GIF VHTR Safety Design Criteria

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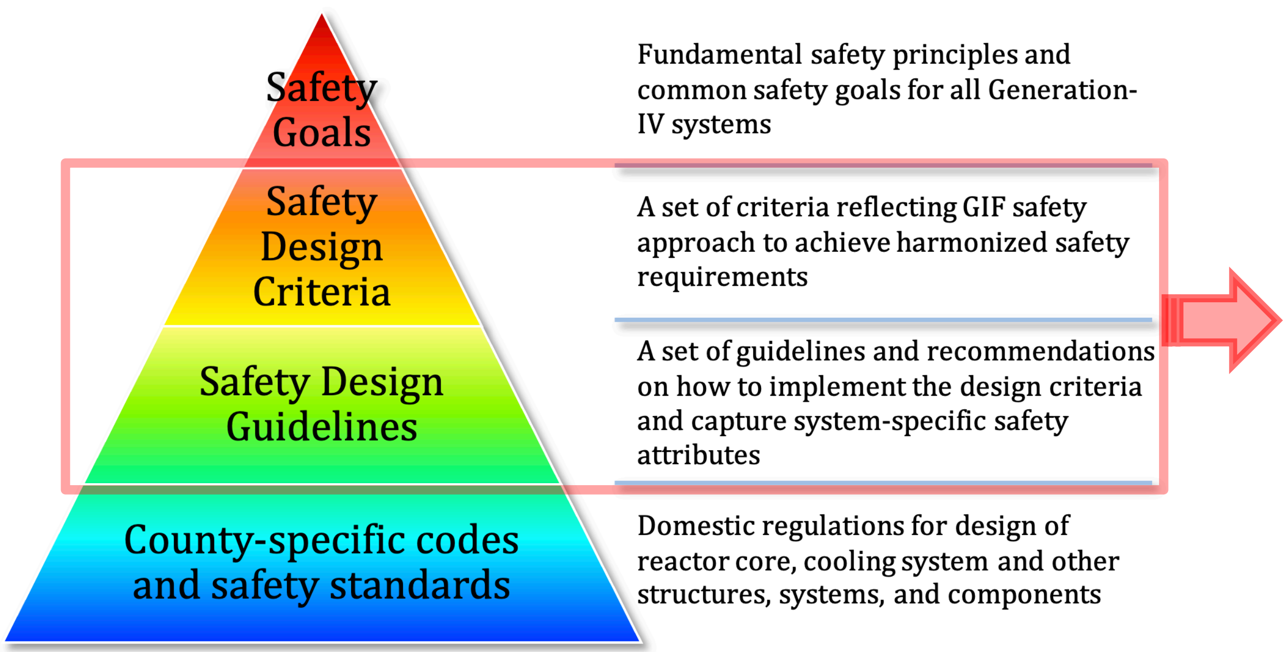
Background

- Generation-IV International Forum (GIF) has been developing Safety Design Criteria (SDC) for specific Gen-IV systems
- To date, the SDC are completed for SFR, LFR and GFR systems
- New SDC report for VHTR system is recently approved for external distribution



Hierarchy of Safety Standards

Aims to establish reference requirements and guidelines for the safety design of VHTR structures, systems, and components consistent with the GIF safety goals

Starting point

Two previous IAEA efforts were considered as our starting point:

- IAEA Nuclear Energy Department CRP on “Modular High Temperature Gas-cooled Reactor Safety Design”
  - Started in 2014 with some participants from GIF
  - Two complementary approaches considered for safety requirements
    - » Bottom-up approach with risk-informed input to selection of event selection and SSC classification to meet high-level safety criteria
    - » Top-down approach based on adoption of IAEA’s LWR-specific safety requirements in IAEA SSR 2/1 for mHTGRs
  - Draft IAEA TECDOC is yet to be published
- IAEA Nuclear Safety Department effort on “Applicability of Design Safety Requirements to Small Modular Reactor (SMR) Technologies”
  - Considered IAEA’s LWR-specific safety requirements in IAEA SSR 2/1 for LWR-SMRs and HTR-SMRs
  - Started after IAEA-CRP and considered its input

GIF VHTR SDC development process

- A subgroup of GIF Risk and Safety Working Group (RSWG) and VHTR System Steering Committee members took the lead
- Process involved revisions of IAEA SSR 2/1* to reflect unique safety characteristics, attributes, and features of GIF VHTR design tracks
  - Intended to provide minimum requirements for design, fabrication, construction, testing, and performance of SSCs important to safety
  - Plant states considered in the design are the operational states (normal operation and anticipated operational occurrences) and the accident conditions (design basis accidents and design extension conditions)

Defense in Depth levels and Plant States for VHTR Systems.

Defence in Depth Levels				
Level 1	Level 2	Level 3	Level 4	Level 5
Normal operation	Anticipated operational occurrences	Design basis accidents	Design extension conditions	Off-site emergency response
Plant states considered in design				

* "Safety of Nuclear Power Plants: Design Specific Safety Requirements"

VHTR safety principles

- VHTR concepts considered within GIF rely on the intrinsic safety characteristics such as
  - low power density
  - large heat capacity of ceramic core internals
  - strongly negative temperature coefficient of reactivity
  - continuous passive heat removal through uninsulated reactor vessel
  - coated fuel particles that act as the primary barrier to radionuclide release (prevent release near the source)
- This combination of attributes allows the VHTR systems to control the reactivity inherently and reject decay heat passively at a rate sufficient to avoid core damage and provide barriers to release

VHTR features that required SDC revisions

- Reactivity control
  - Minimal excess reactivity
  - Loss of helium does not introduce positive reactivity (reactivity feedback at elevated temperatures is dominated by Doppler)
  - Rapid control rod ejection or withdrawal are still evaluated
- Core heat removal
  - Helium does not provide coolant function for decay heat removal
    - Heat transfer to vessel cooling system via conduction and radiation
    - Vessel cooling system to protect the vessel and surrounding concrete while also providing adequate core cooling
    - Helium injection systems are not needed
    - In the event of VCS failure, structures and soil surrounding the reactor building become alternative heat sink
  - A core melt accident cannot happen in a VHTR
    - Several requirements are modified to exclude phenomena related to core melt scenarios, degradation of the reactor core, or severe accidents

VHTR features that require SDC revisions (2)

- Confinement of radioactive materials
  - Coated fuel particles and graphite matrix play an important role to fulfill the confinement function as the primary barriers
    - Maintaining integrity of fuel is an important requirement
  - Other barriers include the graphite matrix, helium pressure boundary, and the vented low-pressure reactor building
  - A dedicated helium purification system is required to keep the circulating activity at levels as low as reasonably achievable, while also monitoring fuel performance
- Concerns for air and water ingress into the reactor core
  - Nuclear grade graphite does not burn but can oxidize above 400C
  - Moderating effect of water and wash-off of trapped radionuclides can also be a concern
- Qualification of high temperature materials such as graphite and metallic alloys (an emphasis, not a revision)

VHTR Safety Design Criteria revisions

- 56 IAEA SSR-2/1 requirements remain unchanged for VHTRs

- Five requirements are eliminated:

Req	Title	
52	Emergency cooling of the reactor core	Not applicable
55	Control of radioactive releases from the containment	Not applicable
56	Isolation of the containment	Not applicable
57	Access to the containment	Not applicable
58	Control of containment conditions	Not applicable

- Three new requirements:

Req	Title
33A	Safety systems, and safety features for design extension conditions, of modules of a multi-module unit
53A	Design of secondary coolant systems to limit water ingress
83	Multi-module units

VHTR Safety Design Criteria revisions (2)

- 13 requirements with minor changes:

Req	Title	
7	Application of defence in depth	Minor[a]
13	Categories of plant states	Minor[a]
28	Operational limits and conditions for safe operation	Minor
30	Qualification of items important to safety	Minor[b]
42	Safety analysis of the plant design	Minor
45	Control of the reactor core	Minor[a]
46	Reactor shutdown	Minor
47	Design of reactor coolant systems	Minor
48	Overpressure protection of the reactor coolant pressure boundary	Minor
59	Provision of instrumentation	Minor[b]
68	Design for withstanding the loss of off-site power	Minor[a]
77	Steam supply system, feedwater system and turbine generators	Minor
81	Design for radiation protection	Minor

[a] Words related to fuel/core melt eliminated
[b] Containment requirement removed

VHTR Safety Design Criteria revisions (2)

- Major revisions in eight requirements:

Req	Title	
20	Design extension conditions	Major
35	Nuclear power plants used for cogeneration of heat and power, heat generation or desalination	Major
43	Performance of particle-based fuel elements	Major
44	Structural capability of the reactor core	Major
50	Cleanup of reactor coolant	Major
53	Heat transfer to an ultimate heat sink	Major
54	Reactor building	Major
80	Fuel handling and storage systems	Major

Examples: Minor changes

- Requirement 7 (Application of defence in depth)
  - 4.13A. The levels of defence in depth shall be independent as far as practicable to avoid the failure of one level reducing the effectiveness of other levels. In particular, safety features for design extension conditions ~~(especially features for mitigating the consequences of accidents involving the melting of fuel)~~ shall as far as is practicable be independent of safety systems.

- Requirement 30 (Qualification of items important to safety)
  - 5.50. Any environmental conditions that could reasonably be anticipated and that could arise in specific operational states~~, such as in periodic testing of the containment leak rate,~~ shall be included in the qualification programme.

Examples: Major changes

- Requirement 20 (Design extension conditions)
  - 5.27. An analysis of design extension conditions for the plant shall be performed. The main technical objective of considering the design extension conditions is to provide assurance that the design of the plant is such as ~~to prevent accident conditions that are not considered design basis accident conditions, or~~ to mitigate their consequences, as far as is reasonably practicable. This might require additional safety features for design extension conditions, or extension of the capability of safety systems ~~to prevent, or~~ to mitigate the consequences of ~~a severe accident~~ severe plant conditions, or to maintain the ~~integrity of the containment~~ confinement function. These additional safety features for design extension conditions, or this extension of the capability of safety systems, shall be such as to ensure the capability for managing accident conditions ~~in which there is a significant amount of radioactive material in the containment (including radioactive material resulting from severe degradation of the reactor core)~~. The plant shall be designed so that it can be brought into a controlled state and the ~~containment~~ confinement function can be maintained, with the result that the possibility of plant states arising that could lead to ~~an early radioactive release or~~ a large radioactive release is ‘practically eliminated’. The effectiveness of provisions to ensure the ~~functionality of the containment~~ confinement function could be analysed on the basis of the best estimate approach.

Examples: Major changes (2)

- Requirement 43 (Performance of particle-based fuel elements ~~and assemblies~~)
  - ~~Fuel elements and assemblies~~ The coated particles for the nuclear power plant shall be designed to maintain their structural integrity, maintain their confinement performance, and to withstand satisfactorily the anticipated radiation levels and other conditions in the reactor core, in combination with all the processes of deterioration that could occur in operational states and accident conditions. The fuel elements that contain the fuel particles shall be designed to maintain their structural integrity in the operational states, and to prevent unacceptable loads to the coated fuel particles in accident conditions.
  - 6.2. Fuel design limits shall ~~include limits on the permissible leakage of fission products from the fuel in anticipated operational occurrences so that the fuel remains suitable for continued use~~ account for (i) key manufacturing parameters, coated fuel particles defect fraction, heavy metal contamination, and (ii) during operations irradiation time and temperature leading to a specified acceptable radionuclide release.
  - 6.2A Fuel shall be designed for acceptable radionuclide retention during accidents based on the spatial and time distribution of fuel temperature leading to a specified acceptable radionuclide release.
  - 6.2B Fuel shall be designed to take chemical attack in all states into account.
  - 6.3. Fuel particles and elements ~~and fuel assemblies~~ shall be capable of withstanding the loads and stresses associated with fuel handling.

Examples: Major changes (3)

- Requirement 44 (Structural capability of the reactor core)
  - The reactor core, including fuel elements ~~and fuel assemblies~~ , reflectors, and their supporting structures for the nuclear power plant shall be designed so that, in operational states and in accident conditions ~~other than severe accidents, a geometry that allows for adequate cooling is maintained and the insertion of control rods is not impeded~~, unacceptable loads to the coated fuel particles are prevented, adequate core cooling can be achieved and maintained, and the core temperature remains within acceptable limits. The reactor core and supporting structures shall also be designed so that, in all plant states, a geometry to allow reactor shutdown (adequate for control of core heat generation) and sufficient heat removal (to the surrounding structures and environment, as necessary) can be maintained.

Summary

- Generation-IV International Forum (GIF) has developed Safety Design Criteria (SDC) for Gen-IV VHTR systems
  - Also considering earlier IAEA projects on HTGR requirements
- VHTR SDC aims to establish reference requirements for safety design of structures, systems, and components consistent with high-level GIF safety goals and RSWG safety approach
- SDC report considers unique VHTR safety principles and design features to assure safe operation and prevention of events, as well as for procedures and organizational processes that are required for mitigating the consequences of such events should they occur