Service Life of PE Geomembranes

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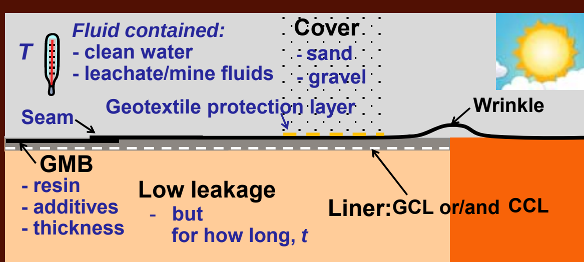
Objectives and Limitations

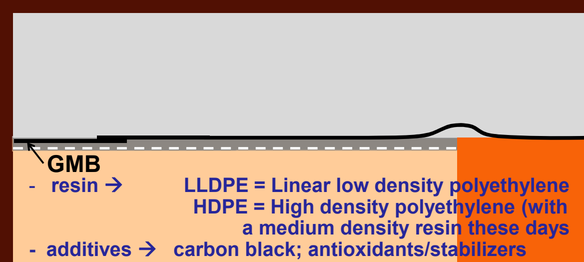
- Introduce concepts to those new to the field
- Present some latest developments
- The material presented is not complete in and of itself; it is intended only to provide direction. Examine published sources for more complete information
- Not all topics are covered

How long will the GMB last (what is its service-life)



T = temperature; *t* = time

How long will the GMB last (what is its service-life)



HDPE Oxidative induction time

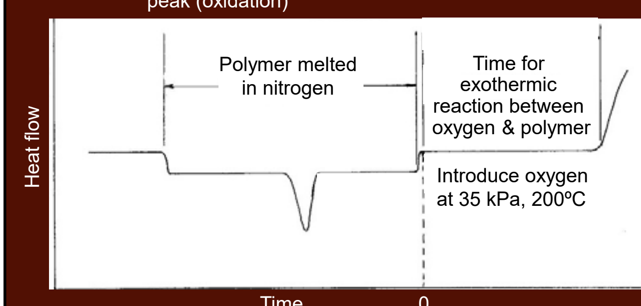
Exposure condition	Standard OIT	or	High pressure OIT
ASTM	D3895		D5885
As manufactured	≥ 100		≥ 400
Oven ageing at 85°C for after 90 days	≥ 55% retained		≥ 80% retained
After UV exposure	-		≥ 50% retained after 1600 hrs

GRI-GM 13

Measuring Std-OIT

Differential Scanning Calorimeter (DSC) using ASTM3895

Std-OIT: time from introduction of oxygen to start of exothermic peak (oxidation)



GMB Specifications

- Typically require a minimum
  - Standard oxidative induction time (Std-OIT)
    OR
  - High pressure oxidative induction time (HP-OIT)

  initially and after 90 days oven aging (in air)

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  (much higher than the 400 min HP-OIT often specified)

GMB Specifications

- Typically require a minimum
  - Standard oxidative induction time (Std-OIT)
    OR
  - High pressure oxidative induction time (HP-OIT)

  initially and after 90 days oven aging (in air)
- Many GMBs now have very high HP-OIT
  (much higher than the 400 min. and maybe uto 4000 min.)
- High HP-OIT is generally attributed to low or high molecular weight hindered amine (light) stabilizers (HAS or HALS)

Specifications for HDPE GMBs

Property	ASTM	Specification
GMB Density	D1505 D792	≥ 0.940 g/cm³
Resin Density		≥ 0.932 g/cm³
Carbon black content	D1603	2-3%
Stress crack resistance	D5397 App A	≥ 500 hrs

GRI-GM 13

Properties of some HDPE GMBs

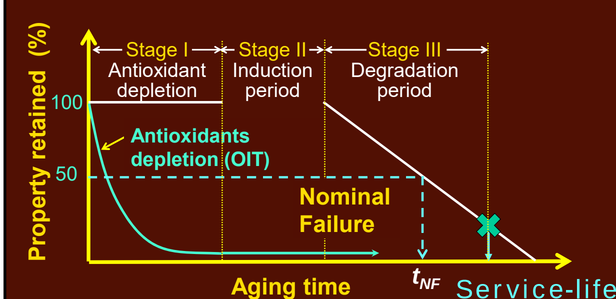
Depends on: Antioxidant package (Std-OIT, HP-OIT); Resin (Stress crack resistance)

	Thick-ness (mm)	Std-OIT (min)	HP-OIT (min)	Stress crack resistance (hrs)
MyA	2	135	380	5200
MyB	1.5	135	660	3700
MyC	1.5	175	900	1000
MxA	1.5	135	245	720
MxC	1.5	160	960	800

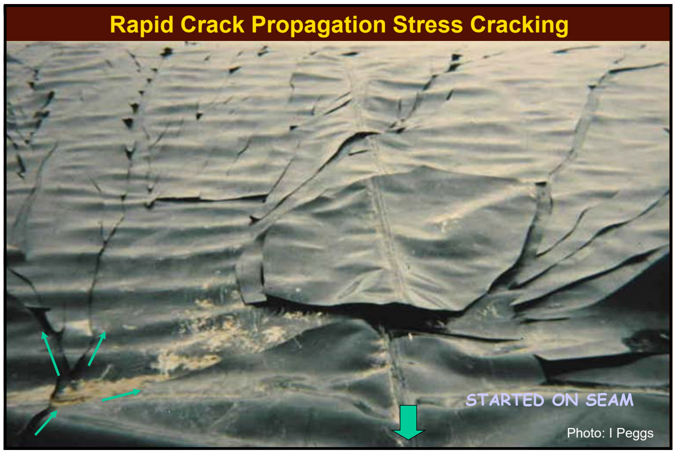
All meet GRI GM13 but do they all have the same time to failure?

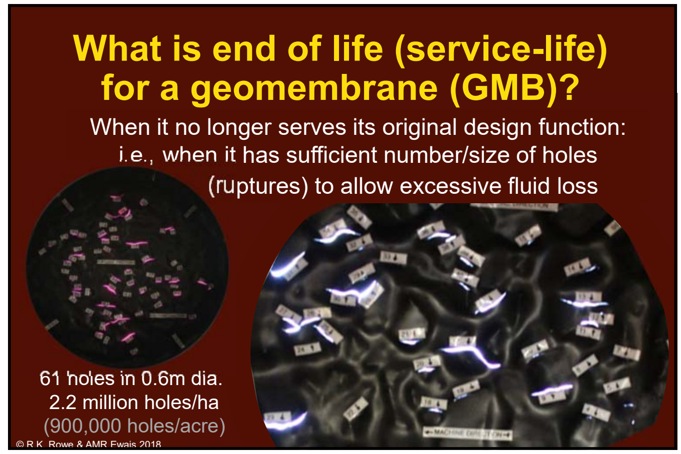
OIT values rounded to nearest 5 mins., SCR to nearest 2 significant digits

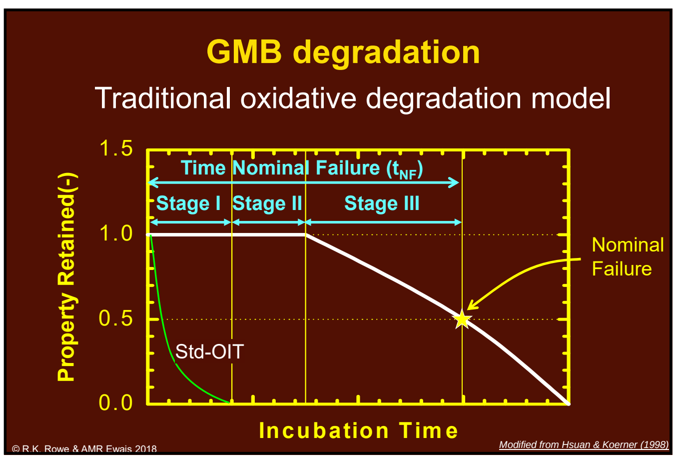
Oxidative degradation

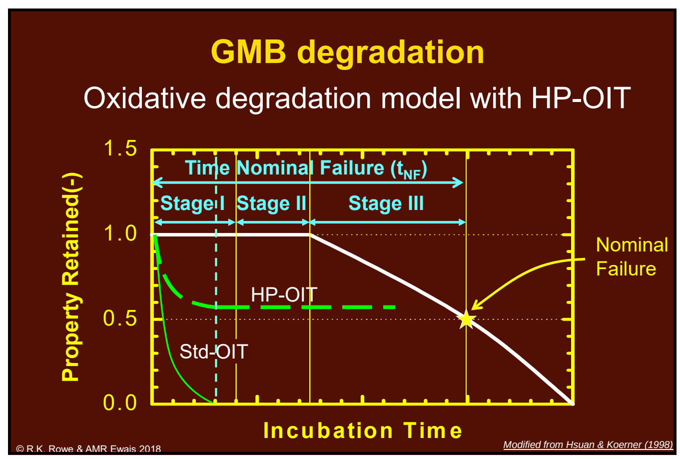


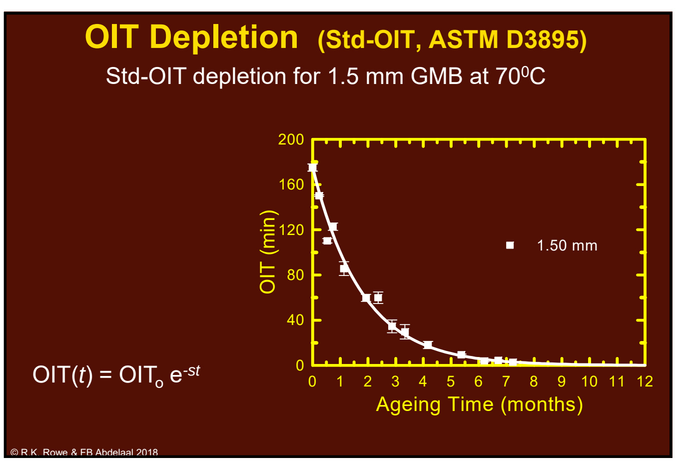
Modified from Hsuan & Koerner (1998)

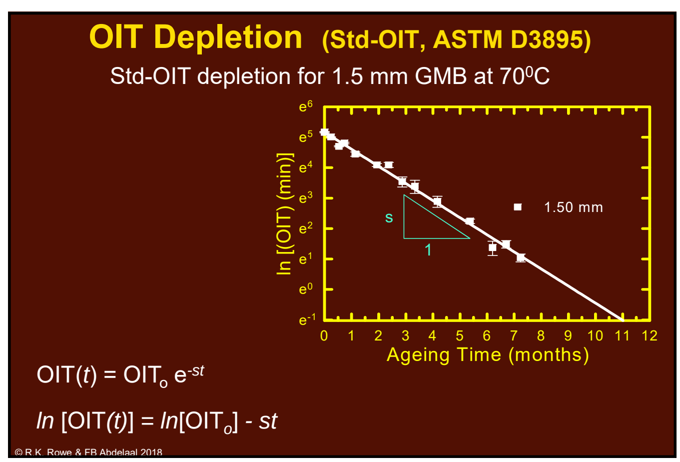

Rapid Crack Propagation Stress Cracking
STARTED ON SEAM
Photo: I Peggs


What is end of life (service-life) for a geomembrane (GMB)?
When it no longer serves its original design function: i.e., when it has sufficient number/size of holes (ruptures) to allow excessive fluid loss
61 holes in 0.6m dia.
2.2 million holes/ha
(900,000 holes/acre)
© R.K. Rowe & AMR Ewais 2018


GMB degradation
Traditional oxidative degradation model
Time Nominal Failure (t_{NF})
Stage I
Stage II
Stage III
Nominal Failure
Std-OIT
Property Retained(-)
1.5
1.0
0.5
0.0
Incubation Time
© R.K. Rowe & AMR Ewais 2018
Modified from Hsuan & Koerner (1998)

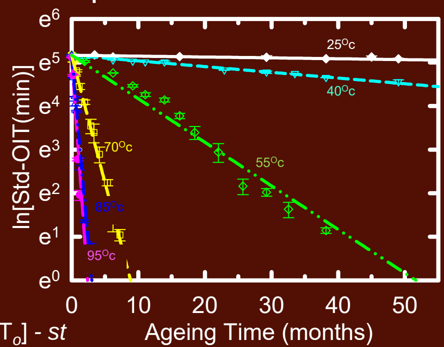

GMB degradation
Oxidative degradation model with HP-OIT
Time Nominal Failure (t_{NF})
Stage I
Stage II
Stage III
Nominal Failure
HP-OIT
Std-OIT
Property Retained(-)
1.5
1.0
0.5
0.0
Incubation Time
© R.K. Rowe & AMR Ewais 2018
Modified from Hsuan & Koerner (1998)


OIT Depletion (Std-OIT, ASTM D3895)
Std-OIT depletion for 1.5 mm GMB at 70⁰C
OIT (min)
200
160
120
80
40
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Ageing Time (months)
1.50 mm
$OIT(t) = OIT_o e^{-st}$
© R.K. Rowe & FB Abdelaal 2018


OIT Depletion (Std-OIT, ASTM D3895)
Std-OIT depletion for 1.5 mm GMB at 70⁰C
ln [(OIT) (min)]
e^6
e^5
e^4
e^3
e^2
e^1
e^0
e^{-1}
0 1 2 3 4 5 6 7 8 9 10 11 12
Ageing Time (months)
s
1
1.50 mm
$OIT(t) = OIT_o e^{-st}$
$ln\,[OIT(t)] = ln[OIT_o] - st$
© R.K. Rowe & FB Abdelaal 2018

Std-OIT – Effect of Temperature

Leachate Exposure - 1.5 mm GMB

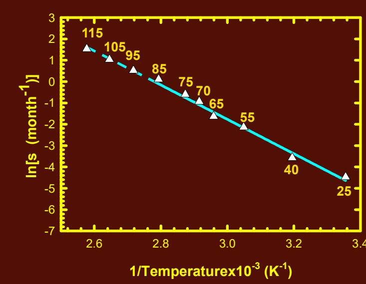


$OIT(t) = OIT_o\, e^{-st}$

$ln\,[OIT(t)] = ln[OIT_o] - st$

Effect of Temperature on OIT Depletion

OIT-Leachate immersion GMB xA 1.5mm



How long will the GMB last (what is its service-life)

T = temperature

Modes of long-term degradation for PE geomembranes

- Biological degradation
- **Ultraviolet (UV) degradation**
- Extraction (e.g., antioxidants)
- Oxidation

Ultraviolet (UV) degradation

UV protection depends on

- carbon black AND the
- stabilizer package

and can be assessed by

- Field exposure (Queen's University, Kingston)
- Laboratory accelerated ageing studies

Ultraviolet (UV) degradation

- Field exposure (Queen's University, Kingston)
  - Several different HDPE and LLDPE geomembranes (the same manufacturer): 2.5 years data
  - For HDPE, antioxidants/stabilizers depleted faster from thinner and slowest from thicker GMB (AO depletion 1 mm > 1.5mm > 2mm > 2.4 mm
  - Specific antioxidant/stabilizer package affected rate of AO depletion
  - LLDPE and HDPE compared: antioxidant/stabilizer has more effect on AO depletion than base resin

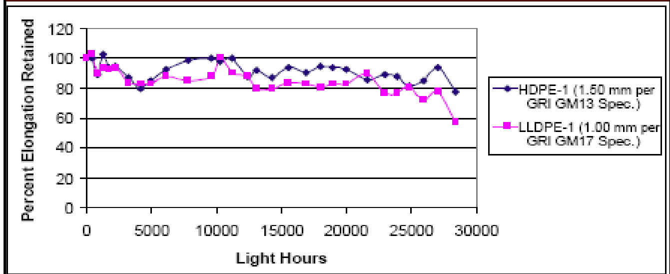
Ultraviolet (UV) degradation

Koerner et al. (2008) used UV-fluorescent radiation at 70°C for about 28,000 hours to examine:

- 1.0-mm thick stabilized LLDPE, and
- 1.5-mm thick stabilized HDPE geomembranes.

Percent Elongation Retained vs. Light Hours (after Koerner et al. 2008)

UV-fluorescent radiation at 70°C for about 28,000 hours



Correlation: 1,000 hrs. lab time ≈ 1 yr exposure life in Texas

AO Depletion with UV exposure (after Mills et al. 2009)

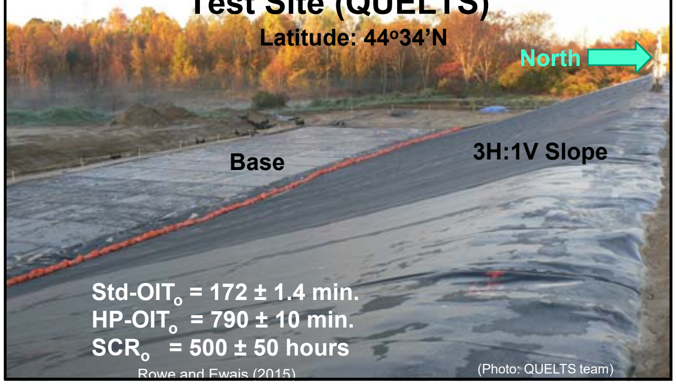
UV-fluorescent radiation at 60°C for 30,000 hours

HP OIT Results	Retained Sample (min)	30,000 Hour Sample (min)	% Retained
0.75 mm Black Polyolefin	4410	3056	69%
1.5 mm HDPE	899	396	44%

Ultraviolet (UV) degradation

- Some have reported that antioxidants deplete faster from stabilized LLDPE GMBs than stabilized HDPE GMBs HOWEVER our tests have faster depletion from some HDPE than some LLDPE
- Difficult to generalize about UV degradation of LLDPE vs HDPE since it depend on the specific antioxidant/stabilizer package and resin
- Loss of strength and elongation in Koerner et al. (2008) laboratory study faster for 1mm LLDPE than 1.5mm HDPE for GMBs tested but it was inferred that the service life of exposed LLDPE (1 mm) and HDPE (1.5 mm) GMBs is greater than 28 years for Texas weather conditions.

Queen's University Environmental Liner Test Site (QUELTS)

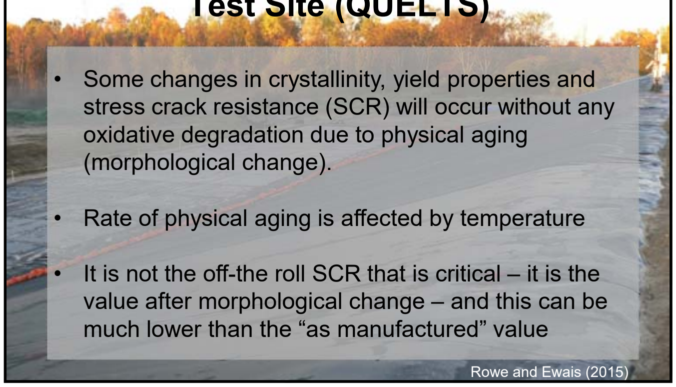


Queen's University Environmental Liner Test Site (QUELTS)

After 6 years field exposure (south facing)
- Std-OIT depleted to 55% Std-OIT$_o$ on base
- Std-OIT depleted to 27% Std-OIT$_o$ on 3H:1V slope so: depletion on slope twice that on base
- HP-OIT depleted to 80% HP-OIT$_o$ on slope & base so: no difference in depletion on slope & base
- Significant antioxidants remained: still in Stage I
- No change in tensile properties or HLMI --- BUT
- Initial SCR reduced to 190 hours from SCR$_o$ 500 ± 50 hours (due to morphological change; in lab, had reduced to 330 ± 40 hours at room temp.)

Rowe and Ewais (2015)

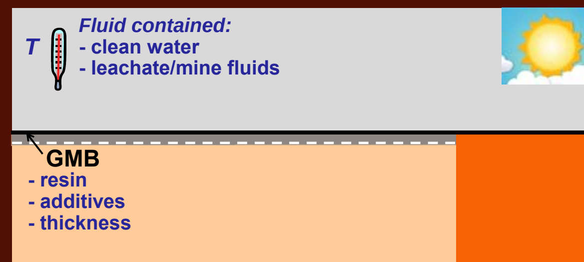
Queen’s University Environmental Liner Test Site (QUELTS)



- Some changes in crystallinity, yield properties and stress crack resistance (SCR) will occur without any oxidative degradation due to physical aging (morphological change).
- Rate of physical aging is affected by temperature
- It is not the off-the roll SCR that is critical – it is the value after morphological change – and this can be much lower than the “as manufactured” value

Rowe and Ewais (2015)

How long will the GMB last (what is its service-life)



T = temperature

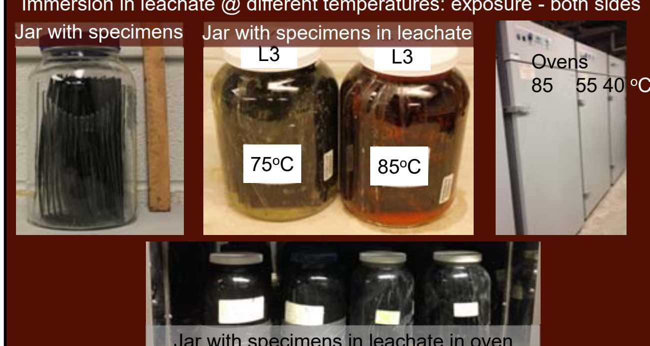
How about submerged or buried GMB liners?

Modes of long-term degradation for HDPE geomembranes

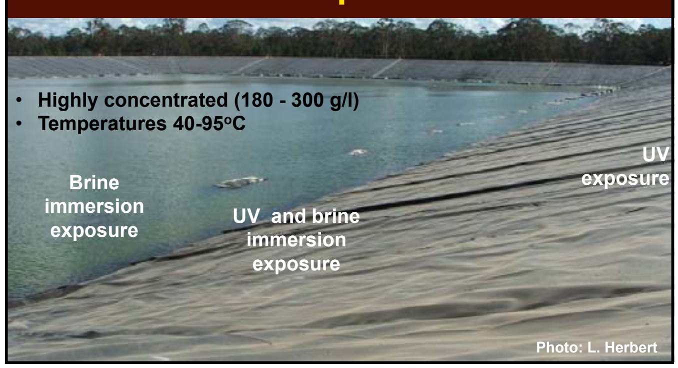
- Biological degradation
- Ultraviolet (UV) degradation
- **Extraction (e.g., antioxidants)**
- **Oxidation**

How long will the GMB last?

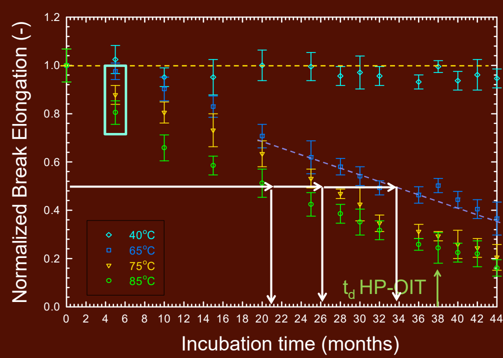
Immersion in leachate @ different temperatures: exposure - both sides



Coal/shale gas extraction brine ponds



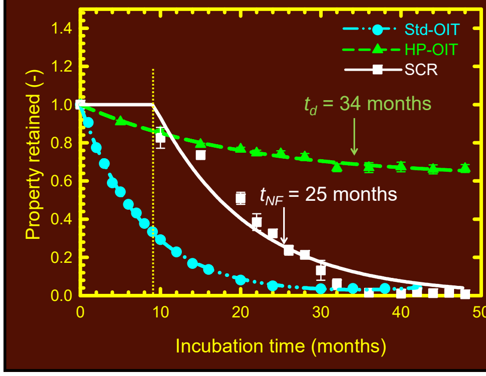
MxA1.5mm in Brine - Break Elongation (XMD)



OIT_o
Std =100 min.
HP = 260 min.
No HALS

Rowe & Shoaib (2017)

MxC1.5mm in Brine at 85°C - SCR



OIT_o
Std =160 min.
HP =960 min.
(HALS)

SCR_o = 800 h.

Rowe & Shoaib (2017)

Summary: 4 GMBs in Brine at 85°C

Degradation Stage		MxA 1.5mm	MxC 1.5mm	MyE 1.5mm	MyEW 1.5mm
	SCR_o (h)	720	800	5200	4000
	HP-OIT_o (min)	260	960	1140	620
	HALS	No	Yes	Yes	Yes
Stage I (HP-OIT)	t_d (month)	38	34	32	30
Stages I+II (SCR)	t_{I+II} (SCR) (month)	15	9	10	11
t_{NF} (250hr)	t_{NF} (SCR) (month)	**30**	**25**	**>48**	**45**

Rowe & Shoaib (2017)

Summary: 4 GMBs in Brine at 85°C

MxA1.5mm: (no HALS) t_{NF} = 30 months had better performance than MxC1.5mm despite lower Std & HP-OIT (similar SCR)

MyE1.5 had the best performance – but more because of the resin and not due to its HP-OIT

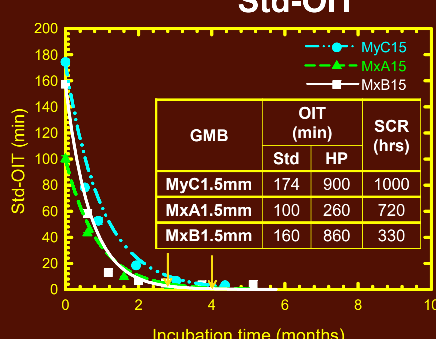
Immersed in brine, high HP-OIT had no real effect on time to nominal failure (but may be beneficial where UV exposure)

There are products with even better resistance

Rowe (2018)

GMBs in MSW Leachate at 85°C

Std-OIT



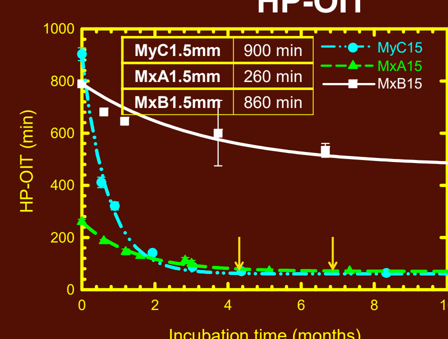
GMB	OIT (min) Std	OIT (min) HP	SCR (hrs)
MyC1.5mm	174	900	1000
MxA1.5mm	100	260	720
MxB1.5mm	160	860	330

t_d = 2.5 months for MxB1.5mmm & MxA1.5mmm

t_d = 4 months for MyC1.5mmm

GMBs in MSW Leachate at 85°C

HP-OIT



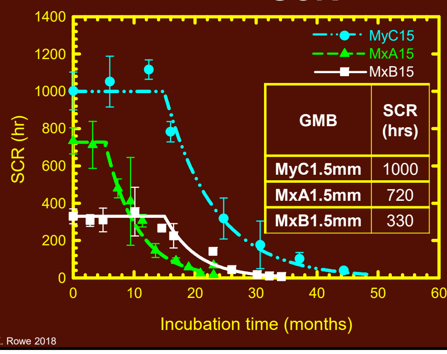
MyC1.5mm: highest HP-OIT_o but fast depletion t_d = 4.4 months

MxA1.5mm (no HALS) t_d = 7 months

MxB15: slowest depletion but high residual $t_d \approx$ 10 months

GMBs in MSW Leachate at 85°C

SCR



MyC15: highest SCR_o and longest t_{NF} = 31 month despite rapid HP-OIT depletion

MxB15: Despite slowest HP-OIT depletion t_{NF} = 19 months < MyC15

MxA15: (no HALS) t_{NF} = 14 months despite better SCR_o than MxB15

Summary: MSW Leachate at 85°C

MyC15: highest SCR_o and longest t_{NF} = 31 month despite rapid HP-OIT depletion (4.4 months)

MxB15:
Despite slowest HP-OIT depletion (10 months)
t_{NF} = 19 months < MyC15

MxA15: (no HALS; t_d = 7 months) t_{NF} = 14 months despite better SCR_o than MxB15

HP-OIT was of very little benefit in this solution

 (Rowe 2018)

How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)

Time to nominal failure, t_{NF},
1.5mm HDPE in simulated MSW leachate at 85°C (185 °F)

GMB	t_{NF} (months)	Relative t_{NF} (-)
MxA	14	1.0
MxB	19	1.4
MyC	31	2.2

Abdelaal & Rowe (2015)

Effect of GMB thickness

- Antioxidant depletion time for:
  - 2.0mm approx 1.3 (not 1.8) x that of 1.5mm
  - 2.5mm approx 1.5 (not 2.8) x that of 1.5mm
- Service life based on 50% SCR for:
  - 2.0mm approx 1.2 x that of 1.5mm
  - 2.5mm approx 1.7 x that of 1.5mm
- Need to specify more than thickness!

Rowe, Islam and Hsuan (2010)

Thickness Summary

- Geomembrane thickness has a significant impact on the depletion of antioxidants.
- The thicker geomembrane has the longest antioxidant depletion time and time to failure based on stress-crack resistance (other things being equal).
- A thicker geomembrane may be warranted when seeking a longer service life than can be provided by a traditional 1.5mm geomembrane.

How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
  - Elements (UV; variable temperature; damage)
  - Chemical composition of fluid in contact with GMB

Effect of fluid on time to nominal failure, t_{NF}, at 30°C (85°F)

Leachate (surfactant)	Stage I (years)	t_{NF} (years)	t_{NF} Ratio (-)
MSW-L3	24	53	1.0
MSW-L1	28	59	1.1
MSW-L2	21	83	1.6

Surfactant and high pH accelerates antioxidant depletion (shortens Stage 1) but salts affect Stages II and III and hence t_{NF}

GMB with best resistance in one fluid may not be best in another fluid

Abdelaal, Rowe & Islam (2014) 1.5 mm thick HDPE GMB MxC-15

Chemical characteristics that can affect PE aging

- Surfactant (in MSW leachate and some heap leach solutions) on OIT depletion
- Salts (not on OIT but on later degradation)
- pH (effect depends on antioxidant package)
- Chlorine (e.g., in treated water)

Tentative Conclusions Submerged – Buried GMBs

- Std-OIT & HP-OIT depletion rates depend on the incubation media (and temperature).
- HP-OIT efficacy in protecting the GMB depends on a package's compatibility with the incubation media AND the degradation mechanism in that fluid.
- One cannot predict how effective a GMB will be in contact with a given liquid from initial OIT values or oven aging in air at 85°C for 90 days.

 Rowe (2018)

Tentative Conclusions Submerged – Buried GMBs

- One can not tell, a priori, which will better protect the GMB Std-OIT or HP-OIT
- High initial values of HP-OIT may sometimes offer improved performance but mostly they do not – it all depends on the specific package, the fluid, and the temperature.
- A GMB that is "best" in one fluid may not be the best in a different fluid

 Rowe (2018)

Tentative Conclusions Submerged – Buried GMBs

Antioxidant depletion: Is higher HP-OIT the answer?

It depends – in some cases yes it helps, in some definitely no.

 Rowe (2018)

How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
  - Elements (UV; rapid changes in temperature)
  - Chemical composition of fluid in contact with GMB
  - Temperature

Liner temperature

- - 40 to 70°C exposed to "sun" in Canada
- Annual average ambient if waste does not generate heat
- 30 to 40°C normal MSW landfill
- 40 to 60°C with extra moisture
- 65 to 70°C in ashfills (also high pH)
- 70 to 80°C some heap leach pads
- > 85°C unusual landfills
- 40 to 95°C brine ponds and solar ponds

Effect of temperature on time to nominal failure, t_{NF}

Immersed in MSW-L1 (an aggressive solution)

Geomembrane:	MyC 1.5mm	MyA 2.0mm
Temperature °C (°F)	t_{NF} (years)	
60 (140)	9	13
50 (120)	15	36
40 (105)	30	120
30 (85)	60	430

Could be shorter or longer for other GMBs and exposure conditions

MyC: 9 years data, Abdelaal, Rowe & Islam (2014)
MyA: 17 years data, Ewais et al. (2018)

How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
  - Elements (UV; rapid changes in temperature)
  - Chemical composition of fluid in contact with GMB
  - Temperature
  - Nature of exposure

How long will the GMB last?

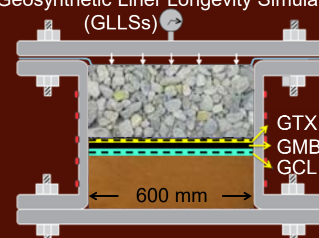
Depends on

- Nature of the exposure to leachate

Immersion tests (Jar)

Leachate exposure: Both sides

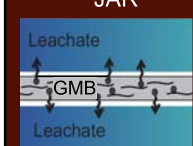
Geosynthetic Liner Longevity Simulators (GLLSs)



Upper side only

How long will the GMB last?

Immersed time to OITdepletion: JAR



MxA 1.5mm
Rowe et al. (2010 & 2013)

GLLS/Jar = 2.1

GLLS/Jar = 3.0

Ratio may vary with GMB, leachate, liner configuration & stage

OIT depletion takes 2-4 times longer in composite liner

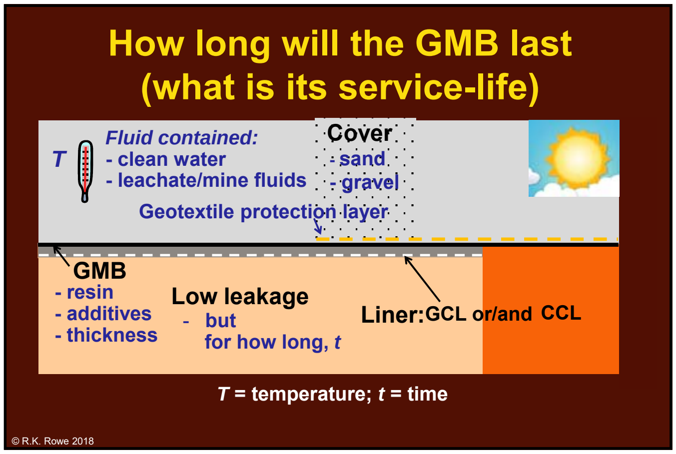
How long will the GMB sheet last?

Based on 17 years of test data at accelerated temperatures in simulated MSW landfill leachate (Ewais et al. 2018)

Temperature °C (°F)	Immersed t_{NF} (years)	Composite liner t_{NF} (years)
60 (140)	13	50
35 (95)	220	880

Assumes: Good construction, covered, and **negligible tensile strain**
Will be different for other GMBs, leachates, and liner configurations

2 mm thick HDPE MyA


How long will the GMB last
(what is its service-life)
Fluid contained:
- clean water
- leachate/mine fluids
T
Cover
- sand
- gravel
Geotextile protection layer
GMB
- resin
- additives
- thickness
Low leakage
- but
for how long, t
Liner: GCL or/and CCL
T = temperature; t = time
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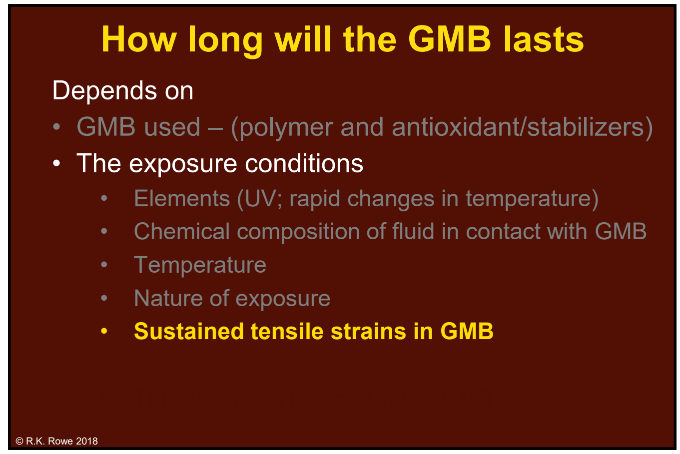
How long will the GMB lasts
Depends on
• GMB used – (polymer and antioxidant/stabilizers)
• The exposure conditions
• Elements (UV; rapid changes in temperature)
• Chemical composition of fluid in contact with GMB
• Temperature
• Nature of exposure
• Sustained tensile strains in GMB
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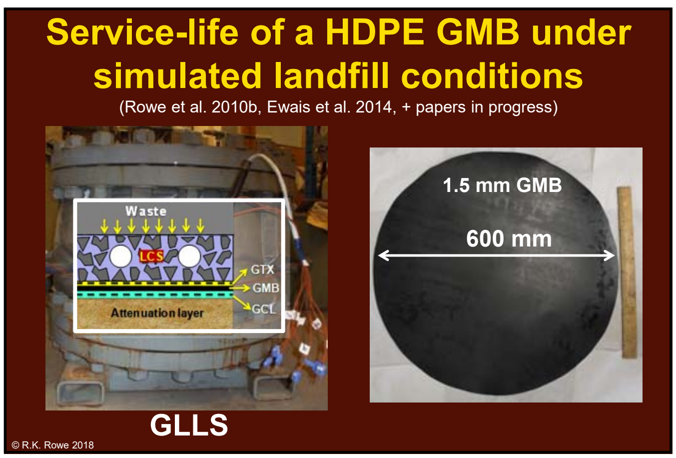
Service-life of a HDPE GMB under simulated landfill conditions
(Rowe et al. 2010b, Ewais et al. 2014, + papers in progress)
Waste
LCS
GTX
GMB
GCL
Attenuation layer
1.5 mm GMB
600 mm
GLLS
© R.K. Rowe 2018


GLLS
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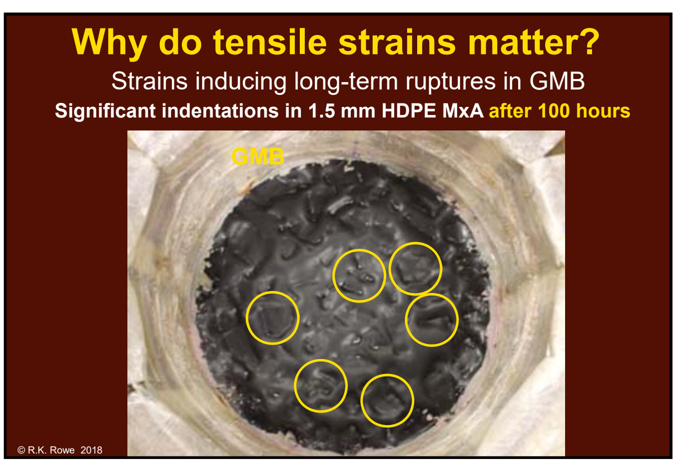
Why do tensile strains matter?
Strains inducing long-term ruptures in GMB
Significant indentations in 1.5 mm HDPE MxA after 100 hours
GMB
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What if we left the applied load on longer?
GMB
© R.K. Rowe 2018

What if we left the applied load on longer?

Ewais, Rowe, Brachman & Arnepalli (2014)

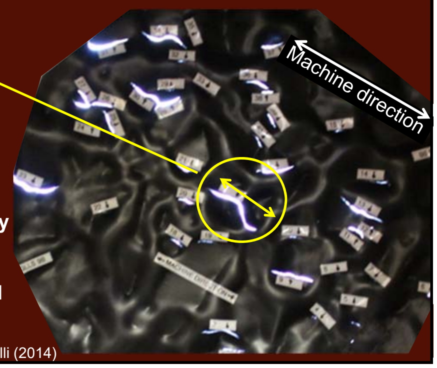
Pre-aged GMB to end of Stage II

Incubated in GLLS @ 85°C for 25.5 months

- Nonwoven needle punched GTX(M_A=580g/m²)

(2.2 million holes/ha)

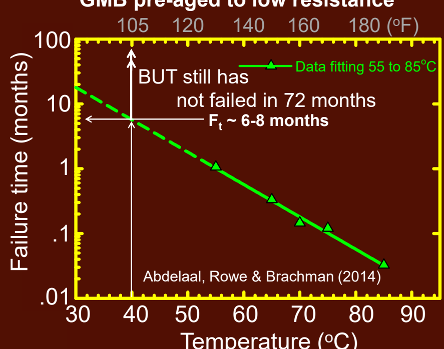
- **Cracks predominantly in machine direction**
- **Crack length reached 100 mm**



Ewais, Rowe, Brachman & Arnepalli (2014)

Temperature effect

GMB pre-aged to low resistance



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GMB Strains

Indentations at 250 kPa and 85°C

GTX 580g/m²
Strains up to 15%
Ruptured in < 3 years

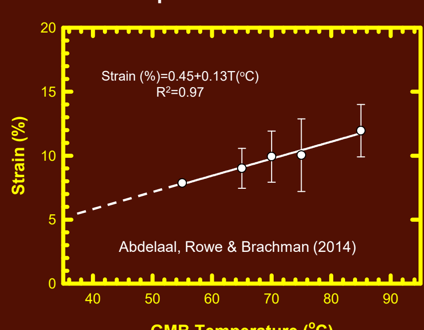
Sand Protection layer
Minimal strains (< 1%)

Ewais, Rowe & Brachman (2014)

Rowe, Abdelaal & Brachman (2013)

Samples pre-aged to 75 SCR hours

Variation in strain at rupture in GLLS tests with temperature



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Strain Conclusions

- No. of Cracks at
  indentation slopes > below gravel > between indentations

BUT the cracks between indentations are most hydraulically longest and most open

- **Time cracking directly related to:**
  - Stress crack resistance (SCR)
  - Temperature

  BUT most critical is the
  - Tensile strain –> protection layer

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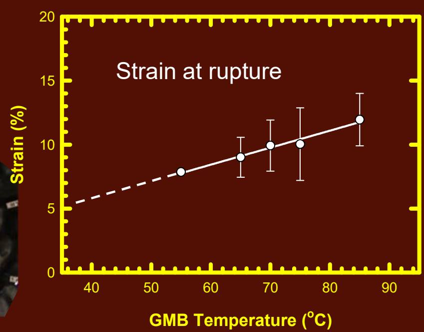
Tensile strains DO matter!



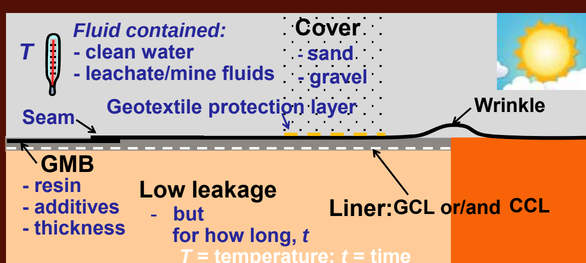
They control service-life

How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
  - Elements (UV; rapid changes in temperature)
  - Chemical composition of fluid in contact with GMB
  - Temperature
  - Nature of exposure
  - Sustained tensile strains in GMB
  - **Seams (welds)**

How long will the GMB last (what is its service-life)



Seams and wrinkles increase strain and decrease resistance

Weld summary

- Typically > 1500 m of weld/ha (2000 ft/acre)
- Welds are a critical location with respect to GMB service-life
- Time to failure needs more investigation but is known to depend on GMB, leachate, and temperature
- Potential for further increased leakage reduced by
  - minimizing covered wrinkles/waves
  - using composite liner with GCL

GMB service-life depends on

- GMB used — Manufacture & design
- The exposure conditions — Design, construction & operations
  - Elements (UV; rapid changes in temperature)
  - Chemical composition of fluid in contact with GMB
  - Temperature
  - Nature of exposure
  - Sustained tensile strains in GMB
  - Seams/Welds

Ranges from years to many centuries

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Various manufacturers – Thank you

All comments in this lecture are those of the speaker and are not necessarily shared by any of those listed above

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