

API RBI User Group

Probability Determinations using ar/t and Remaining
Strength Factor (RSF) Approaches

February 22, 2006

Lynne C. Kaley
The Equity Engineering Group, Inc.
Houston, TX USA



ar/t Calculations for Thinning - V3

- Based on a Limit State function for ductile overload due to wall loss
- Localized thinning is handled by user selection and modifies inspection recommendations only
- $\text{Age} * \text{Corrosion Rate} / \text{Thickness}$ at a given point in time represents % wall consumed due to corrosion, with 65% consumed wall considered failure
- Thickness must be matched with the date or age used in the calculation
- Denominator floats, making updating thickness and inspections a challenge

	No Inspection	1 Inspection				2 Inspections				3 Inspections			
		Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness			
ar/t		Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1
0.1	2	2	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1
0.2	400	300	210	110	15	290	120	20	1	260	60	5	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1
0.3	650	550	400	200	30	400	200	40	4	320	110	9	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5
0.4	900	800	700	400	130	700	400	120	30	600	200	50	10
0.45	1050	900	810	500	200	800	500	160	40	700	270	60	20
0.5	1200	1100	970	600	270	1000	600	200	60	900	360	80	40
0.55	1350	1200	1130	700	350	1100	750	300	100	1000	500	130	90
0.6	1500	1400	1250	850	500	1300	900	400	230	1200	620	250	210
0.65	1900	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500

ar/t Calculations for Thinning - V3

- Basis for ar/t table generation was simplified in order to apply to a wide range of applications and no ASTM specification information
- The basis for generation of DF's was
 - Design Temperature <750°F and Pressure 187.5 psig
 - Thickness: 0.50 inch
 - Corrosion Allowance 0.125 inch (25%)
 - Drum diameter of 60 inch
 - Carbon Steel with 30 ksi yield and 65 ksi tensile
- Limits application to similar cases based on above inputs
- This approach minimized the data needed for probability calculations (material properties and corrosion allowance)
- Bayesian updating used to credit inspection through improved confidence

Limitations of ar/t Approach – V3

- Use general case and material properties to generate the ar/t table
- Based on simple limit state function to determine POF
- Adjusted to specific case based on modification factors, corrosion and inspection history
- Uses ar/t DF table that is not based on:
 - T_{\min} calculation
 - Actual corrosion allowance, based on 25% thickness is CA
 - Actual material specification properties to perform better POF determination

ar/t Calculations for Thinning – V5+

- Improvements on the ar/t approach in V3
 - Multiple thickness capability without losing original data
 - Based on % wall lost compared to fabrication data
 - DF compared to T_{\min}
 - Reduced conservativeness when equipment above T_{\min}
- No longer need to minimize data requirements
- ASTM library contains all material properties needed for T_{\min} , MAWP calculations
- Corrosion allowance now used in ar/t and DF determination
 - If thickness $> T_{\min} + CA$, DF assigned is 0
 - Denominator fixed at $T_{\min} + CA$, % wall loss is cumulative
- Original assumptions in ar/t still apply but ar/t modified calculation
 - Assumption of 25% Corrosion Allowance
- Bayesian updating used to credit inspection through improved confidence

Damage Mechanism - Thinning

$$\frac{ar}{t} = \max \left[1 - \left(\frac{sthk - crate \cdot time}{t_{\min} + C.A.} \right), 0.0 \right]$$

where

sthk – most recent thickness reading

crate – corrosion rate of the base or cladding material, as applicable,
estimate at the time of the most recent thickness reading

time – time difference between the RBI date and the date of the most
recent thickness reading

C.A. – corrosion allowance

Limitations of ar/t Approach – V5+

- Based on simple limit state function to determine POF
- Uses ar/t DF table that is not based on:
 - Actual corrosion allowance, based on 25% thickness is CA
- Possible Solution - Corrosion Allowance correction:
 - Use factor to adjust ar/t up or down
 - Difficulty applying at high and low end of factor range
 - Difficulty applying over time as thickness, POF and risk change

Case 1

- Equipment installed 1985-01-01
- RBI Date 2005-10-01
- Plan Date 2015-10-01
- Fabrication Data
 - Furnished Thickness 3.125"
 - Corrosion Allowance 0.125"
 - Design Pressure 875 psig
 - Design Temperature 1,000°F
- Corrosion/Inspection Data
 - 3 mpy general corrosion rate
 - 2.125 A effectiveness inspection
 - Last inspection date 2002-10-30
 - No measured thickness in inspection history

Case 1 – CA 25%

		Start Date	RBI Date	Plan Date
		1/1/1985	10/1/2005	10/1/2015
Pressure	P	875	875	875
Allowable Stress	S	7,800	7,800	7,800
Outside Diameter	OD	49.25	49.25	49.25
Inner Diameter	ID	43.00	43.12	43.19
Radius	R	21.50	21.56	21.59
Joint Efficiency	E	0.85	0.85	0.85
Corrosion Allowance	CA	0.125	0.125	0.125
Thickness	t	3.125		
Age	Y	0.00	20.7474	30.8524
Wall loss from Start	tloss	0.000	0.0622	0.0926
Corrosion Rate	MPY	3	3	3
Current Thickness		3.125	3.063	3.032

Case 1 – CA 25%

	Start Date	RBI Date	Plan Date
Current Thickness	3.125	3.063	3.063
Tmin	3.081	3.0904	3.0904
MAWP	886.364	867.785	867.785
Insp Credit		2.125A	2.125A
old ar/t	0.000	0.020	0.030
Old DF	0	1	1
New ar/t	0	0.0475	0.0582
New DF	0	1	1
CA Ratio	6.25	6.25	6.25
Old ar/t adjusted	0	0.124	0.185
New ar/t adjusted	0	0.297	0.364

	No Inspection	1 Inspection				2 Inspections				3 Inspections			
		Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness			
ar/t		Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1
0.1	2	2	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1
0.2	400	300	210	110	15	290	120	20	1	260	60	5	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1
0.3	650	550	400	200	30	400	200	40	4	320	110	9	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5
0.4	900	800	700	400	130	700	400	120	30	600	200	50	10
0.45	1050	900	810	500	200	800	500	160	40	700	270	60	20
0.5	1200	1100	970	600	270	1000	600	200	60	900	360	80	40
0.55	1350	1200	1130	700	350	1100	750	300	100	1000	500	130	90
0.6	1500	1400	1250	850	500	1300	900	400	230	1200	620	250	210
0.65	1900	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500

Case 1 – CA 25%

- Equipment is below the calculated T_{\min} at the RBI Date
- ar/t calculation approach in V3 and V5+ generate DF of 1
- Function of the CA $\ll 25\%$ of furnished thickness (6.25%)
- Modify ar/t to calculated result x CA ratio modifies DF
- High level of confidence through inspection still generates a low DF

- Understanding of T_{\min} and MAWP calculation is necessary to understand results

Case 1 – CA 25%

	Start Date	RBI Date	Plan Date
Current Thickness	3.125	3.063	3.063
Tmin	3.081	3.0904	3.0904
MAWP	886.364	867.785	867.785
Insp Credit		2.125A	2.125A
old ar/t	0.000	0.020	0.030
Old DF	0	1	1
New ar/t	0	0.0475	0.0582
New DF	0	1	1
CA Ratio	6.25	6.25	6.25
Old ar/t adjusted	0	0.124	0.185
New ar/t adjusted	0	0.297	0.364

T_{\min} Calculator

- Calculated T_{\min} is based on code (API 579) calculations specific to geometry type
- For a Cylinder:

$$t_{\min}^C = \frac{PR_c}{SE - 0.6P}$$

Where:

P - Pressure

S - allowable stress

R - Radius

E - Joint efficiency

- Uses the larger of a structural T_{\min} (user defined) and Calculated T_{\min}
- Calculated at the RBI Date 2005-10-01

MAWP Calculator

- For a Cylinder:

$$MAWP^C = \frac{SEt_c}{R_c + 0.6t_c}$$

Where:

P - Pressure

S - allowable stress

R - Radius

E - Joint efficiency

t - thickness

- Calculated MAWP for RBI Date based on estimated thickness at date
- Calculated at the RBI Date 2005-10-01

Case 2 - CA Adjusted

- Same fabrication inputs as Case 1
- Corrosion/Inspection Data
 - Adjusted general corrosion rate of 21 mpy to model ar/t adjustment
 - Last inspection date 2002-10-30
 - Model two Inspection Examples
 - + 2.125 A effectiveness inspection, no measured thickness update
 - + 1 D effectiveness on 2002-10-30, with measured thickness update of 2.069

Case 2 - CA Adjusted

		Start Date	RBI Date	RBI Date	Plan Date
		1/1/1985	10/1/2005	10/1/2005	10/1/2015
Pressure	P	875	875	875	875
Allowable Stress	S	7,800	7,800	7,800	7,800
Outside Diameter	OD	49.25	49.25	49.25	49.25
Inner Diameter	ID	43.00	43.87	43.99	44.42
Radius	R	21.50	21.94	22.00	22.21
Joint Efficiency	E	0.85	0.85	0.85	0.85
Corrosion Allowance	CA	0.125	0.125	0.125	0.125
Thickness	t	3.125	2.690	2.690	2.416
Age	Y	0.00	20.7474	2.9213	13.0263
Wall loss from Start	tloss	0.000	0.436	0.0613	0.2736
Corrosion Rate	MPY	21	21	21	21
Current Thickness		3.125	2.69	2.63	2.42

Case 2 - ar/t CA Adjusted

	Start Date	RBI Date	RBI Date	Plan Date
Current Thickness	3.125	2.69	2.63	2.42
Tmin	3.081	3.144	3.090	3.183
MAWP	886.364	757.140	753.201	604.699
Insp Credit		2.125A	1D	1D
old ar/t	0.000	0.139	0.023	0.102
Old DF	0	1	1	2
New ar/t	0.0254	0.1773	0.1825	0.3522
New DF	0	1	212	650
CA Ratio	6.25			

	No Inspection	1 Inspection				2 Inspections				3 Inspections			
		Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness			
ar/t		Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1
0.1	2	2	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1
0.2	400	300	210	110	15	290	120	20	1	260	60	5	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1
0.3	650	550	400	200	30	400	200	40	4	320	110	9	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5
0.4	900	800	700	400	130	700	400	120	30	600	200	50	10
0.45	1050	900	810	500	200	800	500	160	40	700	270	60	20
0.5	1200	1100	970	600	270	1000	600	200	60	900	360	80	40
0.55	1350	1200	1130	700	350	1100	750	300	100	1000	500	130	90
0.6	1500	1400	1250	850	500	1300	900	400	230	1200	620	250	210
0.65	1900	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500

Case 2 - CA Adjusted

- Equipment is below the calculated T_{\min} at the RBI Date
- ar/t calculation approach in V3 and V5+ generate DF of 1 without updated measured thickness
- Function of the CA $\ll 25\%$ of furnished thickness (6.25%)
- Modify ar/t through adjustment of the corrosion rate demonstrates the impact of a CA adjustment, however:
 - Fix does not fully address issue
 - Implementation is difficult to program
 - Potentially causes other problems with the Risk calculations
- TWG decided that the ar/t approach is outdated for current technology and capabilities
- Recommended implementing and evaluating the results of a Remaining Strength Factor (RSF) approach to replace the ar/t calculations

Determining POF

- Probability of failure Limit State Function is:

$$LS = R(r_1, r_2, \dots, r_n) - L(l_1, l_2, \dots, l_n)$$

- R is resistance
- L is the applied load model and variables:
 - Define uncertainty in independent variables
- POF determined using standard structural reliability techniques

Determining POF - Examples

General Thinning

$$LS = \left(\left[\frac{0.25}{n + 0.277} \right] \left[\frac{e}{n} \right]^n \cdot \ln \left[\frac{R_o}{R_o - t - d} \right] \cdot \sigma_{uts} \right) - P_{applied}$$

- **n is the strain hardening** coefficient that is a function of the yield and ultimate tensile strength
- e is the base of the natural logarithm
- R_o is the outside radius
- R_i is the inside radius
- t is the wall thickness
- d is the metal loss
- $P_{applied}$ is the applied pressure

Determining POF - Examples

General Thinning

- Material: UTS & YS
- Geometry: R_o , t
- Inspection parameter: d
- Loading term: P_{applied}
- Data is already available in RBI

Determining POF - Examples

Local Thinning

$$LS = \left(\left[\frac{0.25}{n + 0.277} \right] \left[\frac{e}{n} \right]^n \cdot \ln \left[\frac{R_o}{R_o - t} \right] \cdot \sigma_{uts} \cdot RSF(d, s) \right) - P_{applied}$$

- n is the strain hardening coefficient that is a function of the yield and ultimate tensile strength
- e is the base of the natural logarithm
- R_o is the outside radius
- R_i is the inside radius
- t is the wall thickness
- d is the metal loss
- **s is the length** associated with the metal loss
- **RSF(d,s) is the remaining strength factor**
- $P_{applied}$ is the applied pressure

Determining POF - Examples

Local Thinning

- Material: UTS & YS
- Geometry: R_o , t
- Inspection parameters: d , s
- Loading term: P_{applied}
- All variables are available in RBI, except length of damage or thinning
 - local thinning due d and s is a function of the operating environment and material of construction

Conclusion/Recommendations

- ar/t approach has been enhanced as much as possible in V5+
- Attempts to make further adjustments to an outdated approach may cause unexpected results if done without testing
- Testing of incremental improvements of the ar/t will further delay development of the RSF approach
- An RSF approach can be developed for the purposes of RBI
- Starts better alignment RBI with FFS methodologies in API 579
- Need to fast-track the development to implement in late 2006 release using:
 - Standard structural reliability equations
 - Calculate POF using actual material properties and data
 - Apply statistics to input uncertainty
 - Provide DF to user as an output
 - May eliminate need for Bayesian updating