Indian Point Unit 2

U-Bend PWSCC Susceptibility Investigation

Status Report
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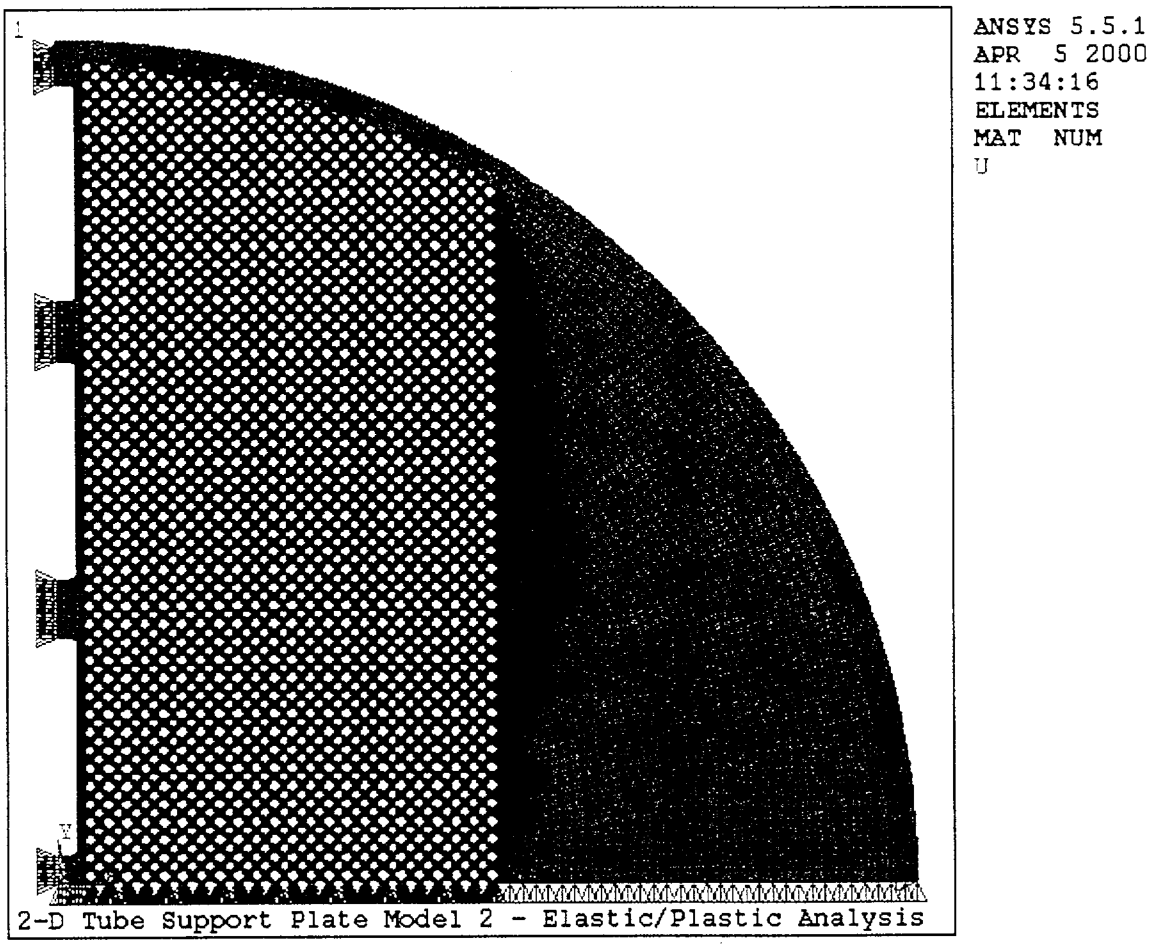
U-Bend Tube Investigations

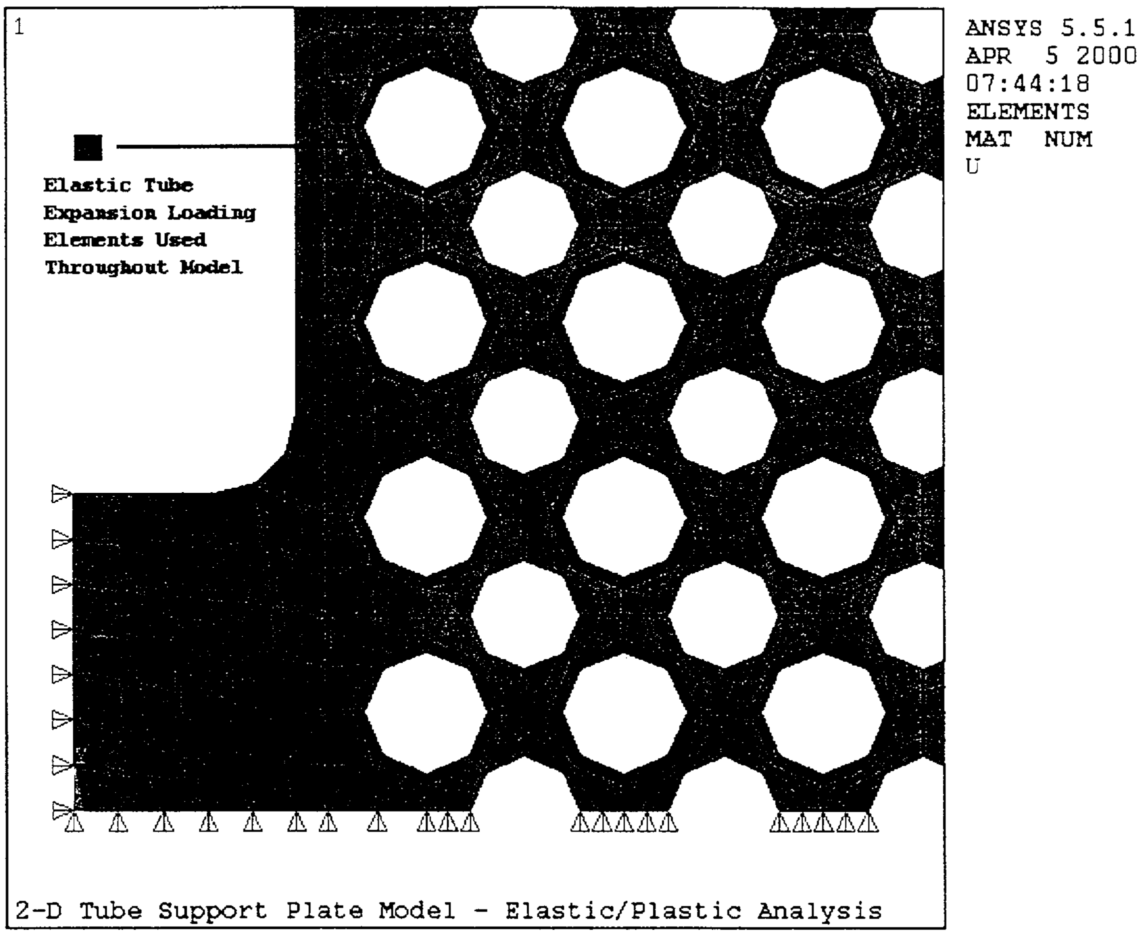
- Purpose: Determine Relative Susceptibility of Small Radius U-Bends to PWSCC
- Approach:
  - Determine tube displacements for specified amount of hour-glassing
  - Determine stresses in U-bends due to TSP deformation and other operating conditions
  - Determine the residual stresses
  - Assess time to initiate cracking due to PWSCC
  - Estimate life expectancy of Row 3 tubes relative to Row 2 tubes
- Analyses and tests performed
  - Tests performed on Row 2 and Row 3 tubes provided by EPRI
  - Stress Analyses performed for Row 2 and higher rows of tubes

Tube Support Plate Motion

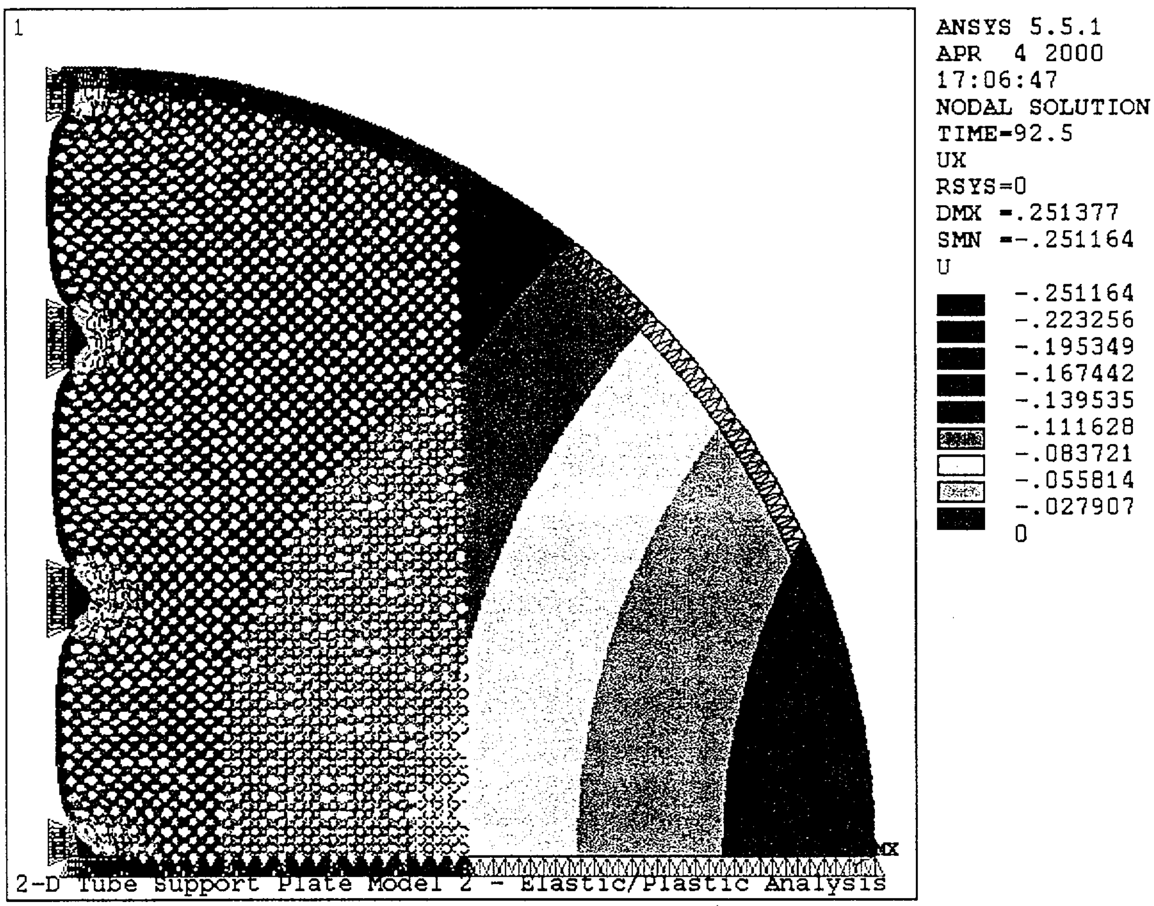
- Analysis Objective: Quantify the movement of Row 2 and 3 tubes for a given amount of hour-glassing
- Analysis Assumptions
  - 3-D Elastic/Plastic Finite Element Model
  - Model consisted of a Quarter Plate
  - Applied corrosion packing loads inside tube holes simulated by thermally expanding elements inside the tube hole
- Corrosion packing load causes in-plane compression in the TSP and hour-glassing at the flow slot
- Analyses performed represent the measured total hour-glassing at flow slot of 476 mils.
  - Row 2 tube displaces approx. 63% to 97% of the flow slot deformation
  - Row 3 tubes displace approx. 63% to 92% of the flow slot deformation



Tube Support Plate
Finite Element Model



Tube Support Plate
Flow Slot/Hole Region Finite Element Plot



Full Quarter TSP Model – Shown with Exaggerated Displacements at Flow Slots

X-Displ. Normalized to R1C7 of Outer Slot				
Column No.	Row 1	Row 2	Row 3	Row 4
3	**67**	**63**	**63**	**63**
4	**85**	**81**	**76**	**73**
5	**93**	**90**	**85**	**80**
6	**98**	**94**	**90**	**85**
7	**100**	**97**	**92**	**87**
8	**100**	**97**	**92**	**87**
9	**99**	**96**	**91**	**86**
10	**96**	**93**	**88**	**83**
11	**91**	**88**	**83**	**78**
12	**83**	**79**	**74**	**71**
13	**67**	**63**	**62**	**63**

X-Displacement for the Tubes at Outer Slot from the Quarter Model; (Values Normalized In Percentage to the Maximum Displacement of Tube R1C7)

U-Bend Tube Investigations

- Stress Analysis Objectives: Quantify Row 2 and 3 tube stresses due to TSP #6 hour glassing
- 3-D Elastic/Plastic Finite Element Model
- Effects include:
  - Temperature and Pressure
  - 0.003" of tube wall thinning and thickening (all rows the same)
  - Residual Stresses (determined from testing)
  - Imposed U-bend leg displacement due to hour glassing
  - Strain hardening in U-bend increases yield strength by approximately 50%
- Analysis performed with 0.238" one side hour glassing
- Range of yield strength data from IP2 Generator tube CMTR, adjusted for strain hardening and operating temperatures.

As-Bent Ovality and Thinning

- Row 2 and 3 U-Tubes were located in the EPRI archives.
- Similar geometry to IP2 tubes – 7/8" tubes with 0.050" walls
- Performed material composition and mechanical property testing
- As-received tubes used for ovality measurements, wall thinning measurements, and measurement of yield stress in bend versus straight run

As-Received U-Tube Samples

Sample Number	Tube Row	Wall Thinning (in.)	Percent Ovality
00603-1	2	0.003	4.99
00603-2	2	0.003	5.48
00603-6	2	0.004	2.28
00603-3	3	0.004	5.30
00603-4	3	0.004	5.65
00603-5	3	0.002	4.99

Ovality Investigation

- Purpose: Investigate effect of as-manufactured ovality and U-tube leg displacements on apex stresses.

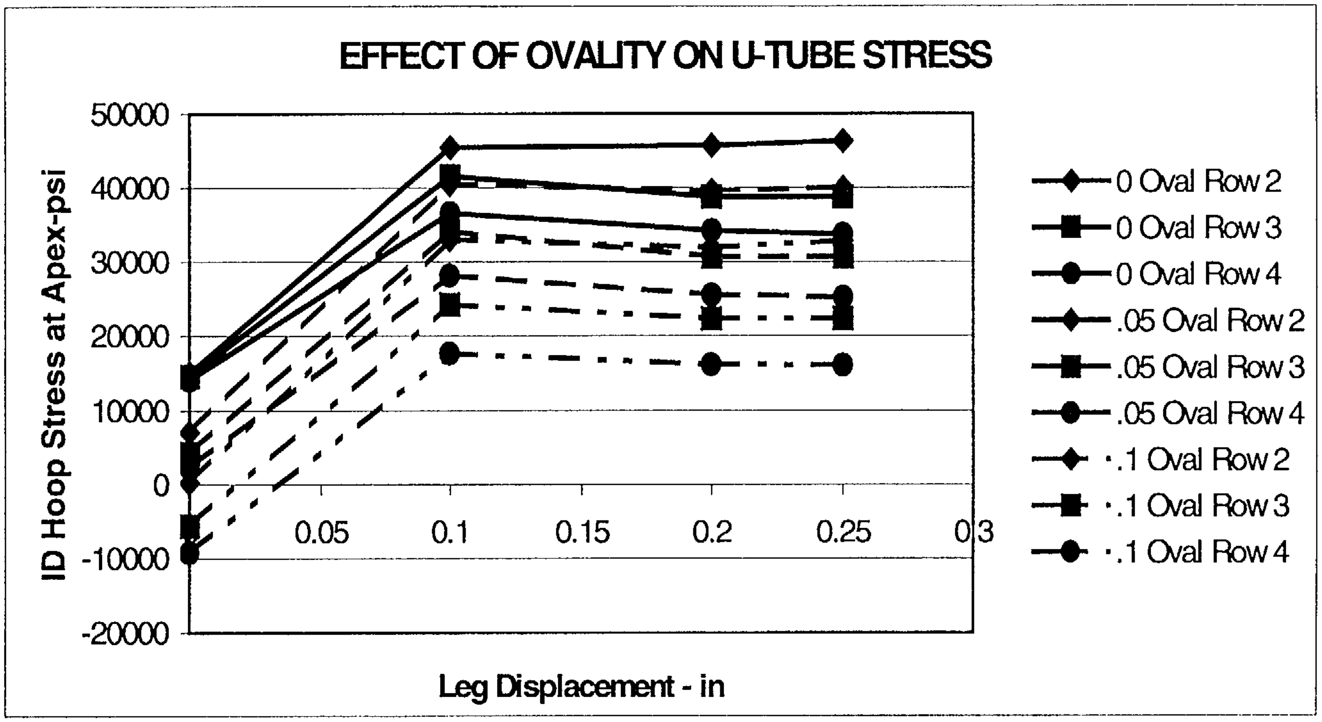
- Elastic-Plastic finite element model with ovality for Rows 2, 3 and 4

- Ovality: 0, 0.05, and 0.10

$$\text{Ovality} = \frac{(\text{Flank Dia.} - \text{Extrados/Intrados Dia.})}{\text{Straight Leg Dia.}}$$

- Lateral displacement of one leg: 0.”, 0.1”, 0.2” and 0.25”

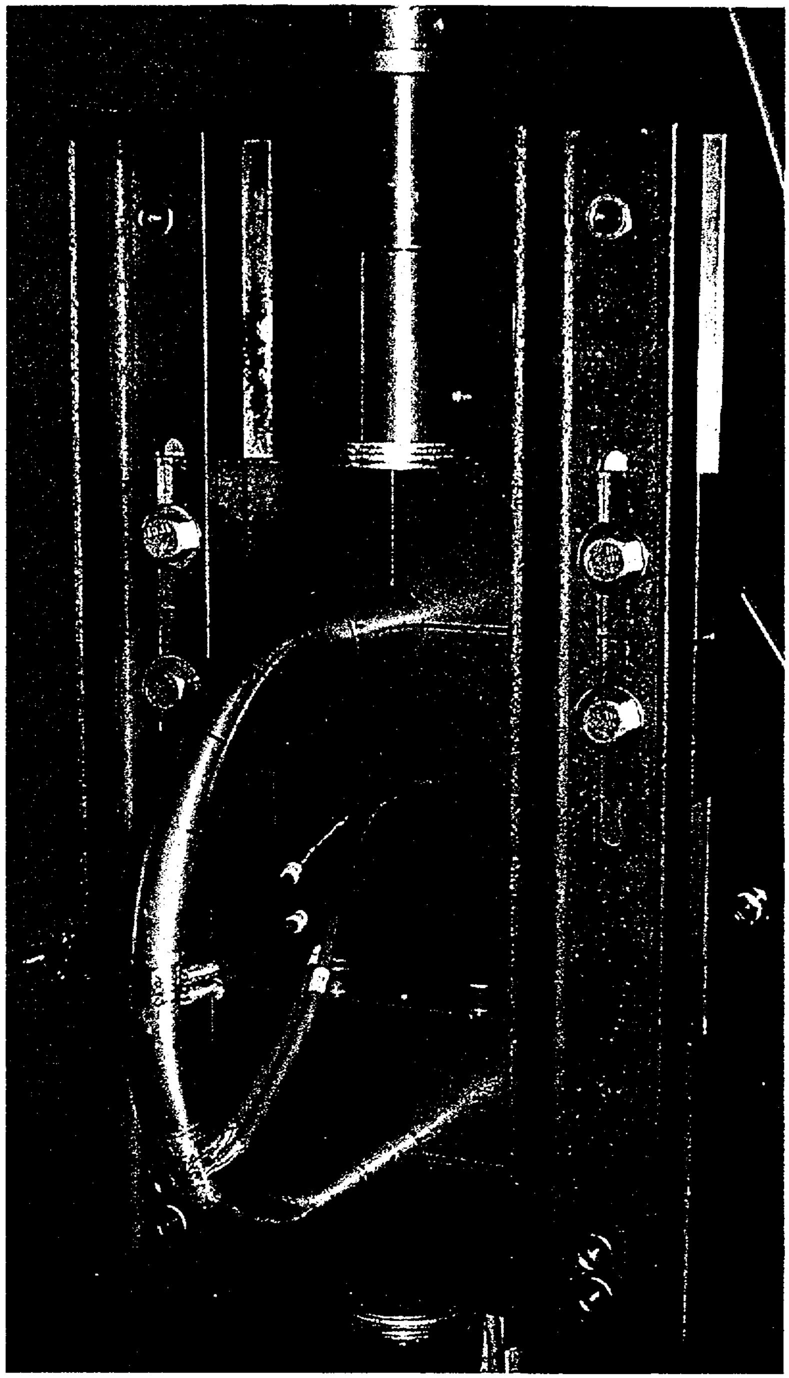
- A U-bend analysis model with a circular cross section will result in conservative ID hoop stress values at the apex.



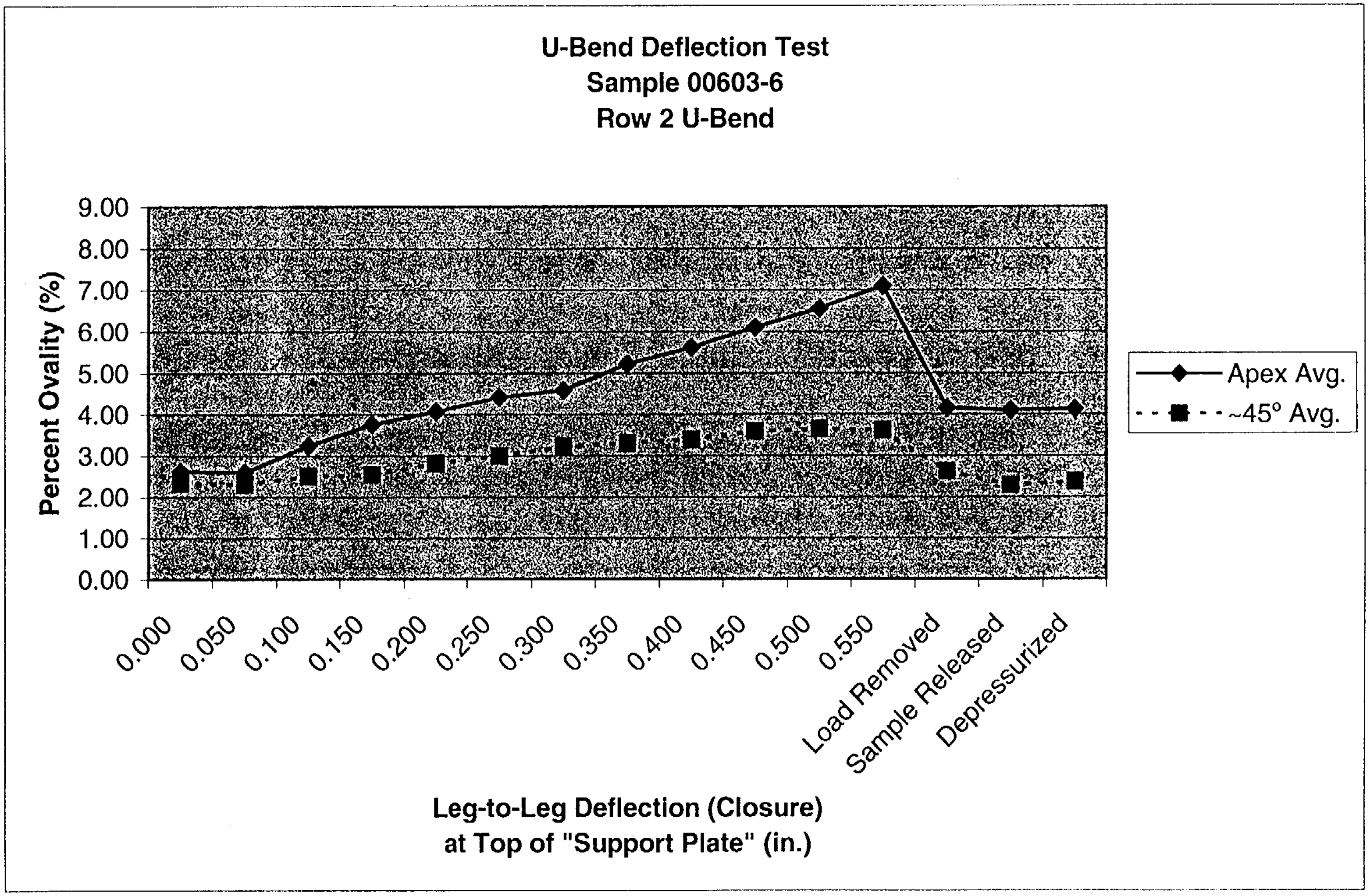
Comparison of ID Hoop Stress of the Extrados at the Apex (Analysis performed with yield stress of 40 ksi)

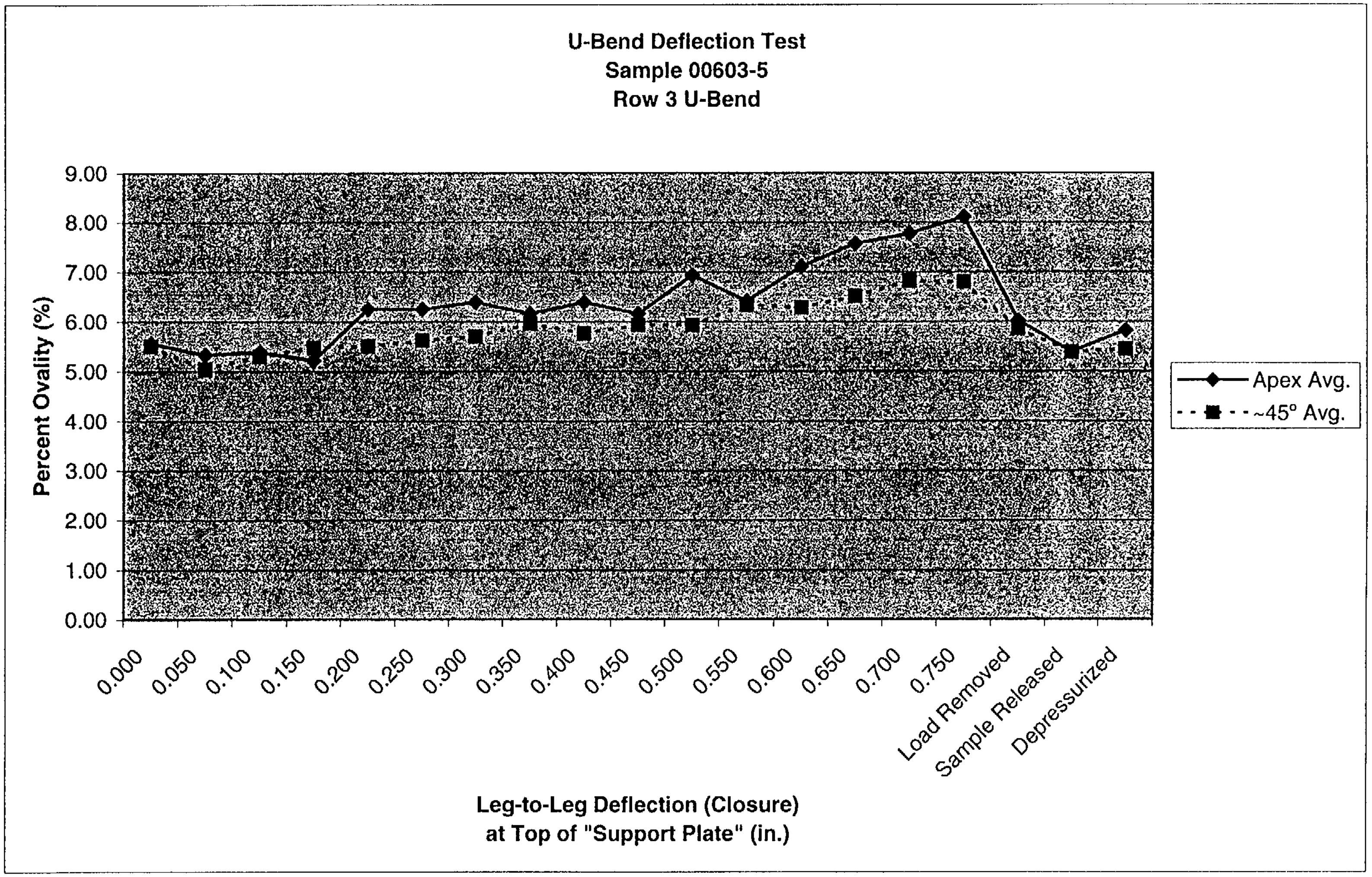
U-Bend Leg Displacement Test

- Fixture designed to apply boundary conditions that allow almost no rotation to simulate the support plate hour-glassing.
- Incremental displacement applied while internally pressurized
- Ovalization, Strain, and Displacement measured



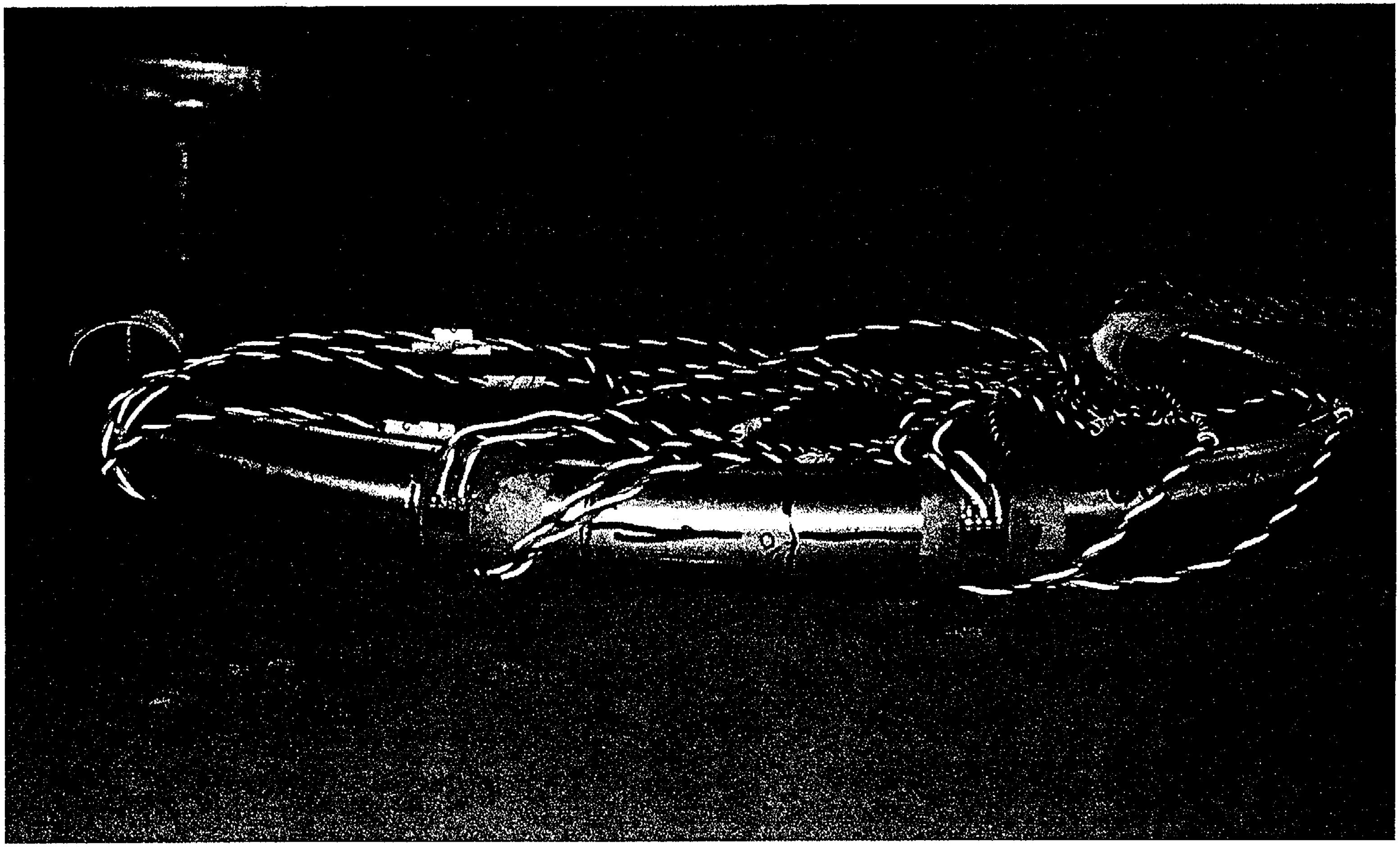
Sample 00603-6 in Test Fixture
Prior to Testing


U-Bend Deflection Test
Sample 00603-6
Row 2 U-Bend
Percent Ovality (%)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.000
0.050
0.100
0.150
0.200
0.250
0.300
0.350
0.400
0.450
0.500
0.550
Load Removed
Sample Released
Depressurized
Apex Avg.
~45° Avg.
Leg-to-Leg Deflection (Closure)
at Top of "Support Plate" (in.)

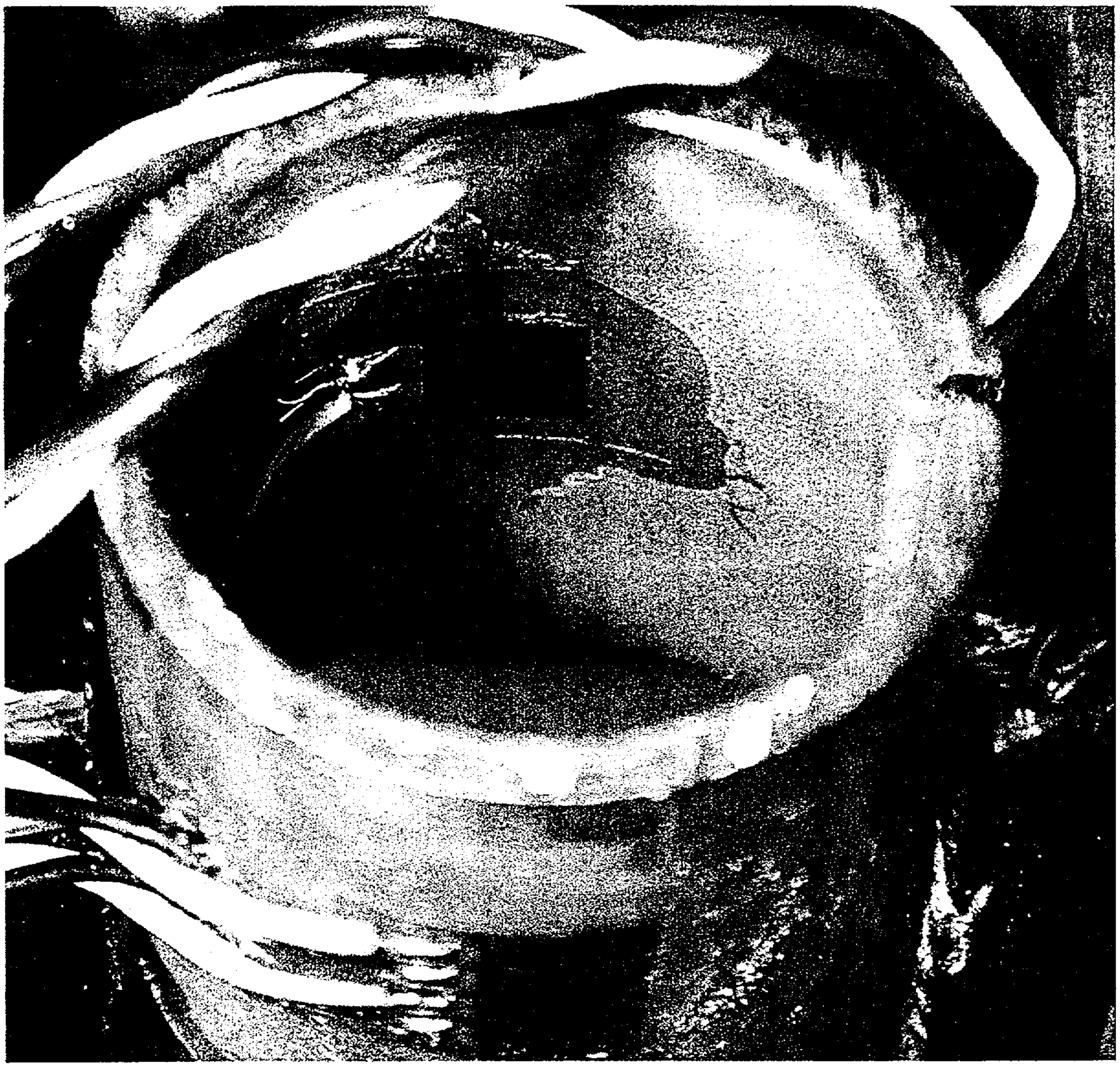

U-Bend Deflection Test
Sample 00603-5
Row 3 U-Bend
Percent Ovality (%)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.000
0.050
0.100
0.150
0.200
0.250
0.300
0.350
0.400
0.450
0.500
0.550
0.600
0.650
0.700
0.750
Load Removed
Sample Released
Depressurized
Apex Avg.
~45° Avg.
Leg-to-Leg Deflection (Closure)
at Top of "Support Plate" (in.)

Residual Stresses

- Tests to determine the residual stress were performed.
- OD strain gages were applied to a Row 2 and a Row 3 tube and the "restraint" initially relieved by cutting the tubes circumferentially.
- ID gages then applied and the tubes were cut axially



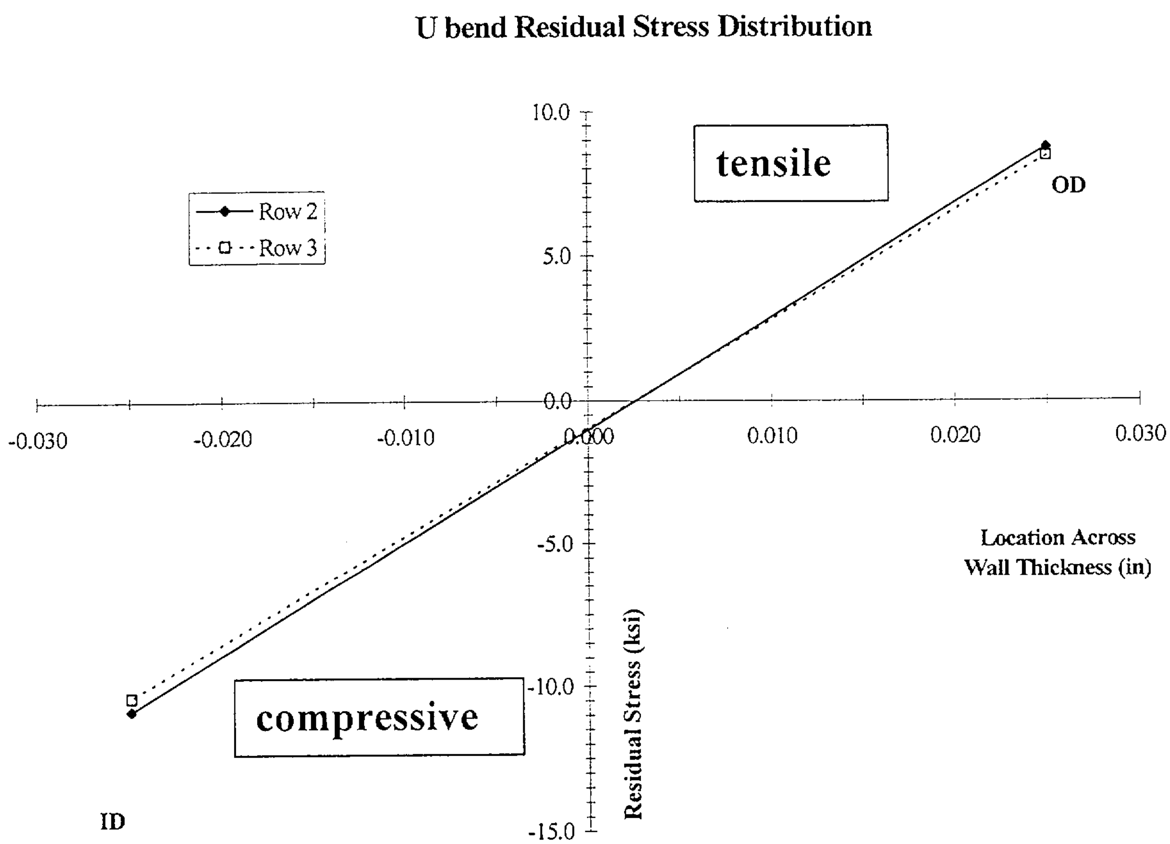
Strain Gages Attached to Extrados
For Residual Stress Measurement
Sample 00603-4



Strain Gage Attached to I.D.
For Residual Stress Measurement
Sample 00603-4

Average Released (Measured) Hoop Strain in Rows 2 and 3 Samples at the Apex

Sample	Average Total ID Hoop Strain (in/in)	Average Total OD Hoop Strain (in/in)
Row 2	0.00038	-0.00030
Row 3	0.00036	-0.00029



Equivalent U-Bend Elastic Residual Stress Distribution

Stress Strain Properties of the Tubes

- Row 2 and Row 3 tube yield stress will be higher than nominal due to strain hardening. Yield strength adjustment determined from elongation induced during bending (Row 2 strain hardening is greater than Row 3).
- Testing showed an increase in yield strength at the tube U-bends of approximately 50% due to strain hardening
- CMTR records from IP2 provided a range of yield strengths in the generator for the various rows
- The analysis model incorporated CMTR data adjusted for strain hardening and operating temperature

Finite Element Analysis

- Analysis was performed with ANSYS.
- Pressure, temperature, residual stress, and leg displacement included
- Yield strengths shown below were utilized in the analysis – these are corrected for temperature and strain hardening.

		Row 2	Row 3
0.2% Yield Stress (psi) – Mil. Test Cert. Values Adjusted for Design Temp.	Lower Yield	44,100	40,300
	Average Yield	61,000	58,800
	Higher Yield	86,000	82,700

Stress Analysis Results

Loading Condition	SUMMARY OF APEX HOOP STRESSES AT CENTER OF FLOW SLOT Apex Hoop Stress (psi)			
	Row 2		Row 3	
	I.D.	O.D.	I.D.	O.D.
Equivalent Elastic Fabrication Residuals	-10,800	8,700	-10,400	8,400
Differential Pressure Plus Thermal Expansion	15,427	8,929	15,009	9,629
Total Loading – Lower Yield Strength	50,845	-35,169	40,743	-13,934
Total Loading - Average Yield Strength	68,496	-48,952	52,711	-30,172
Total Loading – Higher Yield Strength	92,378	-64,060	65,439	-37,204

Crack Initiation

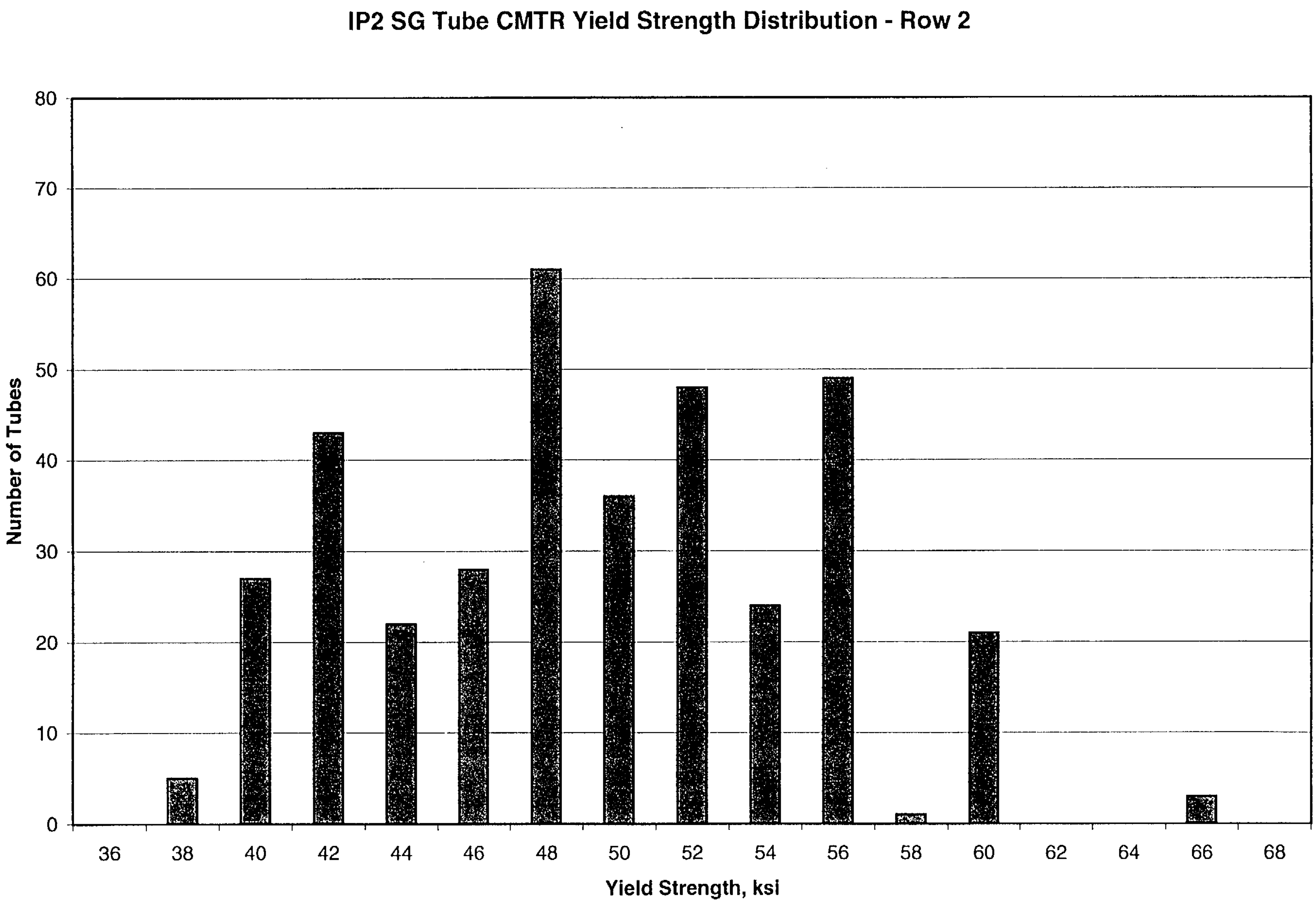
- Time to crack initiation is proportional to the applied stress raised to the 4th power.

- Time to crack initiation in Tube i will be proportionally longer that in Tube j by the following:

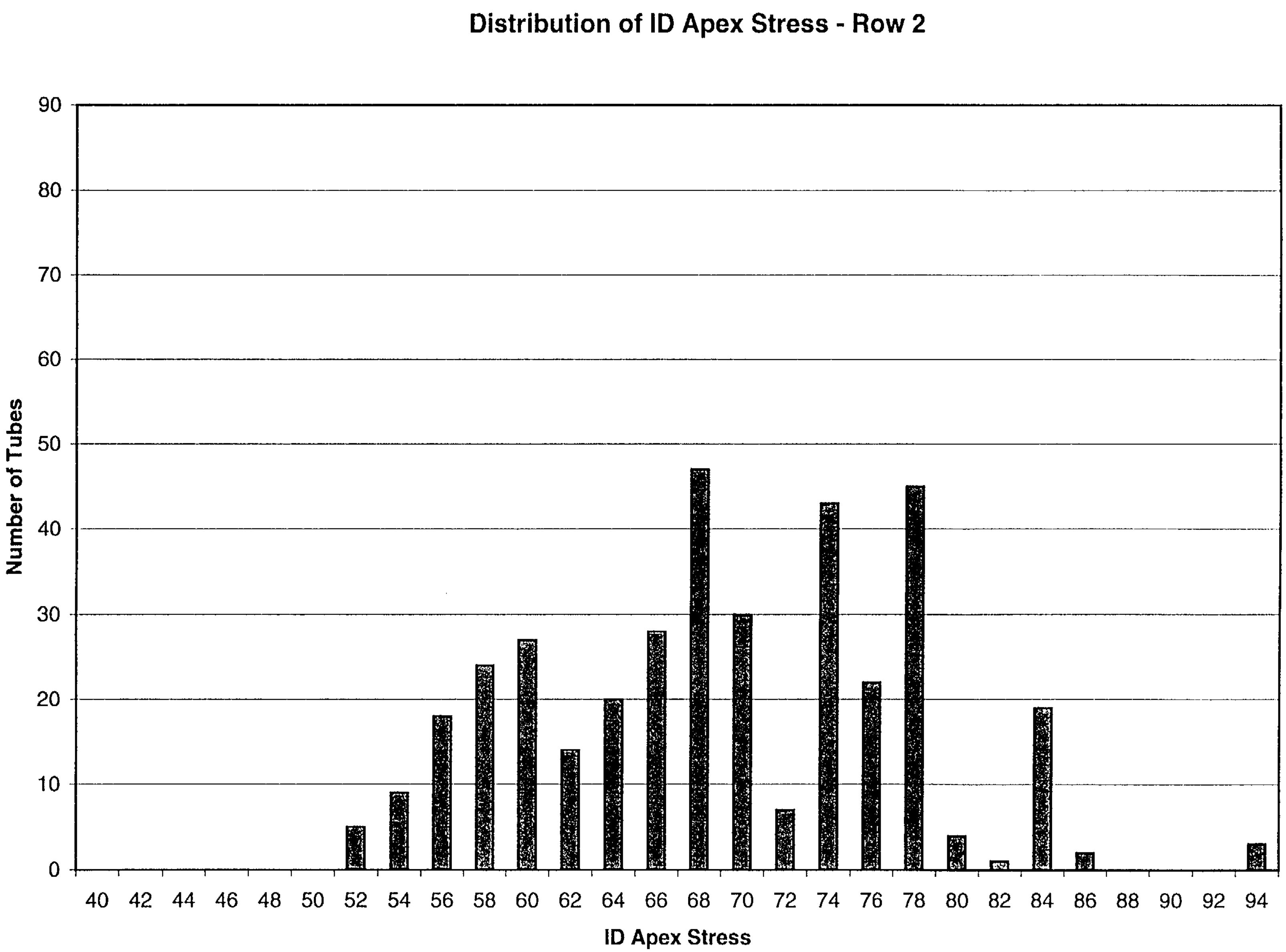
$$t_j = t_i \left[\frac{\sigma_i}{\sigma_j} \right]^4$$

- Cracks will initiate at different times in different Row 2 tubes

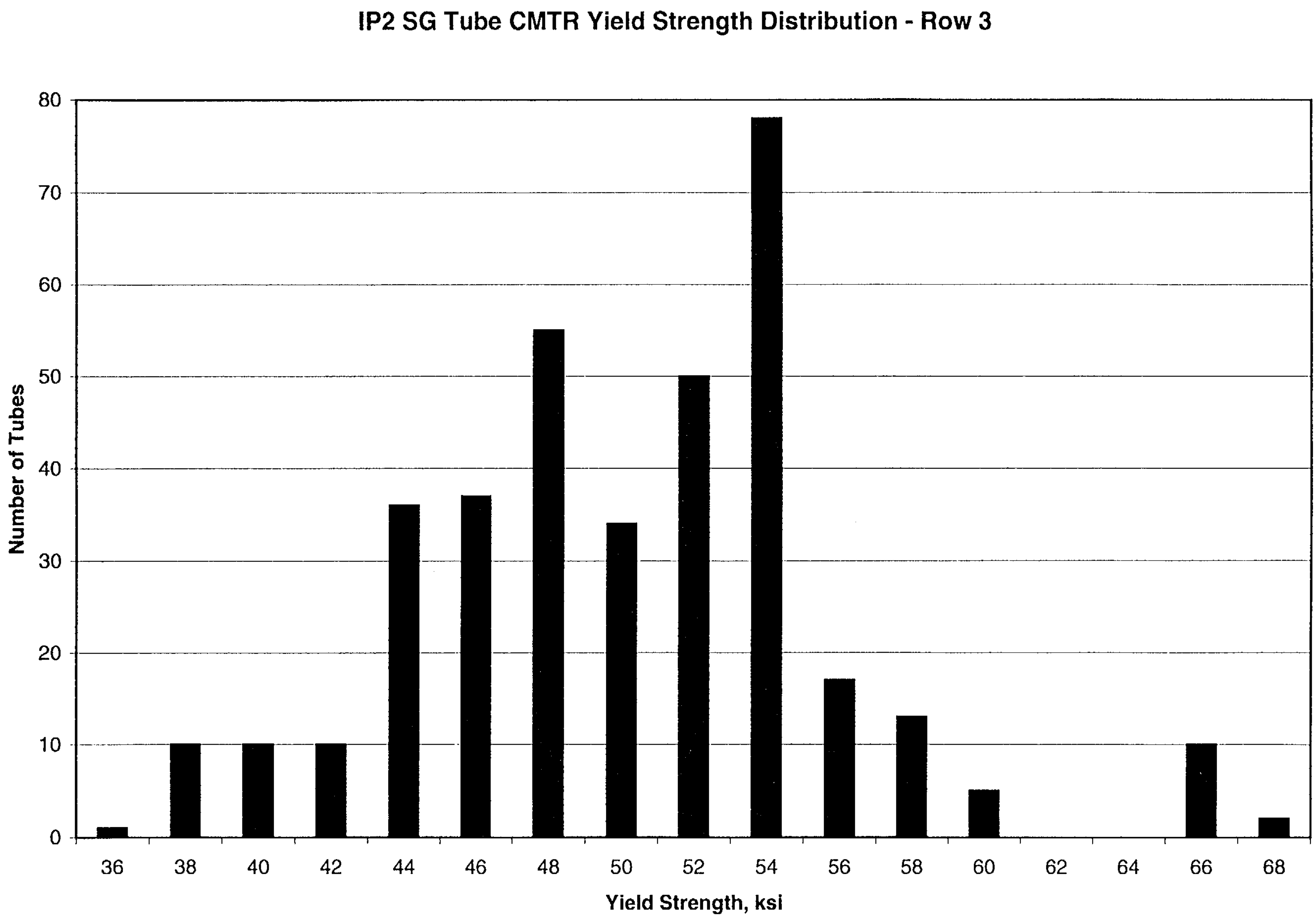
- Cracks will initiate at different time in Row 3 tubes compared to Row 2 and other Row 3 tubes

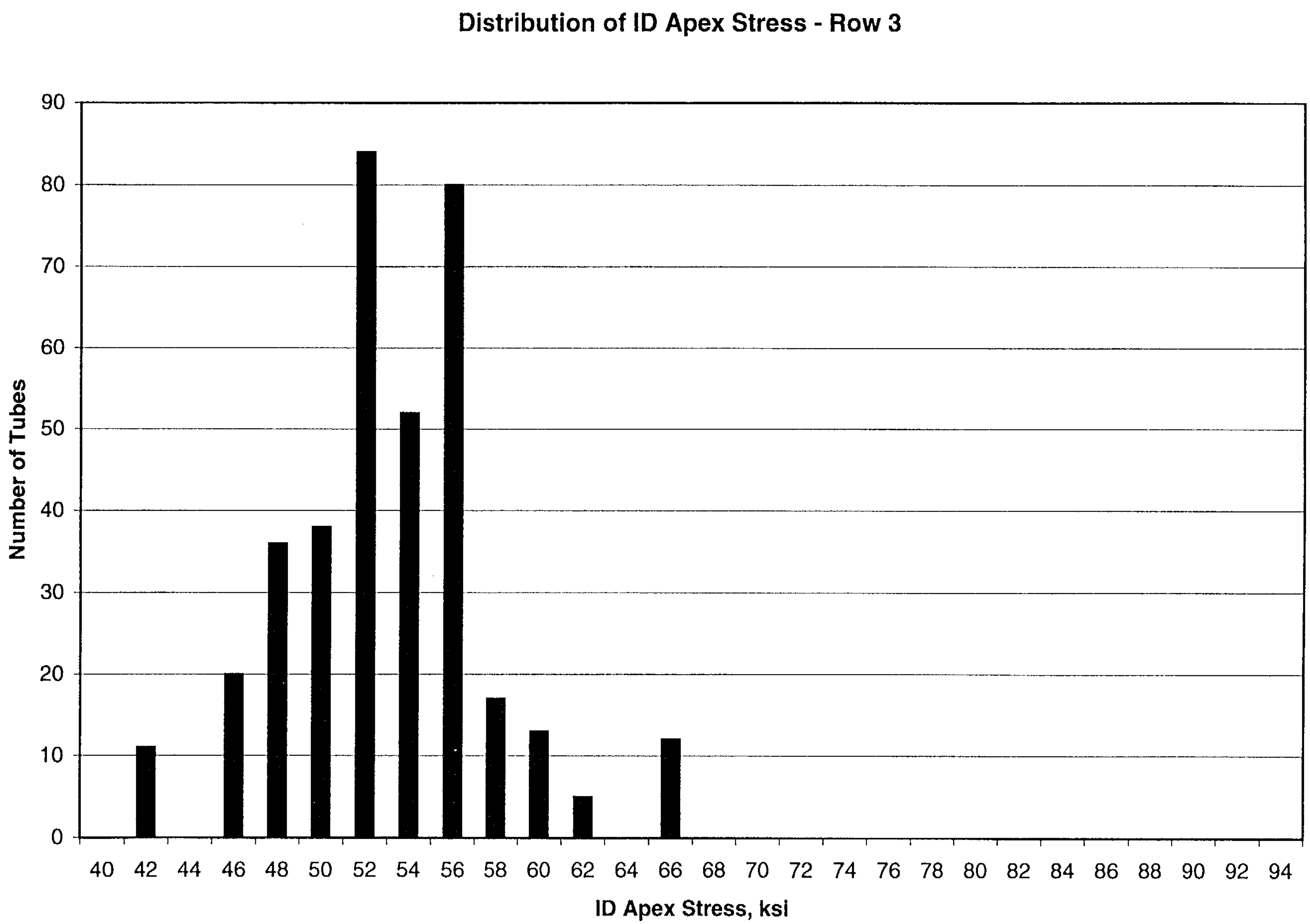


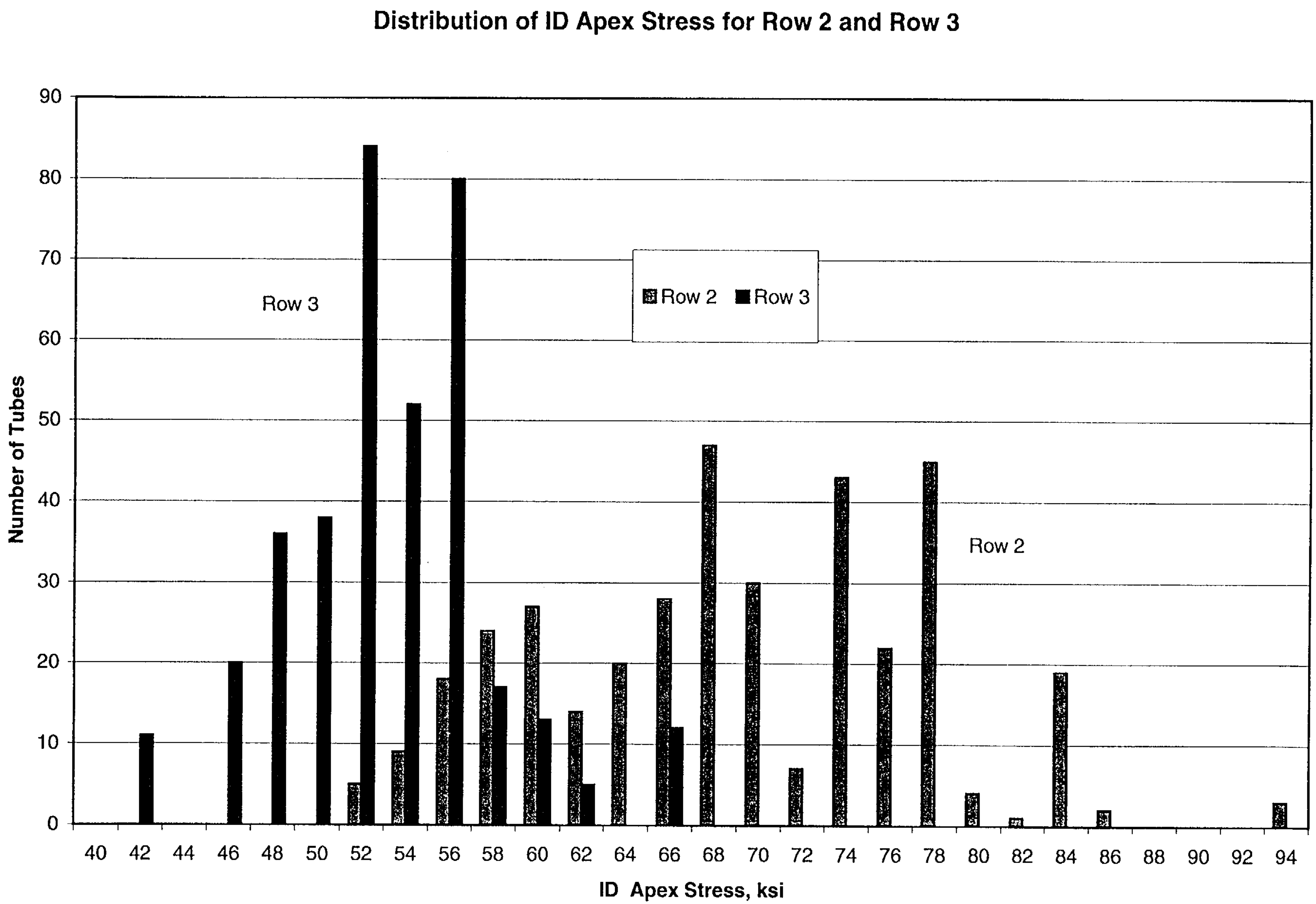
IP2 SG Tube CMTR Yield Strength Distribution - Row 2
Number of Tubes
0
10
20
30
40
50
60
70
80
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
Yield Strength, ksi



Distribution of ID Apex Stress - Row 2
Number of Tubes
0
10
20
30
40
50
60
70
80
90
40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94
ID Apex Stress


IP2 SG Tube CMTR Yield Strength Distribution - Row 3
Number of Tubes
0
10
20
30
40
50
60
70
80
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
Yield Strength, ksi


Distribution of ID Apex Stress - Row 3
Number of Tubes
0
10
20
30
40
50
60
70
80
90
40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94
ID Apex Stress, ksi


Distribution of ID Apex Stress for Row 2 and Row 3
Number of Tubes
0
10
20
30
40
50
60
70
80
90
Row 3
Row 2
Row 2
Row 3
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74
76
78
80
82
84
86
88
90
92
94
ID Apex Stress, ksi

Conclusions

- Ovality appears by test and analysis to not play a significant role in the ID apex stresses
- Cause of cracking linked to hour-glassing in the top TSP
- Row 3 much less susceptible to PWSCC than Row 2 tubes