

ENVR 133
Water Treatment

Mark D. Sobsey

Enteric Microbes, Water Sources and Water Treatment

- Drinking water must be essentially free of disease-causing microbes, but often this is not the case.
 - A large proportion of the world's population drinks microbially contaminated water, especially in developing countries
- Using the best possible source of water for potable water supply and protecting this source from microbial and chemical contamination is the goal.
 - In many places an adequate supply of pristine water or water that can be protected from contamination is not available
- The burden of providing microbially safe drinking water supplies from contaminated natural waters rests upon conventional water treatment processes.
 - The efficiency of removal or inactivation of enteric microbes and other pathogenic microbes in specific water treatment processes has been determined for some microbes but not others.

Water Treatment Processes: Storage

Reservoirs, aquifers & other systems:

- store water**
- protect it from contamination**
- Factors influencing microbe reductions (site-specific)**
 - detention time**
 - temperature**
 - microbial activity**
 - water quality: particulates, dissolved solids, salinity**
 - sunlight**
 - sedimentation**
 - land use**
 - precipitation**
 - runoff or infiltration**

Water Storage and Microbial Reductions

- Microbe levels reduced over time by natural antimicrobial processes and microbial death/die-off
- Human enteric viruses in surface water reduced 400-1,000-fold when stored 6-7 months (The Netherlands)
 - Indicator bacteria reductions were less extensive, probably due to recontamination by waterfowl.
- Protozoan cyst reductions ($\log_{10}$) by storage were 1.6 for *Cryptosporidium* and 1.9 for *Giardia* after about 5 months (The Netherlands; G.J Medema, Ph.D. diss.)
 - Recent ICR data indicates lower protozoan levels in reservoir or lake sources than in river sources; suggests declines in *Giardia* & *Cryptosporidium* by storage

Chemical Coagulation-Flocculation

Removes suspended particulate and colloidal substances from water, including microorganisms.

Coagulation: colloidal destabilization

- Typically, add alum (aluminum sulfate) or ferric chloride or sulfate to the water with rapid mixing and controlled pH conditions**
- Insoluble aluminum or ferric hydroxide and aluminum or iron hydroxo complexes form**
- These complexes entrap and adsorb suspended particulate and colloidal material.**

Coagulation-Flocculation, Continued

Flocculation:

- **Slow mixing (flocculation) that provides for for a period of time to promote the aggregation and growth of the insoluble particles (flocs).**
- **The particles collide, stick together abd grow larger**
- **The resulting large floc particles are subsequently removed by gravity sedimentation (or direct filtration)**
- **Smaller floc particles are too small to settle and are removed by filtration**

Microbe Reductions by Chemical Coagulation-Flocculation

- **Considerable reductions of enteric microbe concentrations.**
- **Reductions In laboratory and pilot scale field studies:**
 - **>99 percent using alum or ferric salts as coagulants**
 - **Some studies report much lower removal efficiencies (<90%)**
 - **Conflicting information may be related to process control**
 - **coagulant concentration, pH and mixing speed during flocculation.**
- **Expected microbe reductions of 90-99%, if critical process variables are adequately controlled**
- **No microbe inactivation by alum or iron coagulation**
 - **Infectious microbes remain in the chemical floc**
 - **The floc removed by settling and/or filtration must be properly managed to prevent pathogen exposure.**
 - **Recycling back through the plant is undesirable**
 - **Filter backwash must be disinfected/disposed of properly.**

Cryptosporidium Removals by Coagulation (Jar Test Studies)

Coagulant	Dose (mg/L)	Oocyst Removal, % ($\log_{10}$)
Alum	5	99.8 (2.7)
	1	87 (0.9)
Iron	6	99.5 (2.3)
	5	97 (1.5)

Water Softening and Microbe Reductions

- **"Hard" Water: contains excessive amounts of calcium and magnesium ions**
 - iron and manganese can also contribute to hardness.
- **Hardness ions are removed by adding lime (CaO) and sometimes soda ash (Na_2CO_3) to precipitate them as carbonates, hydroxides and oxides.**
- **This process, called softening, is basically a type of coagulation-flocculation process.**
- **Microbe reductions similar to alum and iron coagulation when pH is <10**
- **Microbe reductions $>99.99\%$ possible when pH is >11**
 - microbial inactivation + physical removal

Microbial Reductions by Softening Treatment

- **Softening with lime only (straight lime softening); moderate high pH**
 - ineffective enteric microbe reductions: about 75%.
- **Lime-soda ash softening**
 - results in the removal of magnesium as well as calcium hardness at higher pH levels (pH >11)
 - enteric microbe reductions >99%.
 - Lime-soda ash softening at pH 10.4, 10.8 and 11.2 has produced virus reductions of 99.6, 99.9 and 99.993 percent, respectively.
- **At lower pH levels (pH <11), microbe removal is mainly a physical process**
 - infectious microbes accumulate in the floc particles and the resulting chemical sludge.
- **At pH levels above 11, enteric microbes are physically removed and infectivity is also destroyed**
 - more rapid and extensive microbe inactivation at higher pH levels.

Granular Media Filtration

- **Used to remove suspended particles (turbidity) incl. microbes.**
- **Historically, two types of granular media filters:**
 - **Slow sand filters: uniform bed of sand;**
 - **low flow rate <0.1 GPM/ft²**
 - **biological process: 1-2 cm “slime” layer (schmutzdecke)**
 - **Rapid sand filters: 1, 2 or 3 layers of sand/other media;**
 - **>1 GPM/ft²**
 - **physical-chemical process; depth filtration**
- **Diatomaceous earth filters**
 - **fossilized skeletons of diatoms (crystalline silicate);**
powdery deposit; few 10s of micrometers; porous

Slow Sand Filters

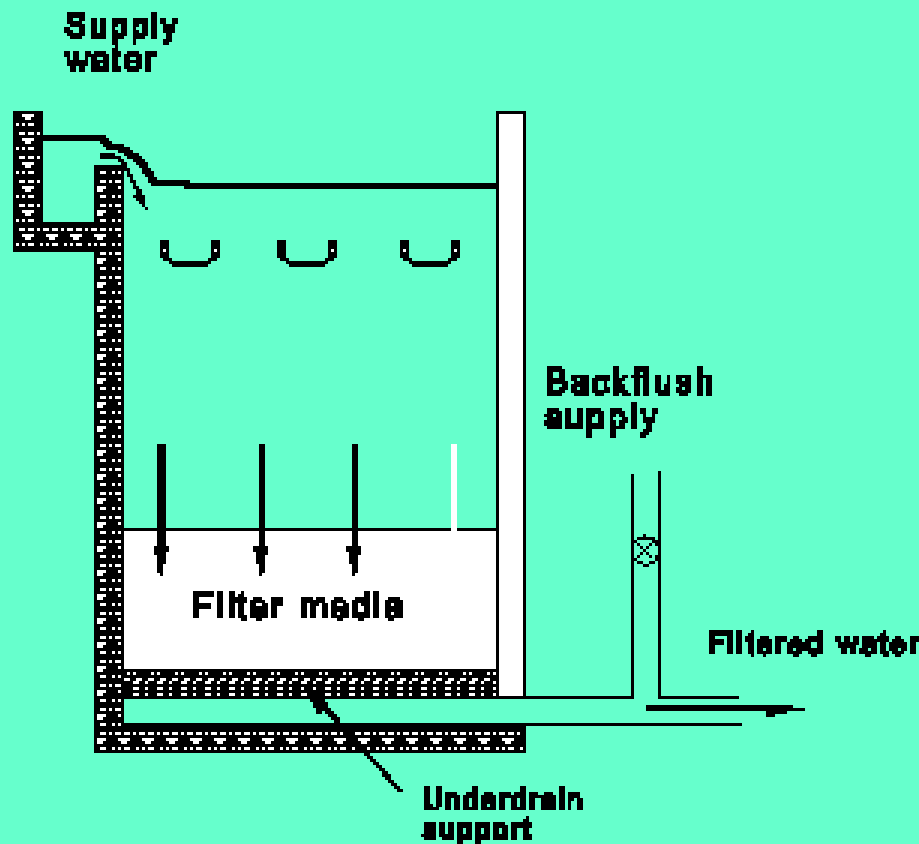
- **Less widely used for large US municipal water supplies**
- **Effective; widely used in Europe; small water supplies; developing countries**
- **Filter through a 3- to 5-foot deep bed of unstratified sand**
- **flow rate ~0.05 gallons per minute per square foot.**
- **Biological growth develops in the upper surface of the sand is primarily responsible for particle and microbe removal.**
- **Effective without pretreatment of the water by coagulation-flocculation**
- **Periodically clean by removing, cleaning and replacing the upper few inches of biologically active sand**

Microbial Reductions by Slow Sand Filtration

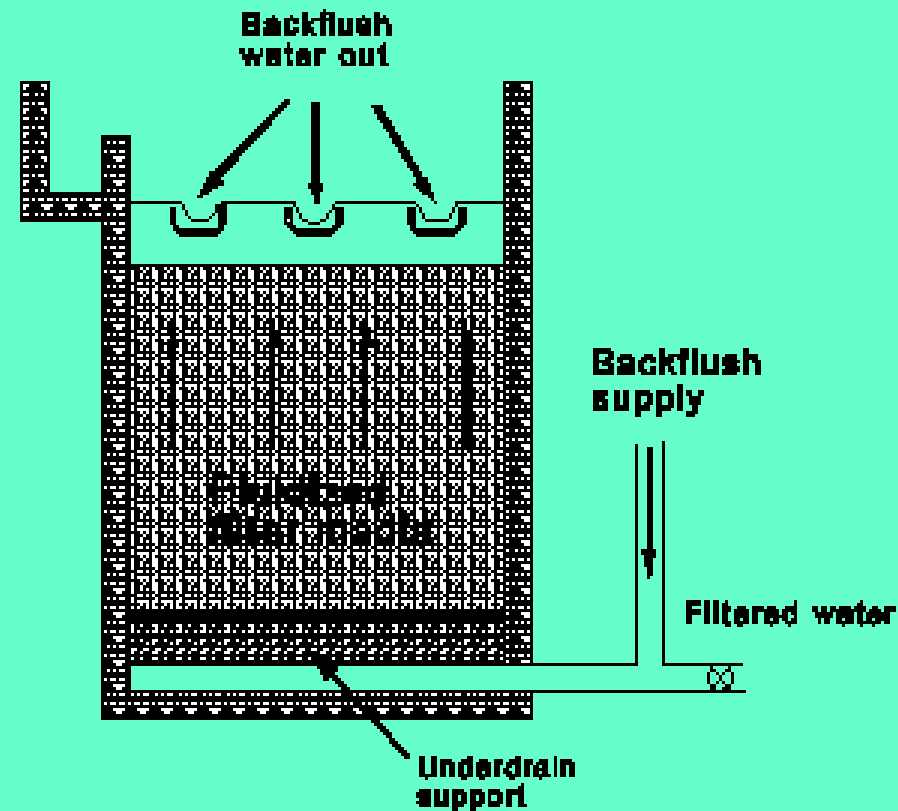
- Effective in removing enteric microbes from water.
- Virus removals >99% in lab models of slow sand filters.
 - Up to 4 log₁₀; no infectious viruses recovered from filter effluents
- Field studies:
 - naturally occurring enteric viruses removals
 - 97 to >99.8 percent; average 98% overall;
 - Comparable removals of *E. coli* bacteria.
 - Virus removals=99-99.9%;
 - high bacteria removals (UK study)
- Parasite removals: *Giardia lamblia* cysts effectively removed
 - Expected removals $\approx$ 99%

Rapid Granular Medium Filter

Key Variables: Filter media (type, particle size, depth), flow rate or flux (filtration rate per unit surface area), length of filter run, backwashing/cleaning conditions, post-backwash start-up conditions



a) Operation during filtration



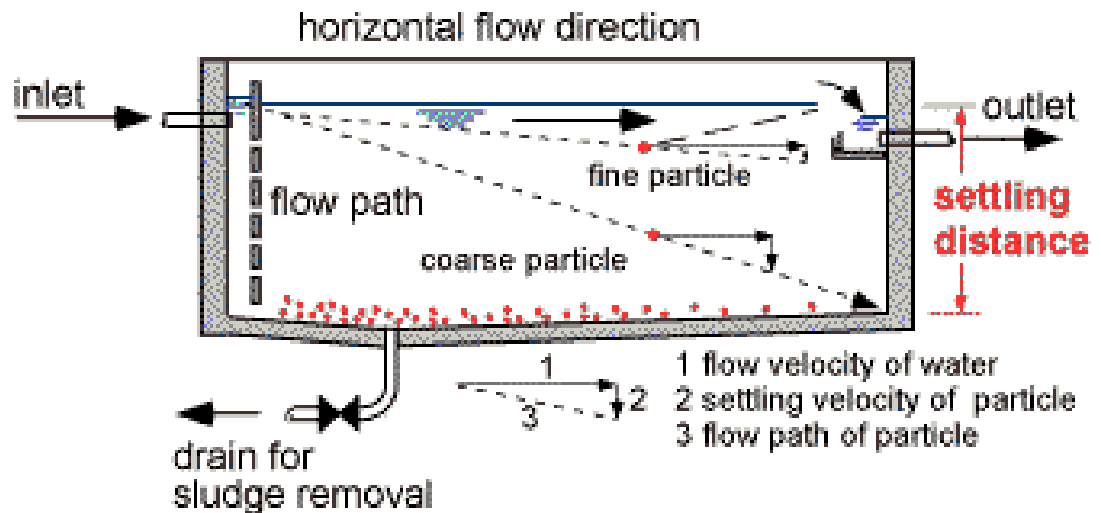
b) Operation during cleaning

Roughing Filter

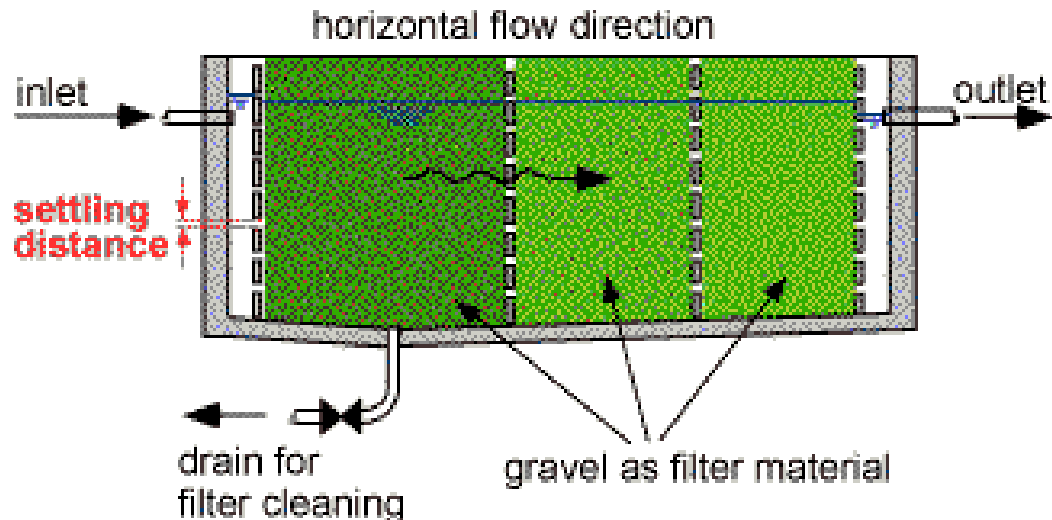
- Used in developing countries
 - inexpensive
 - low maintenance
 - local materials
- Remove large solids
- Remove microbes
 - 1-2 $\log_{10}$ bacterial reduction
 - 90% turbidity reduction

Conceptional Layout of a Sedimentation Tank and a Roughing Filter

Sedimentation Tank



Roughing Filter



Microbe Reductions by Rapid Granular Media Filters

- Ineffective to remove enteric microbes unless preceded by chemical coagulation-flocculation.
- Preceded chemical coagulation-flocculation & sedimentation
- Enteric microbe removals of 90->99 % achieved.
- Field (pilot) studies: rapid sand filtration preceded by iron coagulation-flocculation: virus removal <50% (poor control?).
- *Giardia lamblia*: removals not always high; related to turbidity removal; >99% removals reported when optimized.
 - Removal not high unless turbidity is reduced to ~~2~~ 0.2 NTU.
- Lowest removals shortly after filter backwashing
 - Microbes primarily removed in filter by entrapped floc particles.
- Overall, can achieve ~~90~~ 90% microbial removals from water when preceded by chemical coagulation-flocculation.

Microbe Reductions by Chemical Coagulation-Flocculation and Filtration of River Water by Three Rx Plants in The Netherlands

Organisms	Plant 1	Plant 2	Plant 3
	Log₁₀ Reductions of Microbes		
Enteric Viruses	1.0	1.7	>2
F+ Coliphages	0.4	1.7	No data
Fecal Coliforms	0.2	2.0	>2
Fecal Streptococci	0.6	2.1	>2
Clostridium spores	0.6	2.1	>2

Plant 1 used two stages of iron coagulation-flocculation-sedimentation.

Plant 2 used iron coagulation-flocculation-sedimentation and rapid filtration

Plant 3 used iron coagulation-flotation-rapid filtration.

Cryptosporidium Removals by Sand Filtration

Type	Rate (M/hr)	Coagulation	Reduction % ($\log_{10}$)	
Rapid, shallow	5	No	65	(0.5)
Rapid, shallow	5	Yes	90	(1.0)
Rapid, deep	6	Yes	99.999	(5.0)
Slow	0.2	No	99.8	(2.7)

Cryptosporidium Removal by Coagulation and Direct Filtration

Run No.	Log ₁₀ Reduction of <i>Cryptosporidium</i>	Turbidity
1	3.1	1.3
2	2.8	1.2
3	2.7	0.7
4	1.5	0.2*
Mean	2.5	0.85

Raw water turbidity = 0.0 - 5.0 NTU

Alum coagulation-flocculation;

Anthracite-sand-sand filtration; 5 GPM/ft²

*Suboptimum alum dose

Ongerth & Pecoraro. JAWWA, Dec., 1995

Reported Removals of *Cryptosporidium* Oocysts by Physical-Chemical Water Treatment Processes (Bench, Pilot and Field Studies)

Process	Log ₁₀ Reduction
Clarification by: Coagulation flocculation-sedimentation or Flotation	<1 - 2.6
Rapid Filtration (pre-coagulated)	1.5 - >4.0
Both Processes	<2.5 - >6.6
Slow Sand Filtration	>3.7
Diatomaceous Earth Filtration	>4.0
Coagulation + Microfiltration	>6.0
Ultrafiltration	>6.0

Cryptosporidium Reductions by Coagulation and Filtration

Laboratory studies on oocyst removal:

- Jar test coagulation with 1 hr. setting = 2.0 - 2.7 log₁₀**
- Sand filtration, no coagulant, 10 cm bed depth = 0.45 log₁₀**
- Sand filtration, plus coagulation, 10 cm bed depth = 1.0 log₁₀**

Gregory et al., 1991. Final Report. Dept. of the Environ., UK

Membrane Filters

- More recent development and use in drinking water
- Microfilters: several tenths of μm to μm diameter pore size
 - nano- & ultra-filters: retention by molecular weight cutoff
 - Typically 1,000-100,000 MWCO
- Reverse osmosis filters: pore size small enough to remove dissolved salts; used to desalinate (desalt) water as well as particle removal
- High >99.99% removal of cellular microbes
- Virus removals high >99.99% in ultra-, nano- and RO filters
- Virus removals lower (<99%) by microfilters
- Membrane and membrane seal integrity critical to effective performance

Cryptosporidium Reductions by Membrane Filtration

Membrane, Pore Size Type	Log ₁₀ <i>Cryptosporidium</i> Reduction
A, MF 0.2 µm	>4.4
B, MF 0.2 µm	>4.4
C, MF 0.1 µm	4.2->4.8
D, UF 500 KD	>4.8
E, UF 300 KD	>4.8
F, UF 100 KD	>4.4

MF = microfilter filter; UF = ultrafilter

Jacangelo et al., JAWWA, Sept., 1995

Adsorbers and Filter-Adsorbers

Adsorbers:

- **Granular activated carbon adsorption**
 - remove dissolved organics
 - poor retention of pathogens, esp. viruses
 - biologically active; develops a biofilm
 - can shed microbes into water

Filter-adsorbers

- **Sand plus granular activated carbon**
 - reduces particles and organics
 - biologically active
 - microbial retention is possible

Household and Point-of-Use Drinking Water Treatment in Developing Countries

- **Boiling**
- **Chlorine disinfection**
- **Solar disinfection**
- **Filtration**
- **Combined coagulation-flocculation, settling, filtration and chemical disinfection (chlorination) as commercial products in the form of tablets or powders/granules in sachets**
- **Point-of-use UV lamps**

Chlorination and Safe Storage:

The Safe Water System - A Water Quality Intervention

Objective: make water safe through chlorine disinfection and safe storage at the point of use

Simple, inexpensive and robust technology appropriate for the developing world



**Bottle (or Tablets) of Chlorine
or Electrochemically
Generated Oxidant**



**Safe Storage
(Water Vessel)**



**Social Change: Behavior
Change, Education,
Motivational Interviewing**

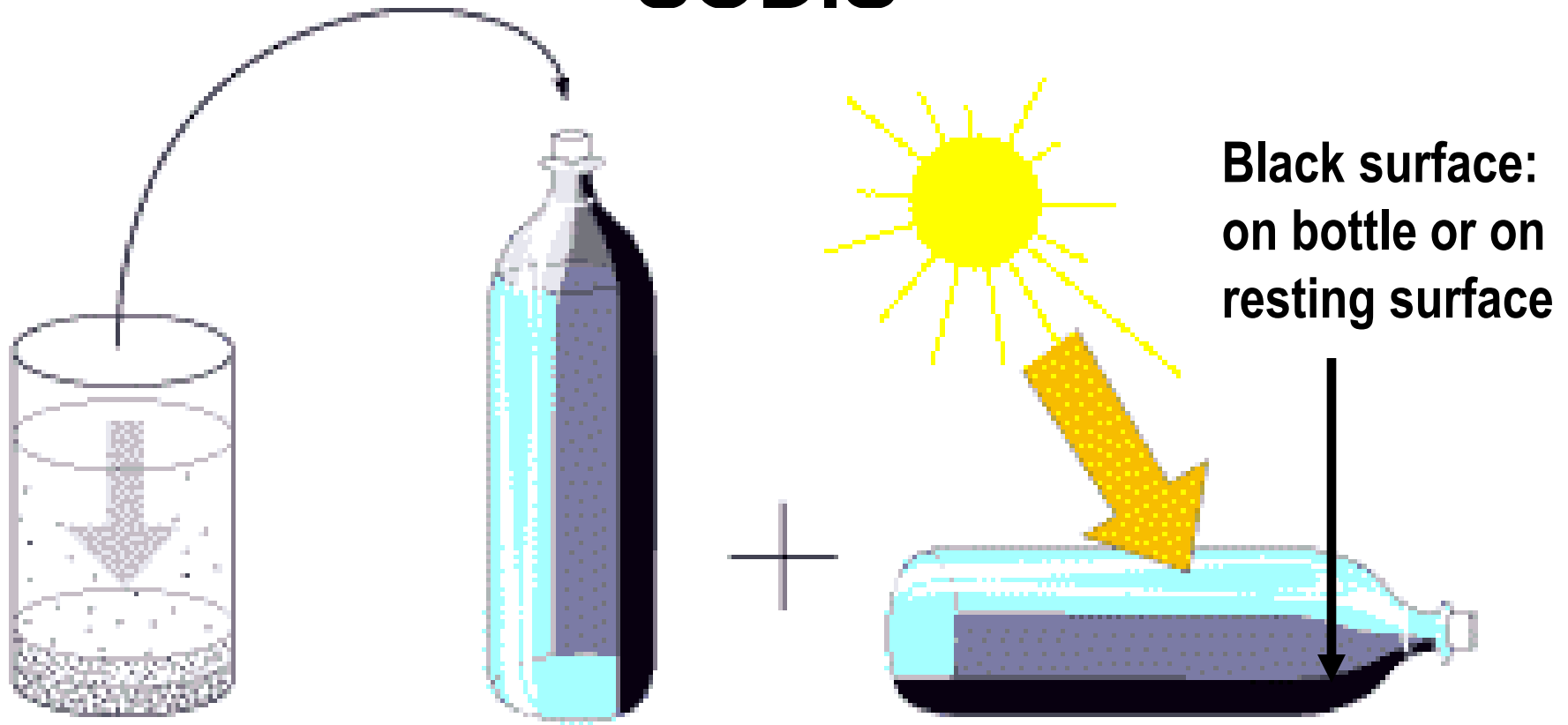
Basis of the Intervention

- **Point-of-use treatment of contaminated water using sodium hypochlorite solution purchased locally and perhaps produced in the community from water and salt using an electrolytic cell (electrochemically generated oxidant) or purchased chlorine tablets (CaOCl or $\text{NaDichloroisocyanurate}$)**
- **Safe water storage in plastic containers with a narrow mouth, lid, and a spigot to prevent recontamination**
- **Behavior change techniques: social marketing, community mobilization, motivational interviewing, communication, and education, to increase awareness of the link between contaminated water and disease and the benefits of safe water, and to influence hygiene behaviors including the purchase and proper use of the water storage vessel and disinfectant.**

Solar Disinfection: SODIS and Solar Cooking?

- **Treatment method to eliminate water-borne pathogens using UV radiation plus heat or heat only from sunlight**
- **Used to disinfect small quantities of water used for consumption**
- **Depends on solar energy only**
- **An alternative water treatment option for use mainly at household level**
- **An old but currently less widely applied water purification method**
- **Does not directly change the chemical quality of the water**

SODIS



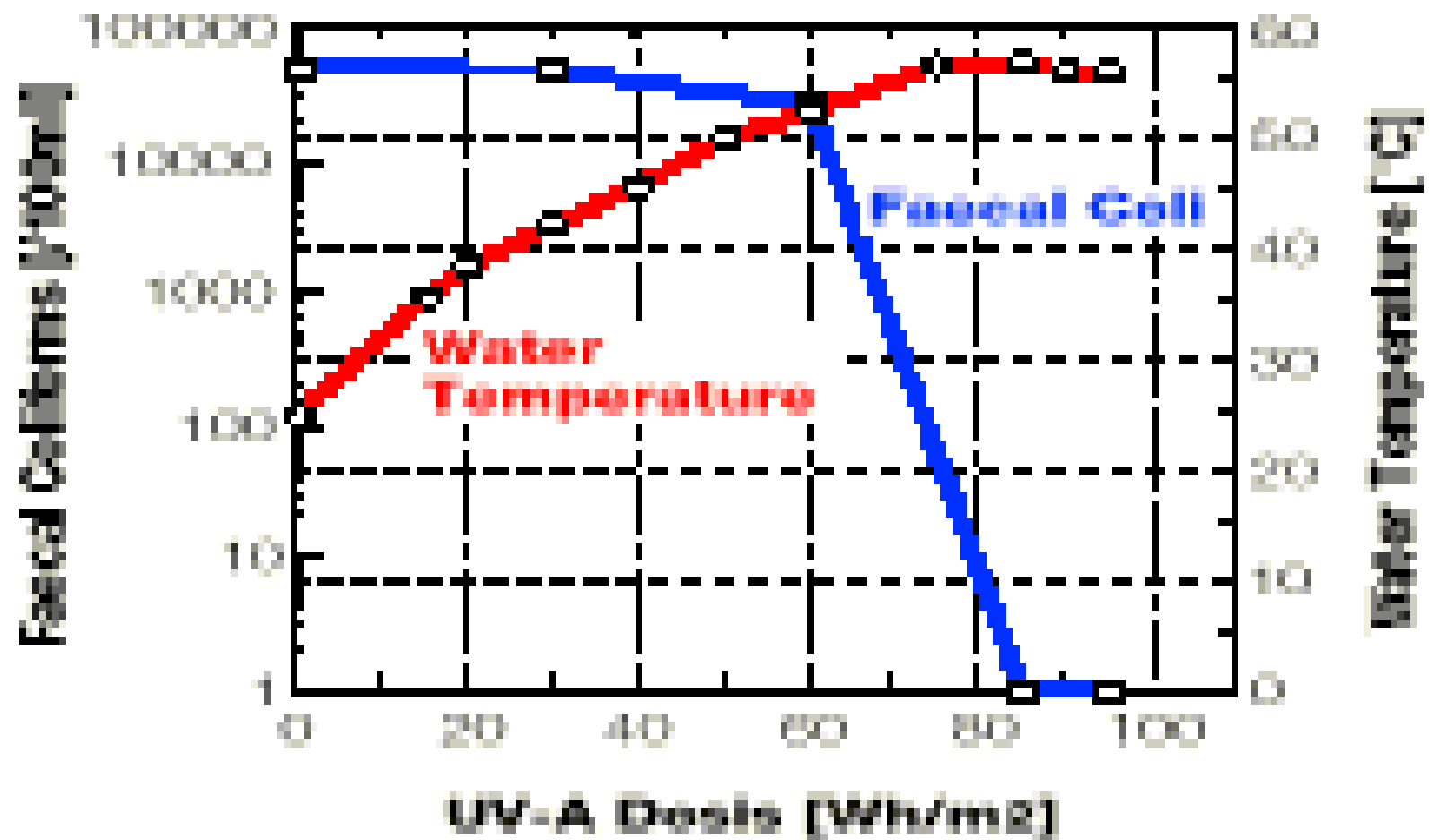
clear plastic bottle

Removal of solids
by sedimentation

Inactivation of micro-
organisms by UV radiation
and thermal treatment

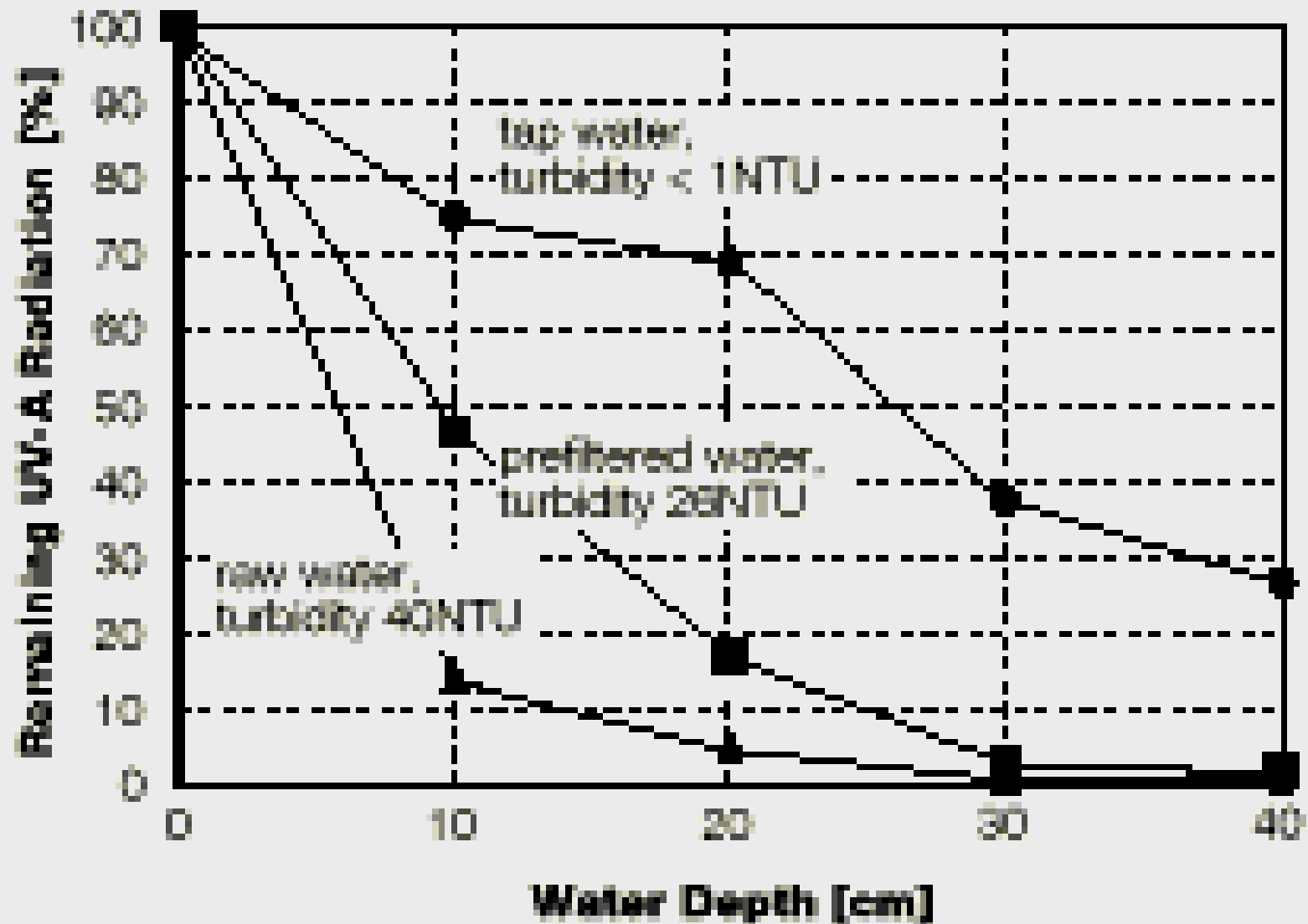
Limitations of SODIS

- does not change the chemical quality of the water quality
- does not change water quantity
- not useful to treat large volumes of water
- requires relatively clear water (turbidity <30 NTU)
- needs solar radiation: exposure times:
 - 5 hours under bright sky or up to 50% cloudy sky
 - 2 consecutive days under 100% cloudy sky



Inactivation of Faecal coliforms with half-coloured PET-bottle

UV-A Radiation as a Function of Depth and Turbidity



Escherichia coli

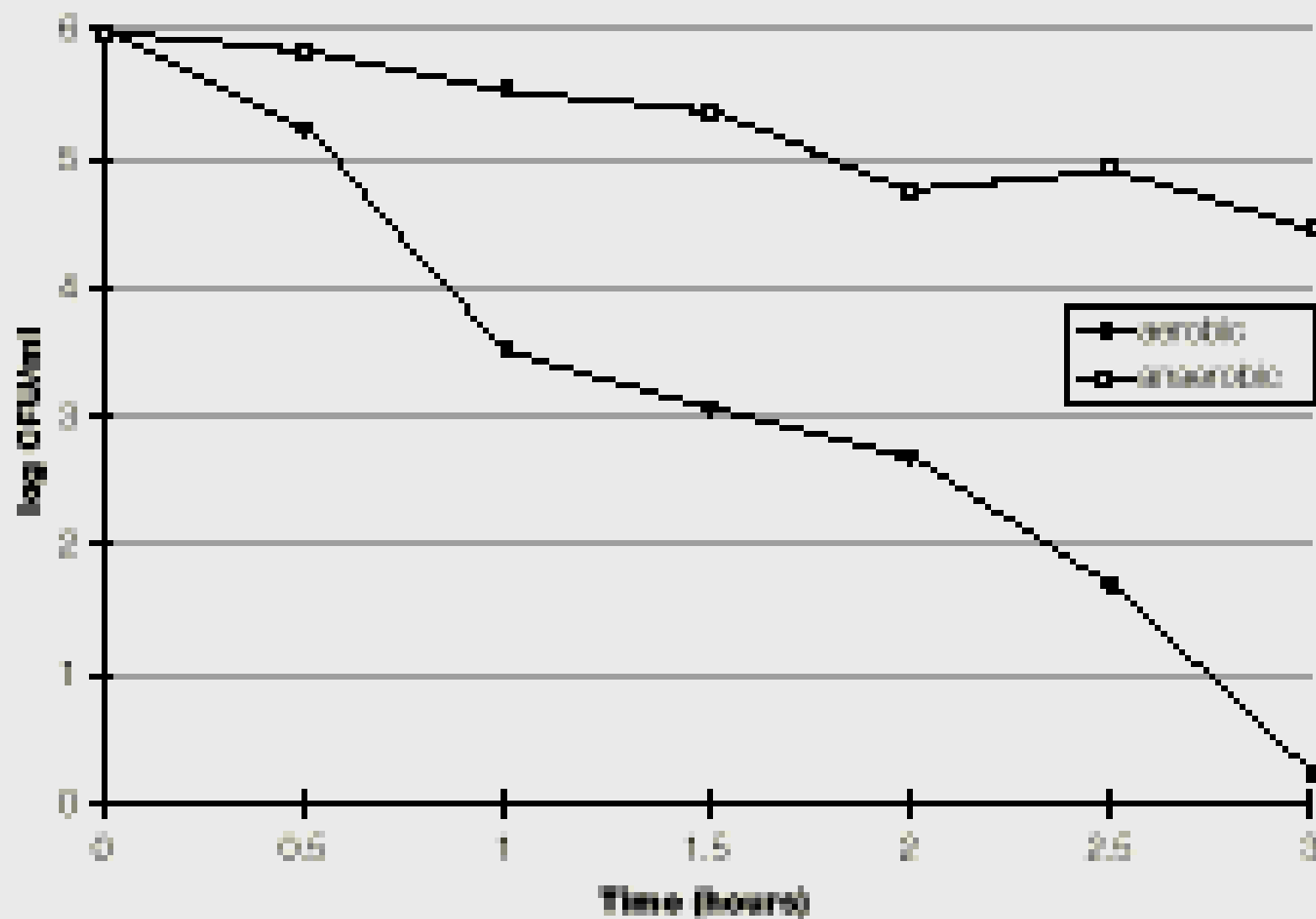


Figure 1: Inactivation under aerobic and anaerobic conditions

Enterococcus faecalis

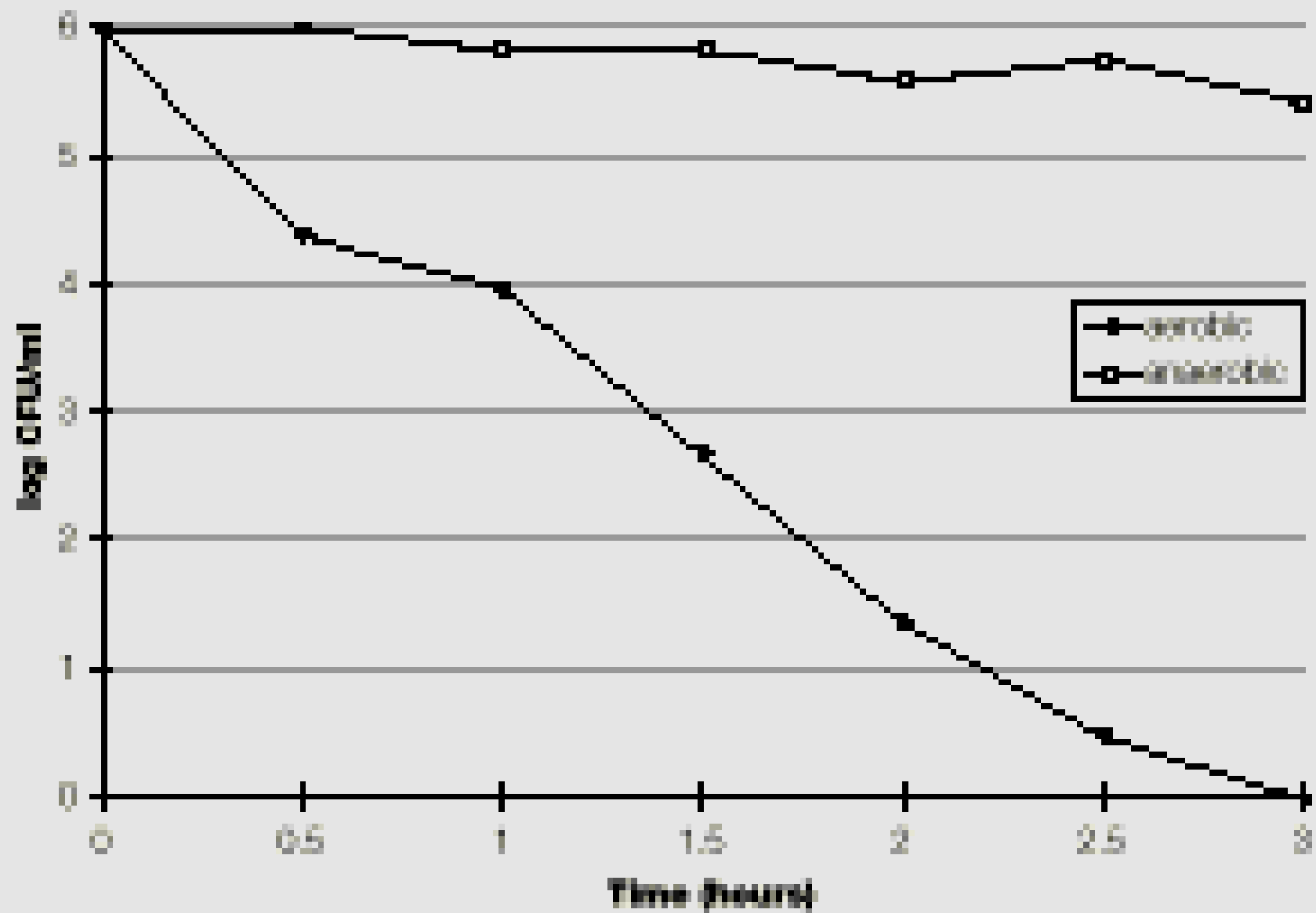


Table 2: Thermoresistance of micro-organisms

Microorganisms	Temperature for 100 % Destruction		
	1 Min.	5 Min.	60 Min.
Enteroviruses			62 °C
Rotaviruses			63 °C for 30 Min.
Faecal Coliforms	at 60 °C complete destruction		
Salmonellae		62 °C	58 °C
Shigella		61 °C	54 °C
Vibrio Cholera			45 °C
Entamoeba Histolytica Cysts	57 °C	54 °C	50 °C
Giardia Cysts	57 °C	54 °C	50 °C
Hookworm Eggs and Larvae		62 °C	51 °C
Ascaris Eggs	68 °C	60 °C	57 °C
Schistosoma Eggs	60 °C	56 °C	50 °C
Taenia Eggs	65 °C	53 °C	51 °C

Figure 1: Synergetic effect of UV-radiation and temperature on Faecal coliforms in raw water.

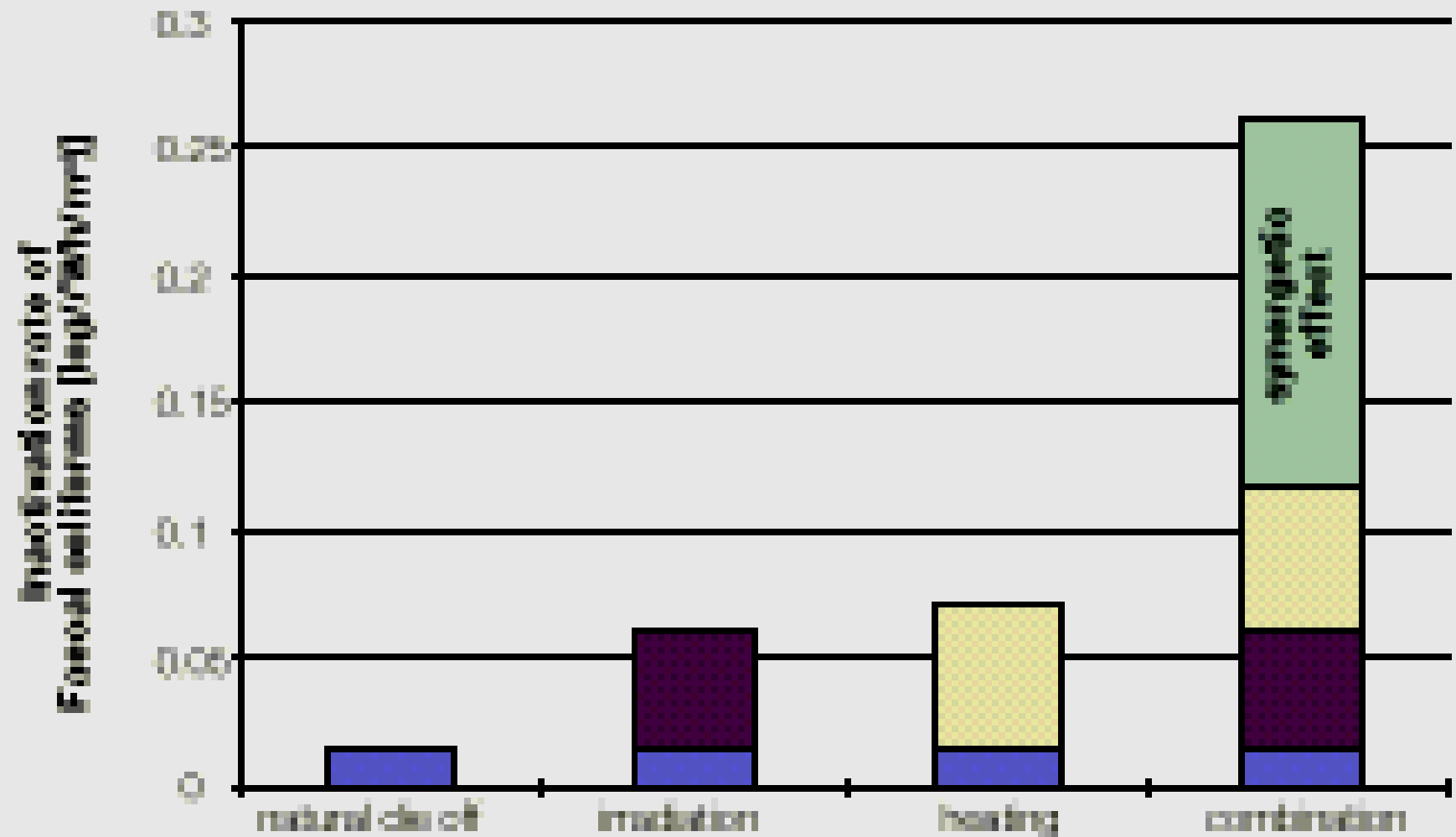
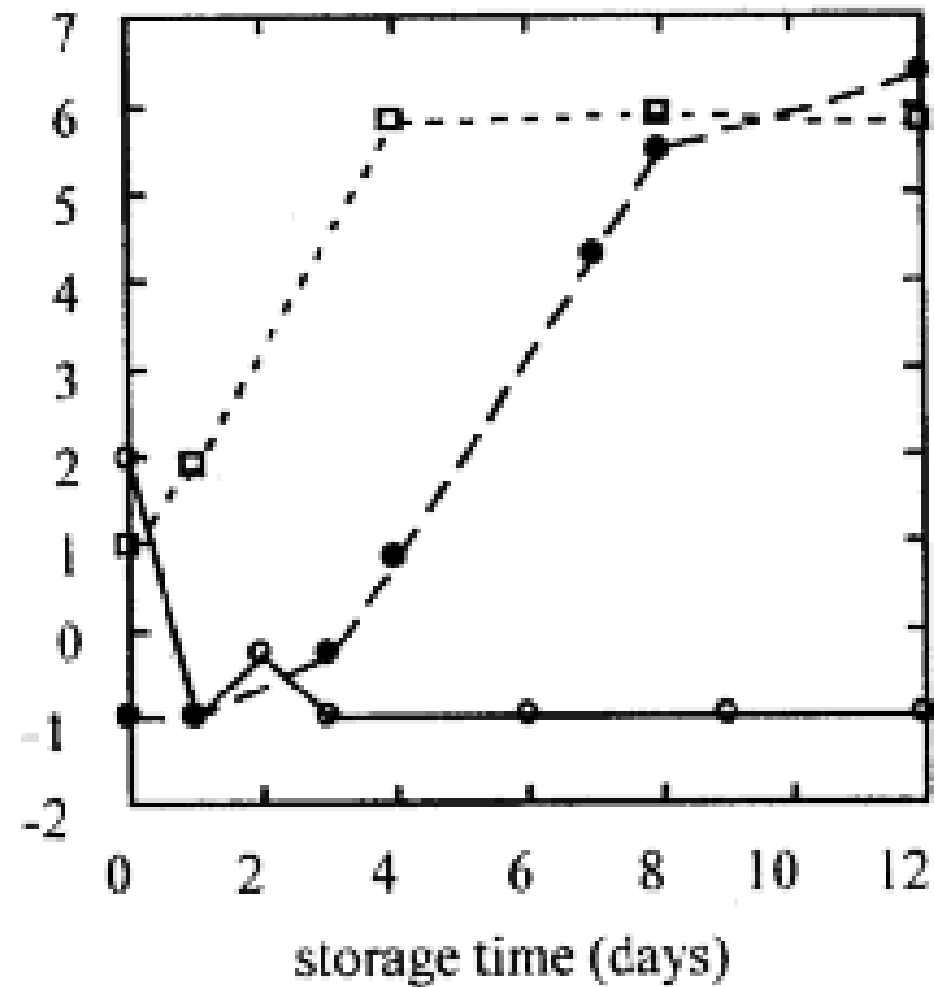
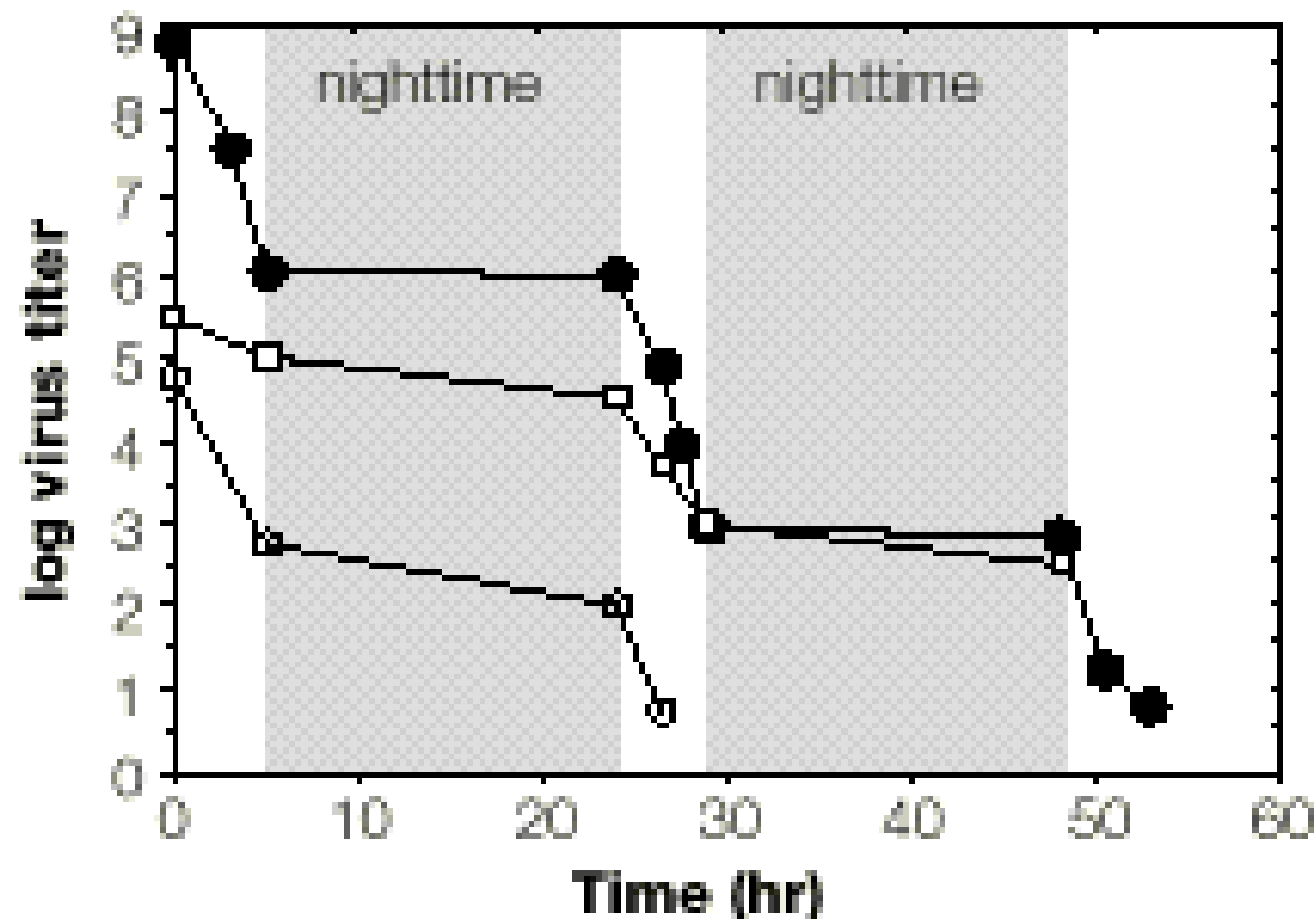


Figure 2: Regrowth of *E. coli* and bacterial mixtures during increasing storage time of the irradiated suspensions.



- *E. coli* irradiated using the undoped lamp and 320 nm cut-off filter
- *E. coli* irradiated with sunlight
- bacterial mixtures irradiated with sunlight

Figure 1: Prolonged SODIS operation (3 days) of ● coliphage 12 and the animal viruses □ EMCV and ○ rotavirus.



SODIS Exposure Procedure

- **Fill the bottles completely with raw water**
- **Screw the plug tightly**
- **Expose the bottles in the morning hours to sunlight on a place which is irradiated the full day**
- **Place the bottles in horizontal position on a firm blackened support, preferably on a corrugated iron sheet/roof or on a tile roof**
- **Collect the bottles in the late afternoon and bring them to a safe place for cooling**

SODIS Exposure and Use Procedures

- **Consume the treated water directly from the bottle using a clean glass or a cup**
- **Store it possibly overnight for additional cooling one hour once the water temperature has reached 50 °C.**
- **At high ambient temperatures and intensive sun radiation one might be able to use the containers two times a day.**
- **Expose the water for five hours during a sunny day in case the water temperature has not reached the required 50 °C. Should the sky be covered with clouds expose the water for two consecutive days before consuming it.**
- **Collect rain water from a clean area (e.g. from a corrugated or tile roof) during rainy days to cover drinking water demand.**

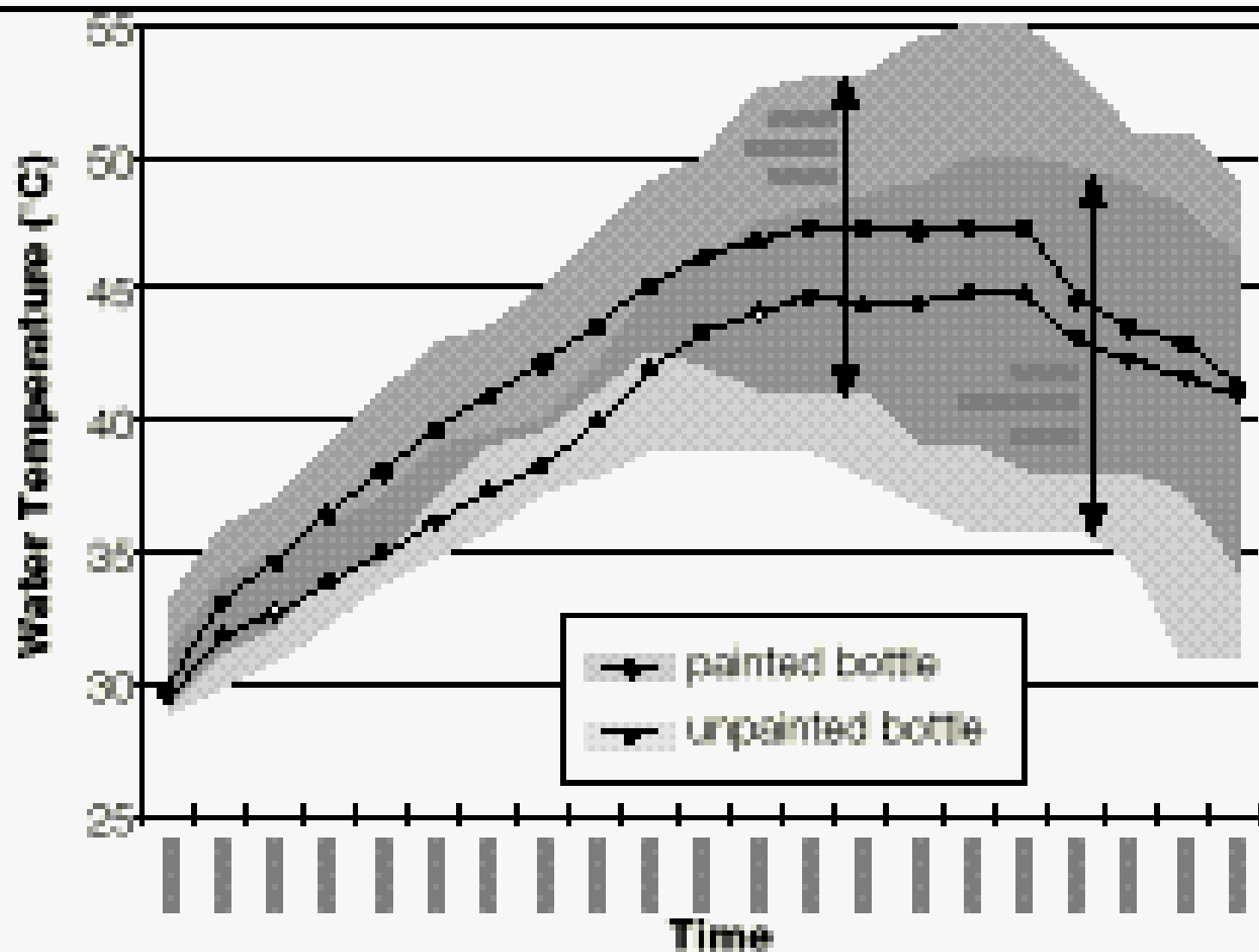


Figure 1. Comparison of water temperature in half-blackened SODIS bottles and clear bottles (cement floor, no black zinc sheet, no wind protection).

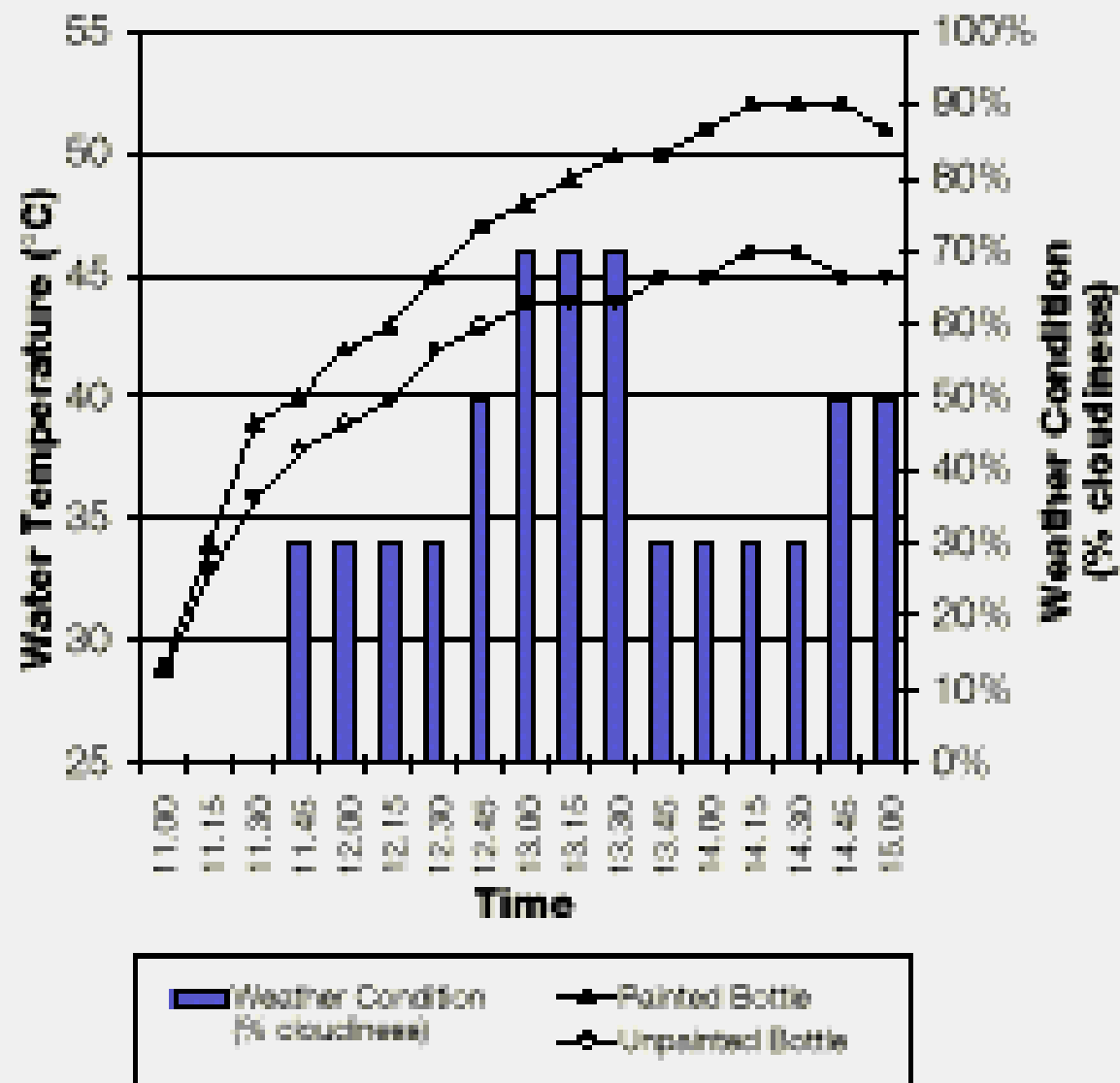


Figure 2. Water temperature in painted and unpainted SODIS bottles placed on a black zinc sheet. The bars illustrate the cloudiness.