FAILURE ASSESSMENT METHODOLOGIES FOR COMPONENTS UNDER SEVERE ACCIDENT LOADING
OUTLINE

● Introduction

● Structure mechanics analysis methods for integrity assessment of a PWR
  – coolant loop under a core melt scenario
  – steel containment under peakwise loads (hydrogen combustion)

● Summary and conclusions
INTRODUCTION

Severe accident scenarios with molten core material

Three Mile Island Nuclear Generating Station (TMI)
March 28, 1979

Fukushima Daiichi Nuclear Power Plants
March 11, 2011
INTRODUCTION

- Safety relevance of the integrity of components under severe accident loading
  - primary circuit components
  - containment structures

- Objectives of research work
  - development
  - provision
  - validation

of structural mechanic analysis methods
SAFETY RELEVANT ISSUE

Which component of a primary circuit fails first during a severe accident scenario?

Primary circuit of German PWR
FAILURE ASSESSMENT METHODOLOGIES

Complex FE-analysis

Simplified FE-analysis/ASTOR

Pipe section

transient pressure

transient temperature

$P(t)$

$T(t)$

$\text{time } t$

$r_i$

$r_a$
LOADING CONDITIONS DURING A CORE MELT SCENARIO

Load case “Total Station Blackout” calculated with MELCOR
LOADING CONDITIONS DURING A CORE MELT SCENARIO

Load case “Total Station Blackout” calculated with MELCOR

![Graph showing pressure over time for primary and secondary systems]
Finite Element Analysis model of a PWR cooling loop (type Konvoi)
MATERIAL PROPERTIES

Temperature dependent stress-strain curves for reactor steel 20 MnMoNi 55 up to uniform elongation
MATERIAL PROPERTIES

Temperature and stress dependent creep curves for reactor steel 20 MnMoNi 55 – linear approximation up to 60 % of uniaxial creep failure strain measured by MPA University Stuttgart

\[ T = 1000 \, ^\circ C \]
FAILURE CRITERIA FOR INTEGRITY ASSESSMENT

- Failure due to **plastification**:
  Uniaxial **Uniform Elongation** / Stress triaxiality factor $TF$

- Failure due to **creep**:
  Uniaxial **failure strain** / Stress triaxiality factor $TF$

\[
TF = \frac{\left| \sigma_1 + \sigma_2 + \sigma_3 \right|}{\sigma_\text{effektiv}} \quad \text{due to Ju and Buttler (1984)}
\]

- **Safety related assessment of failure**:  
  60% uniaxial creep failure strain, $TF > 1$ based on elasto-plastic stress calculation

- **Assessment concerning failure as a matter of fact**:  
  100% uniaxial creep failure strain, $TF = 1$ for failure due to plastification or/and creep
STRUCTURE MECHANICS ANALYSIS RESULTS

Integrity assessment of main cooling line

![Graph showing strain vs. time with markers for MCL failure and MCL failure as matter of fact]
Integrity assessment of surge line

![Graph showing strain over time for surge line analysis.](image)
STRUCTURE MECHANICS ANALYSIS RESULTS

Integrity assessment of main cooling and surge line

![Graph showing temperature over time for different components and failure conditions.](chart.png)

- **inside RPV**
- **outside RPV**
- **surge line**
- **MCL**

- MCL failure
- Safety related
- Surge line failure
- MCL failure as matter of fact
SAFETY RELEVANT ISSUE

Steel containment of German PWR

What is the load carrying capacity of a steel containment during a severe accident scenario with postulated hydrogen combustion?

Wall thickness 38 mm
LOADING DUE TO HYDROGEN COMBUSTION

- Measured and calculated pressure values in TMI-2 containment during severe accident 1979 [EPRI, 2010]:
  - peak pressure ~0,3 MPa
  - peak duration ~10 s increase / >70 s decrease

- Calculated pressure distributions at top floors in Fukushima units during severe accident 2011 [JNES, 2012]:
  - peak pressure ~1,5 MPa
  - peak duration <100 ms

- Calculated pressure / temperature values for postulated severe accident scenarios with consideration of catalytic recombinators [GRS, 2012]:
  - peak pressures < 0,05 MPa
  - peak duration ~40 - 70 s
  - peak temperatures < 370 °C
Load assumptions

Peak values:
800 – 1200 °C / 0.4 – 2.5 MPa

Peak duration:
16 ms – 3.6 s (quasi static)
DYNAMIC BEHAVIOR OF A STEEL CONTAINMENT

- Loadcase:
  Pressure peak with
  - Peak pressure 1 MPa
  - Peak duration 32 ms

local equivalent stress $t = 15,0 \text{ ms}$
DYNAMIC BEHAVIOR OF A STEEL CONTAINMENT

- Loadcase:
  Pressure peak with
  - Peak pressure 1 MPa
  - Peak duration 32 ms

Local equivalent stress \( t = 24.5 \text{ ms} \)
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

- Loadcase: Pressure peak with
  - Peak pressure 1 MPa
  - Peak duration 32 ms

Local equivalent stress $t = 34.0 \text{ ms}$
Loadcase: Pressure peak with
- Peak pressure 1 MPa
- Peak duration 32 ms

Local equivalent stress $t = 43.0 \text{ ms}$
Loadcase: Pressure peak with
- Peak pressure 1 MPa
- Peak duration 32 ms

Local equivalent stress $t = 50.0 \text{ ms}$
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

- Loadcase:
  - Pressure peak with
  - Peak pressure 1 MPa
  - Peak duration 32 ms

  Local equivalent stress $t = 58.5 \text{ ms}$
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

● Loadcase:
  Pressure peak with
  – Peak pressure 1 MPa
  – Peak duration 32 ms

local equivalent stress $t = 67,0$ ms
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

- Loadcase: Pressure peak with
  - Peak pressure 1 MPa
  - Peak duration 32 ms

local equivalent stress $t = 75.5 \text{ ms}$
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

- **Loadcase:**
  - Pressure peak with
  - Peak pressure 1 MPa
  - Peak duration 32 ms

Local equivalent stress $t = 97.5$ ms
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

- Loadcase: Pressure peak with
  - Peak pressure 1 MPa
  - Peak duration 32 ms
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Results of parametric study with pressure peak loading

Max. accumulated plastic strain [-]

Peak pressure [MPa] vs. Peak duration [ms]
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Consideration of temperature peak loading

- **Loadcase:**
  - Pressure peak with
  - Peak pressure 1 MPa
  - Peak temperature 1200°C
  - Peak duration 32 ms
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Consideration of temperature peak loading

- Time [ms]:
  - 8 ms
  - 16 ms
  - 30 ms

- Temperature [°C]:
  - 2 mm

- Pressure [MPa]:
  - Temp
  - Press

- Time [ms]:
  - $t = 16.3$ ms

- Temperature [°C]:
  - $T$
Loadcase:
Pressure peak with
- Peak pressure 1 MPa
- Peak temperature 1200°C
- Peak duration 32 ms
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Integrity assessment with consideration of temperature peak loading

- Loadcase:
  - Pressure peak with
  - Peak pressure 1 MPa
  - Peak temperature 1200°C
  - Peak duration 32 ms

plastic strain * TF at different locations [-]

Failure criteria reached local damage

$t = 16 \text{ ms}$
Loadcase:
Pressure peak with
- Peak pressure 1 MPa
- Peak temperature 1200°C
- Peak duration 32 ms

plastic strain * TF at different locations [-]
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Integrity assessment with consideration of temperature peak loading

- Loadcase:
  Pressure peak with
  - Peak pressure 1 MPa
  - Peak temperature 1200°C
  - Peak duration 32 ms

plastic strain * TF at different locations [-]

\[
\text{t} = 28 \text{ ms}
\]
CONCLUSIONS

- Structural behaviour of a PWR cooling loop under loads due to core melt scenarios
  - plastic strains in the main cooling line and the surge line may reach limit values before the RPV heats up
  - structure mechanics results may effect thermal hydraulic results of accident scenarios
    code coupling, simplified method in system codes
SUMMARY AND CONCLUSIONS

- Structural behaviour of a PWR cooling loop under loads due to core melt scenarios
  - plastic strains in the main cooling line and the surge line may reach limit values before the RPV heats up
  - structure mechanics results may effect thermal hydraulic results of accident scenarios
    code coupling, simplified method in system codes
- Steel containment behaviour under internal peakwise loading
  - oscillations of the pressure loaded area for peak duration 20 – 50 ms
  - quasi-static behaviour for peaks with duration longer than 100 ms
  - pressure peak values up to 0.4 MPa effect no plastification
  - temperature peaks may effect limited plastification and local failure close to the inner surface