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AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

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ABSTRACT

Literature evaluating the potential use of gamma radiation for the treatment of sewage is critically reviewed. It is concluded that irradiation treatment cannot contribute significantly to the improvement of conventional processes for sewage water recovery. Irradiation methods at present have no cost or technical advantage, and no proven biological advantage over known treatment systems.

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The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA–INIS–12 (INIS: Manual for Indexing) and IAEA–INIS–13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

CHARGES; CHEMICAL RADIATION EFFECTS; COST; ESCHERICHIA COLI; GAMMA RADIATION; LIQUID WASTES; PHYSICAL RADIATION EFFECTS; RADIATION DOSES; WASTE PROCESSING; WATER

CONTENTS

1. INTRODUCTION

The authors of this paper constituted a working party established to undertake, as a Research Establishment task, a critical assessment of sewage treatment with gamma radiation. The request was initiated by publication of a report from Energy Systems Incorporated of Florida, USA, claiming advantages for a cobalt-60 irradiation step in the process of recovering useful water from sewage. Other publications on this subject are of more interest than the Energy Systems Incorporated report, and the field has been the subject of a 'watching brief' by Irradiation Research Section of Isotope Division for several years.

The subject was considered under the main headings:

1. Costs in relation to conventional water production and recovery.
2. The physical and chemical effects of radiation on waste water in relation to purification and recovery.
3. The effect of gamma radiation on the microbiology of sewage and waste water.

In making the survey during 1970-71, the authors had valuable assistance from other Research Establishment staff who contributed detailed assessments and bibliographies now reproduced in full in the Appendices.

The general consensus of published work on this subject is that a dose of approximately 100,000 rad should be used in sewage treatment. The effects quoted in the Energy Systems Incorporated report are also consistent with a 100,000 rad dosage.

2. COST OF WATER PRODUCTION AND RECOVERY

Water costs are difficult to assess on a true economic basis. Existing charges (as distinct from costs) have been built up by individual communities on a historical basis and probably do not reflect the true costs incurred in providing the service. The scale of costs and charges appears to be very wide, ranging over three decades; irrigation water can be purchased for as little as \$1/acre-foot (approximately \$1/dam^3) in the Murrumbidgee Irrigation Area of New South Wales, whereas potable water could cost \$1,000/acre-foot (approximately \$1,000/dam^3) if produced by a small desalination plant for stock-watering purposes. Examples of this range of costs are given in Tables 1 and 2 and Figures 1 and 2. It is interesting that specialists in the water field insulate irrigation and domestic water from one another by refusing to discuss domestic water costs in \$/acre-foot (approximately \$/dam^3), or irrigation costs in ¢/1,000 gallons (¢/m^3). Nevertheless, comparisons do appear to be useful and revealing.

In large Australian cities and small municipalities, charges for potable water range over 10¢ to 30¢/1,000 gal (2¢ to 6¢/m^3). This ranges from two or three to a hundred times the charge for irrigation water. By comparison, the additional cost of 'polishing' normally-treated sewage effluent to potable standards is about 10¢/1,000 gal (2¢/m^3) for reasonable-size plants (approximately equalling the more costly irrigation water). Such water could safely be fed directly into reservoirs for subsequent treatment by the normal water treatment processes employed for domestic supplies. However, only in exceptional cases is polished sewage effluent fed directly into domestic water supply stocks. At Windhoek in South West Africa this is done, with 30 per cent of the total supply being treated sewage effluent. In the United States treated sewage effluent (10¢/1,000 gal (2¢/m^3)) is used to recharge aquifers, but it is understood that the water subsequently recovered is used only for industrial purposes.

There are indeed numerous schemes in which polished sewage effluent is used directly for industrial purposes, one notable example being at a metallurgical plant near Bristol, UK , where a mutually beneficial financial arrangement between the company and the local authority results in an industrial water cost of about 10¢/1,000 gal (2¢/m^3) compared with 30¢/1,000 gal (6¢/m^3) for normal domestic quality supplies. Finally, it is thought unlikely that public opinion in Britain would accept direct feed of treated sewage effluent to reservoirs because, at slightly greater cost, alternative supplies are still available. Nevertheless, the intake of water from the Thames for London's water supply contains some 20 per cent of conventionally treated sewage effluent discharged at numerous points upstream, considerable psychological weight being given to the 'natural' treatment obtained during its sojourn in the river.

It has proved to be impracticable to obtain water costs for small remote communities in Australia by reference to central authorities (Water Research Foundation of Australia, Water Conservation and Irrigation Commission of New South Wales, Australian Year Book). It would be necessary to obtain the information from selected Local Authorities. However, the general impression gained is that small remote communities obtain water supplies from roof collection of rain-water, individual wells and storage tanks filled from tank-trucks. Sewage disposal is no problem, soakaways and septic tanks being the norm. Therefore, in this country it appears that very small communities do not require polishing of sewage effluents.

Some compact communities as small as 3,000 - 4,000 people, such as

Caloundra on the Queensland coast, now have sewage treatment plants but have no need to reclaim the effluent. It is possible that some special purpose communities, mining enterprises in particular, may consider using sewage effluent, but preliminary private enquiries (not confirmed) indicate that the larger mining centres of Mt. Isa and Broken Hill do not reuse effluent, having adequate supplies from dammed water storages. They have sewage treatment plants, but are believed to run the treated effluent to waste. It should be added that the volume flowrate of sewage effluent arisings could not compare with normal irrigation water supplies, but that in very special cases (*e.g.* Woomera) treated sewage effluent has been specially reticulated for use in horticulture.

Costs quoted in the Energy Systems Incorporated report (and other reports) are generally above conventional water costs for industrial and domestic use and far in excess of irrigation water costs. The lowest price quoted by Energy Systems Incorporated is 32.793 [*sic*] ¢/1,000 gal (7.214¢/m^3) and this is for a very large system with 40 years' amortisation. However, higher than average costs can be tolerated for small community domestic use, provided there is a guarantee that the product is potable water. It is also conceivable that specialised isolated industrial situations such as mining operations of high value products could tolerate much larger than average water costs.

Ballantine's publications in the USA (see Appendix C) on the subject of radiation treatment of sewage are reliable and his surveys have indicated the following minimum costs at the radiation source prices that presently apply:

Source of Radiation	Cost/1,000 gal - (¢) (at 10 Mgal/day production)	¢/m^3 (at 5 x 10^4 m/day)
Reactor fuel elements	158	35
Cobalt-60 (40¢ per curie)	104	23
Caesium-137 (20¢ per curie)	71	16
(12.5¢ per curie)	41	9
Accelerator	69	15
Reactor loop	13-30	3-7

There is not much prospect of the price of cobalt-60 falling below 40¢/curie, and the price of caesium-137 is likely to rise owing to a lack of general industrial interest. The USAEC has made it available at a subsidised 12.5¢/curie for several years in an attempt, so far with little success, to stimulate industrial use. The figure of 12.5¢ is an estimate of the future economic price if the demand is high enough to justify large scale production. Cobalt-60 prices of about 10¢/curie and the price of caesium-137 at an unlikely 2¢/curie would be necessary to achieve approximately the present normal water costs for large demands.

It is concluded that conventional methods are available for 'polishing' normally treated sewage effluent at 10¢/1,000 gal (2¢/m^3), but that normal water supplies in Australia have so far been sufficiently cheap for resort to reclamation of sewage effluent for domestic use to be unnecessary. If reclamation becomes necessary or desirable in the future, it is unlikely that irradiation methods will be economically competitive.

3. PHYSICAL AND CHEMICAL EFFECTS OF RADIATION ON WASTE WATER

Ionising radiation will affect some of the physical and chemical properties of waste waters and the products of treatment processes. Beneficial effects which may be of most value are the radiation induced oxidation of organic substances, the modification of non-biodegradable (refractory) substances and the changes in properties of colloidal materials and sludges.

Waste water, both treated and untreated, generally contains organic waste matter in solution, colloidal suspension or suspension which may be biochemically oxidised over a period of time. If this water is discharged into a body of fresh water, then the oxygen content of the fresh water can be depleted to such an extent that fish die from lack of oxygen and eventually the fresh water may become septic. A measure of the capability of waste water to deplete the oxygen content of the receiving water is the five day biochemical oxygen demand value (BOD_5). Ionising radiation can reduce the BOD_5 value of a waste water, but the improvement is limited by the radiation chemistry of the reactions and the dissolved oxygen present in the waste water. It is considered that the reduction of BOD_5 by irradiation is not an economically competitive process.

Non-biodegradable (refractory) organic substances which may be present in waste water may include such substances as detergents, DDT, and other pesticides. These substances may pass through a conventional sewage treatment plant and have a virtually unchanged concentration in the effluent. Ionising radiation may modify the structure of these materials so that they become more biodegradable, but the effect is once again limited by the efficiency of the radiation induced chemical reactions. Since contaminating compounds are generally only present in low concentrations, it is considered that radiation treatment is not an alternative to chemical methods particularly as the dose proposed is only 100,000 rad.

The precipitation of colloidal material and an improvement in the settling and filtering characteristics of separated sludge can be achieved by irradiation. Since the volume of sludge handled in a sewage treatment plant is typically only one or two per cent of the total waste volume, and since sludge handling and disposal costs represent nearly half the cost of operation of a two-stage sewage treatment plant, then an improvement in sludge settling and filtering characteristics provided by irradiation could be worthwhile. It has been reported, however, that better results can be obtained more economically by dosing with small amounts of chemical conditioning agents.

There appears to be no supporting information in the scientific literature on this subject for the claims made in the Energy Systems Incorporated report on the chemical and physical effects of radiation on sewage. On the basis of general information available it is difficult to believe these claims unless some novel unrevealed stage has been incorporated in their process, and this process enhances the desired effects so that the improvements in treatment are significant.

Recovery of waste water implies a high percentage of continuous recycling in a closed system. Irradiation purification of sewage in such circumstances has a disadvantage common to most or all systems; the treatment does not reduce the inorganic soluble salts of sewage and their buildup seriously restricts the amount of recycling possible, limiting the percentage of purified sewage water which can be incorporated in the system.

4. MICROBIOLOGICAL CONSIDERATIONS

Raw sewage may contain on average up to 4×10^7 coliforms/mℓ; 10^6/mℓ or more may be *Escherichia coli* and average 500 virus units/100 mℓ. The coliform level may be reduced 100-fold in secondary treatment. Primary sedimentation has little effect on removing viruses but up to 80 per cent may be removed by activated sludge and secondary sedimentation treatments. Water contaminated from sewage has apparently been responsible for many viral outbreaks.

The World Health Organisation (WHO) and health departments of many countries have set microbiological criteria for potable water in terms of a coliform count/100 mℓ. For treated water (chlorinated) no sample should have a coliform count greater than 10/100 mℓ. For untreated water the count should never be greater than 20/100 mℓ. Water is excellent when the coliform count is zero. It is satisfactory when the coliform count is 1-3/100 mℓ, the *E. coli* count being zero, and unsatisfactory when the coliform count is greater than 10 and *E. coli* are detectable.

The radiation inactivation of microorganisms is usually a first order process, a population being reduced ten-fold for equal increments of dose. Large variations occur in the radiation resistance of microorganisms within a genus, and for different species depending on the environmental conditions. Generally, viruses are more resistant than bacterial spores, which are more resistant than fungi and vegetative microorganisms. The choice of dose for a given process therefore requires a knowledge of the numbers and types of contaminating organisms and the degree of kill required.

It is apparent, from the few microbiological investigations associated with the literature on radiation treatment of sewage, that the experiments were designed to evaluate the dose required to meet the criteria for coliform and *E. coli* contamination. This approach is questionable and unsatisfactory because the count for both types of organisms, being among the most sensitive to radiation, will be reduced by several orders of magnitude at a dose which will only marginally inactivate more resistant pathogenic organisms. The WHO criteria for treated water are based on many years' experience with conventional water supplies. The imbalance which would arise using a radiation dose sufficient to meet the coliform count requirements could lead to false assessments of the safety of the treated water.

The investigations which have been made show that 50,000 to 100,000 rad can be satisfactory for coliforms and *E. coli* but the results reveal an imbalance and suggest that higher doses (500,000 rad) are required to reduce the numbers of resistant microorganisms by several orders of magnitude. These considerations are basic to any assessment of the use of radiation for decontaminating sewage for water reclamation because the cost is directly dependent on the choice of radiation dose. The larger the dose the less must be the cost of the radiation source to compete with alternative methods using chlorine and ozone. These conventional processes have the advantage of many years' practical experience. Before radiation can compete it needs to be demonstrated that it is at least as efficient as the alternatives for control of gross microbial contamination.

The use of chlorine or ozone is not without problems. Chlorine does not efficiently destroy many spores, viruses, worms and nematodes. Chlorination at the levels used is probably inadequate to ensure virus free water. Ozone has more effect on spores, parasites and polio viruses than chlorine and is less affected by pH than chlorine for which there is a direct relationship. However, taste and odour changes limit the concentration of chlorine and ozone which can be usefully employed, a disadvantage which would not apply to irradiation treatment. The presence of turbidity and dissolved chemicals can alter the bactericidal efficiency of chemical methods which is a disadvantage compared with a radiation treatment which may not be as dependent on the degree of chemical or solid contamination. Technical interest in radiation will depend on continued acceptabilities of chlorination or ozone treatments.

5. CONCLUSIONS

At the present time, there is little in the literature on this subject to indicate that irradiation treatments can contribute significantly to the improvement of presently accepted methods of sewage water recovery. There is no great inclination yet to accept conventional recovery systems for domestic use and the whole literature on the irradiation plants is evasive on this issue. Sweeping and comprehensive statements on the lethality of radiation to viruses, particularly in the Energy Systems Incorporated report, cannot be validly substantiated, particularly at 100,000 rad, and this is probably why this report suggests, rather than definitely claims, potability of the product.

The danger of reliance on the coliform count as an indicator of effective sewage treatment must be emphasised. At best this test is a 'dilution analysis' technique for estimating untreated sewage contributions in drinking waters. When the sewage has been pretreated by a disinfecting system of any type to which different organisms are differently susceptible, the coliform count on the final product can give dangerously misleading indications about the possible pathogenic bacterial and viral concentrations. For this reason we are of the opinion that the dose of 100,000 rad, commonly mentioned for sewage treatment, is not adequate. As the radiation cost is a major factor, a significant dose increase would make this method even more economically unfavourable.

There is no indication that radiation doses economically applicable to water supplies will have any significant effect on the degradation of pesticides and detergents present and the cost of all quoted irradiation techniques makes the process unacceptable for all but particularly selective circumstances. It may be useful in small isolated communities requiring careful conservation of water used for valuable industrial operations or domestic use, but it is likely that the already evident public disinclination to reuse sewage water would be the major factor militating against its acceptance. Such acceptance may not come until forced by supply exigencies. This situation does not seem to exist yet.

Finally, it is considered that the Energy Systems Incorporated report is substantially speculative with little in the paper or in the current literature to substantiate its apparently conclusive claims. Irradiation methods have at present no cost advantage, no proven technical advantage and no proven biological advantage over known treatment systems and may have a psychological disadvantage owing to the still prevalent public suspicion of all things associated with ionising radiation.

The subject should be continued to be surveyed but at this stage a detailed expensive study is not recommended.

TABLE 1

SOME REPRESENTATIVE WATER COSTS

(Expressed in $A or $US : no conversion has been attempted)

Item	Water Type	Cost to Purchaser*				Remarks	Reference
		\$/acre foot	\$/dam^3	¢/1,000 gal	¢/m^3		
	Irrigation Water						
1	To farmers in Victoria, 1947	1	0.81	0.3	0.066	$0.6 - $1.0/acre foot $0.49 - $0.81 fodder production	Water Research Foundation of Australia (1961) - Report No.2 (March) p.7.
2	Typical in Australia, 1970	2	1.62	0.6	0.132		Clark, C. (1970) - Sydney Morning Herald (15 November)
3	Typical cost in USA	39	31.62	12	3.17 US		Water Research Foundation of Australia (1969) - Report No. 30 (May) p.3.7.
4	Irrigation land in California could pay	10	8.11	6	1.59 US	$6 - $20	Clark, C. (1970) - Sydney Morning Herald (15 November)
5	Irrigation land in Australia could pay	7	5.68	2	0.44	$6.3/1,000 acre, $7.8/300 acre farm .	Clark, C. (1970) - Sydney Morning Herald (15 November)
6	Keepit dam project: Upper estimate	22.8	18.48	7	1.54	7% sinking fund on dam	Clark, C. (1970) - Sydney Morning Herald (15 November)
7	Keepit dam project: Lower estimate	10	8.11	2	0.44		
8	Bradfield plan, Queensland	24	19.46	7.4	1.63	Updated to 1961, £12/acre foot	Water Research Foundation of Australia (1961) - Report No 2 (March) p.7.
	Potable Water						
9	Typical cost in USA	114	92.42	35	9.25 US		Water Research Foundation of Australia (1969) - Report No.30 (May) p.3.7.
10	Typical cost in Australian cities - Sydney	98	79.45	30	6.6		Australian Year Book, (1969) - No.55, p.794.
	- Melbourne	65	52.7	20	4.4		
	(Gumly Irrigation Area) - Riverina	32	25.94	10	2.2	20¢/1,000 gal for first 20,000 gal.	Water Conservation & Irrigation Board of NSW. Charges Schedule for Irrigation Areas and Districts.
	Representative Cost of Dam Supply in USA						
	Mgal/d Impound Treat Move (10 miles)						
11	0.1 8.8 55.0 31.7	310	251.32	95.5	25.23 US	Transport cost proportional to distance	Spiegler, K.S. ed. (1966) - Principles of Desalination. Academic Press, New York.
12	10.0 2.7 11.0 3.1	55	44.59	16.8	4.44 US		
13	100.0 2.0 8.0 1.2	36	29.19	11.2	2.96 US		
	Desalination						
14	Very large nuclear plants, 1,000 Mgal/d, 1980	39	31.62	12	2.64	Note this is the same as item 3	Gall, S.C. (1970) - Symp. on Water Aspects of Energy Distribution, Sydney 24-25 August.
15	Large plant, 100 Mgal/d, 1980	66	53.51	20	4.4		
16	Medium plant, 10 Mgal/d, 1970	163	132.15	50	11.0		
17	Small plant, 5 Mgal/d, 1970	260	210.79	80	17.6		
18	Waste heat, oil refinery, 1 Mgal/d	163	132.15	50	11.0		Water Research Foundation of Australia (1961) - Report No.3 (November).
19	Very small portable plant, 8,400 gal/d	1,140	924.21	350	77.0	Diesel, possibility for stock watering, 12 year life, 50% load	
	Treatment of Sewage for Reuse						
20	Treated water fed to aquifer, 100 Mgal/d	33	26.75	10	2.2	Proposed extension to Los Angeles project	Water Research Foundation of Australia (1966) - Report No.23 (August) p.68.

* *1 acre foot* ≡ 325,852 gal (US) ≡ 271,327 gal (Imp).

Mgal/d - Million gallons per day

$/acre foot ≡ *0.307 x ¢/1,000 gal (US).*

$/acre foot ≡ 0.369 x ¢/1,000 gal (Imp).

$/acre foot ≡ 3.26 x ¢/1,000 gal (US) ≡ 2.71 x ¢/1,000 gal (Imp).

1 acre foot ≡ 1.23348 dam^3.

¢/1,000 gal (Imp) x 0.22 ≡ ¢/m^3.

¢/1,000 gal (US) x 0.264 ≡ ¢/m^3.

TABLE 2

UTILISATION OF SALINE WATER*

SOME SOUTH AUSTRALIAN MUNICIPAL WATERS

A Recent 5-Year Average

Source		Total Hardness as $CaCO_3$ (ppm)	Permanent Hardness as $CaCO_3$ (ppm)	Dissolved Solids (ppm)
Happy Valley Reservoir				
Range	Average	122	48	315
	Minimum	88	28	205
	Maximum	164	69	476
Mannum Adelaide Pipeline				
Range	Average	109	39	364
	Minimum	52	1	116
	Maximum	185	90	717
Blue Lake Reservoir				
Range	Average	186	18	365
	Minimum	176	9	349
	Maximum	198	24	377
Todd River Reservoir				
Range	Average	529	362	2,387
	Minimum	250	165	1,089
	Maximum	700	515	3,197

SALINITY LIMITS IN DRINKING WATER OF LIVESTOCK

Livestock	Total Soluble Salts	Magnesium	
	(ppm)	(ppm)	(meq./litre)
Poultry	3,500	-	-
Pigs	4,500	-	-
Horses	6,000	250	21
Cows in milk	6,000	250	21
Ewes with lambs	6,000	250	21
Beef cattle	10,000	400	33
Adult sheep on dry feed	14,000	500	42

ESTIMATED DESALINATION COSTS FOR SOUTH AUSTRALIA

Output 8,000 to 10,000 gallons per day

	Feed (ppm)	Product (ppm)	Installed Cost ($)	Operating Cost ($/1,000 gal)	Total Cost ($/1,000 gal)
Flash distillation	35,000	10	53,000	7.3 *(b)*	9.0
Vapour compression	35,000	10	70,000	2.8 *(a)*	5.0
				5.9 *(b)*	7.3
				1.5 *(c)*	4.2
Reverse osmosis	35,000	500	50,000	3.4 *(a)*	5.2
				5.7 *(b)*	7.2
Reverse osmosis	35,000	4,000	30,000	2.1 *(a)*	3.1
				3.5 *(b)*	4.4
Reverse osmosis	2,500	500	20,000	1.4 *(a)*	2.1
				2.2 *(b)*	3.0
Electrodialysis	2,500	500	31,000	1.0 *(a)*	2.4
				1.8 *(b)*	3.1
Ion exchange	1,500	400	20,000	0.9	1.6
Solar distillation *(d)*	18,000	10	75,000	2.1	9.2

* *After Blesing, N.V. Wilmshurst, R.E. & Melbourne, J.D. (1969) - Utilisation of Saline Water: The Role of Desalination. Symp. on Technical Aspects of Saline Water, Adelaide. Water Research Foundation of Australia Report No.29.*

(a) Power 2¢ per kWh.

(b) Power 5¢ per kWh.

(c) Diesel operated.

(d) At Coober Pedy producing 3,500 gallons per day.

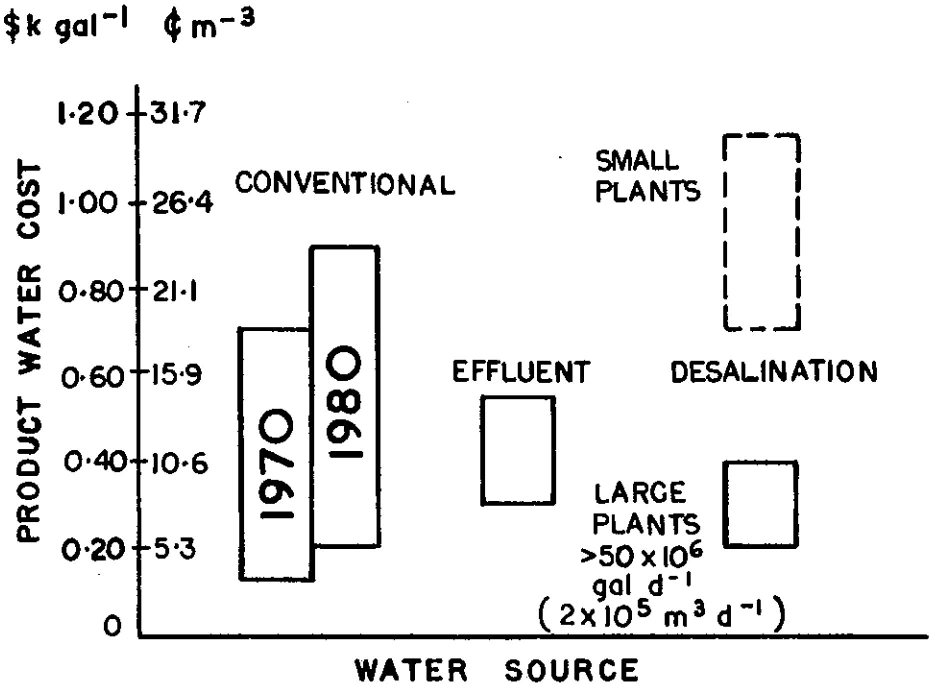

FIGURE 1. COST OF WATER IN U.S.A. FROM THREE ALTERNATIVE SOURCES*

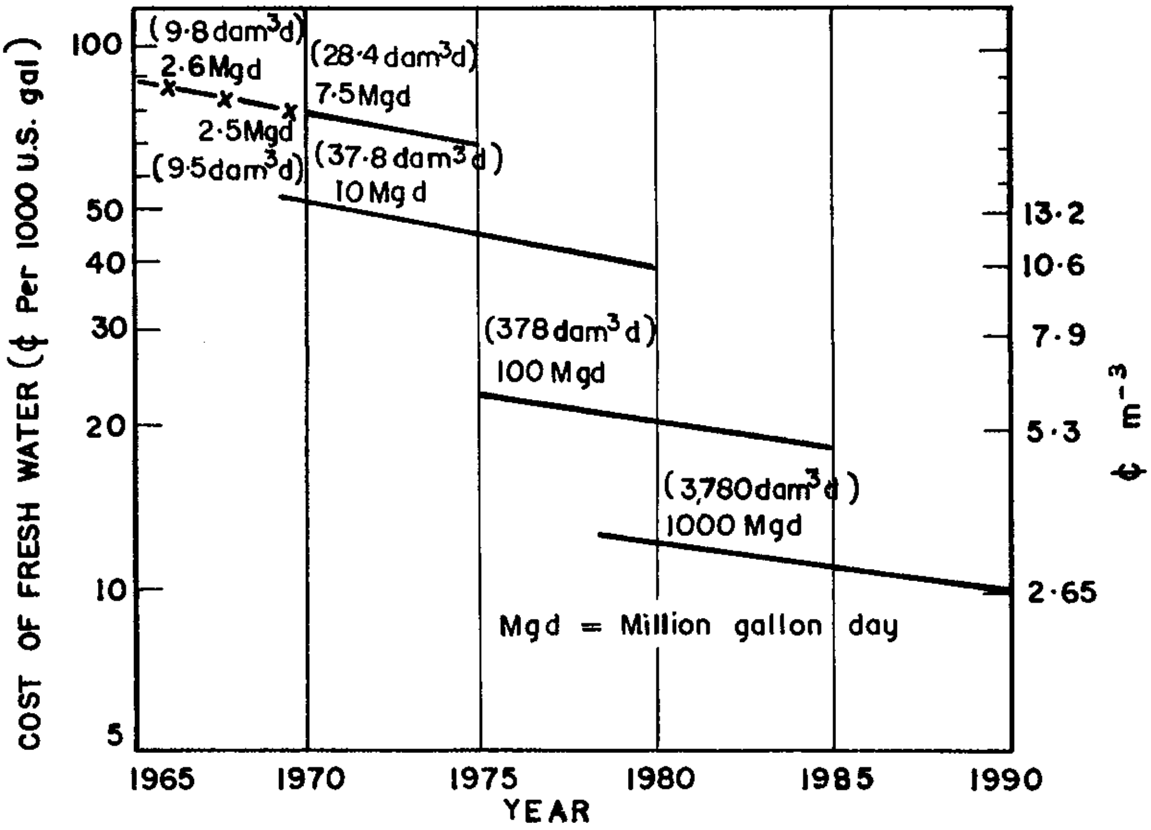

FIGURE 2. EXPECTED COSTS OF WATER FROM DESALINATION PLANTS*

(* Source: Gall, S.C. (1970) - Symp. on Water Aspects of Energy Distribution, Sydney, 24-25 August).

APPENDIX A

THE USE OF RADIATION IN SEWAGE AND WASTE WATER TREATMENT - CHEMICAL ASPECTS

by

D.F. Sangster

A1. SUMMARY

A survey of recent literature dealing with chemical aspects of use of radiation in sewage and waste water treatment shows no decided advantages over conventional methods except perhaps in special circumstances. The general consensus is that the processes are uneconomic.

A2. DRINKING WATER STANDARDS

According to World Health Organisation standards the chemical requirements of drinking water are:

(a) less than stipulated levels of toxic chemical substances;
(b) absence of substances which may affect health;
(c) absence of significant levels of unacceptable chemical compounds such as those affecting taste;
(d) absence of certain chemical substances which are ancillary indicators of pollution.

The following comments can be made on each of these, (a) - (d), if radiation is used to replace secondary (biological) treatment or as a tertiary treatment:

(a) Some toxic substances, in particular, inorganic heavy metal ions, will not be removed by irradiation.
(b) Fluoride and nitrate levels would also be unaffected.
(c) The list given is mainly inorganic but may affect taste, odour and possibly colour and turbidity. Other odour and taste-producing substances in water which may be affected by radiation include phenolics, DDT, parathion and synthetic detergents.
(d) These substances have no effect on health, acceptability or attractiveness of water.

A3. ADVANTAGES OF RADIATION

The following physical or chemical benefits have been advanced in proposals for using radiation in waste water treatment:

- Radiation-induced oxidation of organic substances (industrial wastes, insecticides) reducing chemical oxygen demand (COD) and biochemical oxygen demand (BOD).
- Modification of non-biodegradable substances ('refractory' compounds) to make them biodegradable.
- Changes in colloidal properties (settling rate, filterability of sludges).

A4. EFFLUENT COMPOSITION

The composition of waste water will depend on the sources - domestic, industrial or agricultural. There is no such thing as a known typical composition but effluents from a large enough population complex will contain carbohydrates, amino acids and proteins, fatty acids, fragments of cell walls and other bacterial debris in addition to chemical compounds. Some of these may be biodegradable by wild or acclimated organisms. Some may be refractory. Some may be toxic to the treatment organisms.

Quite obviously in order to draw firm conclusions, experiments must be carried out on actual effluents.

A5. RADIATION OXIDATION

Limits for the G value for single electron oxidations can be estimated from our knowledge of radiation chemical reactions. In general a maximum value of $G \approx 10$ can be assumed. In favourable cases this may be increased up to sixfold. A dose of 10^5 rad, which is often assumed as the dose to be given to effluents, will therefore cause 10^{-3} M of dissolved one-electron reducing agent to react in aerated solution. This is equivalent to a chemical oxygen demand (COD) of 8 mg/ℓ (8 ppm).

Measurements on actual effluents show $G(-O_2) = 2 - 3$ and an initial reduction in COD corresponding to $G = 10$ for effluents continuously aerated during irradiation. On further irradiation the G value decreased.

A6. LUCAS HEIGHTS EFFLUENT

The Lucas Heights COD limit set by the Maritime Services Board for the potassium permanganate test is 5 mg/ℓ (5 ppm) for the 15 minute test and 15 mg/ℓ (15 ppm) for the 4 hour test. Actual measurements show that effluent, after treatment and approximately three to one dilution, is about one half of this value.

Biological treatment of sewage by an activated sludge treatment usually reduces the COD by a factor of about 10. This means that a dose of something greater than one Mrad would be required if the secondary treatment were omitted.

A7. REFRACTORY COMPOUNDS

Some preliminary experiments have indicated that some non-biodegradable compounds, such as DDT, might be modified by irradiation. These are subject to competition by other dissolved materials for the oxidising radicals *etc.*, so traces of these compounds in an actual effluent are unlikely to be affected by radiation.

A8. SLUDGE BENEFICIATION

Studies have been made on the effect of radiation on the filterability, settling rate and moisture content of the sludge. In some cases worthwhile results were obtained but they were variable. One investigation reported a threefold increase in the extent of dewatering under standard conditions, others reported little or no change.

No effects have been found which could not be achieved better (in a more flexible and more reliable manner) and more cheaply by chemical conditioners such as polyelectrolytes. Much research and development effort would be necessary to establish any chemical benefit from irradiation of sludges. Investigations along these lines are being pursued overseas.

A9. ECONOMICS

The general comment in the literature is that irradiation of sewage is not economic and that the same effect can be obtained more cheaply by other methods. Ozonisation is just as effective in its action on chemical contaminants and costs less.

The *total* cost of a conventional activated sludge process is 20¢/1,000 gal (Imp) (4.4¢/m^3).

By comparison the following lower limit costs have been calculated for radiation:

^{60}Co	$0.40 - 1.03/1,000 gal (8.8 - 22.7¢/m^3)
^{137}Cs	$0.71 - 3.00/1,000 gal (15.6 - 66.0¢/m^3)
Accelerator	$0.69/1,000 gal (15.2¢/$m^3$)
Reactor Loop	$0.13 - 0.30/1,000 gal (2.9 - 6.6¢/m^3)
Fuel Elements	$1.58/1,000 gal (34.8¢/$m^3$)

The only one of these that is doubtful is the last one where a charge has been made for the fuel elements. On a reactor site, cooling fuel elements may be available without charge. Costs then become the engineering costs of circulating the material near the radiation source. It is debatable whether fuel elements can be made available without charge for general processing of city effluent. Shielding, safety considerations and maintenance difficulties would complicate plant considerably and increase costs.

Refractory (non-biodegradable) pollutants can be removed by activated carbon absorption at a cost of less than 10¢/1,000 gal (Imp) (2.2¢/m^3).

The volume of sludge in a typical sewage treatment plant is about 1 per cent of the volume of incoming or outgoing water yet its handling and disposal accounts for about one half the total treatment costs. This area is therefore considered to be the most promising for application of radiation in waste water treatment. Any economic advantage may depend on special circumstances such as difficulties in disposing of sludge in heavily populated areas or the possibility of radioactive contamination. Reduction of the volume of sludge which has to be stored is then worthwhile.

A10. CONCLUSION

Whereas there could be marginal benefits in improving the chemical properties of effluents by radiation, studies to date have shown the technique to be uneconomic. Should consideration of biological aspects show further attention is warranted, it is recommended that a preliminary engineering cost study be made before embarking on experiments involving the irradiation of actual effluents.

APPENDIX B

FEASIBILITY STUDY OF THE IRRADIATION OF SEWAGE EFFLUENT FROM THE EPCO PLANT AT THE RESEARCH ESTABLISHMENT USING IRRADIATED FUEL ELEMENTS

by

P.A. Bonhote

B1. INTRODUCTION

Sewage at the AAEC Research Establishment is treated in an EPCO* extended aeration treatment plant which yields an effluent containing an average of 6 mg/ℓ (6 ppm) BOD and 10 mg/ℓ (10 ppm) suspended solids. A recent report (Woodbridge *et al.* 1970) indicates that gamma irradiation can effect a worthwhile improvement to the effluent from such a treatment process. This study examines the possibility of using irradiated HIFAR fuel elements in an inexpensive irradiator to treat the effluent from the existing treatment plant.

B2. BASIC DESIGN CONSIDERATIONS

From the above mentioned report it was calculated that the dose was 100,000 rad. This is a reasonable dose for this purpose and it has been used as the required dose in this study.

The sewage flow averages 400,000 gal/month (1,800 m^3/month), which is 555 gal/h (2.5 m^3/h) or 5,550 lb/h (2,517 kg/h). Although the sewage flow varies with time, it is necessary for the most economical irradiation that the flow rate be constant. This could be achieved by installing a holding basin before the irradiator.

From a report by Clouston (1964), 1 kilowatt of gamma energy is equivalent to 800 Mrad-lb/h (1,363 Mrad-kg/h). Our requirement is to treat 5,550 lb/h (2,517 kg/h) to 0.1 Mrad, *i.e.* 555 Mrad-lb/h (1,252 Mrad kg/h). Now 68,000 Ci of cobalt-60 will give one kilowatt of radiation at 100 per cent efficiency, so the required amount of cobalt-60 would be:

Imperial	S.I.
$\frac{555}{800} \times 68{,}000 = 47{,}000$ Ci	$\frac{1{,}252}{1{,}363} \times 68{,}000 = 47{,}205$ Ci

---

* *Manufactured by EPCO Pty Limited, Melbourne, Australia.*

If it is assumed that the efficiency will be not less than 80 per cent, then the requirement would be 59,000 Ci of cobalt-60, *i.e.* 148,000 gamma MeV Ci.

It is assumed that the irradiated fuel elements will first be used in the Building 23 Irradiation Facility before they are available for this use. They will then be at least one year cooled before use. Cook (1963) showed (his Figure 4) that one Dido-Pluto 150 g fuel element after one year's cooling delivers 2,000 gamma MeV Ci, thus approximately 74 one year old HIFAR elements would be required to deliver the required dose. However, such numbers of elements are never available at the same time because the normal fuel change in HIFAR is about six elements each four week operating period.

To establish the potential total gamma output from HIFAR elements at any point in time, the appended table was constructed making the following assumptions:

- Six elements are removed from HIFAR each operating period, and there are no extended shutdowns.
- Only elements cooled for one year (13 operating periods) and longer are to be used.
- The total gamma output data was taken from the report by Cook assuming that three periods at 15 MW in Dido or Pluto was equivalent to the 4 to 5 periods at 11 MW in HIFAR.
- Elements from one to three years cooled were assessed on the basis of individual HIFAR operating periods.
- Elements from three to nine years cooled were assessed on a yearly basis, using an average value for the output.

The table shows that on these assumptions a total of about 600 elements cooled for more than one year would be required to irradiate the sewage to 100,000 rad.

B3. FUEL ELEMENT SUPPLY

Suitable irradiated fuel elements stored at Lucas Heights are distributed as follows:

Location	Cooling Time	No. of Elements
Dounreay Flasks	5 years 5 months to 10 years 6 months	175
HIFAR Area and Building 23	10 days to 23 months	110
Building 27	1 year 11 months to 6 years 10 months	256
		TOTAL 541

Thus there would not be enough elements available at the AAEC Research Establishment to supply the irradiation requirement if the above assumptions were accepted. Even if enough elements were available, the sheer number required and the size of the resultant facility would make the proposal impractical.

B4. ALTERNATIVE UTILISATION OF FUEL ELEMENTS

In Section B2, it was assumed that elements would be used in the irradiation pond for their first year of cooling. If this requirement could be modified,then the radiation requirement for sewage treatment could easily be met. For instance, four elements used for the period from 10 to 40 days' cooling, or 42 elements used for the period from six months' to 12 months' cooling, would provide the required radiation dose. The use of these short cooled elements would, however, introduce problems in handling and transport which are discussed later.

B5. CONCEPTUAL DESIGN OF IRRADIATION FACILITY

It is considered that the design of the irradiation facility should be similar to the design of the existing storage facility in that the elements would be loaded vertically into tubes extending through a concrete shielding slab into an enclosed cavity through which the sewage would flow. Details of shielding, depth of cavity, geometry of tubes, *etc.* would have to be optimised after the cooling time of the elements had been established.

The facility would have to be served by a crane of capacity adequate to handle the transport flask used, and road access for the transporter would have to be provided. It may be possible to build the irradiator in a one module extension of the present storage facility at Building 27, in which case the road access and crane (limited to ~ 10 tonne capacity) is already available. However, a considerable amount of rock excavation and concrete work is involved, together with the provision of a holding basin, pipework, extension of the crane support structure and provision of the necessary tubes, shields and plugs.

B6. TRANSPORT OF IRRADIATED FUEL ELEMENTS

At present fuel elements are transported from the pond in Building 23 to the fuel storage facility at Building 27 in the General Purpose Waste Disposal Flask. When this flask contains 21-month cooled elements it has a surface dose rate of about 200 mrem/h. It is estimated that for 12-month cooled elements the surface dose rate could be from 600 mrem/h to 1 rem/h, while for six-month cooled elements it could be in the range of 2-3 rem/h, and for 10-day cooled elements it could be in the range 30-40 rem/h.

However, these estimates do not take into account the changing energy spectrum for shorter cooled elements and could be out by an appreciable amount. To obtain more reliable figures it would be necessary to conduct trials.

The present safety approval permits transport of the flask with a surface dose rate of up to 1 rem/h. It is considered unlikely that this limit would be raised for routine operations.

Thus if regular transport of elements cooled for less than 12 months was envisaged, it would probably be necessary to construct a new transport flask. HIFAR flasks cannot be used because they are not suitable for carrying cropped fuel elements and they cannot be handled by the crane in Building 27. The ~ 10 tonne capacity of this crane poses a problem, and it may not be possible to construct a flask to transport ten-day cooled elements which would weigh less than ten tonnes.

B7. CONCLUSION

It is impractical to use HIFAR elements more than one-year cooled to irradiate the sewage flow at the Research Establishment to a dose of 100,000 rad. It would be possible to use shorter cooled elements if Isotope Division could release the elements and if a new transport flask were provided. However, because this would be a continuous process, a guaranteed supply of elements would be needed to ensure continuity of treatment to the required dose.

It is impossible to estimate costs until a decision on the availability of fuel elements is made, as the cost of the installation is directly related to the number of fuel elements required.

It must be realised that the data and estimates in this report have been presented only to establish the feasibility of the operation. Before any firm decisions are taken, a much more detailed analysis of the availability and gamma output of HIFAR fuel elements must be carried out.

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TABLE B1

CUMULATIVE TOTAL GAMMA OUTPUT OF HIFAR FUEL ELEMENTS

Cooling Time (HIFAR Periods)	No. of Elements	Average Output (MeV Ci)	Total Output (MeV Ci)	Cumulative Totals	
				MeV Ci	Elements
13	6	2,000	12,000	12,000	6
14	6	1,570	9,420	21,420	12
15	6	1,285	7,710	29,130	18
16	6	1,120	6,720	35,850	24
17	6	1,020	6,120	41,970	30
18	6	935	5,610	47,580	36
19	6	867	5,200	52,780	42
20	6	800	4,800	57,580	48
21	6	733	4,400	61,980	54
22	6	667	4,000	65,980	60
23	6	600	3,600	69,580	66
24	6	533	3,200	72,780	72
25	6	467	2,800	75,580	78
26	6	433	2,600	78,180	84
27	6	400	2,400	80,580	90
28	6	367	2,200	82,780	96
29	6	333	2,000	84,780	102
30	6	317	1,900	86,680	108
31	6	300	1,800	88,480	114
32	6	283	1,700	90,180	120
33	6	267	1,600	91,780	126
34	6	250	1,500	93,280	132
35	6	233	1,400	94,680	138
36	6	220	1,320	96,000	144
37	6	210	1,260	97,260	150
38	6	200	1,200	98,460	156
39-51	78	150	11,700	110,160	234
52-64	78	120	9,360	119,520	312
65-77	78	110	8,580	128,000	390
78-90	78	100	7,800	135,800	468
91-103	78	90	7,020	142,820	546
104-126	78	80	6,240	149,060	624

APPENDIX C

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by

Elizabeth A. Newland

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APPENDIX E

USE OF RADIATION TO DECREASE BACTERIOLOGICAL CONTAMINATION IN SEWAGE AND INDUSTRIAL WASTE WATERS

by

Pamela A. Wills

E1. INTRODUCTION

Many diseases in man can be caused by water-borne bacteria and other organisms. These include cholera, typhoid, paratyphoid, bacterial and amoebic dysentry, gastro-enteritis from *Salmonella* and *Pseudomonas*, poliomyelitis, hepatitis, Weil's disease, worms and flukes. Because of their small number, pathogenic bacteria and organisms are difficult to detect in a water supply, many being short-lived or else occurring infrequently and irregularly. Routine attempts to isolate pathogenic bacteria are thus not practicable to safeguard a water supply. Instead, evidence of pollution by the excreta of man or animals is indicated by the isolation of coliform organisms. Only one of the coliforms, *Escherichia coli*, is exclusively of faecal origin. *E. coli* is a natural inhabitant of the intestines and crude sewage contains some hundreds of thousands of organisms per cubic centimetre. As the number of pathogenic bacteria will normally be only one to a few hundred per mℓ., the risk of *E. coli*-free water containing pathogenic bacteria is reduced some thousands of times.

E2. MICROBIOLOGICAL STANDARDS

Microbiological standards for industrial wastes have apparently not been set but those for potable water are as follows:

E2.1 World Health Organisation

> " In 90% of the samples of *treated* (*i.e.* chlorinated) water examined throughout any year, coliform bacteria shall not be detected, or, the most probable number (MPN) index of coliform microorganism shall be less than 1.0. None of the samples shall have an MPN index of coliform bateria in excess of 10. "

The MPN index is the most probable number of coliform organisms in 100 mℓ of the original water.

> " An MPN index of 8-10 should not occur in consecutive samples. With the examination of five 10 mℓ portions of a sample, this would preclude three of the five 10 mℓ portions (an MPN index of

9.2) being positive in consecutive samples.

" In any instance in which two consecutive samples show an MPN index of coliform bacteria in excess of 8, an additional sample or samples from the same sampling point should be examined without delay. This is the minimum action that should be taken. It may also be desirable to examine samples from several points in the distribution system and to supplement these with samples collected from sources, reservoirs, pumping stations and treatment points. In addition, the operation of all treatment processes should be investigated immediately.

" In 90% of the samples of *untreated* water examined throughout any year, the MPN index of coliform organisms should be less than 10. None of the samples should show an MPN index greater than 20.

" An MPN index of 15 should not be permitted in consecutive samples. With the examination of five 10 mℓ portions of a sample, this would preclude four of the 5 mℓ portions (an MPN index of 16) being positive in consecutive samples. If the MPN index is consistently twenty or greater, application of treatment to the water supply should be considered.

" In any instance in which two consecutive samples show an MPN index of coliform organisms greater than 10, an additional sample or samples from the sampling point should be obtained immediately."

E2.2 UK Ministry of Health

" Coliform organisms shall not be detected in 100 mℓ of *treated* water. For *untreated* water the suggested classification is:

		Coliforms per 100 mℓ	*E. coli* per 100 mℓ
Class 1	Excellent	0	0
Class 2	Satisfactory	1-3	0
Class 3	Suspicious	4-10	0
Class 4	Unsatisfactory	> 10	0 or more

Throughout the year 50% of samples should fall into Class 1; 80% should not fall below Class 2; remainder should not fall below Class 3."

E2.3 US Public Health Service

" Coliforms shall not be detected in 90% of the 10 mℓ portions examined by the fermentation-tube method. The occasional presence of coliforms in three or more of the five 10 mℓ portions from a single standard sample is not allowed if it occurs in:

- (i) consecutive samples, collected daily,
- (ii) in more than 5% of the standard samples when twenty or more samples have been examined per month, and
- (iii) in one standard sample when less than twenty samples have been examined.

" For drinking water tested by the millipore filter method the arithmetic mean coliform density of all standard samples (at least 50 mℓ) shall not exceed one per 100 mℓ. Coliform colonies per standard sample shall not exceed three per 50 mℓ, four per 100 mℓ, seven per 200 mℓ, thirteen per 500 mℓ in:

- (i) two consecutive samples,
- (ii) more than 5% of the standard samples when twenty or more are examined per month,
- (iii) more than one standard sample when less than twenty are examined per month."

E3. BACTERIOLOGICAL METHODS

E3.1 MPN Index

This is a presumptive test for the presence of coliforms which are all gram-negative, non-sporing rods capable of fermenting lactose with the production of acid and gas within 48 hours at 37°C and of growing aerobically on bile salt agar medium. A 'dilution method' of counting is used. Measured quantities of the bacterial suspension, or of one or more suitable dilutions, are inoculated into at least five tubes of medium, and incubated at 37°C for 24-48 hours. From the number of tubes showing growth in relation to the total number inoculated, the approximate number of living organisms per 100 mℓ original sample can be estimated using suitable probability tables. Because the reaction observed in the tube may occasionally be due to the presence of other organisms, the presumption that the reaction is due to coliform organisms has to be confirmed.

E3.2 Membrane Filter Technique

By filtering a sample of water through a membrane filter, all bacteria present will be retained directly on the membrane surface. When the filter is transferred to an absorbent pad saturated with a liquid nutrient medium, the organisms develop into visible bacterial colonies which may be directly counted after a suitable period (less than 24 hours) of incubation at an appropriate temperature.

E4. LIMITATIONS OF BACTERIOLOGICAL EXAMINATIONS

E4.1 General

- The distribution of bacteria in water is very irregular, even after shaking.
- A single sample only indicates the conditions prevailing at the moment of sampling and may thus not detect intermittent contamination.
- Impracticability of routinely isolating pathogenic bacteria.

E4.2 MPN Method

- It is based on the not necessarily true assumption that growth develops from a single individual.
- Low reproducibility.
- Maximum-likelihood estimates are biased and overestimate the true density.
- The occurrence of false positives (more frequently found in fluids other than potable water) means confirmatory tests must be carried out on all positive samples (the results might be decreased by a factor of 10).

E4.3 Membrane Filter Technique

- Filters may clog with algae or coarse particulate material and reduce the volume of sample available for testing.
- If the noncoliform per coliform ratio is too high, overcrowding and interference with differentiation of the coliforms may occur.
- Individual variation in people's ability to recognise or distinguish the characteristic sheen of coliforms.
- There is some evidence of lower recoveries.

E5. MICROBIAL CONTAMINATION LEVELS

Raw sewage may average 4 x 10^7 coliforms per mℓ, (10^6 or more of which may be *E. coli*) and 500 virus units per 100 mℓ. The coliform level may be reduced up to 100-fold by secondary treatment. Activated waste sludge may contain around 10^6 coliforms per mℓ and digested activated waste sludge about 10^5 coliforms per mℓ and 10^5 streptococci per mℓ. Many viruses, *e.g.* polio, coxsackie, infectious hepatitis, are excreted in large numbers and are found commonly in domestic sewage. Water contaminated from sewage has been responsible for many viral outbreaks. Primary sedimentation has little effect on removing viruses, but activated sludge treatment and secondary sedimentation is more effective (up to 80 per cent may be removed).

E5.1 Efficacy of Radiation in Reducing Contamination

Tables E1 and E2 list the degrees of inactivation achieved for various radiation doses on common contaminants of sewage, irradiated as pure cultures in various suspending media. Tables E3, E4 and E5 are more realistic as they indicate directly the effect of radiation on water after various stages of treatment, and on the sludge (see also Table E2).

E6. ALTERNATIVE METHODS OF DISINFECTION

E6.1 Chlorine

Mechanism. The germicidal factor in free available chlorine is hypochlorous acid

$$Cl_2 + H_2O \rightleftarrows HOCl + H^+ + Cl^- \quad .$$

The bactericidal efficiency of both free and combined available chlorine (chloramines) is directly related to the pH. Increasing the pH above 4 reduces the germicidal activity.

Breakpoint chlorination is the most effective germicidal technique and occurs when approximately 9 ppm of chlorine has been added to water containing 0.9 ppm of ammonia nitrogen. However about 2 ppm of chlorine will 'breakpoint' most waters that are relatively free of pollution.

Microbial inactivation. *E. coli* is inactivated by about 0.3 ppm free chlorine, *Salmonella typhosa* by about 0.2 ppm, and *Pseudomonas aeruginosa* by about 0.7 ppm after five minutes,exposure at 20-25°C, pH 9.8.

In another study *E. coli, Alkaligenes faecalis, P. fluorescens, P. viciaea* were controlled by chlorine residuals from 0.4 to 0.8 ppm. Chlorine does not efficiently destroy many spores, viruses, worms and nematodes.

Disinfection of secondary treated wastes may be the only way to inactivate the enteric viruses. The results using chlorine are conflicting but indicate that more chlorine is needed than for *E. coli* disinfection. Coxsackie virus needed 7 to 46 times more free chlorine. Polio viruses types I and III need more chlorine than type II. Enteric and polio viruses have been isolated from the chlorinated effluent *via* a trickling filter. Free chlorine residuals of 0.1 to 0.3 ppm, and probably up to 1 ppm in raw sewage show no effect on virus content. Viruses have been recovered from activated sludge plant effluents chlorinated to 0.5 ppm for a 15 minute contact period. Combined residuals of 0.5 ppm require up to 4 hours' contact to be effective. Depending on pH and temperature, for a 15 minute exposure at least 9 ppm combined chlorine residual is required to inactivate enterovirus. The infectious hepatitis virus is unaffected by standing 40 minutes in contact with free residuals of 1 ppm, and even superchlorination to residuals of 15-23 ppm led to subclinical hepatic disturbances after 30 to 60 minutes exposure. To summarise, present chlorination treatment is probably inadequate to ensure virus-free water.

E6.2 Ozone

Ozone has more effect on spores, parasites, and polio viruses than has chlorine and is less affected by pH. The dosage requirements are up to 6 parts per million.

Turbidity interferes with the germicidal action. Iron and manganese content must be less than 0.2 ppm, otherwise precipitation occurs and the ozone treatment must be followed by filtration.

E6.3 Comparative Costs of Disinfection

Assuming a plant size for 10 million gallons per day (45 km^3 per day), it has been calculated that to deliver a dose of 50,000 rad would require 20 x 10^6 curies ^{60}Co and would cost 52¢ per 1,000 gallons (11.4¢ per m^3) for 99.9 per cent coliform inactivation. For 99.99 per cent inactivation the source, and consequently the cost, would be doubled. The cost for chlorination has been given as 0.6 - 1.8¢ per 1,000 gallon (0.13 - 0.4 per m^3), although it is stated that the bacterial population is only reduced 95-99 per cent. From 1956 figures, it would appear that ozone disinfection costs 0.4 - 1¢ per 1,000 gallons (0.09 - 0.22¢ per m^3).

E7. CONCLUSIONS

E7.1 Untreated Sewage

Complete sterilisation would require up to 5 x 10^6 rad. Because of the dilution effects that occur when untreated sewage is discharged directly into the sea, to radiosterilise it would appear unnecessary. In Sydney, although most sewage receives a partial primary treatment, some sewage is discharged into the sea without any pretreatment. To prevent re-contamination of beaches, if sewage is to be discharged untreated, the use of undersea pipelines would seem desirable. The optimum length of the pipe could be investigated using isotope tracers, as successfully practised in Denmark.

E7.2 Treated Sewage

Primary treatment only. Because of the initial high contamination of coliforms, doses of at least 500,000 rad would be required to reduce the coliform index to acceptable levels.

Secondary treatment. Because of the fermentation nature of the process, when the presence of microorganisms is an absolute requirement, radiation treatment should not be considered at any stage of the process before the secondary effluent.

In two reports the coliform counts for secondary effluent have been given as 500 and 50,000 counts per mℓ. In the first case 50,000 rad reduced the numbers to an acceptable standard for potable water, but in the second case extrapolation of the graph to 200,000 rad, shows that the final count was 10 organisms per mℓ or 1,000 times higher than the acceptable level for potable water. (Despite this, Touhill *et al.* 1967 (see Appendix C) concluded that coliform organisms do not survive doses above 150,000 rad.)

If it is assumed that the secondary treatment reduces the number of coliforms sufficiently, so that 50,000 rad will reduce the coliforms to an acceptable standard, the question arises as to whether other types of organisms, *e.g. Streptococcus faecalis, Clostridium welchii* (which causes gas gangrene) and viruses are similarly reduced.

From Tables E3 and E4, *Streptococcus faecalis* will not be eliminated by 50,000 rad, but as it is a normal contaminant of the intestine, its presence probably causes little harm.

Clostridium welchii spores have been isolated from sewage and water, but its incidence is not known, nor is its radiation resistance in sewage known. However, in liquid egg medium, 300,000 rad is needed for a 90 per cent reduction in numbers, so 50,000 rad would probably reduce the numbers present by about 20 per cent only.

Except for phage T3, the radiation resistance in sewage of viruses has not been investigated. Although phage T3 is sensitive to radiation, many other viruses are not. Doses up to 4 Mrad are needed to inactivate polio viruses, and at least 500,000 rad are required to reduce foot-and-mouth virus by 90 per cent. Therefore, it seems highly unlikely that doses of 50,000 rad are sufficient to disinfect sewage to the standard of potable water. Doses up to 5×10^6 rad are more likely to be required. Similar high doses are needed to disinfect activated sludge.

The conclusion is that radiation is not economically competitive with conventional chlorination processes for disinfecting water. However, there is some evidence that a synergistic effect occurs with radiation and chlorine and it is possible that with lower doses of radiation it might be possible to overcome the disadvantages of chlorination (bad taste and odour *etc.*). The possibility of using radiation to produce the ozone required for disinfection is also being investigated.

TABLE E1

EFFECT OF RADIATION ON PURE CULTURES OF COMMON CONTAMINANTS OF SEWAGE

Suspending medium: Buffered saline and nutrient broth

Organism	Dose (rad)	Surviving Fraction
Bacillus subtilis	150,000	0.004
Streptococcus faecalis	140,000	0.001
Salmonella paratyphosa	125,000	0.001
Micrococcus aureus	115,000	0.001
Salmonella sp.	110,000	0.001
Shigella sonnei	80,000	0.001
Salmonella typhosa	75,000	0.001
Shigella paradysenteria	55,000	0.001
Escherichia coli	40,000	0.001
Aerobacter aerogenes	30,000	0.001

Reference: Lowe, H.N. et al. (1956) - Amer. Waterworks Assoc. J. 48 : 1363

TABLE E2

DOSE REQUIRED FOR VARIOUS DEGREES OF INACTIVATION

Organism (pure cultures 10^6 per mℓ)	Suspending Medium				
	Distilled Water			Sterilised Settled Sewage	
	90%* (rad)	99%* (rad)	100%* (rad)	99%* (rad)	100%* (rad)
B. subtilis var. *niger*	180,000	340,000	2,000,000	500,000	1,000,000
Mycobacterium smegmatis	66,000	140,000	900,000	160,000	750,000
Escherichia coli	35,000	65,000	500,000	26,000	100,000
Micrococcus pyogenes var. *aureus*	27,000	58,000	200,000	74,000	600,000
E. coli phage T3	19,000	32,000	100,000	62,000	75,000
Air-dried sewage		120,000	5,000,000		
Sewage sludge suspended in water		85,000	2,000,000		

* *The dose (in rad) required to give 90%, 99% or 100% kill.*

Reference: *Lowe, H.N. et al. (1956) - Amer. Waterworks Assoc. J., 48 : 1363.*

N.B. *These figures have been taken from the various tables in the article. However, from the graph in the paper, the figures should be reversed, i.e. with the exception of E. coli, all organisms are more susceptible in sewage than in water.*

TABLE E3

EFFECT OF RADIATION ON WATER OF VARIOUS CONTAMINATION LEVELS

	Radiation Dose (rad)						
	0	25,000	50,000	100,000	150,000	200,000	250,000
River above Sewage Plant							
Total counts/mℓ	4,000	90	44	10	3		
Surviving fraction		0.023	0.001	0.0025	0.00075		
Coliform index/100 mℓ	540	6.8	< 1.8	< 1.8	< 1.8		
Surviving fraction		0.013	< 0.0033	< 0.0033	< 0.0033		
Streptococci/100 mℓ	79	130	11	13	11		
Surviving fraction		1.65	0.14	0.16	0.14		
River below Sewage Plant							
Total count/mℓ	7,700	95	50	17	11		
Surviving fraction		0.023	0.011	0.0025	0.00075		
Coliform index/100 mℓ	35,000	49	2	< 1.8	< 1.8		
Surviving fraction		0.0014	0.00006	< 0.00005	< 0.00005		
Streptococci/100 mℓ	540	70	33	23	< 1.8		
Surviving fraction		0.13	0.06	0.043	< 0.0033		
Primary Effluent							
Total count/mℓ	8 x 10^6		300,000	97,000	23,000	14,000	8,500
Surviving fraction			0.038	0.012	0.0029	0.0018	0.001
Coliform index/100 mℓ	35 x 10^6		350,000	35,000	2,400		240
Surviving fraction			0.01	0.001	0.00007	0.00001	0.000007
Streptococci/100 mℓ	1.4 x 10^6		1.1 x 10^6	160,000	220,000	170,000	35,000
Surviving fraction			0.8	0.11	0.15	0.12	0.025
Plant Effluent after Activated Sludge Treatment but before Chlorination							
Total count/mℓ	85,000		320	74	42	44	13
Surviving fraction			0.0038	0.0009	0.00049	0.00052	0.00015
Coliform index/100 mℓ	54,000		79	< 1.8	< 1.8	< 1.8	< 1.8
Surviving fraction			0.0014	< 0.00003	< 0.00003	< 0.00003	< 0.00003
Streptococci/100 mℓ	92,000		5,400	1,600	540	17	2
Surviving fraction			0.06	0.02	0.006	0.0002	0.00002

Reference: *Ridenour, G.M. & Armbruster, E.H. (1956) - Amer. Waterworks Assoc. J. 48 : 671.*

TABLE E4

EFFECT OF RADIATION ON TYPES OF ORGANISMS FOUND IN SECONDARY EFFLUENT

	Dose (rad)			
	0	50,000	100,000	200,000
Total counts/mℓ	700,000	6,500	1,000	100
Surviving fraction		0.0093	0.0014	0.00014
Coliforms/mℓ	60,000	400	50	10
Surviving fraction		0.0067	0.00083	0.00017
E. coli plaques/mℓ	9,000	500	80	10
Surviving fraction		0.056	0.009	0.0011
Enterococci/mℓ (streptococci)	1,800	200	80	30
Surviving fraction		0.11	0.044	0.017
Spores/mℓ	220	90	60	30
Surviving fraction		0.41	0.27	0.14

Reference: *Touhill, C.J. et al.(1969) - J. Water Pollut. Contr. Fed. 41 : R44.*

(In a second run, initial numbers of organisms were down about 10-fold).

TABLE E5

EFFECT OF RADIATION DOSE ON SLUDGE BACTERIAL COUNTS

	Dose (rad)				
	0	50,000	100,000	200,000	300,000
Waste-activated Sludge					
Coliforms/mℓ	2,400,000	24,000	2,400	240	9.4
Surviving fraction		0.01	0.001	0.00001	0.000004
Digested waste-Activated Sludge					
Coliforms/mℓ	240,000	7,900	540	4.6	1.1
Surviving fraction		0.033	0.0022	0.00002	0.000005
Streptococci/mℓ	220,000	70,000	3-17,000	7-14,000	3,480
Surviving fraction		0.317	0.013-0.078	0.032-0.064	0.016

Reference: *Etzel, J.E. et al. (1969) - Amer. J. Publ. Health 59 : 2067.*

APPENDIX F

POTABLE WATER QUALITY STANDARDS

NOTES FOR TABLE ON PAGE F2

(1) *Permissible or safe fluoride limits vary with mean atmospheric temperature.*

(2) *For WHO: Total solid residue. For USA: Total dissolved salts.*

(3) *0.05 mg/ℓ at pumping station. After 16 hours, contact with new pipes,* $\ngtr$ *3 mg/ℓ.*

(4) SO_4 *250 mg/ℓ, Mg* $\ngtr$ *30 mg/ℓ,* $SO_4 < 250$ *mg/ℓ, Mg* $\ngtr$ *125 mg/ℓ.*

(5) *Treatment includes prolonged storage, coagulation and settling, filtration, etc., separately or together. MPN - most probable number method. MF - millipore filtration method.*

Reference: *D.K.B. Thistlethwayte (1967) - Paper presented at Syd. Univ. Chem. Eng. Soc. Symp.*

(continued)

Quality or Constituent Standardised	World Health Organisation			USA Federal Quarantine Regulations (jointly with Amer. Chem. Soc., & Amer. Waterworks Assoc.)	
	International Standards		European Standards		
	Maximum Acceptable	Maximum Allowable			
Limits of tolerance of toxic substances in piped supplies - mg per litre					
Lead (Pb)		0.05	0.1	0.05	
Arsenic (As)		0.05	0.2	0.05	
Selenium (Se)		0.01	0.05	0.01	
Chromium (as Cr^{6+})		0.05	0.05	0.05	
Cyanide (CN^-)		0.2	0.01	0.2	
Cadmium (Cd)		0.01	0.05	0.01	
Barium (Ba)		1.0		1.0	
Silver (Ag)				0.05	
Nitrate (as NO_3)		45		45	
Fluoride (F)		1.0-1.5		0.8-1.7 (1)	
Limits of tolerance for other substances or quality aspect				"Desirable max"	
Total solids mg/ℓ	500 (2)	1,500 (2)	(In this standard, "constituents, which if present in excessive amounts, may give rise to trouble")	500 (2)	
Colour (Pt-Co units)	5	50		15	
Turbidity (units)	5	25		5	
Taste	Unobjectionable				
Odour	Unobjectionable			Threshold number 3	
Iron (Fe) mg/ℓ	0.3	1.0	0.1	0.3	
Manganese (Mn) mg/ℓ	0.1	0.5	0.1	0.05	
Copper (Cu) mg/ℓ	1.0	1.5	0.05 (3)	1.0	
Zinc (Zn) mg/ℓ	5.0	15	5.0	5.0	
Calcium (Ca) mg/ℓ	75	200			
Magnesium (Mg) mg/ℓ	50	150	Depends on SO_4 (4)		
Sulphate (as SO_4) mg/ℓ	200	400	250	250	
Chloride (Cl) mg/ℓ	200	600	350	250	
Mg + Na_2SO_4 mg/ℓ	500	1,000			
Phenolic substances (as phenol)	0.001	0.002		0.001	
Arsenic (As) mg/ℓ				0.01	
Cyanide (CN^-) mg/ℓ				0.09	
ABS (detergent) mg/ℓ	0.5	1.0	(In this standard "the level of the following should be controlled")	0.09	
Carbonchloroform extract (organic pollutants)	0.2	0.5		0.2	
pH units	7.0-8.5	6.5-9.2			
Ammonia (NH_3) mg/ℓ			≯ 0.5		
Free CO_2			Aggr. CO_2 zero		
Dissolved oxygen mg/ℓ			Not less than 5 mg/ℓ		
Total hardness mg/ℓ			100-500 max.		
Radiological measurement limits, pico-curies per litre					
				Preferable	Mandatory
Strontium (Sr)		30		10	200
Radium (Ra)		10		3	20
Gross α-activity		-	1	3	20
Gross β-activity		1,000	10	1,000	1,000
Bacteriological quality requirements (mandatory)					
Coliform organisms, numbers or colonies per 100 mℓ	1. Chlorinated waters: Normally absent from 100 mℓ sample portions; MPN ≯ 1 per 100 mℓ in 90 per cent of all samples. 2. Treated waters:(5) MPN ≯ 10/100 mℓ in any sample, and ≯ 8/100 mℓ in consecutive samples; mean MF count ≯ 1, and for consecutive samples ≯ 4. 3. Untreated waters: MPN ≯ 10 in 90 per cent of all samples; ≯ 15 in consecutive samples, ≯ 20 in any one sample; MF count mean ≯ 10; not more than 10 per cent of all samples may show ≯ 10 but ≯ 20.		Piped supplies: Coliforms should be absent in all samples, but it is considered reasonable to allow a positive result not more than five times in every 100 samples, but not in any two consecutive samples (not less than 100 samples per year regularly spaced).	Piped supplies: 1. Where 10 mℓ portions are tested not more than 10 per cent of all portions in any month positive; not more than three of 5 x 10 mℓ portions positive for any two consecutive samples and/or 5 per cent of all samples. 2. When 100 mℓ portions are tested not more than 60 per cent of all portions for any month may be positive. 3. Using MF technique, mean count less than 1; total counts may not exceed the following in consecutive or in 5 per cent of all samples: 50 mℓ - 3 100 mℓ - 4 200 mℓ - 7 500 mℓ - 13.	