D.E. Carlson
25.07.01

Examples of Safety Assessment

Gerhard Vogel

REACTOR PHYSICS

- Shutdown Margins
- Reactivity Feedback, Inherent Safety
- Power Density Distribution (Design and Control)

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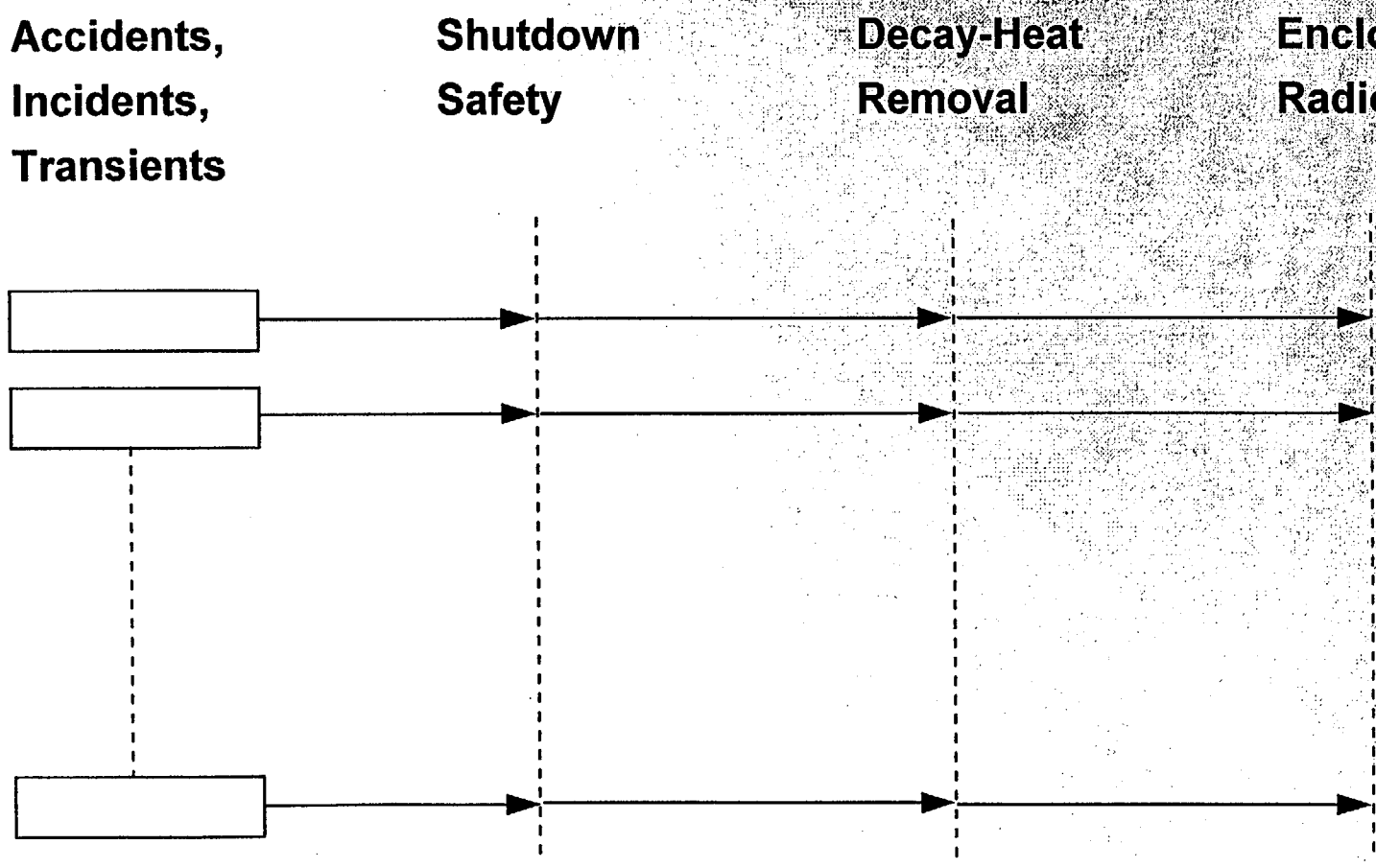
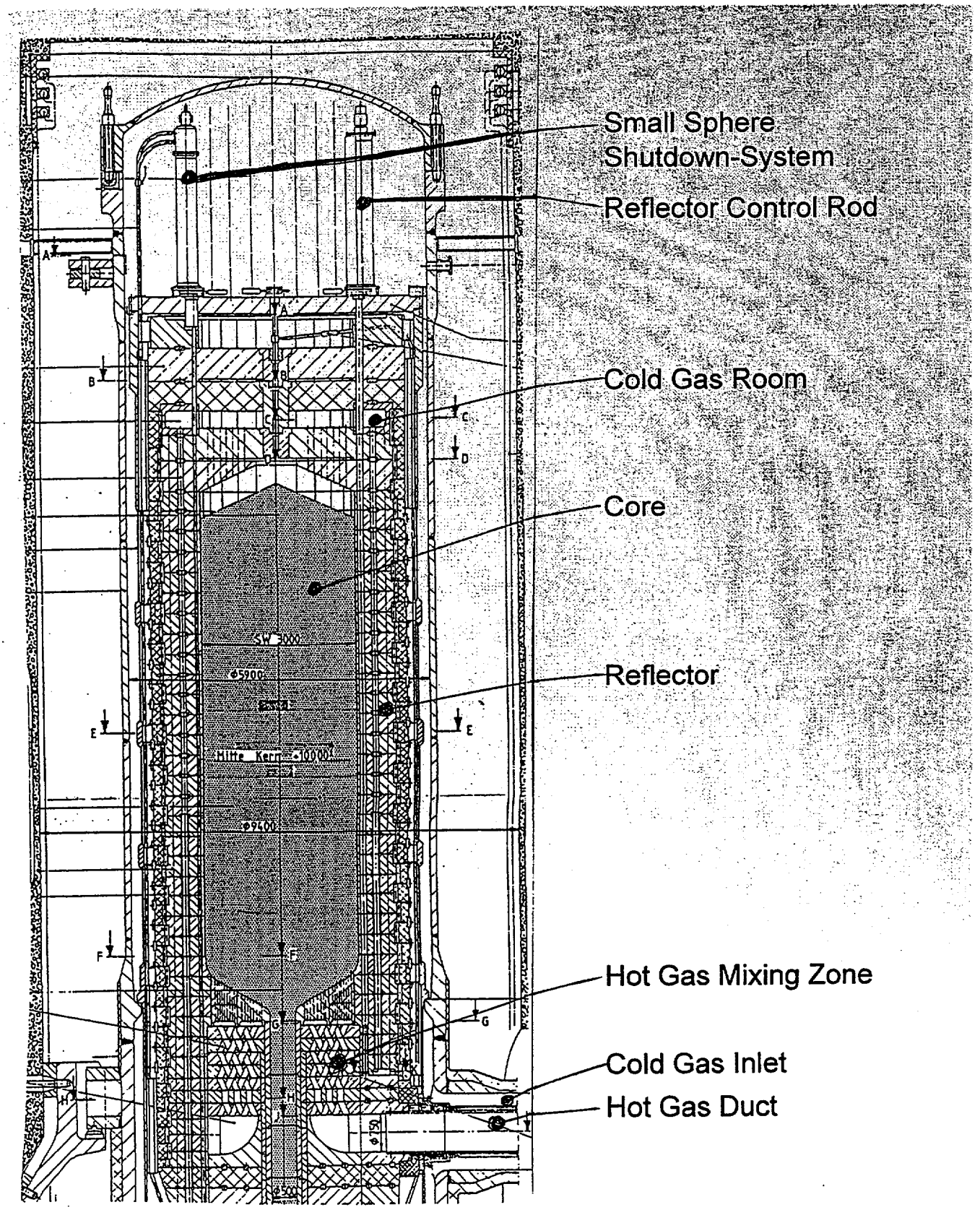
D-28

Design of Plant, Core and Fuel





Modular HTR-2 NPP, Reactor Physics

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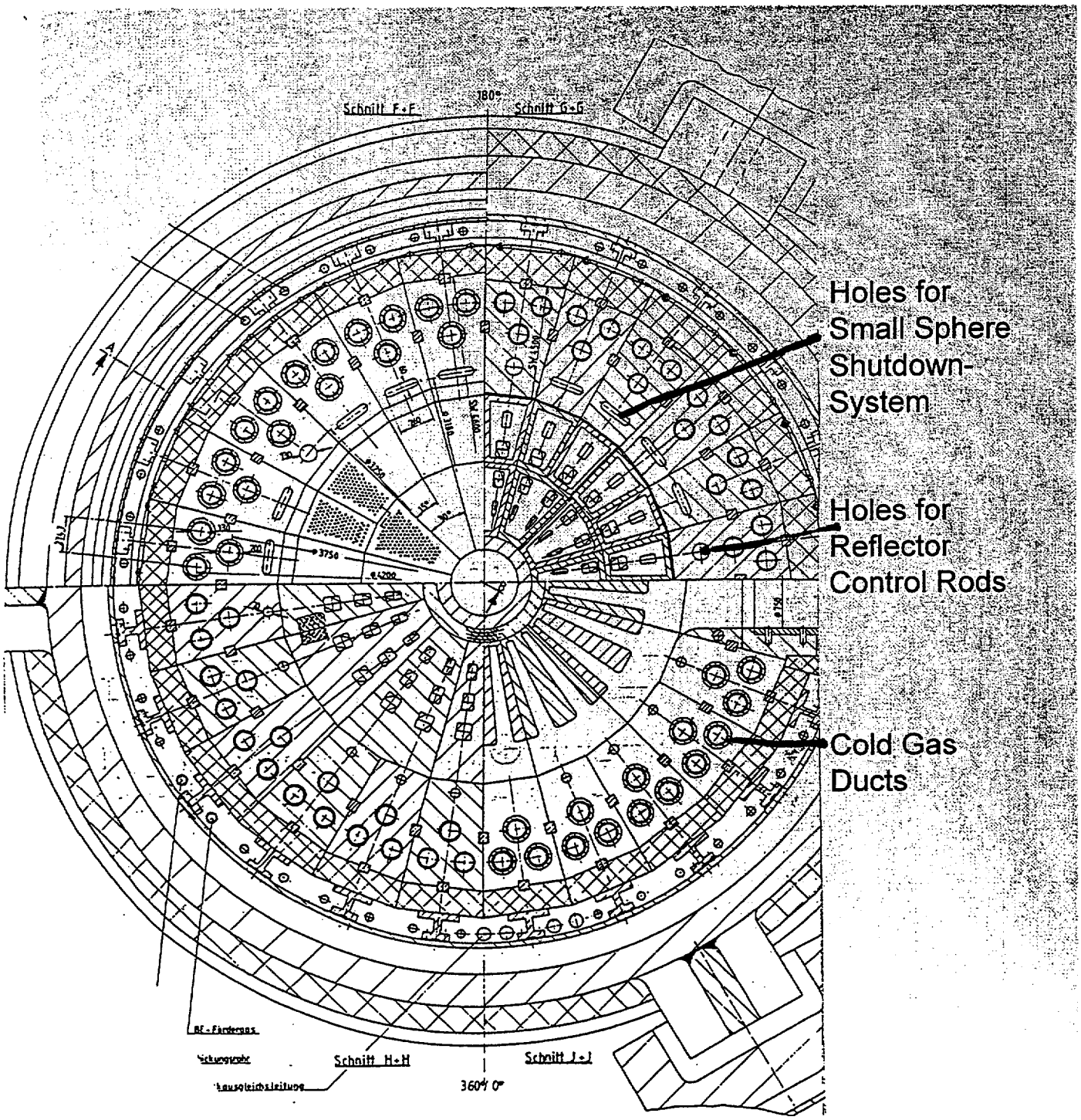

Modular HTR-2 NPP, Reactor Physics

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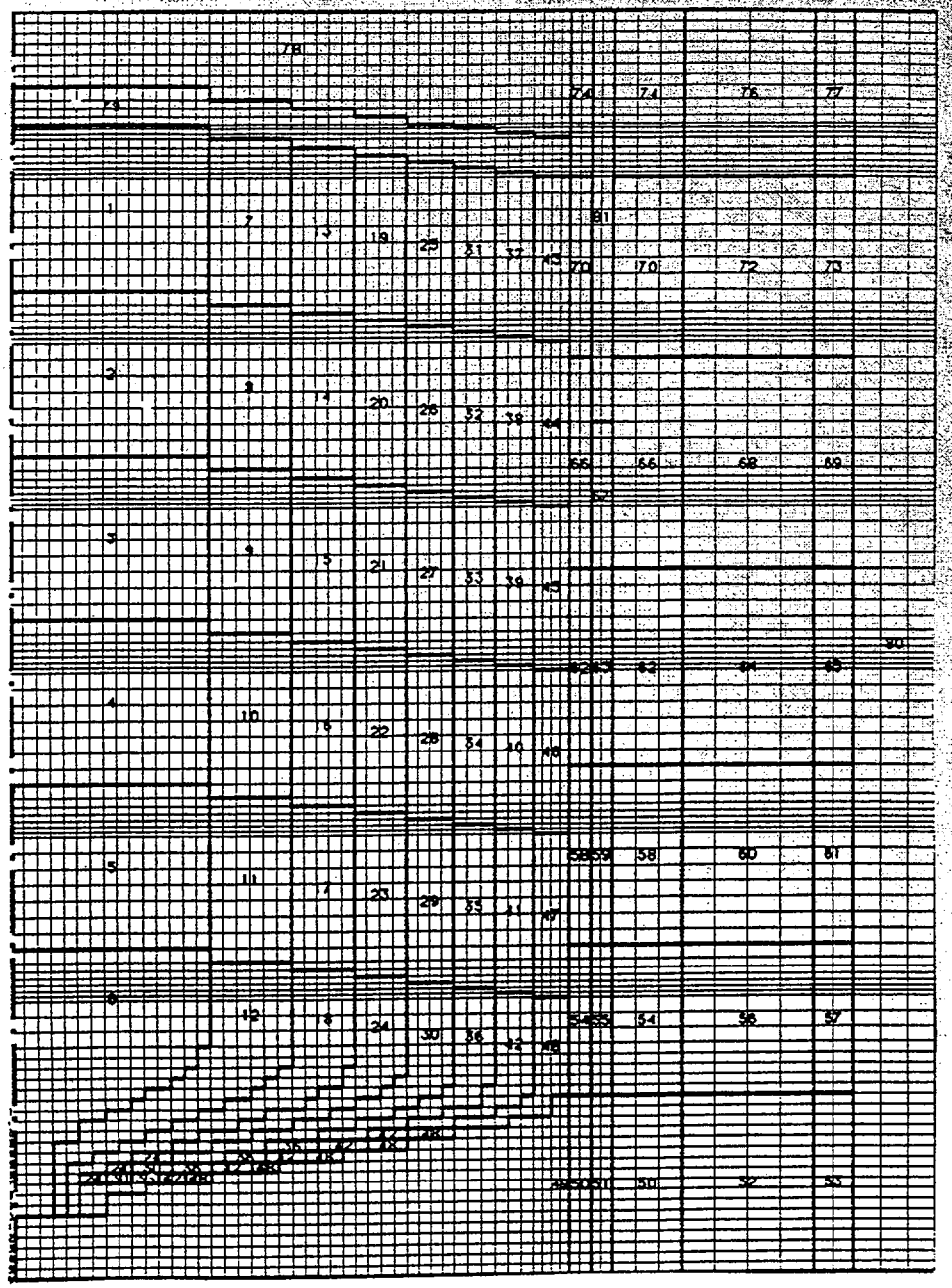
Scheme of Reactor Physics Calculation V.S.O.P (Very Superior Old Programs)

Name of the Program	Application	Result
GAM/THERMOS ZUT-DGL	Spectral-Calculation	Cross-Section of Core- and Reflector Regions
CITATION	Diffusion-Calculation	Multiplication-Factor, Power Density Map
FEVER	Burnup-Calculation	Nuclide-Densities
THERMIX	Temperature-Calculation	Temperatures of: - Fuel (UO_2) - Core-Graphite - Reflector-Graphite in all Regions

Model in R/Z-Geometry



For Example:

48 Core-Zones

(Burnup-Zones)

Calculation of Shut-Down-Margins

Rules
Largely LWR-based

BMI-Kriterium 5.3

RSK-LL, 3.1.2, 22.1.1

KTA 3104

KTA 3103

KTA 3101.2

IAEA Safety Standards

IAEA Safety Guides

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Filter for HTR-Design

Additional Aspects of HTR-Design

Definition of design-basis-accident, incident and normal operation conditions

Calculation of Shut-Down-Margins Results

Starting Core (BOC) Reactivity Balance Hot Shut Down

Control Reserve 100-90-100 %	+ 0,2 %
Reactivity Compensation for Partial Power (Xenon, Temperature)	+ 0,6 %
Accidental Reactivity Increase	+ 0,5 %
Partial Power - Zero Power	+ 0,1 %
Efficiency of 5 of 6 Rods	- 3,4 %
	- 2,0 %

- lower enrichment?
- graphite pebbles?
- lower heavy metal?

"Don't recall" – Vogel

Steady State Core Reactivity Balance Hot Shot Down

Control Reserve 100-50-100 %	+ 1,2 %
Reactivity Compensation for Partial Power (Xenon, Temperature)	+ 0,4 %
Accidental Reactiviy Increase	+ 0,5 %
Partial Power - Zero Power	+ 0,1 %
Efficiency of 5 of 6 Rods	- 2,6 %
	- 0,4 %

Filter for and Additional Aspects of HTR-Design (Shutdown Safety)

Event, Effect	PWR	HTR	
Rod ejection	yes	no	
Uncontrolled rod withdraw	yes	yes	
Boron dilution	yes	no	Max in core is 600 kg
Water ingress	yes	(no)	Reactor Protection System
Uncontrolled fuel addition	no	yes	
Collapsing of holes in the core	no	yes	
Loss of Collant Accident	yes	yes	
Loss of Flow Event	yes	(no)	
Rod drop with reactivity gain	no	yes	
Core densification	(no)	yes	
Boron-loss by earthquake	yes	no	
Burn out of poison in structural materials	no	yes	
Uncontrolled cooling of the core	yes	yes	
Temperature increase of the reflector	no	(yes)	
Error in excess reactivity	(no)	yes	
ATWS	yes	yes	
Changes of reflector geometry	no	yes	
Burn out of reacitivity control devices	yes	yes	
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Inherent Safety

Rules

BMI-Kriterium 3.2

RSK LL, 3.2

DIN 25405

KTA 3101.2

IAEA Safety Standards

IAEA Safety Guides

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HTR-Design-Filter and Additional Aspects of HTR-Design

- Negative Temperatur-Coefficient
- Negative Power-Coefficient
- Accidental Reactivity Increase limited so that the reactor can be shut down and temperature of the fuel elements remaining below a specified value

Temperature Coefficient of the fuel: Negative

Temperature Coefficient of the fuel-graphite: Slightly negative, a small positive value at Xenon-maximum

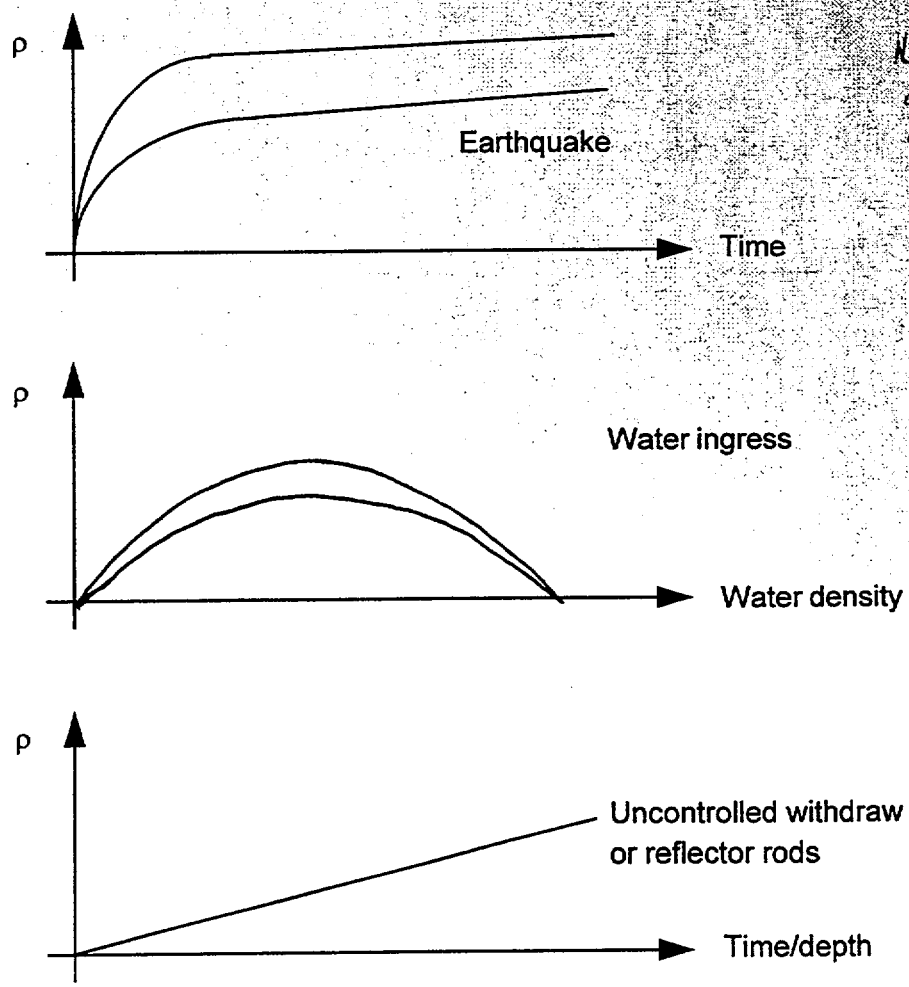
Temperature Coefficient of the reflector: Slightly positive

⇒ Inherent Safety confirmed

Inherent Safety

Search for possibilities of accidental increase of reactivity

- Core densification by earthquake
- Water ingress into the core
- Uncontrolled withdraw of reflector rods

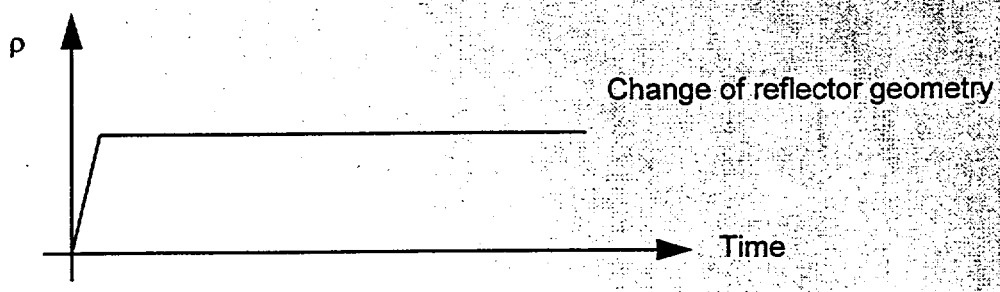


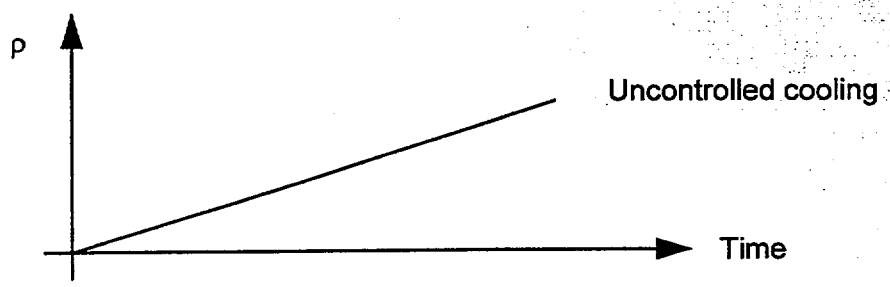
Height reduced - away from control rods

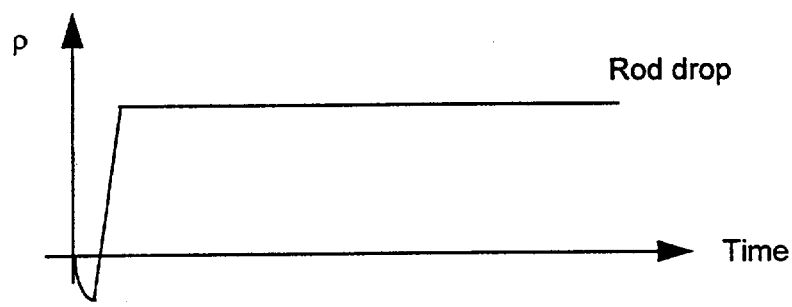
Inherent Safety

Search for possibilities of accidental increase of reactivity

- Change of reflector geometrie
- Uncontrolled cooling of the core
- Rod drop



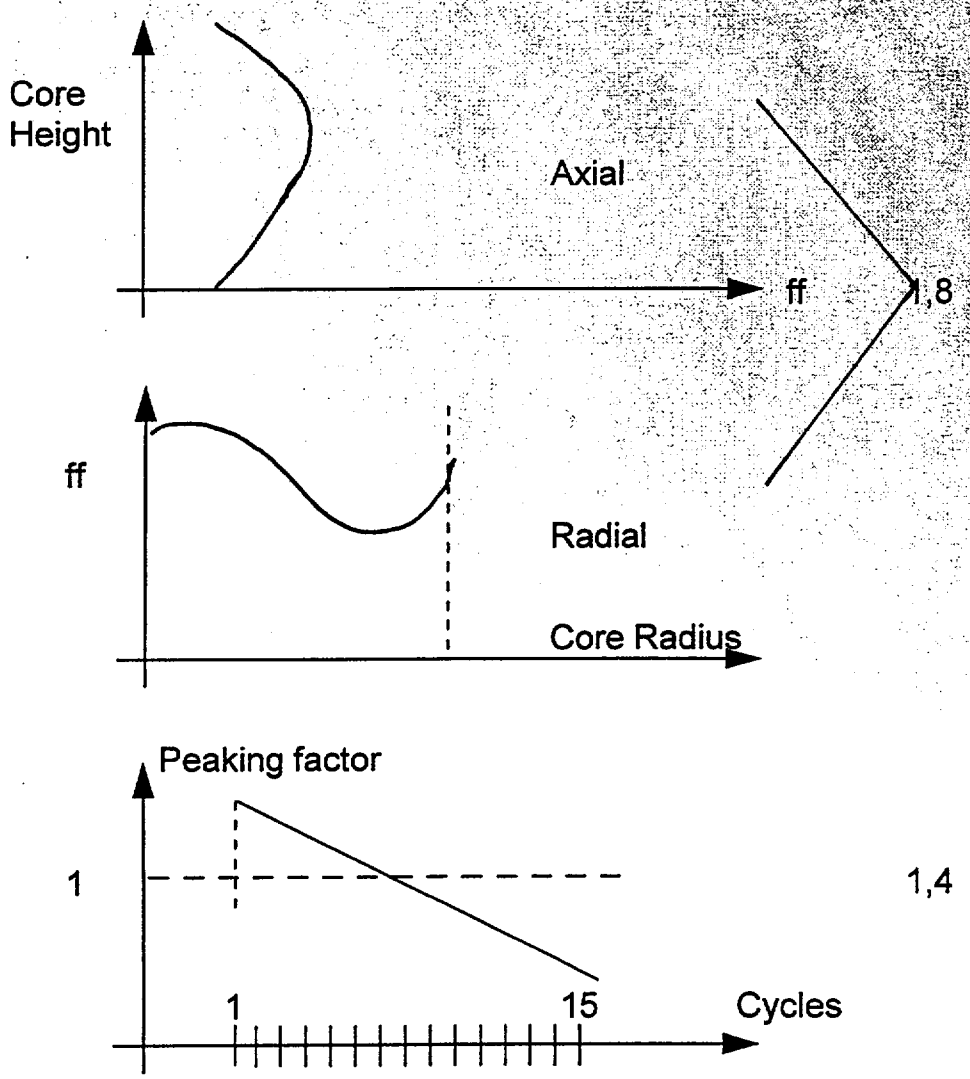




Power Density Distribution

Characterized by three formfactors:

- Axial formfactor
- Radial formfactor
- Peaking factor for fresh fuel element



Power Density distribution

During operation the power density distribution is kept in a proper shape by:

- Reactor Physics calculation,
- Measuring the depth of the reflector rods and by adjusting the rods to the same depth,
- Measuring the height of the columns of the small sphere shutdown system and by adjusting them to the same height.

The power density distribution is controlled by the 3 x 4 neutron flux instrumentation outside the RPV.

An indirect control of the axial shape is given by measuring the helium-inlet and -outlet temperatures.

Under safety aspects the power density distribution is important as start condition for accident analysis.

Accident Analysis

Rules for
BWR, PWR,
Fuel Handling

BMI

RSK

KTA

IAEA SG-50-D1

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HTR-Filter

Additional Aspects
of HTR-Design

List of:
- Design basic accidents
- Incidents
- Transients
- ATWS
- Hypothetical Events

Accident Analysis

Reactivity Accident

Uncontrolled withdraw of reflector rods

Time [sec]	Power [%]	Action	Max. Fuel Temperature
0	105	---	~ 880 °C
(12	120	Scram (Power)	)
90	~ 200	Scram (Coolant Temperature)	~ 950 °C
120	< 10	---	
3700	Decay Heat	---	~ 1050 °C
~ some hours	Decay Heat	---	~ 1240 °C

Conditions:

- Conservative integral power, only area cooler system
- Skipping of first reactor protection limit ← RPS worked

Result:

Fuel temperature well below limit: 1620 °C, also for different starting conditions like zero power, partial power.

Accident Analysis

Loss of Coolant Accident

Starting conditions: pessimistic

- Reactor power 105 % (limitation system limit)
- Inlet temperature 280 °C (near protection system limit)
- Outlet temperature 750 °C (near protection system limit)
- 2. Scram limit ($\frac{dR}{dt} \geq |-20\%/min|$) only 2nd Scram signal works
- Leak of 65 mm Ø

Calculation

Programs TAC 2D (TÜV) and THERMIX

Detailed 2-dim model with evaluation of the main tolerances (1 σ-value):

- Decay heat ± 2,8 %
- Local power density ± 5 %
- Fuel heat conductivity ± 1,15 W/m•K
- Effective core heat conductivity ± 5 %

Results for maximum fuel temperature (incl. 2 σ-tolerance)

THERMIX	TAC 2D	limit
1608 °C	1625 °C	1620 °C

(~ 1 % of the core > 1500 °C)

Accident Analysis

Loss of Coolant Accident

Additional temperature results (THERMIX)

Position	Maximum temperature	Design limits
Reflector rods	880 °C	650 °C
Core container wall	500 °C	500 °C
Core container bottom	380 °C	500 °C
RPV wall	360 °C	500 °C
RPV bottom	350 °C	500 °C
Outlet temperature	750 °C	900 °C

The high temperatures of the reflector rods do not affect the conceptual design, because:

- The mechanical integrity of the rods can perhaps be approved by additional experiments,
- The shutdown safety is not affected by a loss of the rods during temperature increase,
- The rods can be changed.