Risk-Based Management of Mechanical Integrity in Air Products Hydrogen Steam Methane Reformer Plants

Presentation by

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Agenda

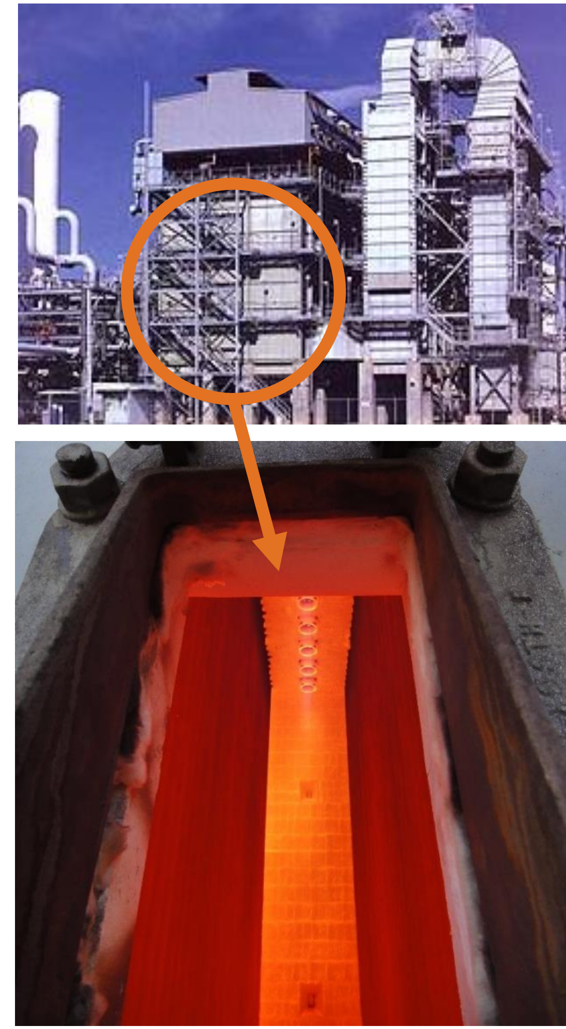
Air Products Global H2 Capabilities
Risk Based Inspection Overview
Case Studies:

1. Hydrogen Purification
2. Steam Methane Reformer Tube Inspection
3. Steam Methane Reformer Outlet System

Questions & Answers
Appendix Case Study: CO2 Absorber Column IOW Shift

Air Products Global Hydrogen Capabilities and Experience

- Worldwide leadership position in outsourced hydrogen production & recovery
  - Supply 3,000 MMSCFD of H2
  - Over 1600 operating years of experience
  - Maintained 40% market share for over 20 years
  - Strong focus on refining and chemical industries
  - Service Air Products and customer hydrogen assets
- Established reputation for high reliability operation
  - Strong pipeline positions
  - Operational excellence at plant level
- Own & operate over 100 hydrogen plants globally
  - 24+ world class high reliability SMR's
  - Operate ~10,000 tubes



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Risk Based Inspection

- A systematic process for factoring risk into decisions concerning how, when, and where to inspect pressure systems equipment, tanks and piping systems.
- Risk is defined using a criticality rating process, that combines the likelihood and the consequence of failure of equipment and piping systems
- Consequence of failure includes evaluation of safety, environmental, and financial impact
- Likelihood of failure is determined by identifying potential damage mechanisms based on mechanical design of the system and the system’s Integrity Operating Window

Downtime Task? (Y/N)	PSM (Y/N)		ESCC	ISCC	CUI	ICML	EGCML	FC	General Visual (ref. 01.20.37)	OTHER	Notes	Safety/ Environmental	Economic	Failure Potential	Total Risk	Risk Ranking	M.I. or P.M.?	Task 1	Frequency 1	Task 2	Frequency 2
20	21	#	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Y	N				X				X			3	2	2	12	H	MI	XXX	XX		
																H		Externa			

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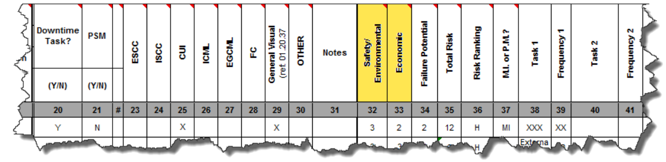
Consequence of Failure



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Type	Consideration
Safety	Process and Personnel safety, off site consequences
Environmental	Potential to approach or exceed permit req.
Financial	Cost to repair, lost sales, contract penalties, loss of goodwill

- All cases presented today share common consequence of failure
  - Release of flammable, toxic material
  - Potential PV Energy based on failure mode
  - Reduced capacity / likely unplanned outage
  - Significant repair costs
  - *Impact on Customer. Air Products works closely with our "over the fence" customers and know the criticality of hydrogen product to their operation and the consequences of unplanned reductions in supply.*

AIR PRODUCTS

Likelihood of Failure

Downtime Task? (Y/N)	PSM (Y/N)		ESCC	ISCC	CUI	ICML	EGCML	FC	General Visual (ref. 01.20.37	OTHER	Notes	Safety/ Environmental	Economic	Failure Potential	Total Risk	Risk Ranking	M.I. or P.M.?	Task 1	Frequency 1	Task 2	Frequency 2
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- Damage mechanisms are identified by evaluating mechanical design considerations and the process's Integrity Operating Windows (IOW)
- Mechanical Design considerations include material of construction, design basis, and fabrication details
  - Design basis considerations include
    - Creep, corrosion allowance, fatigue
  - Fabrication details include
    - Weld procedure, stress relief, weld contour, vessel shape
- Integrity Operating Windows (IOW) include both normal and transient conditions (startup and shutdown)
  - IOWs should be periodically validated to ensure changes have not introduced the potential for new damage mechanisms

Case Study - Hydrogen Purification

- Pressure Swing Adsorber (PSA) to purify Syngas using an adsorbent bed to remove impurities at process pressure, regenerated at low pressure (~5min cycle).
- Multiple vessels are required due to the adsorbent's limited capacity, requiring periodic regeneration

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Hydrogen Purification

Probability of Failure

- Damage Mechanism Assessment
  - For applications operating below 200°C, fatigue is the Primary Damage Mechanism
- Likelihood of Fatigue Damage starts with Design and Fabrication
  - Design
    - Vessel designed for fatigue?
    - Design includes fabrication tolerances?
    - Fatigue design consistent with the actual IOW?
  - Fabrication
    - Roundness of vessel, particularly at longitudinal seams, can greatly impact local stresses
    - Weld quality can increase local stresses and create crack initiation points

Hydrogen Purification

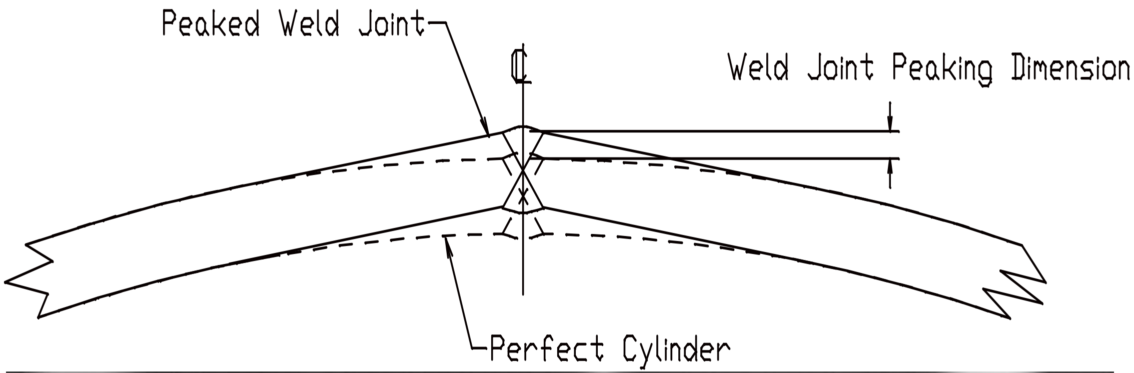
Inspection Strategy

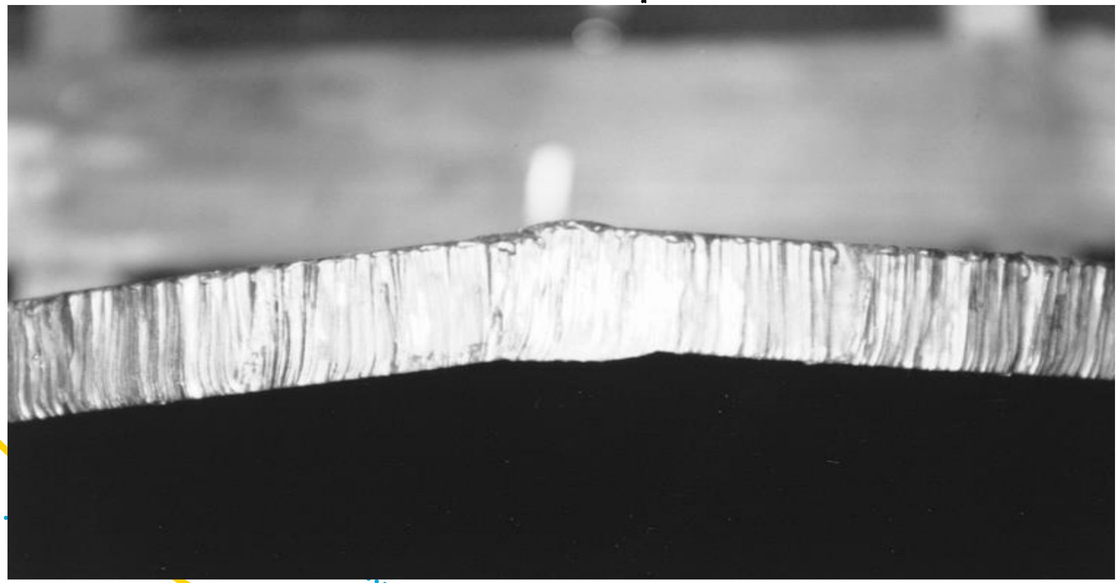
- Inspection strategy should focus on fatigue damage at weld locations
  - Both full penetration and attachment welds
- Likelihood and location of crack formation is strongly influenced by the vessel roundness at the weld seams (peaking) and by weld quality
  - Validating vessel shape during factory acceptance can increase the effectiveness of the inspection program as shape impacts whether a crack will likely initiate on the ID or OD vessel surface
- Timing of inspection is a function of the Integrity Operating Window
  - Condition Monitoring by tracking pressure cycle size (ΔP) and frequency allows inspection optimization

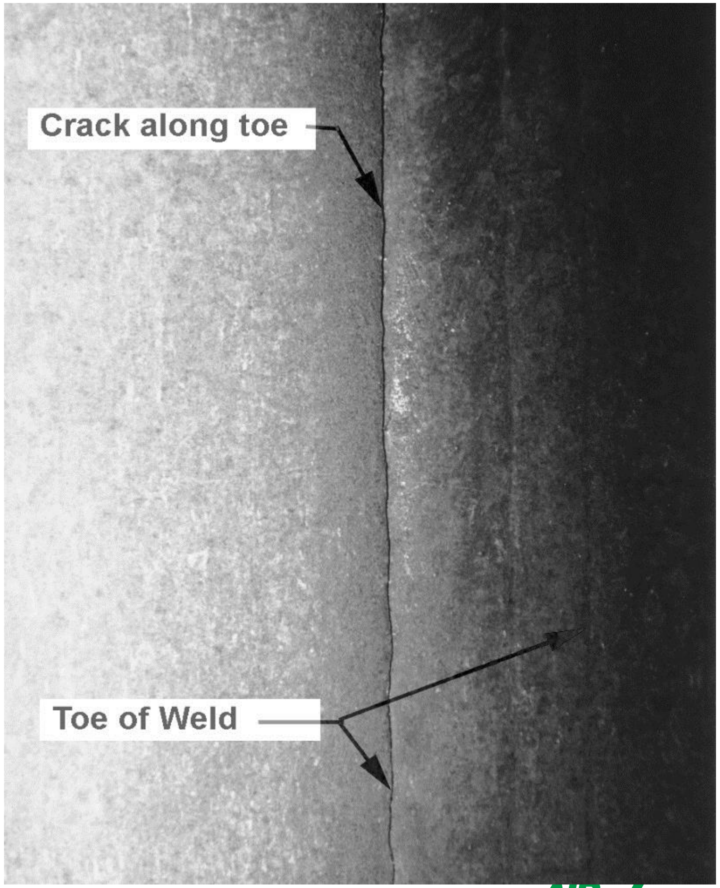
Hydrogen Purification

Fabrication – Weld Seam "Peaking"

- Vessel shape at longitudinal weld joint must be considered, and can add significant local stresses



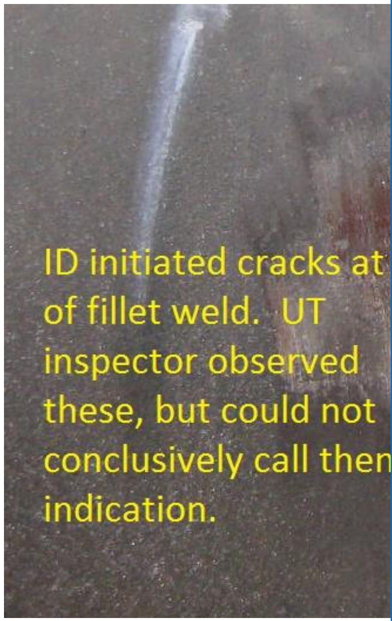


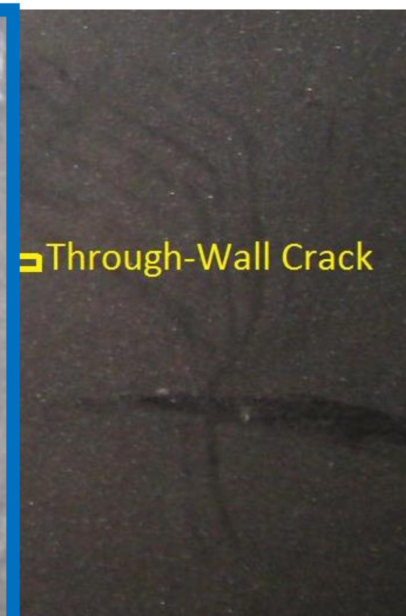


Hydrogen Purification

Design & Fabrication

- Attachment welds create local stress that when placed near longitudinal seams increase potential for fatigue damage





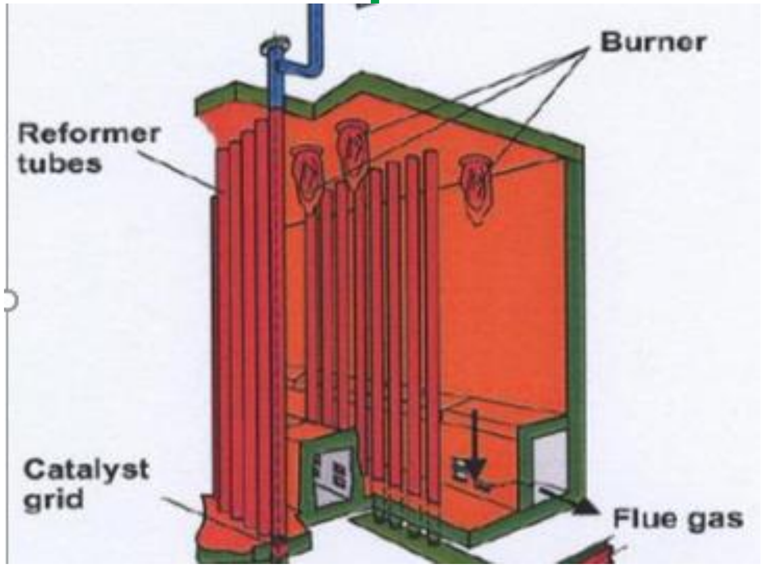
Hydrogen Purification

Inspection Strategy

- The first fatigue inspection typically is executed at the vessel's fatigue design half life
- Common methods of inspection include Ultrasonic Angle Beam Inspection (UTSW), Phased Array, and Magnetic Particle Surface Examination (MT)
- Future inspection requirements can be evaluated using a Fitness For Service (FFS) approach
  - API 579 Part 9 and BS7910 provide FFS guidance
- Industry Guidance Documents
  - CGA H-13 "Hydrogen Pressure Swing Adsorber (PSA) Mechanical Integrity Requirements"
  - API 571 "Damage Mechanisms Affecting Fixed Equipment in the Refining Industry"

Case Study - Steam Methane Reformer (SMR) Tube Inspection

- Typical large reformers contain hundreds of tubes
- Tubes designed to API 530 "Calculation of Heater-tube Thickness in Petroleum Refineries"
- Tubes are centrifugally cast and typically made out of HK40, HP50, or HP MicroAlloy



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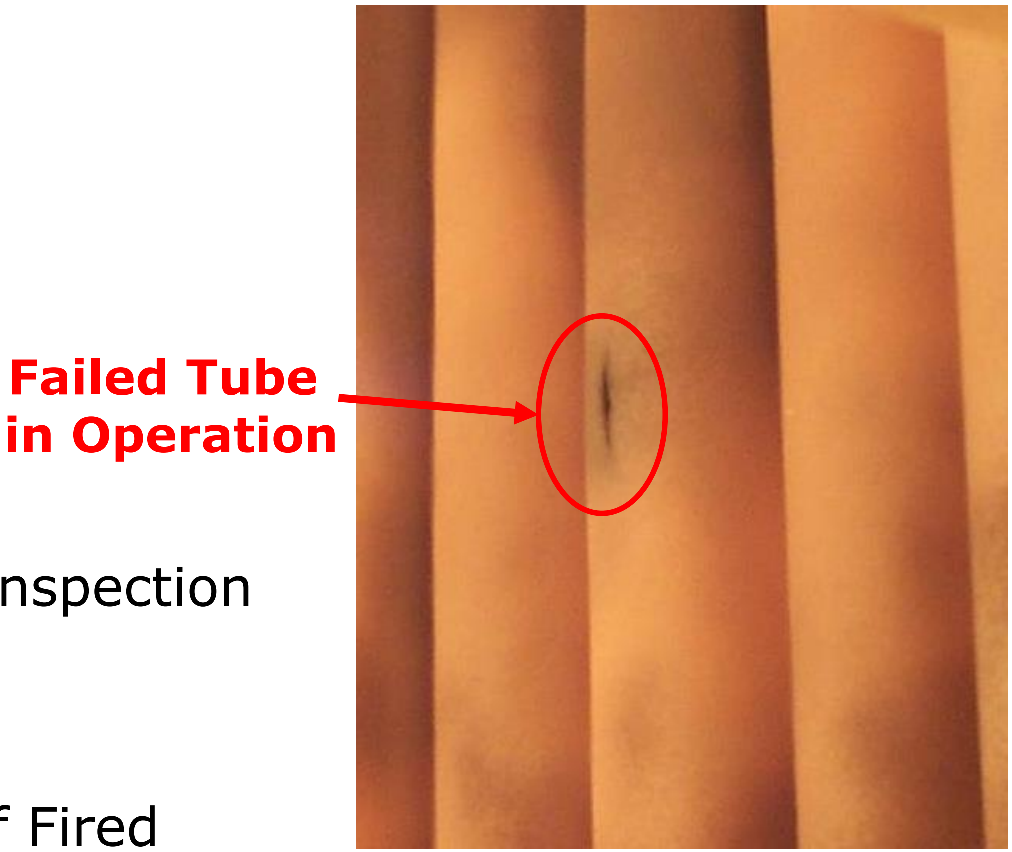
SMR Tube Inspection
Damage Mechanism Assessment

- Primary Failure mechanisms are short term overheat damage, structural deformation, long term creep damage
- Short term overheat from flame impingement and catalyst issues
- Structural deformation (tube bowing) from improper support and uneven heating
- Long term creep from service
  - Tube temperature has large impact on creep life

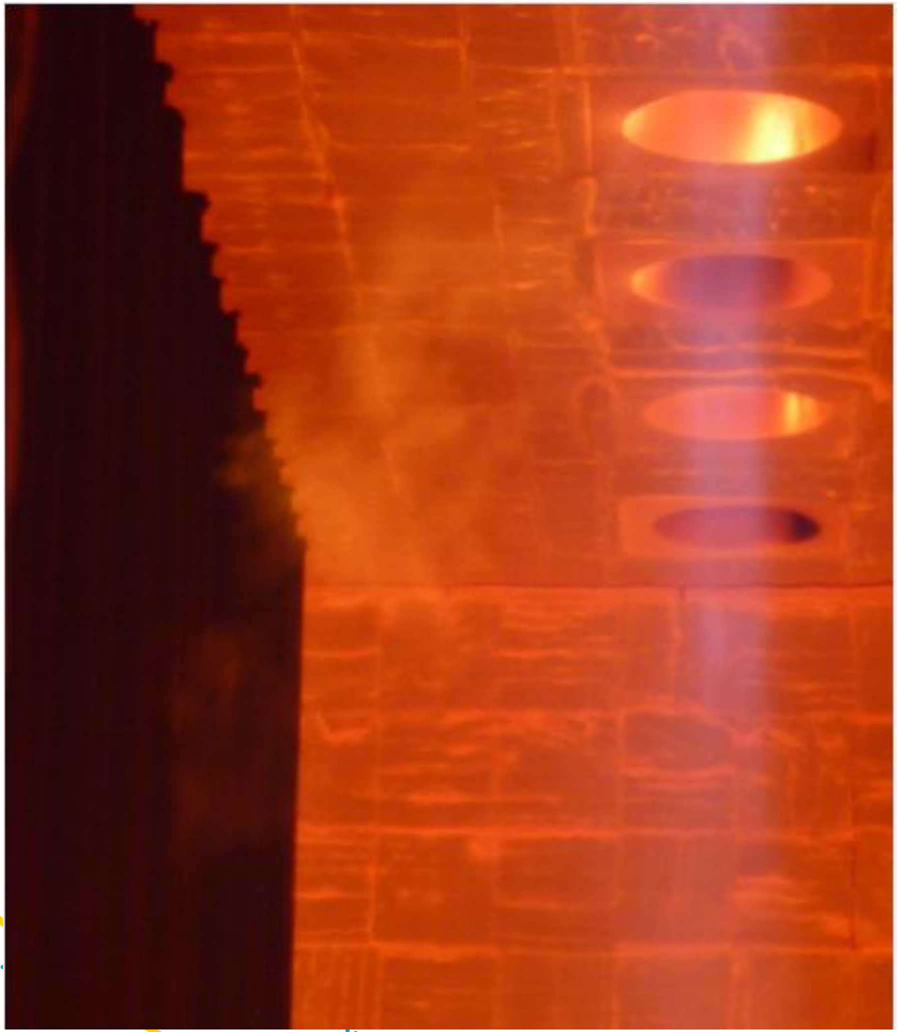
SMR Tube Inspection
Inspection Strategy

- Combination of on-line and off-line inspections
- On-line inspections
  - Burner Firing
  - Tube Temperature Measurement
- Off-line inspection
  - Visual inspection
  - Tube Crawling Creep inspection
  - Destructive Testing
- Industry Guidance
  - API 573 "Inspection of Fired Boilers and Heaters"



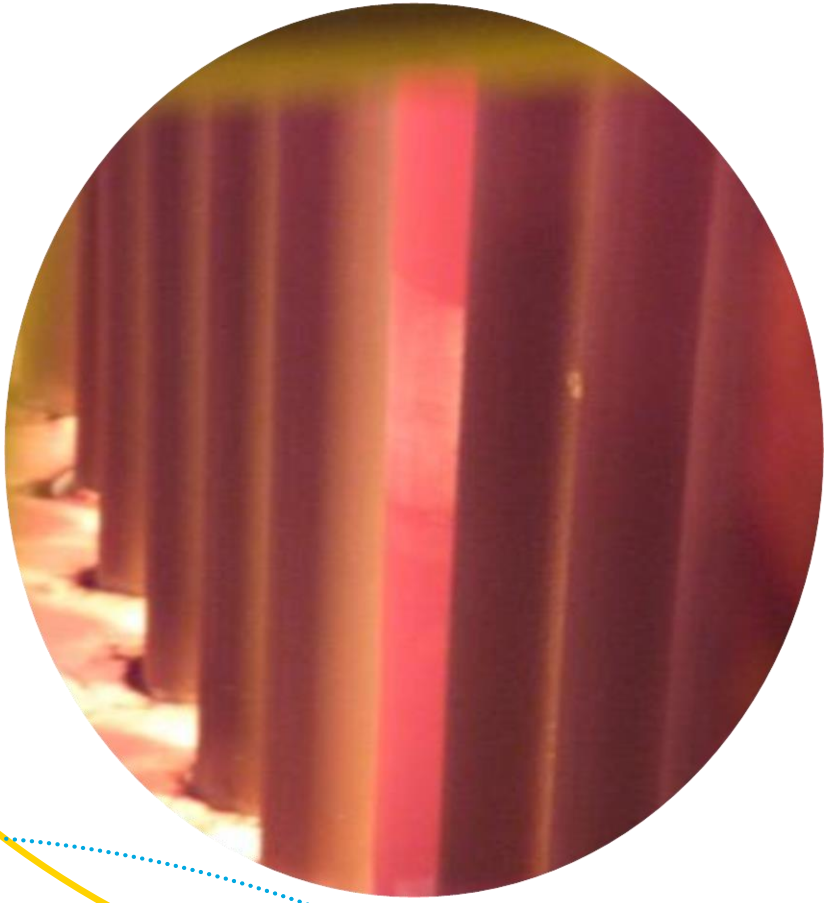
SMR Tube Inspection
Short Term Overheat

- Flame impingement



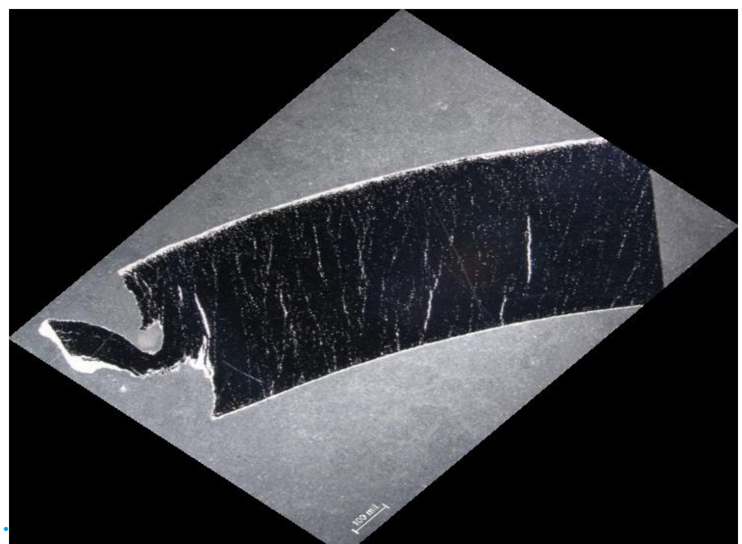
SMR Tube Inspection
Short Term Overheat

- Catalyst issues



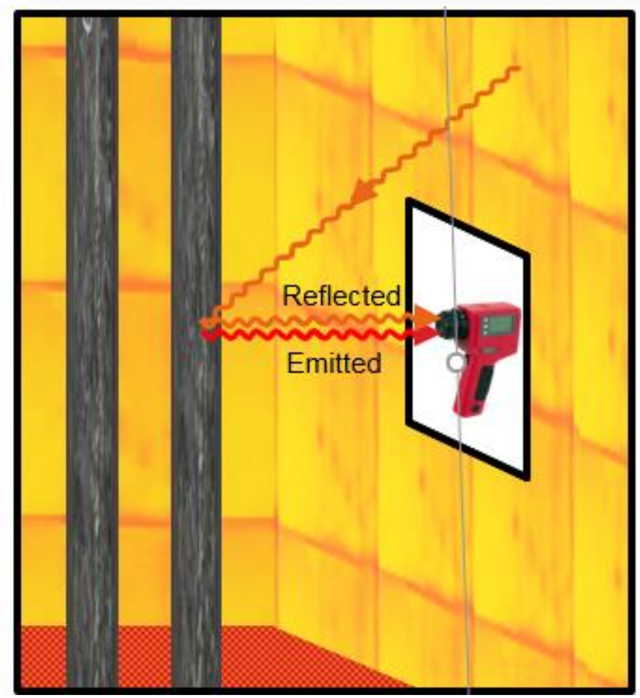
SMR Tube Inspection
Long Term Creep

- Long Term Creep Damage occurs at the consistently hottest part of the tube, typically near the floor on a top fired, down flow furnace
- Creep fissures develop mid-wall and propagate to failure



SMR Tube Inspection

- Visual inspection during operation
- Tightly balanced tube temperatures keep tubes within IOW
- Periodic tube temperature measurement via pyrometer
  - Correction factors must be applied to account for reflected energy error
    - Under-correction results in economic penalty
    - Over-correction can result in tube overheat & reduced tube life

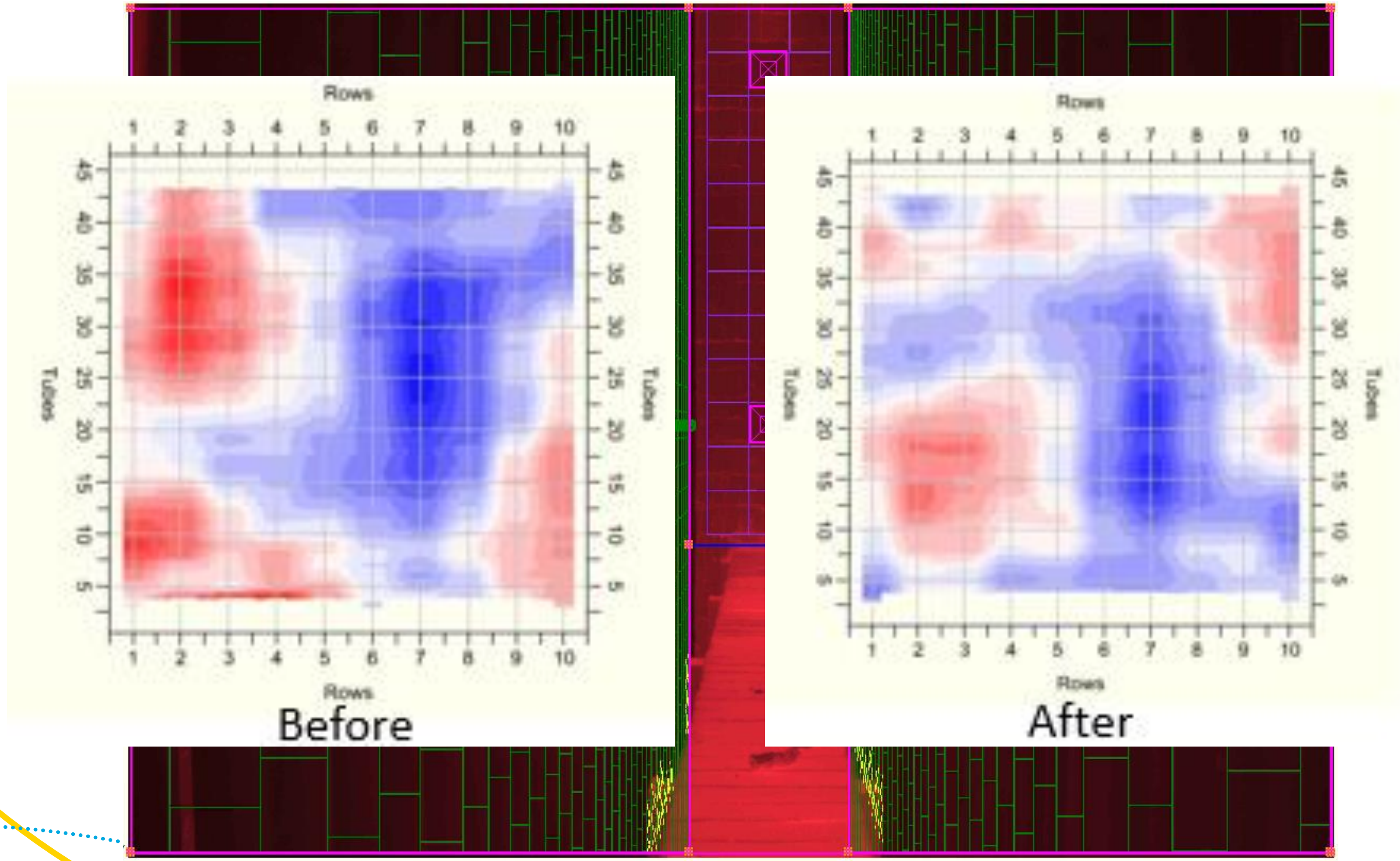


SMR Tube Inspection

- Tube temperature measurement/balancing using AP Proprietary digital imaging and modelling.
- Periodic tube temperature measurement via OmniCam™
  - OmniCam™ is an Air Products developed technology to measure tube temperature. Identifies hot tubes in locations not visible using standard technology.

SMR Tube Inspection

Tube Temperature Imaging & Balancing



SMR Tube Inspection

Off-Line Inspection

- Reformer tube inspection via robotic crawler for creep damage
  - Crack formation
  - Diametrical growth
  - Tube Bowing
- Remaining tube life via destructive testing

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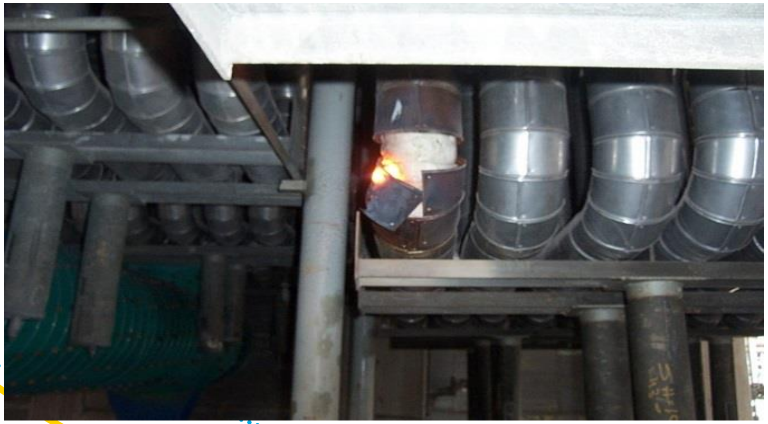
Case Study - SMR Hot Outlet System Inspection

- Comprised cast High Nickel Alloy headers, Inco 800HT wrought pigtails, and low alloy refractory lined piping that conveys ~30 barg, 870 C Syngas to downstream unit operations
- Typically designed with Short or Long Pigtail Design

SMR Hot Outlet System Inspection

- Primary damage mechanisms are:
  - Short term stress overload from improper support or refractory failure
  - Long term creep damage.
  - HTHA possible if internal refractory lining degrades, allowing metal temperature to enter HTHA risk zone.



SMR Hot Outlet System Inspection

- On-line inspection is comprised of visual inspection and infra-red thermography
- Off-line inspection is comprised of creep inspections and visual inspection of refractory lined components
- Industry Guidance Documents
  - CGA H-12 "Mechanical Integrity of Syngas Outlet Systems"
  - API 571 "Damage Mechanisms Affecting Fixed Equipment in the Refining Industry"
  - API 573 "Inspection of Fired Boilers and Heaters"
  - API 941 "Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants"

SMR Hot Outlet System Inspection
On-Line Inspection

- Visual inspection of spring hangers, supports, and outlet system

Spring Hanger
bottomed out (no load)

Gap at Support

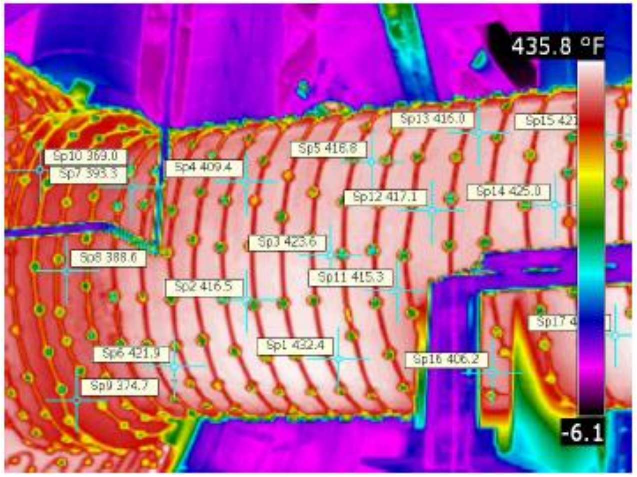
- Visual inspection for damaged insulation that can cause high thermal stress

Insulation gap creates thermal stress

SMR Hot Outlet System Inspection

On-Line Inspection

- IR Thermography of Refractory Line Equipment



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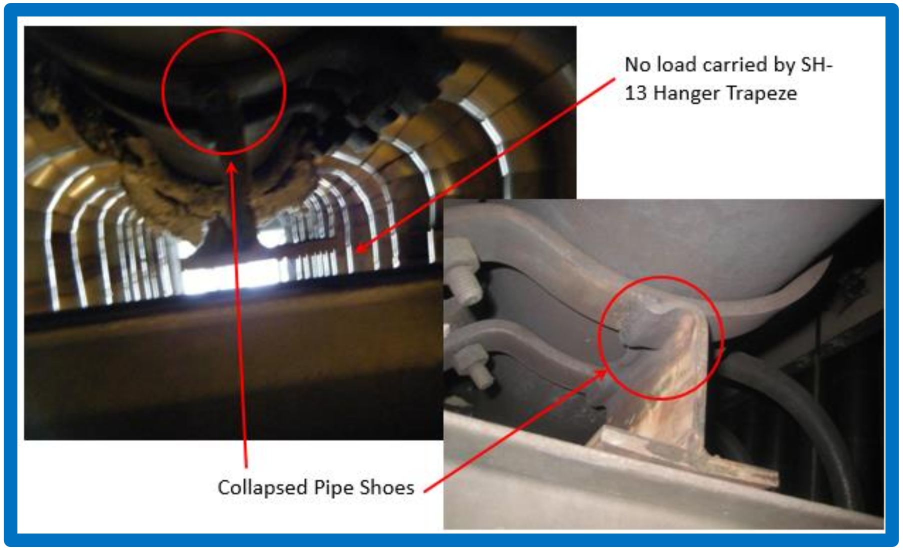
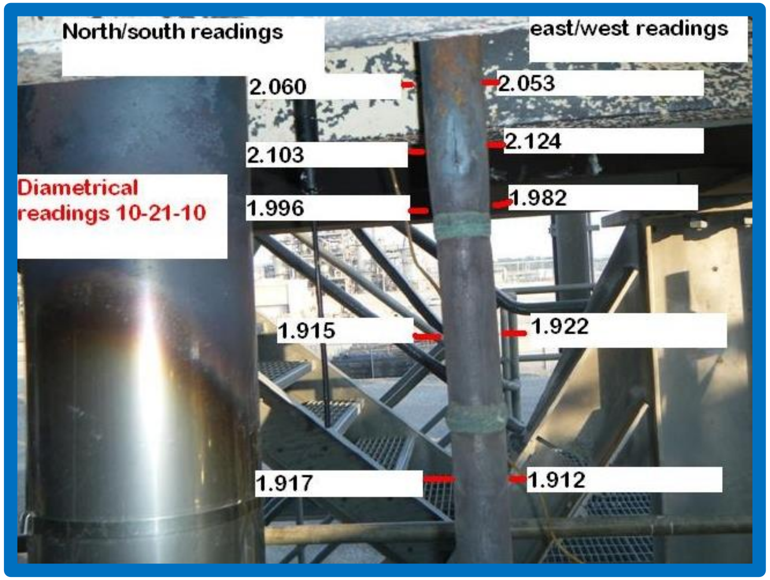
SMR Hot Outlet System Inspection

Off-Line Inspection

- Invasive visual inspections of supports



- Creep inspection via diametrical growth of pigtails



SMR Hot Outlet System Inspection

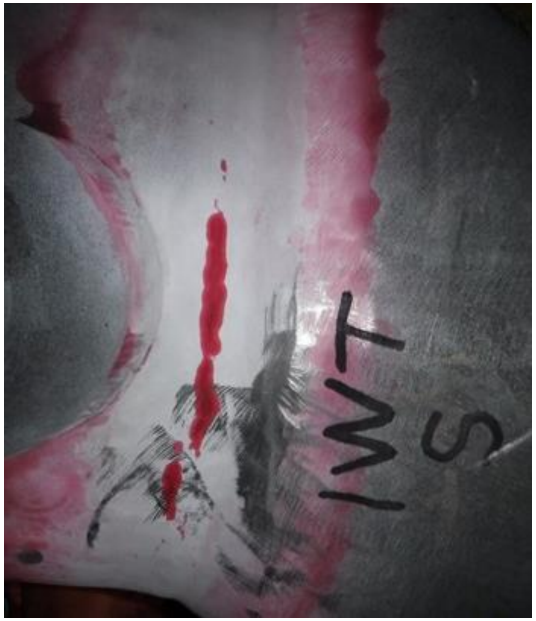
Off-Line Inspection

- Invasive visual inspections of supports

SMR Hot Outlet System Inspection

Off-Line Inspection

- Surface and Radiographic Inspection of Cast Outlet System Welds



- Internal Visual Inspection of Refractory Lined Equipment

Questions?

Thank you
tell me more

Case Study - Process Column – IOW Shift

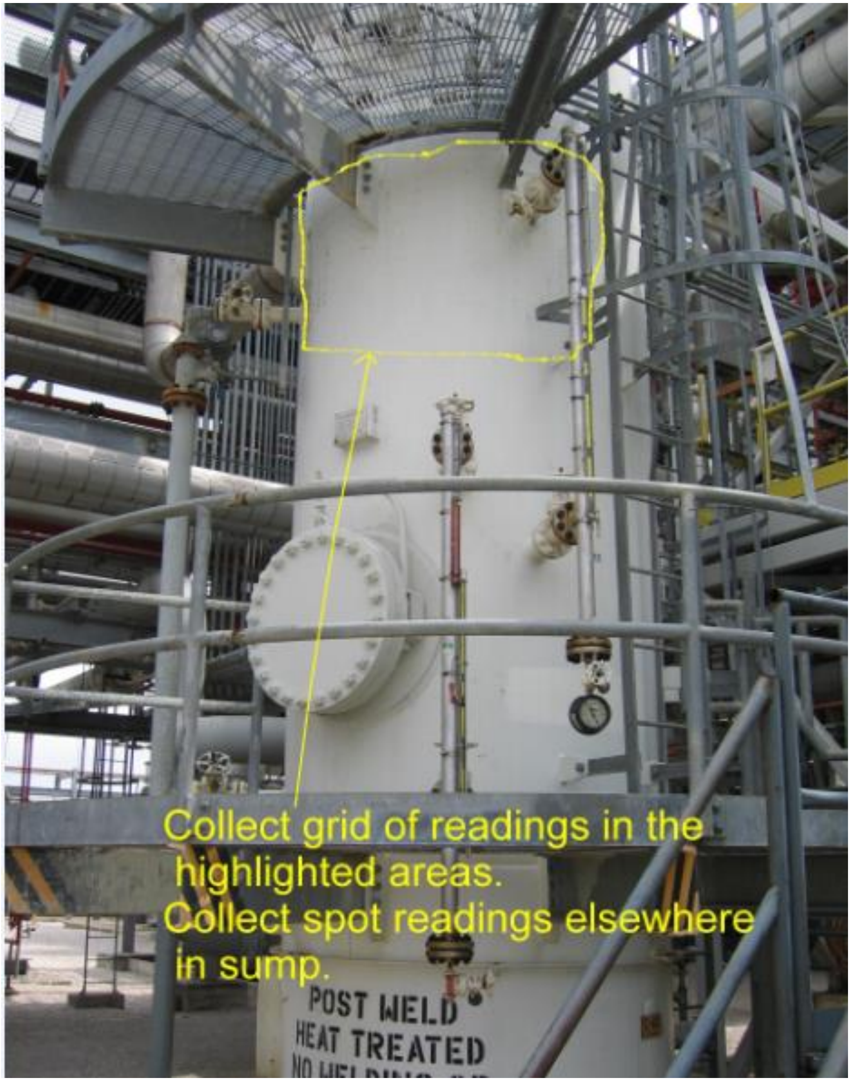
- CO_2 removal service using amine technology
- 20 m tall, CS PWHT Column operates at ~ 40 barg and ambient temperature in Syngas service
- Primary damage mechanism is internal corrosion, which is managed through the use of corrosion inhibitors

Process Column – IOW Shift

- Inspection strategy used a combination of Condition Monitoring, Internal Inspection, and Corrosion Monitoring
- Condition monitoring periodically sampled process for inhibitor and iron levels.
- Sampling showed drop in inhibitor level and increase in iron levels

Process Column – IOW Shift

- Response to IOW shift was to restore inhibitor levels and alert Inspection group
  - Corrosion monitoring accelerated
- Condition monitoring showed restoration of inhibitor levels, but continued elevated iron levels.
  - Column passivation required, but outage window not available
  - Corrosion Monitoring strategy modified to ensure safe operation



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Process Column – IOW Shift

- Corrosion monitoring adjusted to focus on bottom column in areas impacted by inlet distributor
  - Impingement created accelerated corrosion rates
  - API 579 FFS was employed to continue operation of the column until a repair window was available

Elev	1'	2'	3'	4'	5'	6'	7'	8'	9'	10'	11'	12'	13'	14'	15'	16'	17	18'
Design	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375	1.375
Tmin	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231	1.231
A (13')	1.242	1.237	1.257	1.248	1.267	1.273	1.284	1.288	1.238	1.274	1.241	1.237	1.244	1.247	1.253	1.249	1.258	1.251
B (12')	1.235	1.221	1.247	1.274	1.255	Nozz le A	Nozz le A	1.238	1.289	1.284	1.228	1.231	1.246	1.257	1.266	1.270	1.263	1.247
C (11')	1.289	1.194	1.231	1.246	1.197	1.244	1.231	1.233	1.268	1.162	1.073	1.132	1.231	1.142	1.177	1.178	1.129	1.263
D (10')	1.258	1.166	1.246	1.194	1.252	1.263	1.261	1.211	1.178	1.212	1.192	1.128	1.178	1.052	0.987	0.924	1.137	1.141
E (9')	1.289	1.263	1.273	1.284	1.281	1.271	1.268	1.273	1.231	1.204	1.153	1.129	1.166	1.134	1.152	1.147	1.241	1.273
F (8')	1.294	1.294	1.284	1.272	1.252	1.243	1.266	1.221	1.194	1.199	1.183	1.174	1.183	1.242	1.235	1.245	1.238	1.248
G (7')	1.267	1.268	1.297	1.247	1.268	1.248	1.216	1.246	1.266	1.240	1.232	1.253	1.240	1.244	1.248	1.241	1.246	1.255
H (6')	1.212	1.23	1.244	1.231	1.184	1.238	1.262	1.234	1.240	1.240	1.242	1.220	1.238	1.212	1.223	1.221	1.226	1.252
I (5')	1.255	1.262	1.264	1.253	1.252	1.251	1.231	1.233	1.241	1.242	1.244	1.236	1.205	1.245	1.261	1.231	1.209	1.222
J (4')	1.237	1.234	1.227	1.251	1.192	1.214	1.242	1.238	1.208	1.193	1.248	1.243	1.271	1.249	1.226	1.237	1.241	1.221
K (3')	MW	1.222	1.248	1.226	1.194	1.245	1.229	1.221	1.209	1.201	1.222	1.243	1.183	1.252	1.240	1.265	1.253	1.202
L (2')	1.351	1.366	1.369	1.376	1.382	1.371	1.379	1.382	1.385	1.385	1.376	1.372	1.386	1.390	1.389	1.377	1.374	1.376
M (1')	1.382	1.376	1.384	1.380	1.375	1.375	1.377	1.375	1.376	1.374	1.377	1.382	1.378	1.380	1.377	1.383	1.385	1.387