Safety Requirements for HTR Process Heat Applications
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Introduction

• Obvious: Safety Requirements for Nuclear Process Heat Applications must comprise Safety Requirements for Nuclear Installations (including effect of multiple modules)

• Additional Requirements due to collocation of (modular) nuclear reactors with an end-user (e.g. a chemical plant)

• Mutual impact of hazards has to be considered, e.g.:
  ➢ from reactor: radioactive contamination of chemical plant and products
  ➢ from end-user plant: chemical, fire, explosion hazards

These aspects will be addressed later, first: Nuclear Requirements
History of HTR Development, Focus on Safety Features (1)

- HTR development started with experimental reactors:
  - Dragon (UK, 21.5 MW\textsubscript{th}, 750 °C, graphite clad rods)
  - Peach Bottom (USA, 115 MW\textsubscript{th}, 750 °C, graphite clad rods)
  - AVR (Germany, 46 MW\textsubscript{th}, 950 °C, pebbles)

- More recently two other small-scale HTR were built:
  - HTTR (Japan, 30 MW\textsubscript{th}, 950 °C, block)
  - HTR-10 (China, 10 MW\textsubscript{th}, 700 °C, pebbles)
Experimental HTR had inherent safety features in common:

- **Fission product containment**: Coated particle fuel leak tight against fission product release up to very high temperatures
- **Strong negative temperature coefficient**: limits the effect of reactivity transients
- **High thermal inertia**: low power density and large mass of graphite
- **Small unit power**: favors (together with the other safety features) passive decay heat removal
Inherent safety features have been demonstrated and replicated, e.g. AVR and HTR-10, ongoing at HTTR:

- Blower shutdown at full power: active cooling interrupted
- Minimal core heat-up: interruption of nuclear reaction by negative temperature coefficient
- Dissipation of decay heat into structures without significant core heat up due to small unit power and corresponding core geometry
• **Economy of scale:** Larger HTR in Germany and USA to compete with LWR for electricity generation:
  - Fort St. Vrain (USA, 842 MW\textsubscript{th}, 775 °C, block type FE)
  - THTR (Germany, 750 MW\textsubscript{th}, 750 °C, pebble bed)

• **Passive safety features:** coated particle fuel, strong negative temperature coefficient, high thermal inertia

• But: large size calls for **active decay heat removal** to respect max. fuel temperature limit
• **Modular HTR:** development started in Germany after TMI accident, later adopted by other countries

  economy of scale  \(?\)  economy of replication
  economy of simplification

• **Objectives:**

  ➢ Maximize passive safety features known from experimental HTR
  ➢ Maximize unit power, but respect maximum fuel temperature
    (since HTR Modul, 1600°C is often used, but not carved in stone)
  ➢ Build larger power plants from combination of identical modules
Licensing efforts for HTR in Europe:

• Dragon and AVR licensed in 1960s and operated (AVR until 1988)

• THTR licensed in 1970s and 80s and operated from 1986 to 1989

• HTR-Modul underwent a concept licensing process in 1987 – 1988 (licensing was stopped for political reasons after Chernobyl, safety evaluation by TSO was completed as a research effort)
Development of Regulatory Safety Requirements in Europe (2)

- Licensing procedures and regulatory requirements for early experimental HTR are only of historical interest today, do not provide much benefit for current or future licensing efforts.

- During the licensing process of THTR, the current system of regulatory requirements based on principles of defense-in-depth, redundancy and diversity of safety systems, and ALARA was fully developed in Germany.

- Concept licensing for HTR-Modul based on this system of requirements.
• **Defense-in-depth** principle led to categorization of events:
  - normal operation
  - anticipated operational occurrences (AOO)
  - design basis accidents (DBA)
  - beyond design basis accidents (BDBA)

• A set of DBA had to be selected deterministically with a distinction between DBA and BDBA roughly based on assumptions of probability of occurrence.

• For DBA, compliance with regulatory limits for radiological impacts to the public and to workers had to be demonstrated; credited active safety systems must comply with requirements on redundancy and diversity.
• BDBA were subsumed under a "residual risk" which had to be taken by the society, they were not considered in the licensing process itself.

• In Germany, catastrophic failure of the primary pressure boundary could be deterministically ruled out by adherence to the "Basis Safety Concept", a similar approach was applied in the UK (Sizewell B)

• All in all, this system of regulatory requirements was to some degree tailored to LWR with their reliance on active safety systems,

  ➤ Passive safety features of modular HTR were not given much credit
For the HTR-Modul this meant that a set of DBA had to be considered in the licensing process:

- radiologically most relevant event:
  - break of an unisolable DN 65 mm pipe connected to the primary pressure boundary
  - depressurized core heat-up with passive heat removal to an active reactor cavity cooling system

In order to demonstrate the safety features of the HTR-Modul in the beyond design basis range, the concept licence application was supplemented by an informal analysis of several "hypothetical" events (unlimited air and water ingress, fast transients, loss of cavity cooling)
After Chernobyl and Fukushima, regulatory requirements were tightened, especially for the beyond design basis range.

Requirements on accident management measures were defined for ATWS, improbable man-made external events, and multiple failures of safety systems.

Today, a simple reference to a "residual risk" will no longer be accepted, even for very low frequency event sequences.

Instead, current requirements aim at limiting the consequences of any accident to the site boundary or to a small emergency zone.

Preference for passive safety features.
WENRA (Western European Nuclear Regulators Association)

Safety Objectives for new Nuclear Power Plants:

- O3. Accidents with core melt: *(for HTR: degradation of coated particles)*
  
  Reducing potential radioactive releases to the environment, also in the long term, by following the criteria below:

  - accidents which would lead to *early* or *large releases* have to be *practically eliminated*
  - otherwise, design provisions have to be taken such that only limited protective measures in area and time are needed for the public:
    - sufficient time to implement these measures
    - no permanent relocation
    - no need for emergency evacuation outside the immediate vicinity of the plant
    - no long term restrictions in food consumption
Related WENRA Definitions:

- **Early releases**: situations that would require off-site emergency measures but with insufficient time to implement them.

- **Large releases**: situations that would require off-site emergency measures for the public that could not be limited in area or time.

- Occurrence of conditions occurring is considered to be **practically eliminated** if:
  - It is physically impossible for the conditions to occur, or
  - If the conditions can be considered with a high degree of confidence to be extremely unlikely to arise.
Modular HTR Safety Features & Current Safety Requirements (1)

Modular HTR: Extensive reliance on inherent, passive safety features

⇒ Excellent potential to comply with current regulatory requirements
  ➢ on the control of very rare accidents and
  ➢ on the limitation of consequences of any accident to the site boundary or its close vicinity

However: reliance on these safety features implies restrictions in module size and power output as well as in the fuel design (to limit effects of water ingress and other reactivity accidents)
Safety Aspects specific for modular HTR (1):

• Multi-module effects on accident risk and consequences:
  • In a multi-module plant, modules may not only be close but interconnected by:
    • Sharing the same building
    • Sharing auxiliary systems
    • Feeding into the same live steam / hot gas line
  • Reliability on passive safety features which belong to each individual module facilitates accident management, but design provisions have to be taken to ensure that (for example):
    • Passive heat removal from one module does not impede safety of neighbouring modules
    • Water ingress into one module is not sustained by steam from the common live steam line.
Safety Aspects specific for modular HTR (2):

- Gas-tight containment versus controlled initial release:
  - A gas-tight containment is the main barrier against releases of radioactivity for LWR (albeit with filtered venting after core melt accidents)
  - For modular HTR, the main barriers are the coated particles, and design provisions are taken to ensure the function of this barrier even under extreme conditions
  - Under licensing aspects, the aim should be to minimise releases, not to demand specific barrier designs
  - A gas-tight containment for HTR may be detrimental to safety regarding late containment failure (long term high pressure since primary coolant is not condensable, accumulation of fission products from delayed core heat up)
  - If initial releases (eventually filtered) from a primary circuit depressurisation are well below regulatory limits (ALARA), a containment allowing initial release and subsequent reclosure appears preferable
• Severe air ingress: only remaining severe accident of a properly designed modular HTR (and only if incredibility of failure (Basis Safety Concept) cannot be claimed for relevant components of the primary pressure boundary)

• To eliminate even such scenarios:
  ➢ Corrosion-resistant fuel elements
  ➢ Dedicated design provisions to inertize the reactor cavity after larger or multiple breaks of the primary pressure boundary
Specific Requirements for HTR Process Heat Applications (1)

- Radiological Contamination of End-User and Products:
  - There is no agreed license limit for tritium release
  - Downstream contamination with tritium needs to be considered due to its high permeability through metallic walls of heat exchangers
  - Reasonable effort is sufficient to meet plausible tritium release limits for process steam at 567°C (HTR-PM), cf. specific talk
  - For very high temperatures or gaseous working fluids, individual analysis required; if necessary use intermediate heat transfer circuit
Specific Requirements for HTR Process Heat Applications (2)

Impacts on Nuclear Reactor from Hazards of Chemical Plant:

- If nuclear process heat is used in plants involving burnable, explosive or toxic substances, limit potential impact by separation, e.g.:
  - intermediate heat transfer circuit,
  - sufficient distance between reactor and chemical plant,
  - protective walls/berms.

- Depending on their actual site conditions, nuclear plants have to withstand explosion blasts and hazardous substances anyway.
No more steam reformer inside the reactor building (as investigated in Germany in the 1980s).

New safety requirements for nuclear cogeneration with an HTR Demonstrator are currently elaborated in an ongoing European project.
How to switch the HTR on…

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