Recent developments in nuclear safety research

Recent developments in the field of nuclear safety research

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Topical examples of nuclear safety research

For existing plants:

- Analysis of hypothetical reactivity transients due to boron dilution in PWRs

For future plants:

- Analysis of the RPV during a severe core melt accident with corium in the lower plenum

For final disposal:

- Transmutation of Pu and minor actinides and consequences to final disposal

Topical examples of nuclear safety research

Boron dilution transients

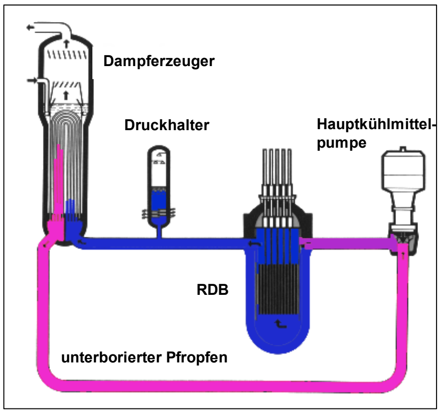
Boron dilution transients in PWRs: cause of problem

One disadvantage of using dissolved boron as neutron absorber:

- Unintended or unavoidable decrease of boron concentration
  - ➔ increase of reactivity
  - ➔ power excursion = boron dilution transient

- Initiators:
  - Accumulation of underborated coolant in SG or loop:
  - ➔ malfunction of chemical / volume control system
  - ➔ LOCA with partial failure of HPIS
  - ➔ unrecognized secondary to primary circuit leak in the SG
  - Start of coolant circulation forwards plug towards the core

Scheme: Boron dilution scenario



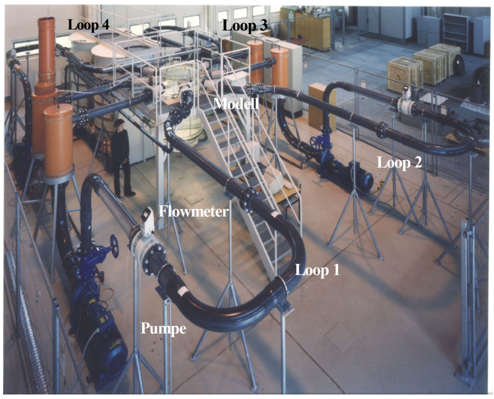
Increase of reactivity depends on:

- Volume of the slug
- Mixing of coolant

- Experiments needed:
- Understanding of the phenomenon
- Development of models
- Validation of models

ROCOM: Rossendorf Coolant Mixing Test Facility

Experiments on coolant mixing in PWRs

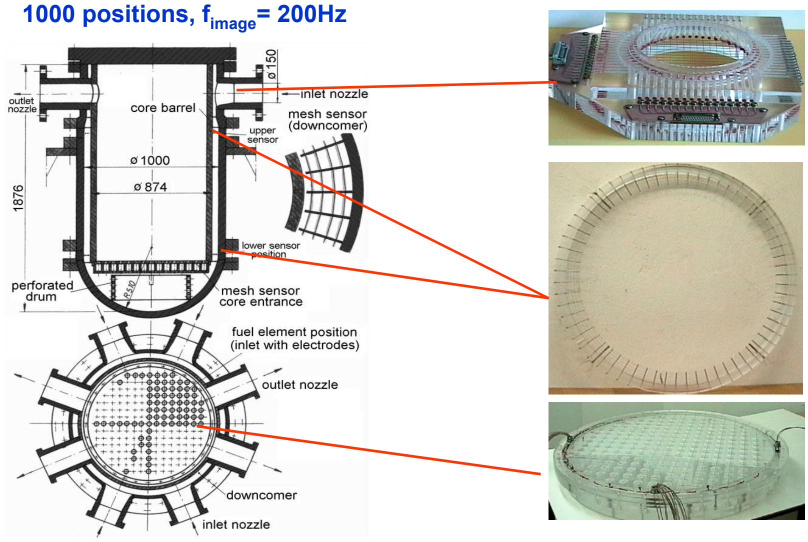


ROCOM: Rossendorf Coolant Mixing Test Facility

- 1:5 (lin. scaling) 4-loop model of KONVOI-PWR
- seperately controlable pumps in all 4 loops
- operated with deionate at room temperature
- simulation of density differences (boron concentration + temperature) by adding alcohol or sugar
- observation of mixing possible by tracering the plug with salt
- measurement of the propagation (= mixing) of the tracered plug by means of electrical conductivity measurements
- wire mesh sensors

Wire mesh sensors in ROCOM

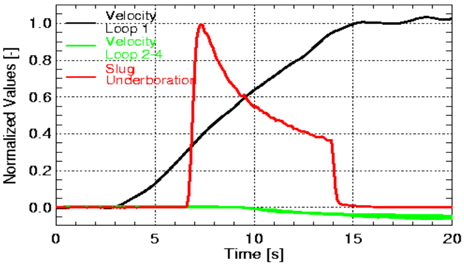
1000 positions, f_{image}= 200Hz

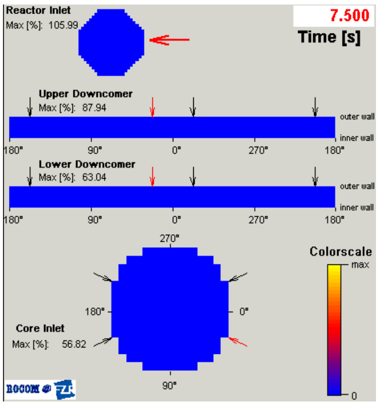


ROCOM-tests on pump start-up after SG leak

Initial and boundary conditions:

- boron free coolant plug in pump loop seal
- start of 1st MCP, full mass flow after 14 s
- ! flow reversal in other loops





CFD calculations

Stream lines calculated by CFX-codes

- slug „surrounds“ the core barrel
- entering the core at the opposite region

Coupled NK-TH core calculation

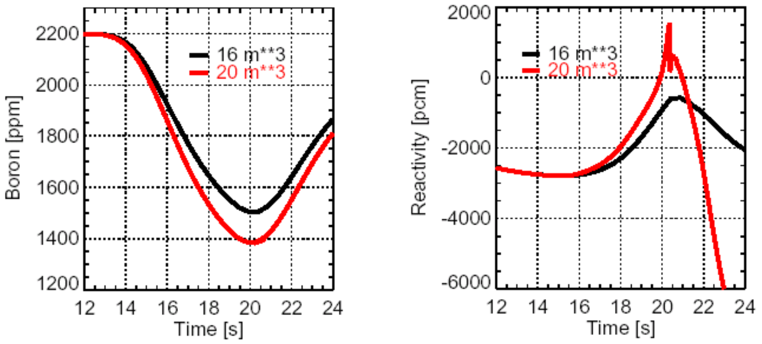
The model:

- coupled core calculations using DYN3D resp. DYN3D-ATHLET
- calculation of mixing by CFD or simplified models

Initial and time dependent boundary conditions:

- initially stagnant fluid + pump start-up within 14 s
- reactor hot sub-critical at begin of transient
  - all rods inserted, except the most effective
  - xenon/samarium like at the end of full power
  - $T_{coolant}$ = 192°C; $C_{Bcoolant}$ = 2200 ppm
  - T_{slug} = 210°C; C_{Bslug} = 0 ppm

Results of transient calculations by DYN3D



Average boron concentration in the core and dynamic reactivity for boron free plugs of 16m³ and 20 m³

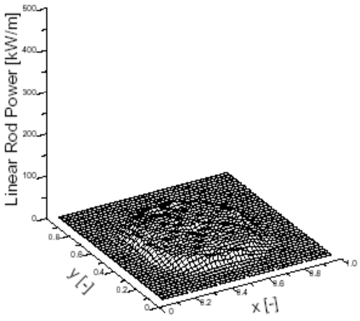
➔ Recriticality only at 20m³, even prompt criticality

➔ Doppler feed back

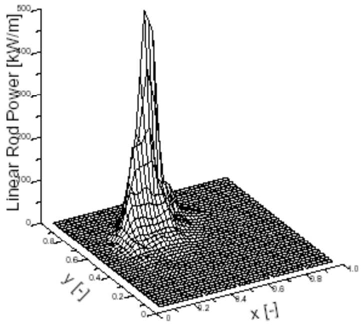
Results of transient core calculations with DYN3D

radiale distribution of pin power [kW/m] with 36m³ slug and additional stuck rod

Normal state

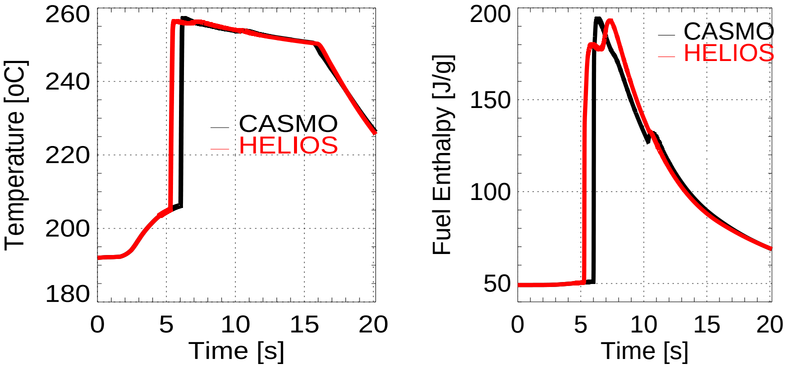


at maximum power



Results of transient calculations by DYN3D

maximum cladding temperature and maximum fuel enthalpy with a 36m³ plug



Resume: Safety assessment of boron dilution transients

Models for coupled core calculation and boron tracking in the core available

Calculation of boron concentration distribution at core entrance with

- **pulse dominated mixing scenarios (starting MCP) possible by semi-empirical and CFD models with sufficient accuracy**

- **density driven scenarios**

- by semi-empirical methods

-or scaling of experiment

- improvement of turbulence models for CFD-codes necessary to consider anisotropy and turbulence generation by bouyancy

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Topical examples of nuclear safety research

Behaviour of RPV during core melt and corium in the lower plenum

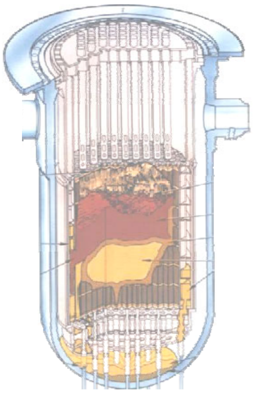
Behaviour of RPV with corium in the lower plenum

Why is the RPV so important?

- is the most important barrier against the release of radioactivity into containment
- loss of this barrier would lead to complete destruction of core and release of total radioactive inventory into containment during core melt accidents
- since TMI-2 accident in Harrisburg, USA, 1978: intensive research on severe accident phenomena world-wide

Behaviour of RPV with corium in the lower plenum

1. How could the RPV stand those ca. 20t corium melt in the LP?
2. When and how would the RPV have failed with progressing core melt?

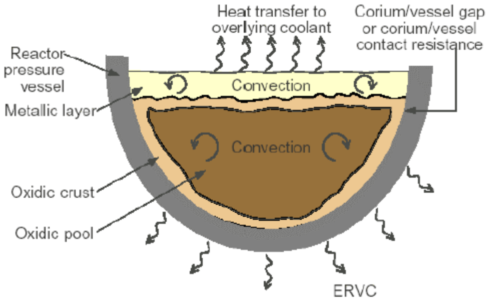


Koch, Steinbrück:FZKA 6935, 2003

Behaviour of RPV with corium in the lower plenum

Important phenomena to be studied

- Heat transport in debris
- Melt pool formation, convection in melt pool, formation of crusts
- Stratification in melt pool and focussing of heat load (knife effect)
- Gap formation between debris / crust and RPV wall, gap cooling
- Thermo-mechanical and chemical loads to the RPV



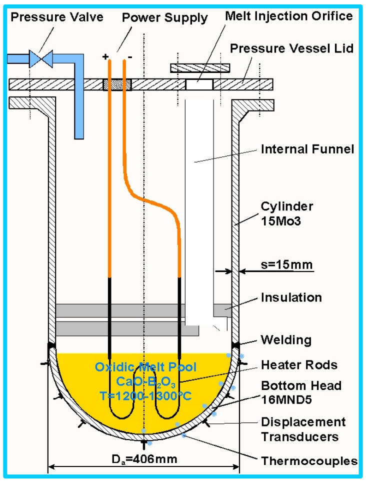
Koch, Steinbrück:FZKA 6935, 2003

➔ Creep behaviour of the RPV ➔ failure mode of RPV

- external RPV cooling

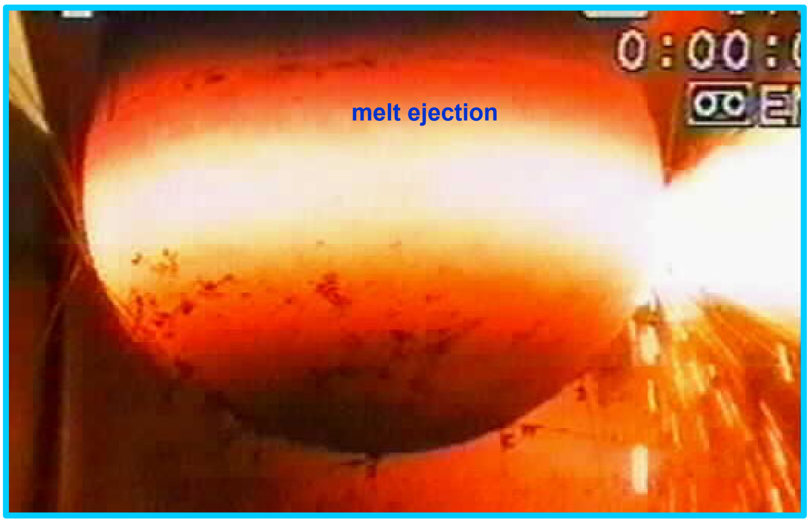
Behaviour of RPV with corium in the lower plenum

1:10 FOREVER-experiments at RIT Stockholm: french steels, melt simulant $CaO\text{-}B_2O_3$



Behaviour of RPV with corium in the lower plenum

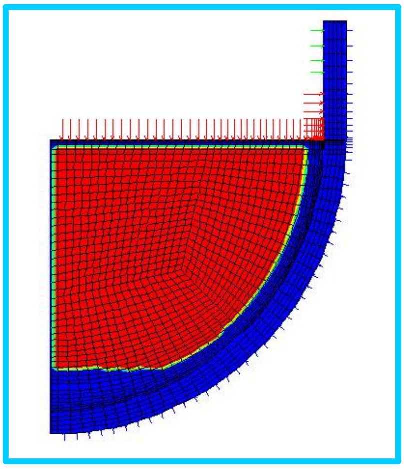
RPV driven to failure by combined heat and pressure loads:



Behaviour of RPV with corium in the lower plenum

Validation of codes

pre- and post-test calculations using an ANSYS-FLOTRAN-model:



Model includes, a.o.:

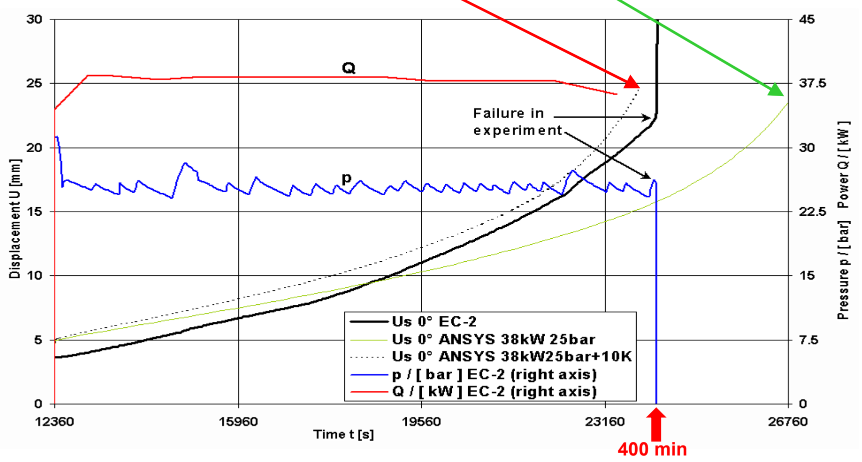
- heat source density (red)
- convection in melt
- heat radiation (arrows)
- heat conduction
- crust formation (dynamic)
- viscoplastic strain of RPV (creep model)
- damaging of the wall material till failure

Behaviour of RPV with corium in the lower plenum

Heat and pressure load (right); displacement of lower calotte (left)

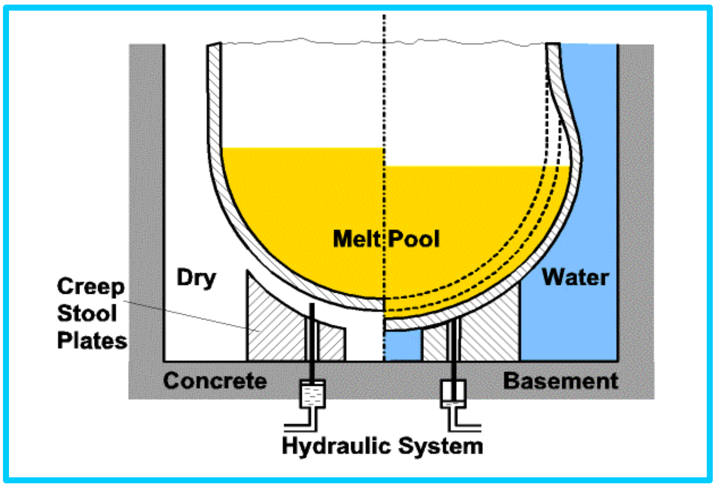
Post-test calculation (+ 10 K): 6 min too early

pre-test calculation : 48 min too late



Behaviour of RPV with corium in the lower plenum

Creep stool: proposal for a SAM - technology even for existing plants



at FOREVER doubling of time to failure without ex-vessel cooling

Behaviour of RPV with corium in the lower plenum

Critical evaluation of the state of the art knowledge:

- **Space dependent composition of the melt not fully clear:**
  stratification and thermal focussing effect
- **Coolability of debris and melt in LP not fully understood:**
  crust formation and critical heat current with gap cooling
- **Knowledge on the interaction of melt and RPV insufficient:**
  chemical-eutectic interaction (MASCA)

Why could the TMI-2 RPV calotte stand the melt ?

Question keeps not answered!

Safety research on final disposal of radioactive waste
Transmutation of long-lived radionuclides

Transmutation of long-lived radionuclides

Safety research on final disposal of radioactive waste
Transmutation of long-lived radionuclides

Where does the problem come from?

Waste emergence
in Europe

Reactors:	**145**
Installed power:	**125 GWe**
Burnt fuel:	**2500 t/a**
Plutonium:	**25 t/a**
MA (Np,Am,Cm):	**3,5 t/a**
Fission products:	**100 t/a**
Long-lived share:	**3,1 t/a**

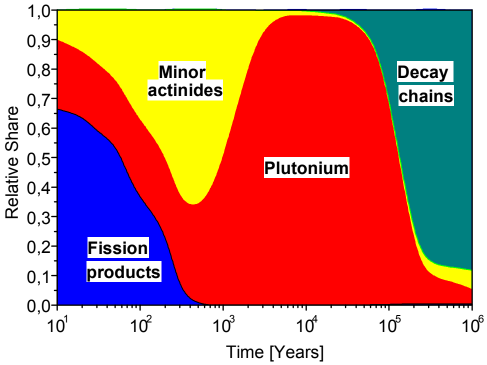
Disposal

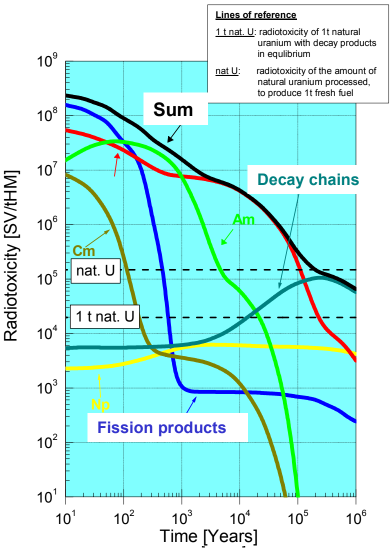
Direct final disposal
Interim and final storage
of burnt fuel elements

K. Gompper, FZK: Vortrag im FZR, 2001

Safety research on final disposal of radioactive waste

Radiotoxicity in final disposal for direct disposal*





Lines of reference

1 t nat. U: radiotoxicity of 1t natural uranium with decay products in equlibrium

nat U: radiotoxicity of the amount of natural uranium processed, to produce 1t fresh fuel

*) Enrichment: 4% U-235; burn-up: 40 GWd/t;
Radiotoxicity related to ingestion

K. Gompper, FZK: Vortrag im FZR, 2001

The way out: Partitioning & Transmutation (P&T)

P: Separation (Partitioning) of Pu and MA from burnt fuel

Reprocessing into new fuel

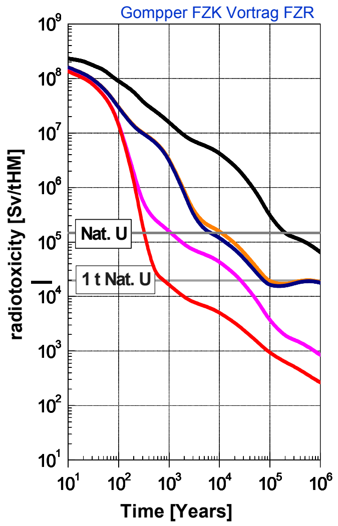
T: burning / transmuting into stable or short-lived nuclides in LWR, FR, ADS

+ Energy

Influence of P&T on radiotoxicity in the final disposal

Partitioning	Radiotoxicity at level of nat. uranium (after years)	
none	200.000	*ca.70 Mio*
99 % Pu	11.300	*97.000*
99,9 % Pu	6.500	*74.000*
99 % Pu, MA	1100	*26.500*

1 t Nat. U



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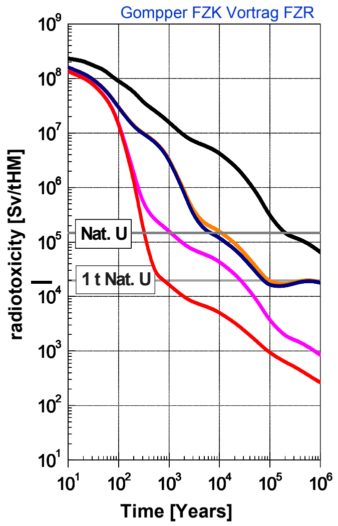
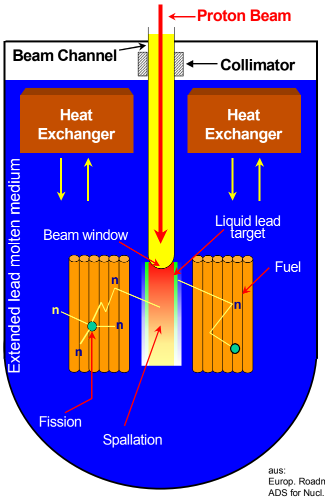


Safety research on final disposal of radioactive waste

ADS-principle

- A high energetic (1,5GeV, 45mA) proton beam hits a HLM (e.g. PbBi) target .
- Neutrons are generated in the target by spallation reactions.
- This source of fast neutrons sustains the chain reaction in the subcritical reactor.



aus:
Europ. Roadmap for Developing ADS for Nucl. Waste Incineration ENEA, (2001)

Text Gompper FZK bei Vortrag im FZR

Safety research on final disposal of radioactive waste

Why ADS ?

1. Lowest circulating TRU-inventory compared with other strategies:

   safety relevance for accidents leading to release of radioactive materials

2. Burning of the existing TRU-inventories in ADS when finishing the use of fission for nuclear energy production (phase out strategy)

Safety research on final disposal of radioactive waste

R&D needs

- Improvement of partitioning technologies
    - better separation quality, e.g. between MA and Lanthanides
    - development of heat and irradiation resistent extraction technologies
- new fuels for higher burn-ups and with high content of actinides
- more accurate measurement of neutron crosss sections of LL radionuclides for optimised design of transmuters
- development of proton accelerators of high power and reliability

EU-IP EUROTRANS

The end

Thank you for your attention!