fluence on the reactor pressure vessel
  - ✓ Primary circuit water chemistry vs. corrosion, …
  - ✓ Coolability to avoid flow blockage (e.g. loose of spare parts)
  - ✓ Static and Dynamic loads, including thermal stress to be considered

- **Uncontrolled movement of reactivity control devices to be prevented**

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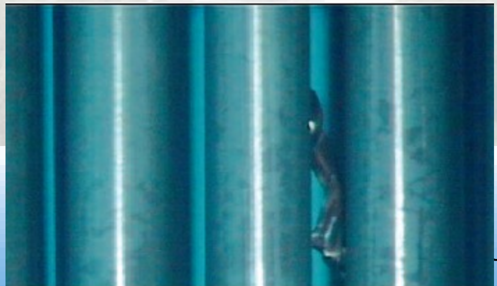
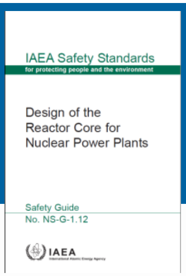
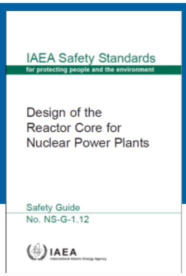


← **Example of loose of spare part**



Fuel Elements and Assemblies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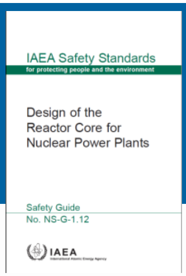
- **WHICH ARE THE EIGHT EFFECTS TO BE CONSIDERED IN THE FE and FA DESIGN?**
  - **Thermal and Burnup Effects**
  - **Effects of Irradiation**
  - **Effects of Variation in Power Levels**
  - **Mechanical Effects in Fuel Elements**
  - **Mechanical Effects in Fuel Assemblies**
  - **Effects of Burnable Poison**
  - **Corrosion and hydriding of Fuel Elements**
  - **Thermal-hydraulic effects in fuel assemblies**



➢ FUEL AND BURNUP EFFETS

- **Fuel Pellet Temperature**

  ✓ Changes in the thermal conductivity of the pellets and in thermal conductance of the gap (pellet /cladding) due to burnup dependent effects (oxide densification, swelling, fission products, changes in microstructure of the pellet

  ✓ Peak fuel Temperature < Fuel Melting Temperature, including margins and uncertainties

- **Design of the Fuel**

  ✓ Changes in mechanical properties (strength, creep and stress relaxation) and changes in corrosion related behaviour of the cladding with temperature

  ✓ effects of solid and gaseous fission products (fission gas releases dependant of fuel power history), effects on cladding corrosion

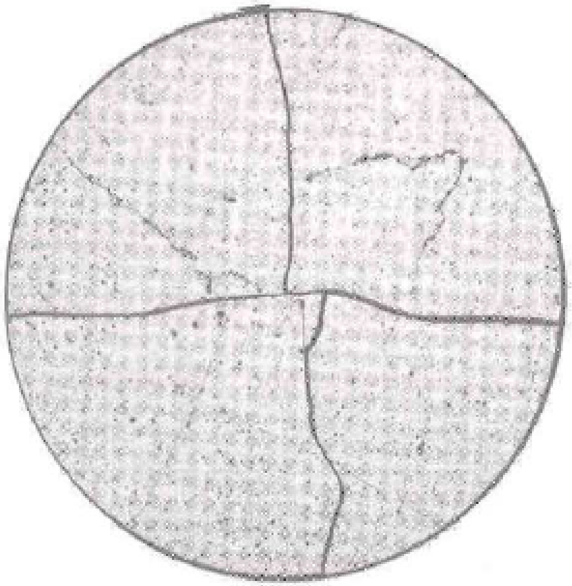
  ✓ Fuel Design Criteria to be met (e.g. Stress, Strain, Oxidation, Internal Pressure, etc.)

EFFECT OF IRRADIATION

Mechanical behaviour : pellet cracking

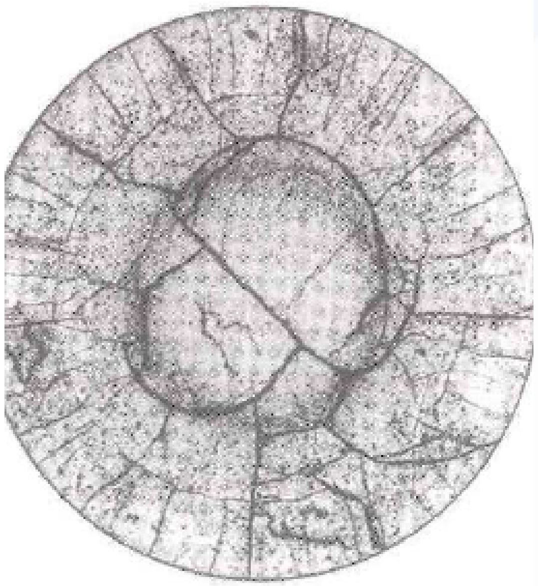
UO_2 as most ceramics is brittle

1 cycle - 200 W/cm



(a) après 1 cycle annuel d'irradiation en REP : fractures radiales

2 cycles – power ramp at 450 W/cm



N cracks ~ P lin

Typically # 6 to 8 cracks

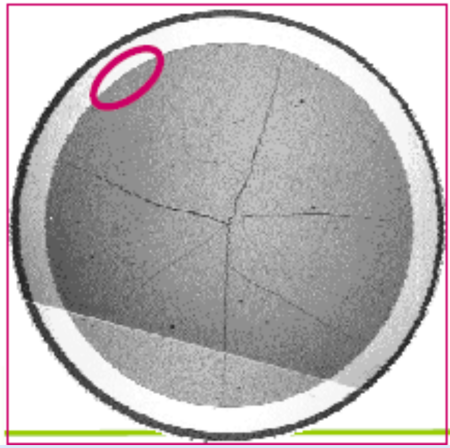
CONDUCTANCE OF THE GAP

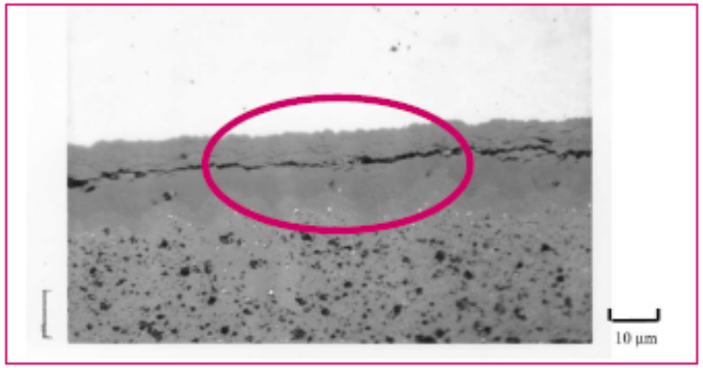
- **Gap open:**

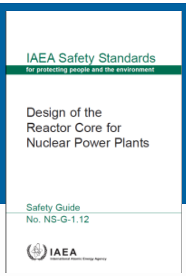
  Conduction in the gas predominant

- **Gap closed (high burn-up):**

  Conduction by solid contact predominant





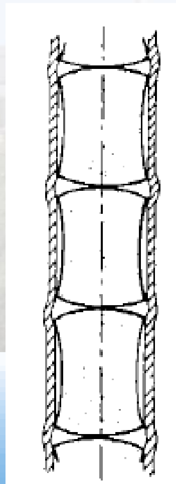


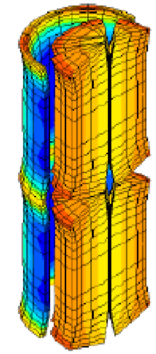
SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
FUEL ELEMENTS AND ASSEMBLIES

➢ EFFECTS OF IRRADIATION

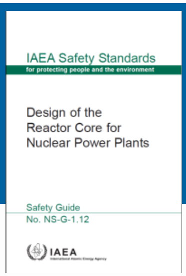
- **Metallurgical Properties**
  - ✓ effects of fast neutrons on fuel assemblies (including control devices and burnable poisons), on metallurgical properties such as the tensile strength of the cladding, ductility and creep behaviour, fuel densification and swelling (in radial and axial directions), and on the geometrical stability of all materials should be considered in the design.

➢ EFFECTS OF VARIATIONS IN POWER LEVELS





- **Integrity of the Cladding**
  - ✓ Pellet Cladding Interaction due to local and global power variations
- **Power Distribution of the Core and the Fuel Assemblies vs. burn-up**
- **Anticipated Power Transients on Peak Heating Rates on the Fuel/Core Design**



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
FUEL ELEMENTS AND ASSEMBLIES

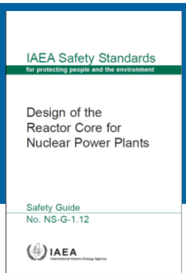
➢ MECHANICAL EFFECTS IN FUEL ELEMENTS

- **Stress Corrosion Cracking**
  - ✓ Stress corrosion cracking induced by pellet–cladding interactions in the presence of fission products should be minimized.

- **Fuel / Cladding Design**
  - ✓ Stress and Strain on the cladding to be limited (swelling and thermal expansion of fuel pellet, fission gas release)
  - ✓ Mechanical Loading (gaps between pellets, fuel densification, etc.)

➢ EFFECTS OF BURNABLE POISON IN THE FUEL

- **Fuel / Cladding Design**
  - ✓ Effects on thermal properties, chemical, mechanical and metallurgical properties
- **Core design**
  - ✓ Effects on the core reactivity, temperature coefficients of reactivity of the fuel and the moderator and on local power)



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
FUEL ELEMENTS AND ASSEMBLIES

EFFECTS OF CORROSION AND HYDRIDING

- **Fuel Element Design**
  - ✓ Compatible with the coolant environment
  - ✓ Corrosion and hydriding dependant on cladding material and temperature and on environmental conditions (water chemistry, etc.)
  - ✓ Build-up of deposits (oxidation, crud) to be limited
  - ✓ Hydrogen cladding content to be limited (embrittlement of the cladding)

THERMAL-HYDRAULICS EFFECTS iN THE FUEL ASSEMBLIES

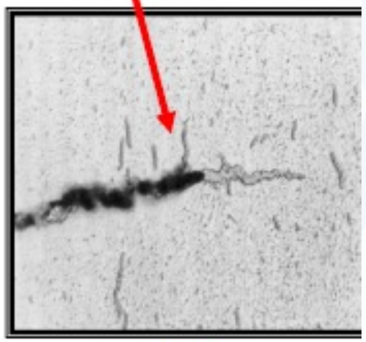
- **CHF for LWR or CPR for BWR**
  - ✓ Fuel design dependant
  - ✓ Influenced by coolant conditions
  - ✓ Supported by experiments
  - ✓ Conservatively evaluated

If $e_{ZrO2} \geq 100$ µm ➔ Spalling (ZrO_2 layer cracks and leaves) ➔ Cold points ➔ Hydride precipitation ➔ Clad embrittlemen

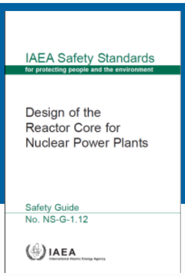
E.g. Zy4 limit :

~ 60 GWd/t rod

~ 52 GWd/t (ass)



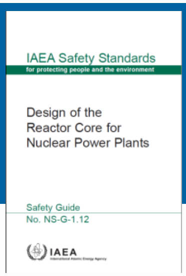
ZrH_2 overconcentration at crack end



➢ CONSIDERATION OF MECHANICAL SAFETY IN THE DESIGN

- **Fuel Assembly subject to Mechanical Stresses**

  - ✓ Fuel handling and loading;
  - ✓ Power variations;
  - ✓ Hold down loads for PWRs;
  - ✓ Temperature gradients;
  - ✓ Hydraulic forces, including cross-flows between open fuel assemblies;
  - ✓ Irradiation (e.g. radiation induced growth and swelling);
  - ✓ Vibration and fretting induced by coolant flow;
  - ✓ Creep deformation;
  - ✓ External events such as earthquakes;
  - ✓ Postulated initiating events such as a loss of coolant accident.



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
FUEL ELEMENTS AND ASSEMBLIES

➢ CONSIDERATION OF MECHANICAL SAFETY IN THE DESIGN

- **Design of the Fuel Assembly**

  - ✓ The **clearance** within and adjacent to the fuel assembly should **provide space to allow for irradiation growth and swelling**;
  - ✓ **Bowing of fuel elements** should be **limited** so that thermal-hydraulic behaviour and fuel performance are not significantly affected;
  - ✓ **Strain fatigue** should **not** be able to **cause the failure** of a fuel assembly;
  - ✓ The **fuel assembly** should be **able to withstand the mechanical and hydraulic holddown forces** without unacceptable deformation;
  - ✓ The performance of the functions of the fuel assembly and the support structure should not be unacceptably affected by damage due to vibration or fretting;
  - ✓ The fuel assembly should be **able to withstand irradiation** and its materials should be compatible with the chemical properties of the coolant;
  - ✓ Any deformation of the fuel element or the fuel assembly should not affect the **capability for the insertion of control rods** for the safe shutdown of the reactor.

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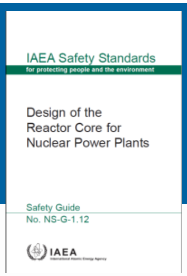
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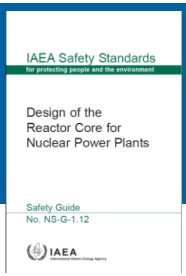
Coolant/Moderator



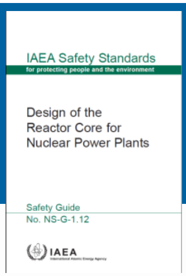
SPECIFIC SAFETY CONSIDERATIONS IN DESIGN COOLANT AND MODERATOR (LWRs)

COOLANT

- **Physically and chemically stable with respect both to high temperatures and to nuclear irradiation (FSF cooling)**

- **Safety Consideration should include**

  - ✓ Ensuring that the **coolant system** is **free of foreign objects and debris prior to the initial startup** of the reactor and for the **operating lifetime of the plant**;
  - ✓ Keeping the **activity** of the coolant **at an acceptably low level** by means of **purification systems and the removal of defective fuel as appropriate**;
  - ✓ Determining the capabilities of the **reactor control system and shutdown systems** for operational states and design basis accidents;
  - ✓ Determining and controlling the physical and **chemical properties** of the coolant in the core to ensure compatibility with other components of the reactor core, and minimizing corrosion and contamination of the reactor coolant system;
  - ✓ Ensuring a **sufficient supply of coolant** for operational states and in design basis accidents;
  - ✓ Ensuring that the core is designed to **prevent or control flow instabilities** and consequent fluctuations in reactivity.



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
COOLANT AND MODERATOR (LWRs)

➢ MODERATOR

- **For LWRs, Coolant acts also as Moderator**

  ✓ **Effects of changes in coolant density (including fluid phase changes) on core reactivity and core power, both locally and globally to be considered in the design**

  ✓ **Chemical additives to the coolant are used as neutron absorbers to provide a second system of control over the core reactivity (e.g. Boric Acid in PWRs. Other additives are used to control the chemistry of the coolant (e.g. control of the pH and the oxygen content)so as to inhibit the corrosion of core components and reactor internals or to reduce the contamination of the reactor coolant system.**

  ✓ **Means of controlling corrosion products and hydrogen resulting from radiolysis of the coolant should be provided in the design.**

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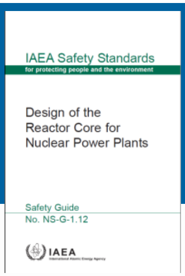
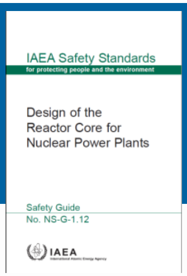


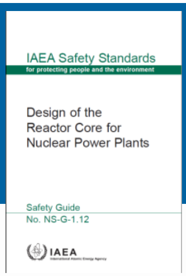
Reactor Core and Associated Features



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
REACTOR CORE AND ASSOCIATED STRUCTURES

➢ POSSIBLE DAMAGES MECHANISMS TO BE CONSIDERED IN THE DESIGN

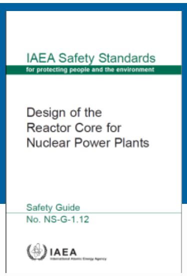
- Vibrations (coolant flow)
- Fatigue
- Mechanical Effects (internal missiles)
- Thermal, Chemical, Hydraulic and Irradiation Effects
- Seismic Motions
- Damage to Shutdown and Hold down Systems
- Insufficient capability for cooling the fuel
- Damage to fuel and to the reactor coolant pressure boundary
- Effects of high pressures, high temperatures, temperature variations and the temperature distribution, corrosion, radiation absorption rates and the lifetime radiation exposure on physical dimensions, mechanical loads and material properties should also be considered.



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN REACTOR CORE AND ASSOCIATED STRUCTURES

➢ DESIGN OF REACTOR CORE AND ASSOCIATED STRUCTURES

- **Expected radiation heating of the structures to be calculated and proper cooling provided.**
- **Adequate safety margins for the thermal stresses generated in NO and in DBAs.**
- **Chemical effects of the coolant and the moderator on the structures to be considered.**
- **Provisions for the necessary inspection of the core components and associated structures should be included in the design.**



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN REACTOR CORE AND ASSOCIATED STRUCTURES

➢ REACTOR COOLANT BOUNDARY

- Fuel assemblies and other core components in pressure vessel arranged to ensure **low neutron flux at the wall of the reactor vessel**

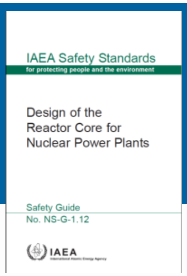
- Where necessary, neutron flux at locations that are vulnerable to **neutron irradiation embrittlement should be monitored**.

➢ REACTOR CORE SUPPORT STRUCTURES

- To maintain the fuel assembly support structures in the desired geometrical position against the reactor coolant pressure boundary.

- Designed to remain intact and capable of performing their functions throughout the lifetime of the reactor for operational states and DBAs

- Mechanical loads (induced by hydraulic forces and by normal refuelling and postulated abnormal refuelling) to be considered.



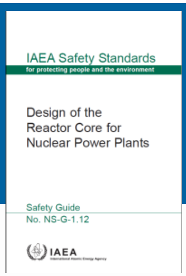
SPECIFIC SAFETY CONSIDERATIONS IN DESIGN REACTOR CORE AND ASSOCIATED STRUCTURES

➢ FUEL ASSEMBLY SUPPORT STRUCTURES

- Designed to hold the fuel assembly in the desired geometrical position for operational states and DBAs

➢ GUIDE STRUCTURES FOR SHUTDOWN AND REACTIVITY CONTROL DEVICES

- Designed to perform their functions under operational states and in DBAs
- Possibility of physical interaction (between Guide and FA) and damage during operation and shutdown and in DBAs to be considered for design
- Fatigue due to high neutron flux irradiation and/or gamma heating to be considered
- Design to facilitate the replacement of the reactivity control and shutdown devices whenever necessary without causing damage to the reactor core, unacceptable insertion of reactivity or undue radiation exposures.



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
REACTOR CORE AND ASSOCIATED STRUCTURES

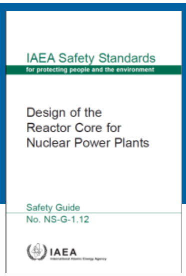
➢ SUPPORT STRUCTURES FOR IN CORE INSTRUMENTATION

- **Structures/Guide Tubes containing instrumentation for detection of accidents and the mitigation of their consequences within and in close proximity to the core, to be designed to perform their functions in all operational states and in DBAs**

- **Possibility that flow induced vibration of structures and guide tubes that may result in fretting and consequent failure in long term operation to be considered**

- **Structures/Guides Tubes designed so that instrumentation is accurately located and cannot be moved by inadvertent operator actions, strains on equipment, forces due to coolant flow, in operational states or in DBAs**

- **Design should facilitate the replacement of the instrumentation whenever necessary.**



➢ OTHER REACTORS VESSEL INTERNALS

- Reactor type dependant (e.g. feedwater spargers, steam separators, steam dryers, core baffles, reflectors and thermal shields)

- Designed so that mechanical performance does not jeopardize the performance of any associated safety functions throughout their service life.

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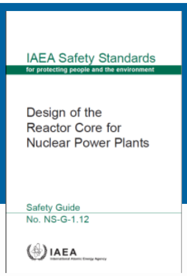
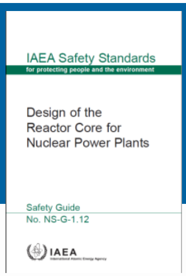


Core Management



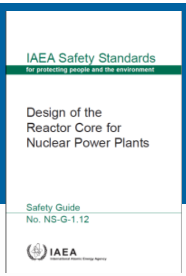
SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
CORE MANAGEMENT: SAFETY LIMITATIONS

➢ OPERATIONAL STATES

- **No cladding rupture**
  - ✓ But no failure goal difficult to achieve (manufacturing defects in fuel elements, wear due to debris fretting or unexpected transients in operational states…)
  - ✓ Some fuel cladding failures can be accepted since the concentration of radioactive material in the reactor coolant systems can be reduced by the reactor coolant cleanup function. (to be provided in the design

➢ DESIGN BASIS CONDITIONS

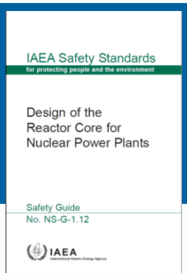
- **Permissible degree of fuel failures**
  - ✓ depends on the likelihood of the conditions arising and the expected radiological consequences.
  - ✓ operational limits should be placed on the fuel that are more restrictive than those resulting from normal operational demands (e.g. margins to DNB)



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN CORE MANAGEMENT :SAFETY LIMITATIONS

➢ DESIGN INFORMATION FOR REACTOR OPERATION

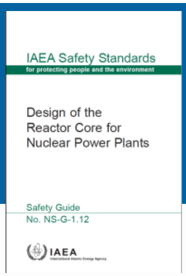
- **To achieve the desired core reactivity and power distribution the core management programme should provide the operating organization with the following information:**
  - ✓ **The pattern of fuel assemblies in each fuel cycle;**
  - ✓ **The schedule for the subsequent unloading and loading of fuel assemblies;**
  - ✓ **The configurations of reactivity control and shutdown devices;**
  - ✓ **The fuel assemblies to be shuffled;**
  - ✓ **Burnable poisons and other core components to be removed, inserted or adjusted.**



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
CORE MANAGEMENT

➢ REACTOR CALCULATION ANALYSIS

- **Safety parameters (e.g. fuel and cladding temperatures, peak linear heat rate, are not directly measurable and their values are not available to the reactor operators (calculation needed)**
  - ✓ Sufficient instrumentation to be provided to be able to verify the results of the analysis by measurement.
- **Analytical methods and associated computer codes should be verified and validated by comparison with one or more of the following:**
  - ✓ Measurements made in experimental reactors;
  - ✓ Measurements made in prototype reactors;
  - ✓ In-core measurements of fuel elements and assemblies made under simulated conditions;
  - ✓ Operating data for cores of similar design;
  - ✓ Measurements made during commissioning;
  - ✓ Measurement made during the operation of reactors: at different power levels after each refuelling and at different times during the cycle;
  - ✓ Post-irradiation measurements made on fuel elements and assemblies to evaluate fine structure and burnup effects;
  - ✓ Benchmark calculations made with other validated codes.

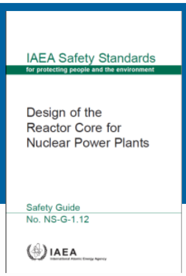

IAEA Safety Standards
for protecting people and the environment
Design of the Reactor Core for Nuclear Power Plants
Safety Guide
No. NS-G-1.12
IAEA

➢ REACTOR CALCULATION ANALYSIS (Cont'd)

- A reactor core analysis should be carried out at appropriate times to ensure throughout the reactor's operating lifetime that the operational strategy and the limitations on operation do not violate the design limits.

- The analysis should cover typical cases from the entire operating cycle for the following reactor core conditions:

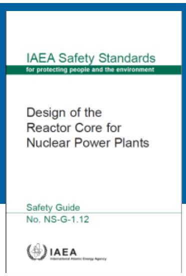
  - ✓ Full power, including representative power distributions;
  - ✓ Load following;
  - ✓ Approach to criticality and power operation;
  - ✓ Power cycling;
  - ✓ Startup;
  - ✓ Refuelling;
  - ✓ Shutdown;
  - ✓ Anticipated operational occurrences;
  - ✓ Operation at the thermal-hydraulic stability boundary for BWRs.



REACTOR CALCULATION ANALYSIS (Cont'd)

- To derive **peak channel power and peak linear power rates** for normal full power operation, **steady state power distributions should be calculated for each assembly location and axially along the fuel assemblies.** Allowance should be made for the effects of changes in the geometry of the assembly on neutronic and thermal-hydraulic effects (e.g. changes in the moderator thickness due to bowing of the assembly). To identify hot spots, the radial power distribution within a fuel assembly and the axial power distortion due to spacers, grids and other components should be superimposed.

- The **power and temperature distributions** throughout the lifetime of a fuel element should be predicted (see previous bullet) to assess the behaviour of the fuel in the core and to demonstrate the continuing integrity of the fuel elements.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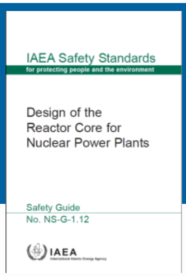
➢ REACTOR CALCULATION ANALYSIS (Cont'd)

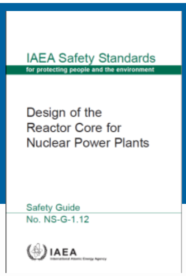
- **When fuel assemblies of different types are loaded into the core (a so-called mixed core), their mechanical and thermal-hydraulic compatibility (e.g. in terms of the pressure drop characteristics through the fuel assemblies), as well as their compatibility in terms of the nuclear characteristics of the core, should be analysed.**

➢ REFUELLING

- **Administrative control measures may be used to ensure that the individual fuel assemblies are loaded into their intended positions in the core.**
  - ✓ Reactivity monitors to verify the correct fissile enrichment of the fuel assemblies (PWRs and BWRs);
  - ✓ Mechanical means to prevent the inadvertent loading of fuel assemblies (PWRs and BWRs).
- **Measurements of the in-core flux distribution may be made to provide an ultimate verification of the fuel loading pattern.**



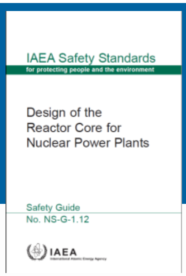
Core Monitoring System



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
CORE MONITORING SYSTEMS

➢ INSTRUMENTATION FOR MONITORING CORE PARAMETERS (DESIGN DEPENDANT)

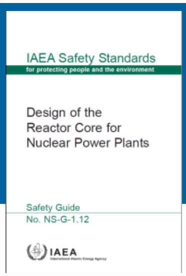
- **Core Power**
  - ✓ Level, distribution and time dependent variation
- **Conditions and physical properties of the coolant and moderator**
  - ✓ Flow rate, Temperature
- **Expected efficiency of the means of shutdown of the reactor**
  - ✓ Insertion rate of absorbers devices vs. insertion limits
- **Activity levels in the coolant vs. design limits**
- **Control systems may be used to ensure the necessary variation of core parameters and to maintain them within defined operating ranges.**
- **Actuation of Monitoring Systems (automatic or manual, depending on the rapidity of the variation in a parameter)**



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
CORE MONITORING SYSTEM

➢ CHARACTERISTICS OF INSTRUMENTATION FOR MONITORING SYSTEMS

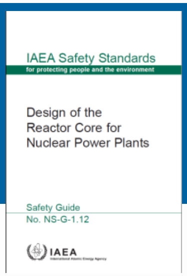
- **Accuracy, speed of response, range and reliability of all monitoring systems should be adequate for performing their intended functions**
- **Testability : design to allow continuous or periodic testing of monitoring systems.**
- **If core monitoring is needed in accident conditions within the design basis, instrumentation to be qualified for the environmental conditions**
- **Spatial power distribution to be monitored by means of ex-core or in-core instrumentation (e.g. neutron detectors and gamma thermometers).**
  - ✓ Measurements of local power to be performed to ensure adequate safety margins.
  - ✓ The in-core flux distribution should be regularly monitored.
  - ✓ Both ex-core and in-core neutron detectors should be periodically calibrated.



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
CORE MONITORING SYSTEM

➢ MONITORING SYSTEMS DURING OPERATIONAL STATES

- **During reactor shutdown**
  - ✓ a minimum set of instruments should be available (i.e. neutron flux detectors with an adequate sensitivity)
  - ✓ At least one means of shutdown should be available to ensure a safe response following an inadvertent criticality.
- **During startup, (especially during the first startup)**
  - ✓ more sensitive neutron detectors may be needed temporarily.
  - ✓ a neutron source may be necessary to increase the flux to a level that is within the range of the startup neutron flux monitors.
  - ✓ the design of the neutron sources should be such as to ensure that he sources are compatible with the fuel assemblies and the fuel assembly support structures.



SPECIFIC SAFETY CONSIDERATIONS IN DESIGN
CORE MONITORING SYSTEM

➢ MONITORING SYSTEMS DURING OPERATIONAL STATES

- **Analysis of neutronic and acoustic noise**
  - ✓ may provide useful information on loose parts or the incipient mechanical failure of core components or core internals, or the malfunctioning of the measurement equipment
  - ✓ At least one means of shutdown should be available to ensure a safe response following an inadvertent criticality.

- **Computerized core monitoring system**
  - ✓ May be used to ensure that the status of the core is within the operating limits assumed in the safety analysis.
  - ✓ Qualification of the system to be ensured where it is coupled to a protection system

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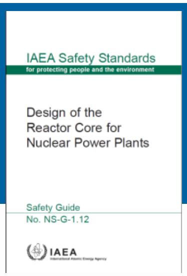
➢ PROVISIONS FOR INSPECTION AND TESTING

- **Qualification Programme to be set up**
  - ✓ to confirm the capability of the reactor core equipment to perform its function, for the relevant time period, with account taken of the appropriate functional and safety considerations under given environmental conditions

- **Example of Method of Qualification**
  - ✓ Performance of a type test on equipment representative of that to be supplied;
  - ✓ Performance of a test on the equipment supplied;
  - ✓ Use of pertinent past experience;
  - ✓ Analysis based on available and applicable test data;
  - ✓ Combination of the above methods.



QUALIFICATION AND TESTING

➢ PROVISIONS FOR INSPECTION AND TESTING (Cont'd)

- **Provision for Inspection and Testing**
  - ✓ ALARA principle applicable to testing and inspections operations
  - ✓ Provisions made in the design for in-service testing and inspection to ensure performance of their intended functions throughout the lifetime.
  - ✓ A system should be designed to allow the identification of each assembly as well as its orientation within the core.
  - ✓ Provision should also be made for inspecting each fuel assembly before and after irradiation to detect any possible damage.

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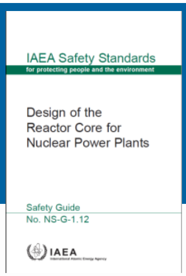

QUALITY ASSURANCE IN DESIGN

- **High quality design and fabrication to be ensured for fuel and core components by means of the establishment and application of satisfactory quality assurance procedures**

- **High level of quality assurance to be applied in the development and assessment of computer codes and associated methods for safety analysis.**

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International Atomic Energy Agency

…Thank you for your attention