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BADAN RISET DAN INOVASI NASIONAL

JAEA Japan Atomic Energy Agency

Safety Analysis of Pebble Bed

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Follow Up Training Course on Reactor Engineering and Safety: High-Temperature Gas-Cooled Reactor

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Biodata

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- Reactor Engineering & Safety, JAEA Jepang (2010)
- HTGR Safety Design, NUKEM Technologies Jerman (2015)

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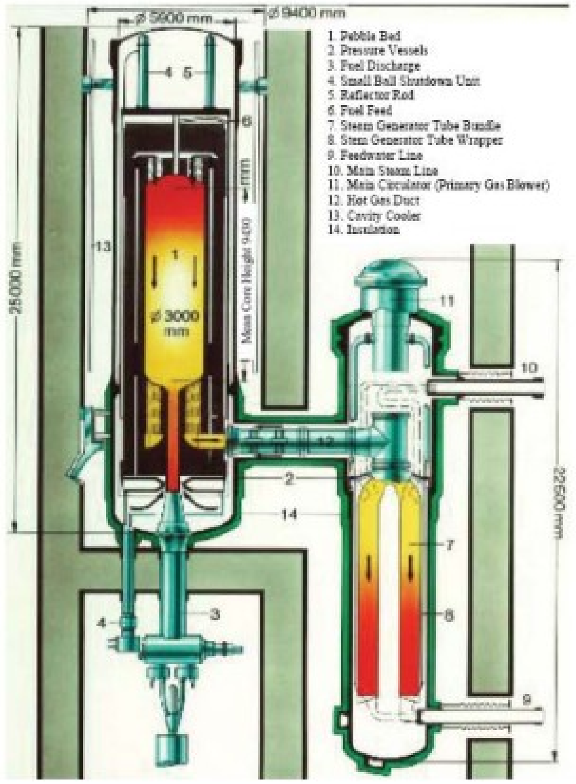
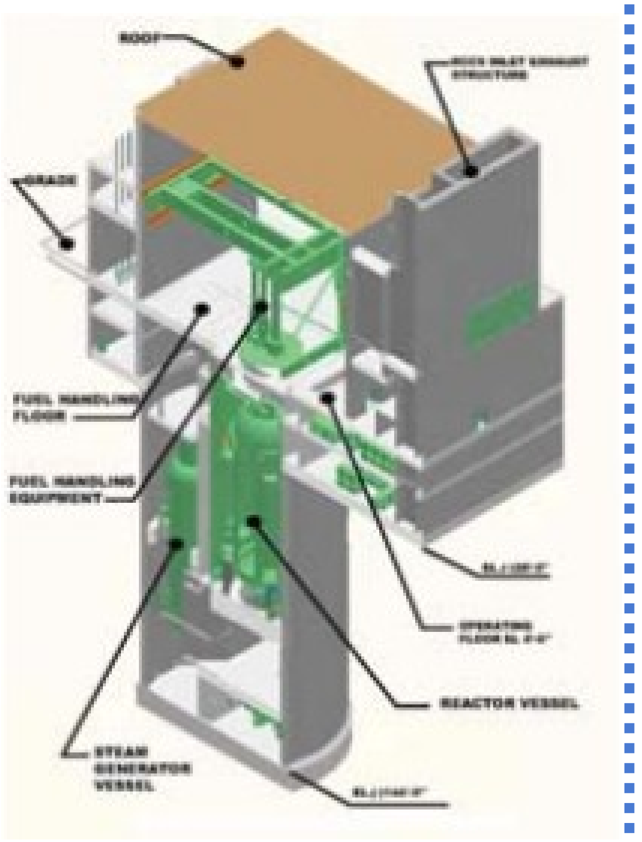
I S I

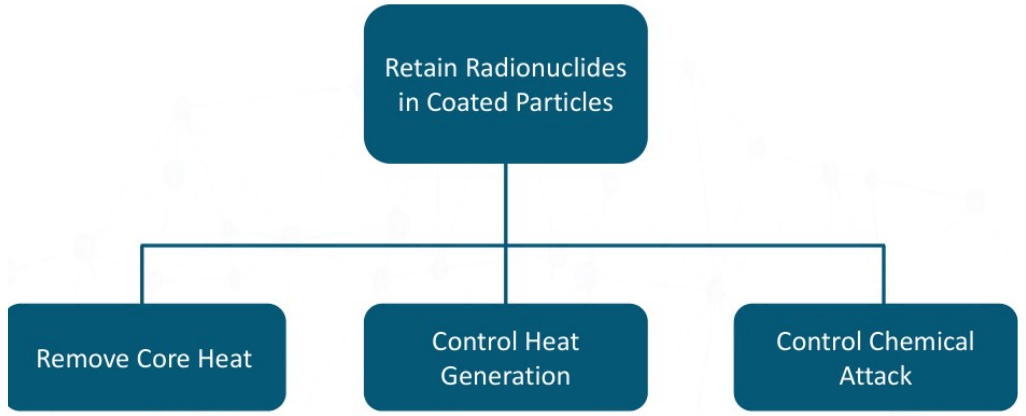
- *Overview HTGR Safety Basis and Approach*
- Tujuan Pelatihan
- Sistem Keselamatan dan Proteksi
- *Initiating Events & Accident Groups*
- Skenario Kecelakaan

Overview HTGR Safety Basis and Approach

- *INHERENT AND PASSIVE SAFETY FEATURES*
- *RADIONUCLIDE RELEASE BARRIERS*
  1. *Fuel Particle Kernel*
  2. *Fuel Particle Coatings*
  3. *Core Graphite*
  4. *Helium Pressure Boundary*
  5. *Reactor Building*
- *FUNCTIONAL SAFETY APPROACH*
  1. *Remove Core Heat*
  2. *Control Heat Generation*
  3. *Control Chemical Attack*







Tujuan Pelatihan

Safety Analysis of Pebble Bed HTGR

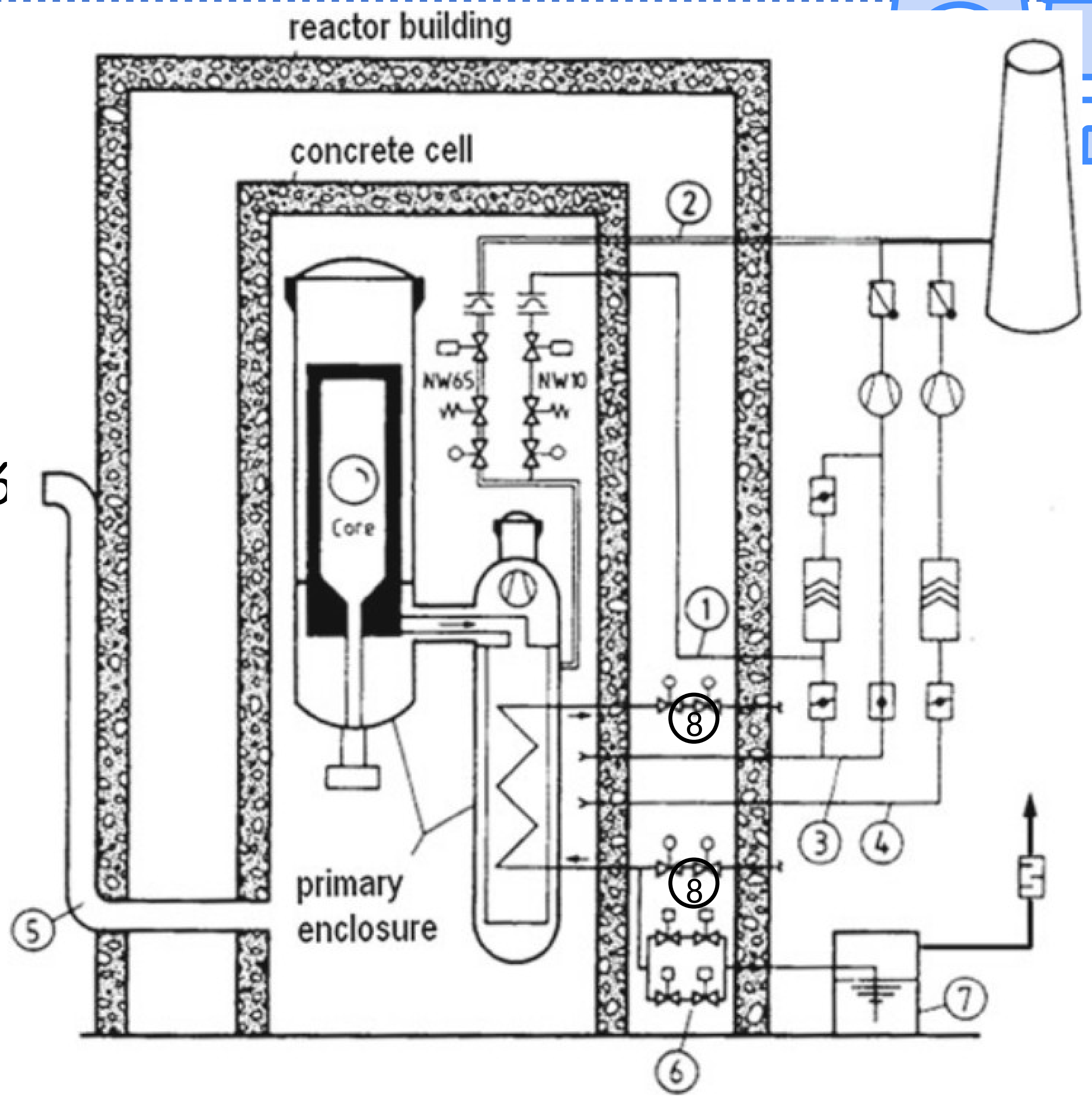
Setelah pelatihan ini, peserta akan:

1. Memahami sistem keselamatan dan proteksi reaktor HTGR tipe Pebble Bed.
2. Mengenali peristiwa awal (*initiating event*) dalam analisis keselamatan.
3. Mempelajari skenario kecelakaan serta langkah antisipasi.

Sistem Keselamatan dan Proteksi

Sistem Keselamatan

1. *Primary pressure release system (1&2)*
2. *Reactor Cavity Cooling System (RCCS)*
3. *Reactor Pressure Vessel support cooling system*
4. *Secondary circuit isolation system (8)*
5. *Steam Generator (SG) emergency drainage system (6*
6. *Ventilated low pressure containment (VLPC) (3,4,&5)*
7. *Helium purification system*



Sistem Proteksi

- *Dropping of control rods*
- *Shutdown of blower and close of blower flap*
- *Isolation of secondary circuit*

Sistem Keselamatan dan Proteksi

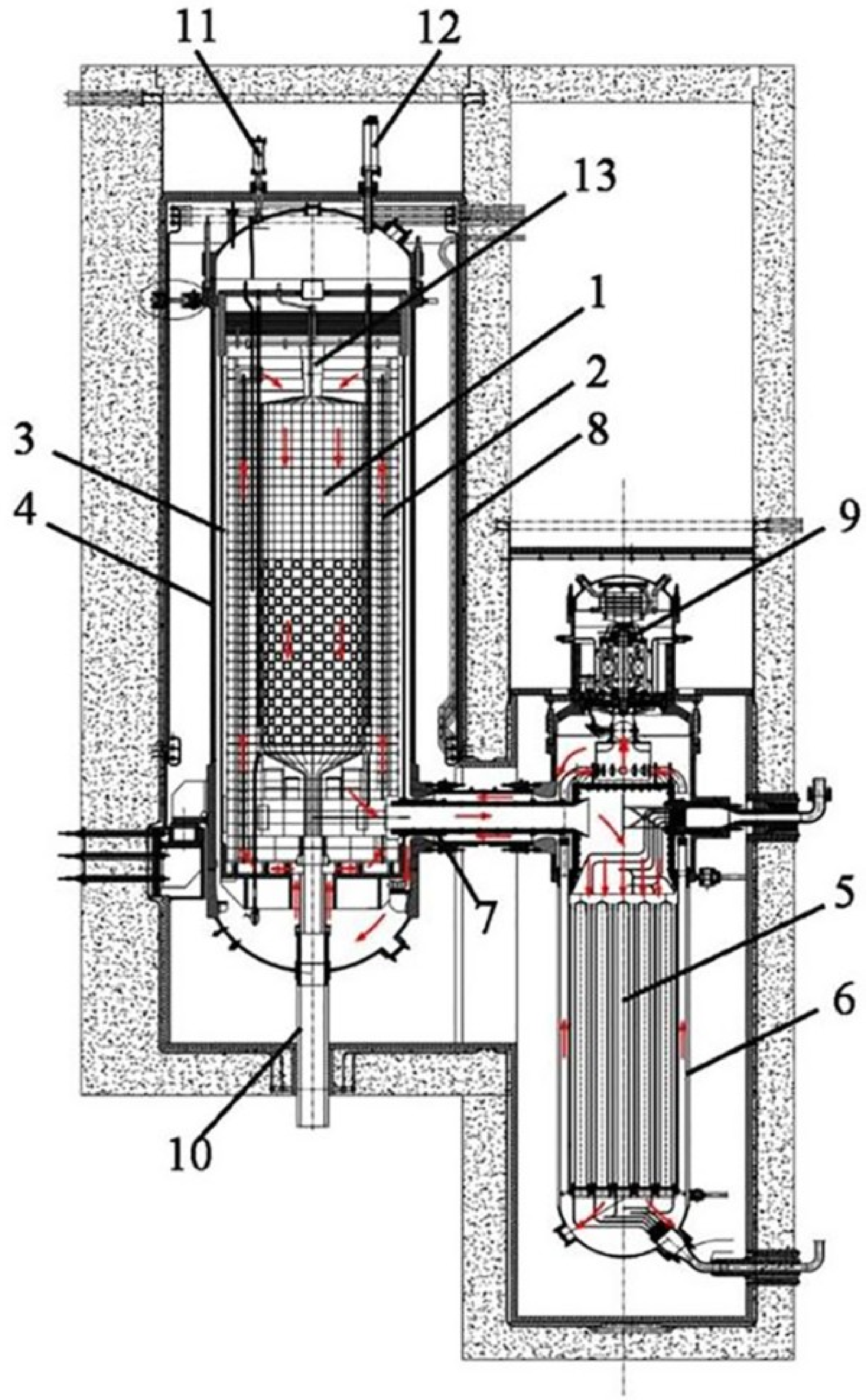
Sistem Keselamatan

2. Reactor Cavity Cooling System (RCCS) (8)

Sistem Proteksi

- Dropping of control rods (11)
- Shutdown of blower and close of blower flap (9)
- Isolation of secondary circuit

- Variabel Proses yang Dimonitor dan diproses
  - Neutron flux
  - Temperature (Hot gas, Cold gas)
  - Moisture in the primary system
  - Pressure (primary system, secondary system)
  - Mass flow (primary system, Feed water)
  - Earthquake acceleration.



Sistem Keselamatan dan Proteksi

Sistem Keselamatan

1. Primary Pressure Release System – HTR-PM

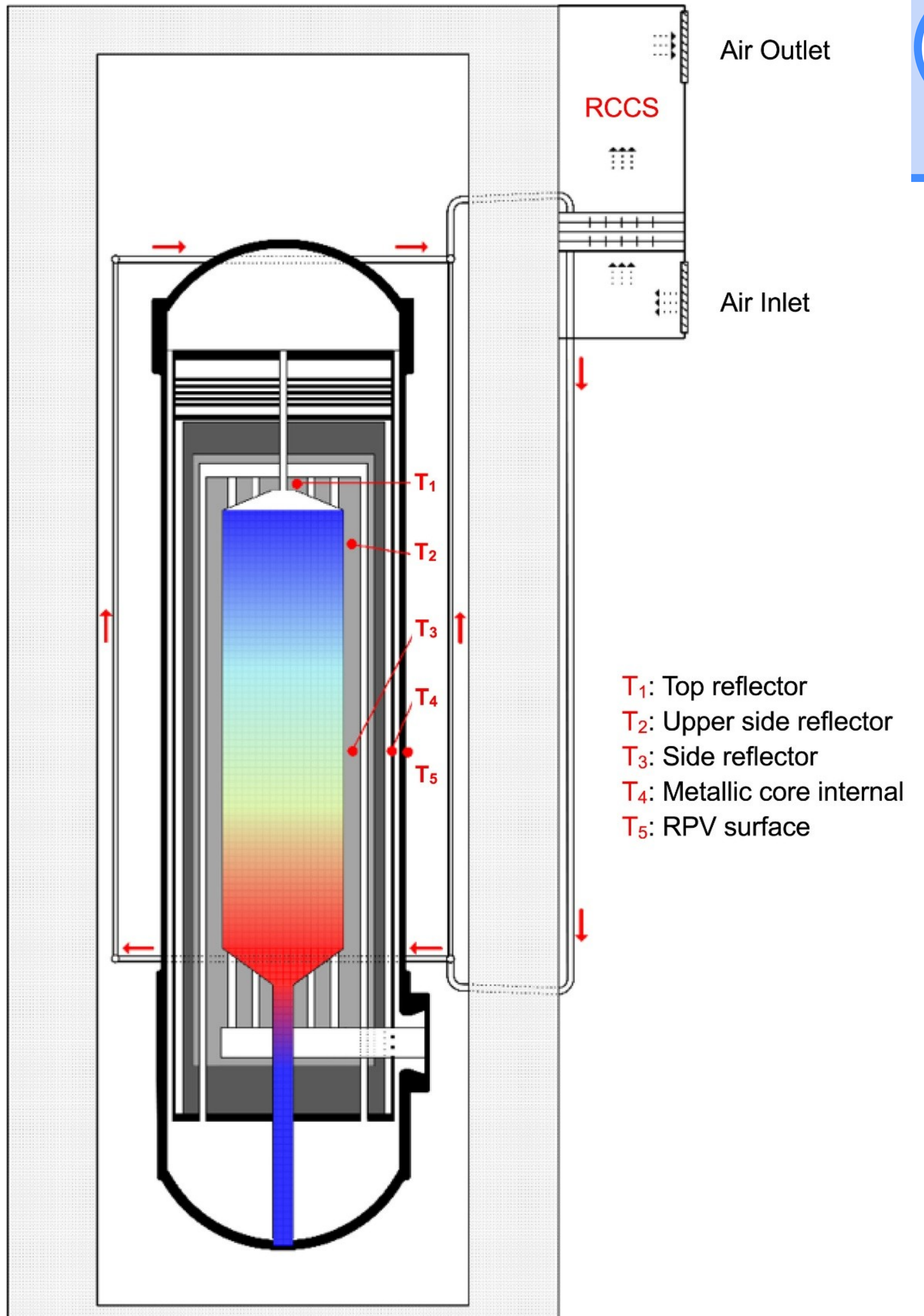
- **Tekanan desain RPV**: 8,1 MPa
- **Batas AOO**: 110% dari desain
- **Redundansi ganda**: 2 katup keselamatan
  - Katup 1: set point 7,9 MPa, debit ±0,17 kg/s
  - Katup 2: set point 8,4 MPa, debit ±11,7 kg/s
- **Kedua katup menutup kembali** saat tekanan turun ke 6,9 MPa

(HTR-PM: High-**T**emperature gas-cooled **R**eactor **P**ebble-bed **M**odule)
(**RPV**: **R**eactor **P**ressure **V**essel)
(AOO: Anticipated **O**perational **O**ccurrence)

Sistem Keselamatan

2. Reactor Cavity Cooling System (RCCS) – HTR-PM

- **Sistem pasif** untuk membuang panas dari RPV & cavity ke atmosfer.
- **Tujuan**: menjaga integritas termal RPV dan beton cavity.
- **Komponen utama**: panel pendingin air (plat silinder + pipa vertikal).
- **Kondisi kecelakaan**:
  – Setelah scram & sirkulasi paksa berhenti → panas peluruhan pindah lewat konduksi, radiasi, dan konveksi alami.
  – Air dalam pipa naik ke menara pendingin udara → panas dilepas ke atmosfer.



https://doi.org/10.1016/j.joule.2024.06.014

Sistem Keselamatan

3. RPV Support Cooling System – HTR-PM

- **Sistem pasif** menjaga suhu beton di sekitar RPV support.
- **Kapasitas desain**: 23 kW.
- **Normal operation**: suhu beton < 65 °C.
- **Abnormal condition (BDBA, RCCS gagal total)**: suhu beton tetap < 90 °C.

4. Secondary Circuit Isolation System – HTR-PM

- **Komponen utama**:
  – 2 katup isolasi feed-water
  – 2 katup isolasi live-steam
- **Fungsi**: menutup otomatis saat kondisi kecelakaan terdeteksi.
- **Tujuan**: melindungi sistem dengan aksi proteksi cepat.

BDBA (Beyond Design Basis Accident)

Sistem Keselamatan

5. SG Emergency Drainage System – HTR-PM

- **Tujuan**: menangani kecelakaan *water ingress*.
- **Komponen utama**:
  – Tangki drainase kedap udara di bawah SG
  – 2 jalur relief paralel, masing-masing dengan 2 katup relief
- **Fungsi**:
  – Mengalirkan uap & air ke tangki dalam ±60 detik saat kelembaban tinggi terdeteksi
  – Katup menutup kembali setelah tekanan primer & sekunder seimbang
- **Tangki**: berisi sedikit air dingin, mendinginkan uap & air panas agar tetap di bawah batas desain.

SG: **S**team **G**enerator

Sistem Keselamatan

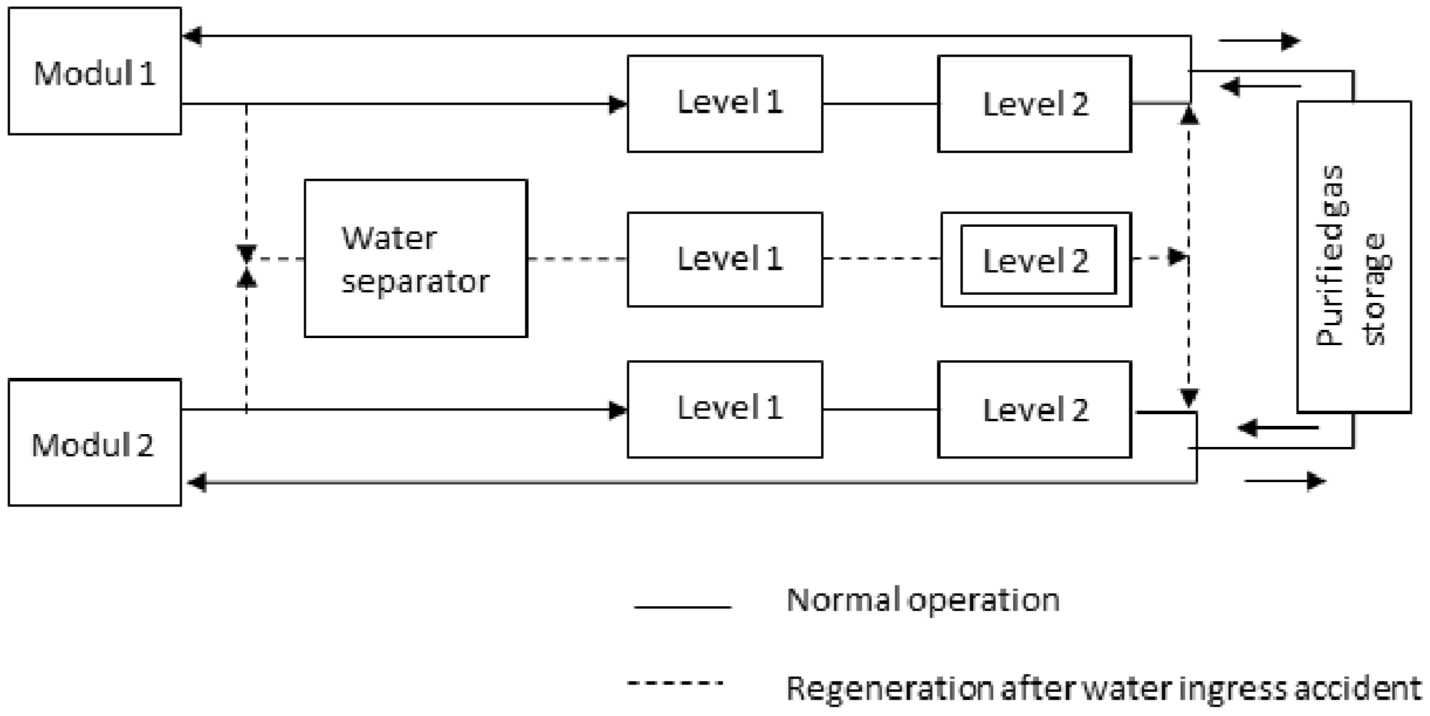
6. *Ventilated Low Pressure Containment* (VLPC) – HTR-PM

- **Struktur khusus** dibanding containment kedap udara.
- **Normal operation**: tekanan negatif (−50 Pa), udara keluar lewat stack setelah difilter.
- ***Accident ventilation system***: gas difilter sebelum dilepas (misalnya setelah DLOFC).
- **Kecelakaan kecil (pipa <10 mm)**: pelepasan gas terfilter.
- **Kecelakaan besar (pipa >10 mm)**: ada pelepasan singkat tanpa filter.
- **Tujuan**: mencegah pelepasan besar material radioaktif, sesuai desain keselamatan inheren.

Sistem Keselamatan

7. *Helium Purification System* – HTR-PM

- **Fungsi utama**:
  - Memurnikan pendingin primer dari impuritas (H_2O, O_2, CO, CO_2, N_2, H_2, CH_4, dll.)
  - Mengatur inventori helium & tekanan primer
- **Kondisi kecelakaan (water ingress)**:
  - Setelah scram, jalur purifikasi darurat aktif
  - Dilengkapi water separator, melayani kedua modul
  - Menghilangkan kelebihan air & mendinginkan teras panas → mitigasi kecelakaan



Sistem Proteksi

Protection System – HTR-PM

- **Normal operation**: jika kecelakaan terdeteksi → aksi proteksi segera:
  - Jatuhkan control rods
  - Matikan blower & tutup flap
  - Isolasi secondary circuit
- **DLOFC accident**: isolasi primary circuit (deteksi laju turun tekanan besar).
- **Water ingress accident**: sensor kelembaban → SG emergency drainage aktif.
- **ATWS (tanpa scram)**: SAS dijatuhkan → reaktivitas negatif, jika control rods gagal.

Initiating Events & Accident Groups (DBA)

Initiating Events & Accident Groups **– HTR-PM**

- **Reactivity Accident**
  - Withdrawal control rod (normal, low power, subcritical)
  - Pebble bed densification (OBE)
  - Inadvertent acceleration of helium blower
- **Main Heat Transfer System Malfunction**
  - Loss of off-site power
  - Loss of feed water
- **Primary Circuit Depressurization**
  - Break of primary tube Ø65 mm
  - Break of primary tube Ø10 mm
- **Water Ingress**
  - Double-ended guillotine break of SG heating tube

DBA (Design Basis Accident)
OBE (Operation Basis Earthquake)

Typical BDBAs (Beyond Design Basis Accidents)

Typical BDBAs – HTR-PM

1. Loss of off-site power + **ATWS**
2. Loss of feed water + **ATWS**
3. Inadvertent withdrawal of one control rod + **ATWS**
4. Pebble bed densification (OBE) + **ATWS**
5. Loss of feed water + blower flap gagal tertutup
6. SG tube break + SG emergency drainage gagal
7. SG tube break + 2 safety valves gagal
8. Primary tube break + RCCS gagal total
9. Control rod withdrawal + RCCS gagal total
10. Air ingress (rupture fuel charging & discharging tubes)

Skenario Kecelakaan

Desain utama:

- Koefisien umpan balik suhu negatif besar
- Margin kenaikan suhu tinggi
- Densitas daya rendah
- Kapasitas panas besar
- Mekanisme pasif pembuangan panas peluruhan

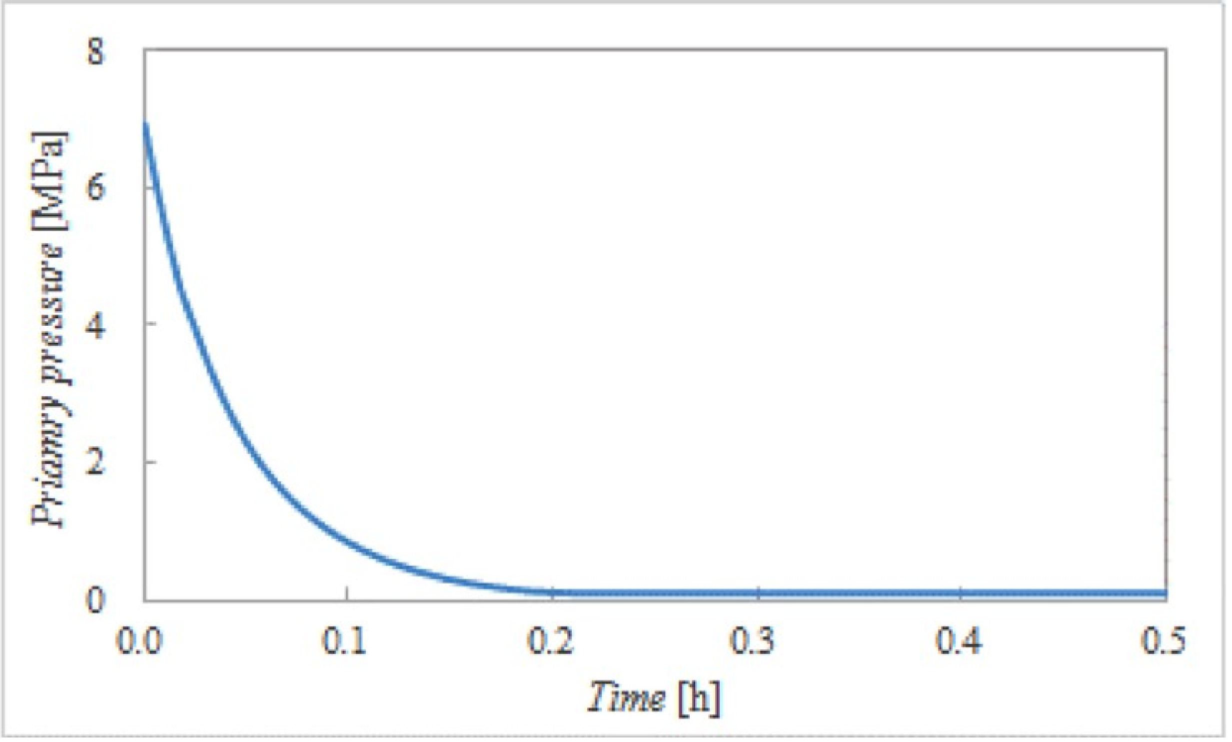
Implikasi:

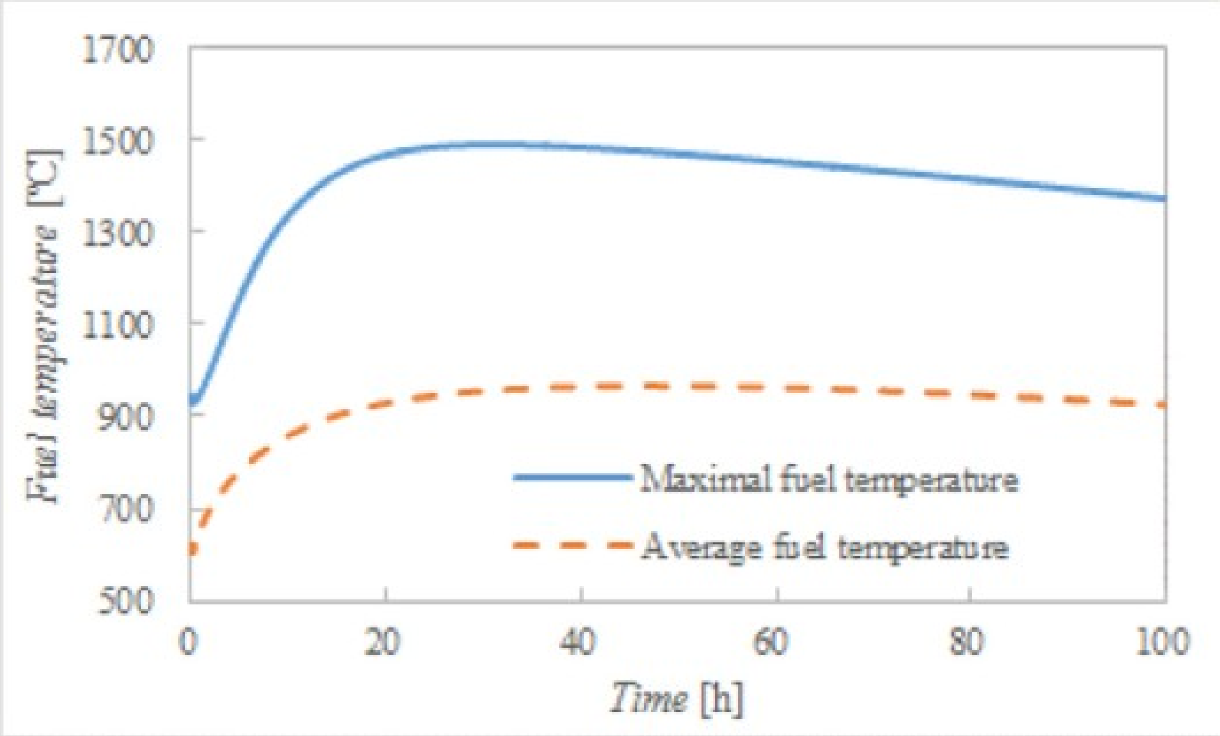
- Mencegah transien cepat & tidak dapat diterima
- Semua kecelakaan dapat dikelompokkan → fenomena serupa / langkah mitigasi sama

- **Accident Categories – HTR-PM**
- **Design Basis Accidents (DBA)**
  - **DLOFC**: Depressurized Loss of Forced Cooling → suhu bahan bakar tertinggi.
  - **PLOFC**: Pressurized Loss of Forced Cooling → mayoritas DBA tanpa depresurisasi / water ingress.
  - **Water ingress**: kebocoran SG tube → air/steam masuk ke primer → reaktivitas, korosi grafit, tekanan naik.
- **Beyond Design Basis Accidents (BDBA)**
  - **ATWS**: Anticipated Transient Without Scram → HTR-PM aman karena feedback negatif & margin suhu besar.
  - **Air ingress**: ruptur pipa → korosi grafit, CO/CO_2 terbentuk.
  - **Water ingress BDBA**: pecah ≥ 2 SG tube atau SG tube break + emergency drainage gagal.
  - **DLOFC/PLOFC + RCCS gagal**: sangat jarang, bisa mengancam RPV & cavity.
  - **Lainnya**: misalnya loss of feed water + blower flap gagal, control rod withdrawal + OBE.
- **Catatan**
  - Beberapa skenario dengan probabilitas sangat kecil ($<10^{-8}$ per tahun) dikecualikan.

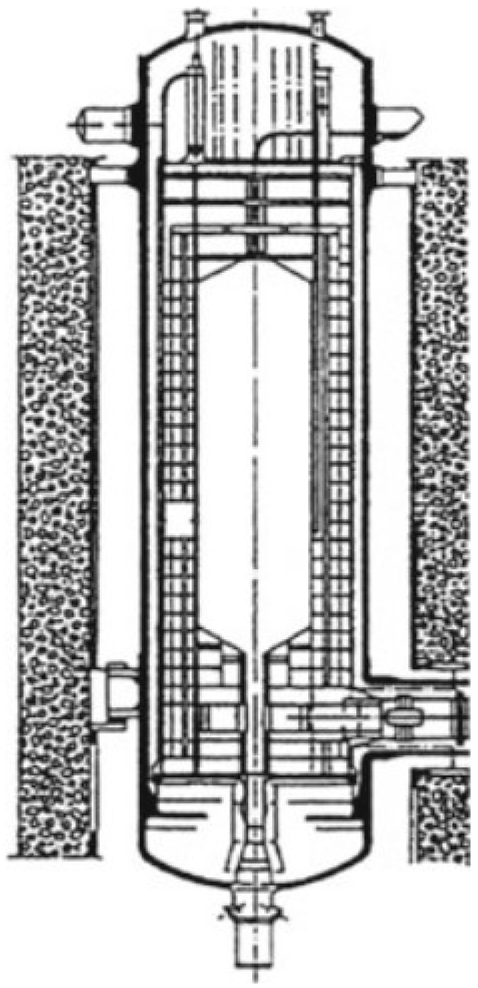
DBA – DLOFC Accident

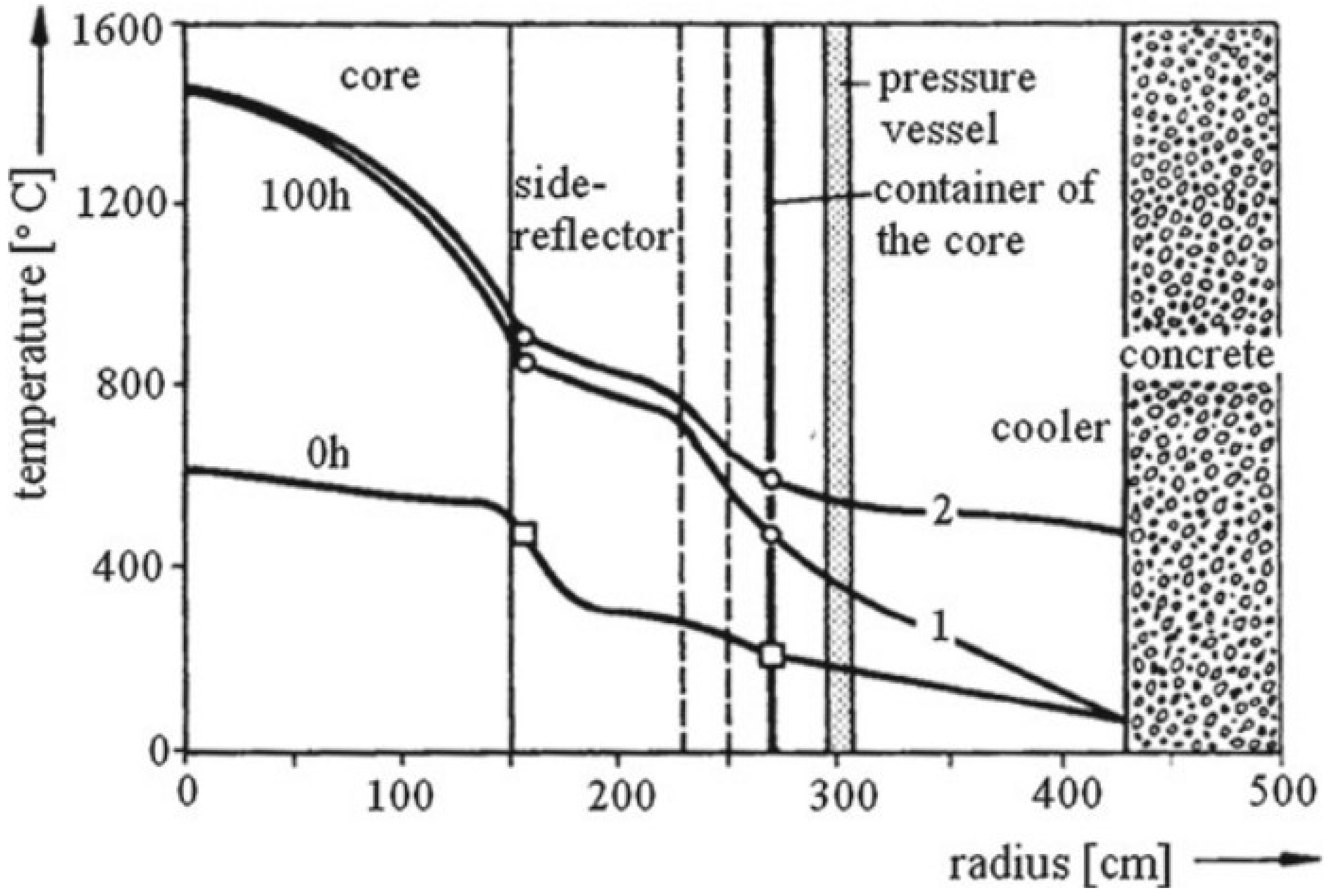
- **DBA – DLOFC Accident (HTR-PM)**
- **Skenario:**
  - Pecah pipa primer Ø65 mm → pendingin helium keluar cepat ke cavity.
  - Rupture disk pecah → gas keluar tanpa filter, lalu isolasi valve menutup → pelepasan berikutnya terfilter.
- **Dampak:**
  - ±800 kg debu grafit selama umur reaktor → hanya ±1/500 dilepas saat DLOFC.
  - Setelah depresurisasi → sisa helium ±1 bar.
  - Panas peluruhan dipindahkan via radiasi & konduksi ke RPV → RCCS buang panas.
- **Perilaku suhu bahan bakar:**
  - Suhu naik setelah shutdown → puncak ±1500 °C dalam 20–30 jam.
  - Batas desain 1620 °C tidak terlampaui.
- **Keselamatan:**
  - Radioaktivitas rendah → pelepasan tetap di bawah batas regulasi.



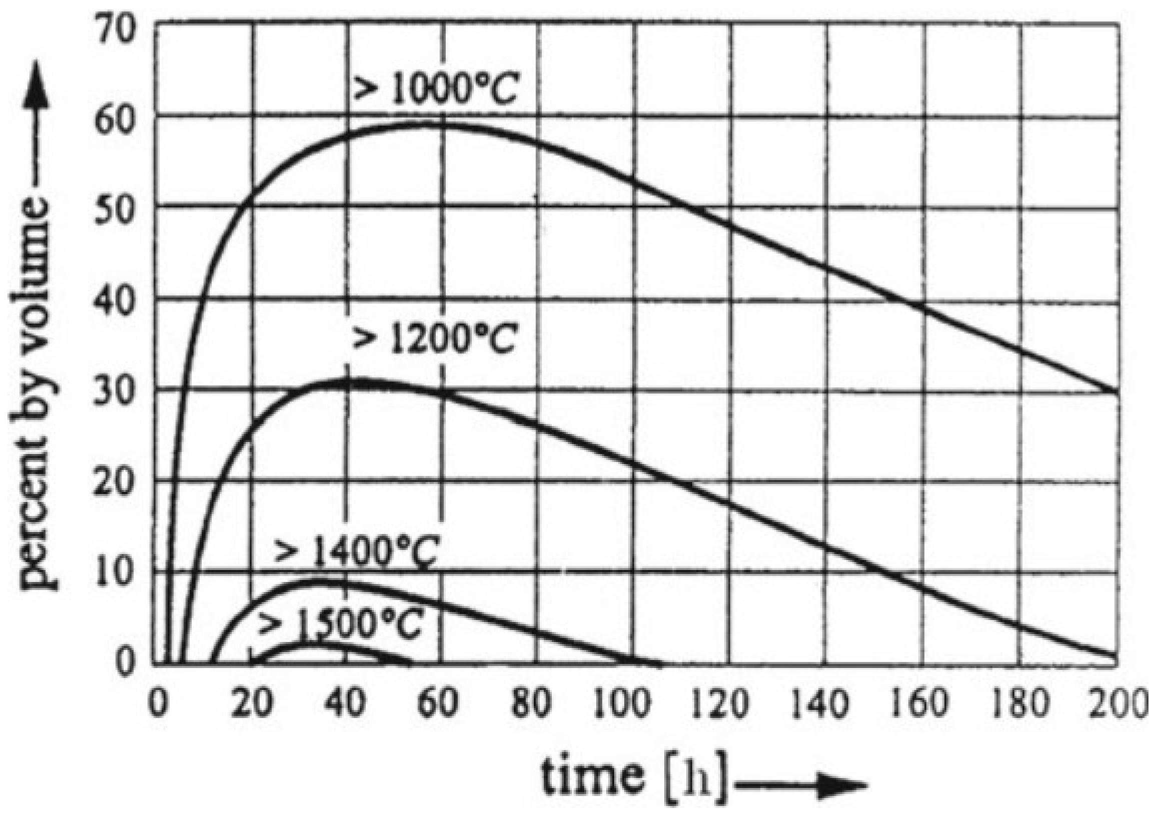


DBA – DLOFC Accident





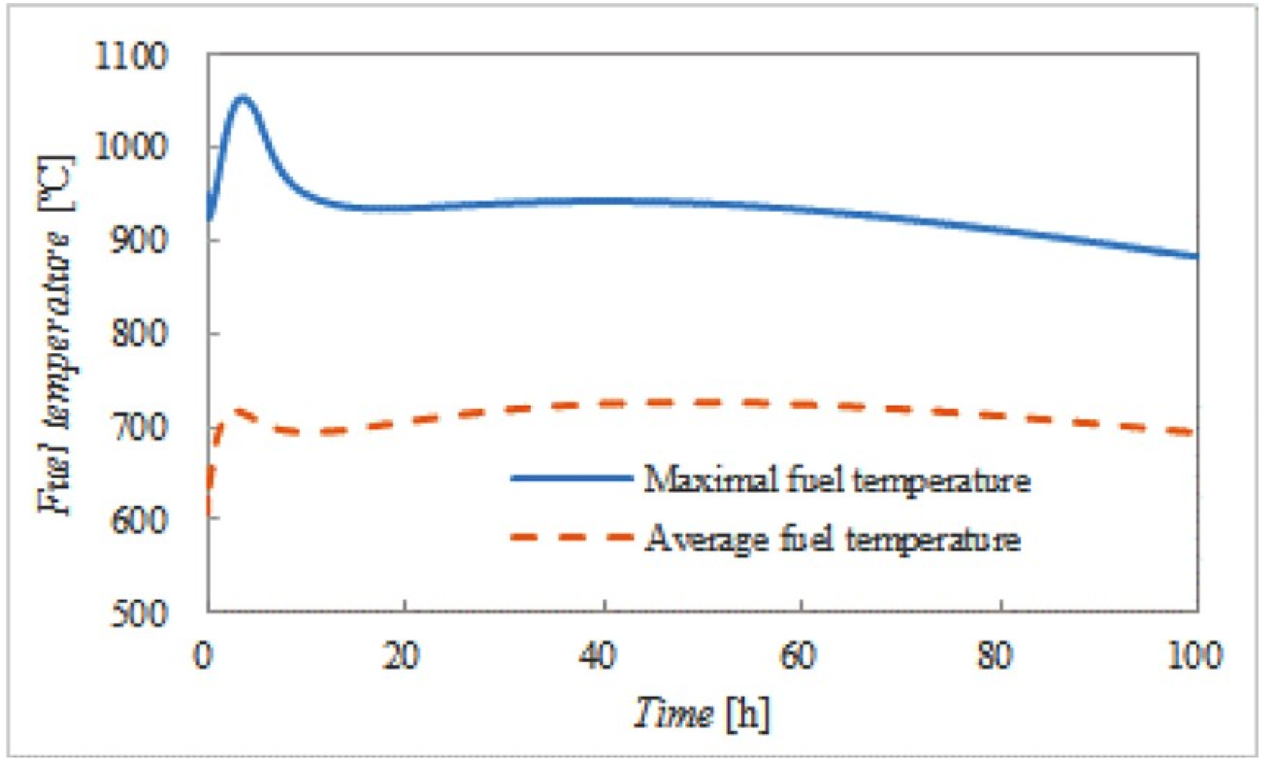
(1): the outer surface cooler works, (2): the outer surface cooler has failed too
radial dependence of fuel temperatures in the core at starting time of accident (total loss of active cooling) and at 100 hours

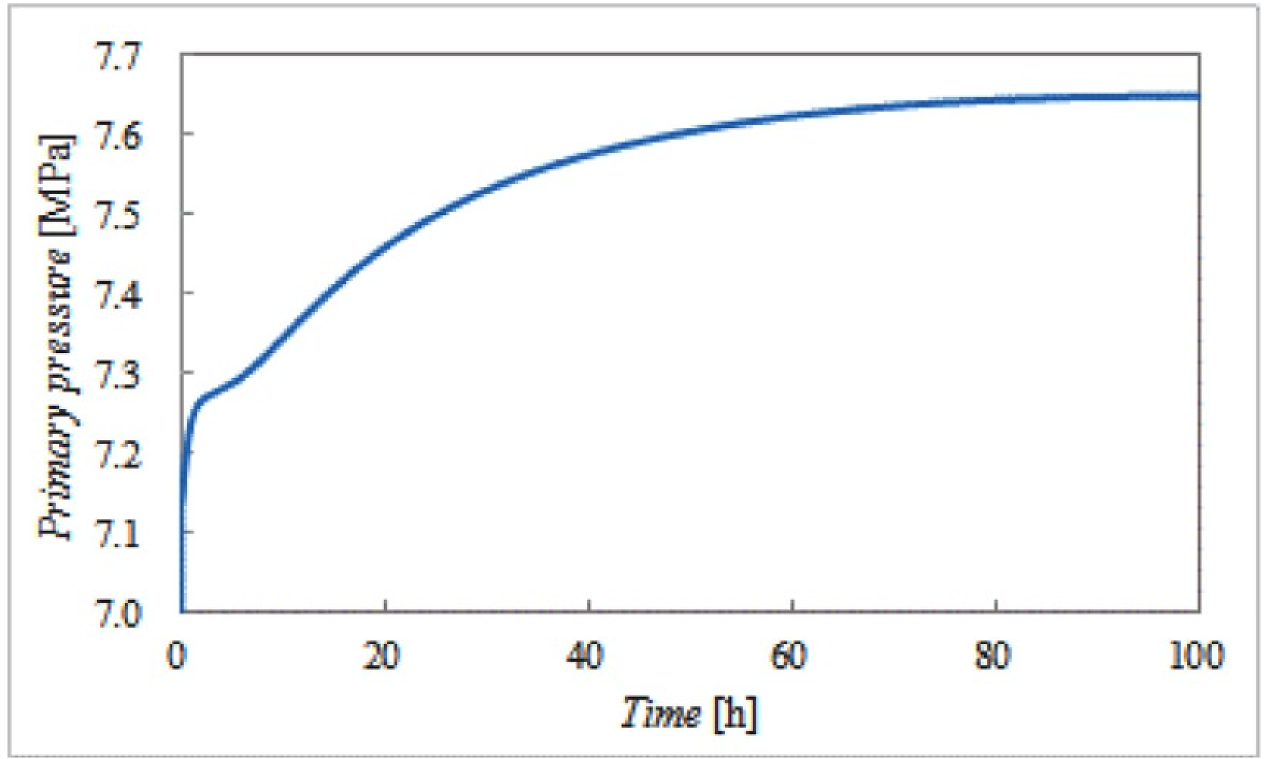


histogram of the fuel temperatures dependent on the time and temperature in the core (assumption: total loss of active cooling, outer surface cooler works)

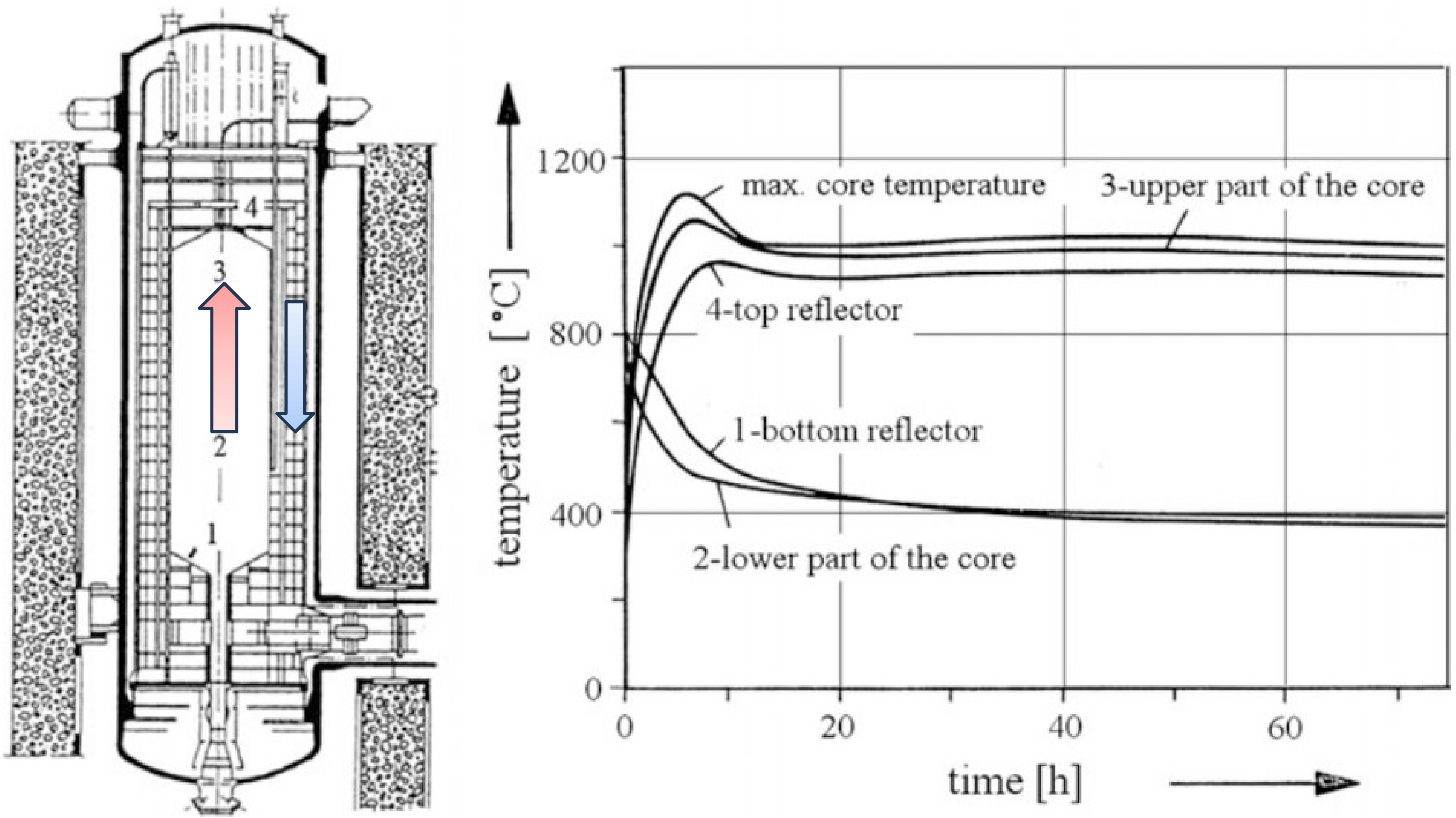
DBA – PLOFC

- **DBA – PLOFC Accident (HTR-PM)**
- **Skenario:**
  - Contoh: withdrawal 1 control rod.
  - Setelah scram → kehilangan forced cooling.
- **Mekanisme pendinginan:**
  - Terjadi **konveksi alami signifikan** karena beda suhu besar & helium bertekanan tinggi.
  - Efektif meningkatkan transfer panas → pendinginan inti.
- **Perilaku suhu & tekanan:**
  - Suhu bahan bakar puncak < **1100 °C** (batas 1620 °C aman).
  - Tekanan primer tetap < **7,9 MPa** → safety valve tidak terbuka.
- **Kesimpulan:**
  - PLOFC lebih ringan dibanding DLOFC.
  - Mayoritas DBA (kecuali DLOFC & water ingress) menunjukkan fenomena serupa → terkendali oleh desain keselamatan inheren (feedback negatif, margin suhu besar, densitas daya rendah, kapasitas panas besar).





DBA – PLOFC



Temperatures in the core in case of loss of forced convection in a modular HTR core at full helium pressure (e.g., HTR-Module, 200 MWth)

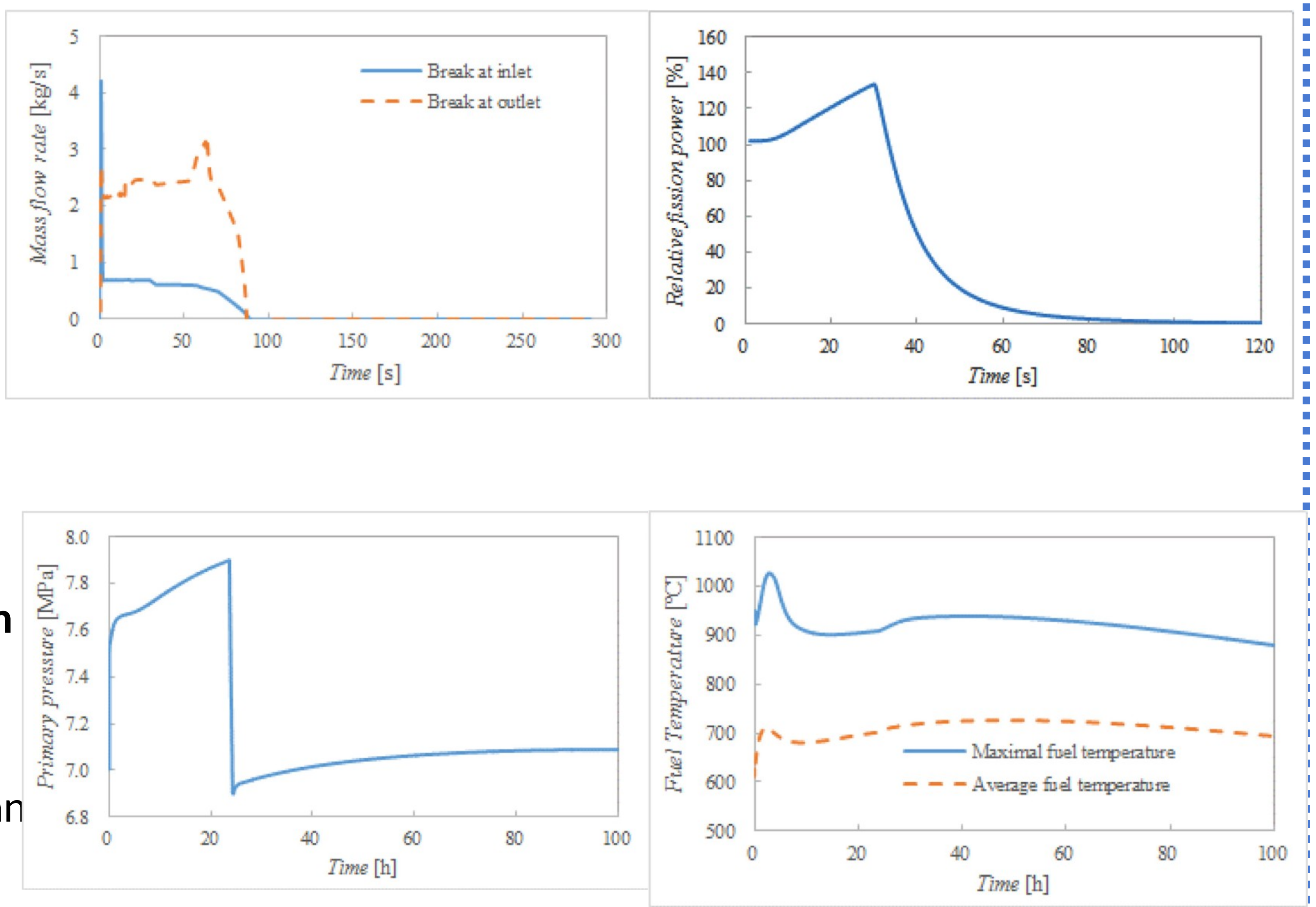
Tambahan sistem pendingin kecil dapat digunakan untuk melindungi komponen sensitif.

Hal ini bukan karena alasan keselamatan, melainkan untuk menjaga investasi.

DBA – Water Ingress Accident

DBA – Water Ingress Accident (HTR-PM)

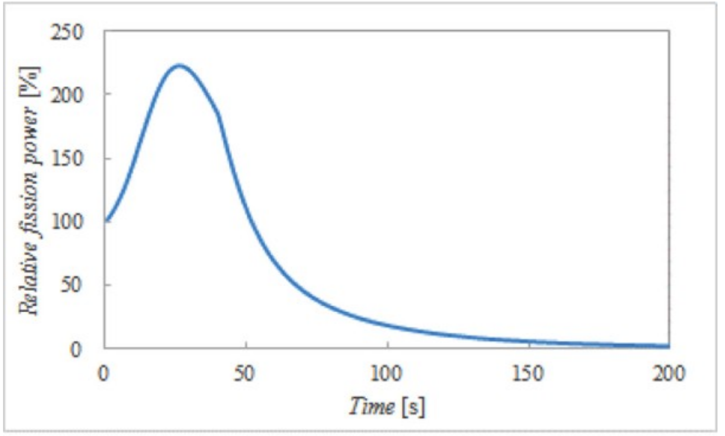
- **Skenario utama:**
  - Pecah SG heating tube (double-ended guillotine).
  - Tekanan sekunder lebih tinggi → ±200 kg steam masuk ke primer.
  - Setelah tekanan seimbang → ±400 kg steam tersisa di SG & jalur feed-water/live-steam.
  - 3000 kg air/steam dibuang ke tangki drainase.
- **Dampak & mekanisme:**
  - ±600 kg steam masuk ke primer dalam 2 menit (5 kg/s).
  - Uap air → **reaktivitas positif** → daya naik sebentar.
  - Segera turun karena **feedback negatif** & jatuhnya control rods.
  - Suhu bahan bakar mirip PLOFC (< batas 1620 °C).
  - Tekanan naik lebih cepat → safety valve bisa terbuka.
- **Keselamatan:**
  - Helium yang keluar tetap difilter → pelepasan radioaktif **di bawah batas regulasi**.
  - Dalam banyak kasus, difusi uap ke primer sangat lambat → pelepasan radioaktif bisa nihil.
  - Operator aktifkan **helium purification system** untuk mengeluarkan uap dari primer.



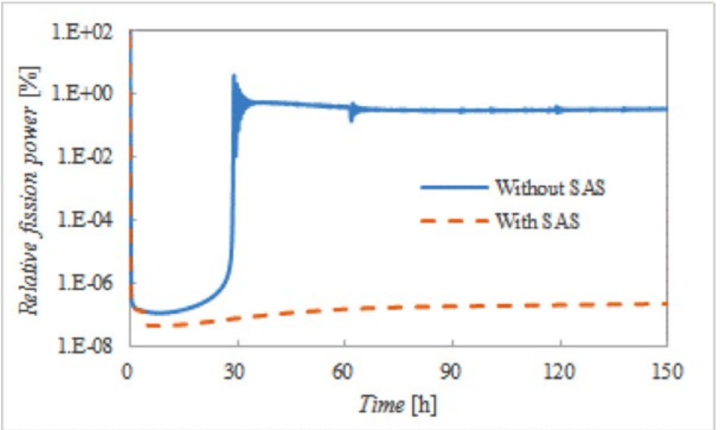
BDBA – ATWS Accident

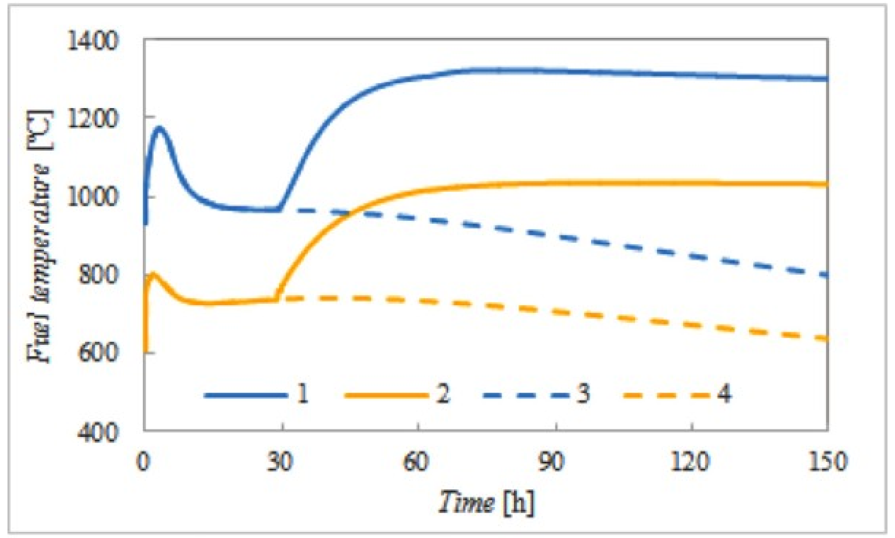
BDBA – ATWS Accident (HTR-PM)

- **Skenario:**
  - Withdrawal 1 control rod, semua control rods gagal jatuh.
- **Mekanisme proteksi:**
  - **Aksi utama:** blower ditutup → hilang forced cooling.
  - **Desain inheren:** suhu naik → feedback negatif → reaktor shutdown sendiri.
  - **SAS system:** dapat menambah reaktivitas negatif → reaktor tetap subkritis.
- **Perilaku suhu & tekanan:**
  - Suhu & tekanan naik sebentar, lalu turun perlahan.
  - Jika SAS juga gagal (probabilitas sangat rendah):
    - Reaktor bisa kritis lagi ±30 jam kemudian.
    - Feedback negatif menjaga daya <0,5% dari daya nominal.
    - Tekanan primer bisa mencapai set point safety valve.
  - Suhu bahan bakar tetap **di bawah batas 1620 °C**.
- **Kesimpulan:**
  - Transien berlangsung lambat → operator punya waktu untuk perbaikan.
  - ATWS tidak menimbulkan konsekuensi yang tidak dapat diterima.

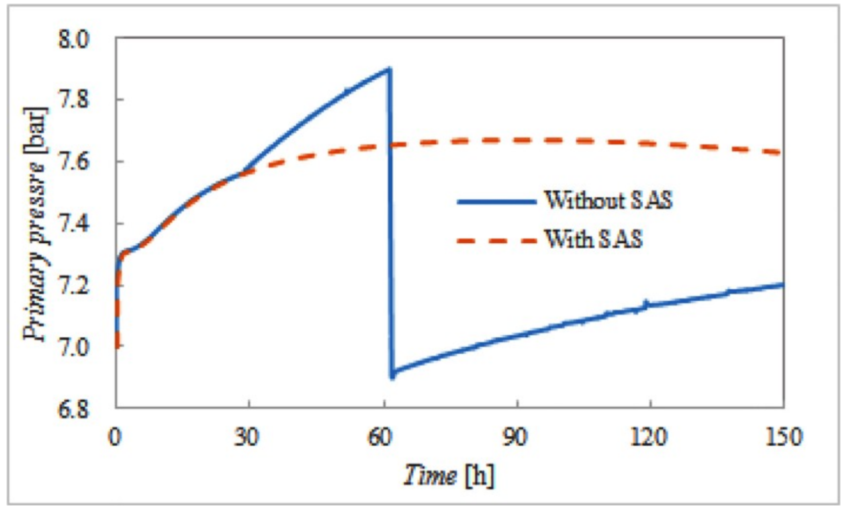


a) Short-term





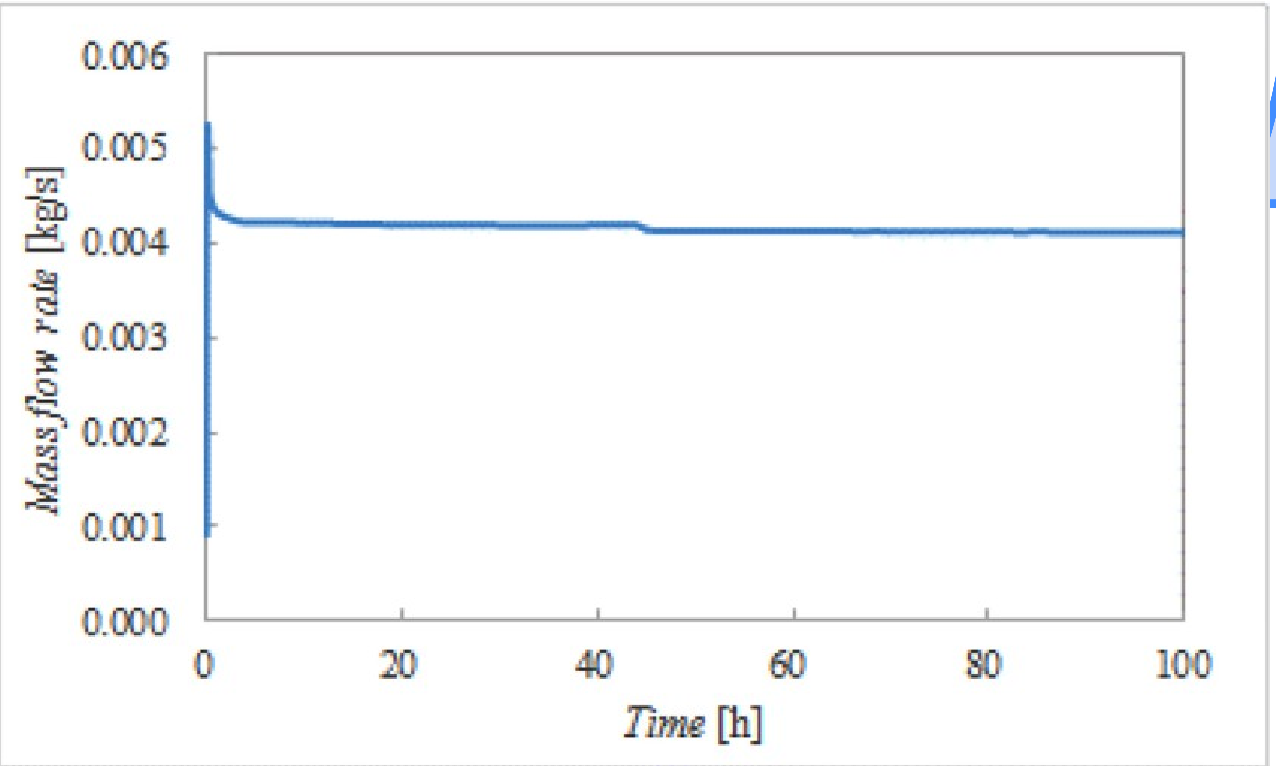
1: Maximal fuel temperature (without SAS)
2: Average fuel temperature (without SAS)
3: Maximal fuel temperature (with SAS)
4: Average fuel temperature (with SAS)

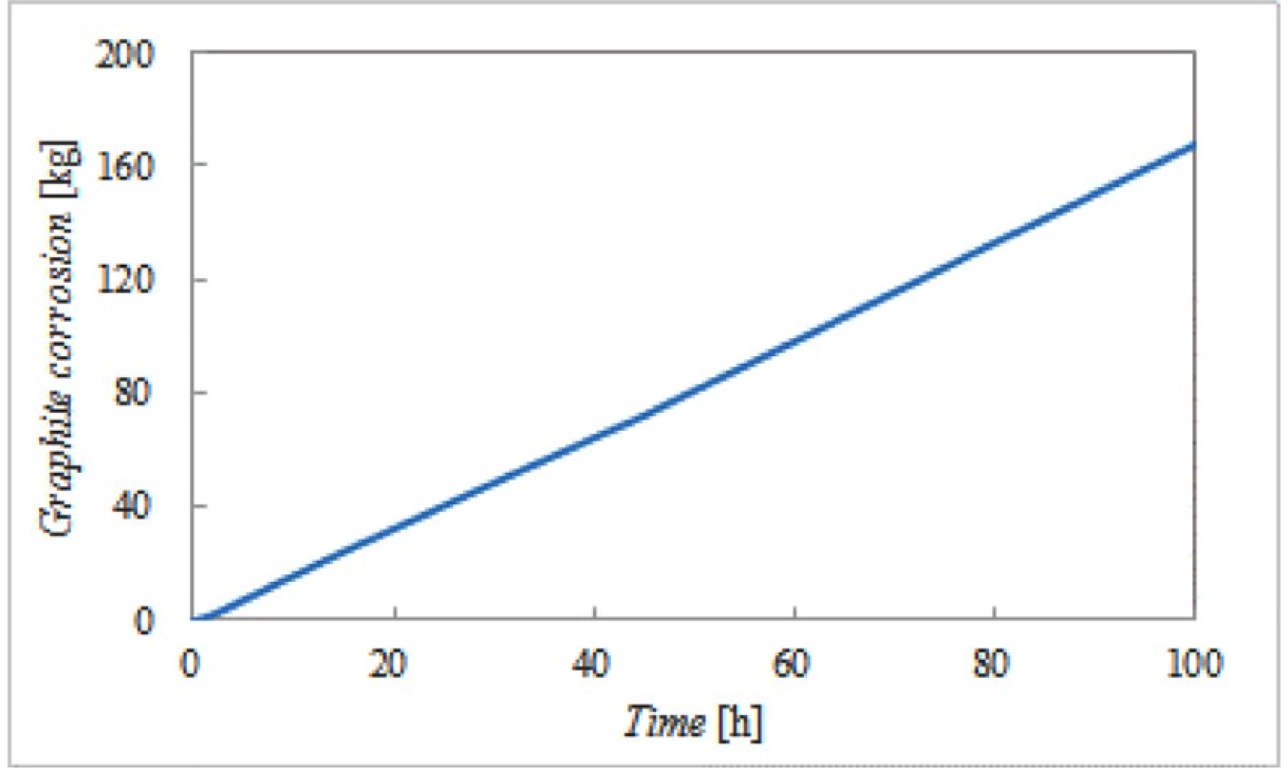


BDBA – Air Ingress Accident

BDBA – Air Ingress Accident (HTR-PM)

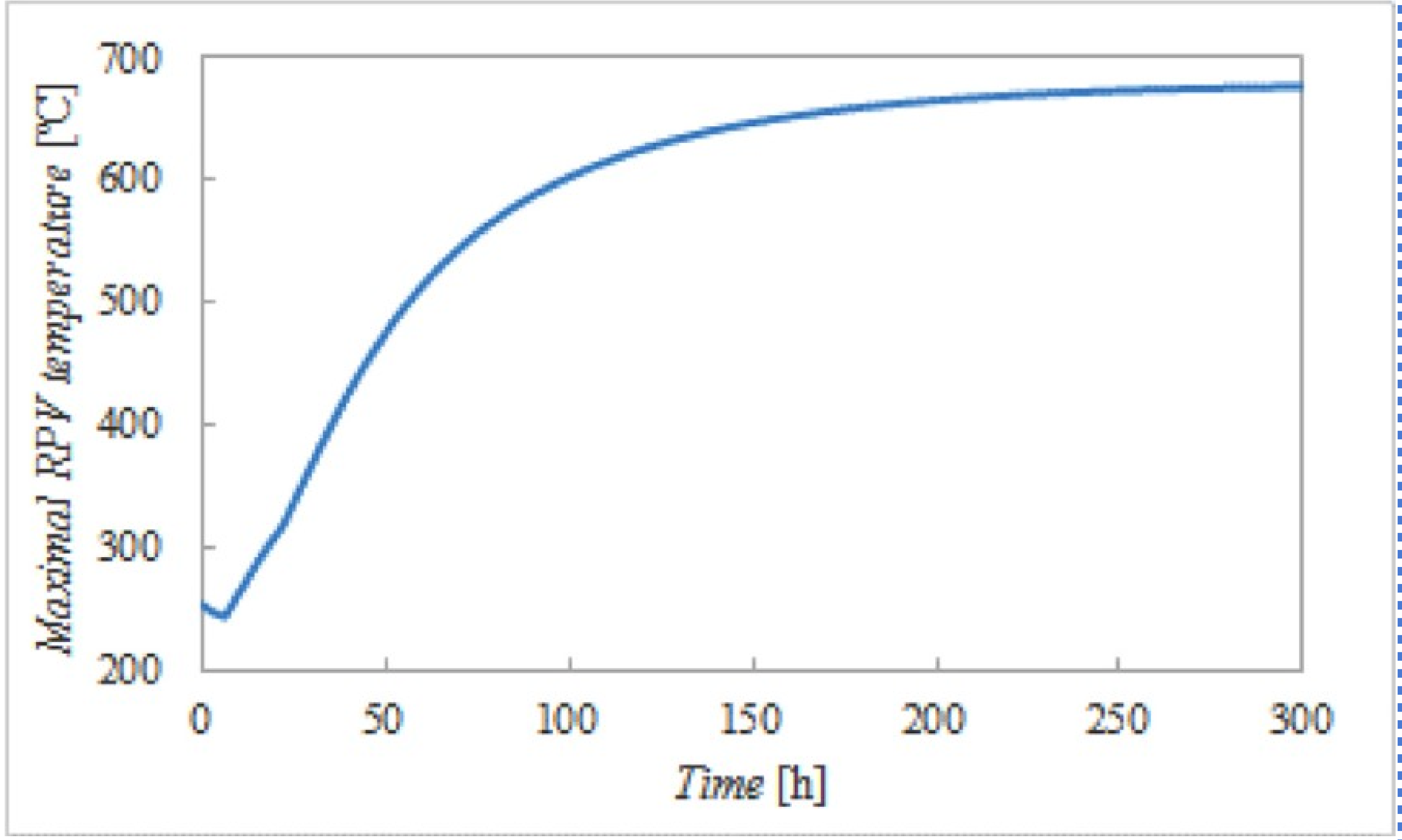
- **Mekanisme**
  - Ruptur simultan fuel charging tube & fuel discharging tube
  - Chimney effect: udara dingin masuk → teras panas → keluar pipa atas
  - Probabilitas: < 1×10^{-10} per tahun per reaktor
- **Kondisi**
  - Campuran gas: 20% udara + 80% helium (200 °C)
  - Laju alir oksigen: ~0.02 mol/s
- **Dampak**
  - Korosi grafit sangat lambat
  - Hanya sedikit grafit terkorosi dalam beberapa hari pertama
  - Partikel berlapis tetap terlindungi
- **Implikasi Keselamatan**
  - Paparan partikel tidak terjadi segera
  - Operator punya waktu beberapa hari untuk mitigasi:
    - Menutup pipa rusak
    - Injeksi gas inert





BDBA – Primary Tube Break + RCCS Failure

- **BDBA – Primary Tube Break + RCCS Failure (HTR-PM)**
- **Mekanisme**
  - RCCS: **3 train independen (3 × 50%)**
  - Normal: 2 train cukup menjaga RPV & beton
  - **Jika semua RCCS gagal** → panas peluruhan tidak bisa dibuang ke lingikungan
- **Kondisi & Dampak**
  - Panas peluruhan tetap ditransfer via **konduksi, radiasi, konveksi alami**
  - **Fuel temperature < 1620 °C** (aman)
  - **Kenaikan suhu RPV lambat** → ada waktu respons
  - Tanpa tekanan: RPV tetap utuh meski suhu tinggi
- **Keselamatan & Mitigasi**
  - **Tidak ada core meltdown** berkat TRISO fuel
  - Operator dapat:
    - Memperbaiki RCCS
    - Aktifkan pendinginan paksa
    - Lakukan **pressure relief**
  - **Slow transient** → cukup waktu untuk diagnosis & tindakan



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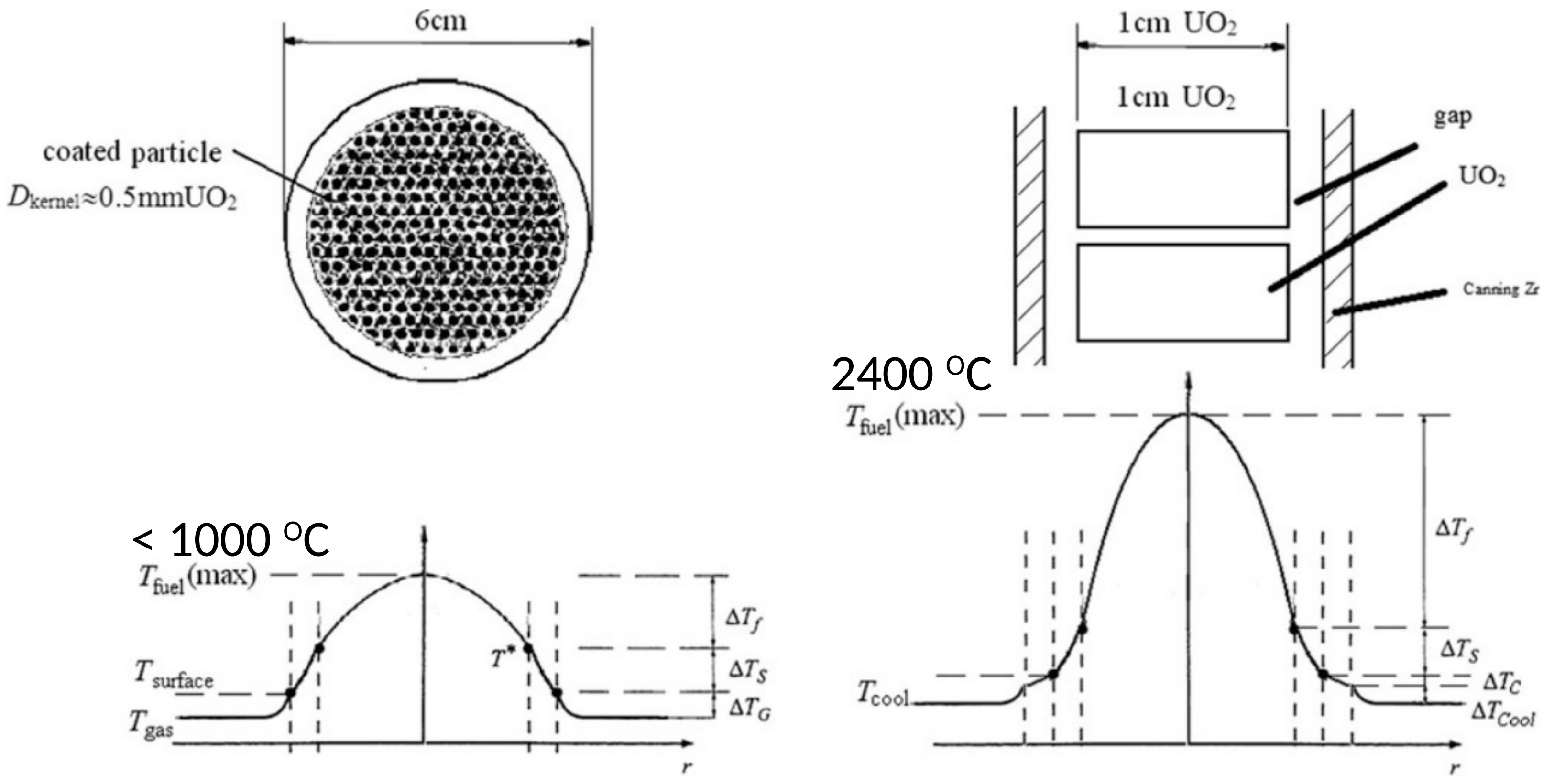
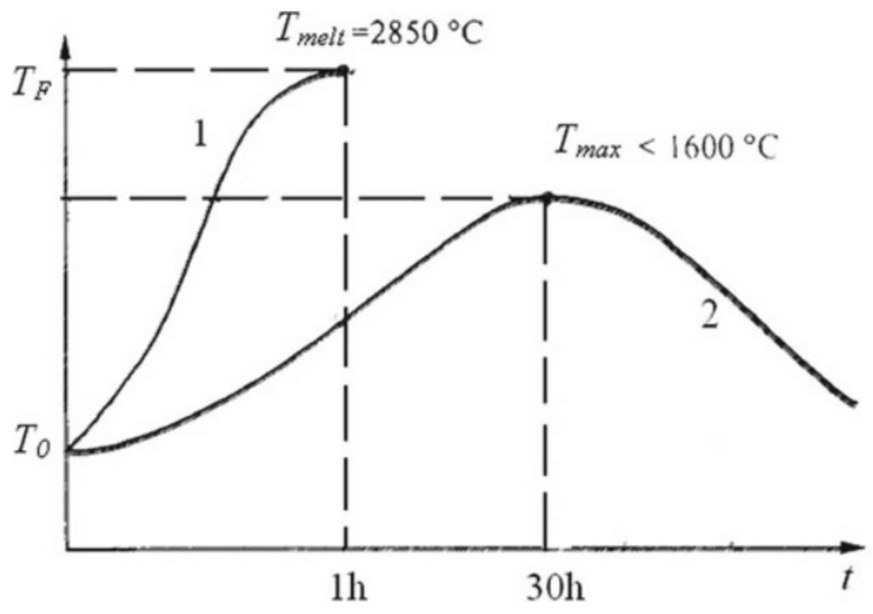
HTGR vs LWR

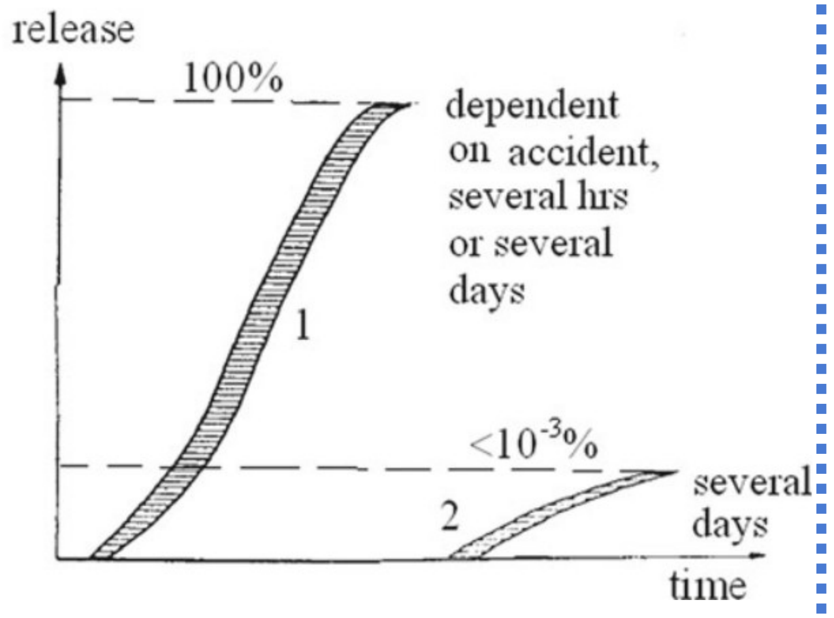


Fuel elements of HTR (left) and PWR (right) and temperature profiles in normal operation

1: PWR, 3800 MW, 2: modular HTR, 250 MWth



(a) time dependence of max. fuel temperature

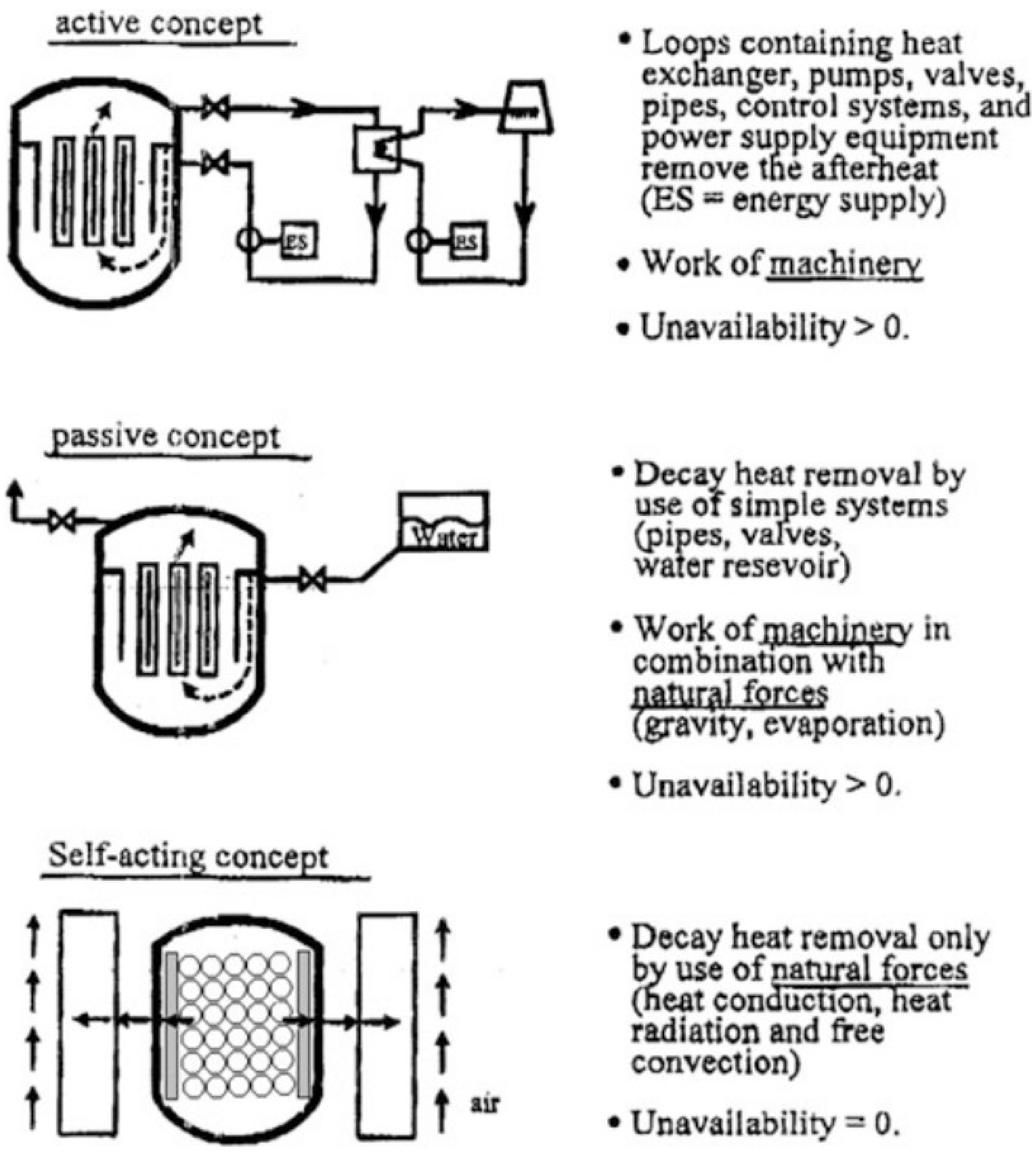


(b) time dependence of fission product release from the fuel elements

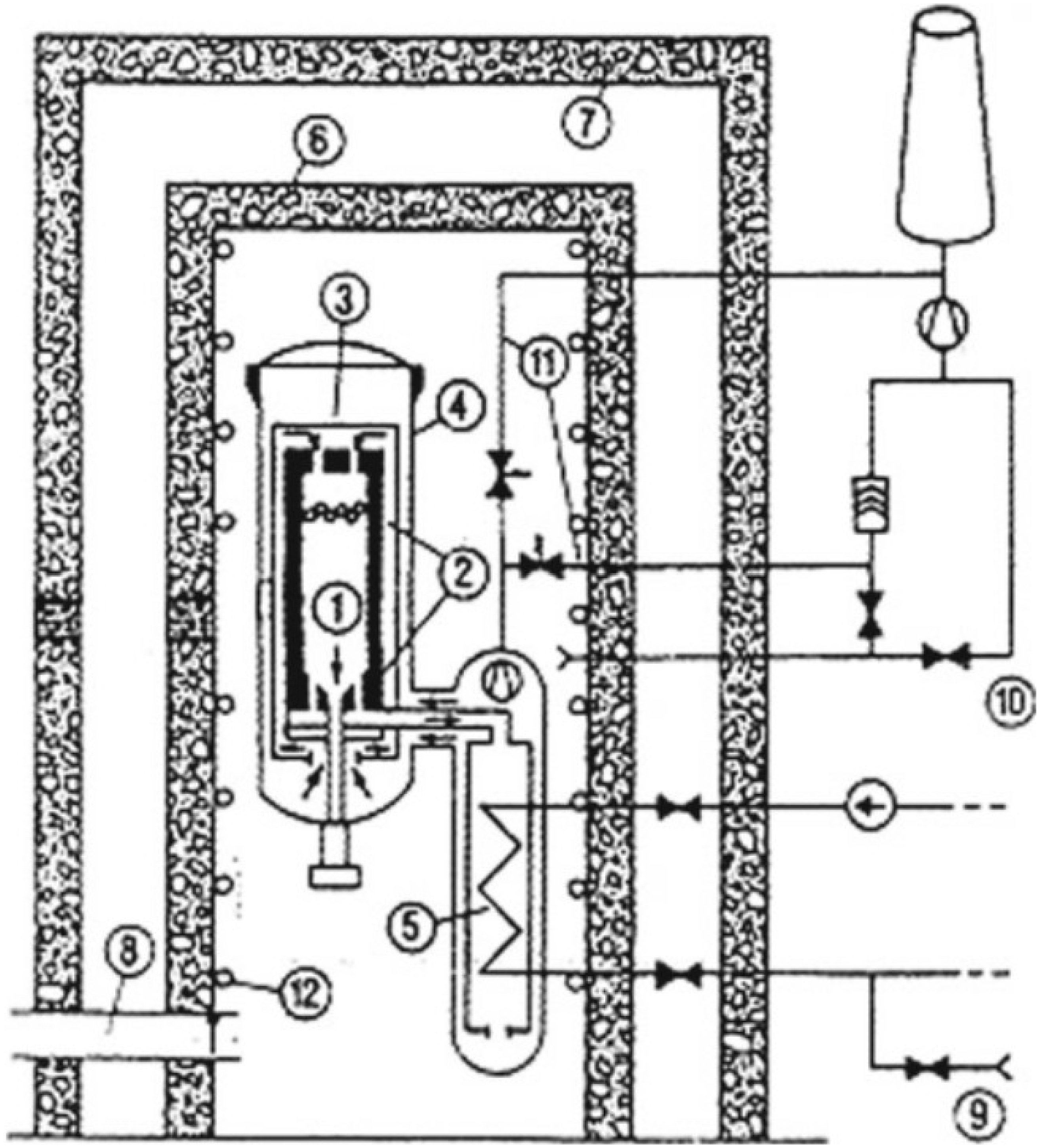
Comparison of behavior of reactors in case of the accident “total loss of decay heat removal”

Parameter	Dimension	Modular HTR	Large PWR
Thermal power of core	MW	200	3800
Average core power density	MW/m^3	3	90
Permanently available material for heat storage	g/kW	200	25
Reason for limit in case of loss of cool and accident	-	Enlarged fission product release	UO_2-melt

Active, Passive, Self-acting

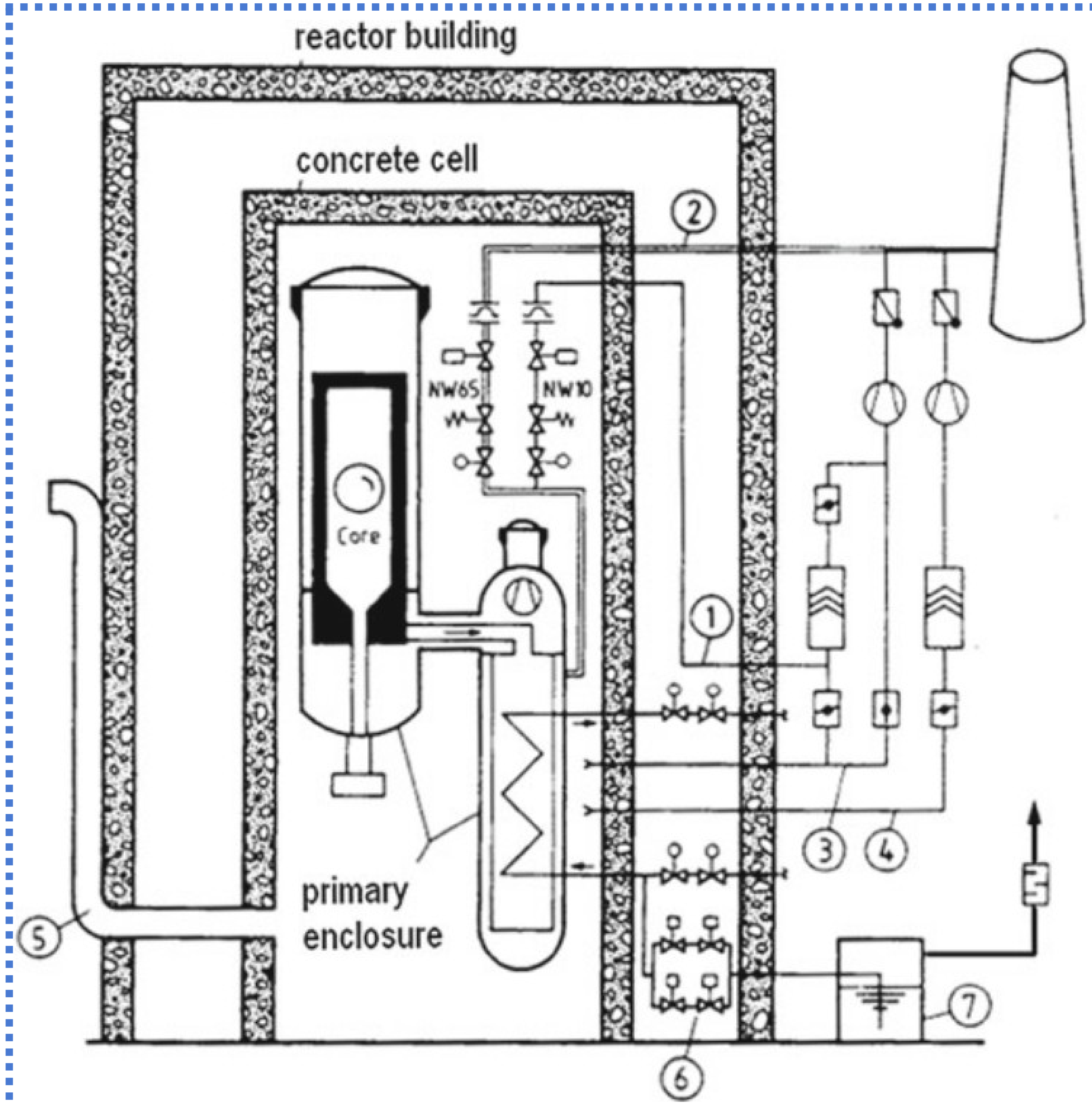


Principles of decay heat removal



1: pebble bed core
2: graphitic reflector
3: core barrel
4: pressure vessel
5: steam generator
6: reactor cell
7: reactor building
8: pressure relief system of reactor cell
9: steam generator dump line
10: exhaust air system
11: pressure relief system
12: surface cooler

Decay heat removal in a modular HTR (e.g., HTR-Module 200 MW) [102]



1: system for pressure limitation,
2: system to avoid too high pressure,
3: system to establish under pressure in the inner cell,
4: filter system for helium leaking from primary system,
5: depressurization system for inner cell after leaks at primary circuit,
6: steam generator depressurization system (feed water side),
7: water pool

Principle of primary helium circuit, feed water supply, and possibilities to remove water [102]

Terima kasih