J. Sievers (GRS) – J. Arndt (GRS) – H. Grebner (GRS) – P. Bachmann (GRS)

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)

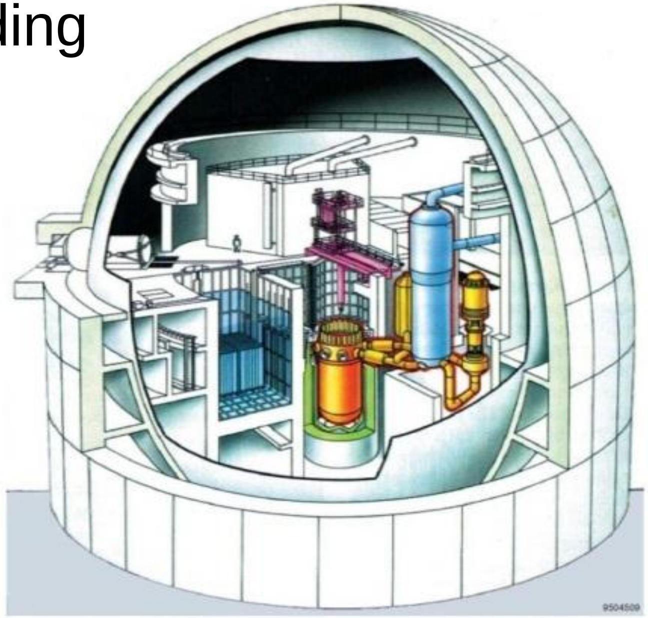
March 28, 1979

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



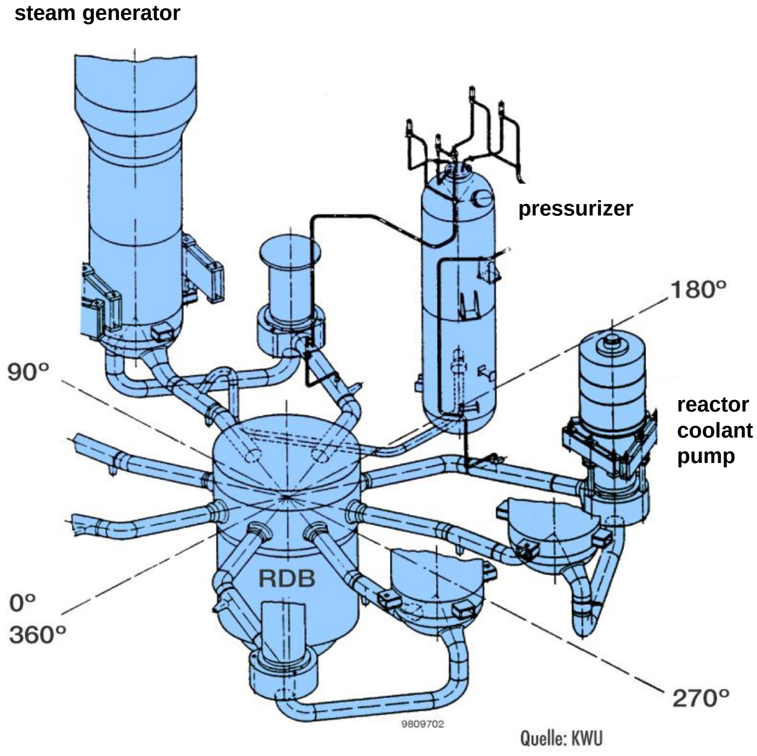
- Objectives of research work
  - development
  - provision
  - validation

  of structural mechanic analysis methods

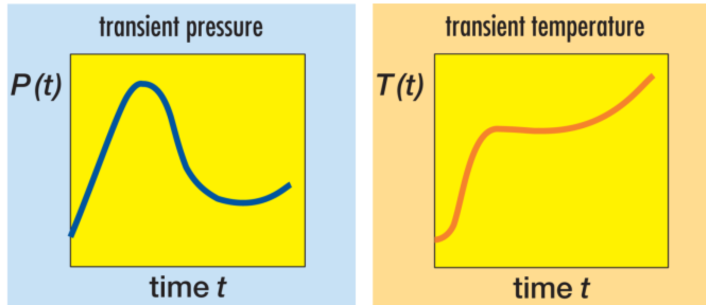
SAFETY RELEVANT ISSUE

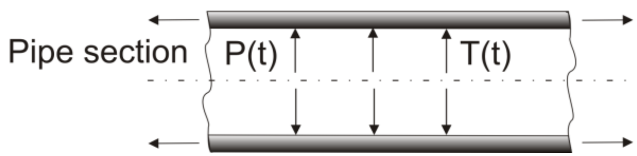
Which component of a primary circuit fails first during a severe accident scenario?

Primary circuit of German PWR

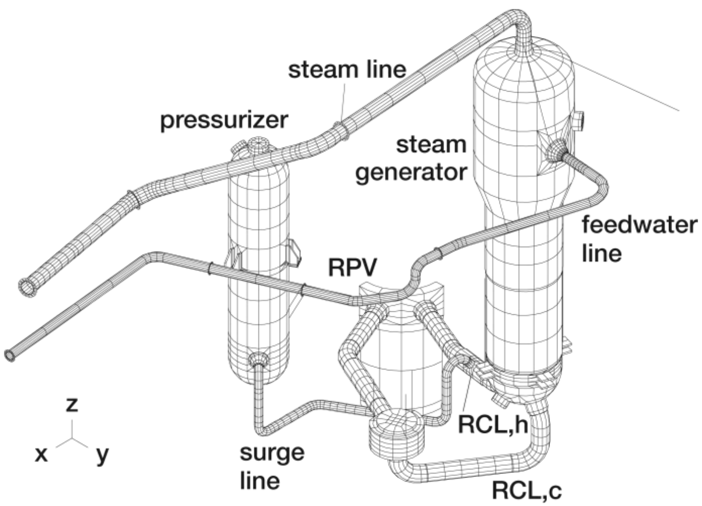


FAILURE ASSESSMENT METHODOLOGIES

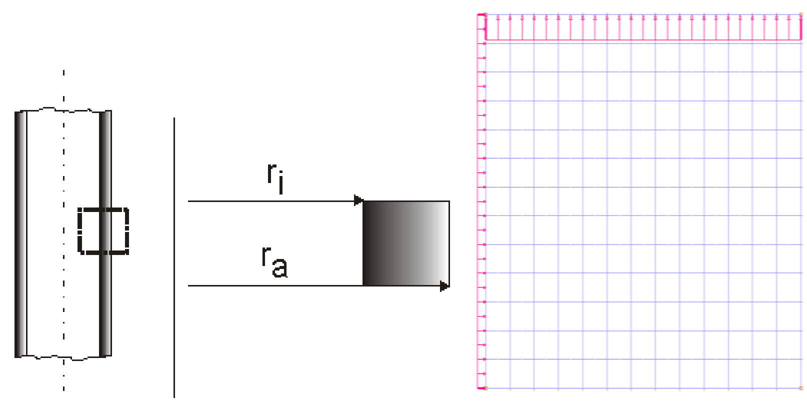




Complex FE-analysis

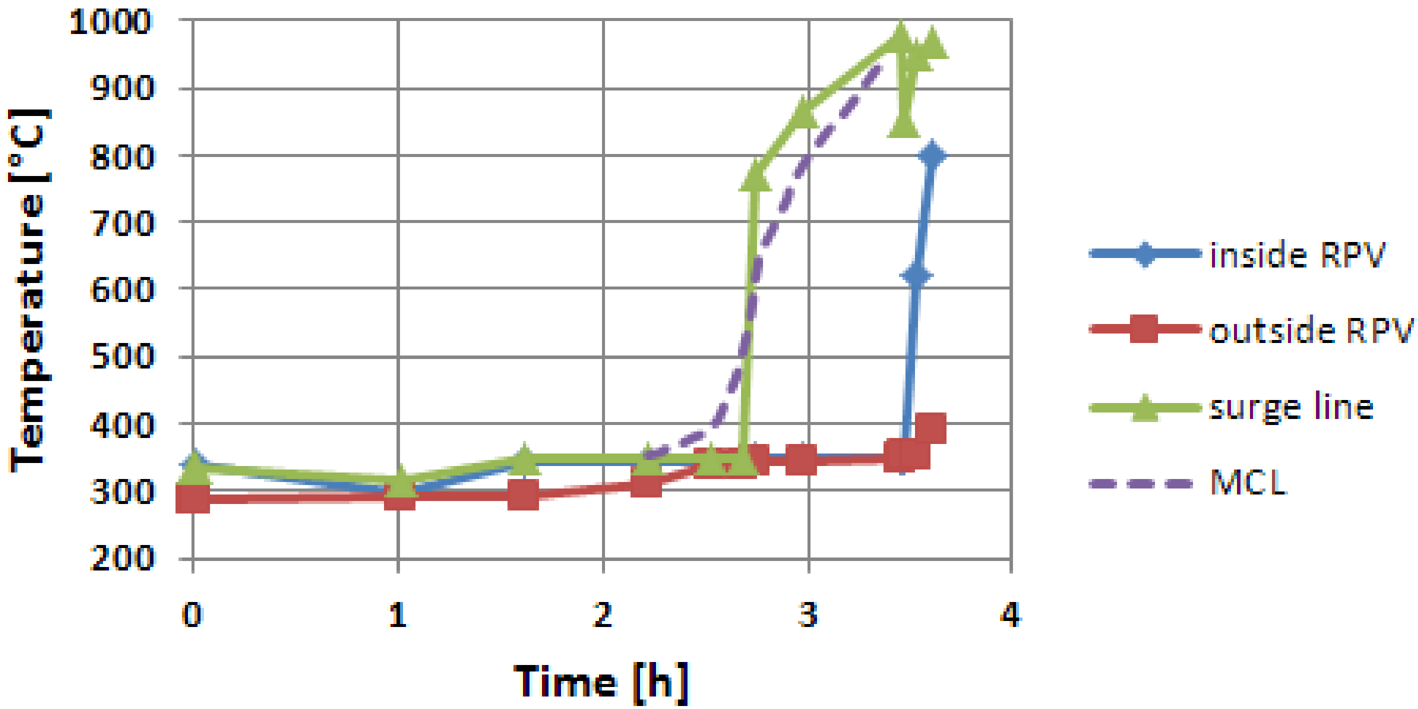


Simplified FE-analysis/ASTOR



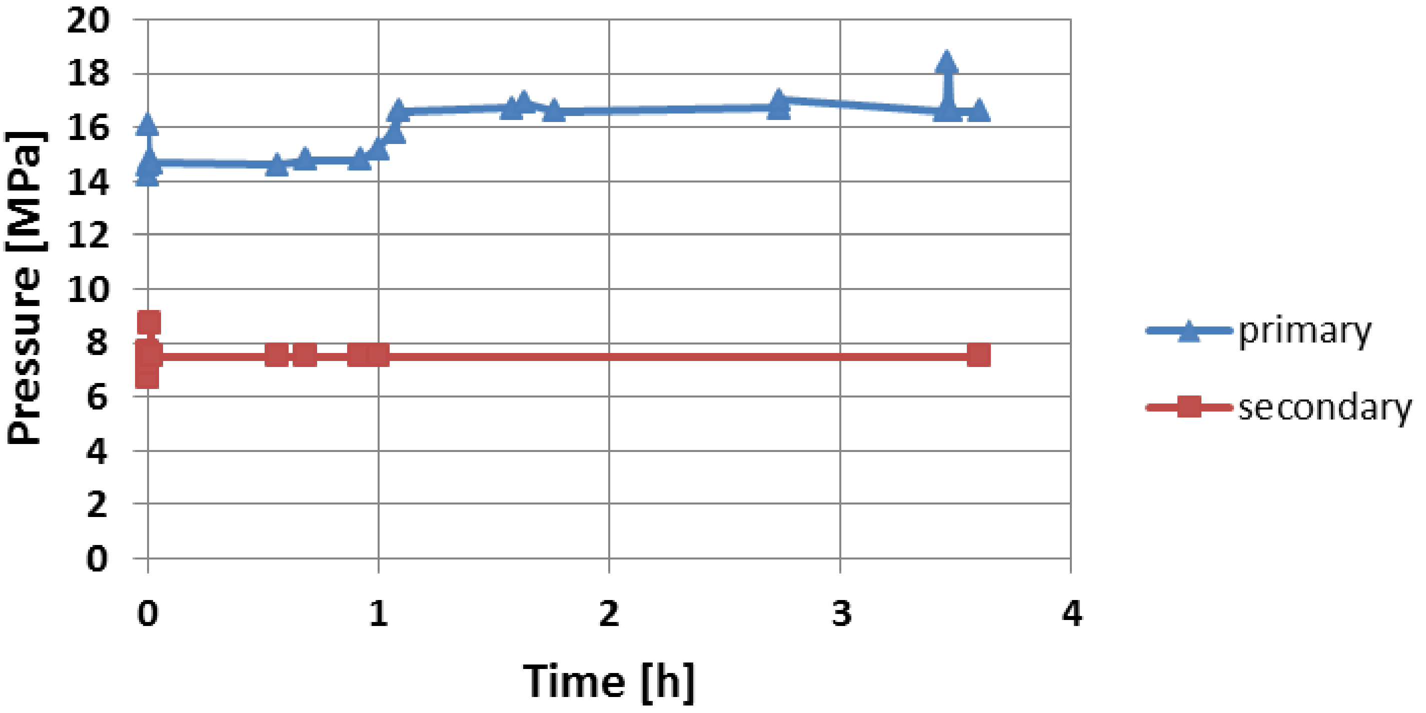
LOADING CONDITIONS DURING A CORE MELT SCENARIO

Load case “Total Station Blackout” calculated with MELCOR



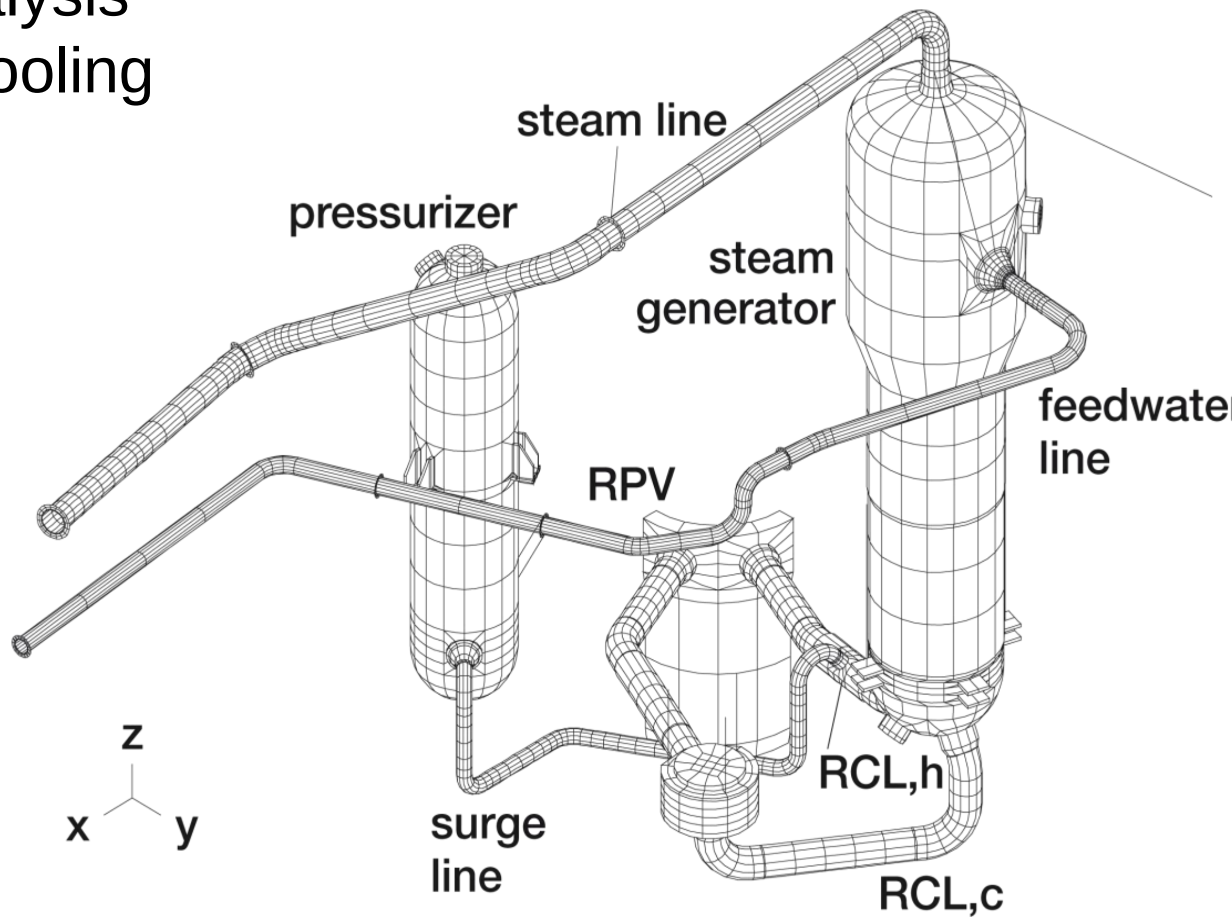
LOADING CONDITIONS DURING A CORE MELT SCENARIO

Load case “Total Station Blackout” calculated with MELCOR



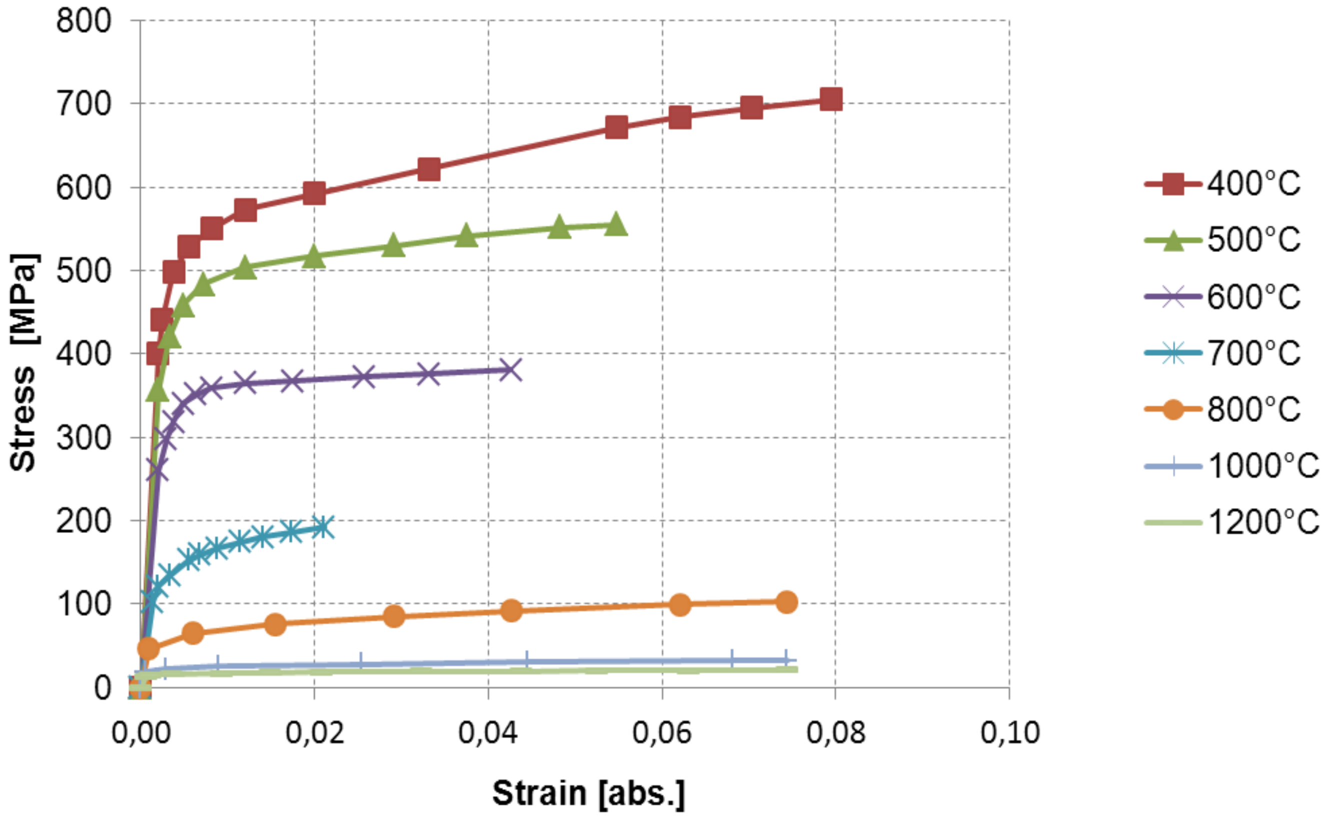
STRUCTURE MECHANICS ANALYSIS MODEL

Finite Element Analysis model of a PWR cooling loop (type Konvoi)



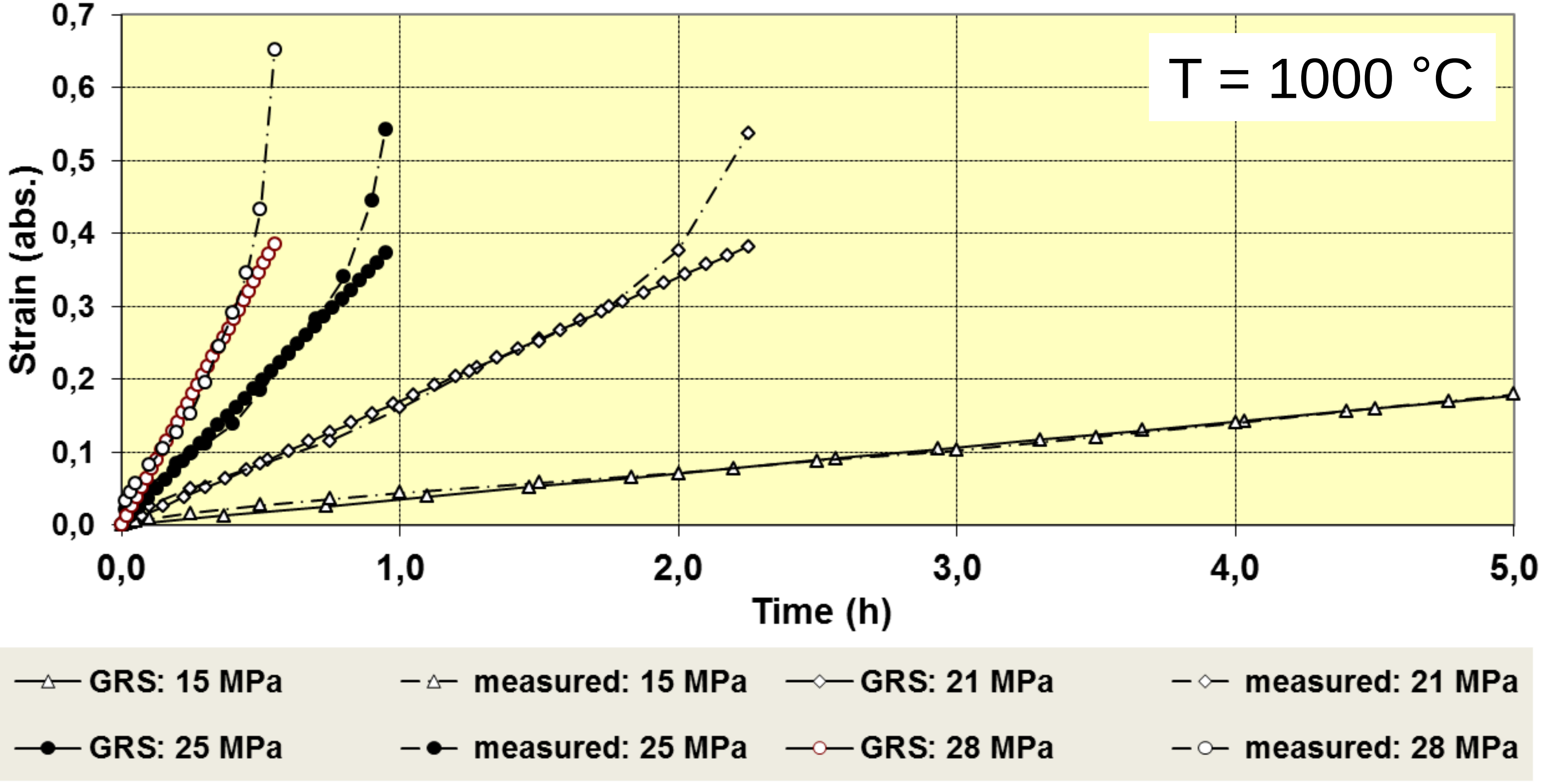
MATERIAL PROPERTIES

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



FAILURE CRITERIA FOR INTEGRITY ASSESSMENT

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

- Failure due to **creep**:
  Uniaxial f**ailure strain /** Stress triaxiality factor **TF**

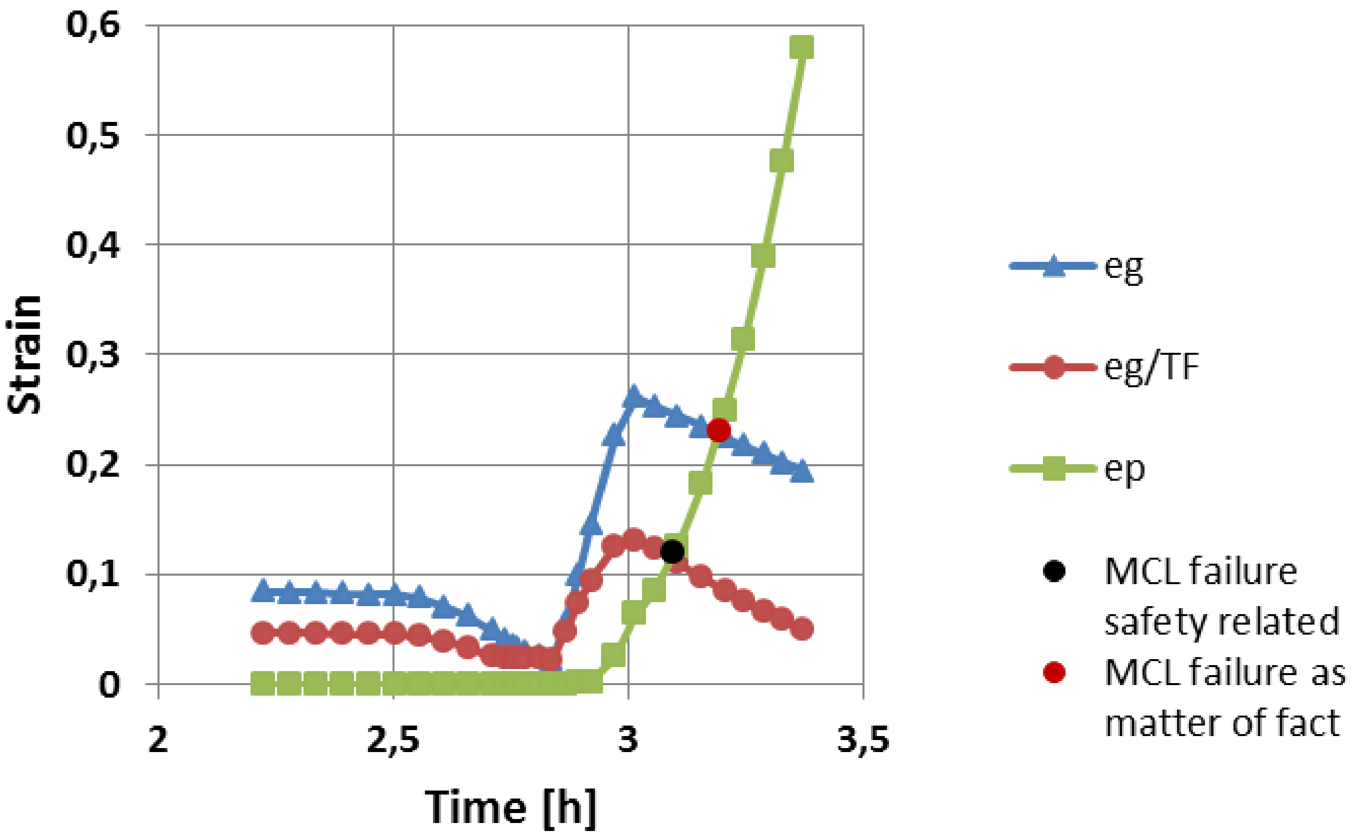
$$TF = \frac{\left|\sigma_1 + \sigma_2 + \sigma_3\right|}{\sigma_{effektiv}} \quad \text{due to Ju and Buttler (1984)}$$

- **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

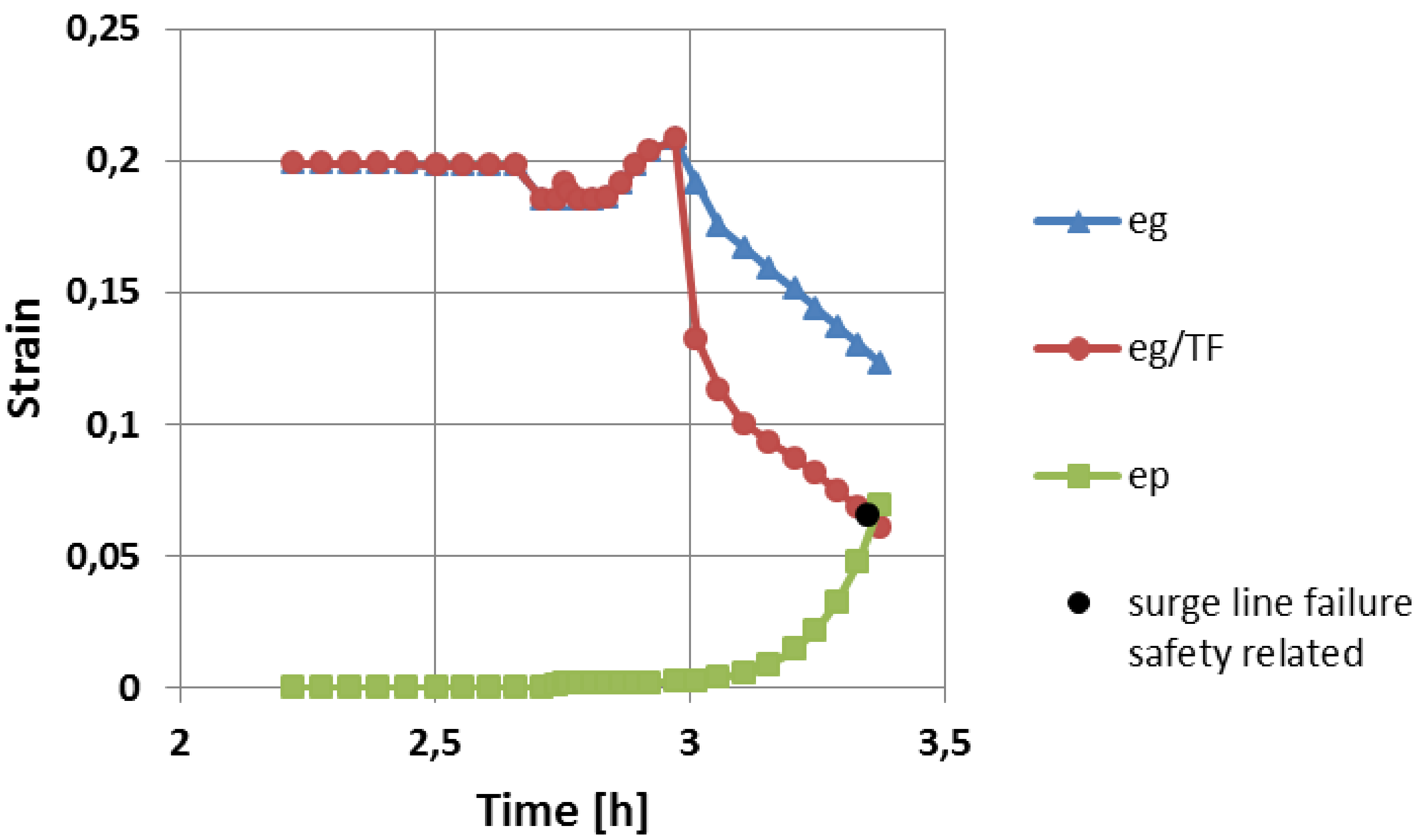
STRUCTURE MECHANICS ANALYSIS RESULTS

Integrity assessment of main cooling line



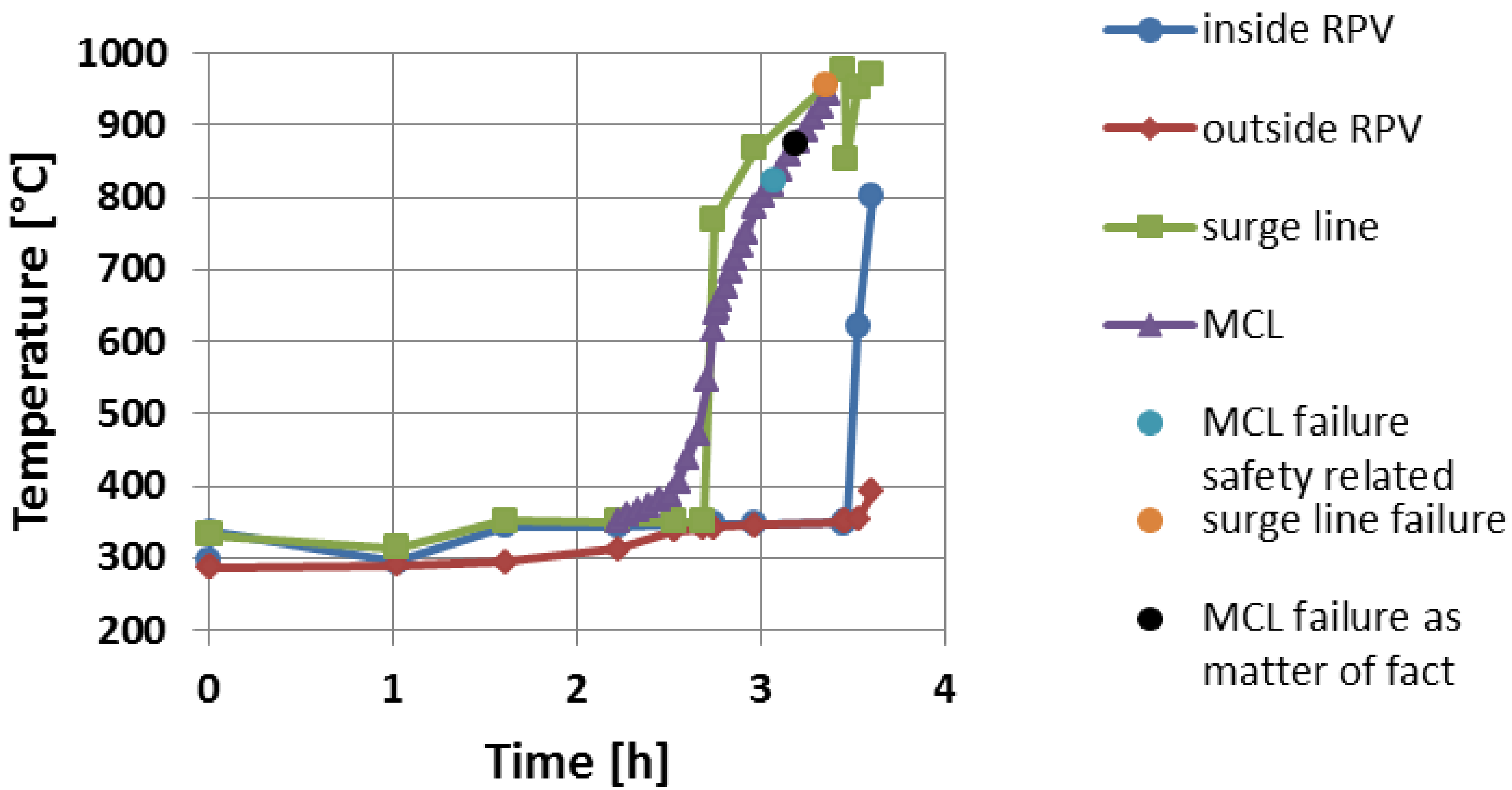
STRUCTURE MECHANICS ANALYSIS RESULTS

Integrity assessment of surge line



STRUCTURE MECHANICS ANALYSIS RESULTS

Integrity assessment of main cooling and surge line

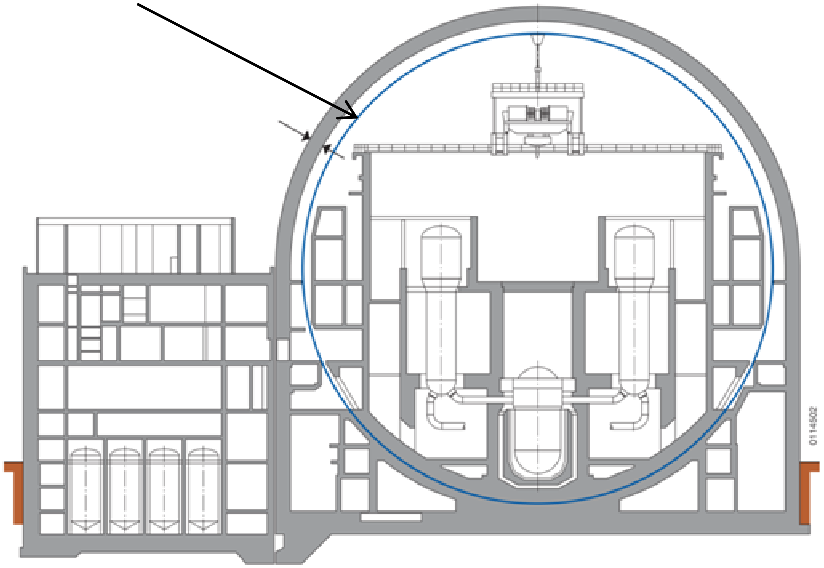


SAFETY RELEVANT ISSUE

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



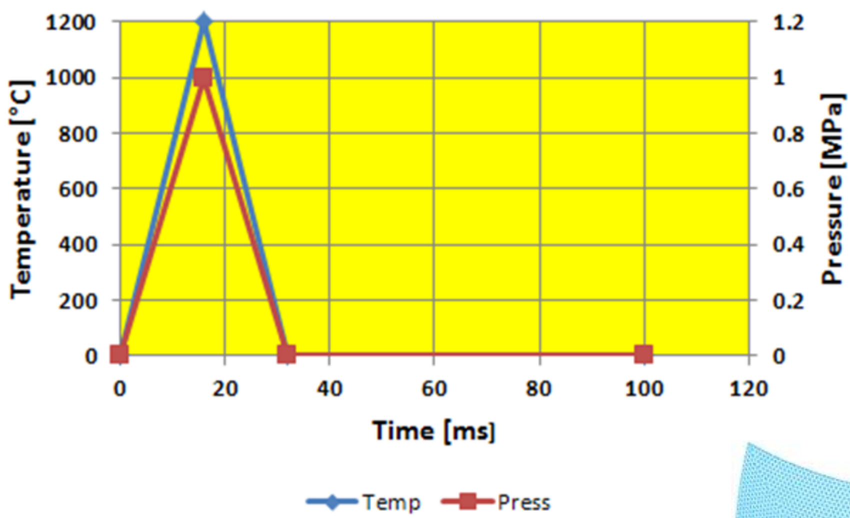
LOADING DUE TO HYDROGEN COMBUSTION

- 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

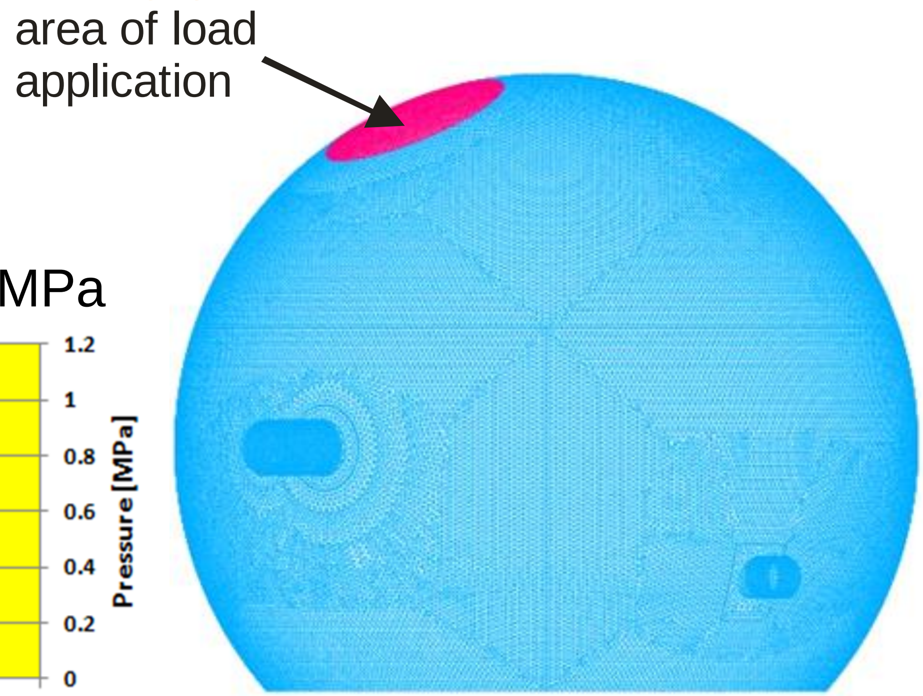
STRUCTURE MECHANICS ANALYSIS MODEL OF A PWR STEEL CONTAINMENT

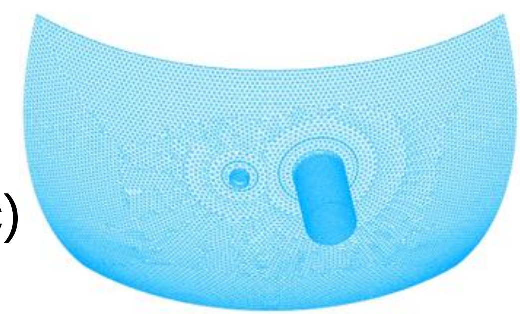
Load assumptions

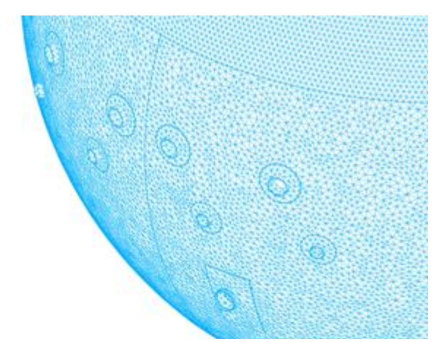
Peak values:
800 – 1200 °C / 0.4 – 2.5 MPa



Peak duration:
16 ms – 3.6 s (quasi static)

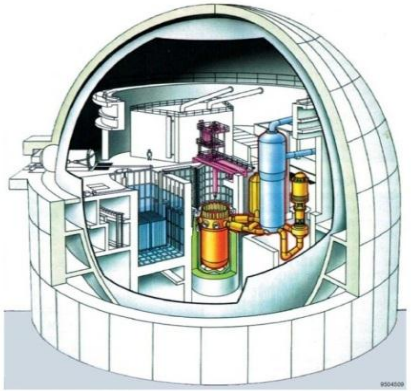




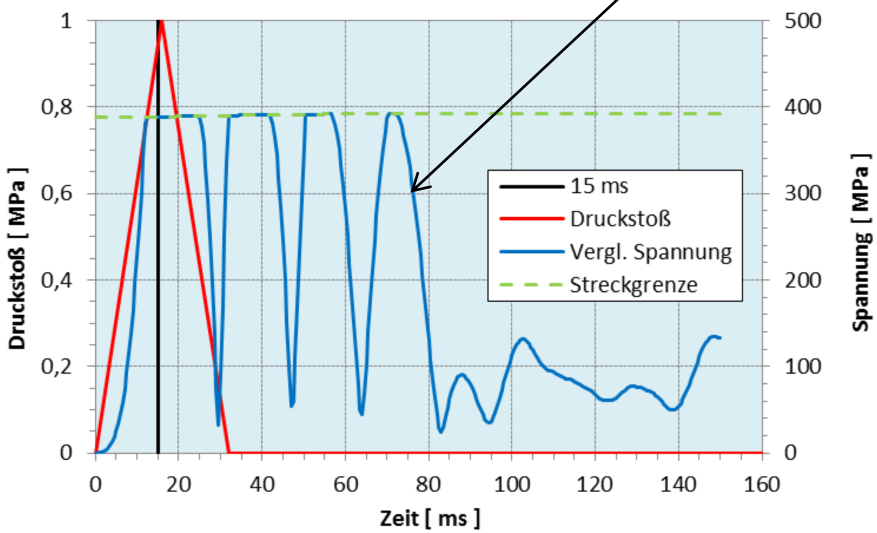


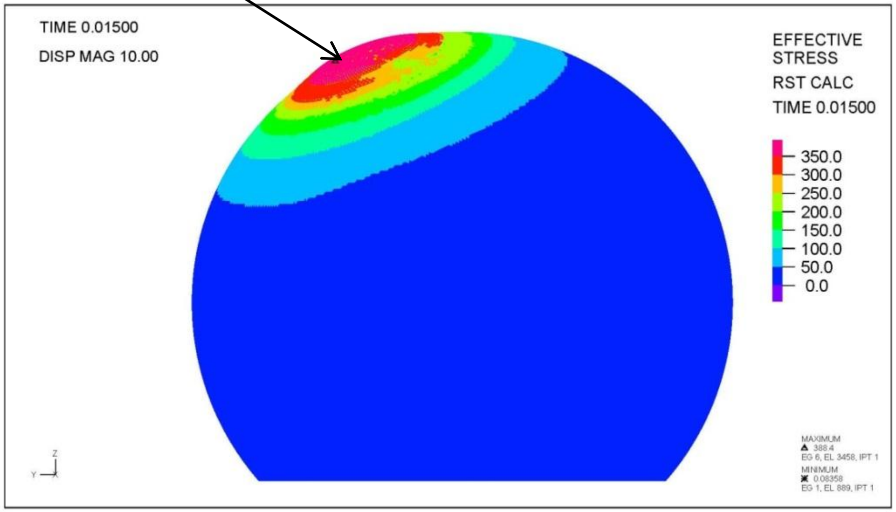
DYNAMIC BEHAVIOR OF A STEEL CONTAINMENT

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



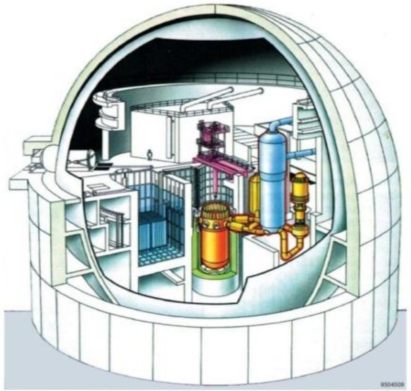
local equivalent stress t = **15,0 ms**



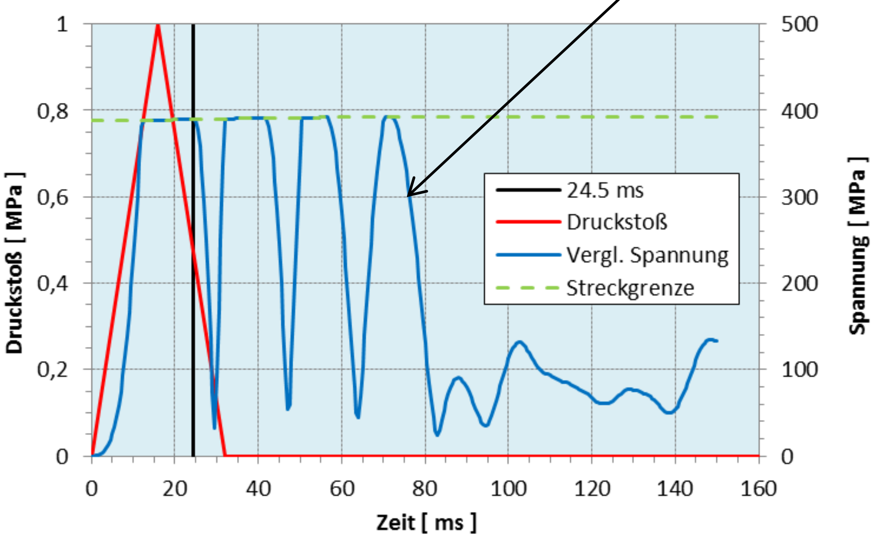


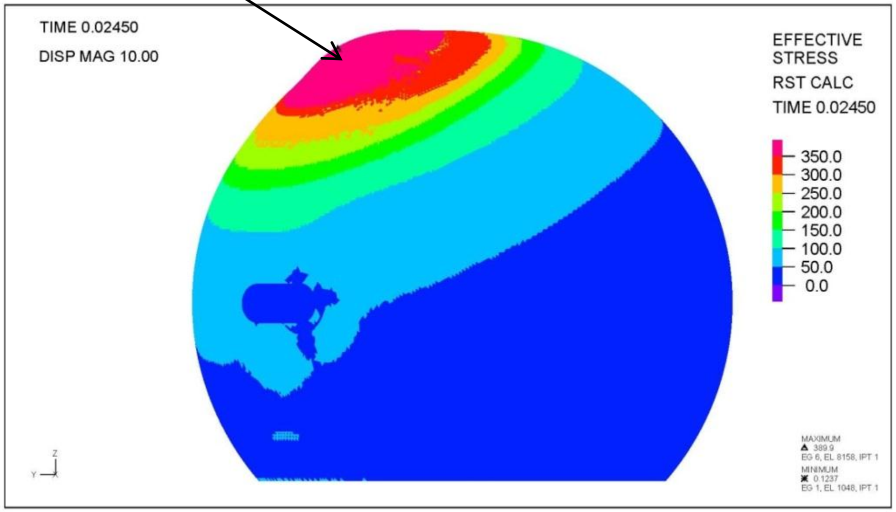
DYNAMIC BEHAVIOR OF A STEEL CONTAINMENT

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



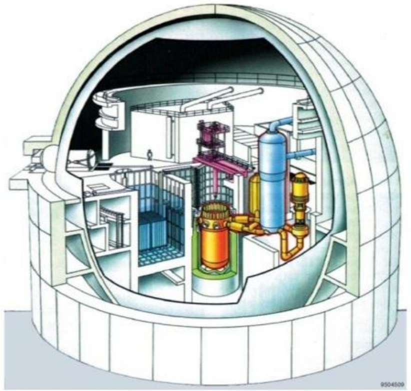
local equivalent stress t = **24,5 ms**



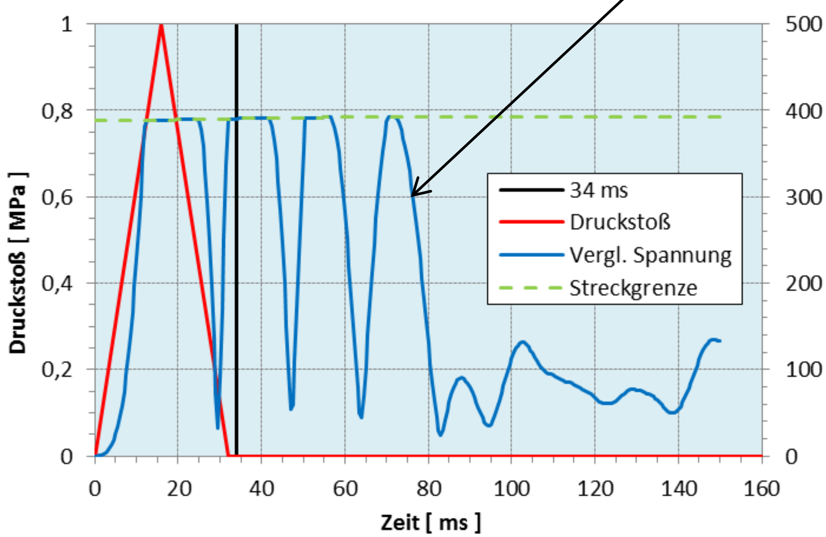


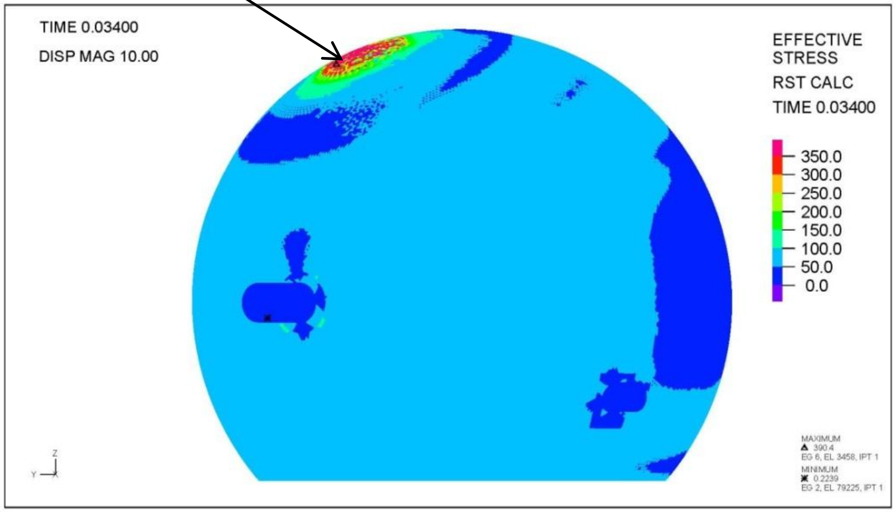
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

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



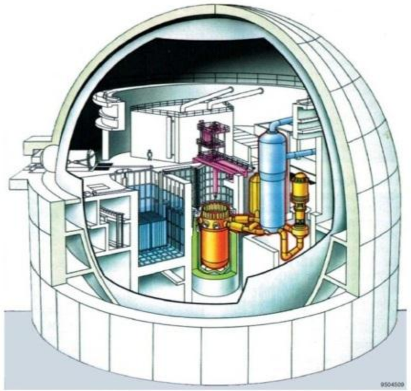
local equivalent stress t = **34,0 ms**



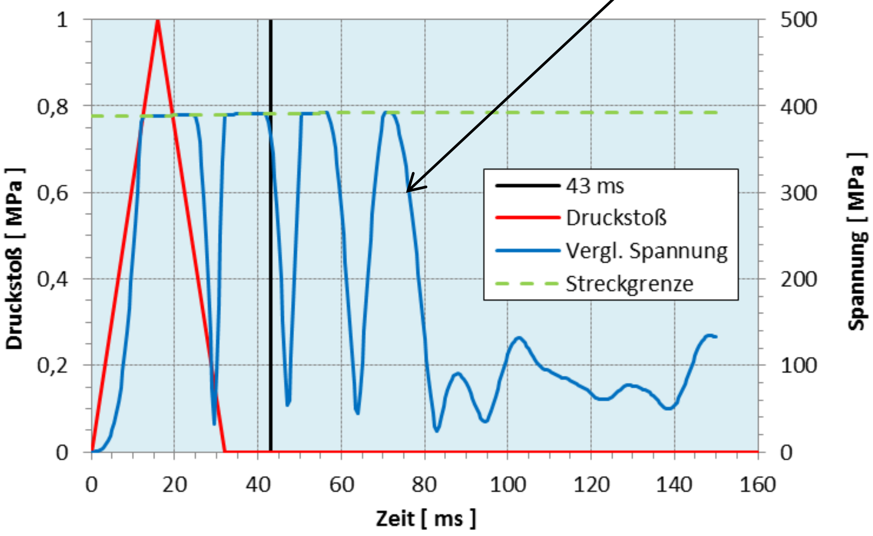


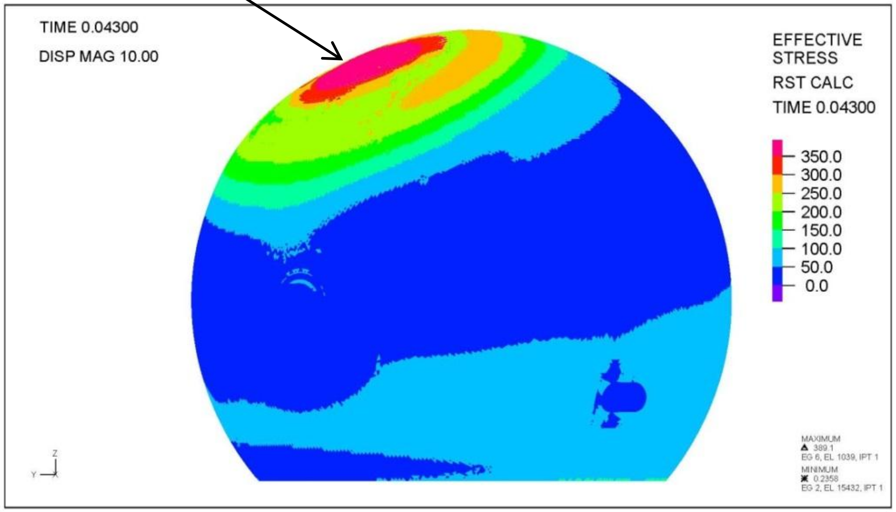
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

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



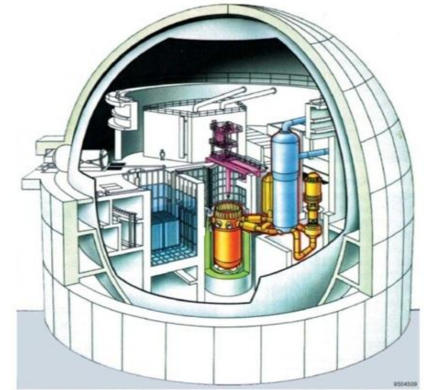
local equivalent stress t = **43,0 ms**



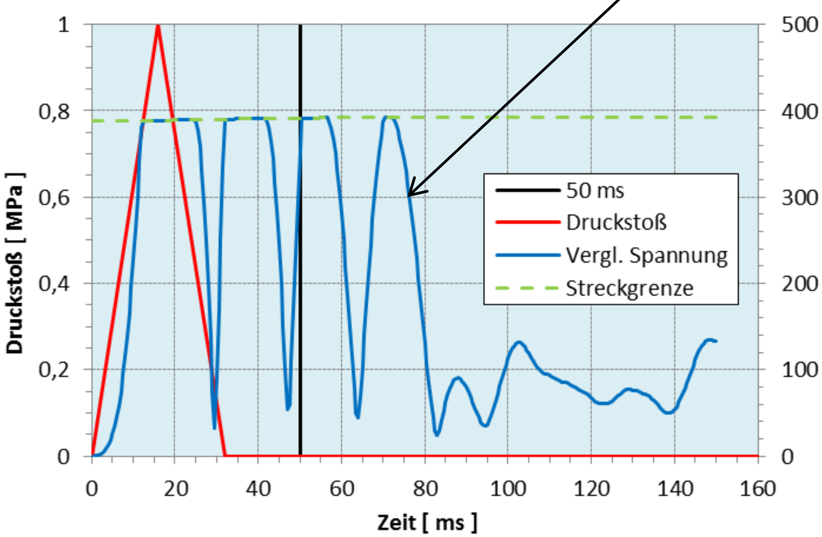


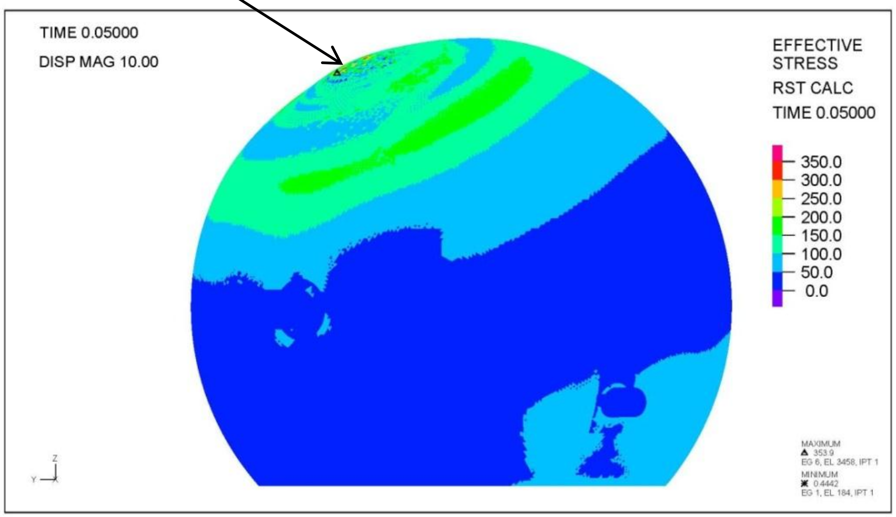
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

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



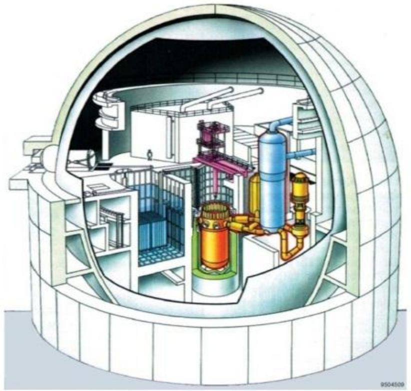
local equivalent stress t = **50,0 ms**



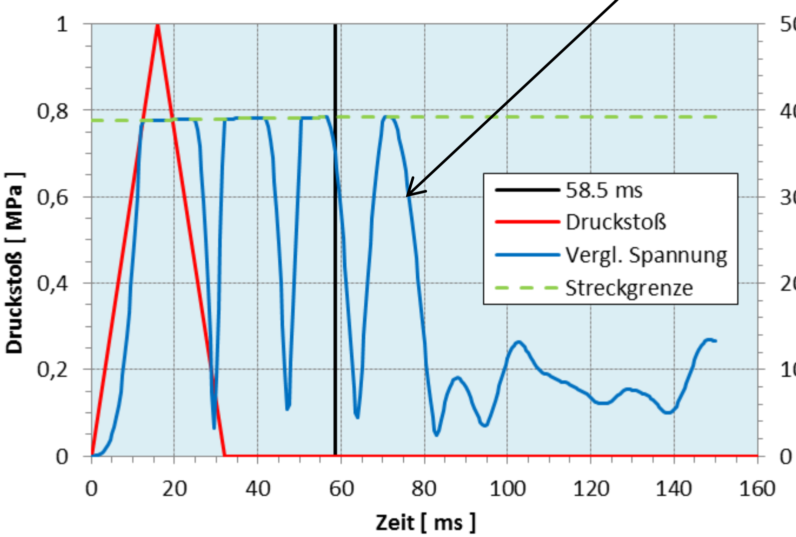


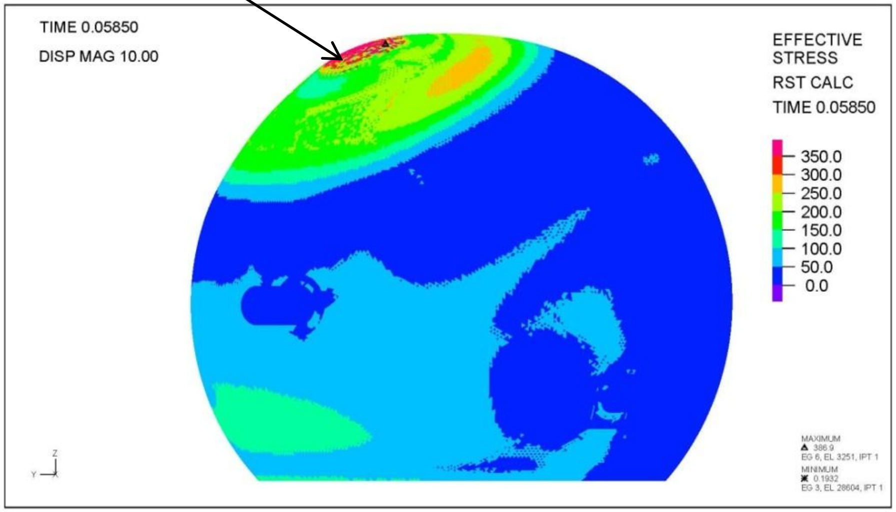
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

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



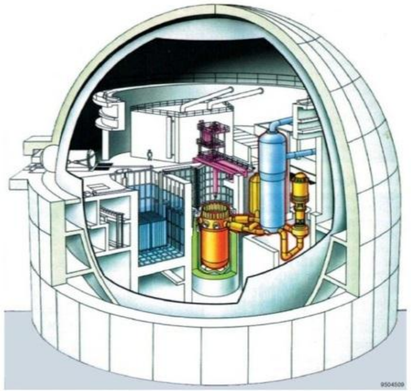
local equivalent stress t = **58,5 ms**



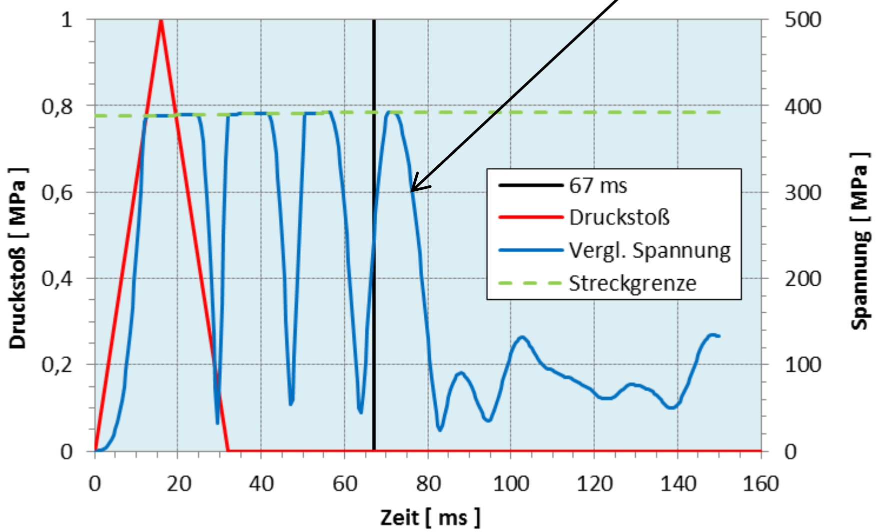


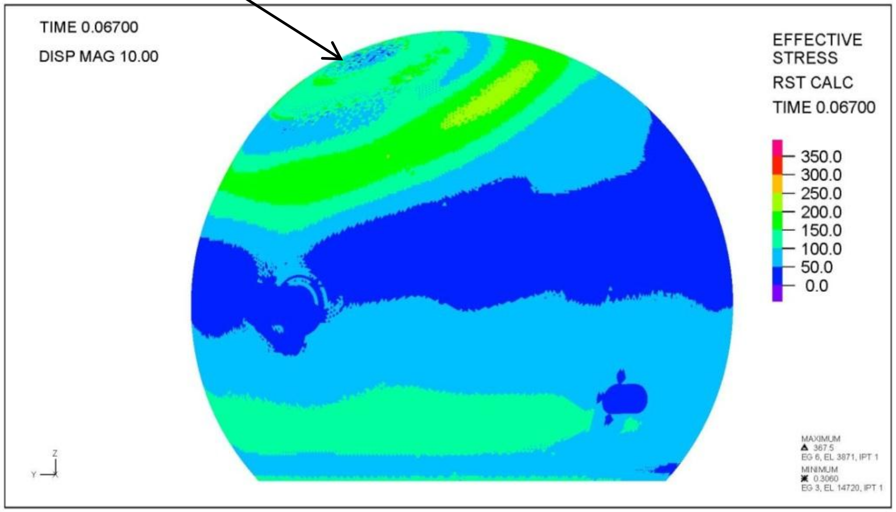
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

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



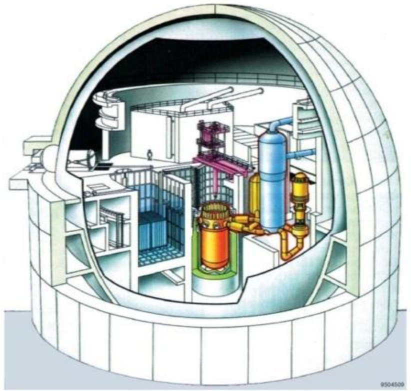
local equivalent stress t = **67,0 ms**



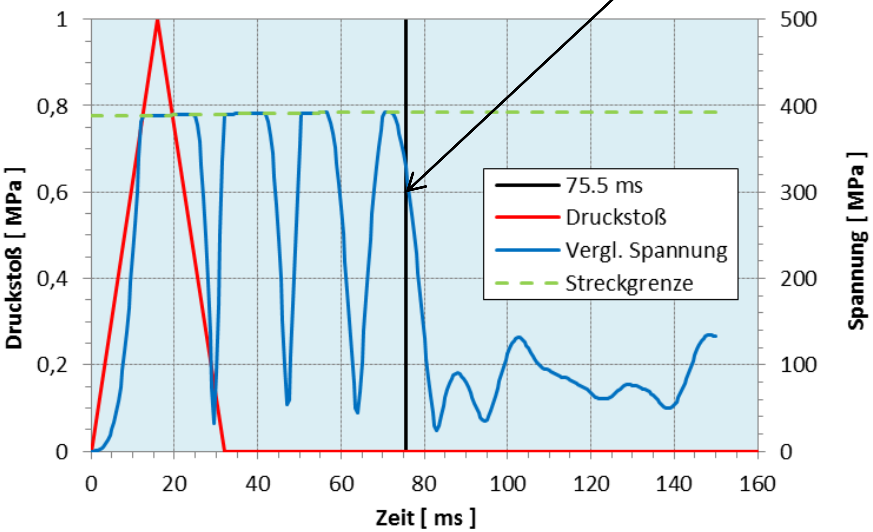


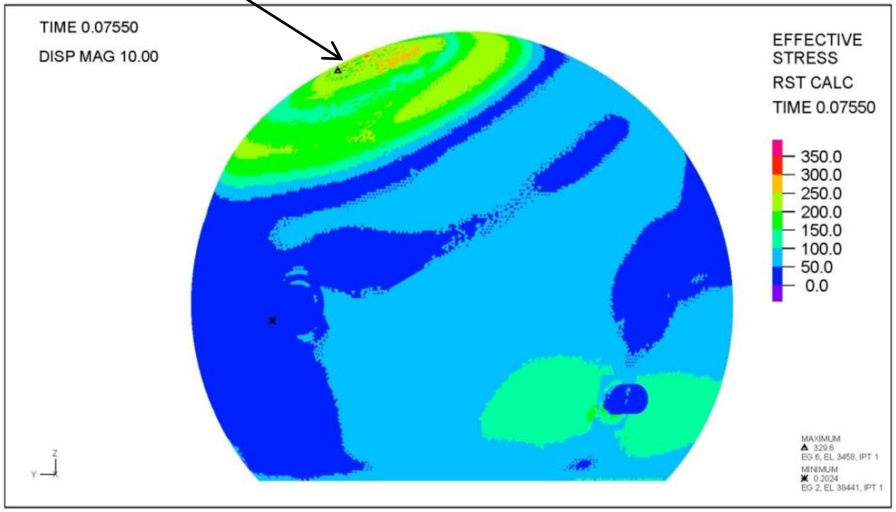
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

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



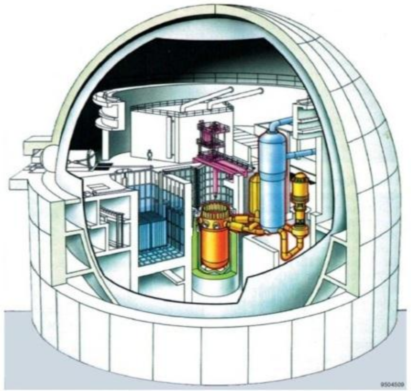
local equivalent stress t = **75,5 ms**



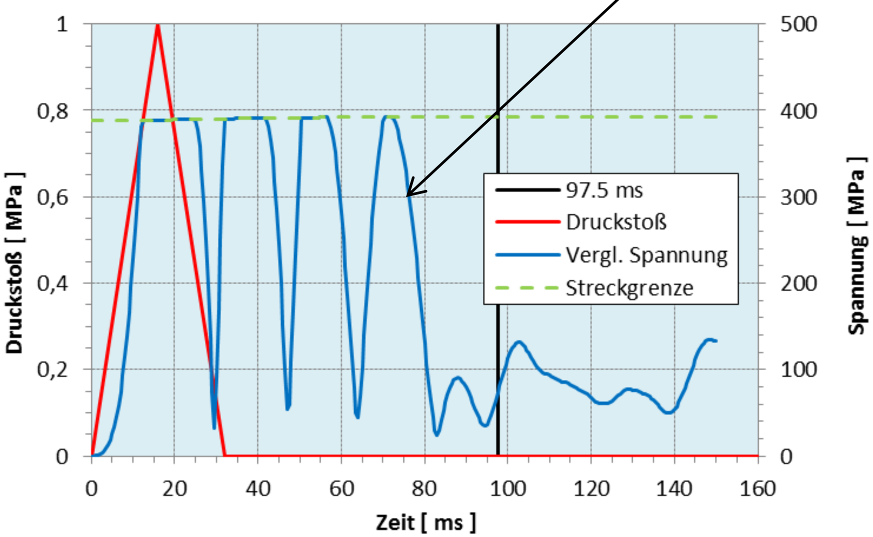


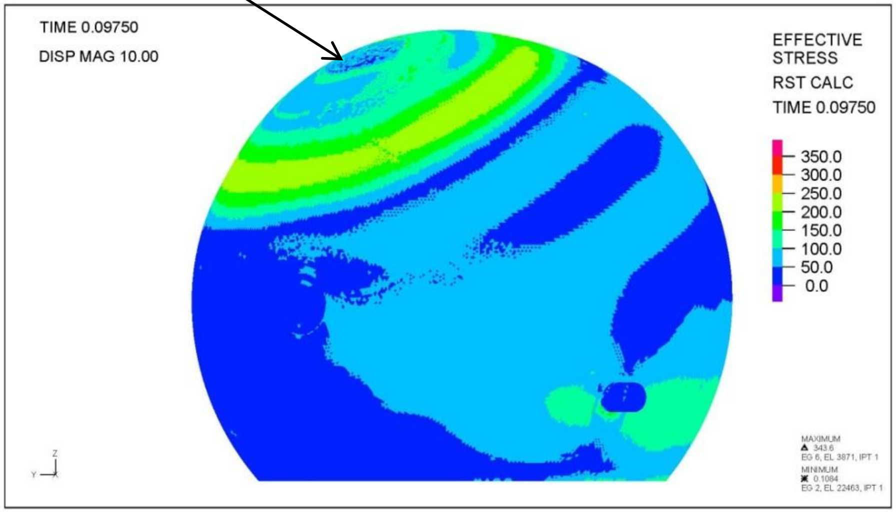
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

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



local equivalent stress t = **97,5 ms**

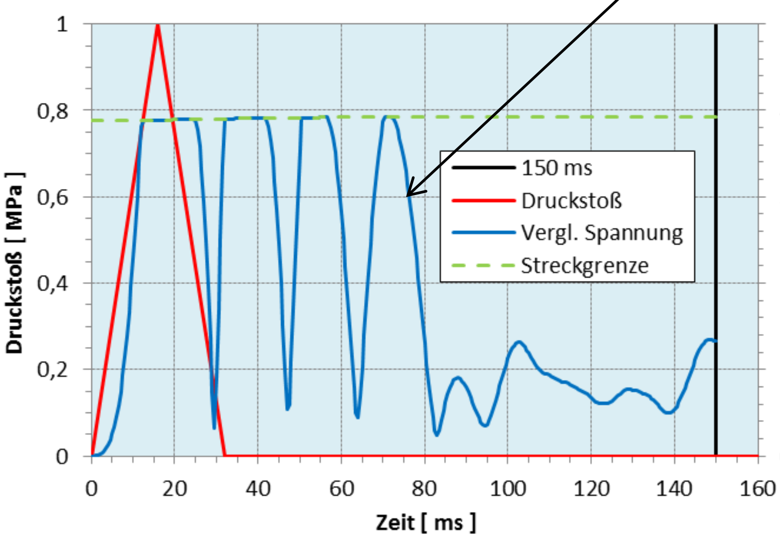


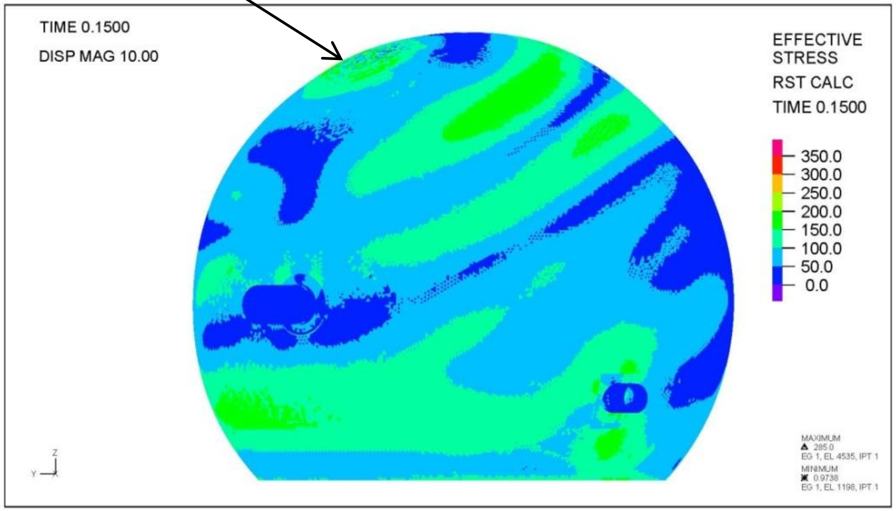


DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

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

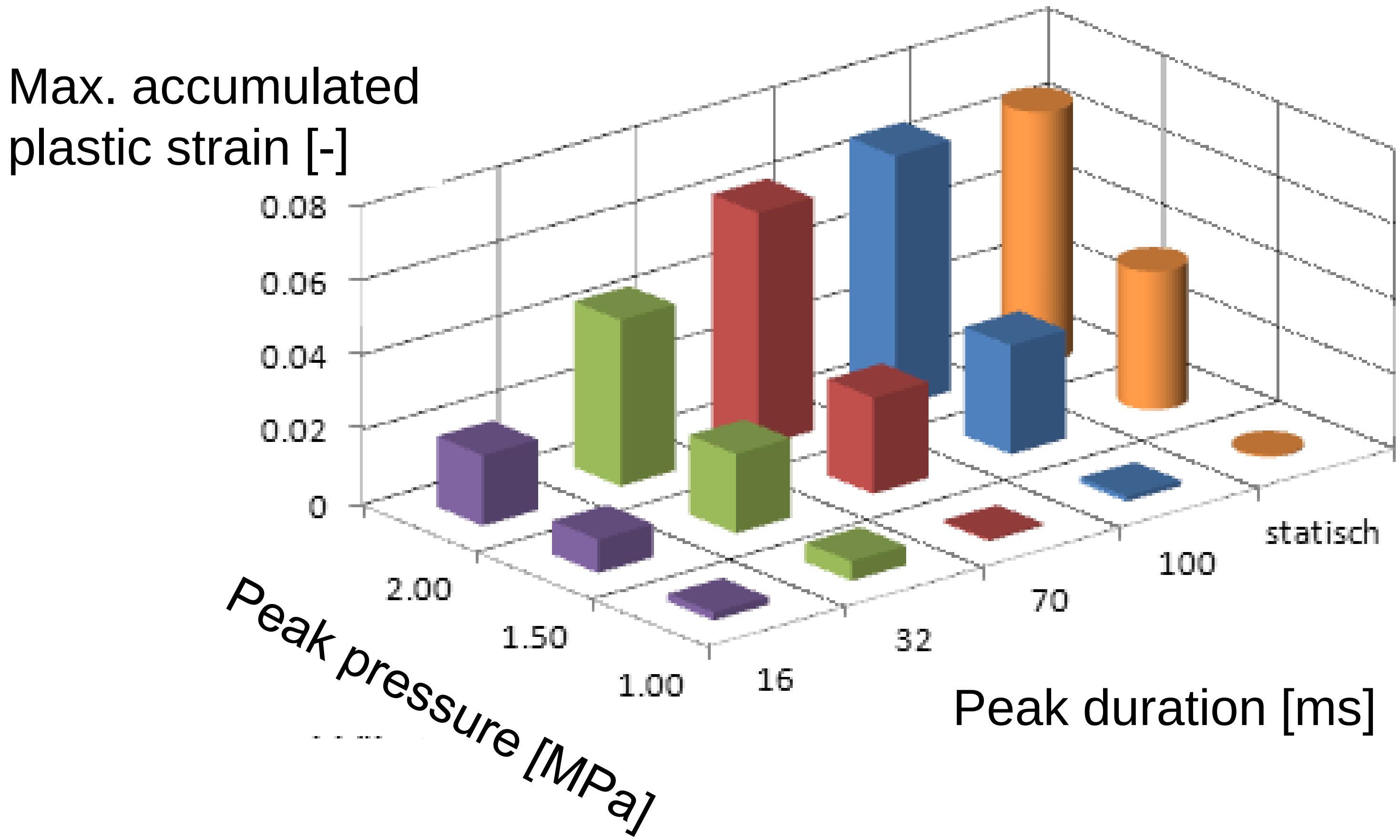
local equivalent stress t = **150,0 ms**





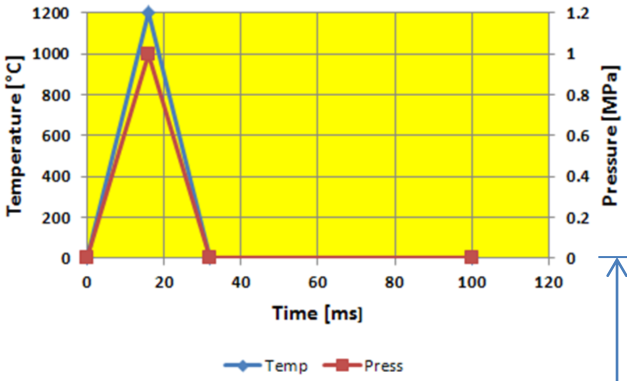
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Results of parametric study with pressure peak loading

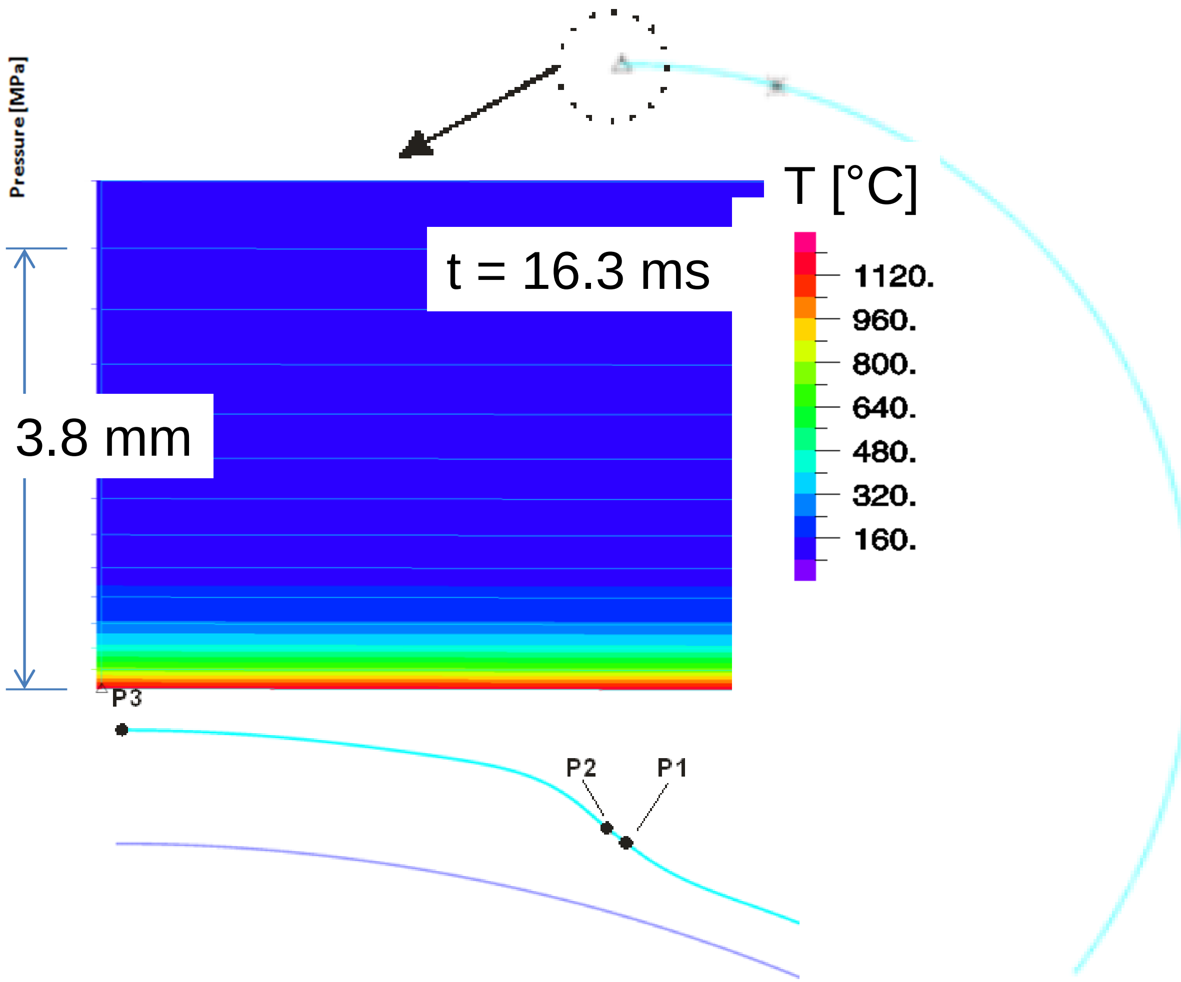


DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Consideration of temperature peak loading

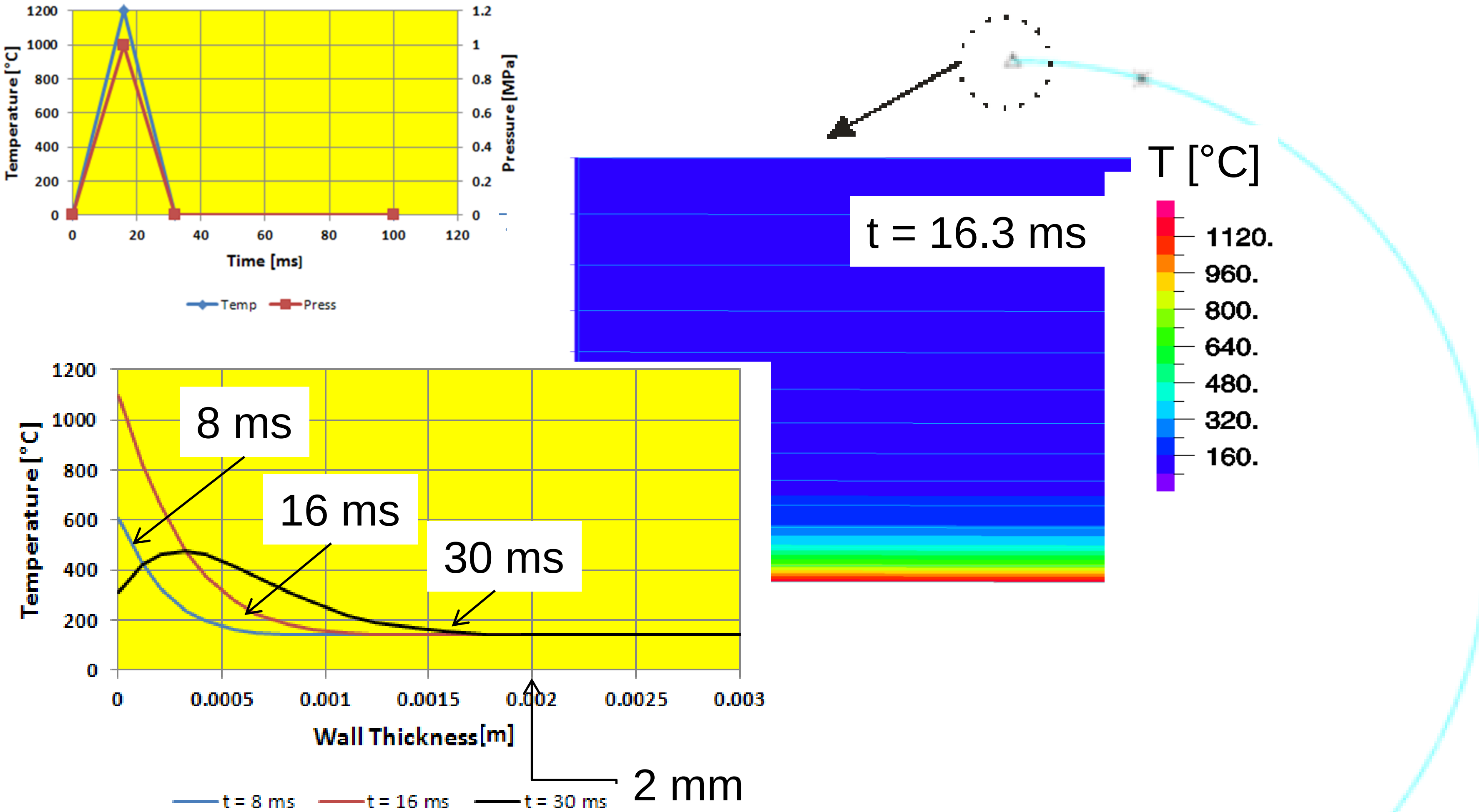


- Loadcase:
  Pressure peak with
  - Peak pressure 1 MPa
  - Peak temperature 1200°C
  - Peak duration 32 ms



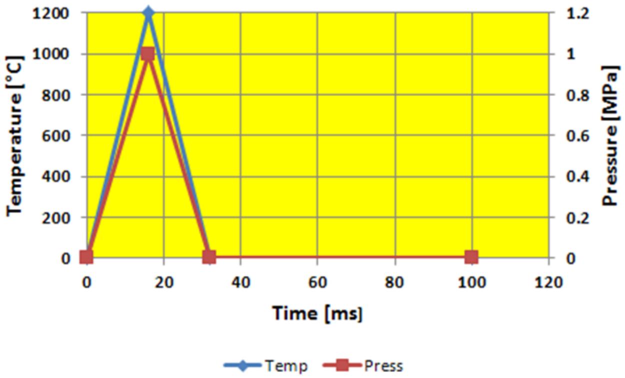
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Consideration of temperature peak loading



DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

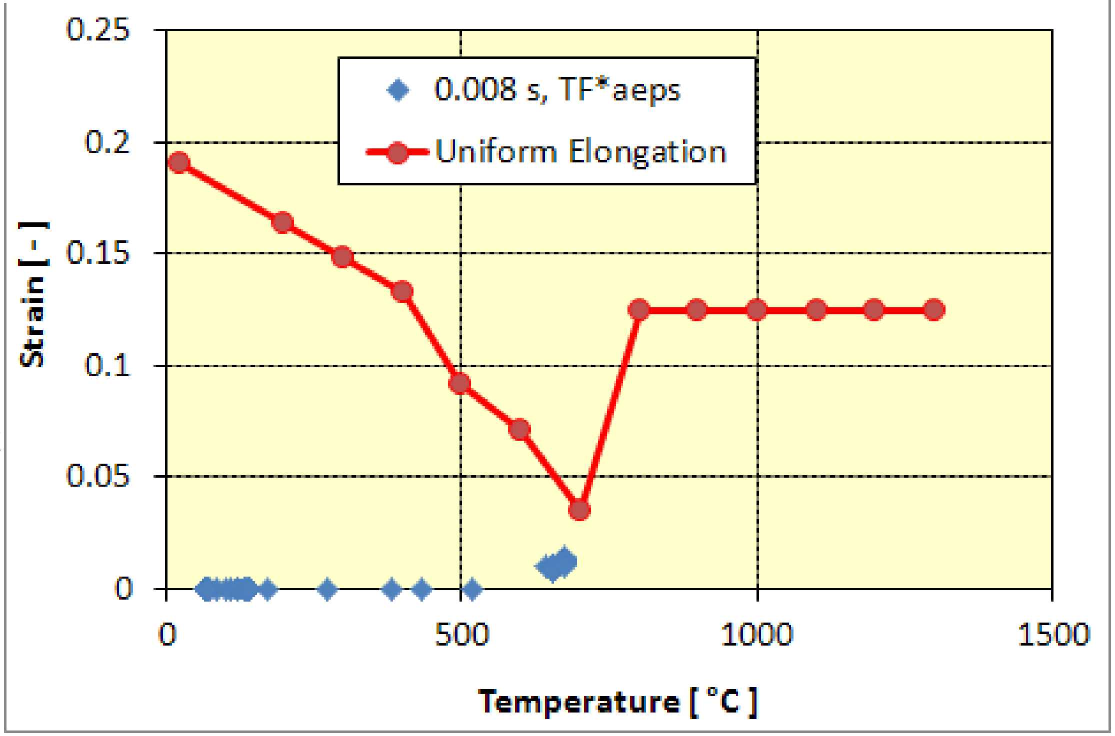
Integrity assessment with consideration of temperature peak loading



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

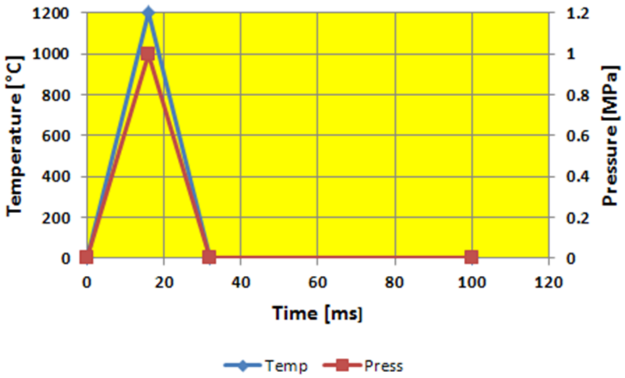
t = 8 ms

plastic strain * TF at different locations [-]



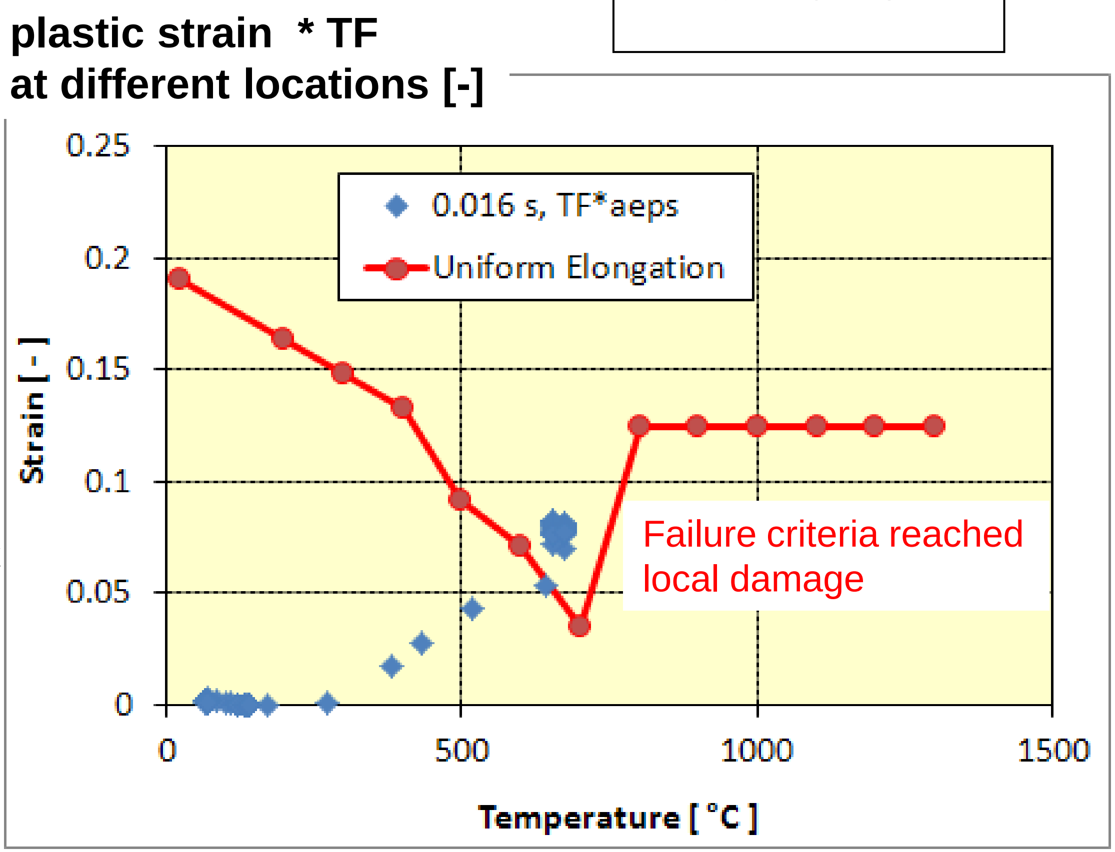
DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

Integrity assessment with consideration of temperature peak loading



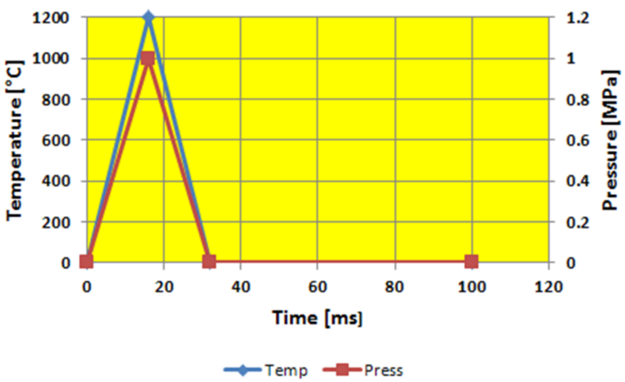
- Loadcase:
  Pressure peak with
  - Peak pressure 1 MPa
  - Peak temperature 1200°C
  - Peak duration 32 ms

t = 16 ms



DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

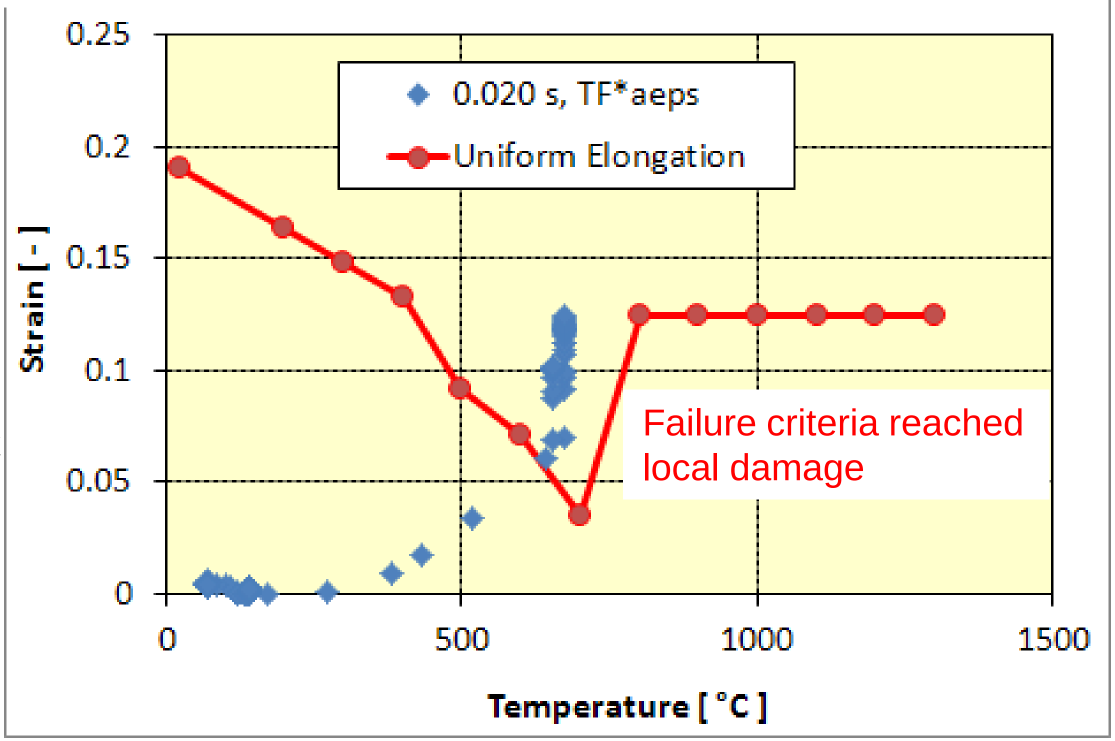
Integrity assessment with consideration of temperature peak loading



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

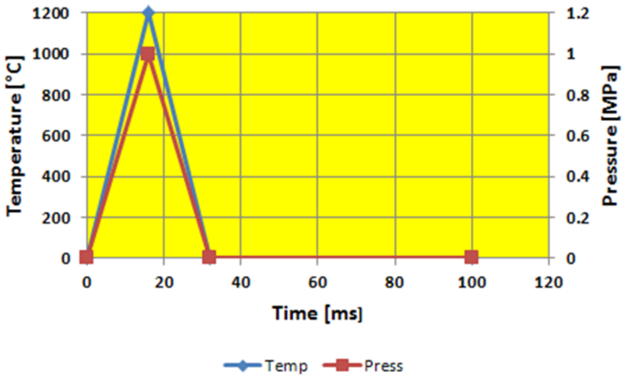
t = 20 ms

plastic strain * TF at different locations [-]



DYNAMIC BEHAVIOR OF STEEL CONTAINMENT

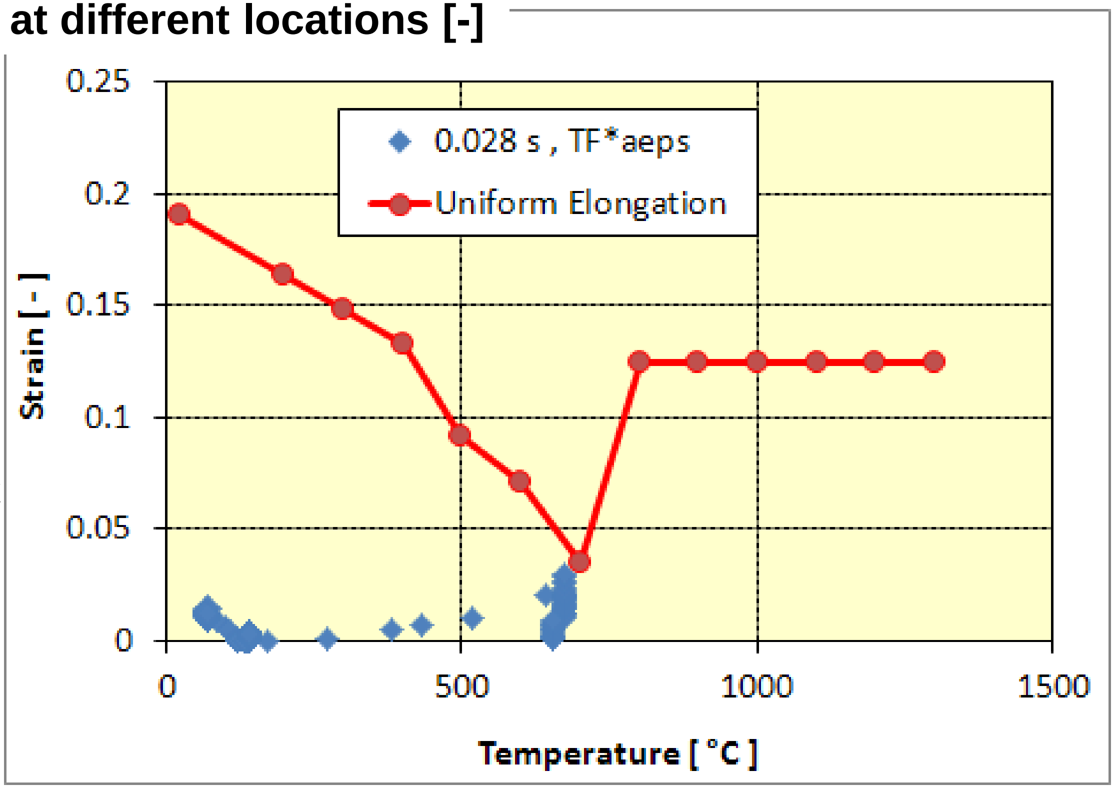
Integrity assessment with consideration of temperature peak loading



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

t = 28 ms

plastic strain * TF at different locations [-]



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