STANDARD PROBLEM EXERCISE (SPE)

PERFORMANCE OF CONTAINMENT VESSEL UNDER SEVERE ACCIDENT CONDITION

Project

- Scanscot organization
  - Patrick Anderson — Co-ordination, etc. (Phase 1 and 2)
  - Björn Svärd — Model 1, tendon study (Phase 1)
  - Oskar Elison — Model 2 and 3, liner study (Phase 1)
  - Torulf Nilsson — Failure criteria (Phase 1 and 2)

  - Ola Jovall — Initial planning, reviewing
  - Jan-Anders Larsson — Advising

- Financiers
  - Swedish Radiation Safety Authority (SSM) and Swedish / Finnish nuclear power industry

Overview

- Scope
- Scanscot SPE, Phase 2 studies
  - General
  - Size of liner tears
  - Leakage estimation
- Conclusions

Scope

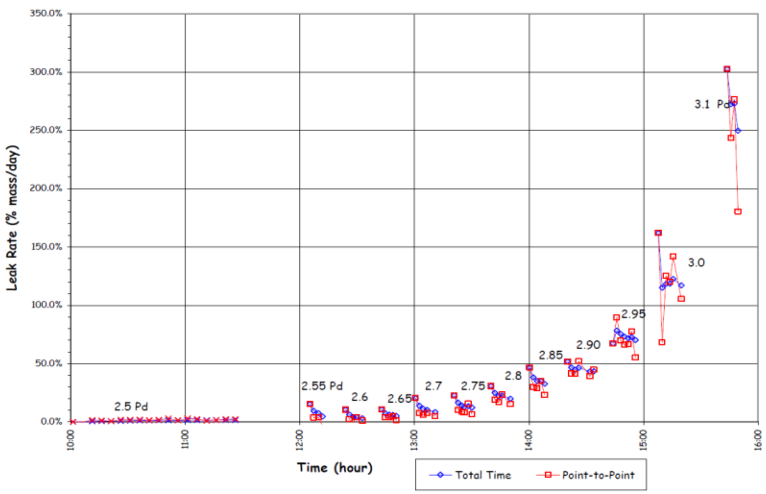
- Phase 2, studies

<u>Study 1</u> Estimate liner tear size in Sandia ¼ test. FE-model based on fracture mechanics is used (introduced in SPE phase 1).

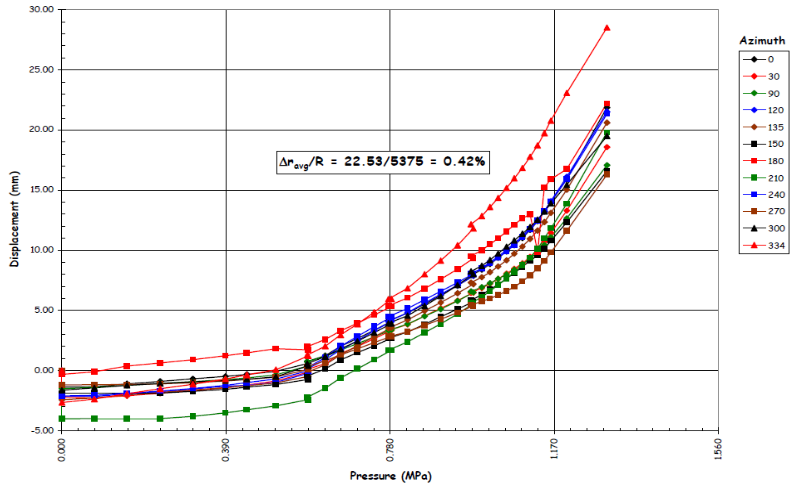
<u>Study 2</u> Measured leakage in Sandia ¼ test is compared with gas flow estimations based on liner post-inspections data.

SPE studies
General

- Sandia ¼ test measurements



LST – Leak Rate at 2.5 to 3.1 Pd (final ~900% at 3.3 Pd)

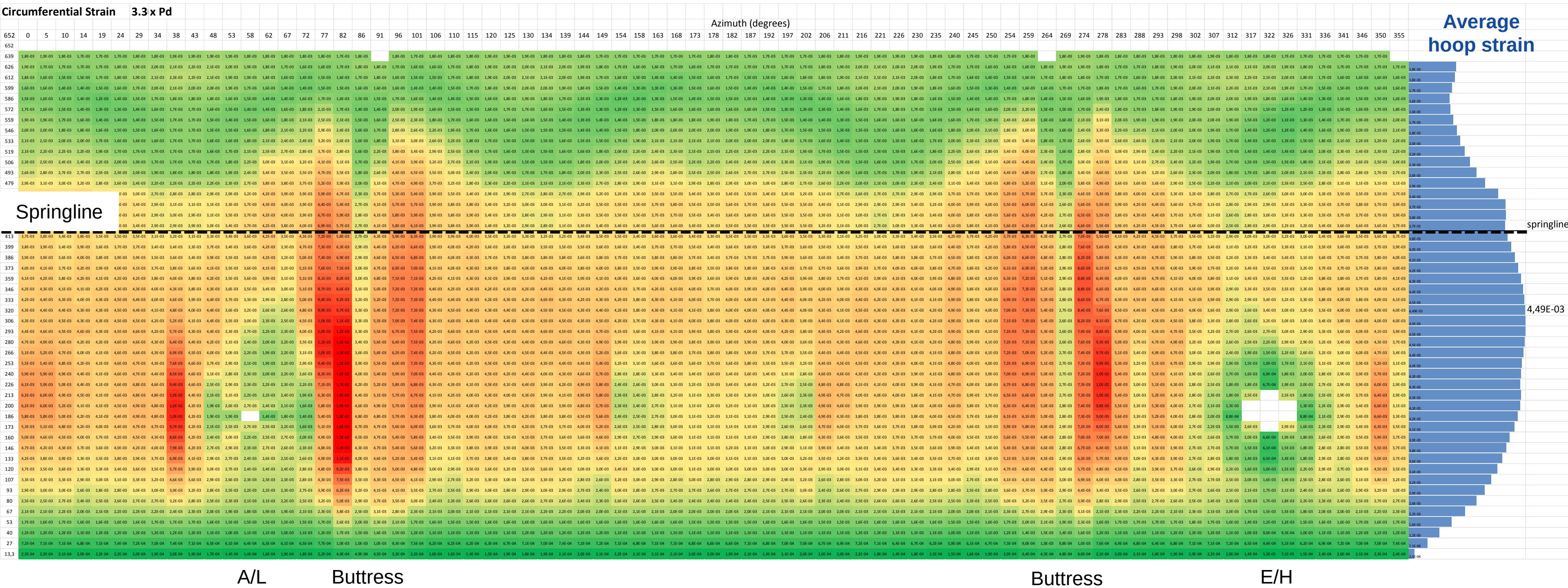


LST – Radial displacement at mid-height, final ~0.42% strain

SPE studies

General

- Hoop strain at 3.3 Pd, from Model 3 (strain mapping results)

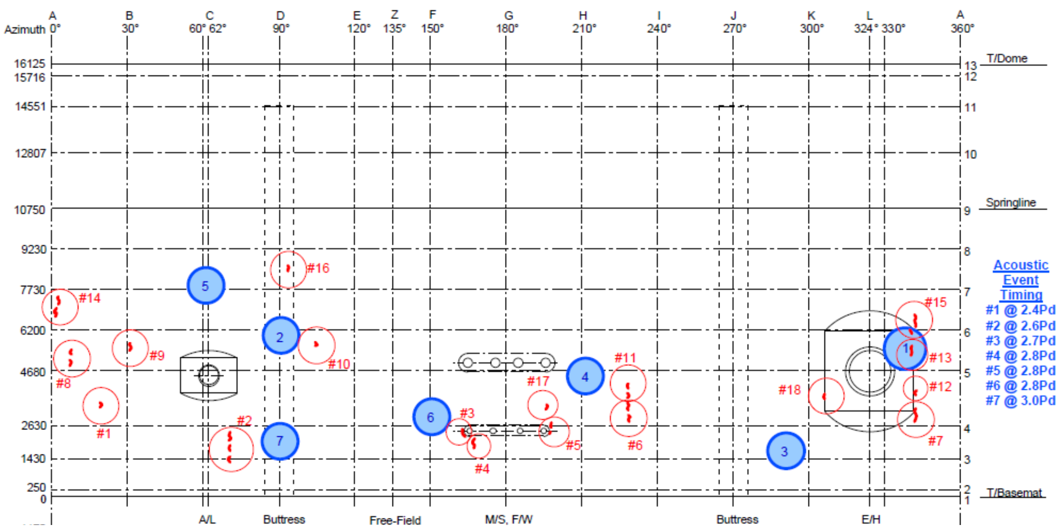


- Average strain at mid-height 0.45 % (measured 0.42%)
- Elevation below E/H up to springline show high strain level

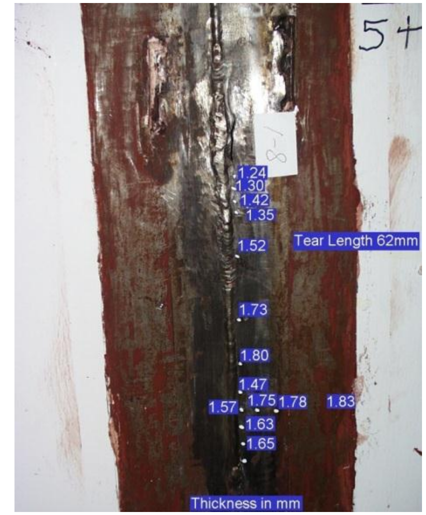
SPE studies

General

- Sandia ¼ post-test liner inspections



Stretch-out sketch of liner (red circles, identified liner tears)



Examples of data from liner post-test inspections,

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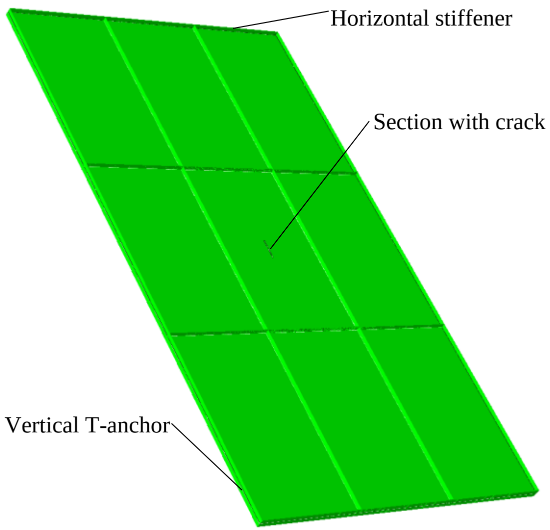
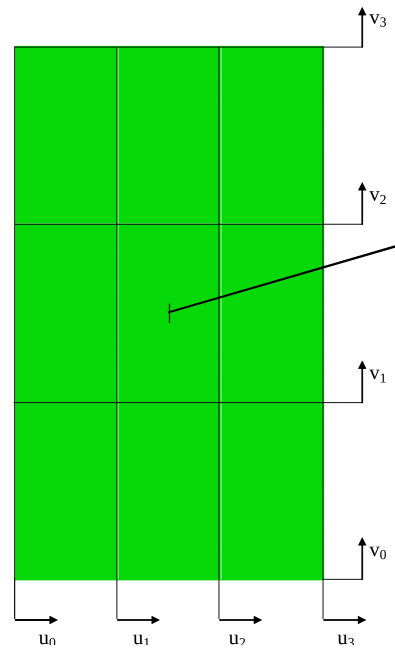
SPE studies

Size of liner tears

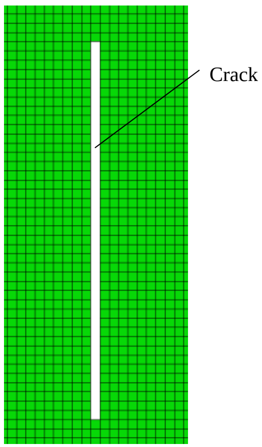
- Model introduced in Phase 1 studies



General liner field



Displacement load (average strain at 3.3 Pd)
horisontal ~0.4%, vertical ~0.1%

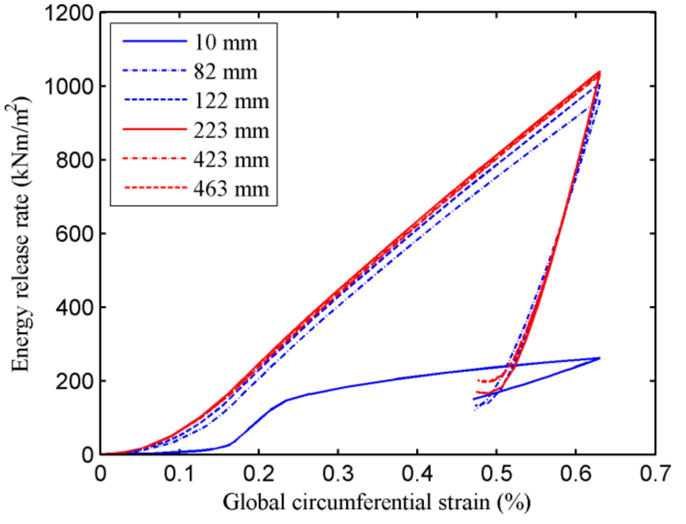


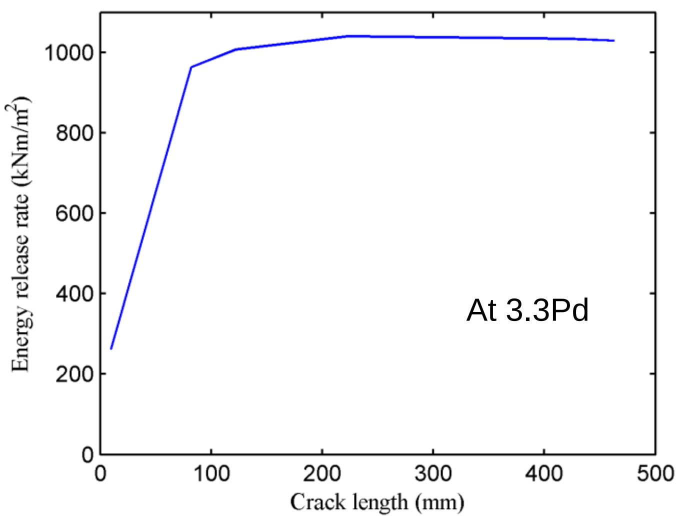
Mesh in crack region

- Plain strain elements, plastic material model
- Method based on non linear fracture mechanics (similar “phase 1 analysis definition”)
- Separate analyses. Increasing crack length is simulated by removing elements

SPE studies
Size of liner tears

- Results from Phase 1 studies





J-integral values from non-linear fracture mechanics evaluation.

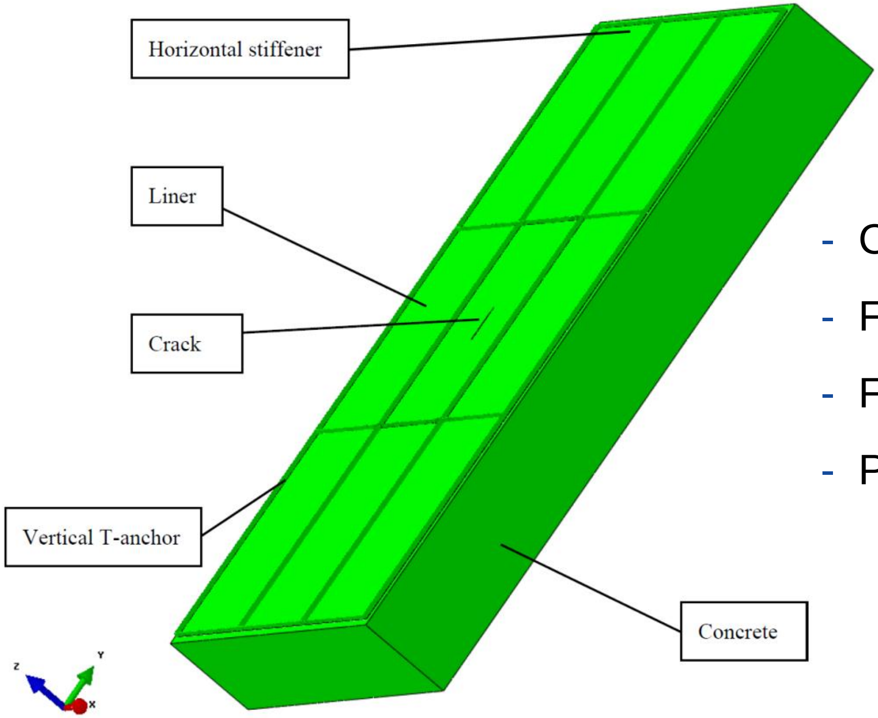
J-integral (energy release rate) >> J_{cr} => no apparent crack arrest found

Possible reasons: - Variation in liner thickness, material properties, etc.

- Friction between liner and concrete not modeled.

SPE studies
Size of liner tears

- Model, Phase 2 studies (including friction)



General liner field model, model including friction

- Concrete and liner modeled by shell elements
- Friction contact between liner and concrete
- Friction coefficient 0.6
- Pressure on liner 3.3Pd

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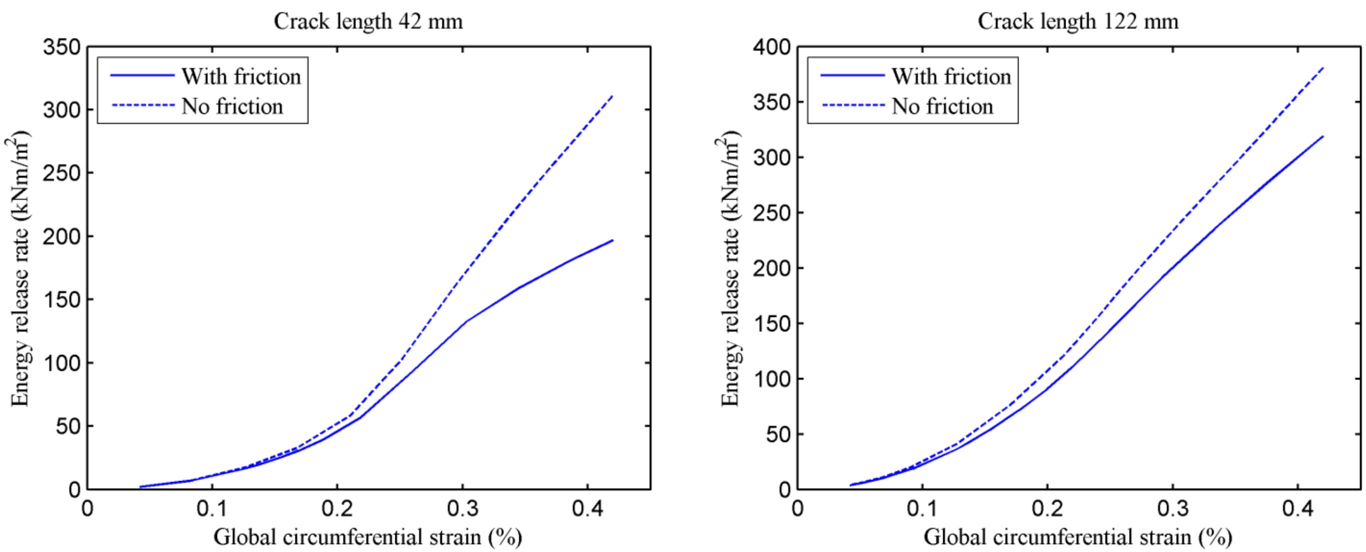
SPE studies
Size of liner tears

- Results, Phase 2 studies (including friction)



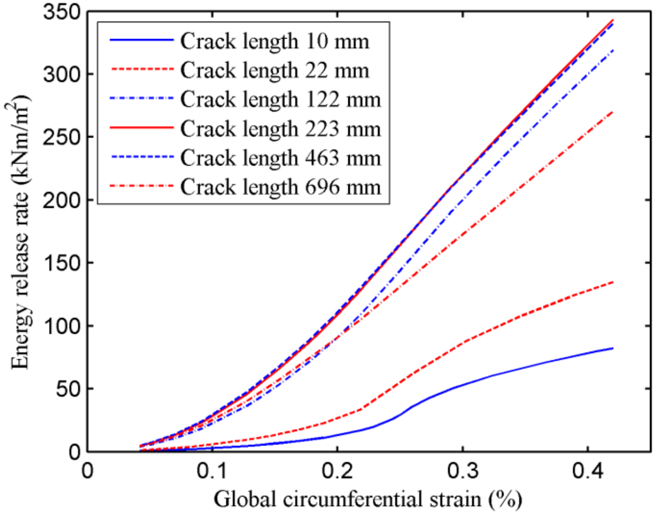
J-integral values from non-linear fracture mechanics evaluation.

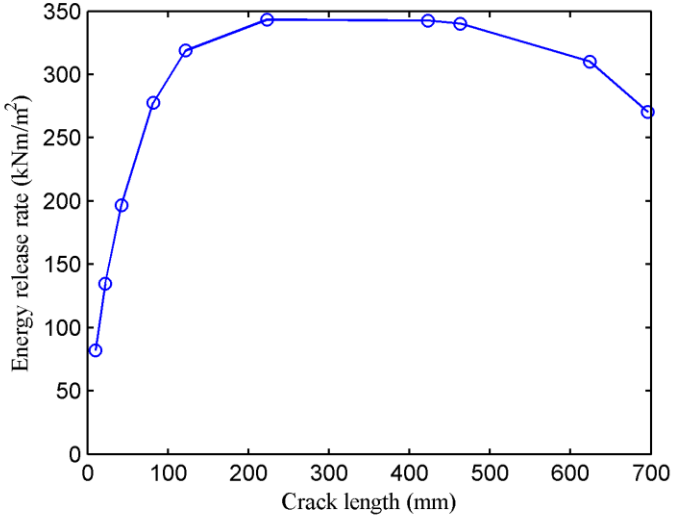
Friction decreases the energy release rate (J-integral)

The decrease in energy release rate seems to be less for increased crack length

SPE studies
Size of liner tears

- Results, Phase 2 studies (including friction)





J-integral values from non-linear fracture mechanics evaluation at global strain corresponding to 3.3Pd.

J-integal > J_{cr} ≈ 80 kNm/m^2 => no apparent crack arrest found

Possible explanations: - Variation in liner thickness and material properties

- Boundary conditions (stiffness in liner-concrete anchors)

SPE studies
Leakage estimation

- Estimation using Sandia ¼ post-inspection liner data
  - Leakage prediction at pressure level 3.3 Pd
  - Measured length of tears (post-test inspections)
  - Width and shape of tears from FE-model
  - Influence of cracked concrete

SPE studies

Leakage estimation

- Estimated liner tear area
  - Length of tears from post-inspection measurements
  - Width and shape of tears at 3.3 Pd estimated from FE-model
  - Shape of tears more or less rectangular acc. to FE-analysis (non-arrest)
  - An arrested tear assumed to be closer to elliptic shape (less plastic strain)
  - Rectangular shape ⇔ upper bound, elliptic shape ⇔ lower bound for liner tear area.

Tear	*Estimated crack area (mm^2)*
1	11.0
2-1	47.2
2-2	52.4
2-3	155.7
3	100.5
4-1	15.4
4-2	3.2
4-3	37.5
5-1	6.4
5-2	16.8
6-1	98.9
6-2	106.4
7	82.0
8-1	41.0
8-2	21.4
9	112.6
10	5.7
11-1	84.0
11-2	53.4
12	14.0
13	24.7
14-1	56.5
14-2	108.8
15	21.0
16	67.9
17	1.6
Sum	1346.0

<u>Estimated crack area (upper bound)</u>

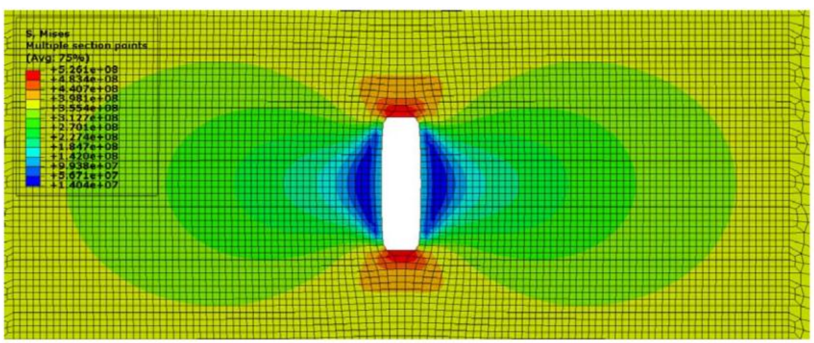
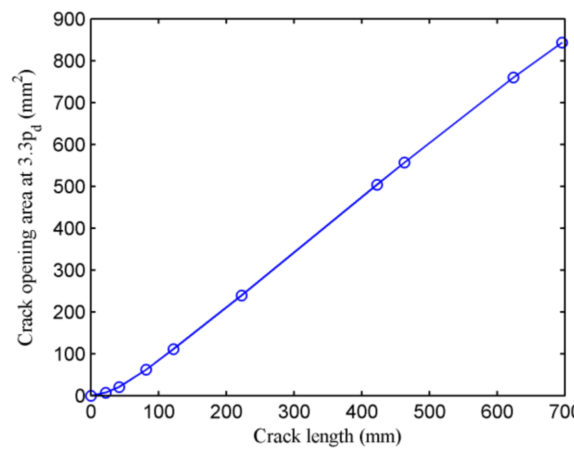


Figure 3.9 Crack shape according to FE-analysis, crack length 42 mm (Deformation magnified 20x).



SPE studies

Leakage estimation

- Influence of cracked concrete

- Leak area for liner and concrete

$A_{liner} \sim \underline{1.35*10^{-3}}\ m^2$ (acc. estimation on previous slide)

$A_{concrete} \sim \varepsilon_g*\pi*D*h = 0.0042*\pi*10.75*10 = \underline{1.42}\ m^2$ (all strain located to crack)

- Estimated concrete crack space and corresponding crack width at 3.3 Pd

	ε_g (%)	Max. crack space (mm)	Max. crack width (mm)
Model Code 1990	0.42	350	1.5
Eurocode 2	0.42	590	2.5

The influence of cracked concrete on the measured leakage is assumed to be small at high pressure levels. Also shown in literature (see e.g. EPRI research)

SPE studies

Leakage estimation

- Results, estimated leakage

- Expressions for mass flow through convergent nozzle
- At 3.3Pd the maximum capacity of pressurization system was reached 142 std.m^3/min
- Assuming IUPAC Standard Temperature and Pressure (not given), 142 std.m^3/min ⬄ 3.0 kg/s
- Calculated mass flow 4.3 kg/s, ~45% overestimation.
- Possible reasons for overestimation:
    - * Crack shape, assuming elliptic shape => decreased leakage
    - * Concrete, liner tears in less cracked regions

Frictionless mass flow through convergent nozzle

$$\left(\frac{p_2}{p_1}\right)_c = \left(\frac{2}{k+1}\right)^{k/(k-1)}$$

$$\left(\frac{p_2}{p_1}\right)_c = 0.5283$$, sonic flow =>

$$\boxed{\dot{m} = \frac{A_2 p_1}{\sqrt{T_1}} \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}}$$

$A_2 = 1.3*10^{-3}$ m^2 (total leakage area)
$p_1 = 0.1 + 3.3*0.39 = 1.39$ Mpa (pressure at 3.3 Pd)
$k = 1.4$ (for nitrogen gas)
$R = 296.5$ J/kgK (gas konstant)
$T_1 = 293$ K. (around 20 °C)
=>
$\dot{m} = 4.3$ kg/s

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Conclusions

- Liner tear size
  - FE-model based on fracture mechanics
  - No final tear length could be found (no crack arrest found)
  - Friction influences the J-integral
  - Explanations: Varying liner thickness and material properties
    Liner boundary conditions (liner ⇔ concrete)
- Leakage estimation
  - Prediction made for the Sandia ¼ test at 3.3Pd
  - Measured length of tears (post-test inspections)
  - Width and shape of tears from FE-model
  - Influence of cracked concrete assumed to be low
  - Frictionless gas flow through convergent nozzle
  - Calculated mass flow, 45% overestimation
  - Explanations: shape of liner tears, friction from concrete