Geomembranes Used in Dam Waterproofing and Lifetime Prediction

1.0 Relevant Applications
2.0 Geomembranes
3.0 Degradation and Lifetime Prediction
4.0 GM Lifetime Prediction
5.0 Summary and Recommendations

1.0 Relevant Applications

1.1 Earth and Earth/Rock Dams

1.2 Roller Compacted Concrete Dams

1.3 Concrete and Masonry Dams

(First, let's look at some leakers)!

Downstream Masonry Dam Water Markings

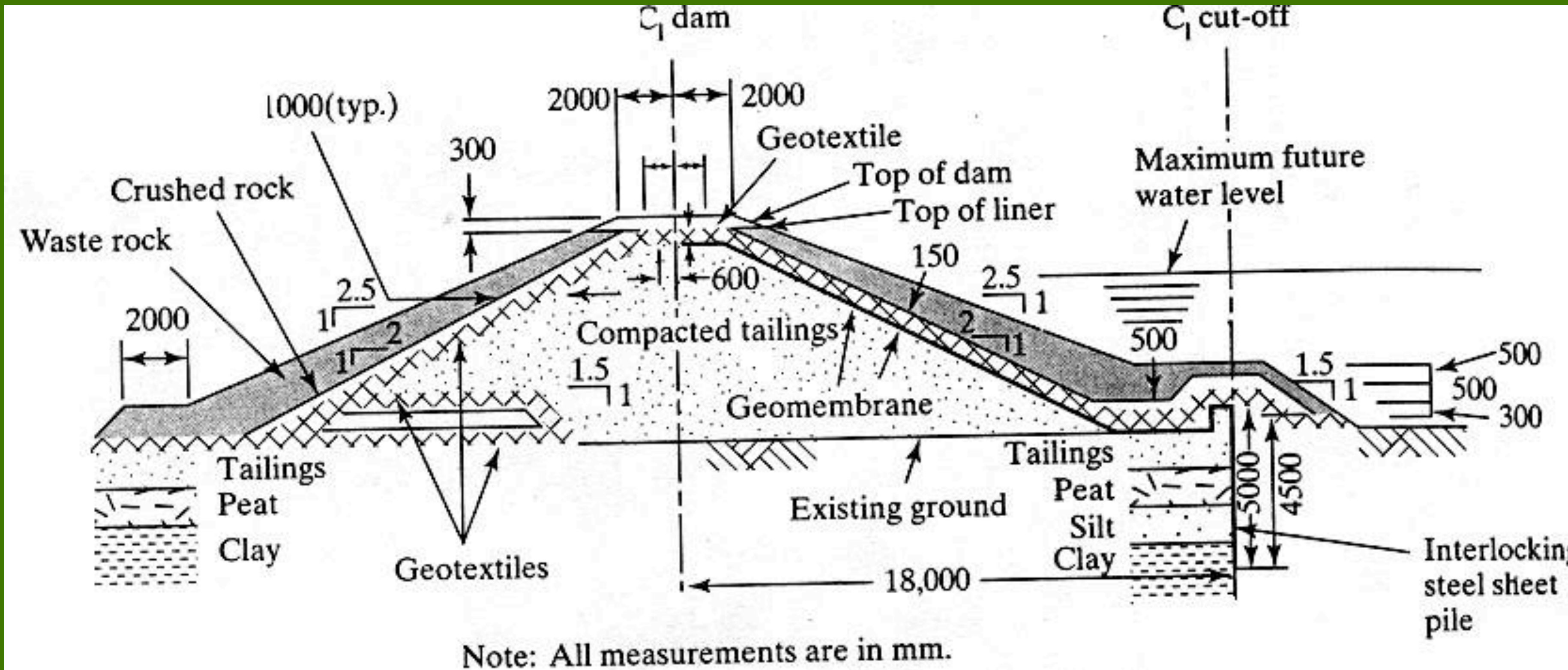
Major Upstream Vertical Crack in Concrete Dam

Downstream Seepage in Concrete Dam

Same Dam as Before with Upstream Water Level Increased!

1.1 Earth and Earth/Rock Dams

- GM placed against upstream face
- stone rip-rap placed above GM
- requires GT cushion between GM and rip-rap… GT mass is critical issue and a crisp design method is available
- typ. slopes are 2/1 to 4/1 (26° to 14°)



Tailings Dam, Eigenbrod, et al., 1984


The GM
before
GT & rip rap
covering

THE GEOMEMBRANE IS THE ONLY WATERTIGHT ELEMENT OF THE DAM

MORAVKA DAM, Czech Republic, 26,400 m2 installed in 80 days

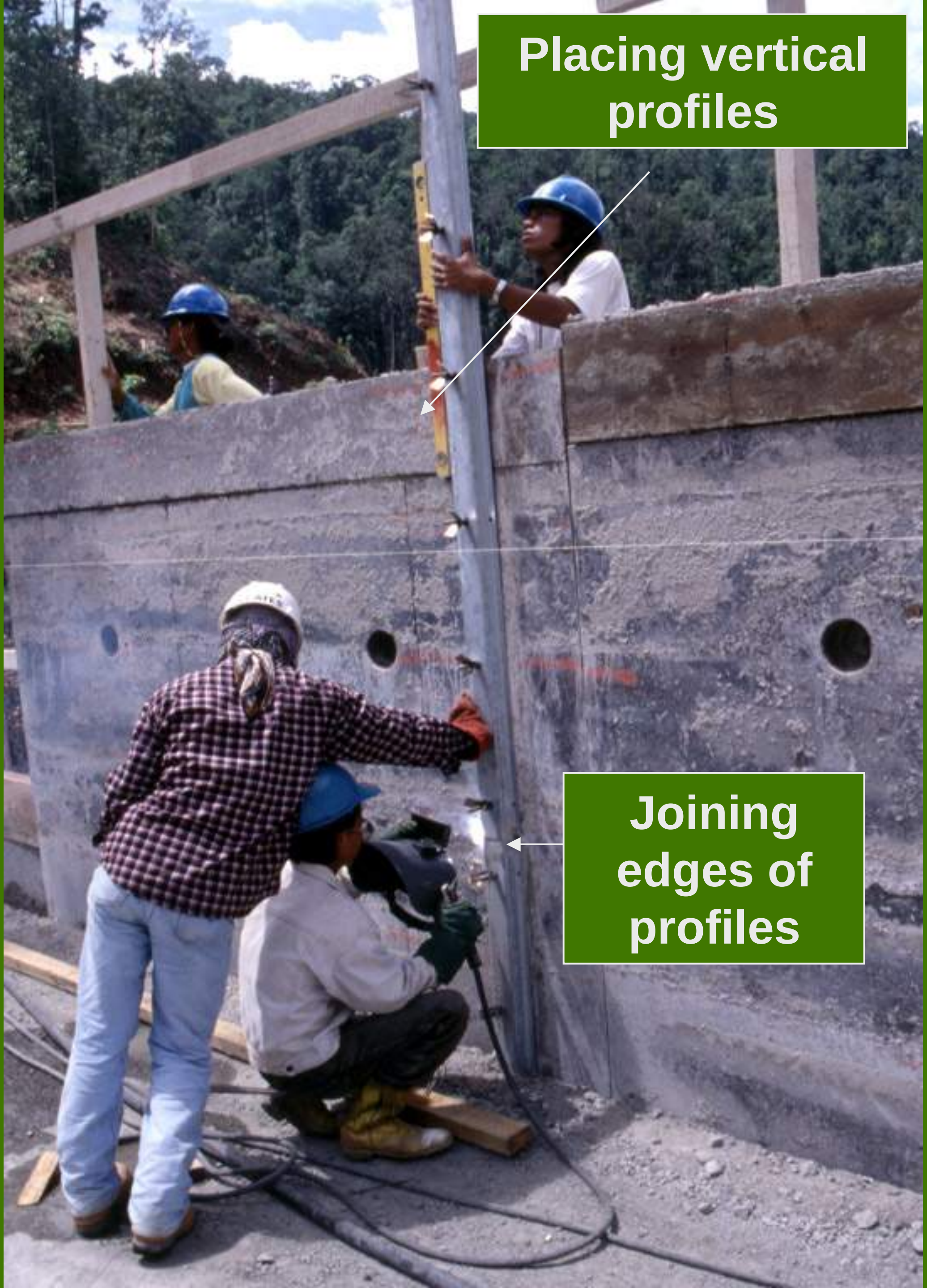
1.2 Roller Compacted Concrete Dams

- consists of cement/soil mixture
- placed and compacted in horizontal lifts
- results in steep sloping or vertical face
- upstream GM waterproofing methods:
  (a) rip-rap/GT/GM if sloping, or if vertical (b) channel inserts placed in RCC for subsequent GM fixity, or if vertical (c) prefabricated panels of GM/GT/concrete panels
- several case histories available; see following

Method (a) – Rip-rap/GT/GM

- for sloping upstream surfaces, the method is identical to earth and earth/rock dams
- critical aspect becomes the stability of the rip-rap for steep slopes
- when > 2 to 1 (26°); a different strategy must be used (method "b" or "c")

Method (b) – Channel Insert (or Profiles) Placed on Formwork Before RCC Placement



Insert and Channel Will be Embedded in RCC


NEW RCC DAMS WITH EXPOSED GEOMEMBRANE AS PART OF THE INITIAL DESIGN
After RCC Cures, Panels are Stripped and GM inserted between Profiles and attached accordingly.

Method (c) – GM Attached to Panels

- CARPI – Winchester Method
- concrete panels ~ 100-150 mm thick
- factory precast with GT/GM facing
- at site, panels used for upstream falsework
- GM is protected accordingly

Placing geocomposite on precast concrete panels

GT (white) Against Concrete; GM Above

Cured Panels Being Placed; Note Edge Strips

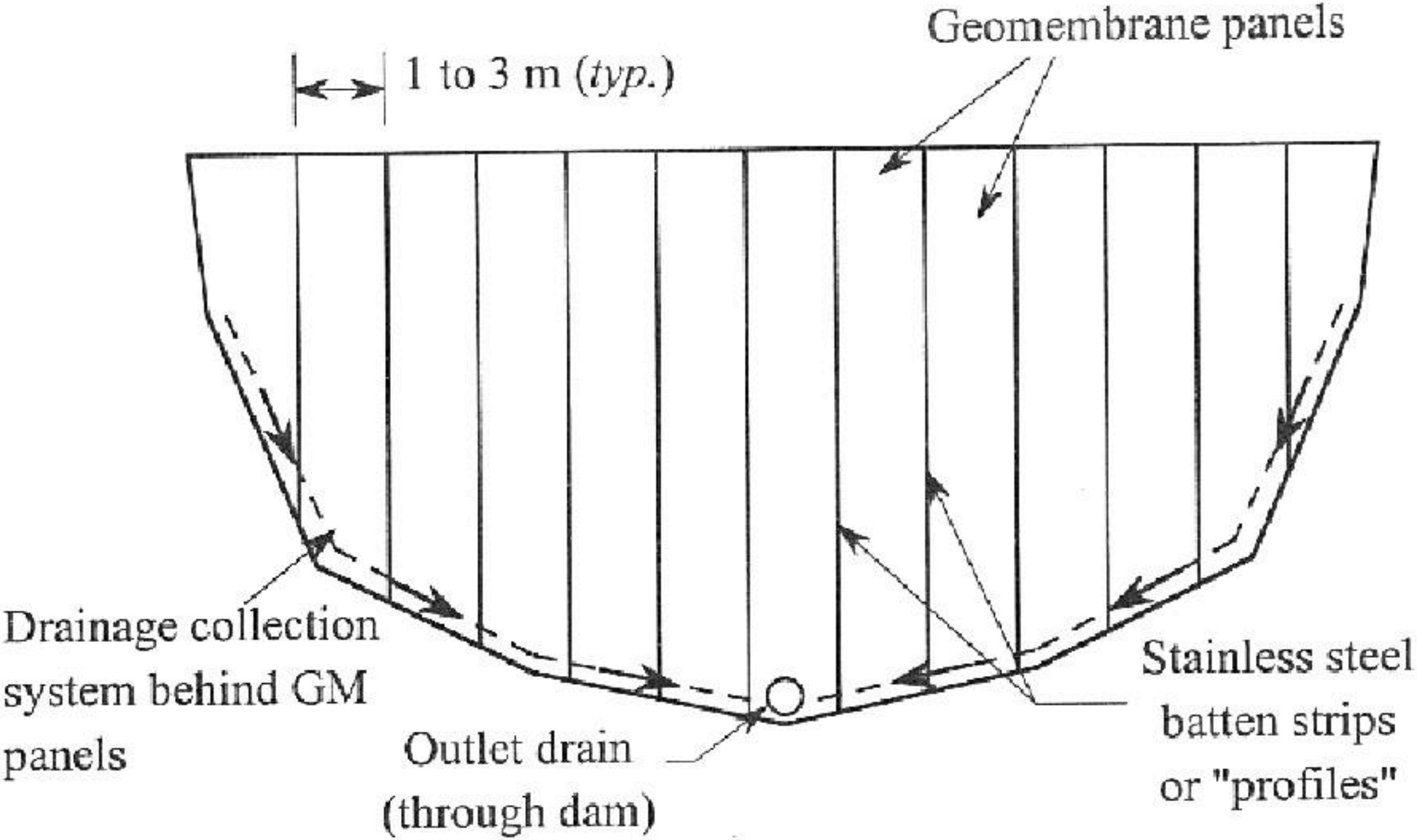
Initially Placed Panels; GM to Interior

Welding PVC strips along panels

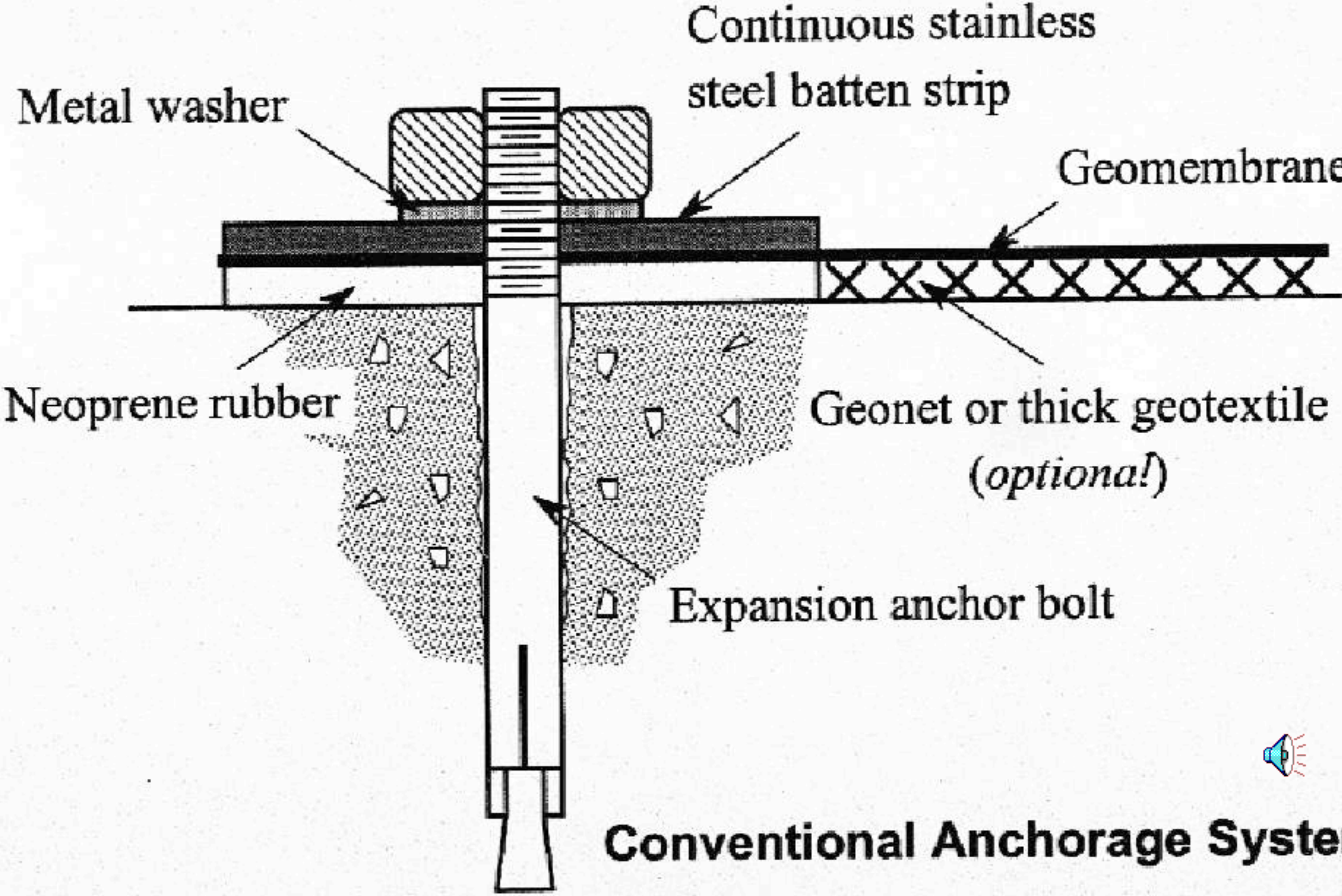
Placement of RCC Using Panels as Falsework

1.3 Concrete and Masonry Dams

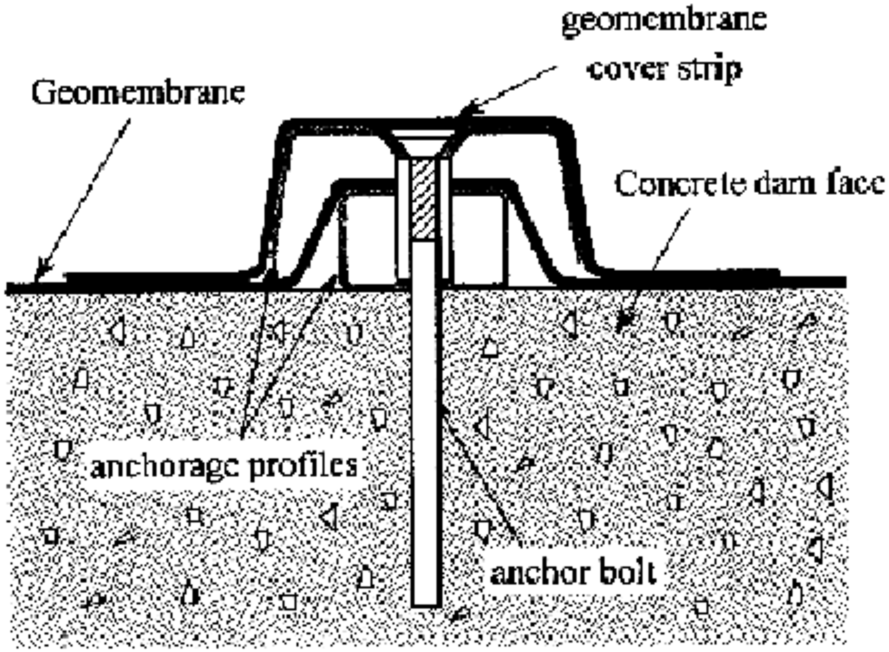
- GM in vertical strips $\simeq$ 2 m wide
- held against dam by metal batten strips
- anchor bolts must be installed first
- this is the major cost item
- several clever schemes available
- following is the CARPI-method



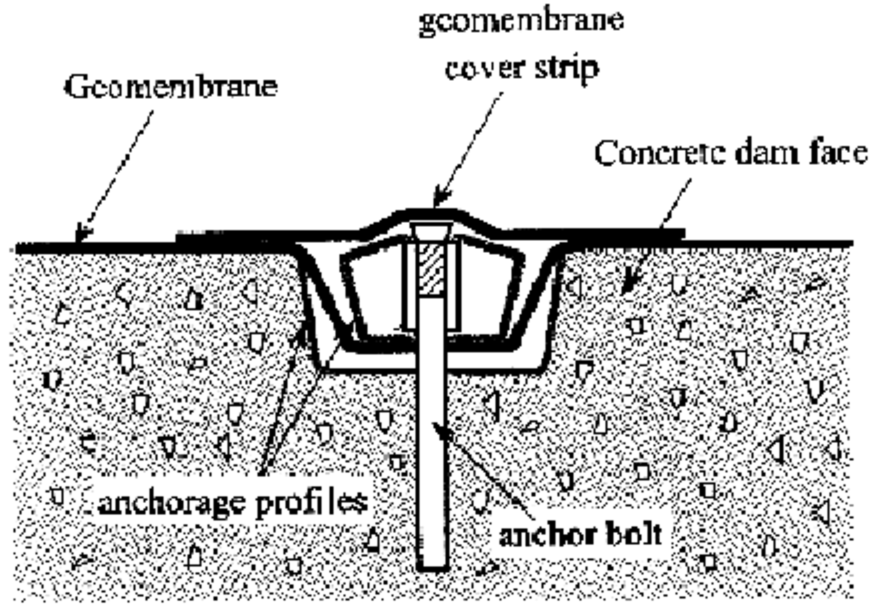
Typical Layout of GM Panels



Conventional Anchorage System



(a) Protruding Attachment



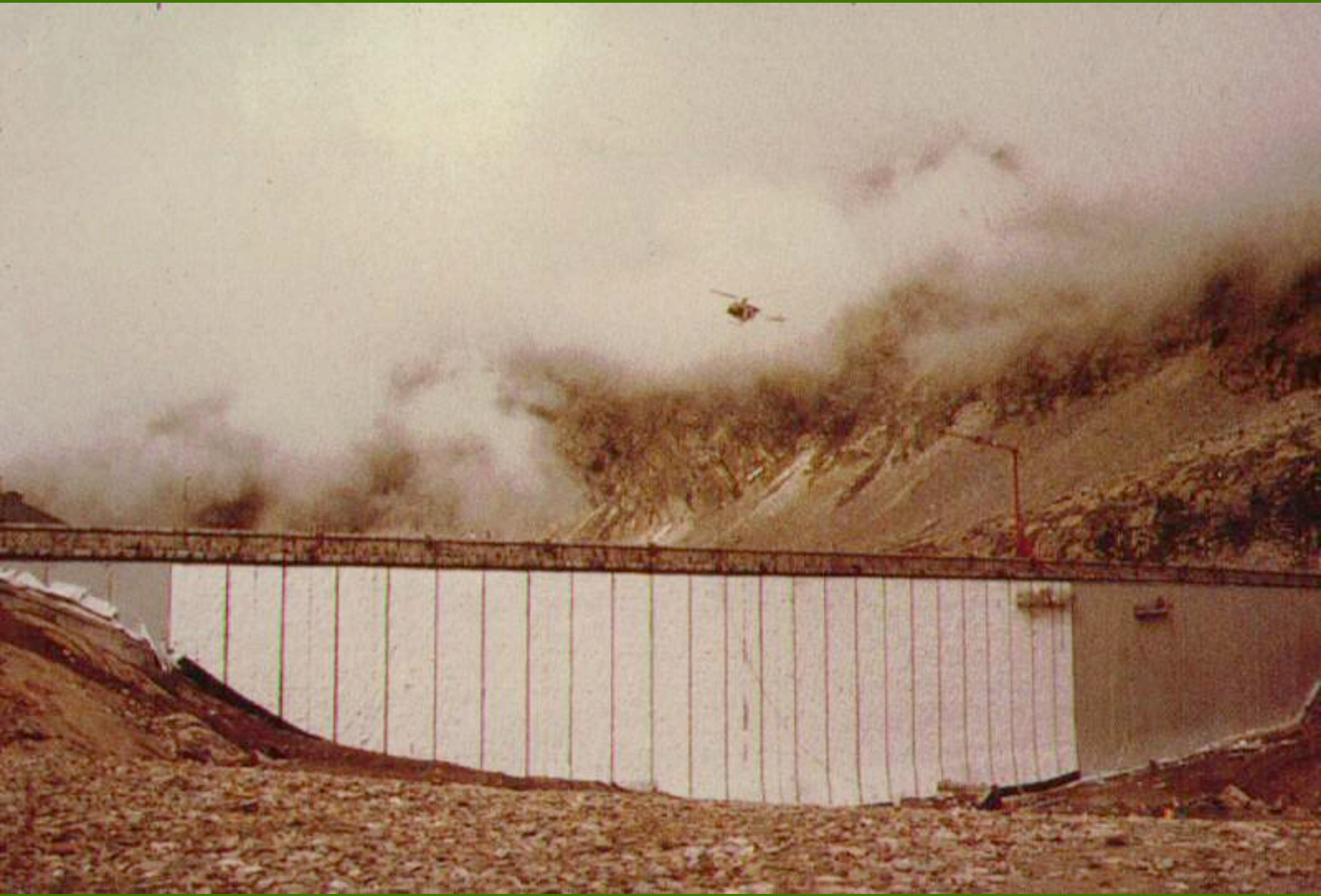
(a) Recessed Attachment

CARPI Method of Attaching Geomembrane Panels to Dam Face Using Continuous "Profiles"

Work in Progress – Inserting Anchor Belts

Placing GM/GT Composite Within Profiles

Closeup of Work Progress



Several Completed Sections

Photo Taken in 1996 When GM was 15-year in Service

DAMS WITH COMPLICATED SHAPE, GIROTTE DAM, France

What a Design? It needed Help!


Geocomposite
mechanically fastened

Concrete and Masonry Dam Rehabilitation in Italian Alps by ENEL (after Cazzuffi, 1987)

Name	Sabetta	Bartone	Miller	Nero	Locone	Castroceioni	Cignana	Barbellino
Height (m)	32	37	11	40	13	67	58	69
Age (years)	30	60	62	63	new	new	62	61
Installation	1959	1969	1976	1980	1982	1984	1986	1986
Area (m^2)	2600	3500	1500	4000	28,000	46,000	10,000	5500
Type	TS	TS	PVC	PVC	TS	PVC	PVC	PVC
Thickness (mm)	2.0	2.0	1.8	1.9	1.5	1.2	2.5	2.5
Drainage	no	no	no	yes	yes	yes	yes	yes

← Problematic →	← Successful →
Sabetta, Bartone, Miller	Nero, Locone, Castroceioni, Cignana, Barbellino

Some Observations

- work initiated in Italy by ENEL and CARPI
- 2004 report by Intl. Comm. on Large Dams shows 380 dams retrofitted using GMs
- majority are in Europe and China
- very few in USA; an obvious reluctance exists (why???)
- let’s assume its polymer lifetime!

2.0 Geomembranes

- name obtained by parent resin, yet
- all geomembranes are formulations
- specially formulated PVC used widely
- patented products by one company
- parallel PVC product or other comparable resins are desirable
- let’ s see what’ s available

Commonly Used Geomembranes and Their Approximate Weight Percentage Formulations

Type	Resin	Plasticizer	Fillers	Carbon Black	Additives
HDPE	95-98	0	0	2-3	0.25-1
LLDPE	94-96	0	0	1-3	0.25-4
fPP	85-98	0	0-13	2-4	0.25-2
PVC	50-70	25-35	0-10	2-5	2-5
CSPE	40-60	0	30-40	5-10	5-15
EPDM	25-30	0	20-40	20-40	1-5

HDPE = high density polyethylene
LLDPE = linear low density polyethylene
fPP = flexible propylene

PVC = polyvinyl chloride (plasticized)
CSPE = chlorosulfonated polyethylene
EPDM = ethylene propylene diene terpolymer

Important Issues

- within same polymer type, different AO's, plasticizers, and fillers will give vastly different performance
- comparison of performance (field and lab) must be done on same polymer and its specific formulation
- particularly the case for exposed versus nonexposed applications

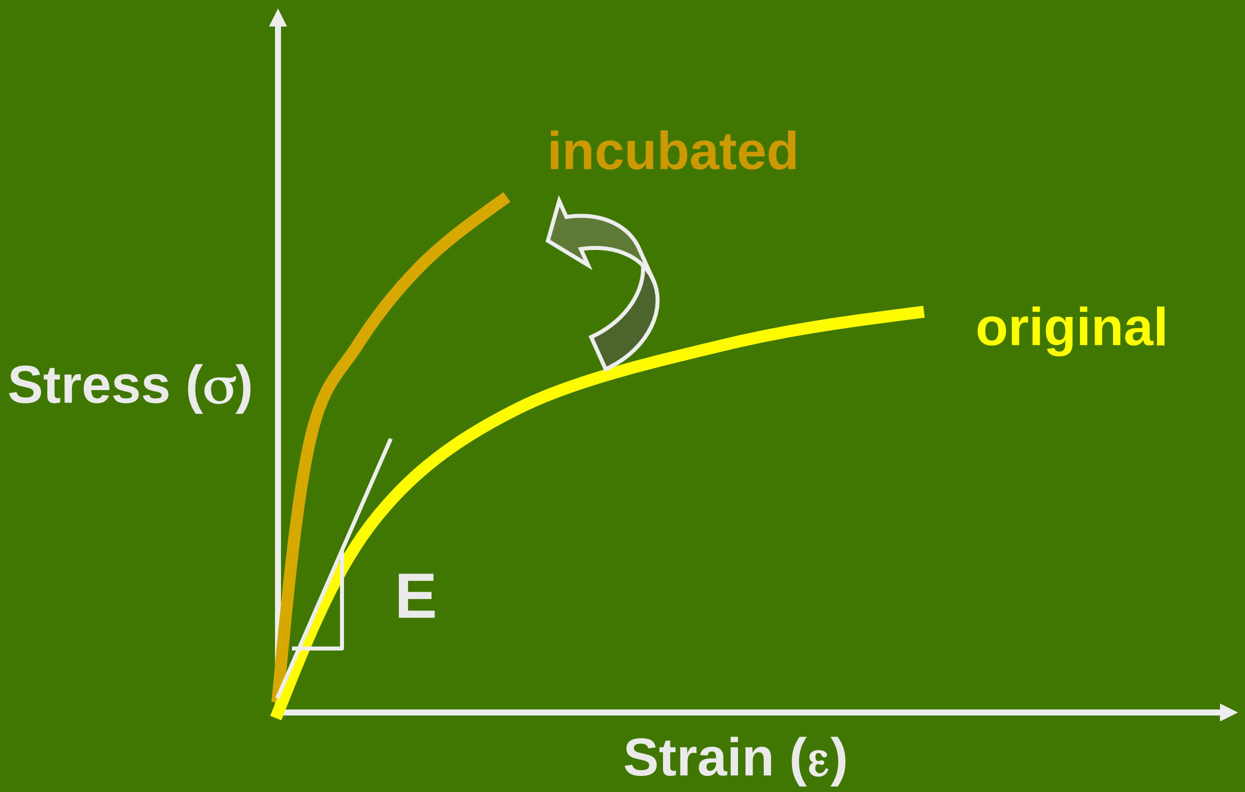
3.0 Degradation and Lifetime Prediction

Degradation Mechanisms

- oxidation (all types)
- hydrolytic (all types)
- chemical (all types)
- stress cracking (HDPE only)
- plasticizer extraction (PVC only)
- crosslinking (TS’ s only)
- ultraviolet (exposed only)

In General:

Reaction will cause ductile-to-brittle behavior



ε_f decreases

E increases

σ_f increases some then decreases

Thus, a limit could be the time required for a 50% reduction in "ε_f"; this is called a "halflife" value and is a good target

Investigative Options*

(a) “try, wait and see”

- without monitoring
- with monitoring

(b) let others “try, wait and see”

- without monitoring
- with monitoring

(c) perform accelerated laboratory studies

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*Let’ s look into option “c” or else we don’ t have anything to present !!!

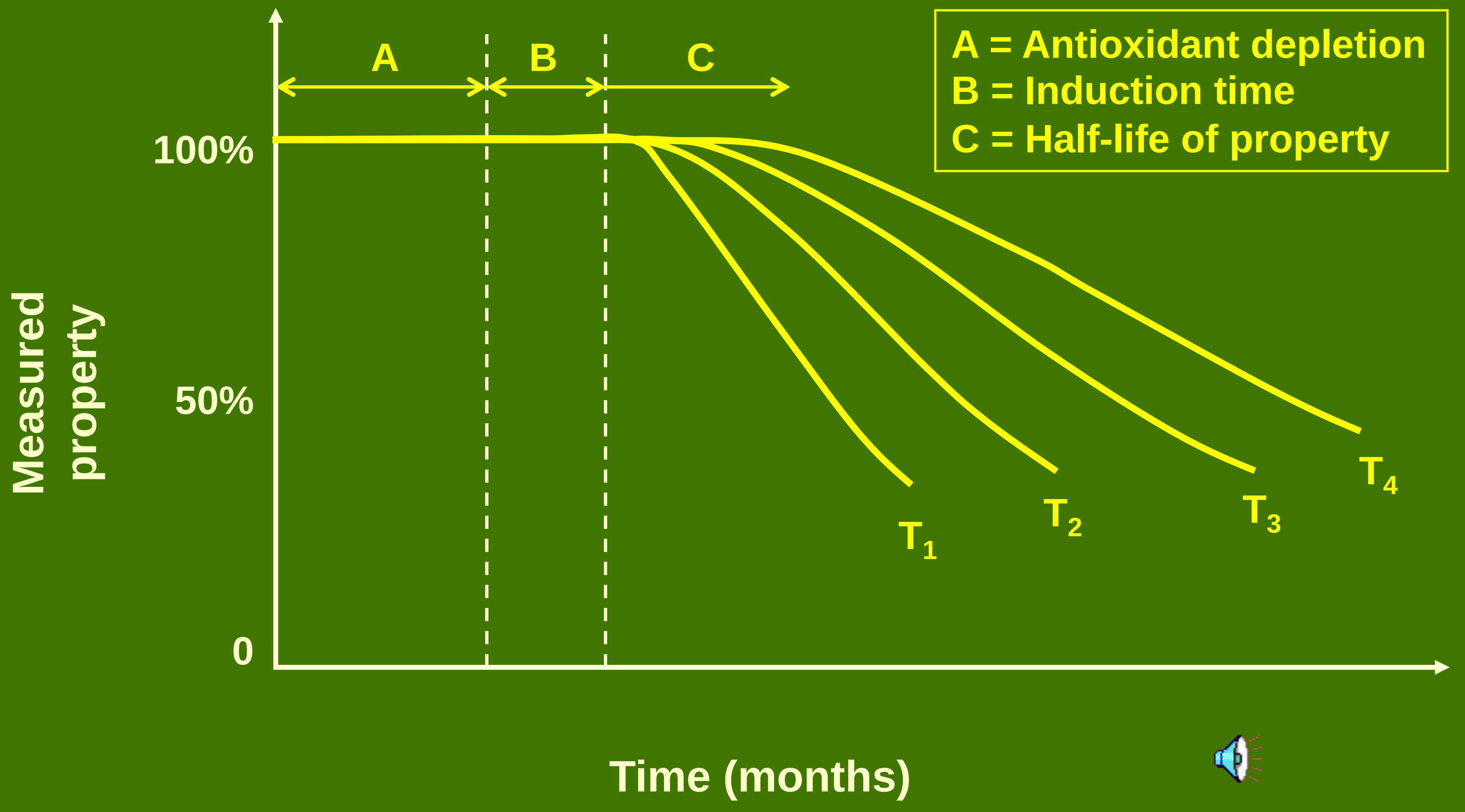
Time-Temperature Superposition

- most (all?) degradation mechanisms occur proportionate to temperature
- higher the temperature; faster the reaction
- holds for oxidation, hydrolysis, chemical, ultraviolet, migration, biological, radioactive mechanisms (but does not apply to stress)
- target is a predetermined change in some engineering property, e.g., “50% failure strain”

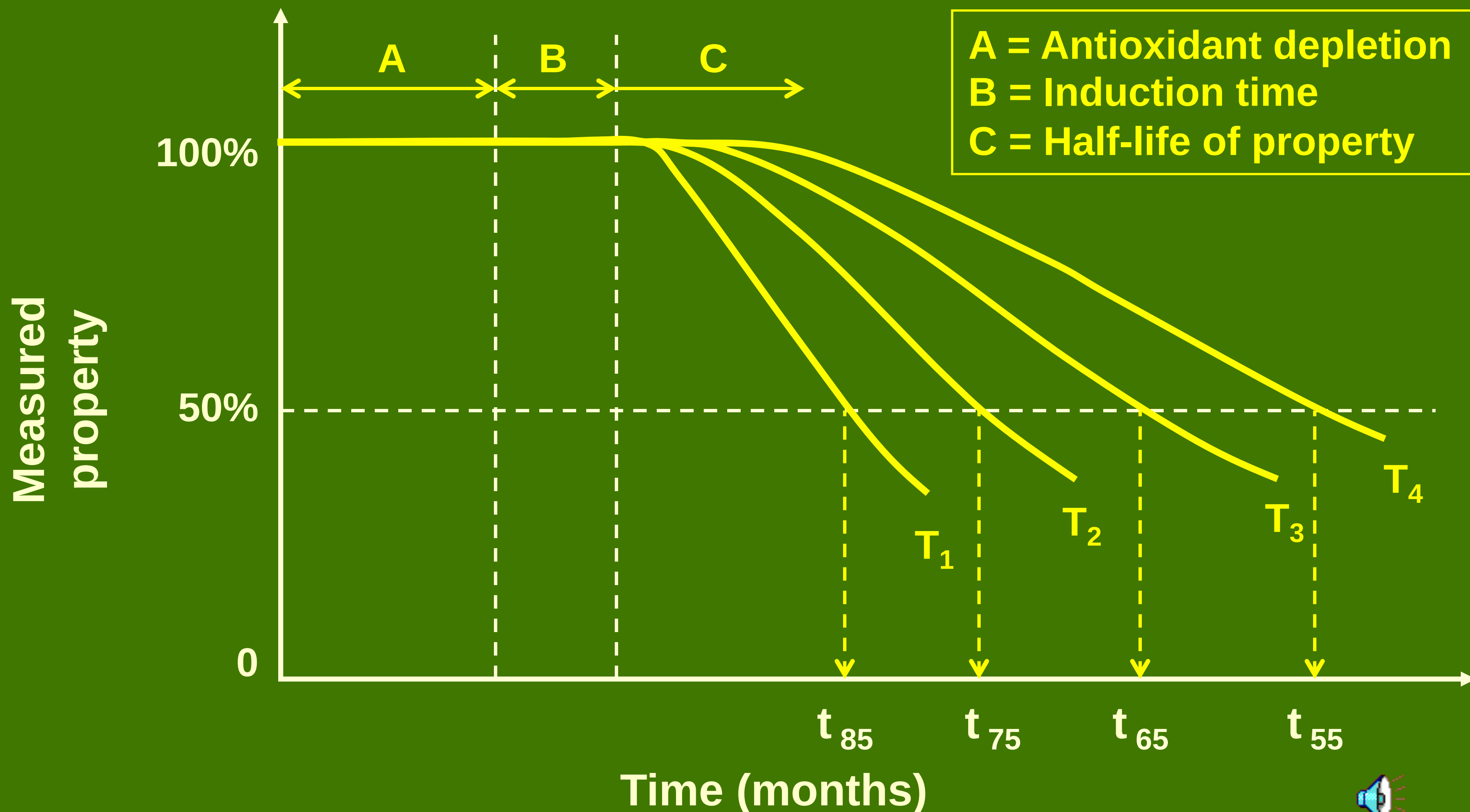
Lifetime Prediction

- following is common for many materials, including plastics (100’s of references)
- uses time-temperature superposition
- then plots data on Arrhenius graph for extrapolation down to the site-specific temperature
- 3-stages are defined…

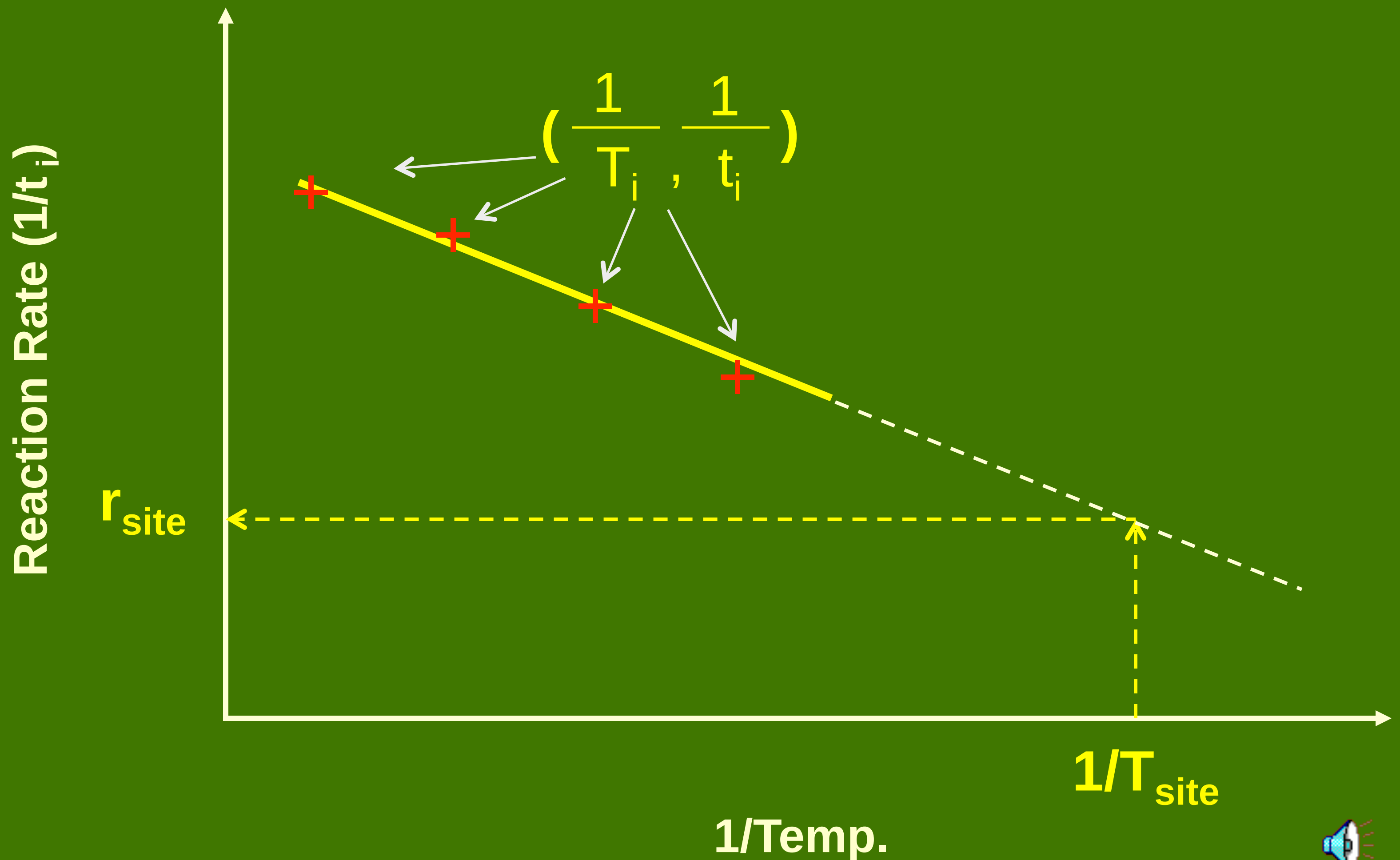
Incubated Property Behavior



Incubated Property Behavior



Arrhenius Plot for Stage “C” (1/2 Life)



In General…

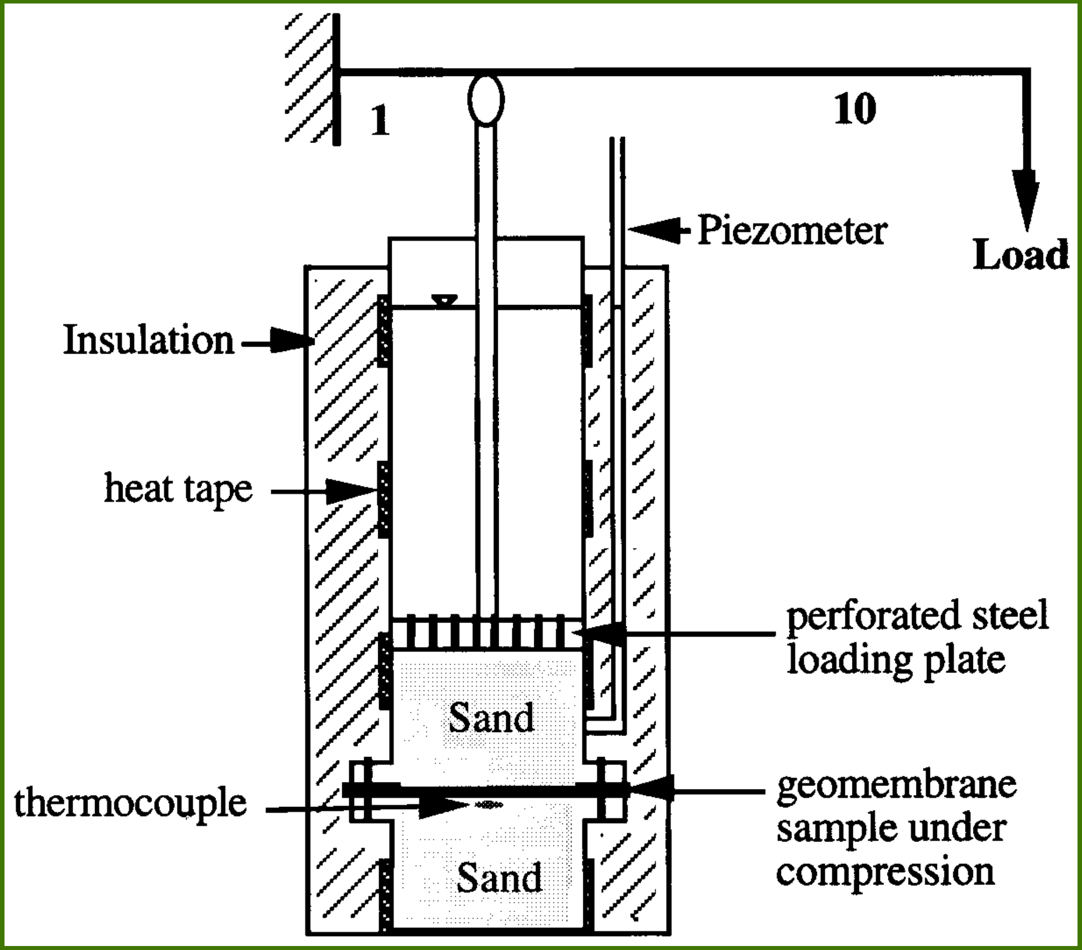
- above is for HDPE, LLDPE, and fPP
- for PVC; Stage A is plasticizer migration
- for CSPE & EPDM; Stage A is crosslinking
- let’s see some numbers!

4.0 Geomembrane Lifetime Prediction

- its all time-temperature superposition
- followed by Arrhenius plotting
- governs entire plastics industry
- GRI work on nonexposed HDPE follows… (it was driven by landfill concerns)
- EPA sponsored all of the work (about 7-years and expensive)

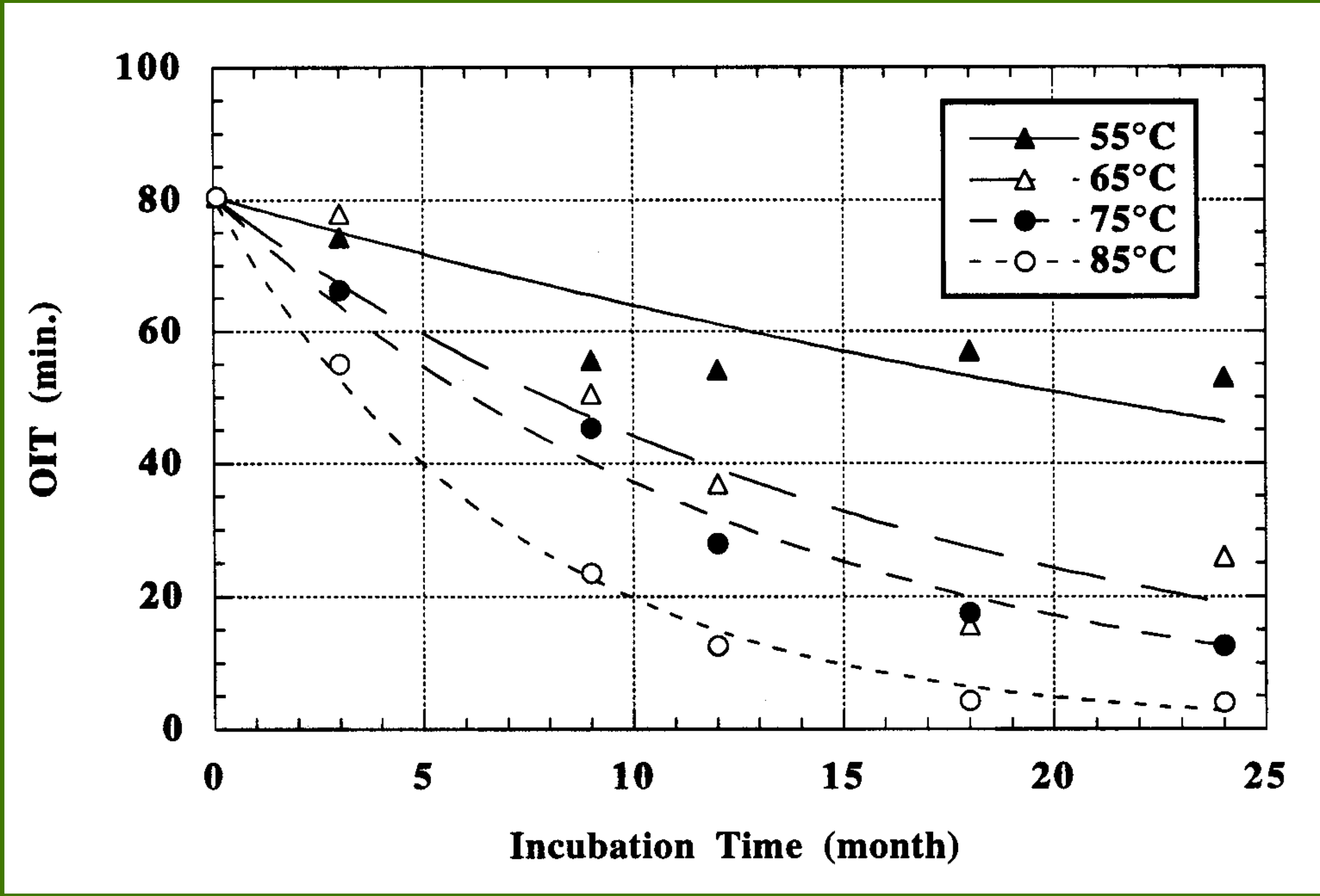
4.1 Behavior of HDPE Geomembranes

Diagram of compression column for incubation at different temperatures (Setup simulates GM beneath landfills)




8
9
10

(a) Depletion of Antioxidants



Standard OIT versus incubation time plot

Assuming that the service lifetime is 20°C and the OIT of unstabilized HDPE fluff is 0.5 min. in standard test and 25 min. in high pressure test

(a) for standard-OIT tests:

$$\ln(OIT) = \ln(P) + (S) * (t)$$

$$\ln(0.5) = \ln(80.5) + (-0.0033) * (t)$$

$$t = 2397 \text{ months } (200 \text{ years})$$

(b) for high pressure-OIT tests:

$$\ln(OIT) = \ln(P) + (S) * (t)$$

$$\ln(25) = \ln(210) + (-0.0014) * (t)$$

$$t = 2590 \text{ months } (215 \text{ years})$$

(b) Induction Time

- we retrieved HDPE containers from the bottom of a failed landfill
- adjacent articles were 25-30 yrs. old
- containers were unstabilized HDPE
- 1 water jug and 3 milk containers
- tested old vs. new specimens

Predicted Induction Time

- it’ s based on lean data
- if samples were 25-30 yrs. old and typical of new containers …
- properties just beginning to degrade
- therefore, induction time ~ 30 yrs.

(c) Time to Reach Halflife

- need slope of Arrhenius curve
- GRI data just becoming available
- Viebke, et al. (1994) found for unstabilized polyethylene pipe over temperature range of 115 to 70°C

  E = 80 kJ/mol

- at 115°C the reaction time was 90 days

Extrapolation from 115°C to 20°C (site-specific)

$$\frac{R_{r@115}}{R_{r@20}} = e^{\frac{-E_{act}}{R}\left[\frac{1}{115+273} - \frac{1}{20+273}\right]}$$

$$\frac{R_{r@115}}{R_{r@20}} = e^{\frac{-80,000}{8.314}\left[\frac{1}{388} - \frac{1}{293}\right]}$$

$$\frac{R_{r@115}}{R_{r@20}} = e^{8.04} = 3027 \text{ (times faster at 115°C than 20°C)}$$

Thus,

$$R_{r@20} = (3027)(90)$$

$$= 272,000 \text{ days}$$

$$= 746 \text{ years}$$

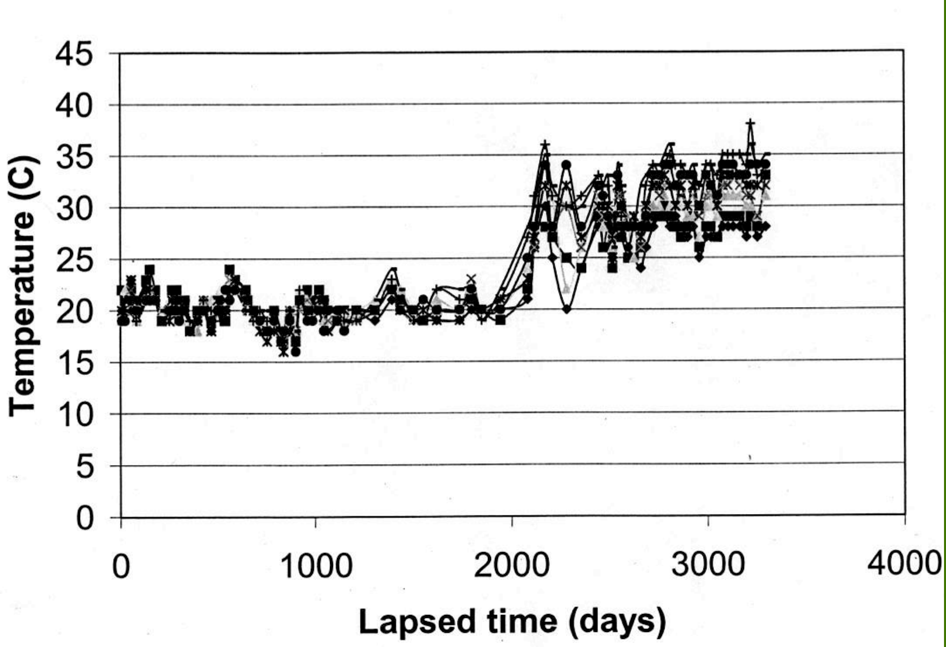
(d) Summarizing the Previous Calculations

Stage	Description	Duration (years)
A	Antioxidant Depletion	200
B	Induction Time	30
C	Halflife of Engineering Property	740
Total	Lifetime Estimate*	~ 970

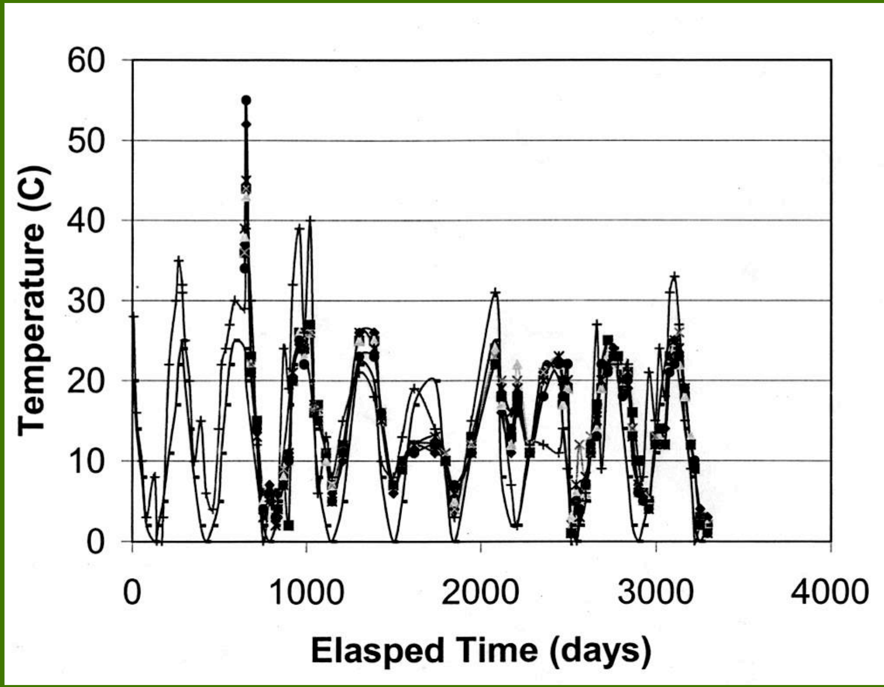
*to halflife of strain at failure at 20°C exposure temperature!

Now the Bad News!

Dry Cell Liner Temperature



Dry Cell Cover Temperatures



Temperature Readings via Thermocouples Placed Directly on the Geomembranes Beneath and Above a Municipal Solid Waste Landfill in Pennsylvania

Lifetime Prediction of HDPE at Elevated Field Service Temperatures

Field Temperature		Stage “A” (yrs.)		Stage “B” (years)	Stage “C” (yrs.)		Total Ave. Years
C (deg)	F (deg)	Std OIT	HP-OIT		Ref. 1	Ref. 2	
20	68	200	215	30	208	740	712
25	77	135	144	25	100	441	435
30	86	95	98	20	49	259	270
35	95	65	67	15	25	154	170
40	104	45	47	10	13	93	109

Notes: Stage “A” measured values from G. Hsuan research
Stage “B” estimated values from field samples
Stage “C” literature values from Martin & Gardner[17] and Viebke, et al.[18]

4.2 Halflife of Different Nonexposed Geomembranes*

HDPE	~ see previous
LLDPE	~ somewhat less
fPP	~ somewhat less
PIB, IIR, EPDM	~ seam concerns
PVC-P	~ plasticizer dependent

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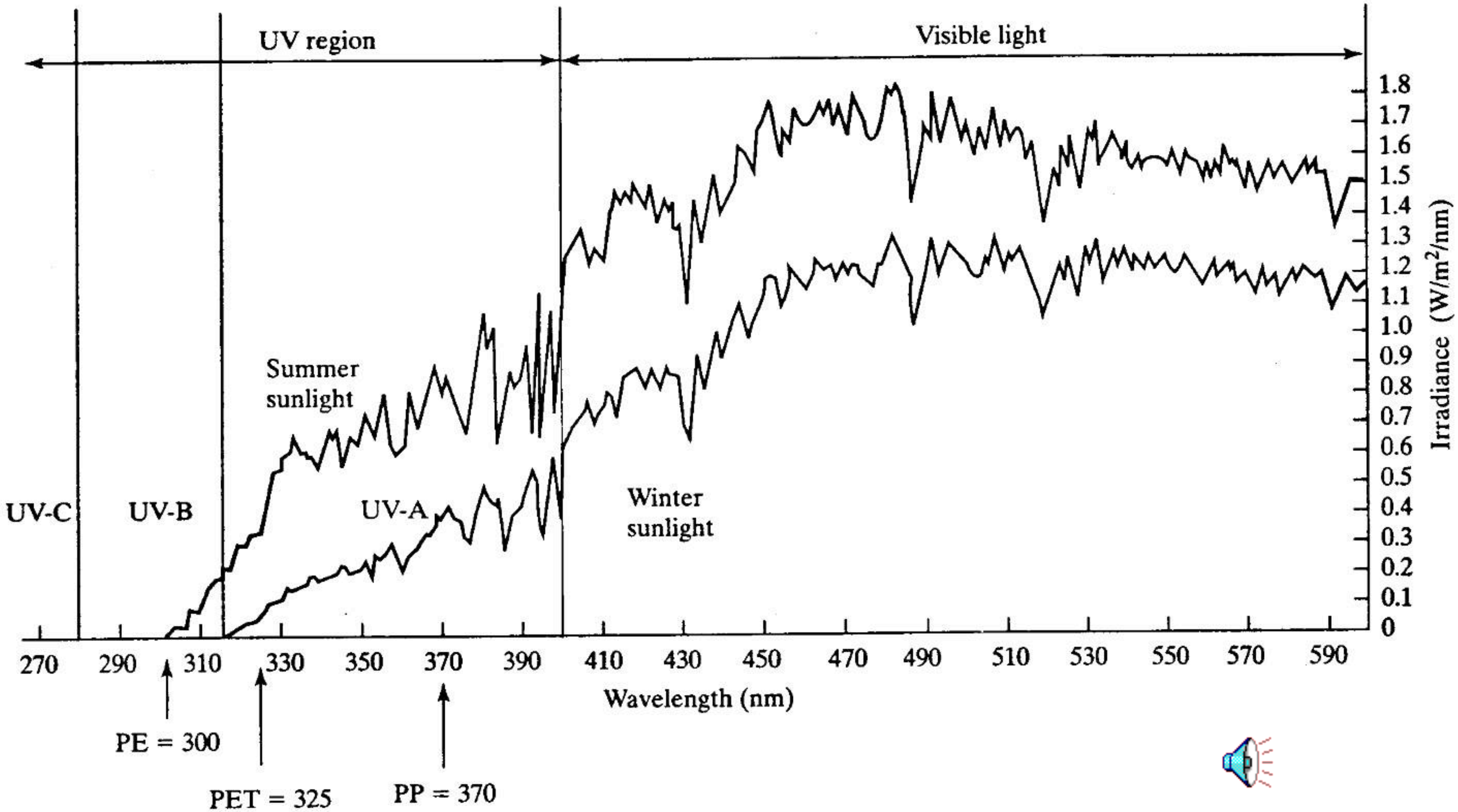
*this is essentially arm-waving; a tremendous research effort is necessary to quantify

4.3 Exposed Durability and Lifetime

- degradation mechanisms are the same as nonexposed “plus” ultraviolet and high ambient temperatures
- both are more severe than other mechanisms
- experimental approach is completely different
- laboratory weatherometers are used which impose UV, elevated temperature and moisture
- predictive methods are available; but very approximate (example will follow)



The wavelength spectrum of visible and UV solar radiation. (After Q-Panel Co., Cleveland, OH)

Various Accelerated Weathering Devices

Weathering Device	Test Standard	Special Items	Radiation (nm)	Temperature (°C)	Water
Xenon Arc	ASTM G155 ASTM D4355	borosilicate filters	300 – 800	60-65	spray
Ultraviolet Fluorescent	ASTM G154 GRI-GM11	solar eye system	300 – 400	65-75	condensation
EMMAQUA (Outdoor)	ASTM G90	none	full solar range	40-60	spray

Predictive Methodology

Example: A geotextile reached its halflife elongation in Xenon Arc device (517.8 W/m^2) in 2000 hours. What is the equivalent lifetime in Philadelphia exposure? Note: Jewell (J) = watts (W) x seconds (sec)

Solution:

$$E_{test} = (517.8)(2000)(3600)(1 \times 10^{-6})$$

$$= 3728\ \mathrm{MJ/m^2}$$

$$E_{Phila} = (5021\ \mathrm{MJ/m^2 - yr.})(1/4\ \text{sun time})$$

$$= 1255\ \mathrm{MJ/m^2 - year}$$

$$T_{Phila} = \frac{3728}{1255} = 2.97\ \text{years}$$

Thus: Acceleration Factor of the Weatherometer is

$$AF = \frac{(2.97)(365)}{(2000)(1/24)} = 13!$$

Comment:

- previous example was for a geotextile
- geomembranes are much more durable due to their lower surface area and more AO’s (e.g., a 50-yr GM would require 3.8-yrs of testing)
- formulations (plasticizers and antioxidants are critical issues)
- light color is an important consideration
- to evaluate GMs is a lengthy process

5.0 Summary & Recommendations

Dam Application	UV-Exposed	Temperature	Freeze/Thaw Cycle	Wet/Dry Cycle
Earth or Earth Rock	no	below ambient	varies	yes
Roller compacted concrete	no	below ambient	nominal	yes
Masonry or Concrete	yes	ambient	yes	yes

Recommendations

- GMs well suited for dam waterproofing
- covered durability of GMs is excellent
- exposed durability is significantly shorter
- GM polymer and formulation is critical
- additives (e.g., antioxidants and plasticizers) are particularly critical
- GSI will mount a major initiative (CPHyS)
- GMs won’t always be the best solution; but they should always be considered

Your attention and interest is appreciated !