STANDARD PROBLEM EXERCISE (SPE-3) ON PERFORMANCE OF CONTAINMENT VESSEL UNDER SEVERE ACCIDENT CONDITIONS

Phase-2

Part- II: Estimation of Leakage through Containment wall

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Outline of the Presentation

- **Introduction**
- **Methodology**
- **Results**
- **Conclusions**

Introduction

Objective of Phase-2: Part-II of SPE3

- Estimation of leakage rate through PCCV
  - Internal pressure only
  - Internal pressure and temperature.
    - Case-1 (Pseudo time history)
    - Case-2 (SBO)
- Transition to probabilistic space

Methodology

Assumptions

- Crack width and number of cracks in PCCV section are functions of strain in prestressing cables.
- Vertical through-the-wall cracks due to hoop strains only are considered.
- Leak rate through concrete cracks is controlled by extent of liner damage at co-locations.
- Properties of air are considered constant throughout.

Methodology

Calculation of concrete crack width

(Rizkalla et. al., 1984, Jnl of Struc. Engg, ASCE, 110(9))

$$Wtwc := \varepsilon \cdot L0 + \varepsilon m \cdot Lt$$

$$L0 := \frac{fs2\_cr1}{6500} \cdot db$$

(Lost bond length)

$$Lt = s - L0$$

(Bond transfer length)

$$\varepsilon m := \varepsilon \cdot \left[1 - \left(\frac{fs2\_cr}{stress} \right)^2 \right]$$

Where,

Wtwc=average through-the-wall crack width

ε=strain in prestresing cable

εm= mean strain in the section

s= spacing of cables parallel to cracking

fs2_cr= cable stress at on-set of cracking

fs2_cr1=same as fs2_cr in psi

db=equivalent dia of cable

stress=stress in cable

Methodology

Number of cracks in PCCV

(Rizkalla et. al., 1984, Jnl of Struc. Engg, ASCE, 110(9))

$$Ntwc := \begin{cases} \dfrac{L}{s} & \text{if } s \le 2 \cdot tw \\ \left(2 \cdot \dfrac{L}{s} - 1\right) & \text{otherwise} \end{cases}$$

$$Nc := \begin{cases} \left(Ntwc \cdot \left| \dfrac{\varepsilon - \varepsilon s2\_cr}{0.002 - \varepsilon s2\_cr} \right| \right) & \text{if } \varepsilon < 0.002 \\ Ntwc & \text{otherwise} \end{cases}$$

Ntwc= No. of through-the-wall cracks for strain (ε) ≥ 0.002

Nc= No. of through-the-wall cracks for strain (ε) < 0.002

L= gauge length, here 0.2m

s= spacing of cables parallel to cracking

εs2_cr= strain in cable at on-set of cracking

The numbers of cracks are rounded off to the nearest whole number

Methodology

Leakage rate calculation

- In this study, it is assumed that air leaks through cracked concrete but amount of leakage is controlled by the degree of damage in the co-located liner.
- The leakage path would be through the co-located parts of concrete and liner as this would also be the path of least resistance for air flow.
- It is assumed that the liner damage permitting leakage initiates when the induced liner stress correspond to the liner fracture toughness, Jcr.

Methodology

Leakage rate calculation

- The ultimate liner damage, when it ceases to control the leakage through cracked concrete, is assumed to occur when the induced liner strain reaches the rupture strain.

- The rupture strain value is modified using a triaxiality factor for the biaxial state of strain in the containment wall.

- $$TF = \frac{\sqrt{2}(\sigma_1 + \sigma_2 + \sigma_3)}{\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2}}$$

Assuming hoop stress to meridional stress ratio of 2.0, the triaxiality factor (TF) works out to be 1.7.

Methodology

Leakage through concrete cracks

(Rizkalla et. al., 1984, Jnl of Struc. Engg, ASCE, 110(5))

$$\frac{p_1^2 - p_2^2}{t} = \left(\frac{k^n}{2}\right)\left(\frac{\mu}{2}\right)^n (RT)^{n-1} \left|\frac{p_2 Q}{b}\right|^{2-n} \frac{1}{\sum_{i=1,j} W_j^3} \quad ; \quad \sum_{i=1,j} W_j^3 = 1.42 N W_{av}^3$$

$$n = \frac{0.133}{\left(\sum W_i^3\right)^{0.81}} = \frac{0.195}{\left(N W_{av}^3\right)^{0.063}} \qquad k = 2.907x10^7 \left(\sum W_i^3\right)^{0.428} = 8.702x10^6 \left(N W_{av}^3\right)^{0.367}$$

Where, Q = flux through the wall (ft^3/s), b = extent of crack (ft), W = crack opening (ft), t = wall thickness, p_1 = upstream pressure (lb/ft^2), p_2 = downstream pressure (lb/ft^2), m = dynamic viscosity of air or gas used ($lb\ s/ft^2$), T = absolute temperature (R), R = gas constant ($sqft/s^2$ per R) and N =number of cracks.

Methodology

Step by step leakage rate calculation:

(i) Strains and stresses of cables and strains of liner in hoop direction in each element (0.2 x 0.2 sqm), at each load step are captured and stored.

(ii) Cable strains are checked against concrete cracking strain to establish on-set of cracking for each element.

(iii) Crack width and number of cracks are calculated for each cracked element. Crack height is assumed as element height.

(iv) Gross leakage through concrete is calculated for each element

Methodology

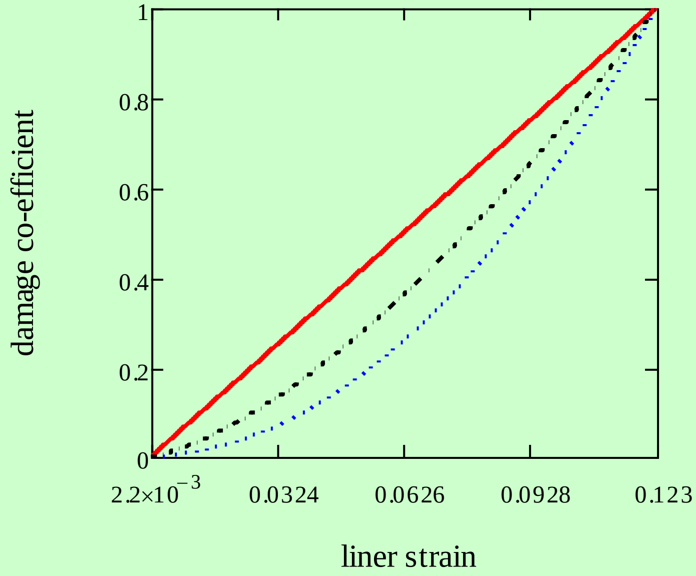
Step by step leakage rate calculation:

(v) Liner strain checked in each element for initiation of liner damage

(vi) If liner strain is more than damage initiation strain, damage co-efficient is calculated for each of the three assumed variations of the damage co-efficient between zero to one, viz. linear, parabolic and power variation.

Damage co-efficient is 1.0 at failure strain, which is 20% strain multiplied with ductility factor (μ=2^(1-TF))

For strains less than the initiation strain, damage coefficient is considered zero.



Methodology

Step by step leakage rate calculation:

(vii) Effective leakage rate=gross leakage rate x damage co-efficient

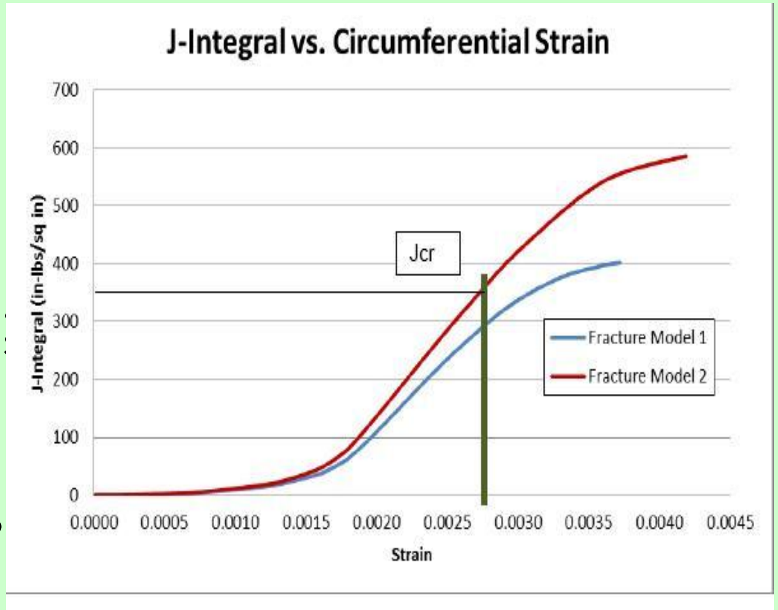
(viii) Total leakage rate =sum of effective leakage rates in all the elements.

This leakage rate is then converted to %volume of containment per day.

(ix) Repeat step-(i) to (viii) for various load steps.

Results

Liner damage initiation is estimated based on Jcr (taken from the tech memo by Dameron et. al.)



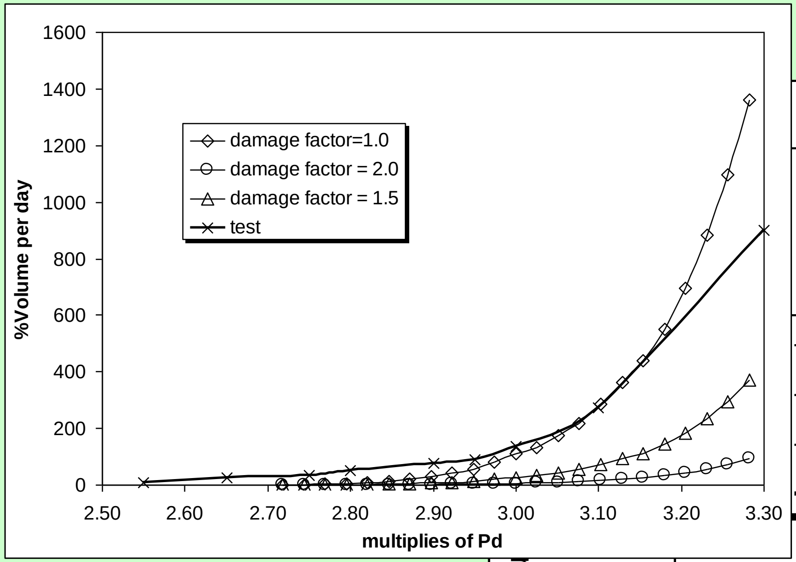
Three values of Jcr are considered; 200,350 and 500 in-lbs/sq in.

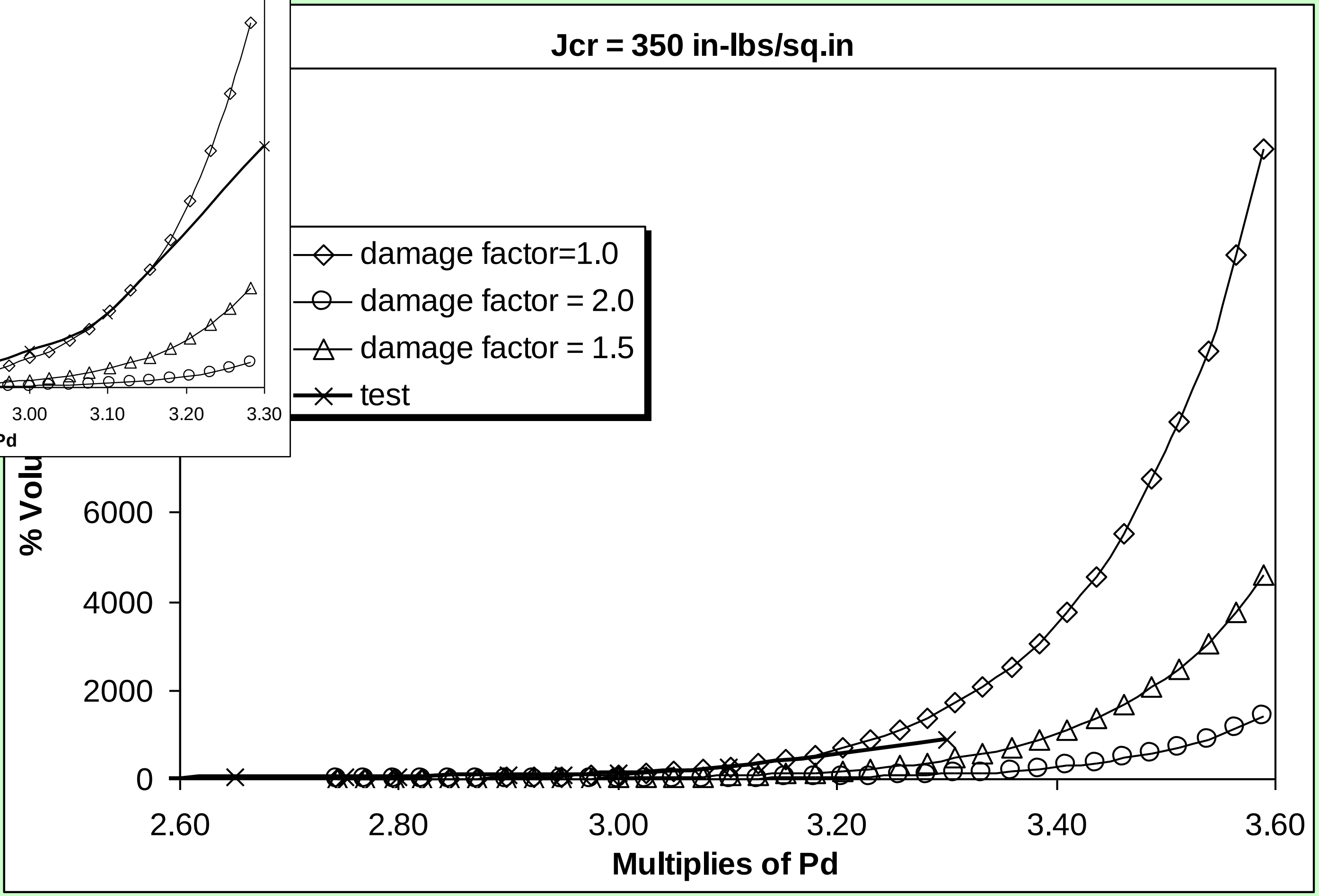
The corresponding average strains for damage initiation are 0.0022, 0.0028 and 0.0034 respectively.

The cracking strain of the homogenized composite section was calculated to be 0.000629.
Leakage rates were estimated for Phase-1, Phase2:case-1 and Phase-2:case-2 exercises.

Results

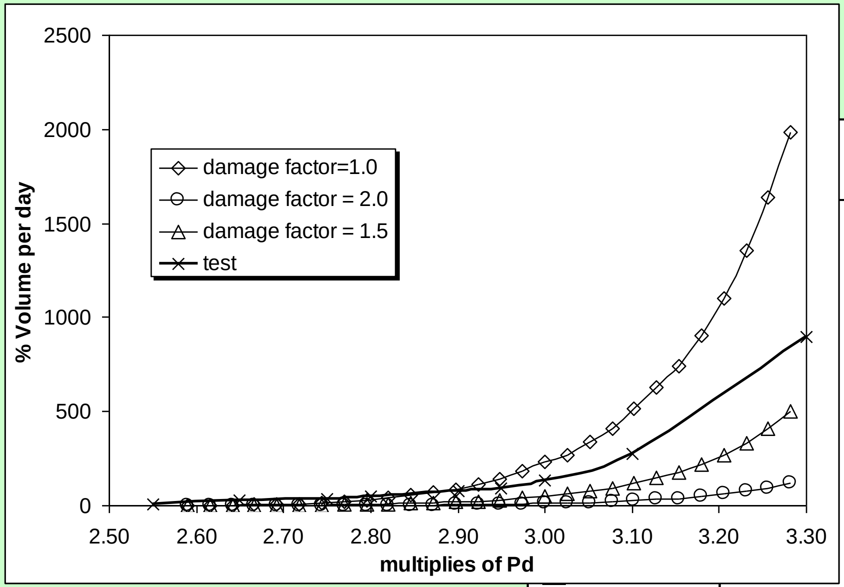
Phase-1 exercise

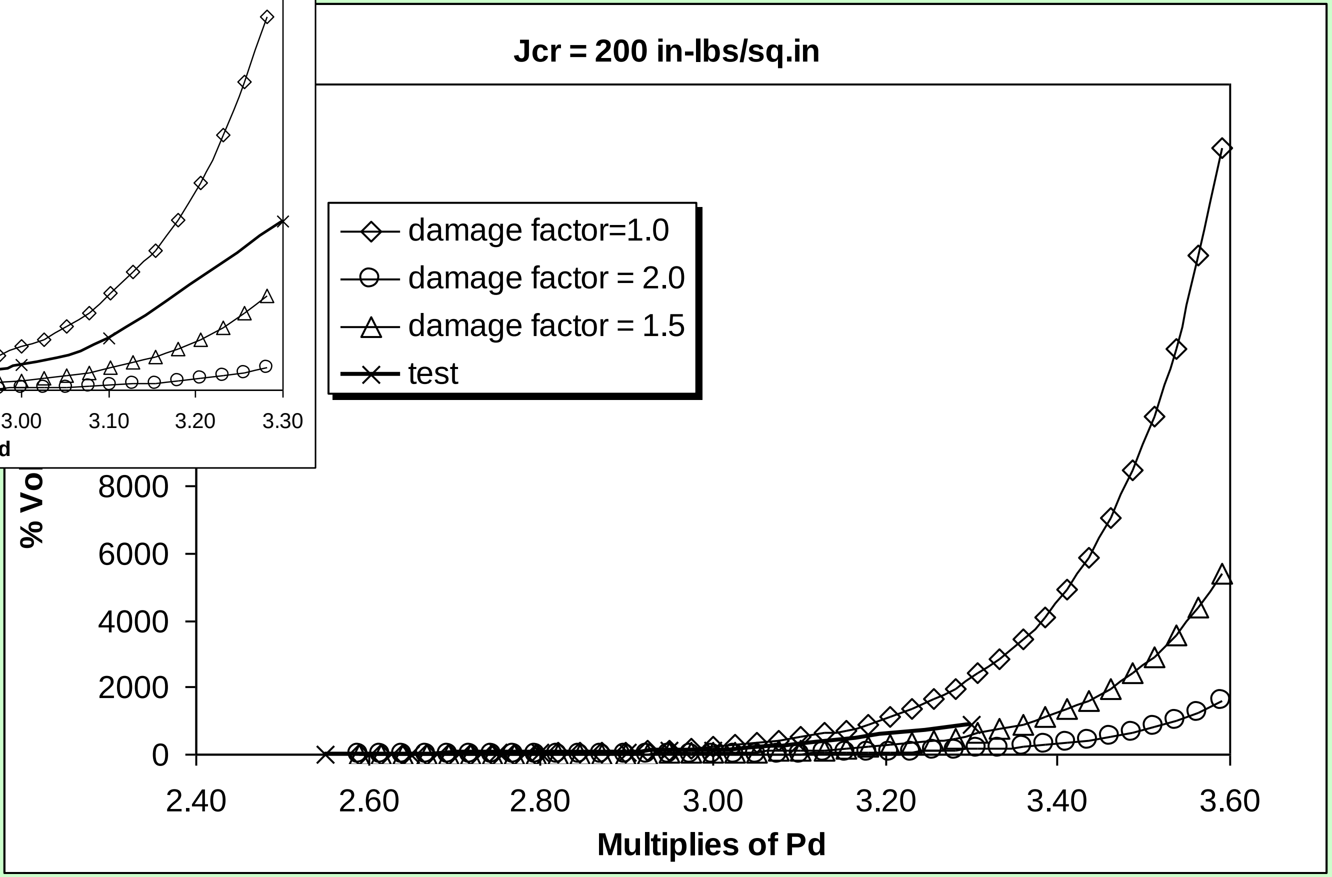




Results

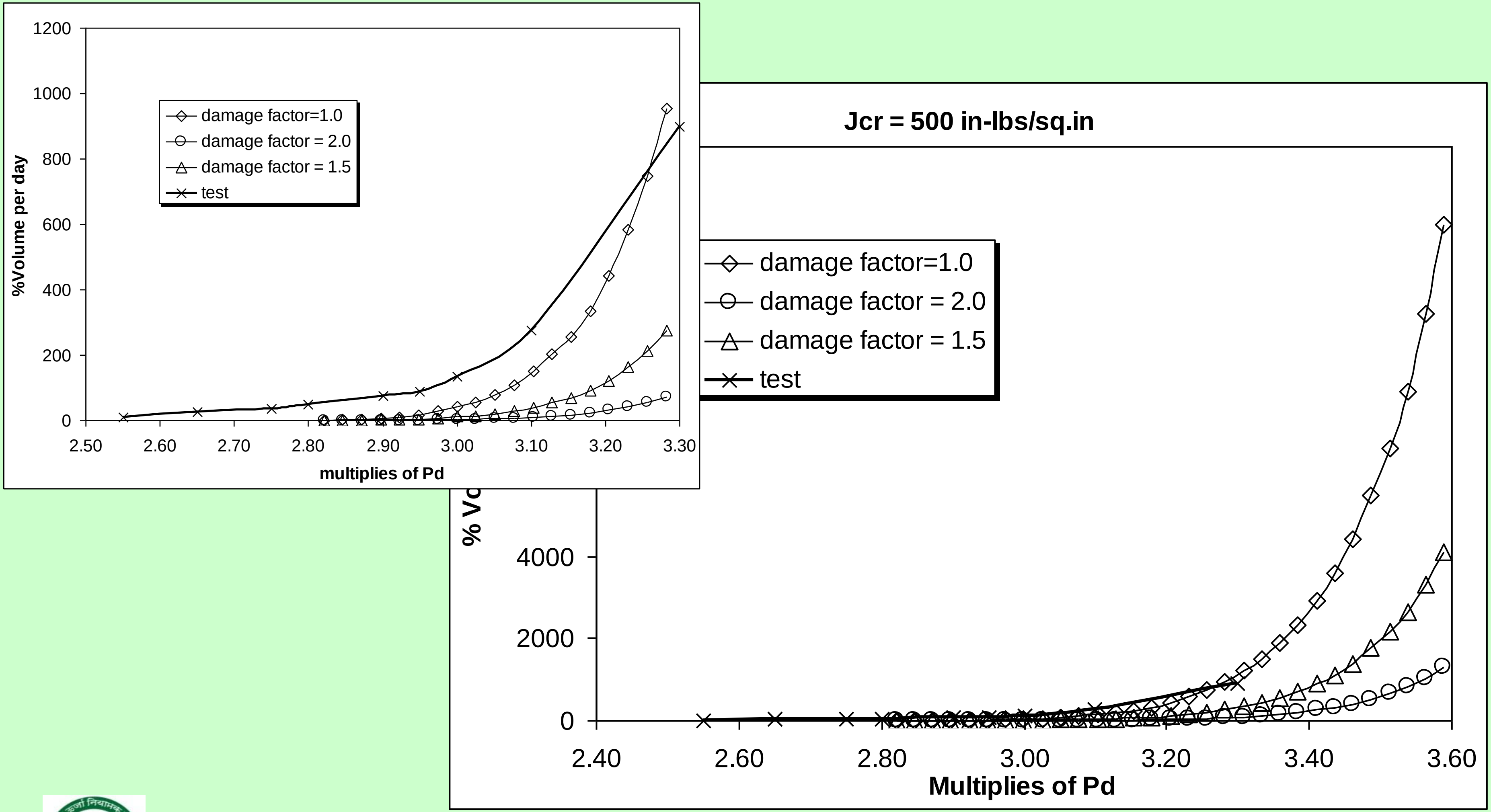
Phase-1 exercise





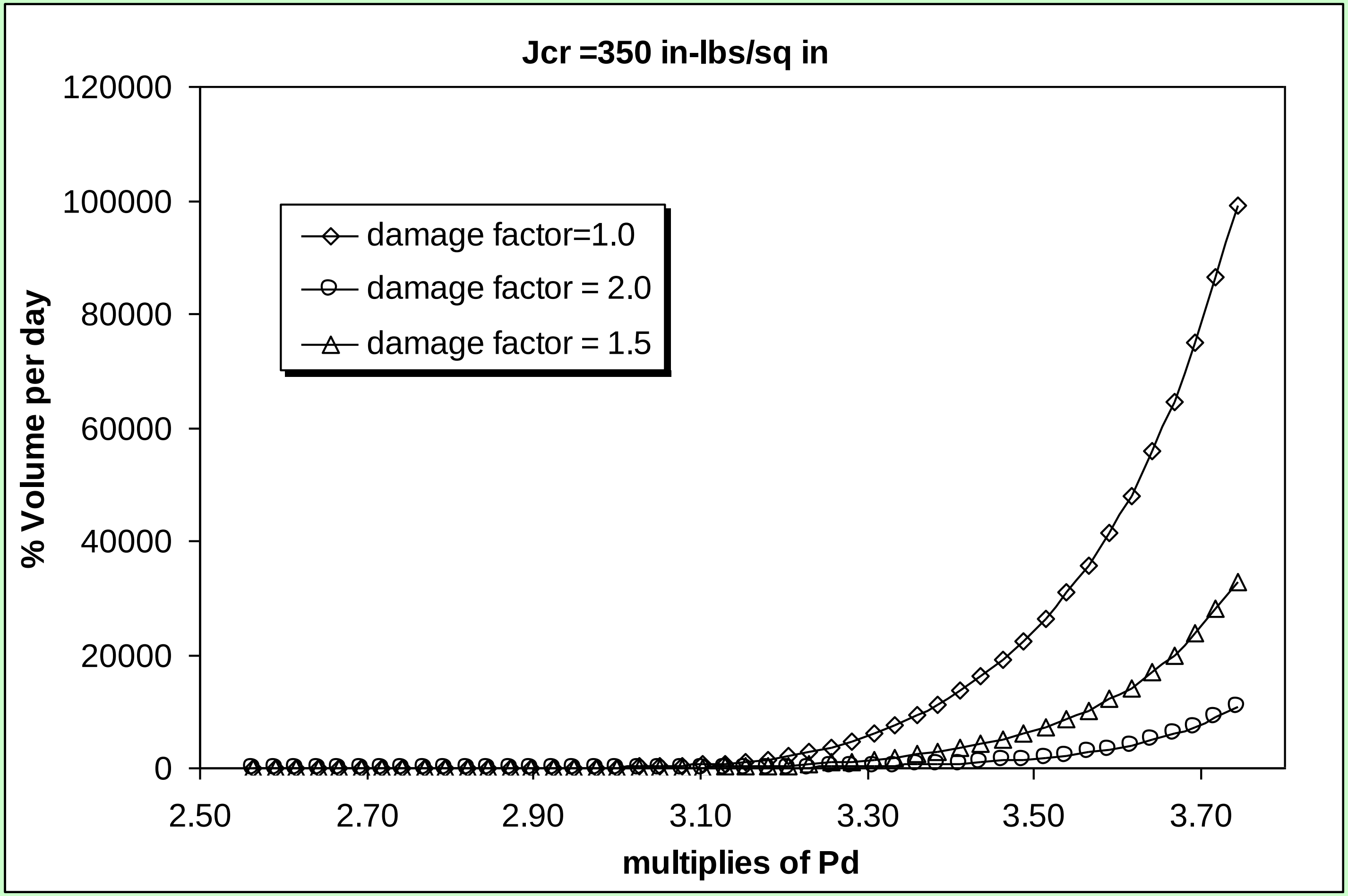
Results

Phase-1 exercise



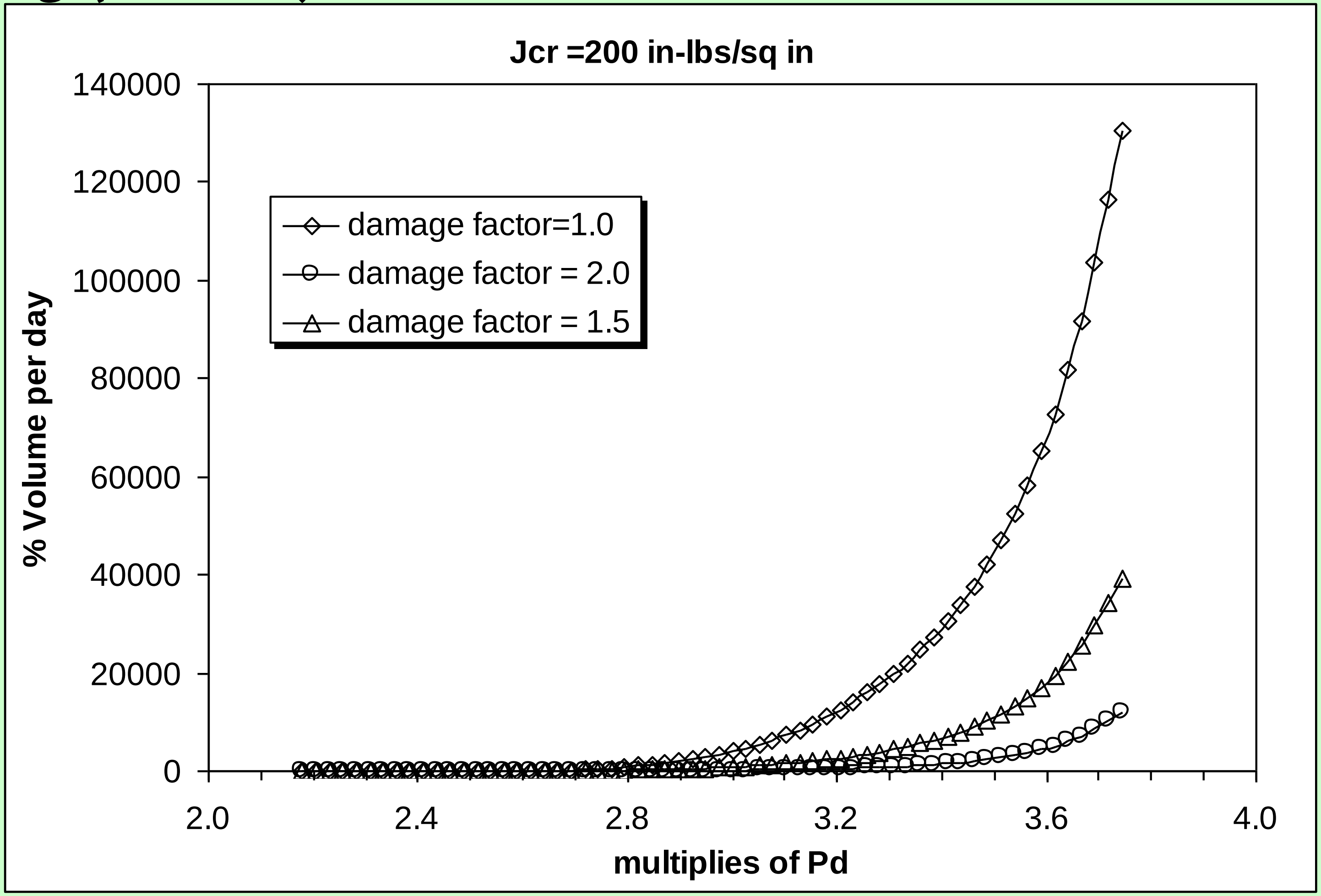
Results

Phase-2 exercise: saturated steam pseudo time-history (case-1)



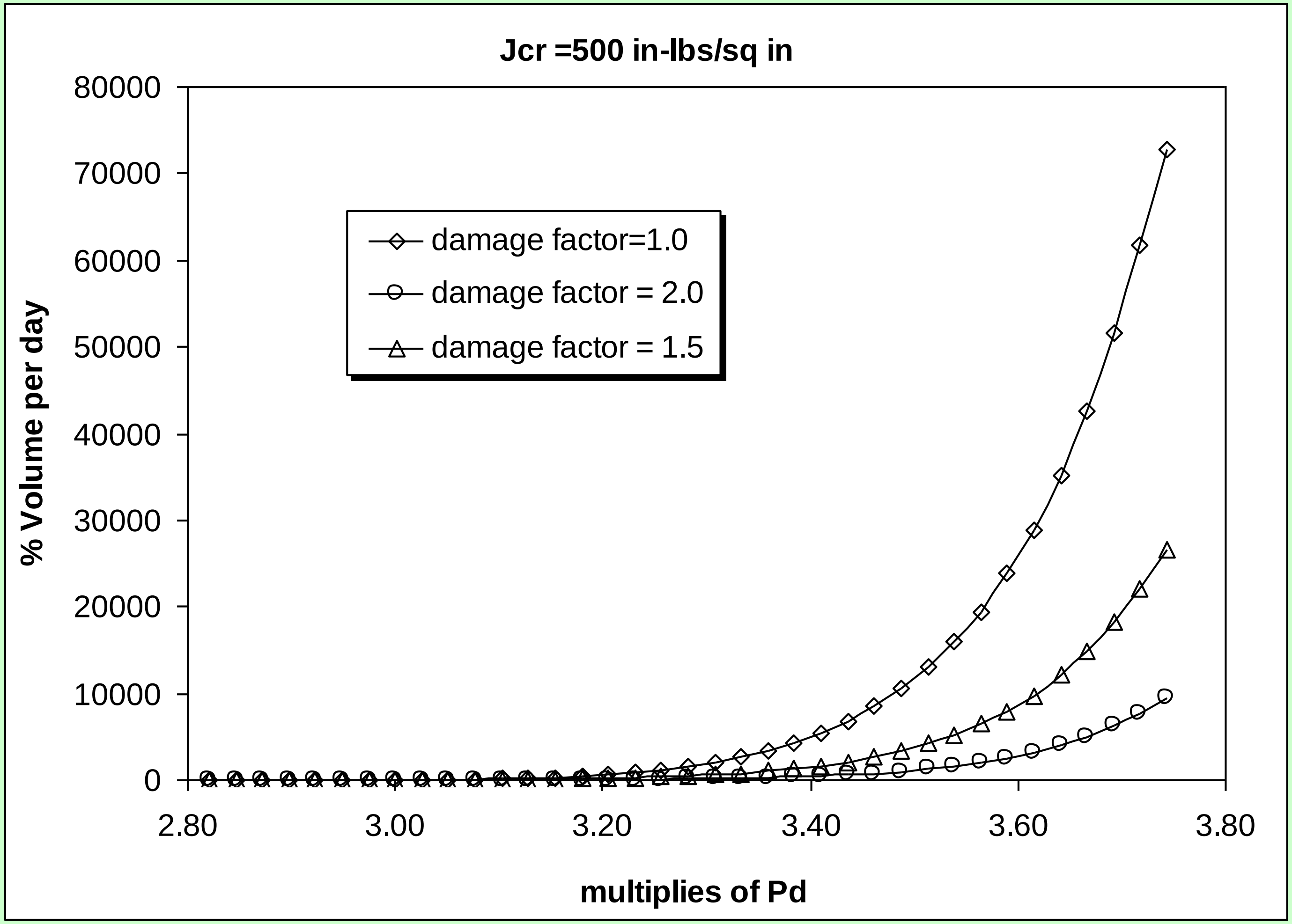
Results

Phase-2 exercise: saturated steam pseudo time-history (case-1)



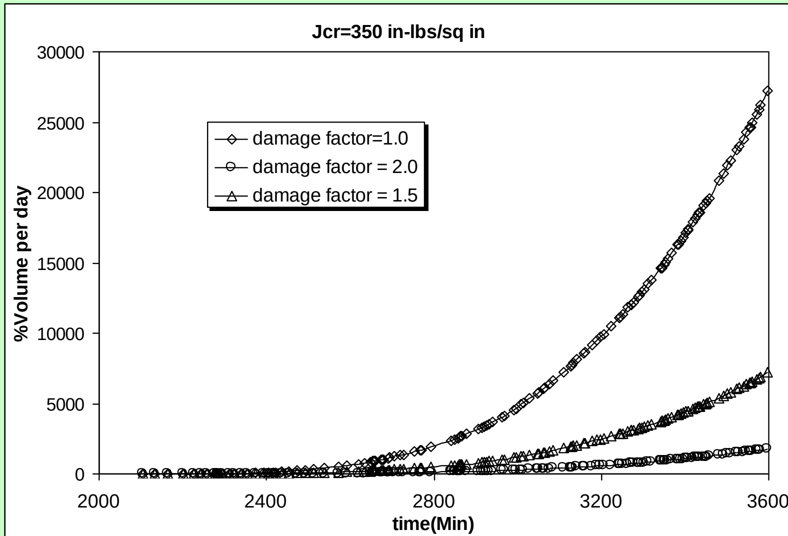
Results

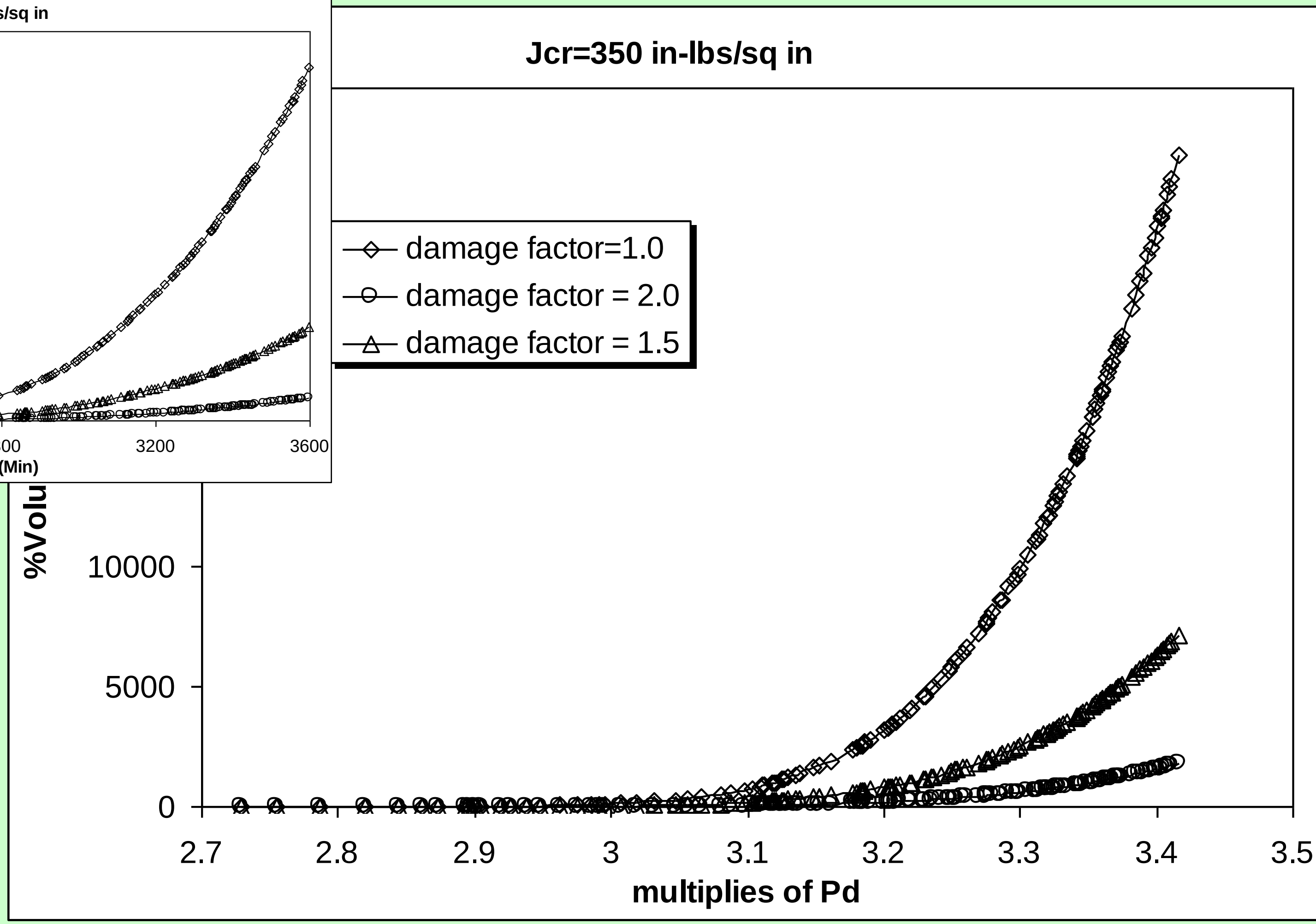
Phase-2 exercise: saturated steam pseudo time-history (case-1)



Results

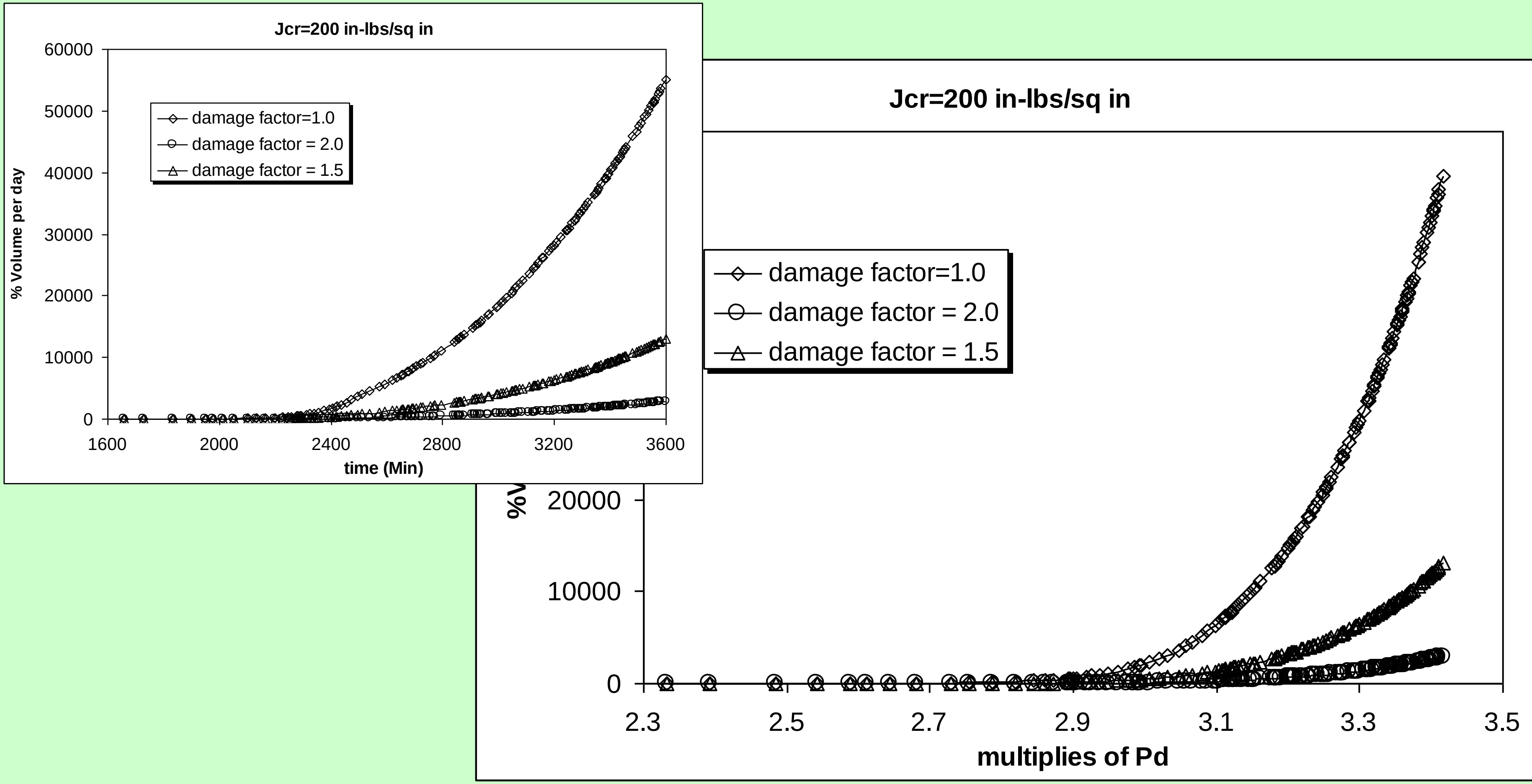
Phase-3 exercise: SBO condition (case-2)





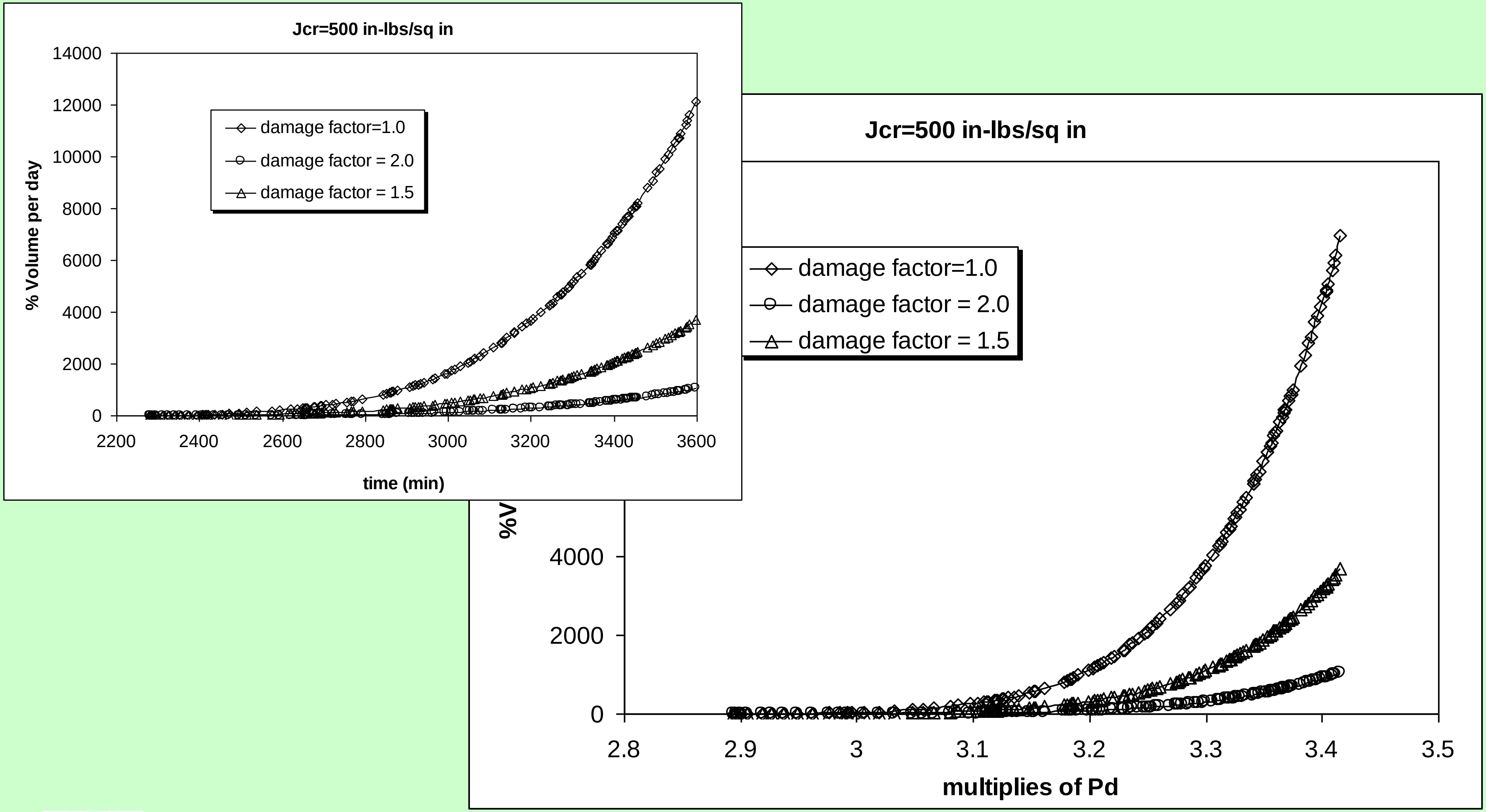
Results

Phase-3 exercise: SBO condition (case-2)



Results

Phase-3 exercise: SBO condition (case-2)



Conclusion

(i) The leakage rate follows a power law with respect to internal pressure.

(ii) Initiation of leakage depends on initiation of liner damage, though concrete section cracks much earlier than initiation of liner damage.

(iii) Parabolic damage variation (damage factor = 2.0) of liner produces minimum leakage, whereas linear damage (damage factor = 1.0) produces maximum leakage.

Conclusion

(iv) A comparison of leakage rates (%volume per day)

(Jcr = 200 in-lb/sq in and DF = 1)

multiplies of Pd	Phase-1	phase2: case-1	phase2: case-2
2.6	*0.15*	*7.56*	*5.61*
2.8	*8.36*	*209.83*	*48.34*
3.0	*52.55*	*840.35*	*477.94*
3.2	*268.21*	*2666.37*	*3204.39*
3.4	*1346.28*	*7093.23*	*11958.43*

Conclusion

(v) This exercise shows that temperature has strong effect on leakage rate. Leakage starts early when temperature is considered with internal pressure. High strain in steel liner due to temperature along with internal pressure triggers liner tear at early pressure.

(vi) The study shows that saturate pseudo time-history case-1 produces enhanced leakage compared to SBO condition (case-2) till 3.0Pd. At later stages, case-2 leakages are more than case-1 as the maximum temperature is high for case-2.

Conclusion

(vii) This trend could be attributed to temperature profiles. For case-1, temperature varies from 100^{o}C to 200^{o}C within 40 min, whereas, in case-2 temperature varies from 25^{o}C to 350^{o}C in 3600 min.

Thank You