ANALYSIS OF COKE DRUM CRACKING FAILURE MECHANISMS & COMMENTS ON SOME PUBLISHED RESULTS

Coking.com
MORE PRODUCTION - LESS RISK!

Conference

Calgary, Alberta

14 – 17 Sep 2009

EDA
Engineering Design & Analysis Ltd.

UNIVERSITY OF ALBERTA

J Aumuller, P. Eng.

Z Xia, Ph.D., P. Eng.

- Why stress determination
  - vessel bulging and cracking attributable to mechanical mechanism rather than metallurgical
  - primary mechanical failure mechanism is

    → low cycle thermal strain cycling ←

- What are
  - the various loadings
  - their nature
  - contribution to the proposed failure mechanism

- Major loadings identified

  - pressure, live weight, dead weight
    - pressure is nominally constant over operating cycle - cyclic
    - live weight load from bitumen feed, quench water - cyclic
    - dead weight load is constant

  - mechanical load due to coke crushing
    - as drum contracts, load due to restraint created by solid coke residual mass – cyclic, global

  - temperature load due to varying temperature of incoming streams – cyclic, variable, global & localized

→ appears to be most damaging load mechanism ←

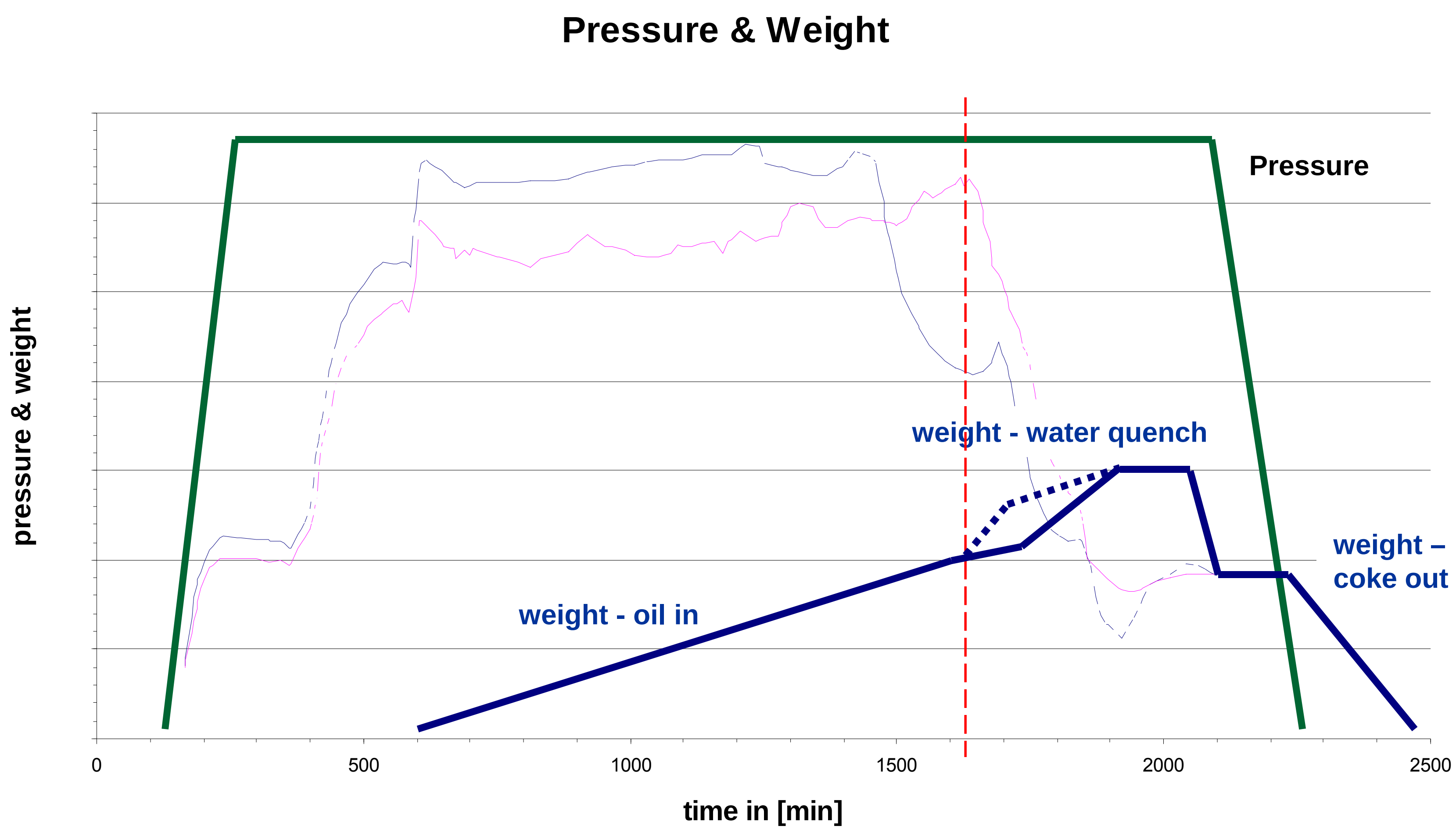
- Contribution to failure
  - pressure, live weight, dead weight
    - not likely due to design stresses well within elastic region, no evidence that stresses exceed elastic
  - mechanical load due to coke crushing
    - feasible load, but not sufficiently severe
    - laser scan results do not generally support this mechanism
    - incremental distortion not evident
  - temperature load due to varying temperatures of incoming streams – cyclic, variable, global & localized aspects during operational cycle

→ <u>magnitude & distribution consistent with nature of failures</u> ←

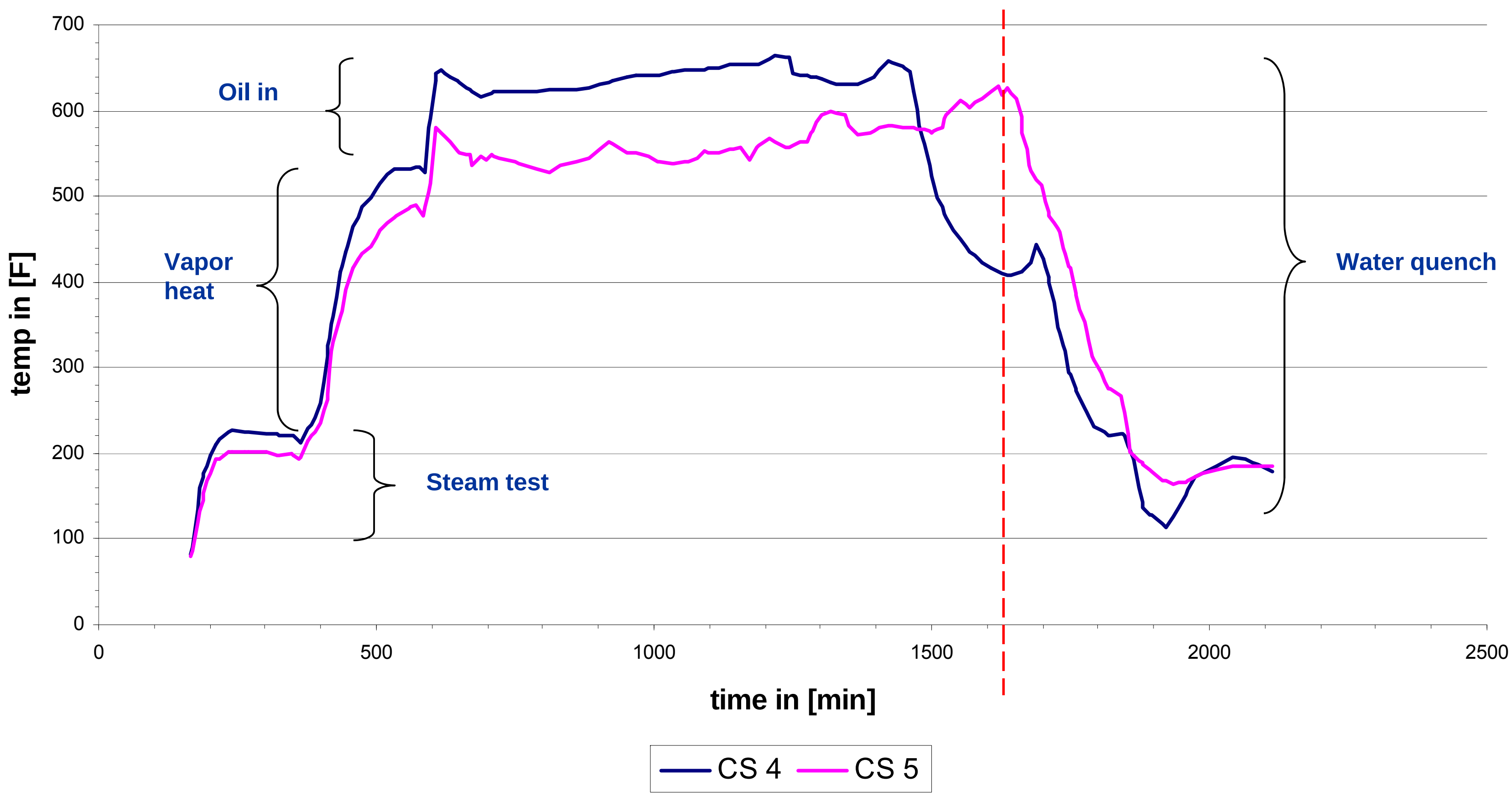
- Character of temperature loading is complex
  - variation and variability in fluid stream temperatures & impacts on drum metal temperature [DMT]
    - vapor heat [~ 550 °F], nominally causes uniform rise in DMT; however, vapour heat temperature can vary widely per operator intervention – can go directly from steam to oil-in step → thermal shock
    - oil-in [~ 750 °F to 900 °F], nominally causes uniform rise in DMT
      - as bitumen solidifies and cools, uniform effects give way to localized effects

- Character of temperature loading is complex [cont'd]
    - water quench [~ 250 °F]
        - extreme thermal shock imposed on DMT
            - ~ 850 °F → 250 °F - oil-in & water quench temperatures
        - highly variable DMT due to flow channeling imposing hot & cold spots upon the drum shell that are also time variable, i.e. T = T (x, y, z, t) or T(θ, z, t)

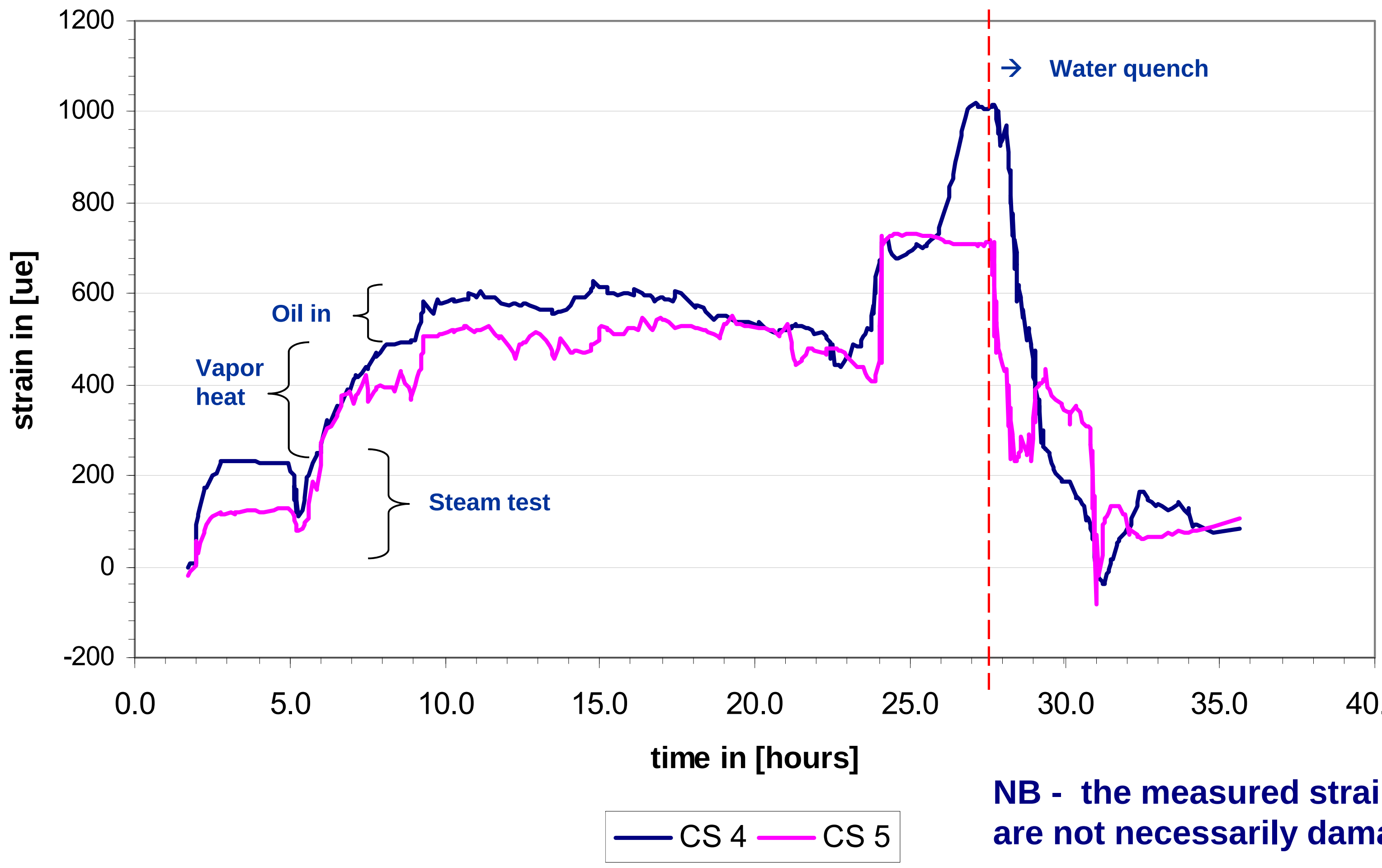
→ <u>highest potential impact on shell structural integrity</u> ←


Pressure & Weight
Pressure
weight - water quench
weight – coke out
weight - oil in
pressure & weight
0
500
1000
1500
2000
2500
time in [min]

Shell Course Temperature

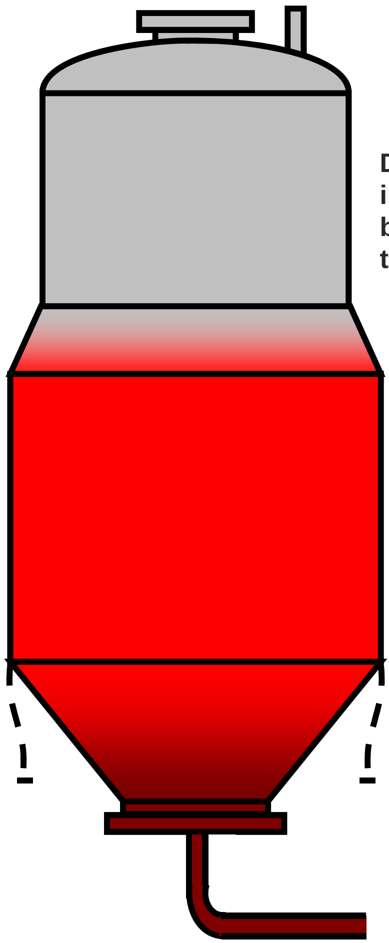


Shell OD Strain - Measured



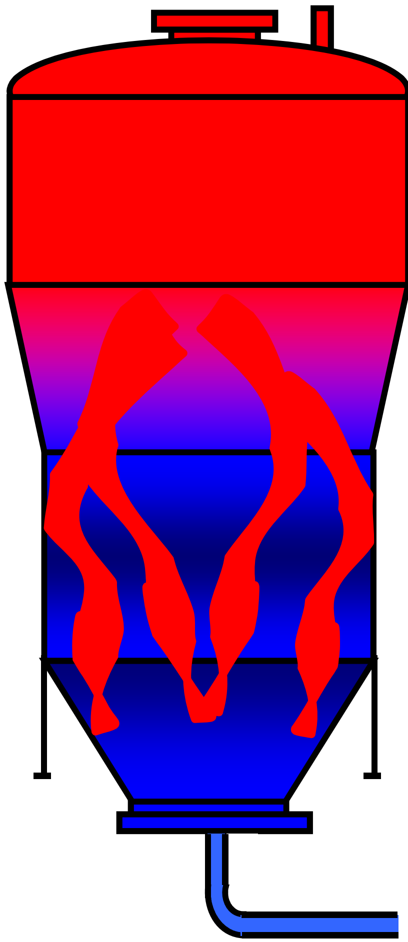
NB - the measured strains are not necessarily damaging

- Coke Drum Vasing -



- an effect of temperature loading
- occurs during oil-in operational step
  - condensation heats up lower elevations sooner than upper
  - differing temperatures in axial direction cause variable radial growth in drum
  - distortion in drum shell → stresses – but where?

- Coke Drum Vasing -



- drum vasing also occurs during
  - coke cool-down due to insulating effect as coke forms, liquid → solid
  - water quench addition
- vasing action is a nominal response
  - bitumen filling, water filling occur over same repeating nominal time period, nominal temperature range → plug flow nature
- localized distortions superimposed
  - system hydraulics cause channel flow & deviations in temperature → strain, stress

- Comments on available published data
  - Field data validity
    - temperature data likely okay, except where insulation is left off
    - strain data is highly suspect – fundamental errors in methodology
      - thermal strain, e_{TH} is
        - inconsistently accounted for, or
        - not accounted for entirely
    - evaluation of strain gauge readings is incorrect
      - closed form expressions are not appropriate, equivalent strain expression premised on 2D model; however, 3D strain state is present
    - no data measured at most susceptible locations

- Comments on available published data
  - base material failure is accelerated likely due to HEAC
    - field & published data regarding base material failure –
      - proceeds rapidly in comparison to clad layer failure, months versus years
    - dependant on operational specifics

- Temperature loading – understanding the fundamentals
  - for isotropic material, temperature increase results
    - in uniform strain
    - no stress when body is free to deform
  - the total strain in a body, e_T is composed of two components
    - mechanical portion = e_M [due to pressure, weight, + others]
    - thermal portion = e_{TH}
    - then, $e_T = e_M + e_{TH}$
      - when thermal growth is constrained, $e_T = 0 \rightarrow e_M = - e_{TH}$
      - since $e_{TH} = \alpha \cdot \Delta T$, where $\alpha \equiv$ coefficient of thermal expansion or CTE and, the coke drum is in a biaxial stress state, then

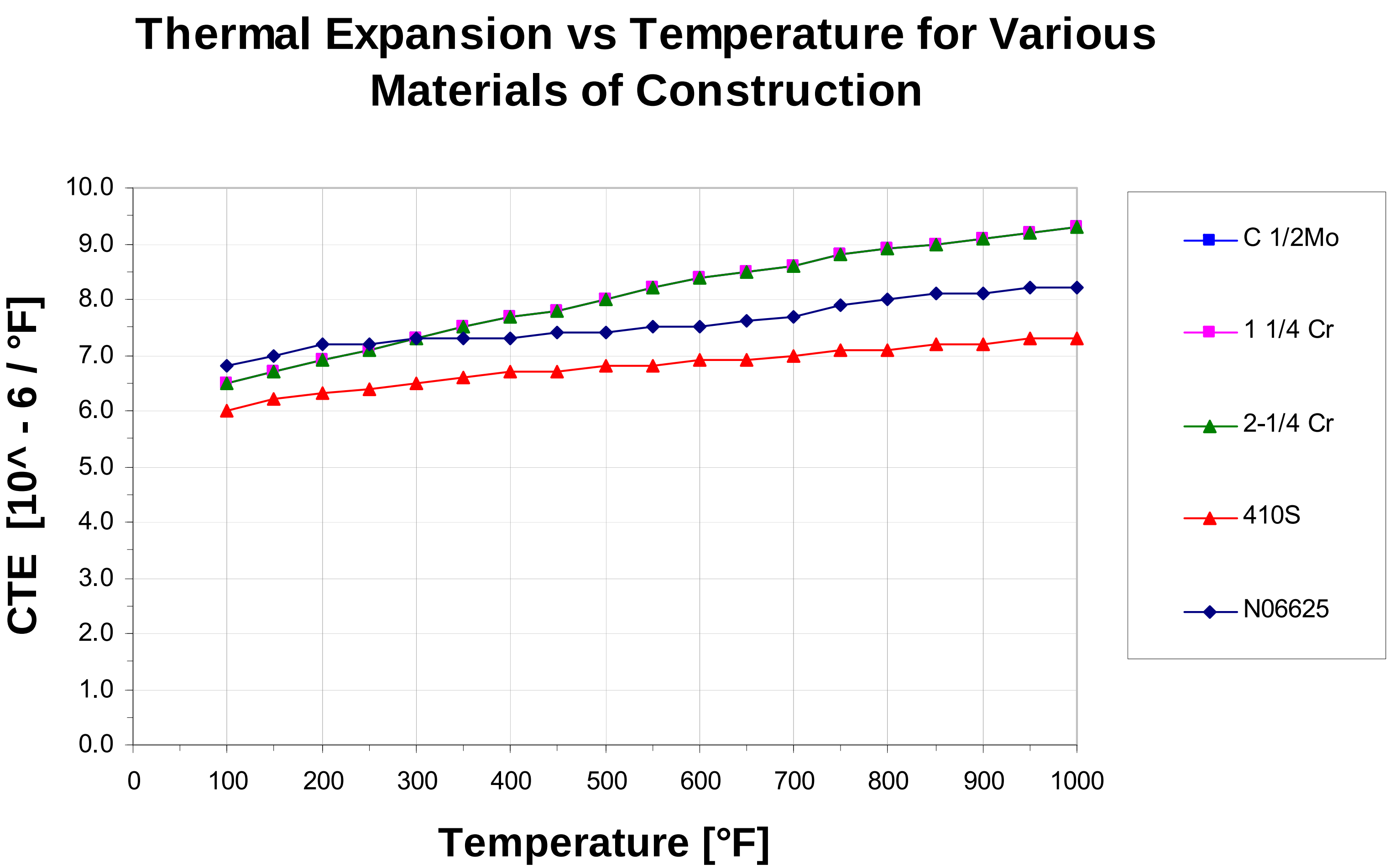
$\rightarrow$ thermal stress, $\sigma_{TH} = - E \cdot \alpha \cdot \Delta T / (1 - \mu)$

- Temperature loading [cont'd]
  - thermal expansion in coke drum is constrained due to several mechanisms
    - skirt structure
    - cladding – base material differential expansion due to mismatch in coefficient of thermal expansion, CTE

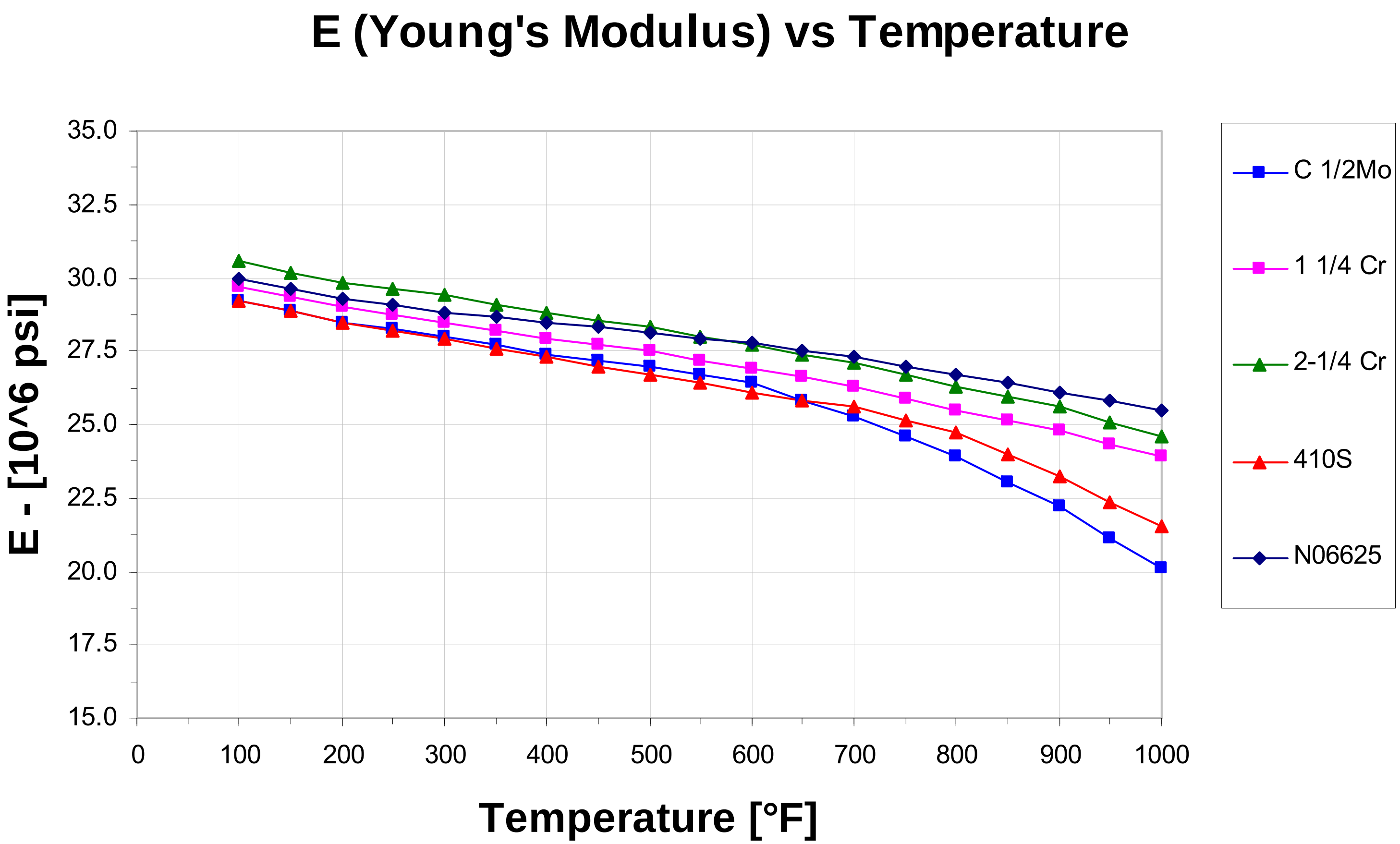
	100 F [in/in/F]	800 F [in/in/F]
CTE-clad	6.0E-6	7.1E-6
CTE-base	6.6E-6	8.9E-6

    - ΔT between adjacent parts of the structure due to varying exposure to incoming streams, i.e. bitumen [hot] and quench water [cold]

- Temperature loading [cont'd]

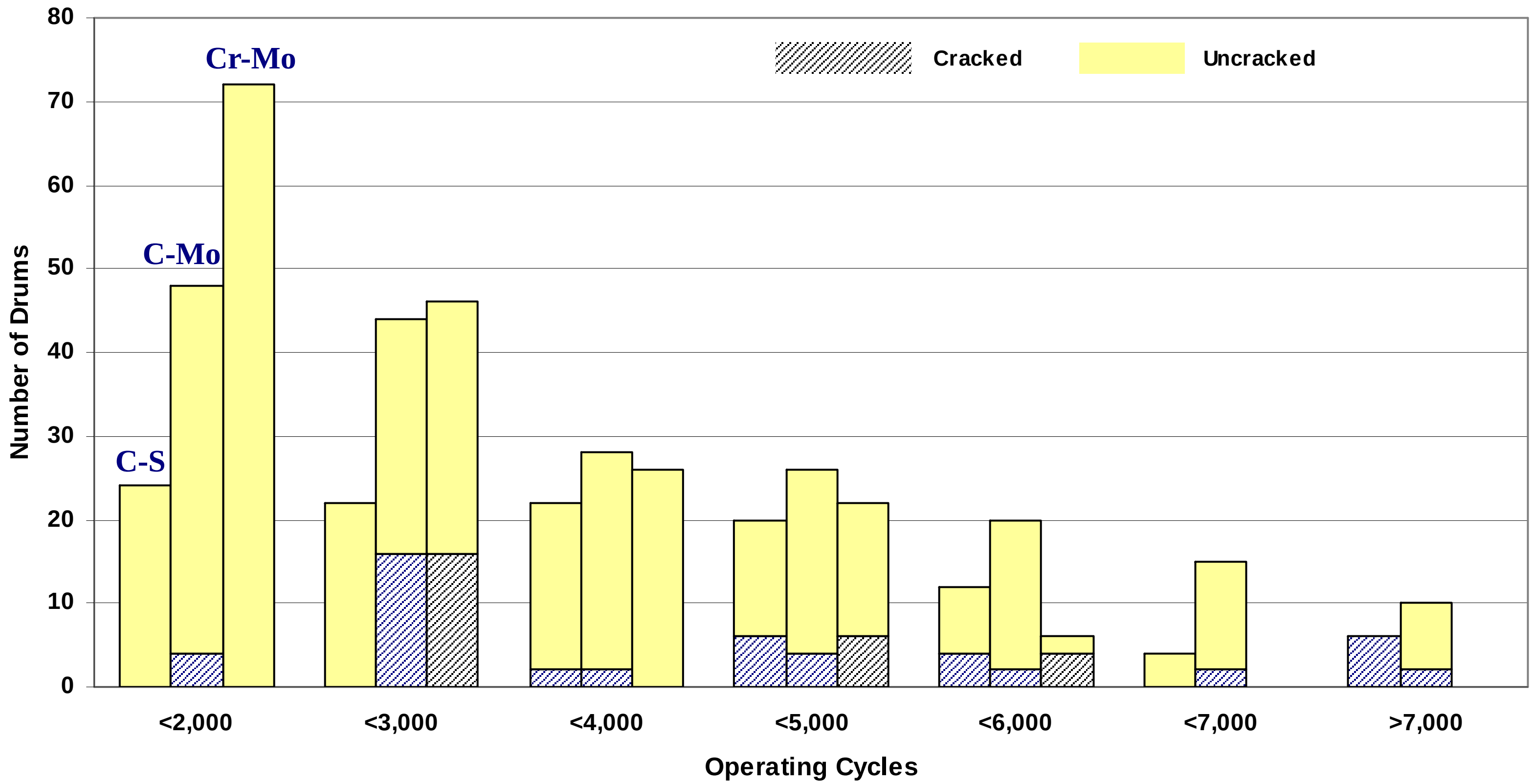


- Temperature loading [cont'd]



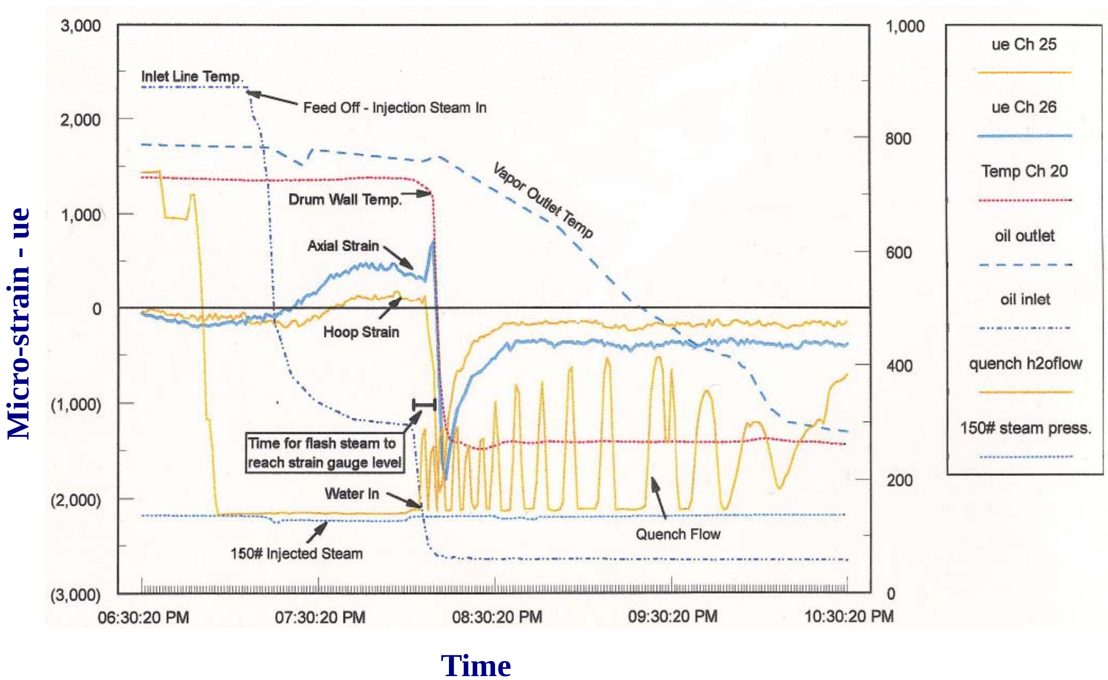
- Nature of Drum Failures
  - Low Cycle Fatigue – da / dN
    - characterized by high strain– low cycle
      - exacerbated by presence of code acceptable defects
      - cladding crack failure initiation < 1,000 ~ 2,000 cycles
      - cladding crack propagation thru thickness ~ 2,500 cycles
  - Environmentally assisted fatigue – da / dt
    - exposure of base material to hydrogen assisted mechanism
    - short time to through failure – hours to months
    - cleavage surfaces evident

- Number of Drums Reporting 1st Through Wall Crack – API Survey



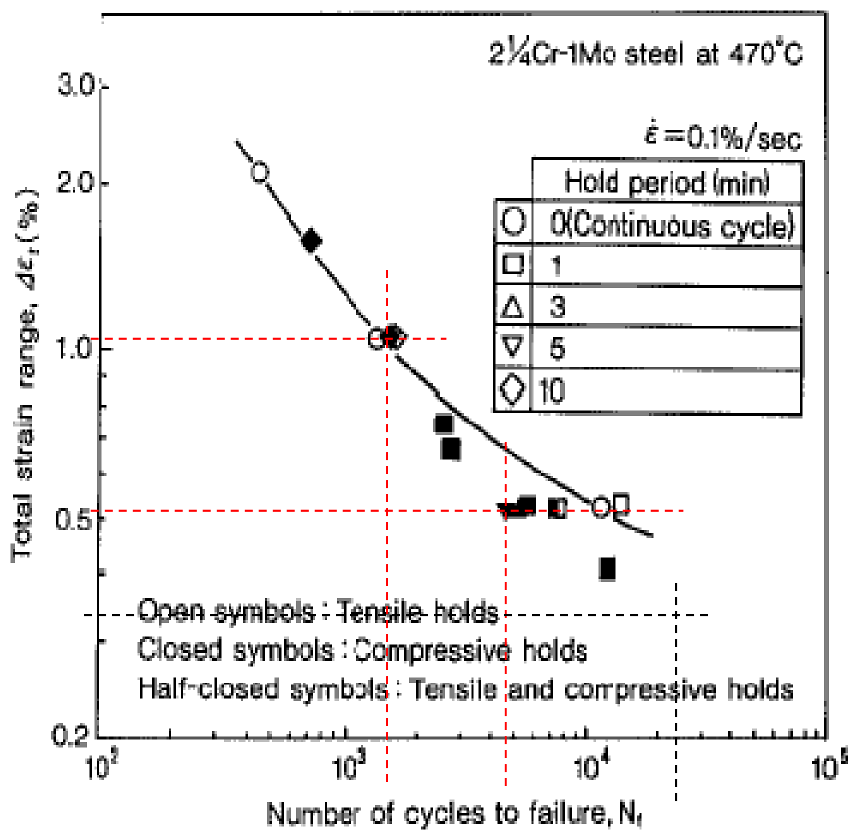
* Final Report, 1996 API Coke Drum Survey, Nov 2003, API, Washington, D.C.

- Nature of Drum Failures – cont'd
  - Upper bound strain
    - measured strain range, Δε = 2,500 ue ~ 3,400 ue
    - calculated possible, Δε = 5,140 ue ~ 10,080 ue



- **measurements fall well below values governed by system parameters**
- **system parameters indicate that strains repeat and will cause failure at susceptible locations**

- ε - N Low Cycle Strain Life Curve for SA 387 12 Plate [2¼ Cr – 1Mo]

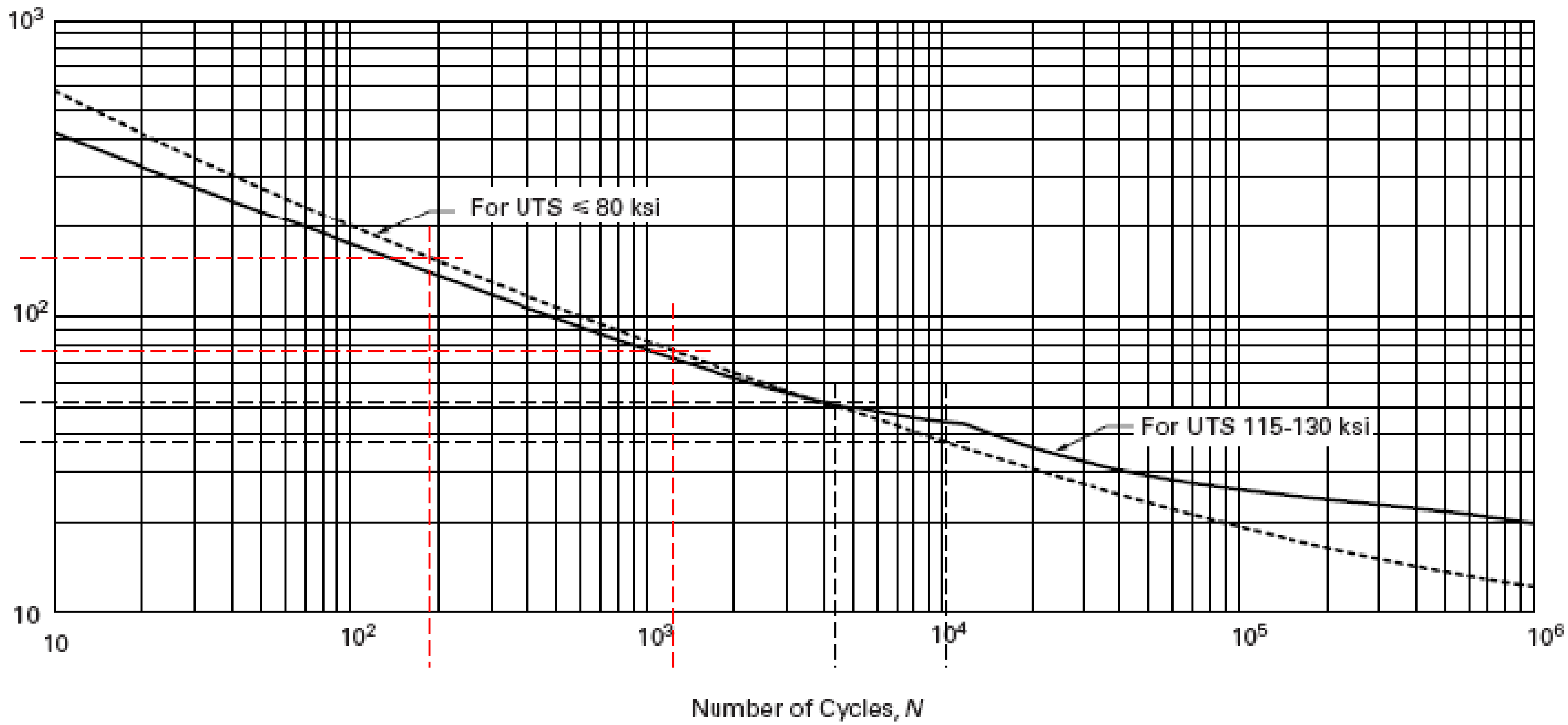


	ε				
	2,570	3,400	5,140	7,200	10,080
N	100,000	25,000	4,800	2,500	1,500
Years	274	68	13	7	4

- **extremes**
  - **failure can occur within 4 years**
  - **potential service life of 274 years**
- **actual performance of unit is function of system specifics**

* **Sonoya, K., et al., ISIJ International v 31 (1991) n 12 p 1424 - 1430**

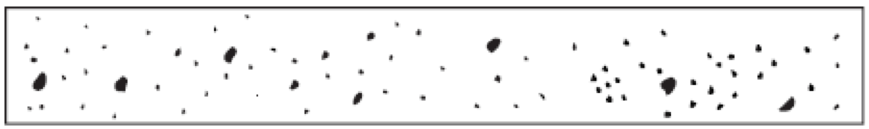
- σ - N Low Cycle Strain Life Curve per ASME VIII Div 2



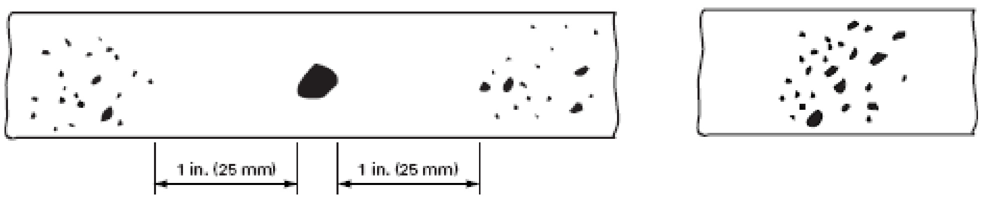
- **ASME VIII Div 2 S – N chart is not appropriate for service life determination**

ε	2,570	3,400	5,140	7,200	10,080
σ	77.1	102.0	154.2	216.0	302.4
N	10,000	4,200	1,200	550	180

- Influence of Internal Defects
  - Code allows internal defects

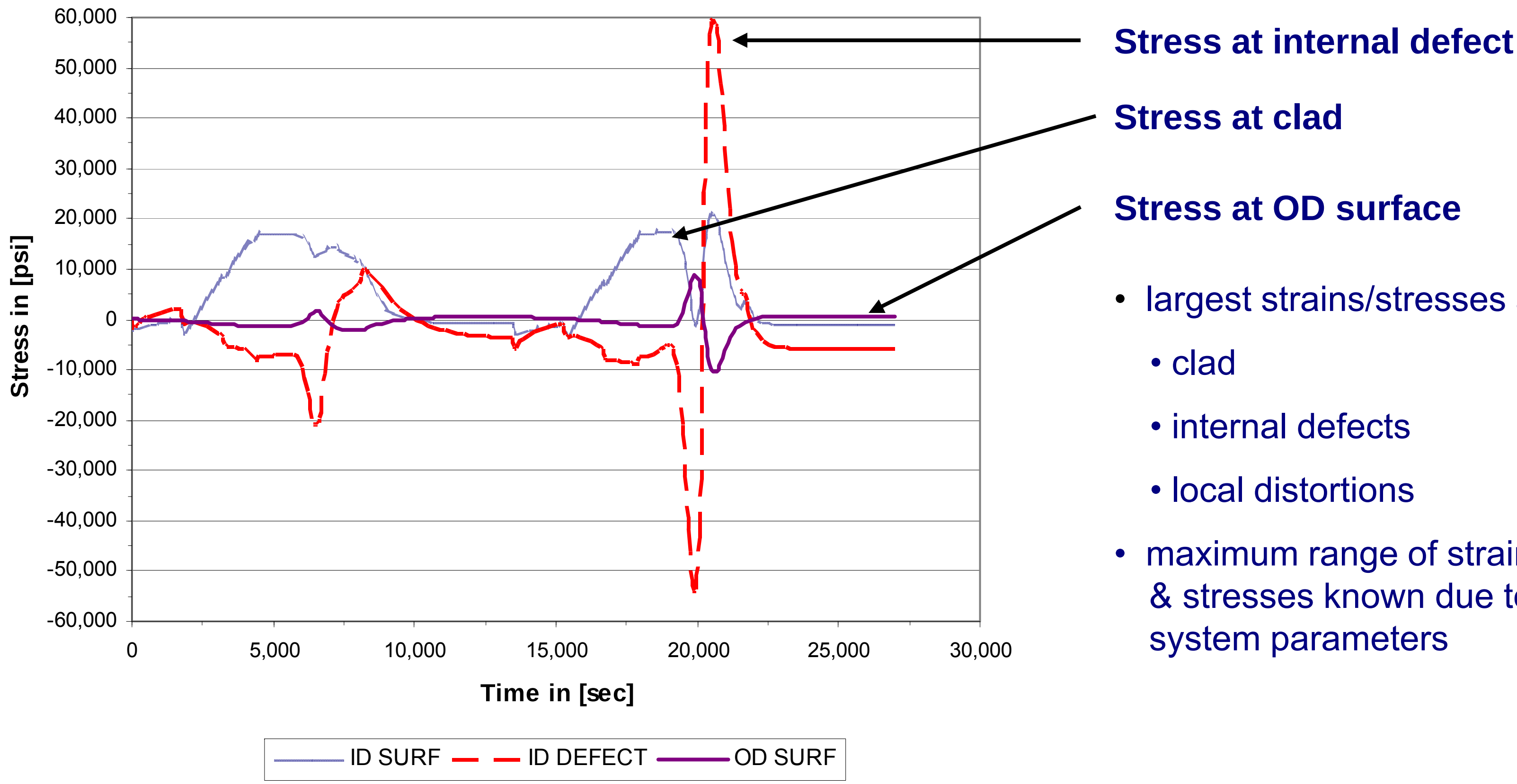


(a) Random Rounded Indications [See Note (1)]



- **For material thickness over ¾ inch to 2 inch, inclusive [19 mm to 50.8 mm]**
  - **Maximum size for isolated indication is ¼ " [6.4 mm] diameter**
  - **Table limiting defect size is given in ASME VIII Div 1**

- Stress at Internal Defects



- largest strains/stresses at
  - clad
  - internal defects
  - local distortions
- maximum range of strains & stresses known due to system parameters

- Conclusions
  - field measurement techniques problematic
    - thermal strain interpreted as mechanical strain
    - measured strains well below upper bound strains
    - strains at internal defects inaccessible, no measurement
    - strains at material interface inaccessible, no measurement
  - upper bound approach determines maximum strains obtainable
    - strain level, # of exposure incidents governed by system hydraulics
    - strain level, # of exposures govern service life
    - local shell deformations will further affect strain levels
    - crack initiation function of clad & base material integrity
    - through-wall base material failure related to HEAC susceptibility

- Evaluation
  - improve field measurement techniques
  - improve design procedures –
    - ASME VIII Div 1 not adequate to address complex loadings
    - more detailed & accurate estimation of stress required
    - need to consider more than material yield strength properties
  - material selection opportunities – less expensive options for same performance
  - preventative maintenance & repair opportunities identifiable

- Follow up work opportunities
  - develop improved field stress measurement technique
  - detection of internal defects and assessment technique
  - assessment of influence of local shell distortions
  - material constitutive modeling for better FEA modeling
  - characterization of base material performance in HEAC environment
  - identify alternative clad materials
  - develop appropriate design methodologies for coke drum
- Joint industry program – to leverage industry & NSERC resources

- Contact

- Dr. Zihui Xia, University of Alberta
  - zihui.xia@ualberta.ca

UNIVERSITY OF ALBERTA

- John Aumuller, EDA Ltd.
  - aumullerj@engineer.ca

EDA
Engineering Design & Analysis Ltd.