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

Coke Drum Reliability Workshop

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EDA
Engineering Design & Analysis Ltd.

UNIVERSITY OF ALBERTA

J Aumuller, P. Eng.

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

- Coke Drums

Coke drums are large pressure vessels used in oil sands plants & refineries for the recovery of hydrocarbon product from reduced bitumen

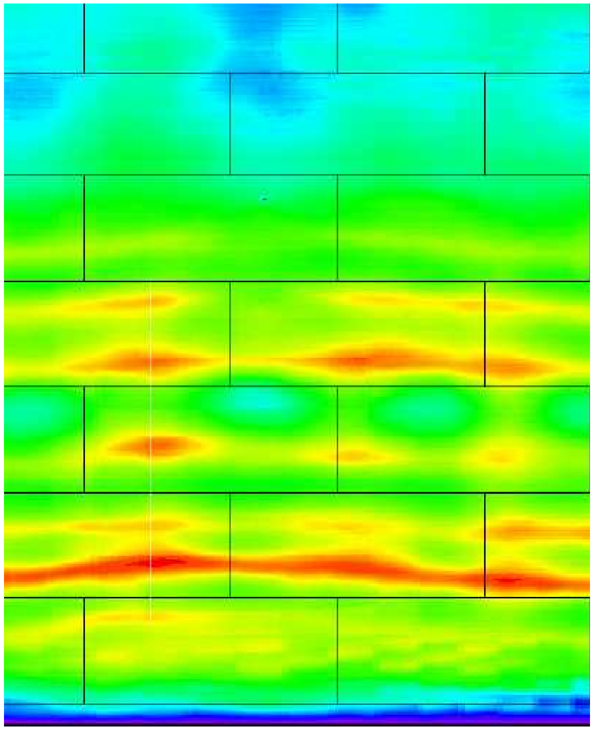
- **30 feet Ø x 90 feet height**
- **operate to 50 psig, 900 °F, cyclic**

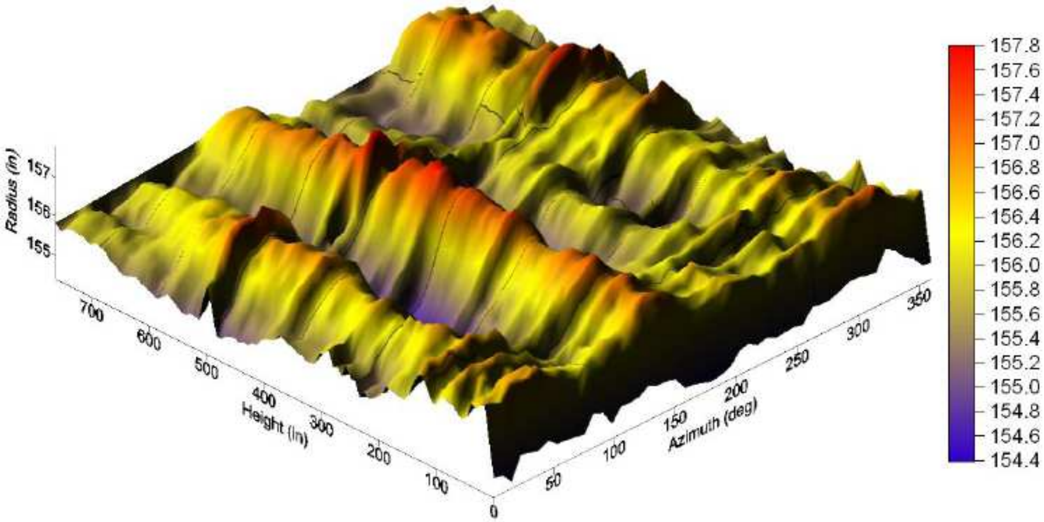
Construction materials

- **composite plate construction, 1" nominal thickness consisting of**
  - **TP 410S stainless steel cladding**
  - **carbon steel or low alloy carbon steel (CS, C -½ Mo, Cr - Mo)**

Problem – cracking of shell, attributed to presence of bulges and low cycle fatigue

- Coke Drum Bulging

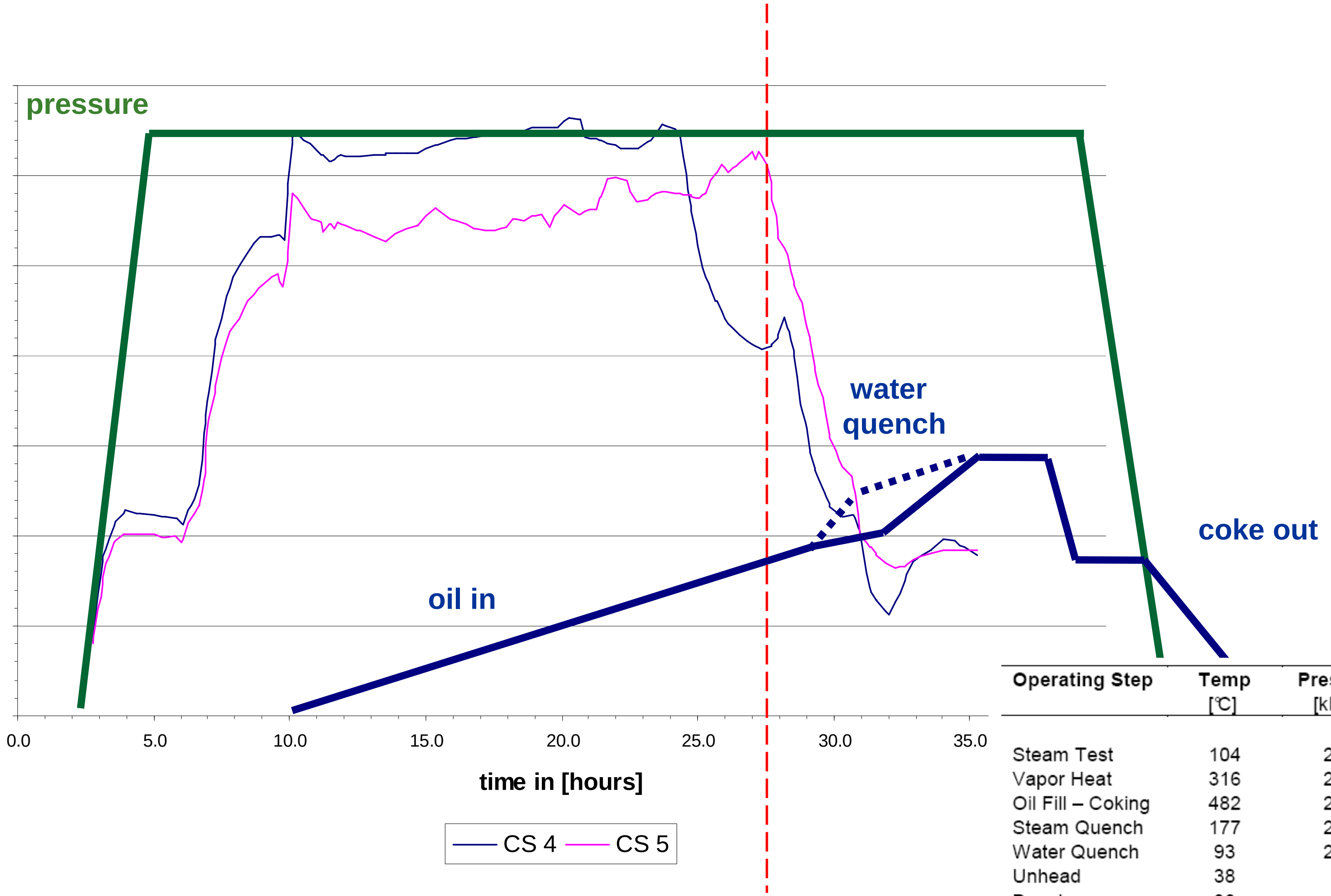




- Why stress determination
  - vessel bulging and cracking attributable to mechanical mechanism rather than metallurgical
  - primary mechanical failure mechanism is

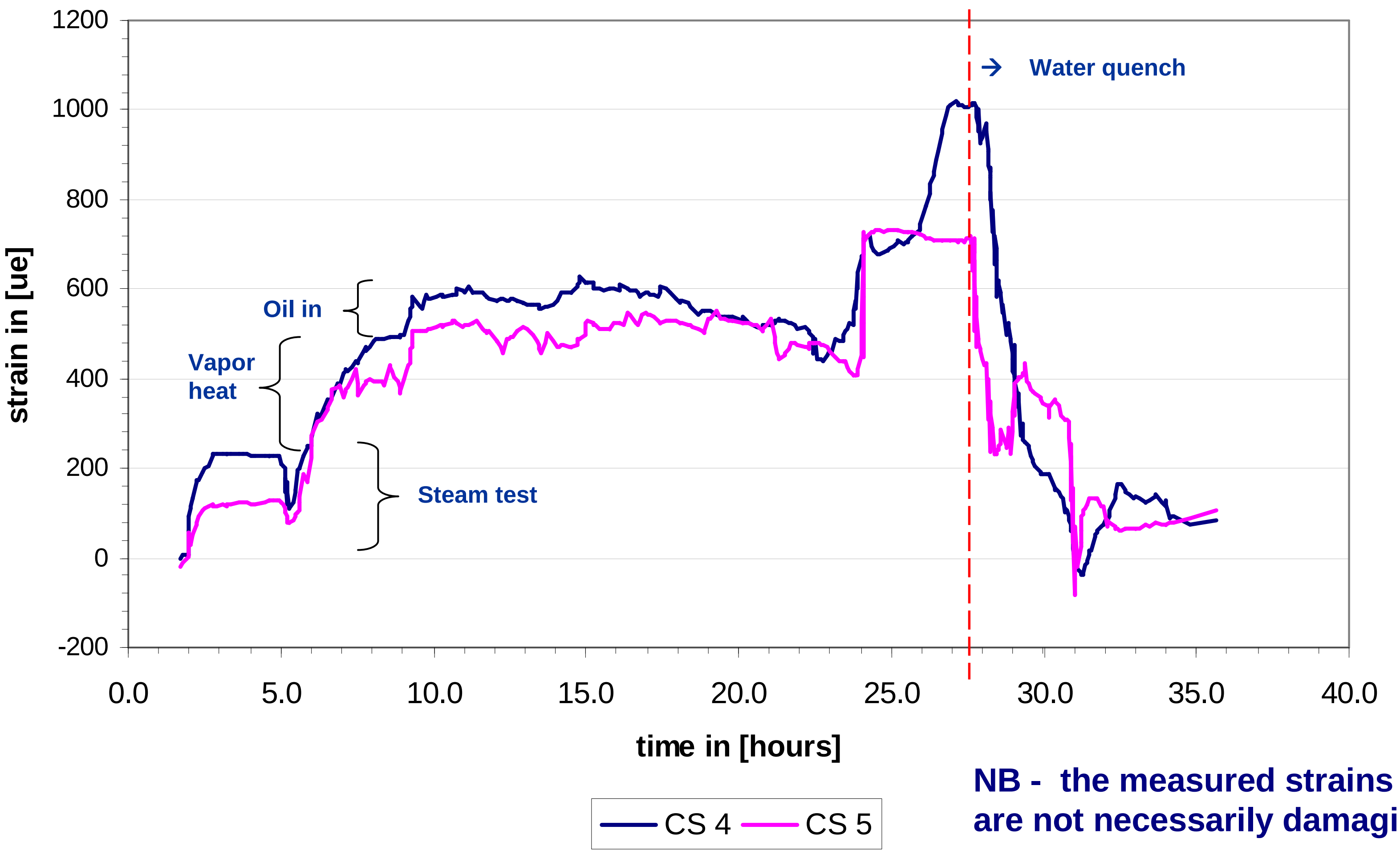
    → <u>low cycle thermal strain cycling</u> ←

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



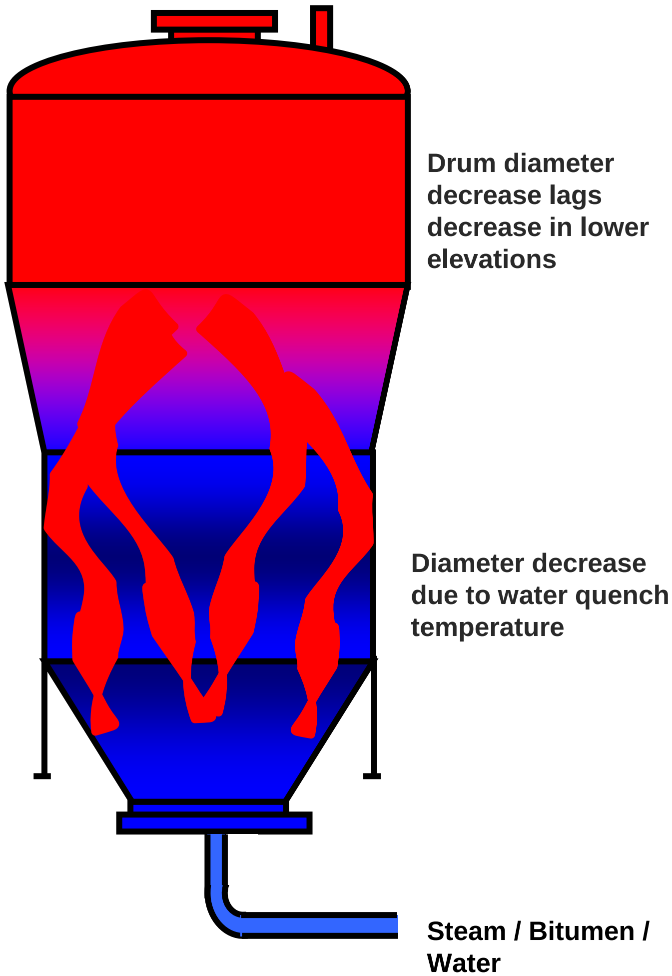
Operating Step	Temp [℃]	Pressure [kPa]	Duration [hrs]
Steam Test	104	241	< 3
Vapor Heat	316	241	3
Oil Fill – Coking	482	241	11 – 15
Steam Quench	177	241	< 1
Water Quench	93	241	3
Unhead	38	0	< 1
Decoke	38	0	1 – 3
Total Time			24 – 28

Shell OD Strain - Measured



NB - the measured strains are not necessarily damaging

- Coke Drum Vasing, “Hot”, “Cold” Spots, & Transients



- vasing action is a nominal response
  - bitumen filling, water filling occur over same repeating nominal time period, nominal temperature range
    → plug flow nature
- drum vasing also occurs
  - during coke cool-down due to insulating effect as coke forms, liquid → solid
  - water quench addition
- 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

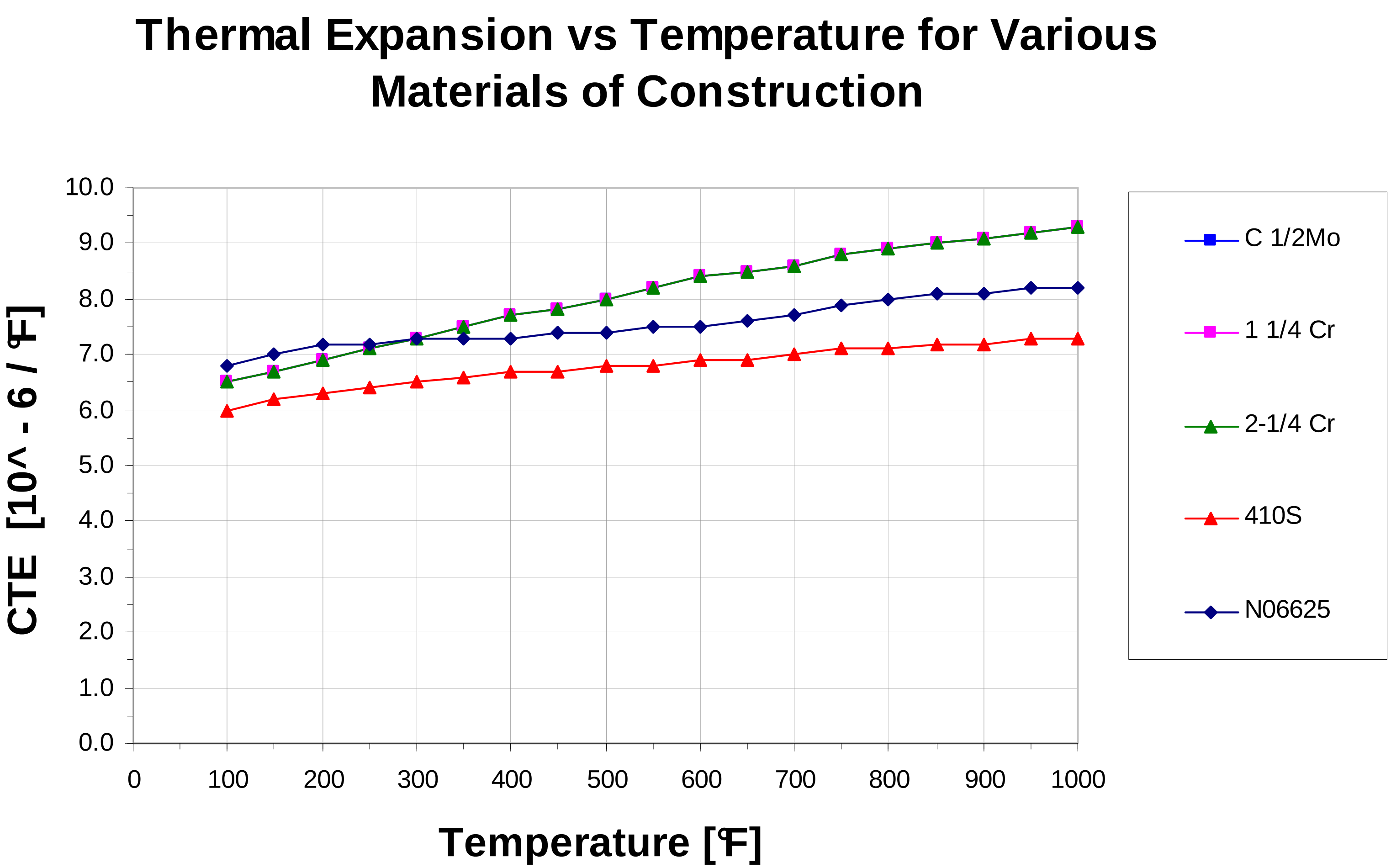
$\rightarrow$ thermal stress, $\sigma_{TH} = - E \cdot \alpha \cdot \Delta T / (1 - \mu)$

- 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

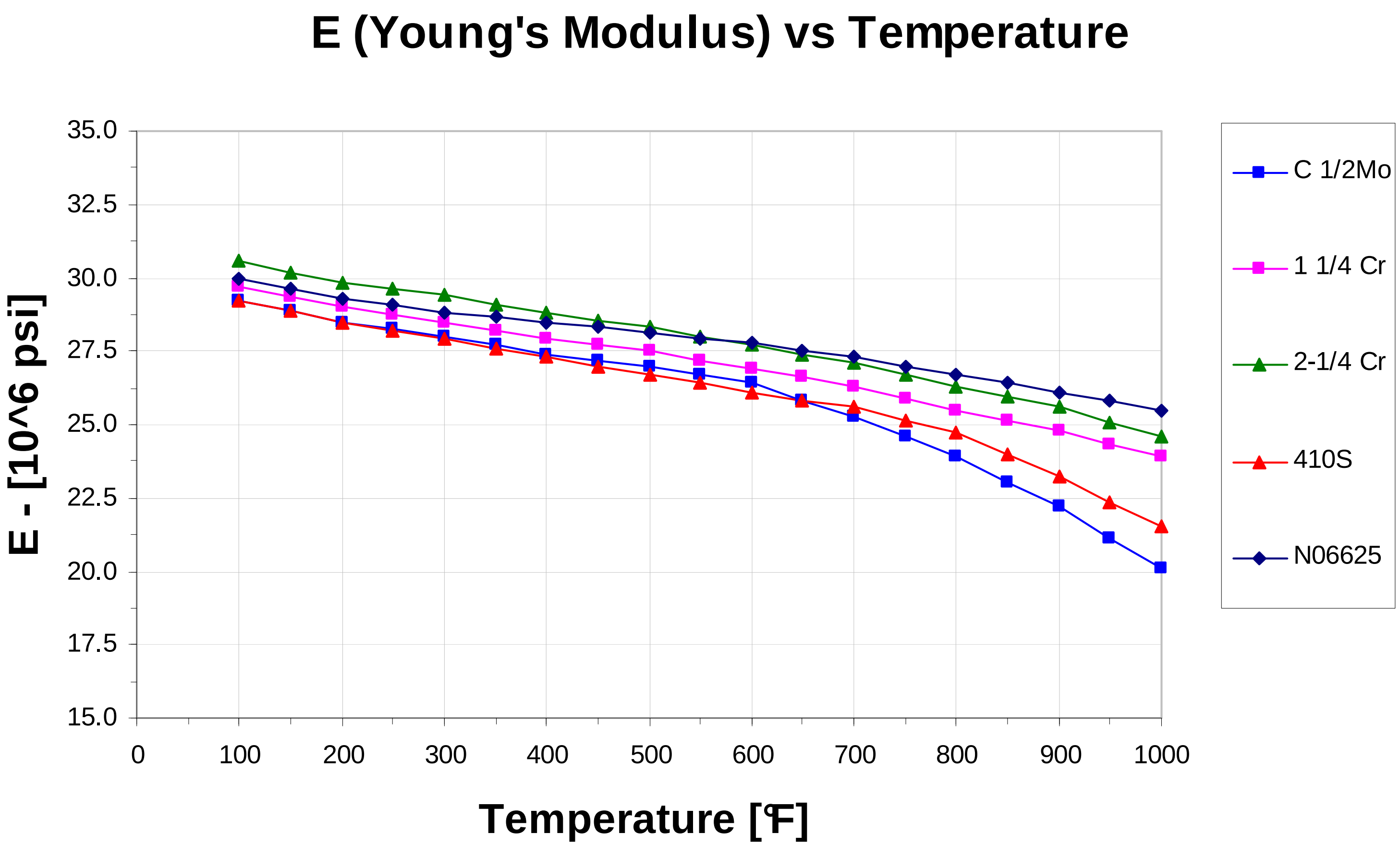
	100 F [in/in/F]	800 F [in/in/F]
CTE-clad	6.0E-6	7.1E-6
CTE-base	6.6E-6	8.9E-6

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

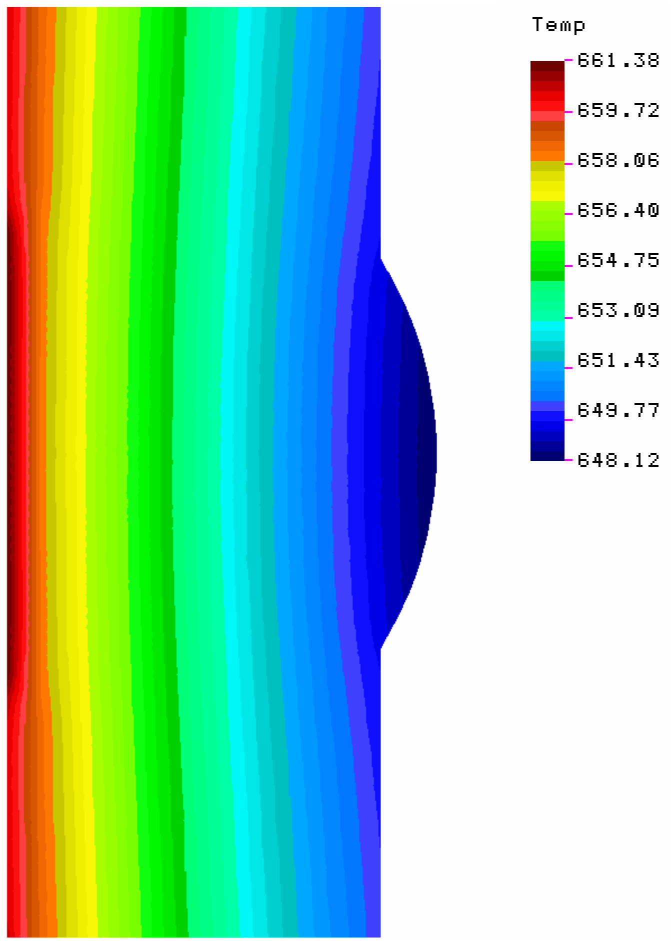
- Temperature loading [cont'd]

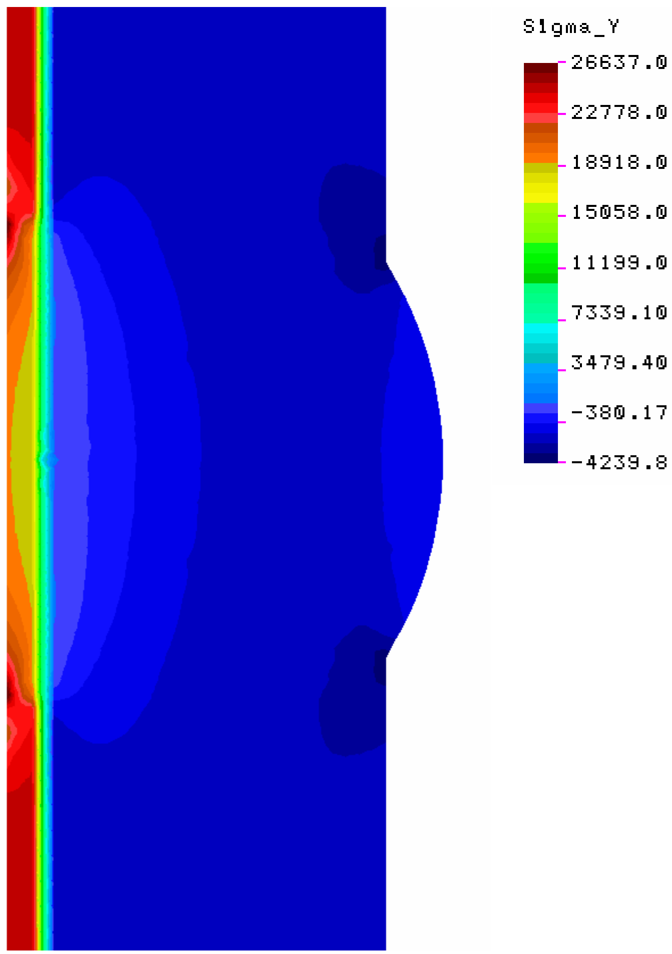


- Temperature loading [cont'd]



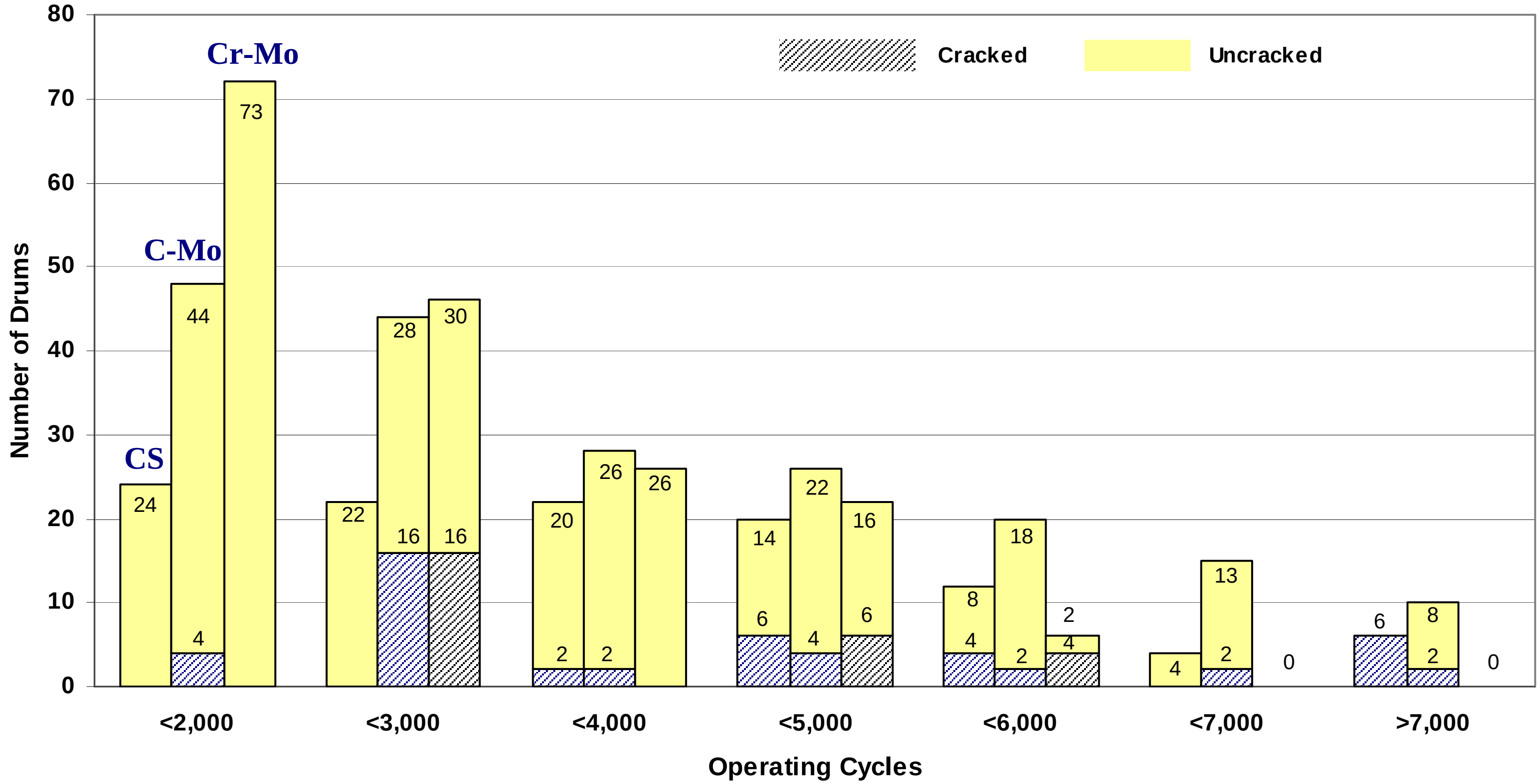
- Temperature loading [cont'd] - Temperature - Stress Profile Comparisons





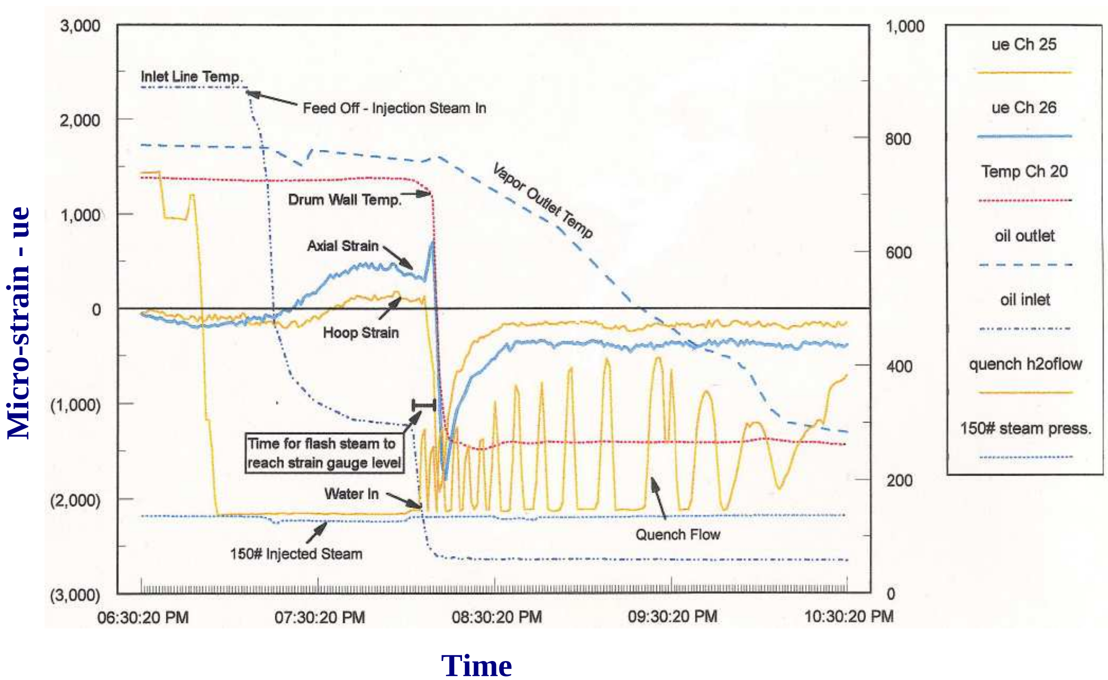
- Nature of Drum Failures
  - Low Cycle Fatigue – da / dN
    - characterized by high strain– low cycle
      - exacerbated by presence of code acceptable defects
      - cladding crack failure initiation < 1,000 ~ 2,000 cycles
      - cladding crack propagation thru thickness ~ 2,500 cycles
  - Environmentally 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



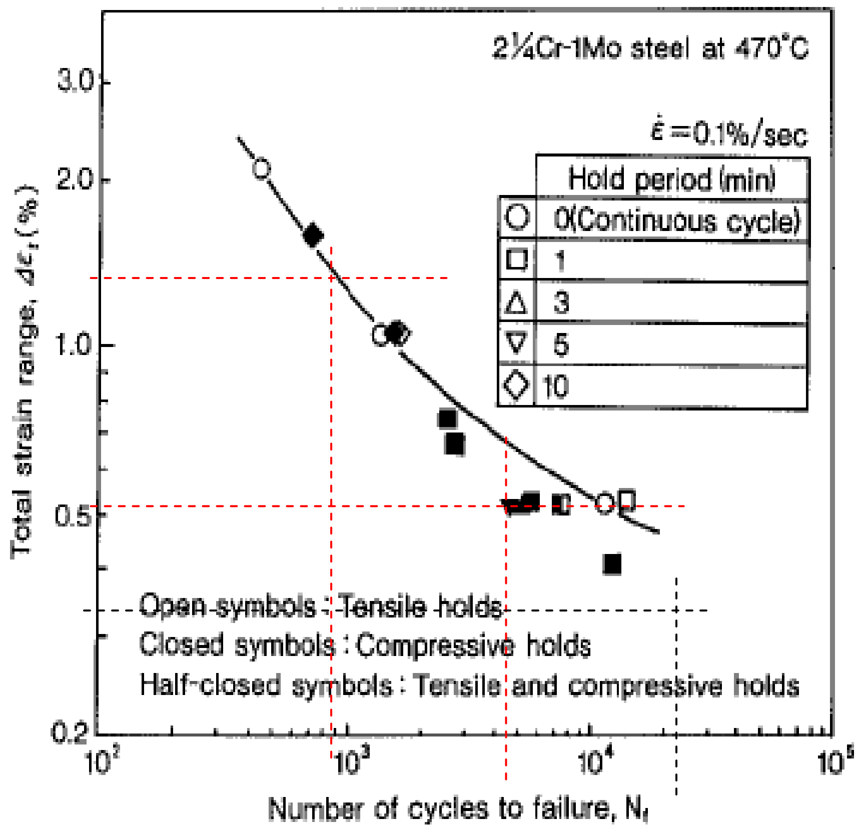
* Final Report, 1996 API Coke Drum Survey, Nov 2003, API, Washington, D.C.

- 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 ~ 14,400 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]

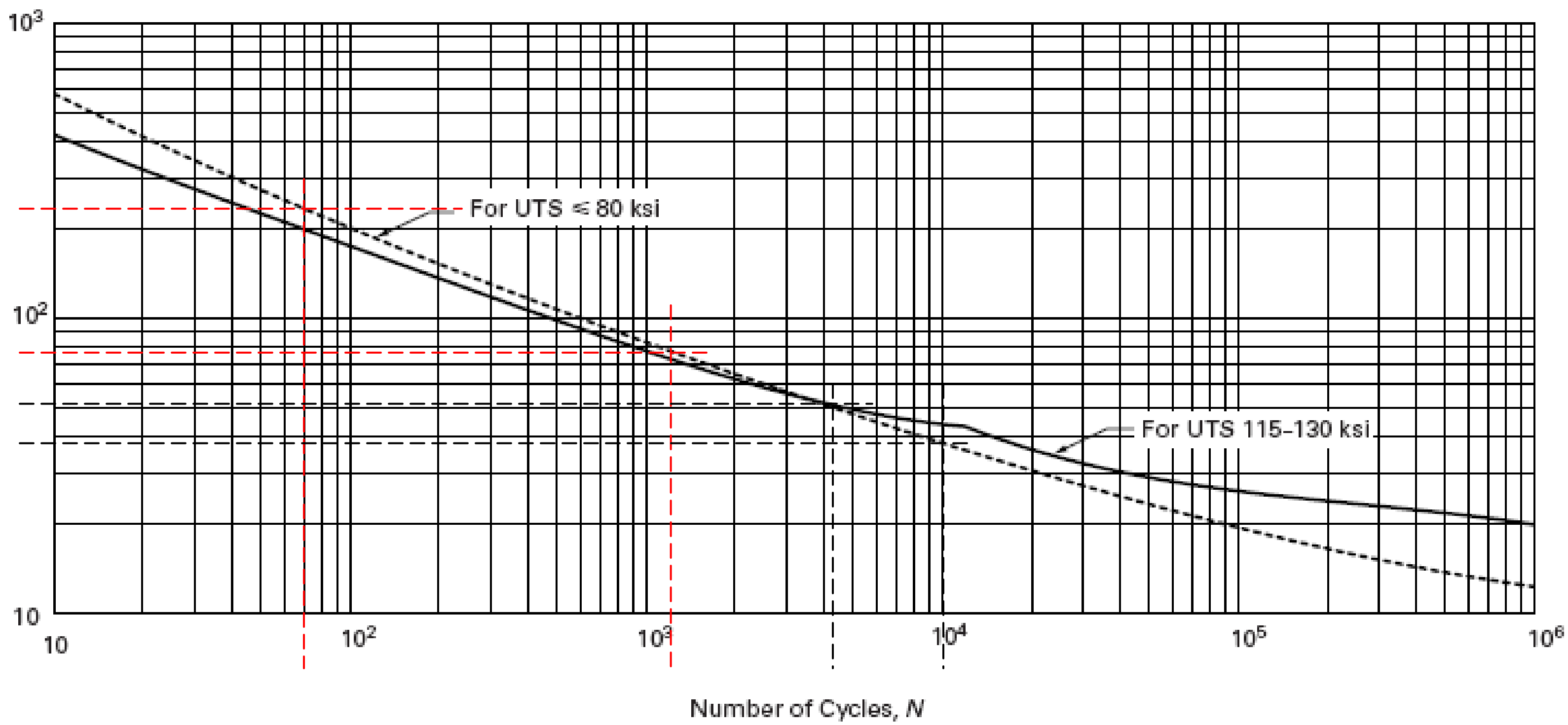


	ε				
	2,570	3,400	5,140	7,200	14,400
N	100,000	25,000	4,800	2,500	900
Years	274	68	13	7	2.5

- **extremes**
  - **failure can occur within 2.5 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**

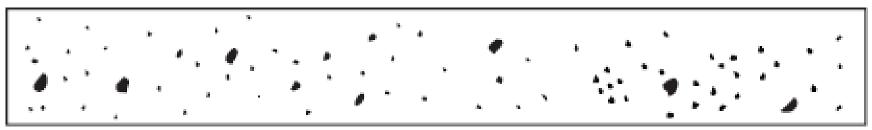
- σ - N Low Cycle Strain Life Curve per ASME VIII Div 2



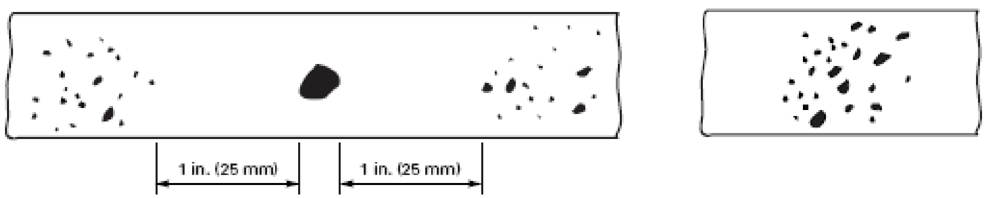
ε	2,570	3,400	5,140	7,200	14,400
σ	77.1	102.0	154.2	216.0	432.0
N	10,000	4,200	1,200	550	70
Years	27	11.5	3	1.5	0.2

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

- Influence of Internal Defects
  - Code allows internal defects

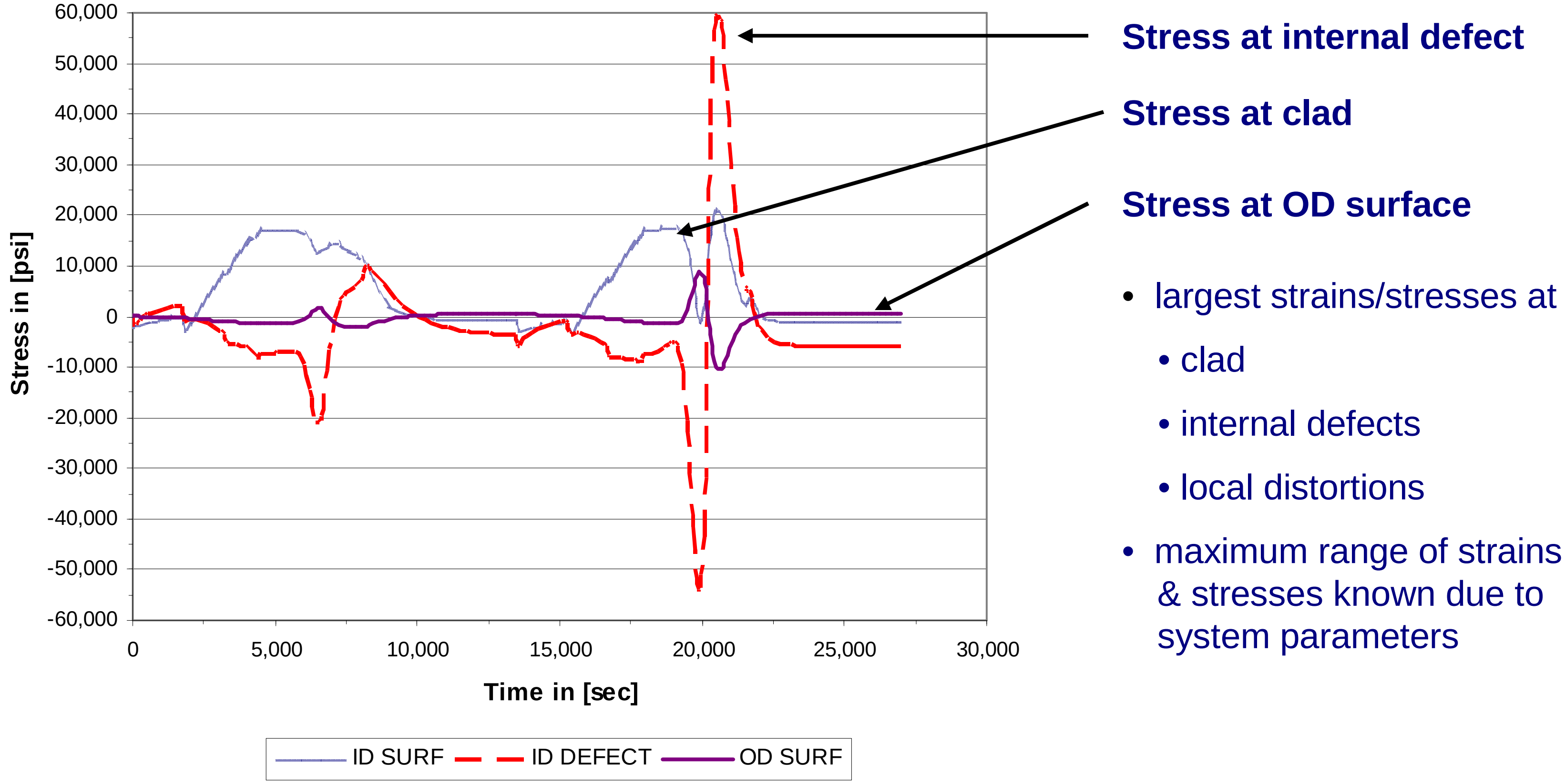


(a) Random Rounded Indications [See Note (1)]



- **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
    - T: 780 492 3870

  - John Aumuller, EDA Ltd.
    - aumullerj@engineer.ca
    - T: 780 484 5021

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Engineering Design & Analysis Ltd.