Introduction to the CRP on modular HTGR Safety Design:
Background and Overview; Definition of modular HTGR; Status

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Background

- Improvements in the development of nuclear power plant safety requirements for design have led to improved nuclear power plant designs
  - Was further strengthened due to the lessons learned over the last 40 years and the three major accidents
- All modern NPPs designs explicitly include specific design features, strategies and actions to mitigate severe accidents.
- These principles are also well established in the “IAEA Specific Safety Requirements No. SSR-2/1 Safety of Nuclear Power Plants: Design” document
- The IAEA safety requirements are largely developed for WCRs:
  - “It is expected that this publication will be used primarily for land based stationary nuclear power plants with water cooled reactors designed for electricity generation … may also be applied, with judgement, to other reactor types, ..”
Lessons from the past

• For several decades (1960’s to 1980’s) the nuclear power industry has suffered from uncertainty in the licensing environment
  – Many projects were delayed due to changing requirements and licensing procedures.
  – This also had an impact on the HTGRs of that time
• With the safety first culture in the nuclear industry any delays to improve safety is of course appropriate …
  …. but some changes in the safety requirements were not necessarily applicable to the non-water-cooled technologies and could indeed be counterproductive.
• A selection of examples from the licensing of the Fort St. Vrain plant (and large HTGR) in the USA and the THTR-300 plant in Germany.
• These examples should not leave the impression that HTGR licensing in a WCR world was the main reasons for delays and eventual early shutdown of these reactors (many other factors and design issues probably played a major role).
• The examples rather show the importance that HTGR specific safety requirements need to be in place to ensure success in the future
Example of FSV

- Fisher and Orvis reported that “The licensing requirements for the Fort St. Vrain (FSV) plant have changed since the operating license was issued.”
  - Most changes was due to new requirements for all reactors in the USA (e.g. fire protection, security, and Three Mile Island accident) but others were introduced based on FSV operational experience.

- At that time the vendors tried to instill a heighten awareness in the regulatory authority of some HTGR specific safety advantages but it seems this did not succeed in all cases.
  - The coated particle fuel and its ability to contain fission products are one important aspect together with the large safety margins inherent in gas-cooled reactor technology.
  - In the case of FSV the license required a release rate from the fuel to be assumed that exceeded the rate showed in fuel test experiments.

- For future large HTGRs under discussion at that time an even more conservative release model was prescribed that would have needed a similar exclusion zone and containment building leak rate required for a similar sized WCR.
  - This clearly should not be the case for coated particle fuel where there are no credible accident conditions that can lead to a large early release and where meltdown is impossible. It also gave no credit for the time-delayed diffusion of fission products out of the fuel material.
Lessons learned

• The one lesson learned always emphasized is never to initiate a new HTGR (or other innovative nuclear power plant) without first having the appropriate regulatory criteria in place.

• Unfortunately in practice this is probably not easily achievable.
  – From 1999 till 2010 the South African Pebble Bed Modular Reactor (PBMR) project pursued a license from the national nuclear regulator (NNR).
  – Unfortunately once again the specific requirements were developed in parallel. Although the first basic licensing guidance for the PBMR was available in 2001, the Licensing Requirements (RD-019) for the core design was first officially published in 2006.

• One success story that needs to be emphasized is the example of China
  – the Preliminary Safety Analysis Report (PSAR) for the HTR-PM has been reviewed and accepted and construction has started in December 2012.
  – The FSAR acceptance is imminent and operation is expected in 2020.
  – In this case the process has started much earlier with the licensing and experience gained with the HTR-10 test reactor that went critical in 2000. Both the designer and regulator have been prepared through this process.
The need for specific safety requirements for advanced reactors

• Many role players in the nuclear community are calling for a different approach to be followed to perform the safety and licensing evaluation of new advanced technologies
  – This is largely driven by the Small Modular Reactors and Molten Salt Reactor designers / vendors but has been under discussion for HTGRs for a long time.

• Some actions are also being taken by the regulators.
  – The US NRC Advanced Non-Light Water Reactor Design Criteria …
  – Also the OECD NEA WGSAR activities
  – Canada pre-licensing process
What is modular HTGRs

.. and its specific safety philosophy
High Temperature Gas Cooled Reactors is an advanced reactor system (part of GEN-IV) with the following main characteristics:

- High temperatures (750-1000°C)
- Use of coated particle fuel
- Helium coolant
- Graphite moderated
- Small reactor units (~100 - 650 MWth)
- To be deployed as multiple modules
- Low power density (typically 3-6 W/cc compared to 60-100W/cc for LWRs)
- Two basic design variations – Prismatic and pebble bed design
Prismatic (block-type) HTGRs

2 different pin-in-block fuel designs

USA, Japan, Korea, Russian Federation
Pebble type HTGRs

- Spherical graphite fuel element with coated particles fuel
- On-line / continuous fuel loading and circulation
- Fuel loaded in cavity formed by graphite to form a pebble bed

Germany, China, South Africa, USA, (Indonesia)
SAFETY PHILOSOPHY OF MHTGR

• The approach is well known in the HTR community…
  … but many different definitions exist

• Good summary by Syd Ball:
  “No fuel failure for loss of coolant flow and coolant accidents, or for all foreseeable reactivity events, even with no corrective actions”
More detailed description...

- HTGRs have many favorable inherent safety characteristics based on a few properties:
  - High quality ceramic coated particle fuel
  - Single phase helium as coolant
  - Strong negative reactivity coefficients
  - Slow transients due to large mass of graphite in the core

- Furthermore **modular** high temperature gas cooled reactors refer to the HTGR designs that are based on design principles that ensure:
  - no core meltdown or significant radionuclide release are possible even in the event of depressurization of the helium coolant and loss of all active forced convection systems.
  - The residual heat removal is ensured solely through physical processes (thermal conduction, radiation, convection).
More detailed description...

• In order to achieve this, the reactor designs typically have the following properties:
  – Low power density
  – Long slender core and/or annular design
  – A Reactor Cavity Cooling System external from the reactor to remove the decay heat
  – Uninsulated reactor pressure vessel

• Note: The scope of the CRP only consider HTGR designs that follow the modular HTGR safety design principles…
Pillars of MHTGR safety

- A quick reminder of the most important pillars of the safety case:
  - Coated particle fuel
  - Helium coolant
  - Reactivity and reactor shutdown
  - Core thermodynamic characteristics
  - Residual heat removal
Coated particle fuel

- contain almost all fission products for the expected operating and postulated accident temperatures in a modular HTGR.
- core design and operating parameters ensure large margins
- **No large early release of fission products due to coated particle failure is therefore possible (no credible conditions).**
- The failure mechanisms of CP fuel are decoupled and totally independent.
  - One coated particle failure cannot lead to the failure of a neighboring CP, as it is driven by the maximum fuel temperature.
  - A CP failure also has no effect on the cool-ability of the fuel as a failure will not change the heat removal path.
  - The amount of fission products that can potentially be release when a failure occurs is of course very small, and many CP will need to fail to be of any consequence.
  - In this respect it is very different from WCR fuel where one pin failure can inhibit the cooling of neighbors and cause significant additional failures or a partial core melt.
Helium coolant

• inert noble gas it does not undergo any phase change and has a very low chemical reactivity.
  – It is also invisible to neutrons, with basically no core reactivity effect.
  – Relative high heat transfer coefficient with no heat transfer limits.

• Unlike in the case of loss of coolant in WCRs, helium, when leaked out of the primary pressure boundary, does not condense.
  – In a sealed containment this will lead to a sustained elevated pressure that cannot be reduced by cooldown.
Reactivity and reactor shutdown

- The modular HTGR designs have a negative temperature coefficient of reactivity over the complete operating and accident temperature range. The individual effects of these coefficients are as follows:
  - The Doppler or fuel temperature coefficient acts promptly. This effect stabilizes the nuclear chain reaction.
  - The moderator coefficient effects is very slightly delayed as the heat is transferred from the very small kernels to the surrounding graphite material.
  - The reflector temperature coefficient, that may be positive, has a delayed effect since its temperature changes are not strongly coupled to power changes in the fuel. Temperature changes induced by changes in the coolant temperature will be slow due to the large thermal capacity and mass of graphite.

- In general either by on-line refueling (as for pebble bed designs) or by the use of burnable poisons (some prismatic designs) the modular HTGR has a relatively low excess reactivity that also reduce the safety demands on the reactivity control and shutdown systems.
Core thermodynamic characteristics

• Typical modular HTGR:
  – is quite low in power (typically 100-650MWth)
  – has large reactor vessels and low power density
  – has large graphite moderated cores and the thick graphite reflectors used.

• The large mass of graphite, with its high heat capacity, causes very slow core temperature changes and thus very slow transient response.

• Combined with the large temperature coefficient of reactivity this makes for benign behavior and enough time for the operators to respond.
Residual heat removal

• Modular HTGRs typically rely on passive residual heat removal if none of the active systems are available.
  – independent if the helium coolant is still present or has been lost.
  – post shutdown decay heat removal is solely through physical processes
  – decay heat is dissipated from the core through the reactor structures to the uninsulated reactor vessel and then primarily by radiation to the reactor cavity cooling system (RCCS) on the outside.
  – (This does not mean that an active system may not be included in the designs but these are not needed in the safety argument).

• Typically the maximum accident temperatures are kept well below temperatures at which point fission product retention of some coated particles may be challenged or coatings may start to fail.

• Coated particle failures only occur if these high temperatures are maintained for a long time (several 100 hours).

• More importantly only a very small fraction of the fuel (typically < 5%) will be at these high temperatures, while the rest of the fuel is substantially cooler.
No early or large FP release

Ceramic fuel retains radioactive materials up to and above 1800°C

Heat removed passively without primary coolant – all natural means

Coated particles stable to beyond maximum accident temperatures

Fuel temperatures remain below design limits during loss-of-cooling events
No early or large FP release

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Other aspects important to safety

• Water Ingress
  – Since graphite used as moderator the HTGR systems are under-moderated relative to water ingress
  – For Rankine systems (without any intermediate loop) the heavy metal loading and the amount of water that enter the core should be limited
  – Water (or steam ingress) does increase release from fuel (but only from damaged coated particles and small amount of activity already in the matrix)

• Graphite dust as transport mechanism for fission products / activation products or radioactivity
  – Most mHTGR potential source term for release so low that the dust transport mechanism is unimportant (good fuel and large temperature margins)
  – Some designs (higher T and higher allowable coated particle failure rates) may need to take the specific mechanism into account

• Air Ingress
  – Is considered and a DEC / very low probability event
  – Design features and mitigation measures can limit air ingress
  – Only at very high temperatures are the coated particle integrity challenged
CRP I1026 on Modular High Temperature Gas cooled Reactor Safety Design

... contributing to the development of modular HTGR appropriate safety design requirements

A key lesson learned for FSV and THTR... cannot be licensed under LWR rules

Also the experience in the PBMR project and a key difference in the approach followed in the HTR-10 and HTR-PM licensing.

Neither the IAEA opinion nor a consensus view - but rather the result of a CRP with limited participation done in the Nuclear Energy department

GIF VHTRs may use this as an starting point to continue work (similar to the SFR efforts)
Background to CRP specifically...

HTGR community in Member States aim:

The development and implementation of comprehensive safety design criteria (SDC) that take HTGR-specific characteristics into account would provide a high level of assurance that modular HTGRs are consistently designed, constructed, and operated in a manner that takes advantage of these intrinsic properties, while also avoiding unintended compromises in plant safety.

Important to note that this is not how the IAEA establish safety requirements...

Member States develop their own SDC and after same time of implementation and experience the IAEA may on request facilitate a comprehensive (several year) process to develop through consensus safety requirements.
IAEA Coordinated Research Project (CRP)

CRP Purpose
Develop modular HTGR safety design criteria to assure that an acceptably broad spectrum of design and beyond design basis events are addressed in the international design and development community.

CRP Approach
• CRP collaborators have chosen to develop and assess two approaches to SDC development for modular HTGRs.
• Results will be assessed for key strengths and weaknesses, and will then be evaluated for integration into a common set of SDC.
Implementation started December 2014
Good support for the CRP
10 participating organizations from 9 member states: China, Germany, Indonesia, Kazakhstan, Korea (Republic of), Japan, UK, Ukraine, USA
- 1st RCM took place 9-12 June 2015
- 2nd RCM took place 13-17 June 2016
- 3rd RCM took place 19-23 June 2017
- 4th RCM 11 – 14 June 2018
- CM 17-20 June 2019 agree on final content
Outcomes:
- NE series report: Modular High Temperature Gas-cooled Reactor Safety Design Criteria
- TECDOC: Modular High Temperature Gas-cooled Reactor Safety Design Methodology and Implementation Examples
CRP I1026 on Modular High Temperature Gas cooled Reactor Safety Design

- Investigate modular HTGR safety design criteria to assure that an acceptably broad spectrum of design and beyond design basis events are addressed in the international design and development community
- **Approach 1** limits scope to qualitative, functional statements of how top requirements are to be met for only SSCs that are safety-related for public safety with examples from conceptual design of MHTGR (steam cycle for electricity)
- **Approach 2** study the IAEA SSR-2/1 SDC for applicability / interpretation for modular HTGRs
Next steps

• Completion and publication of:
  – NE series report: Modular High Temperature Gas-cooled Reactor Safety Design Criteria
  – TECDOC: Modular High Temperature Gas-cooled Reactor Safety Design Methodology and Implementation Examples

• Joint IAEA–GIF Technical Meeting on the Safety of High Temperature Gas Cooled Reactors; 9-11 December 2019
  – Activity agreed in IAEA-GIF Interface meeting in March 2019
  – Expectation: GIF to develop its SDC and SDG using the CRP publications / working material as input
  – (similar to on-going cooperation on LMFR)
Thank you!

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