APRONUKI
Perkumpulan Profesi Nuklir Indonesia
Indonesia Nuclear Professional Association
SK Menteri Hukum dan HAM
nr. AHU-0003674.AH.01.07/2017

Bahan Diskusi Filosofi Design SMR & Potensi Pelelehan Bahan Bakar (*Core Melting*)

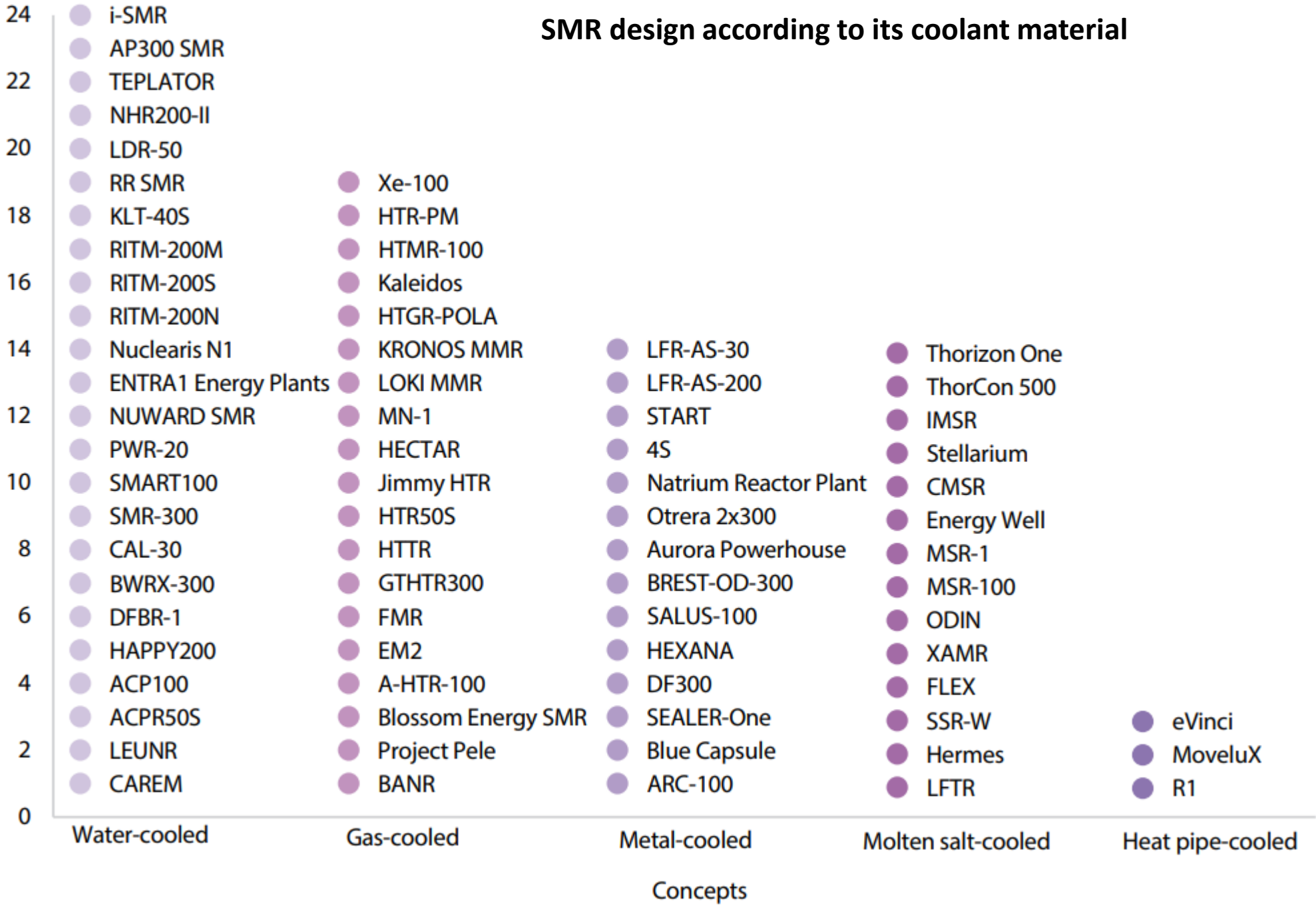
Discussion Material on SMR Design Philosophy & Fuel Melting Potential

Portal Diskusi APRONUKI (profesinuklir.org)

Moderator: DR.Ir. Widi Setiawan


elideo.com

SMR design according to its coolant material

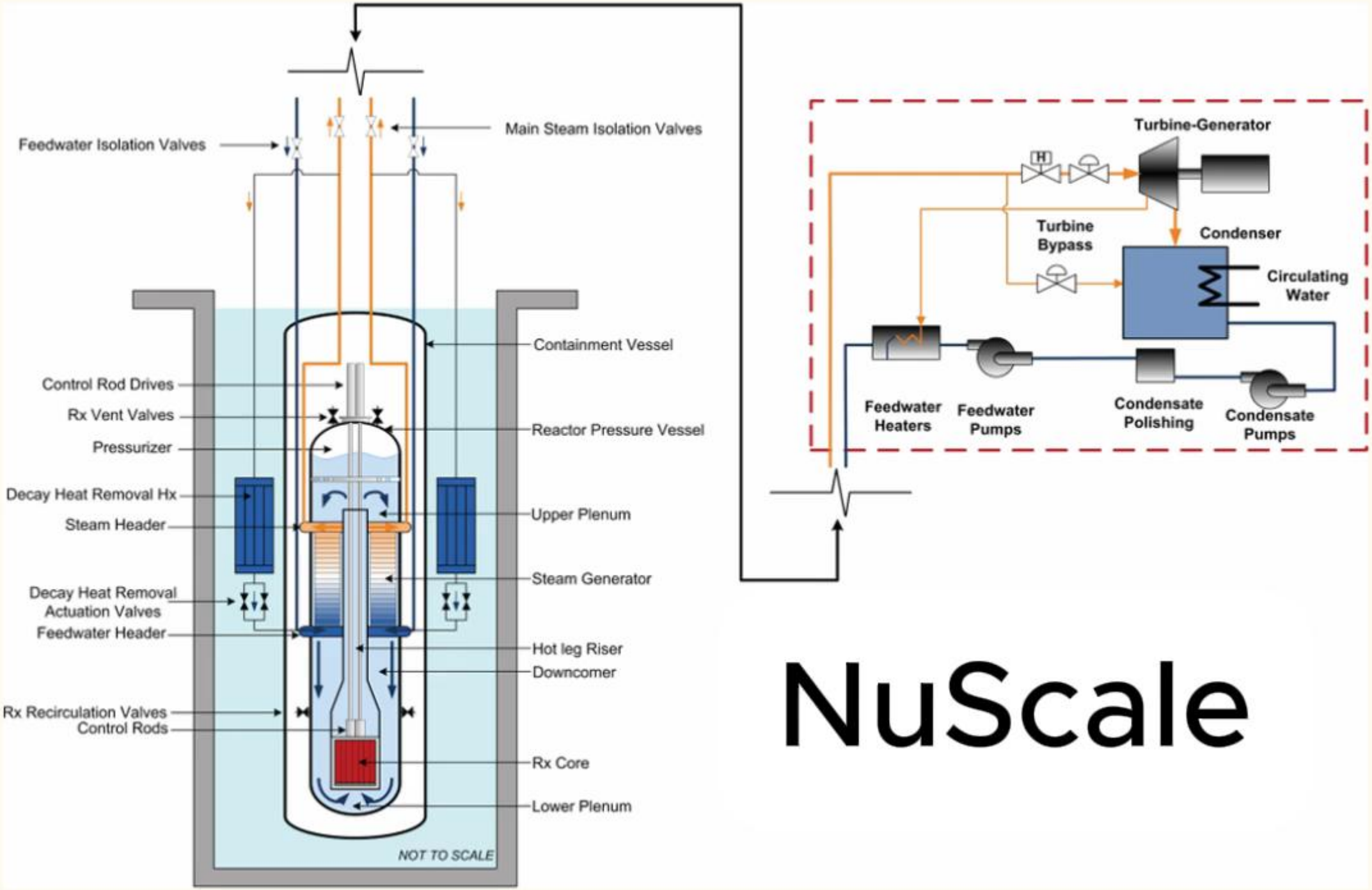


SMR yang siap deployment

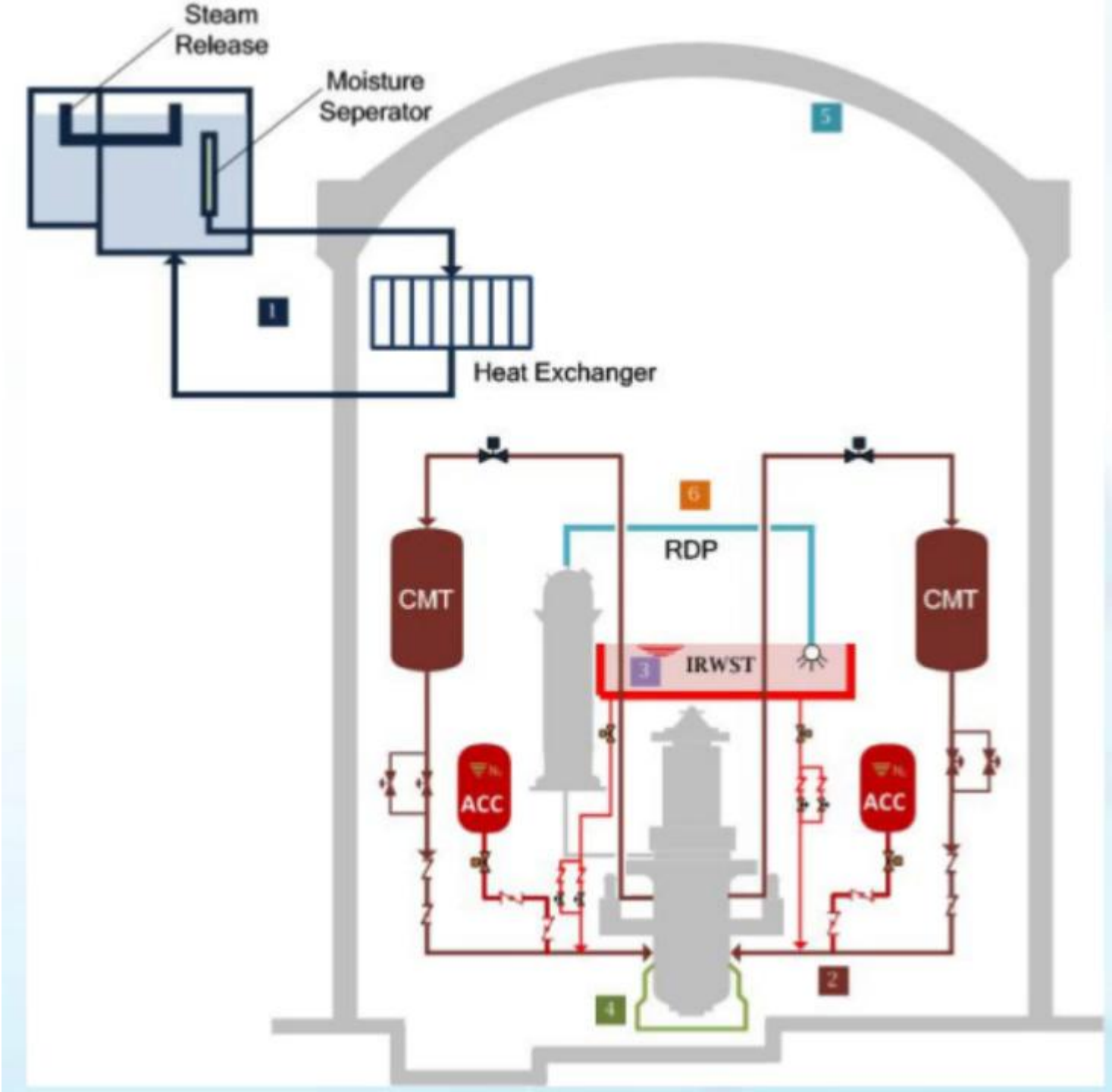
SMR ready for deployment

Reaktor	Site Licensing	Construction Licensing	Operation Licensing	Status 2026
NuScale VOYGR	✔ (proyek tertentu)	Belum ada proyek yang memasuki konstruksi komersial di AS	Belum	Design telah disetujui NRC, tetapi belum ada pembangkit komersial
ACP100 (Linglong One)	✔	✔	Commissioning berlangsung, operasi komersial belum penuh	Tahap akhir commissioning
BWRX-300	✔ (Kanada, Darlington)	✔ (Kanada, 2025)	Belum	Sedang dibangun
RITM-200N	✔	✔ (Yakutia)	Belum	Sedang dibangun
RITM-200S	✔	✔ (berbasis teknologi PLTN terapung)	Belum	Tahap pengembangan proyek
HTR-PM	✔	✔	✔	Beroperasi komersial

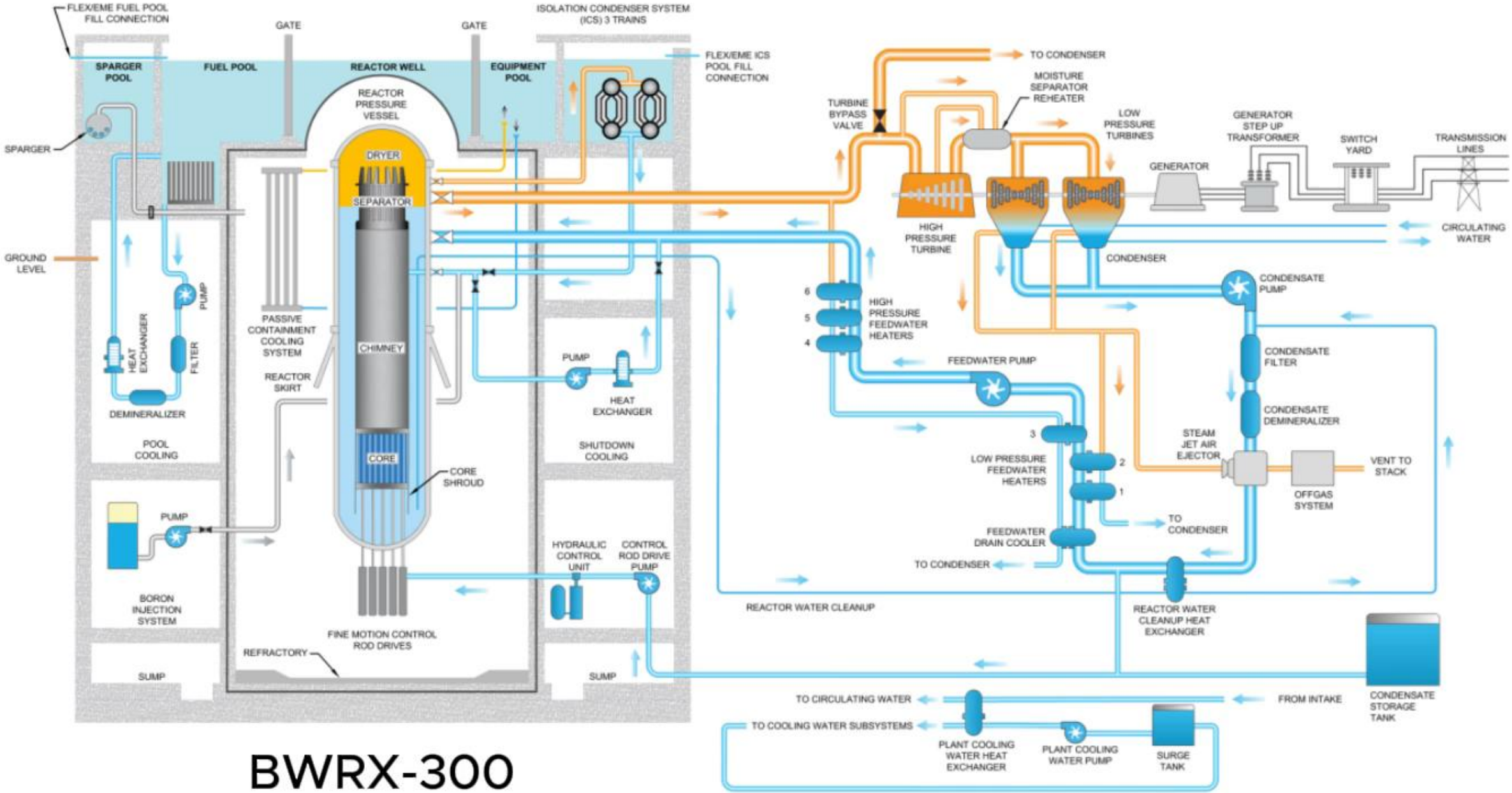
NuScale VOYGR



China National Nuclear Corporation (CNNC) – ACP100

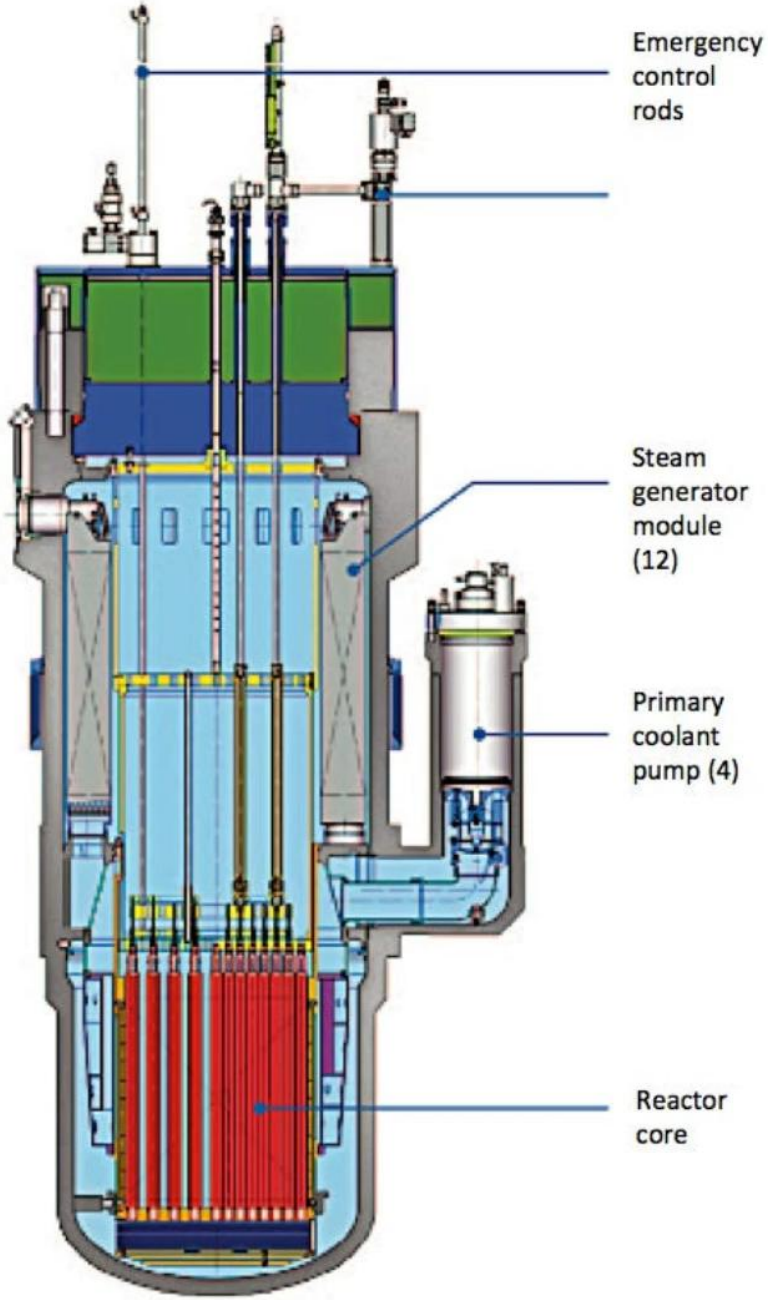


BWRX-300



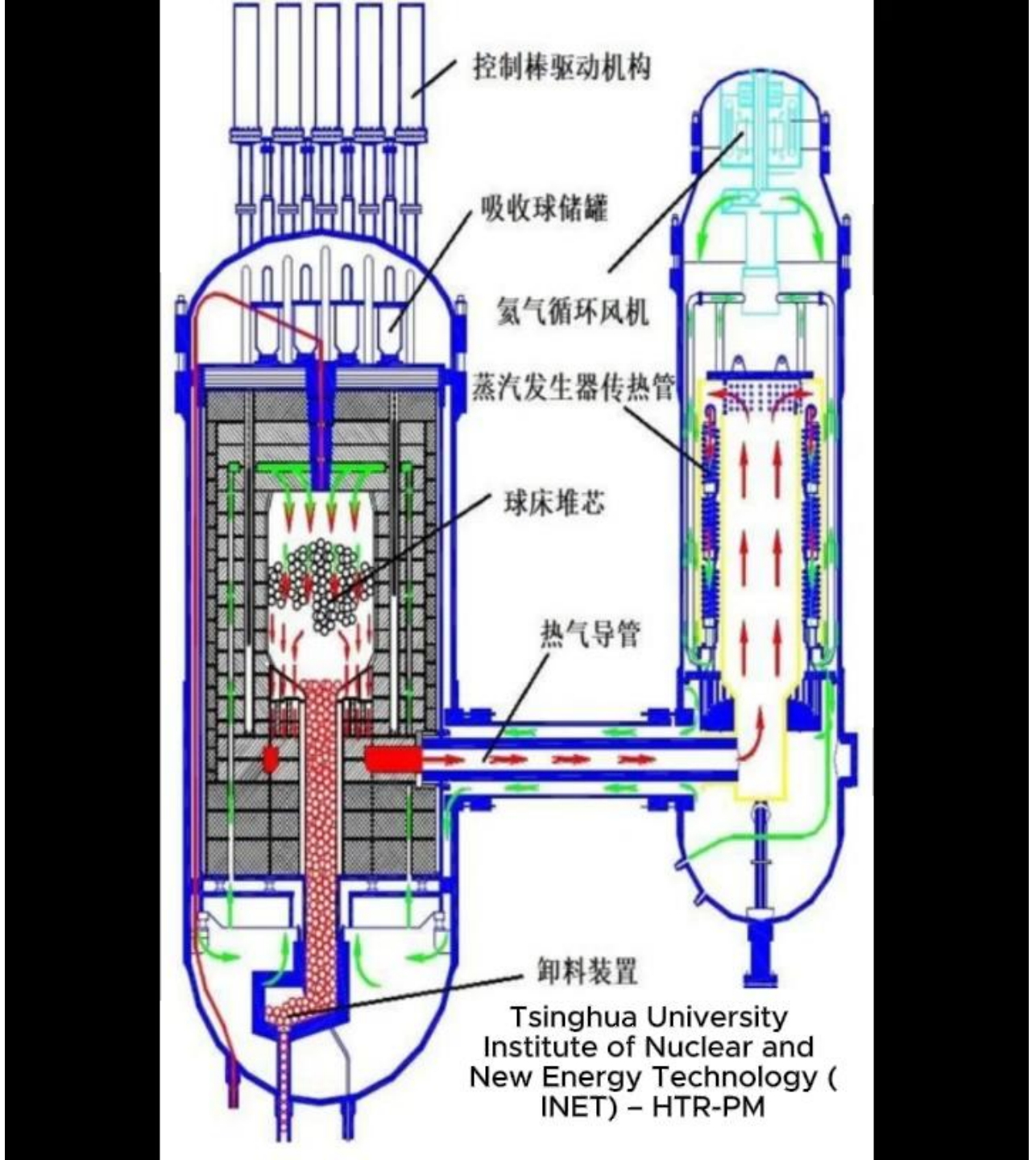
BWRX-300

OKBM Afrikantov (OKBM) – RITM-200N



RITM-200. Source: adapted from OKBM Afrikantov

Tsinghua University Institute of Nuclear and New Energy Technology (INET) – HTR-PM

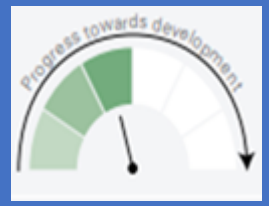


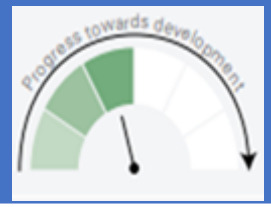
Tinjauan Potensi *Core Melting*

Review of Core Melting Potential

SMR	Tipe	Konsep ECCS	Passive Safety	SBO tanpa AC	Ultimate Heat Sink	Catatan
NuScale VOYGR	Integral PWR	Passive vent & recirculation ECCS		Unlimited	Reactor pool	Salah satu ECCS paling pasif; sirkulasi alami melalui containment dan kolam reaktor. (Frontiers)
ACP100 (Linglong One)	Integral PWR	Passive ECCS + Passive Decay Heat Removal + ADS		≥7 hari	Reactor cavity + passive containment	Memiliki passive containment cooling dan reactor cavity flooding untuk severe accident. (Advanced Reactor Information System)
BWRX-300	BWR	Gravity Driven Cooling + Isolation Condenser + Passive Containment Cooling		≥7 hari	Suppression pool & containment	Memanfaatkan pengalaman ESBWR dengan natural circulation dan sistem pasif. (GE Vernova)
RITM-200N	Integral PWR	Active ECCS + Passive Hydro-accumulators		Beberapa jam hingga beberapa hari (bergantung desain tapak)	Air/kolam pendingin	Berasal dari reaktor kapal pemecah es; menggabungkan sistem aktif dan pasif.

Kriteria OECD-NEA	NuScale VOYGR	ACP100 (Linglong One)	BWRX-300	RITM-200N	RITM-200S
Core Damage Frequency (CDF)					
Severe Accident Behaviour					
Accident Progression					
Safety Case					
Deterministic Safety Analysis (DSA)					

SMR	Tipe	Konsep ECCS	Passive Safety	SBO tanpa AC	Ultimate Heat Sink	Catatan
RITM-200S	Floating PWR	Active ECCS + Marine passive features		Didukung sistem kapal	Laut sebagai heat sink	Keunggulan utama berasal dari ketersediaan laut sebagai pendingin tak terbatas.
SMART100	Integral PWR	Passive Residual Heat Removal + Active ECCS		≥72 jam	PRHRS	Salah satu desain integral PWR paling matang dari Korea. (ScienceDirect)
CAREM-25	Integral PWR	Passive injection + natural circulation		≥36–72 jam	Containment cooling	Reaktor integral Argentina dengan sistem primer berbasis sirkulasi alami.
Rolls-Royce SMR	Loop PWR	Active ECCS + Passive residual heat removal		Bergantung baterai & diesel	Ultimate heat sink konvensional	Evolusi PWR Gen III+, lebih mengandalkan sistem aktif dibanding NuScale/ACP100.

Kriteria OECD-NEA	NuScale VOYGR	ACP100 (Linglong One)	BWRX-300	RITM-200N	RITM-200S
Probabilistic Safety Assessment (PSA)					
Severe Accident Mitigation					
Residual Risk					

KESIMPULAN

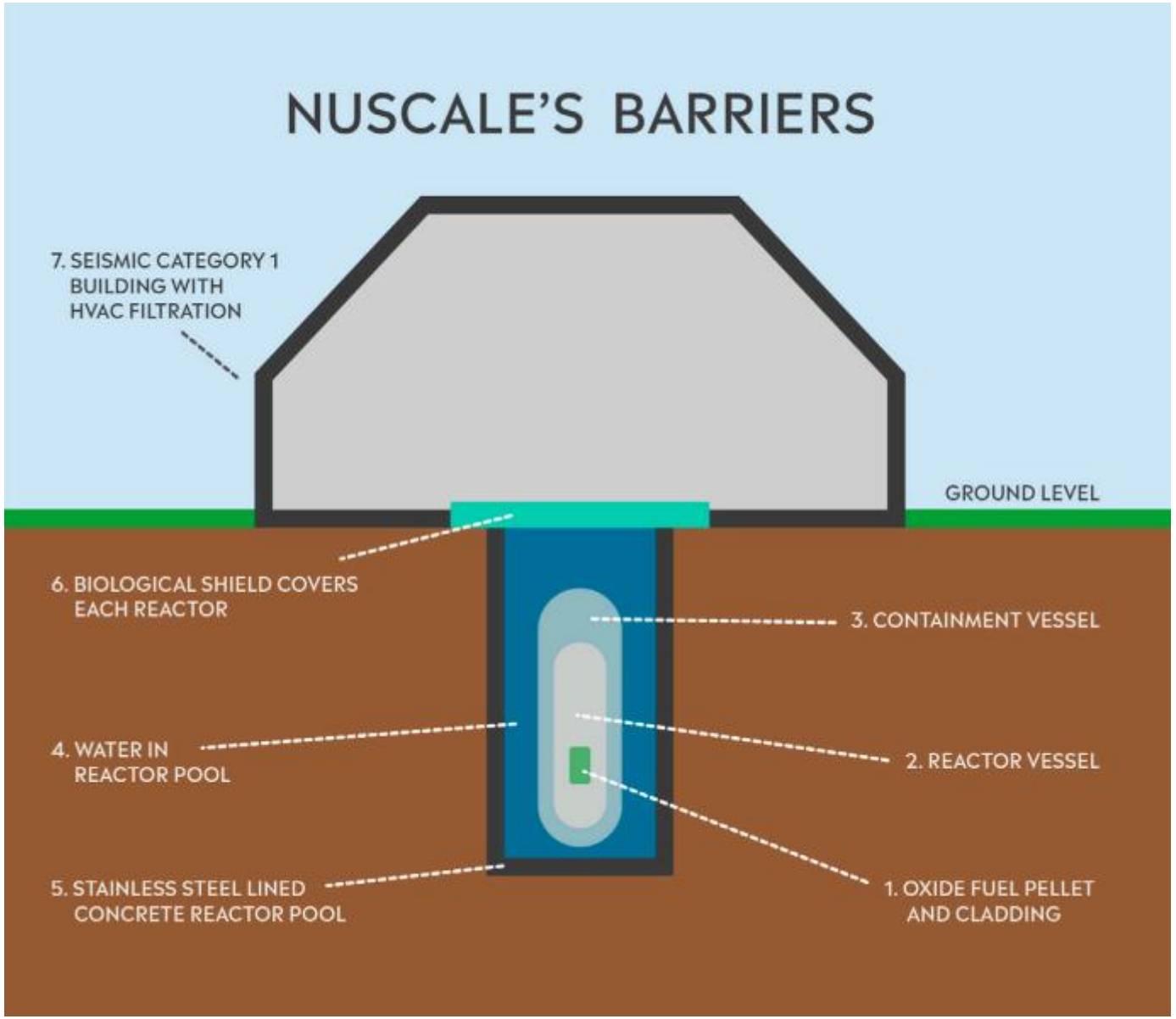
Meminimalkan probabilitas core melting (core damage) merupakan salah satu **target desain utama** SMR berbasis **PWR** maupun **BWR**.

1. **Mencegah terjadinya core damage** (prevention),
2. **Membuat probabilitasnya sangat kecil** (risk reduction),
3. **Membatasi konsekuensinya apabila tetap terjadi** (mitigation).

Sebaliknya, untuk beberapa reaktor Generasi IV seperti **HTR-PM**, filosofi desainnya bergeser dari sekadar menurunkan probabilitas menjadi **menghilangkan mekanisme fisik terjadinya pelelehan teras (practical elimination of core melt)**.

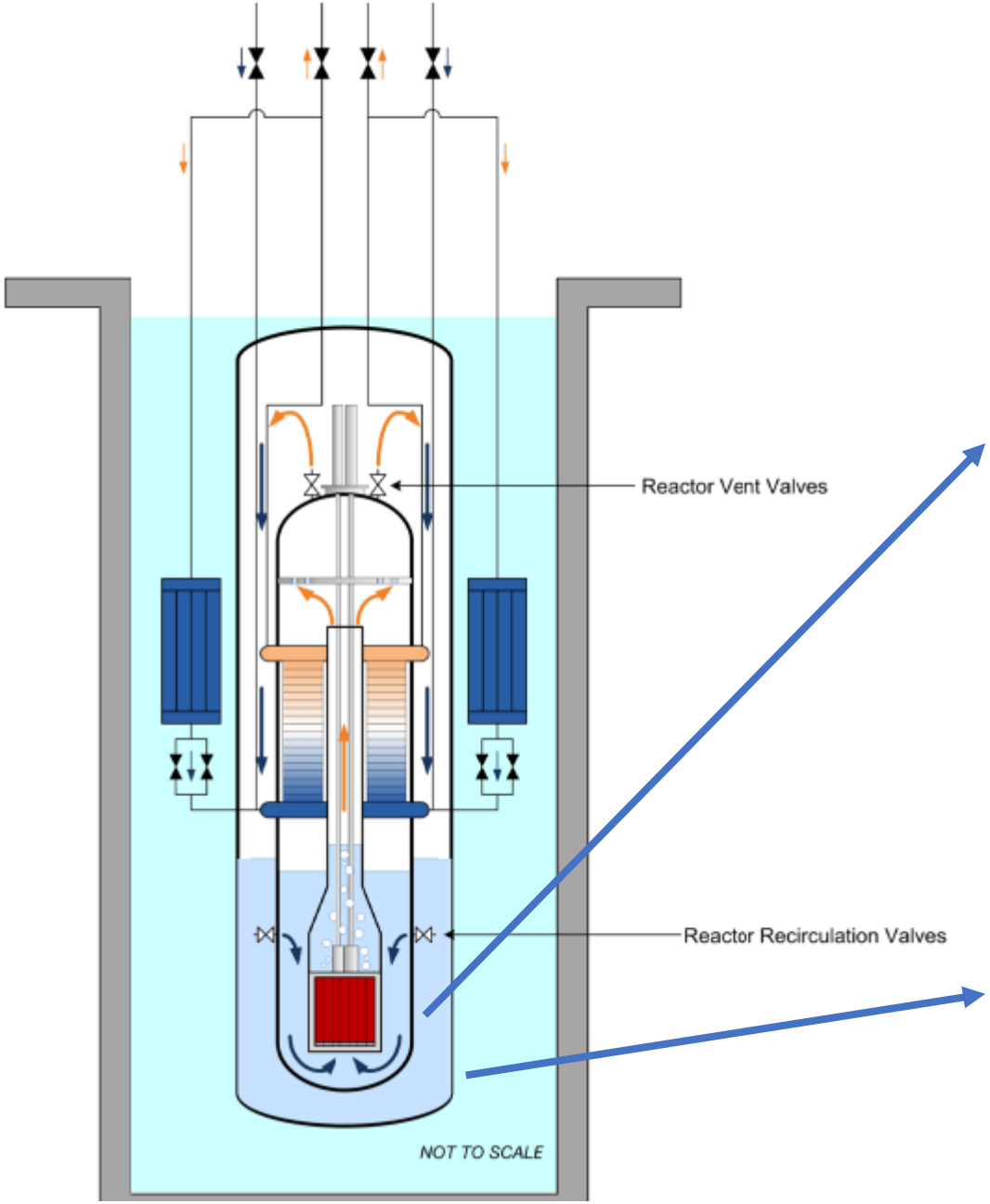
Bagian-bagian reaktor

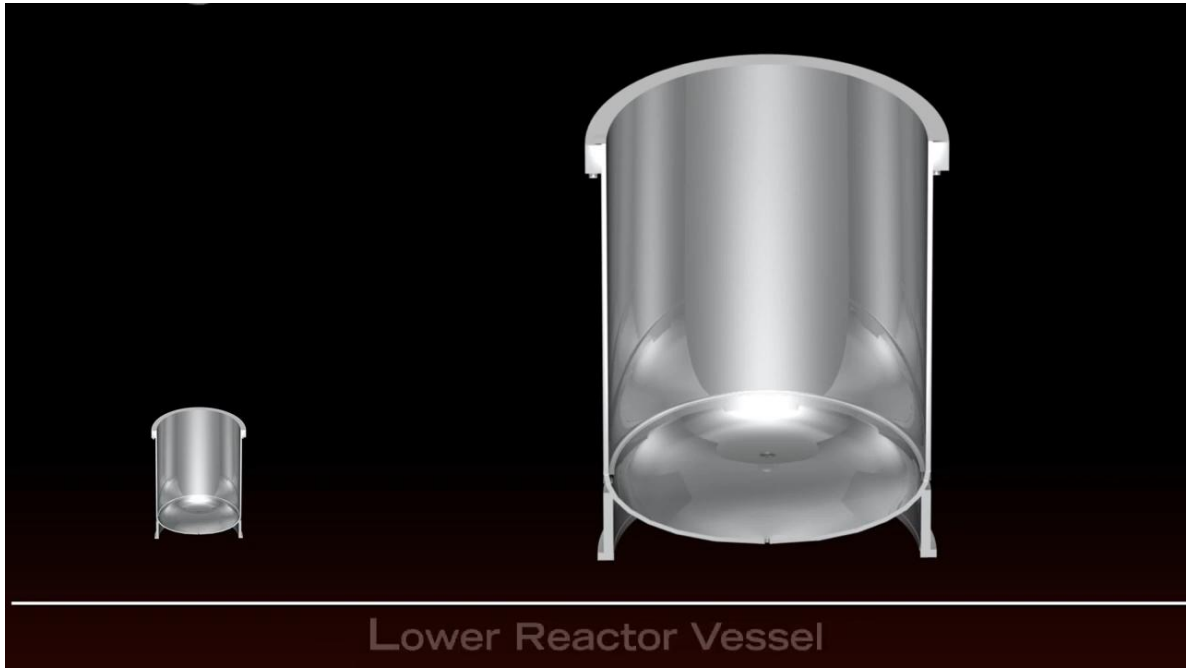
NuScale Dipilih Sebagai Contoh Untuk PWR (Fitur Keselamatan Terbaik)

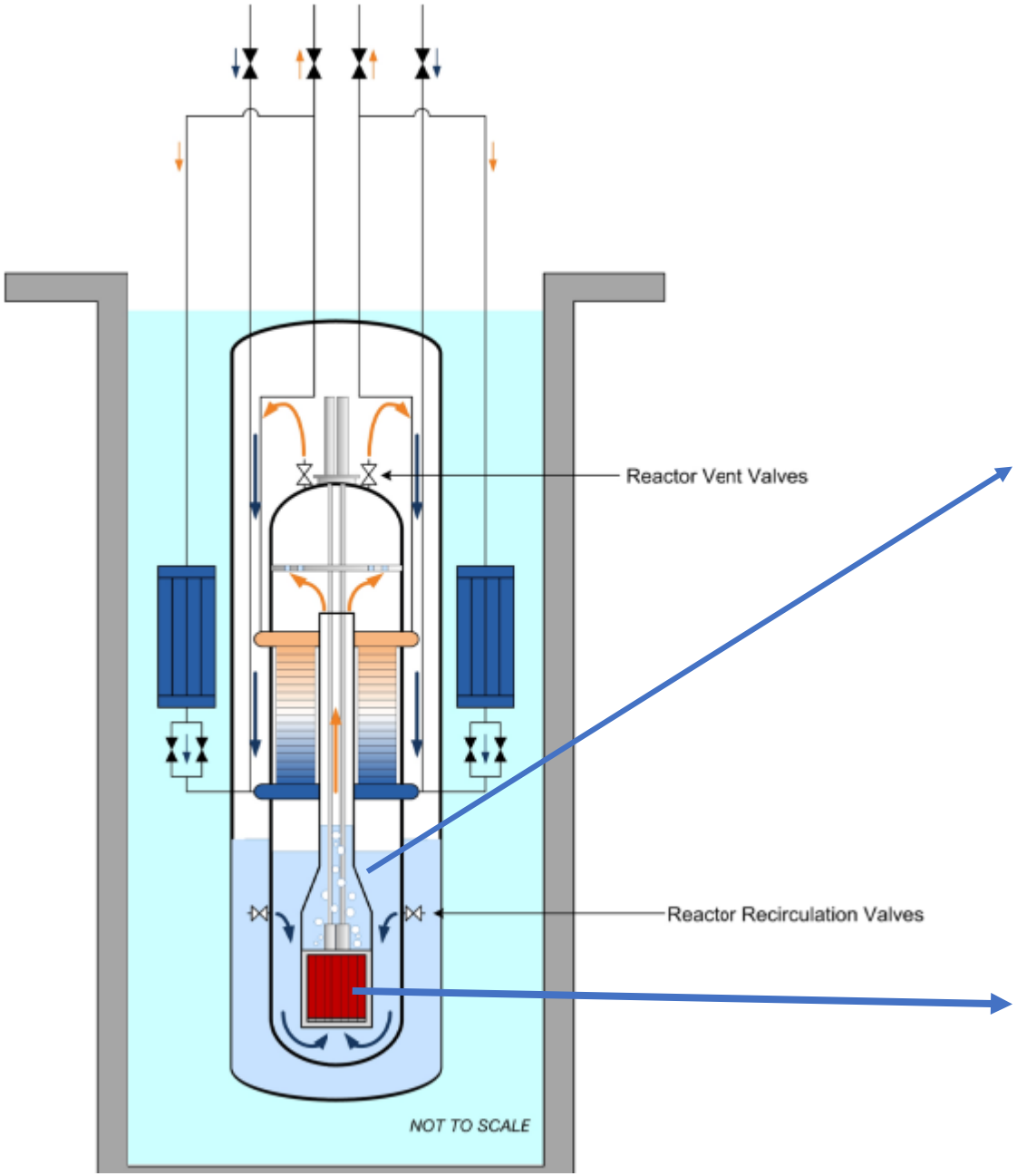


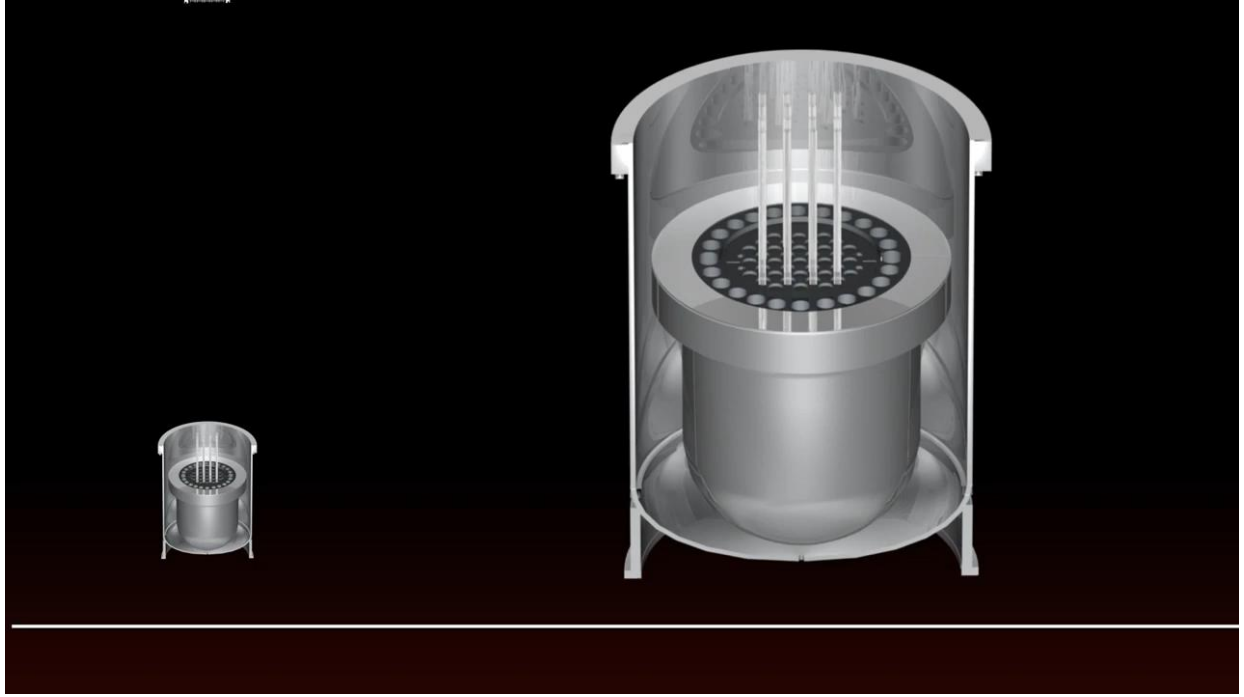
NuScale radiation and fission product barriers.

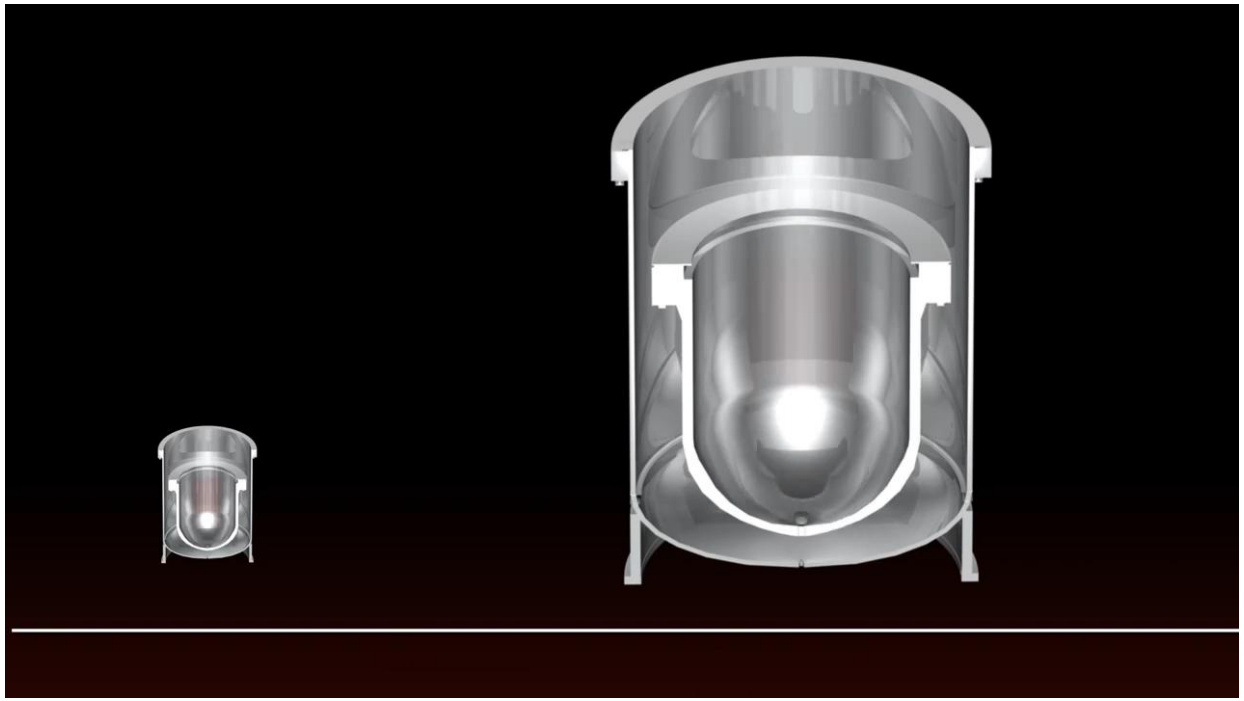
NuScale Plant Design Overview Augut 2012

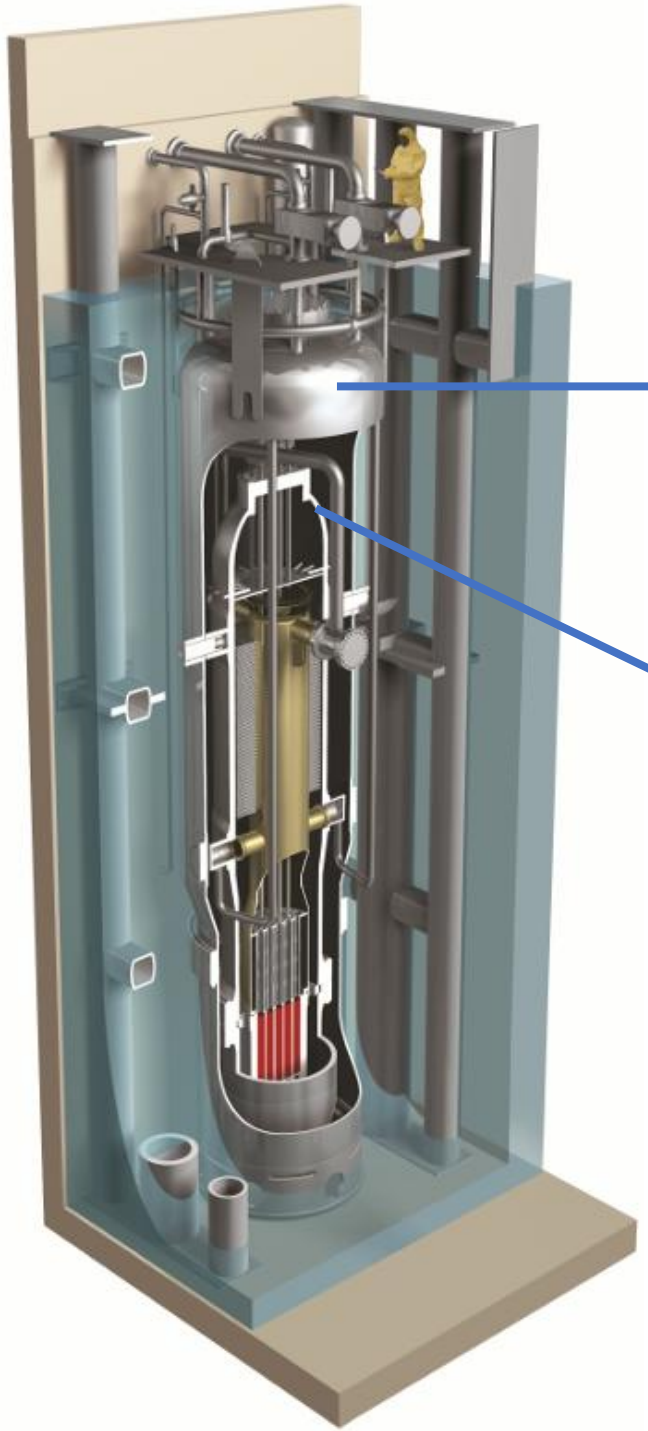


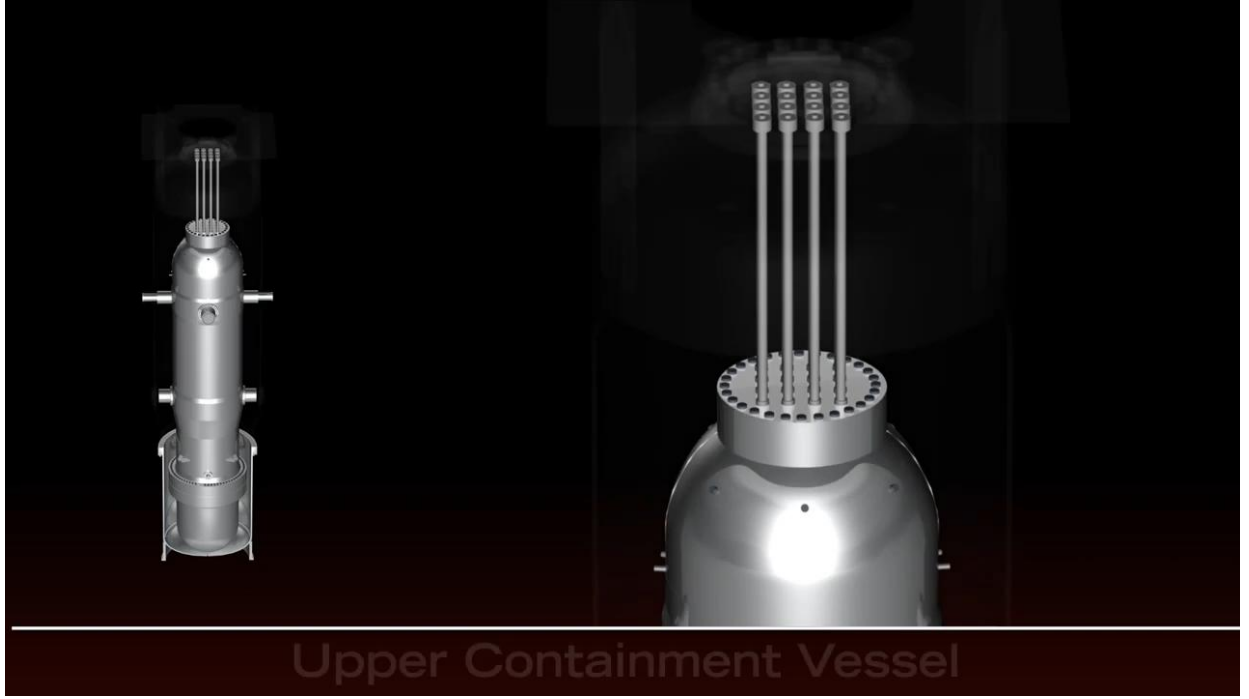


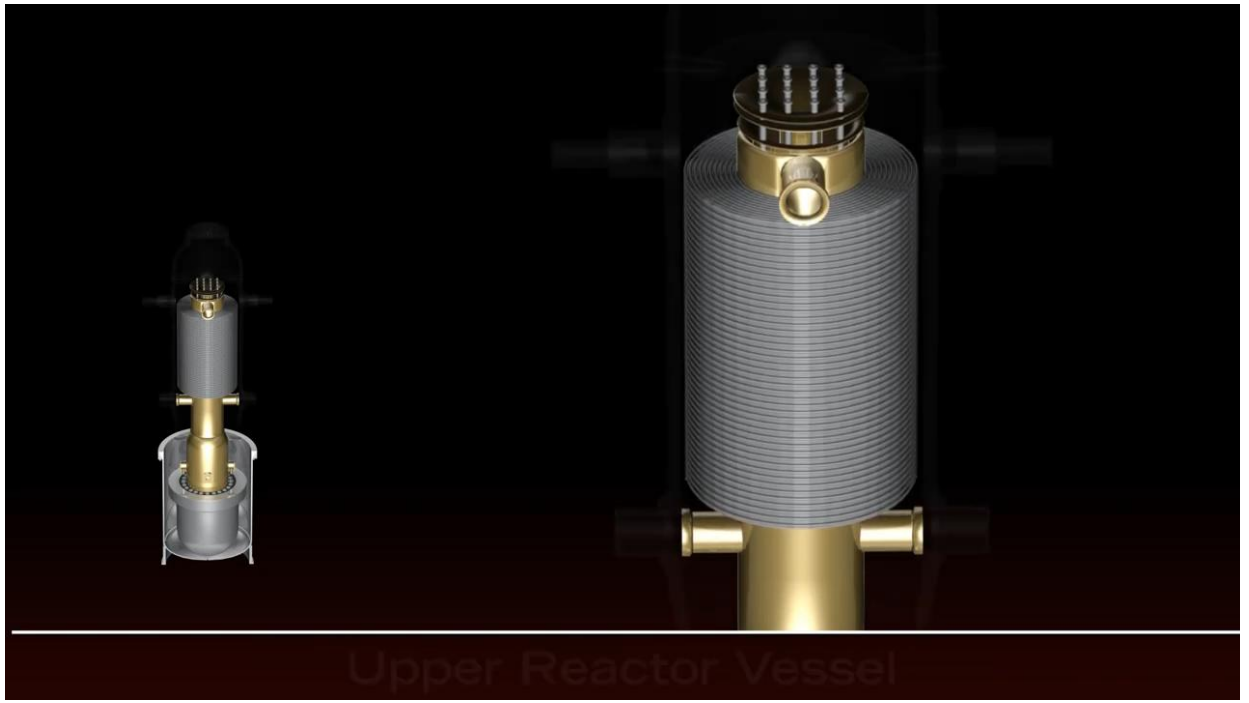

Reactor Vent Valves
Reactor Recirculation Valves
NOT TO SCALE

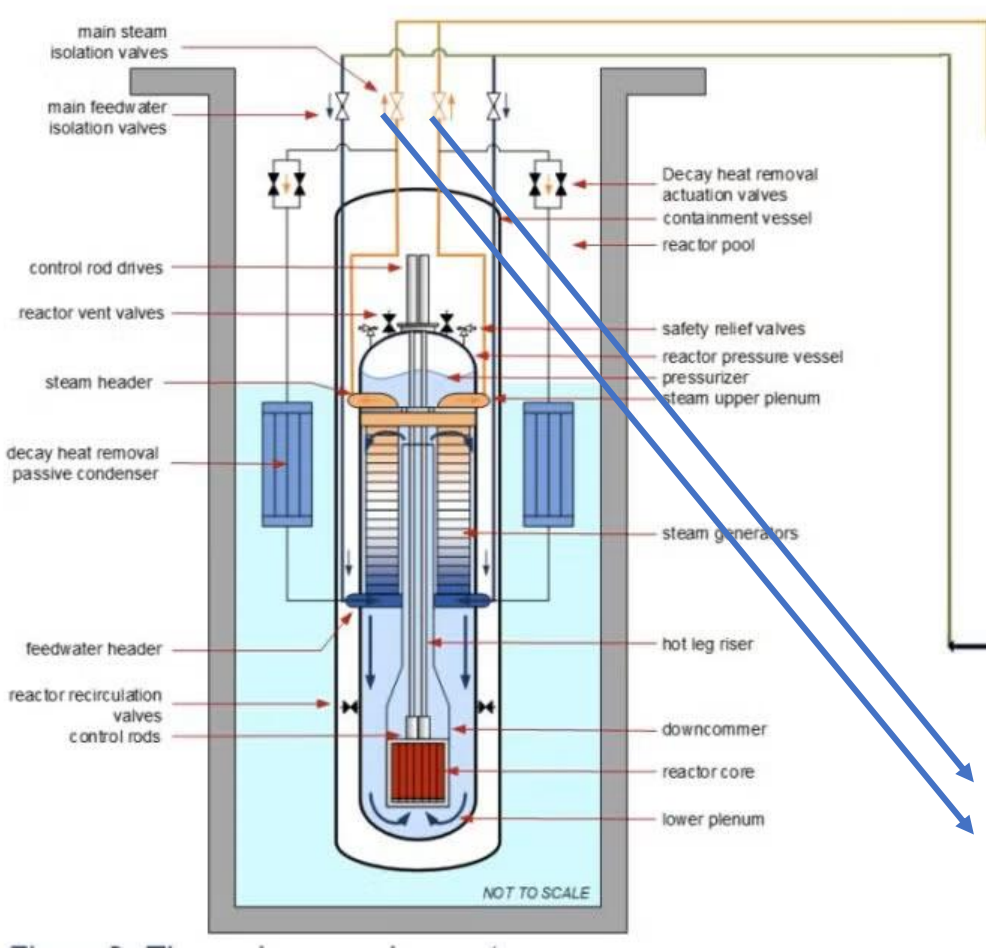


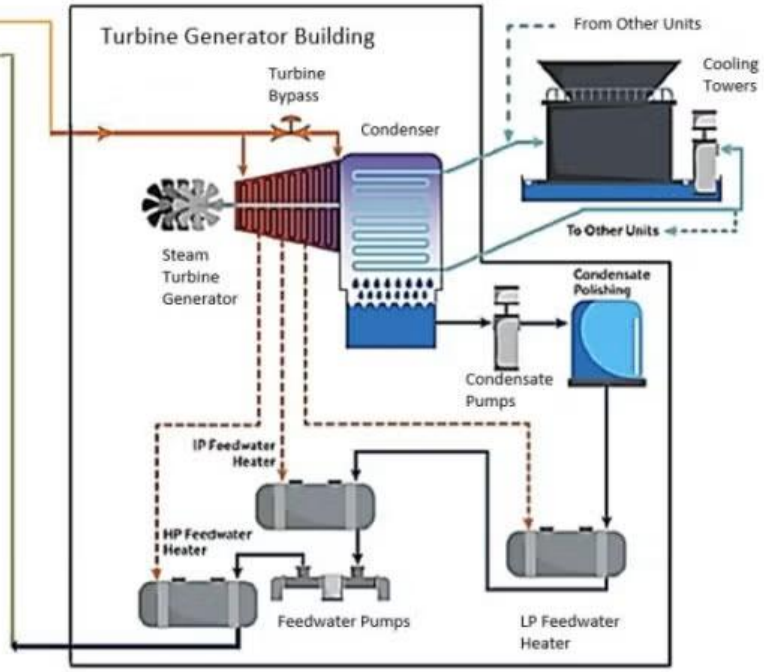


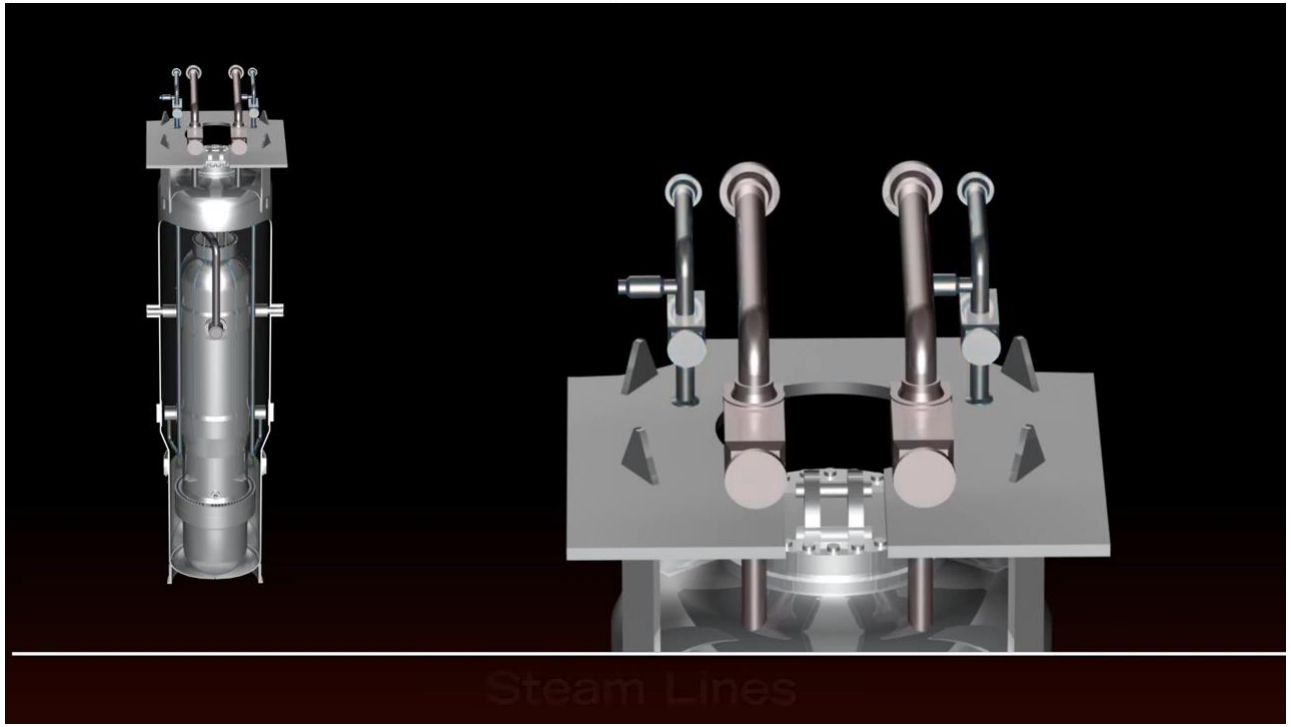


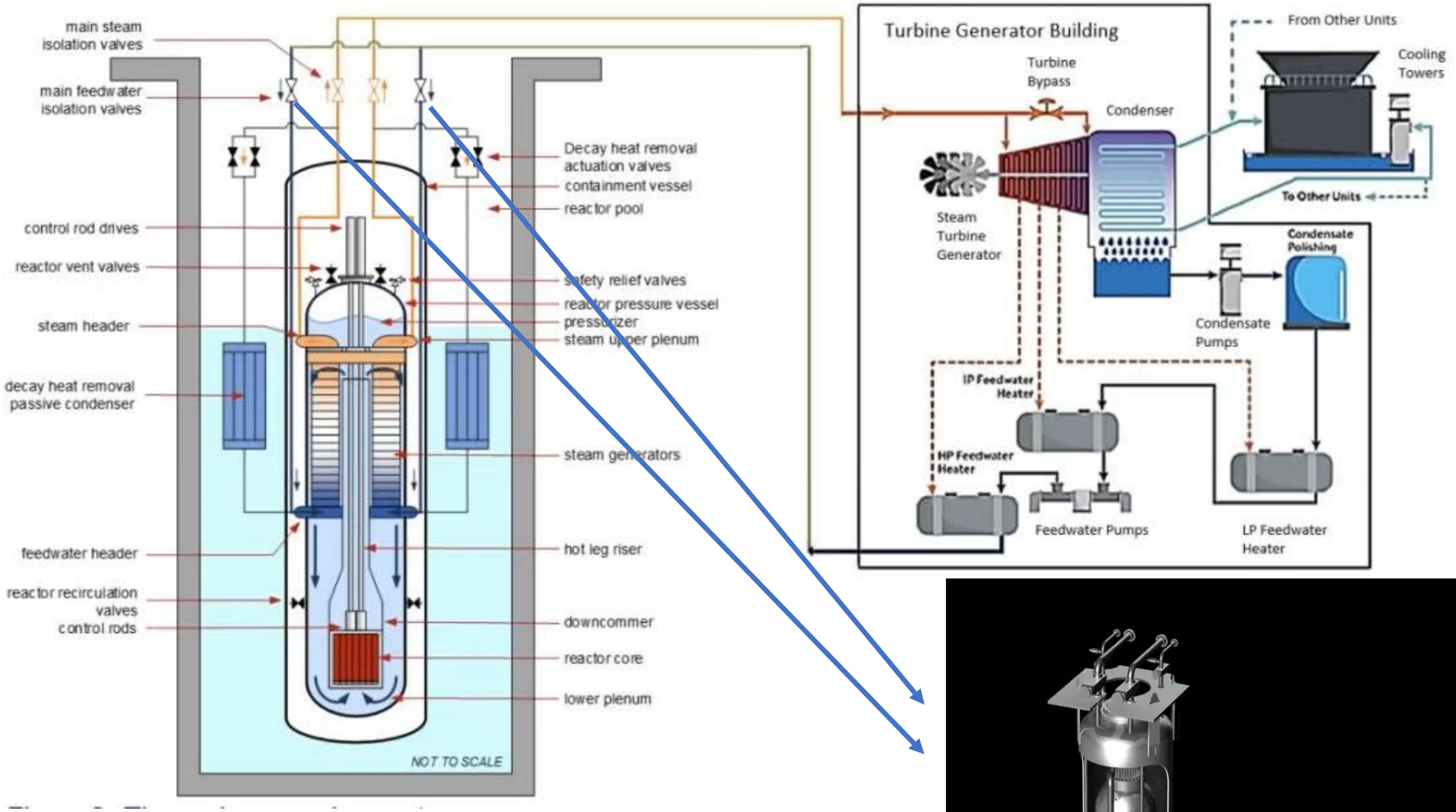

Upper Containment Vessel


Upper Reactor Vessel


main steam isolation valves
main feedwater isolation valves
Decay heat removal actuation valves
containment vessel
reactor pool
control rod drives
reactor vent valves
safety relief valves
reactor pressure vessel
steam header
pressurizer
steam upper plenum
decay heat removal passive condenser
steam generators
feedwater header
hot leg riser
reactor recirculation valves
control rods
downcommer
reactor core
lower plenum
NOT TO SCALE


Turbine Generator Building
Turbine Bypass
Condenser
From Other Units
Cooling Towers
To Other Units
Steam Turbine Generator
Condensate Polishing
Condensate Pumps
LP Feedwater Heater
HP Feedwater Heater
Feedwater Pumps
LP Feedwater Heater


Steam Lines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HP Feedwater Heater
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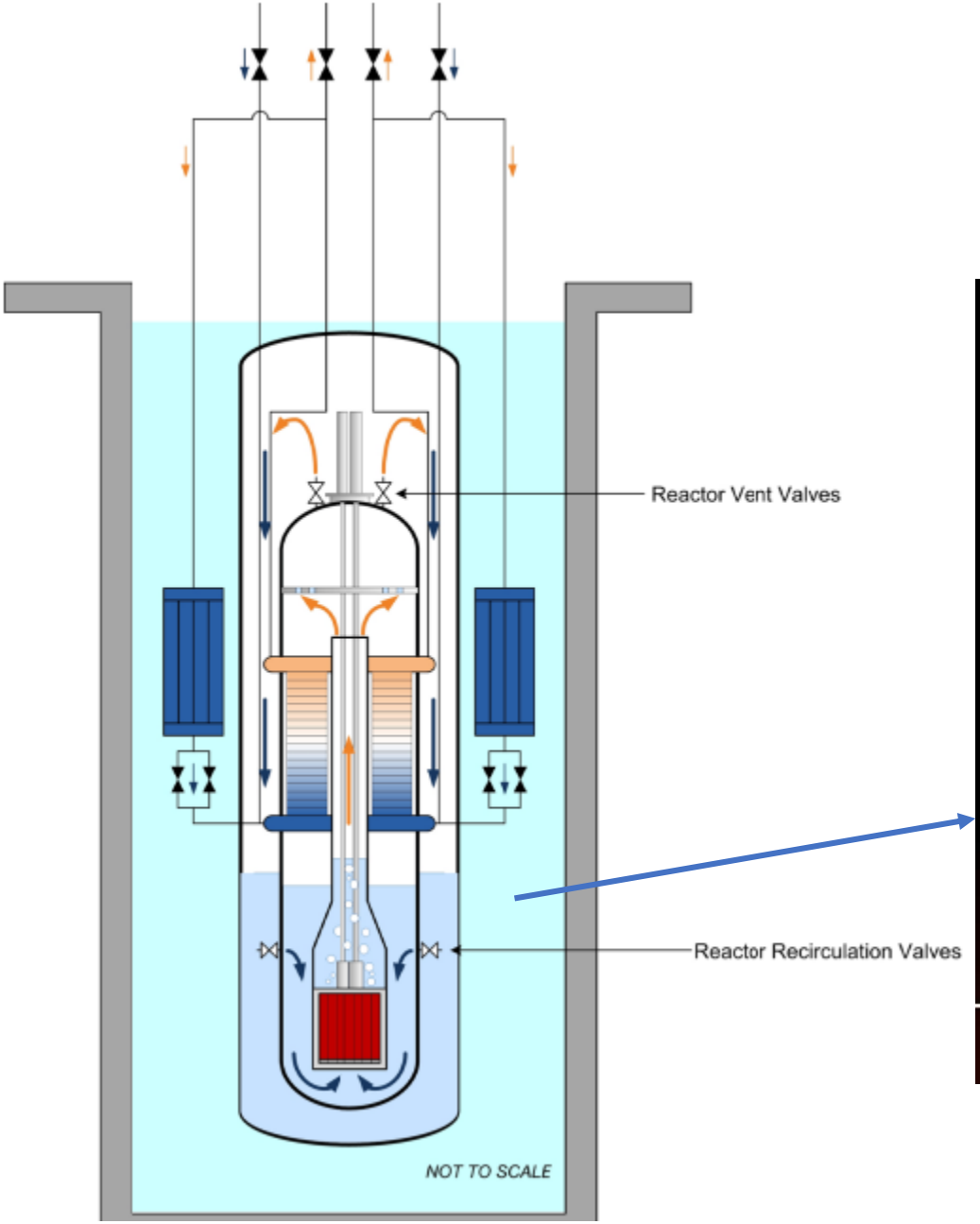
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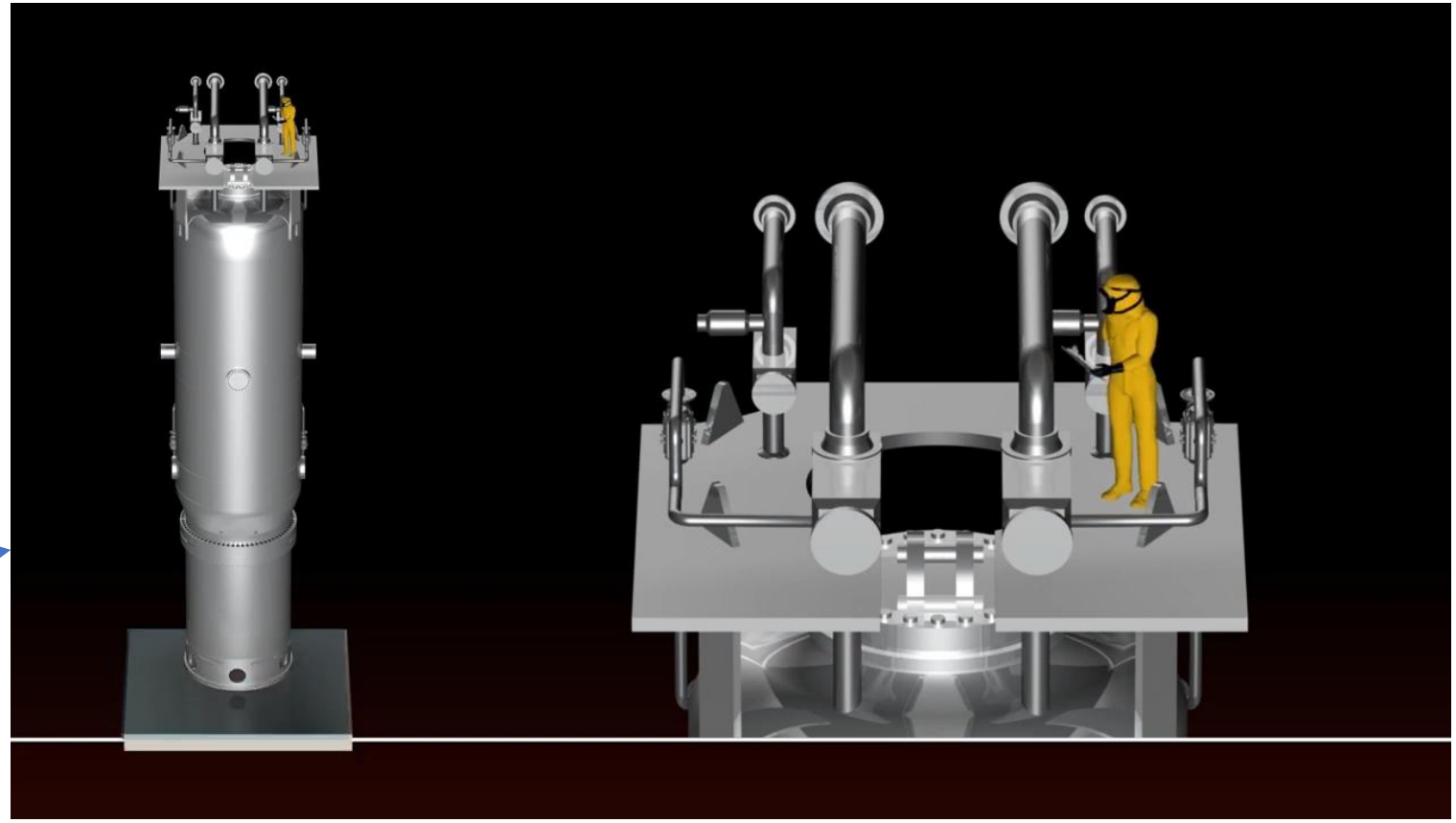


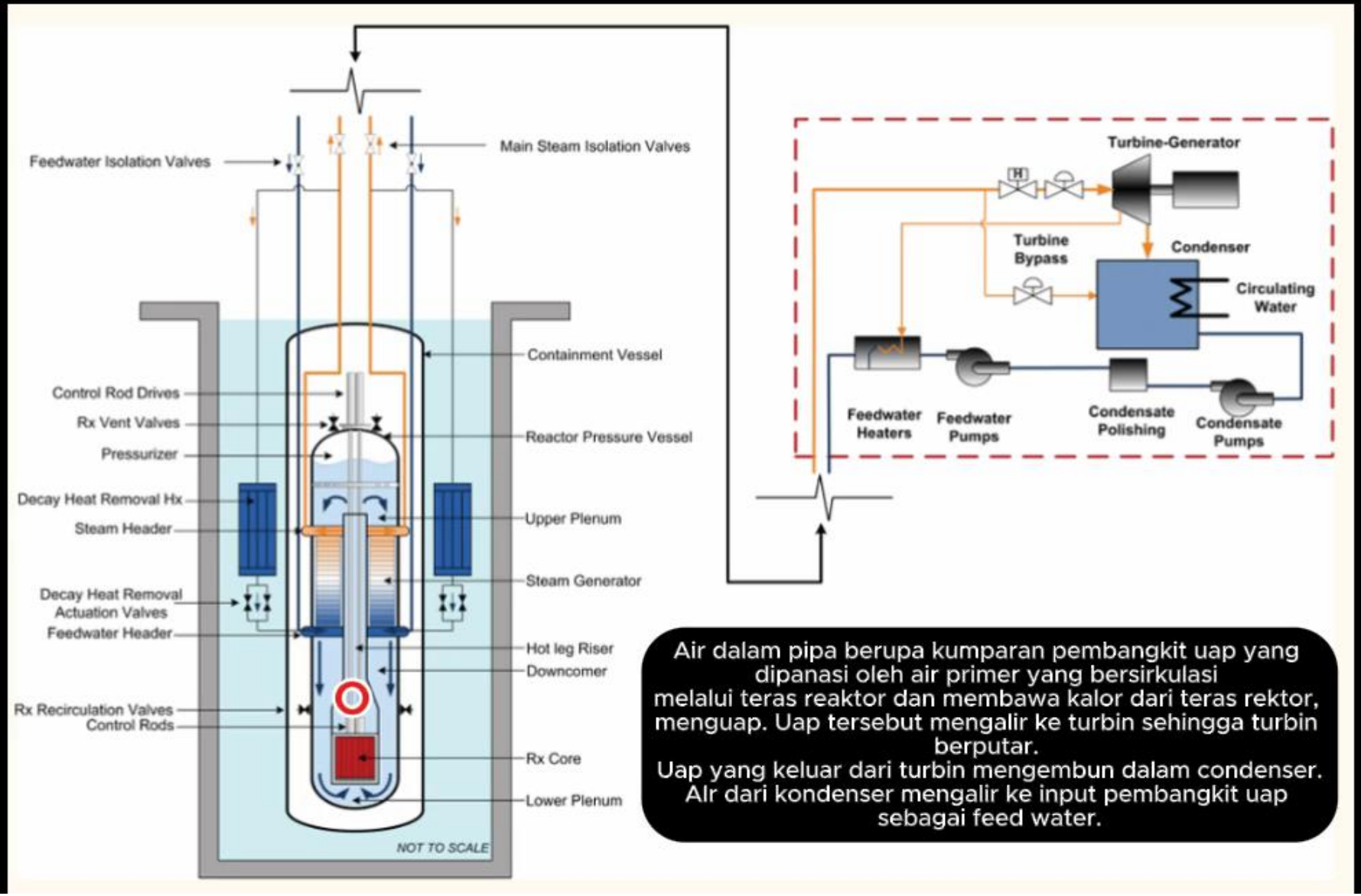
Teknik Pengambilan *Decay Heat*

NuScale

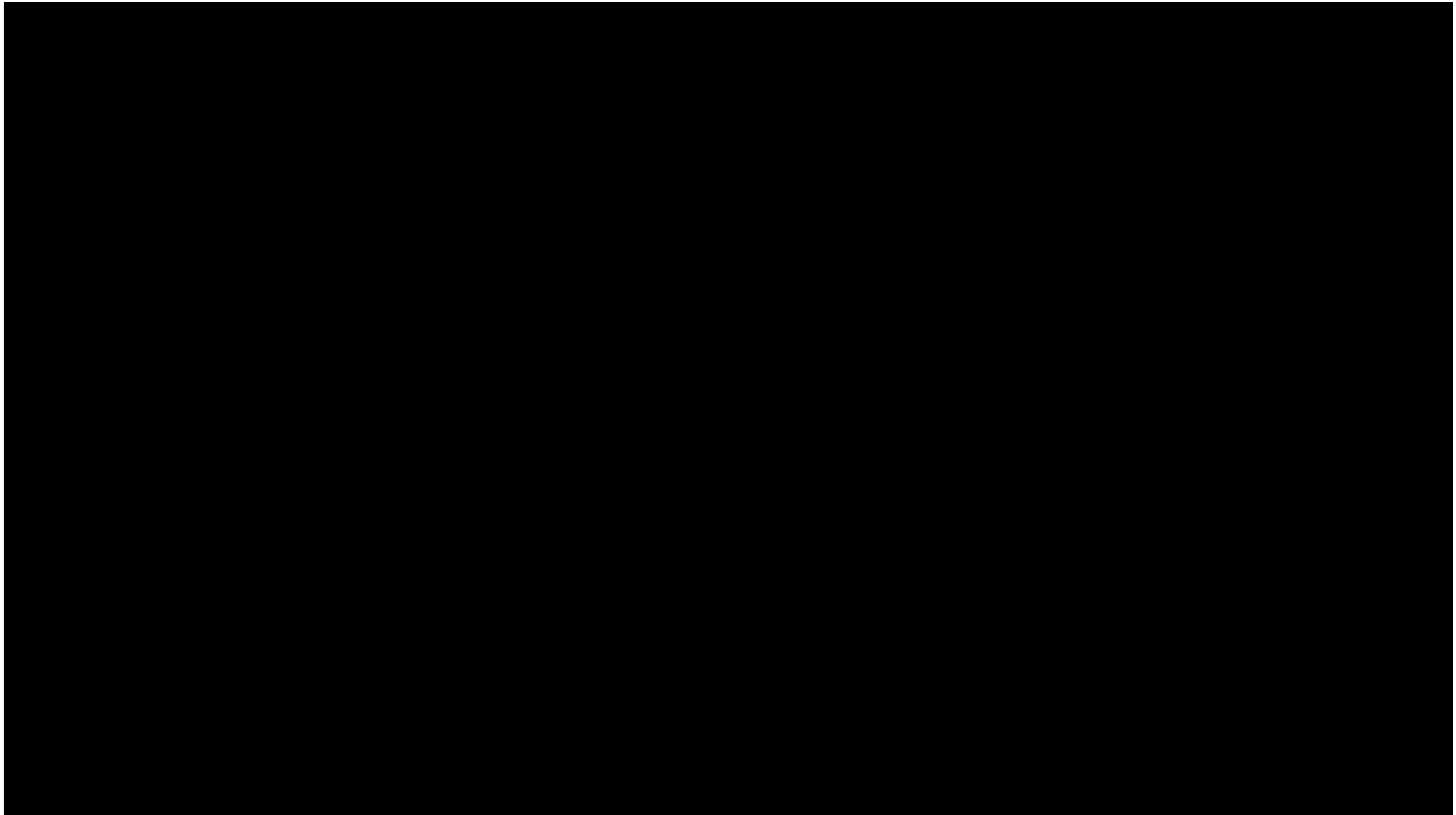
Operasi Normal

Decay Heat Removal System

Teknik Pengambilan *Decay Heat*



Emergency Core Cooling System



Melting-free High Temperature Reactor (HTR)

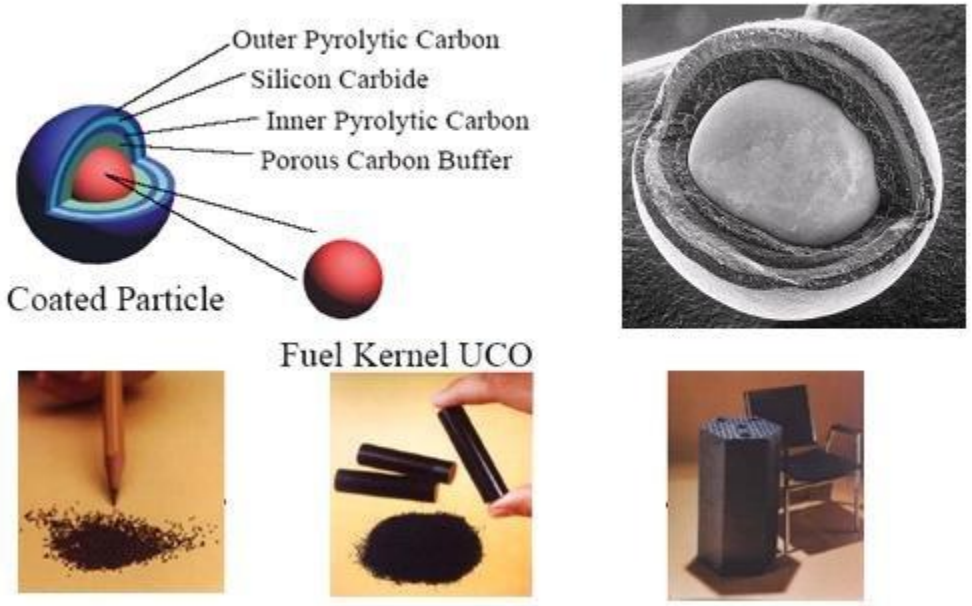
Perbandingan filosofi keselamatan

Aspek	PWR/BWR SMR (NuScale, ACP100, BWRX-300, RITM-200)	HTR-PM
Target utama	Meminimalkan Core Damage Frequency (CDF)	Praktis menghilangkan kemungkinan core melting
Pendinginan	Air bertekanan / air mendidih	Helium
Batas keselamatan	Cladding tidak meleleh, integritas teras dipertahankan	Temperatur TRISO tetap di bawah batas kegagalan
Filosofi	Prevention + mitigation	Inherent safety + practical elimination

- **Optimasi geometri reactor core:** memastikan **temperatur maksimum bahan bakar TRISO, lapisan SiC, grafit moderator, dan struktur lainnya selalu berada di bawah temperatur batas kerusakan,** bahkan pada kondisi kecelakaan seperti **Loss of Forced Cooling (LOFC)** atau **Depressurized Loss of Forced Cooling (DLOFC)**.

- **TRISO coated particle fuel**

TRIstructural ISOtropic (TRISO) Fuel



Batas temperatur SiC

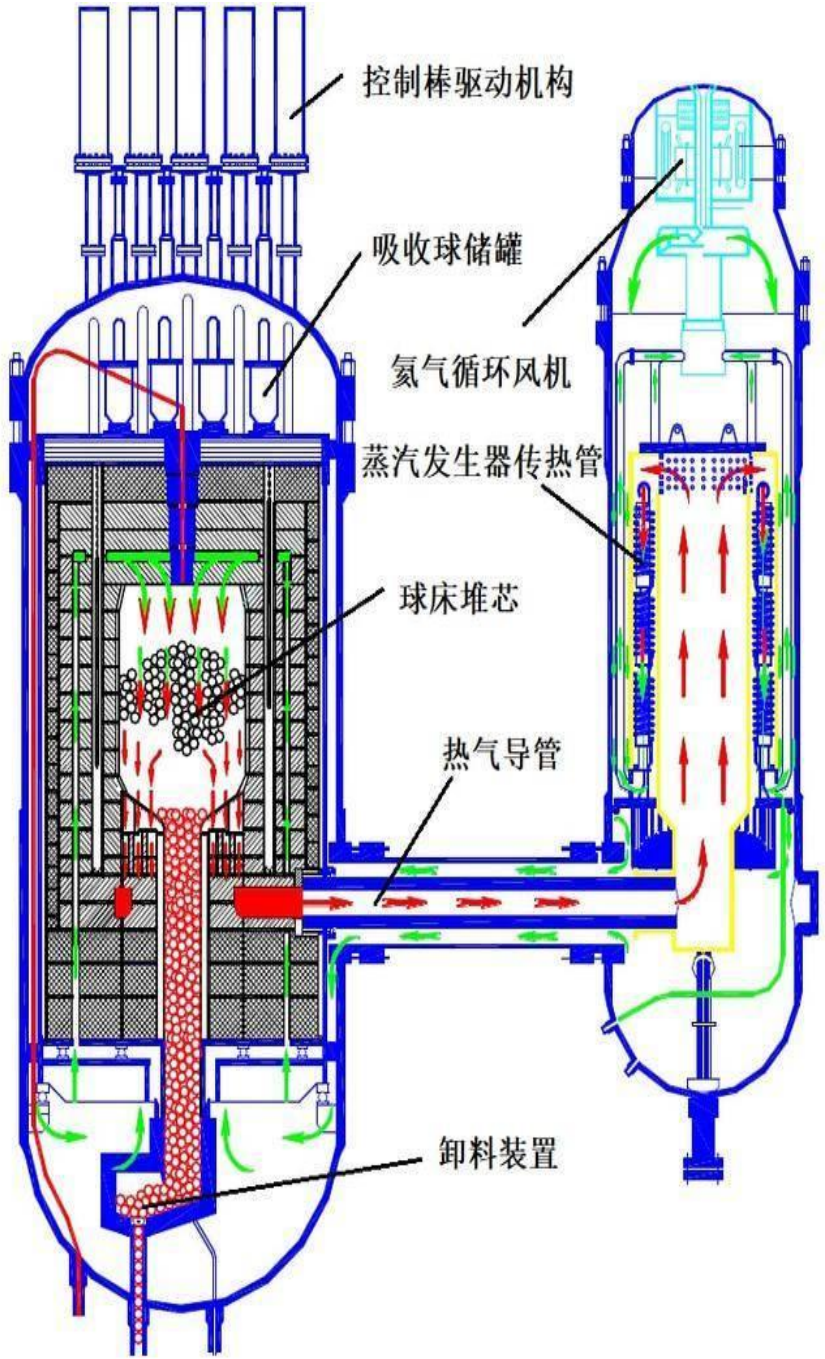
Parameter	Nilai
Operasi normal	900–1200°C
Target maksimum operasi	<1250°C
Mulai terjadi degradasi creep	1400–1500°C
Kerusakan signifikan	1600°C
Kegagalan serius	>1700°C

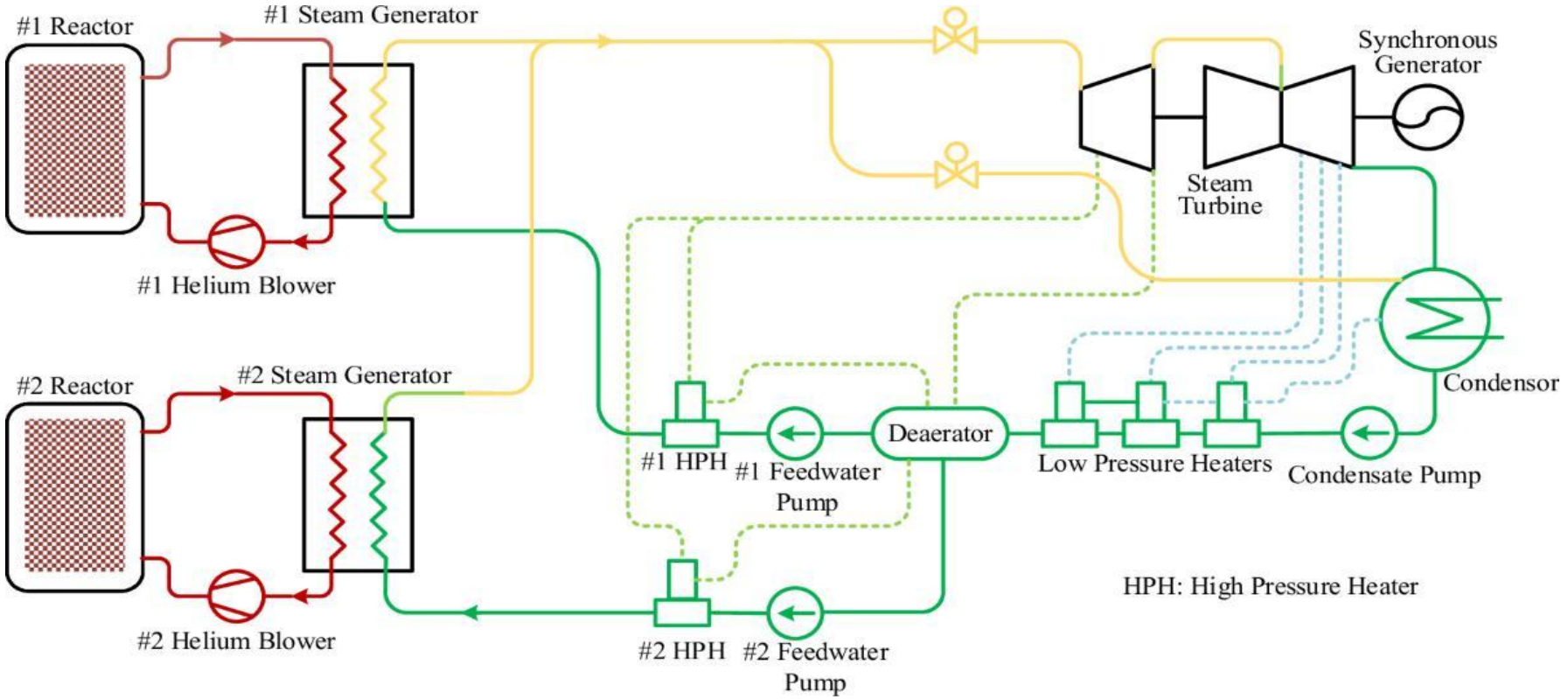
Eksperimen yang telah dilakukan di AVR

Bidang	Eksperimen	Kontribusi
Fuel	Uji berbagai jenis TRISO/BISO	Kualifikasi bahan bakar
Termal	Operasi hingga ~950–990°C	Data temperatur tinggi
Keselamatan	Loss of Forced Cooling	Demonstrasi keselamatan inheren
Keselamatan	DLOFC (Depressurized Loss of Forced Cooling)	Validasi pendinginan pasif
Operasi	Continuous refuelling	Optimasi manajemen bahan bakar
Material	Grafit	Perilaku material suhu tinggi
Produk fisi	Transport & deposisi	Estimasi source term

Reactor

China – HTR-PM





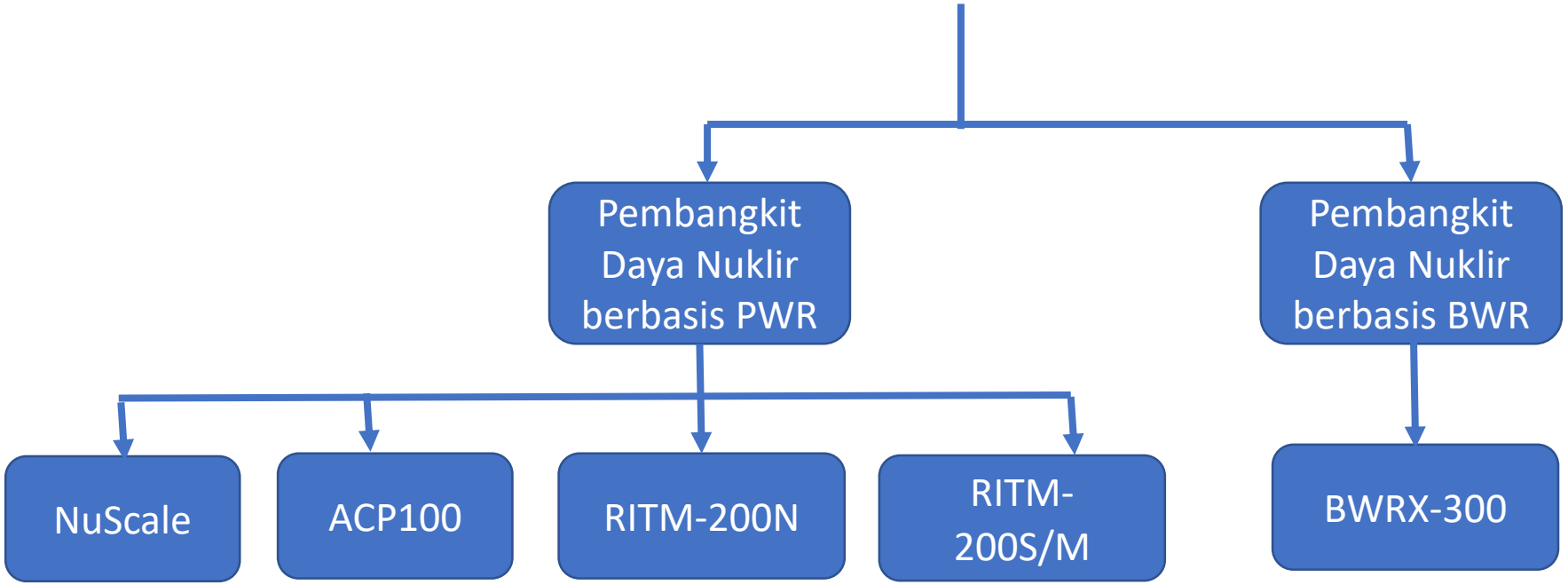
HTR-PM terdiri atas:

- 2 modul reaktor masing-masing **250 MWth**
- 1 turbin uap bersama
- Daya listrik sekitar **210 MWe**
- Pendingin helium
- Moderator grafit

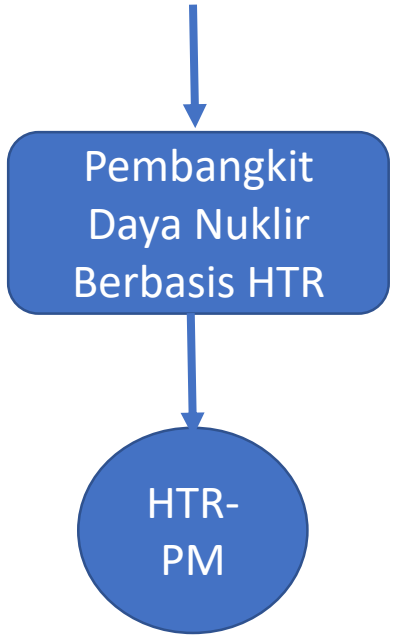
Bahan bakar pebble berisi partikel TRISO.

KESIMPULAN

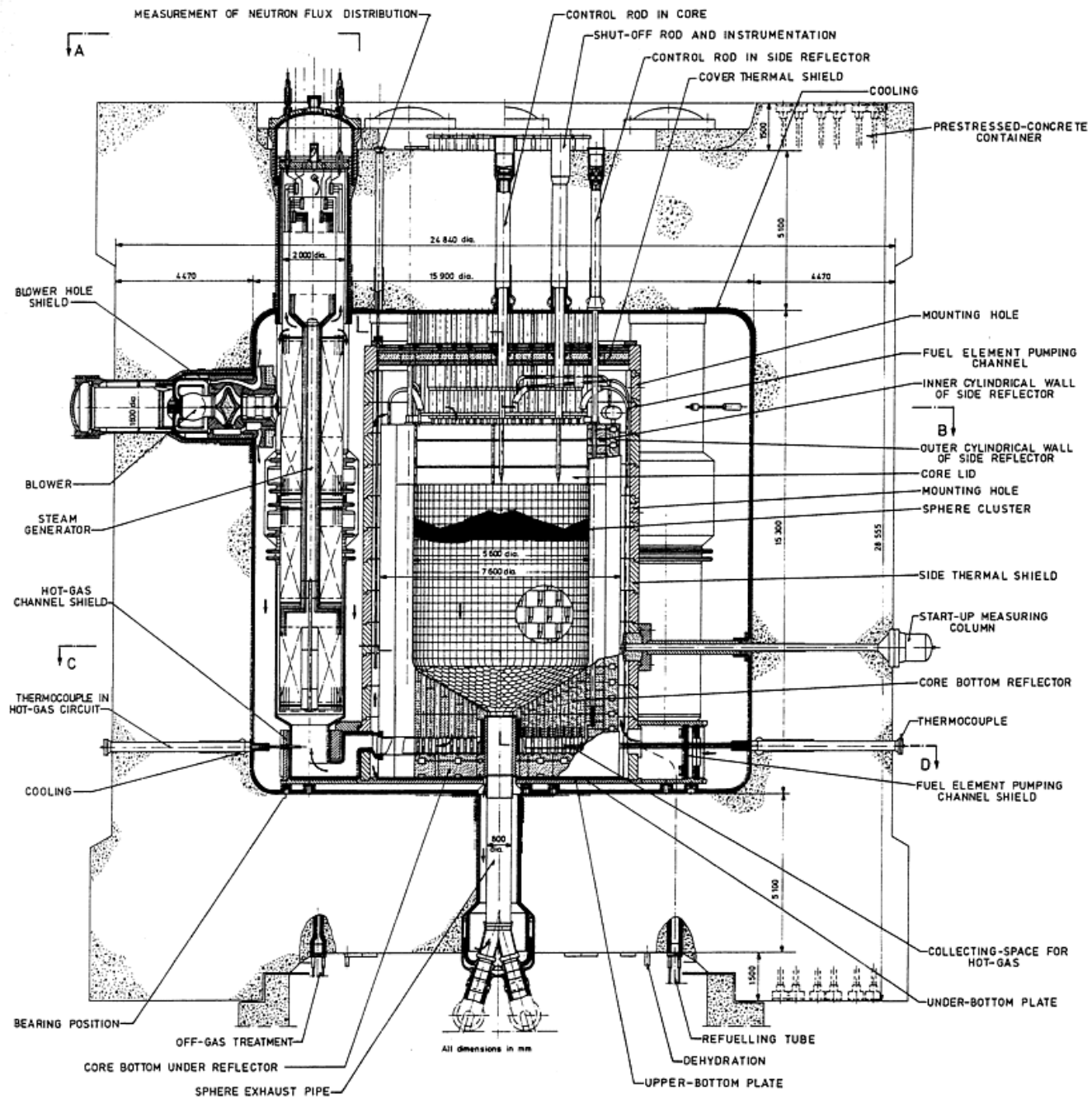
Kombinasi **inherent safety** (koefisien reaktivitas negatif) dan **engineered safety features** (ECCS, containment, sistem pasif, dsb.). Pengalaman operasional puluhan tahun memberikan basis data yang sangat besar untuk validasi desain dan peningkatan keselamatan.



Keselamatan terbaik dicapai dengan desain berbasis **karakteristik fisik** untuk membatasi konsekuensi kecelakaan



Peluang Kandungan Lokal HTR



VERTICAL SECTION E-F REACTOR THTR-300

図５－２　THTR-300炉の原子炉垂直断面図