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Management of Discharge of Low Level Liquid Radioactive Waste Generated in Medical, Educational, Research and Industrial Facilities

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International Atomic Energy Agency

MANAGEMENT OF DISCHARGE OF LOW LEVEL LIQUID RADIOACTIVE WASTE GENERATED IN MEDICAL, EDUCATIONAL, RESEARCH AND INDUSTRIAL FACILITIES

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FOREWORD

Although published information on management technologies suitable for radioactive effluents is readily available, smaller facilities such as hospitals, universities and research laboratories in some countries can benefit from more detailed guidance on identifying optimal arrangements for effectively managing their radioactive liquid effluents. A wide range of circumstances exist globally, given that the generation of radioactive liquid effluents may be regular or irregular, and the liquid effluents may be suitable for direct discharge to the environment, or may require a period of decay storage prior to discharge. Countries typically fit into one of the four following categories with respect to the status of their arrangements for the management of radioactive liquid effluents:

(1) The country does not have sufficient technical, regulatory and organizational infrastructure to effectively manage its radioactive liquid effluents;

(2) The country's technical infrastructure for effectively managing its radioactive liquid effluents is almost sufficient, but it is not supported by an acceptable level of regulatory and organizational capacity (e.g. legal infrastructure, administrative infrastructure);

(3) The country has sufficient technical, regulatory and organizational capacity, but it is known that the application of the requirements for proper management of radioactive liquid effluents is, in many cases, not being carried out to the standard indicated by official reports;

(4) The country has well developed and established regulatory and organizational capacity, which is complemented by an acceptable level of relevant technical infrastructure such that the radioactive liquid effluents can be properly managed.

Facilities, as well as countries, in the first three categories will find information in this publication to assist their further development. Even countries that already have the necessary infrastructure to properly manage their liquid radioactive effluents may benefit from the information in this publication, particularly with respect to design optimization for decay tanks or guidance provided on quality assurance arrangements.

The most appropriate management option for the country and for individual facilities may be selected on the basis of local organizational preferences and experience, consistent with the national regulatory requirements. Due to the costs involved, the potential complexity of technical and environmental considerations, and the need to ensure adequate performance of any required decay storage arrangements, the process of selecting the optimized liquid effluent management option may be complex. This is especially true in countries with limited liquid radioactive effluent generation, limited practical experience and inadequate resources.

This publication is intended for decision makers in countries generating radioactive effluents in the areas of medicine, education, research and industry with non-nuclear power applications. It provides guidance and information on how to implement and optimize their radioactive effluent management practices and describes methodologies, criteria and options for the selection of appropriate technology for the discharge of liquid radioactive effluents into the sewer system. The report reviews both technical and non-technical factors important for decision making and planning, and for the implementation of the most appropriate process design for effluent discharges at the country and facility levels. It makes practical recommendations for the selection of decay storage arrangements for different scales of radioactive effluent generation.

The publication was prepared by the Secretariat with the assistance of consultants from five countries through a series of consultants meetings. The IAEA would like to express its thanks to all those who helped in the preparation of the report and its revision. The IAEA officers responsible for the publication were A. Kahraman and M. Al-Mughrabi of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Radioactive 'liquid' wastes are generated in a wide range of medical, educational, research and industrial facilities, and often they are not fully and adequately managed. Environmental and public protection and protection of the workers are not always adequately considered when the discharges are initially proposed.

Safe storage of radioactive effluents for decay and subsequent discharge requires a technical and administrative infrastructure as well as radiation protection controls. A number of factors need to be considered for decay storage of aqueous effluents. These include the administrative and technical arrangements, design of the facility, safety assessment and the quality assurance programme. Although decay storage can be applicable for all types of waste containing a wide range of radionuclides, it is more applicable to those with half-lives shorter than 100 days. The decay storage covers an appropriate time period for decay of the radioactive effluents and the waste collection period.

The volume of radioactive effluents arising from medical and other institutional applications, in some cases, may not be regular. For example, some effluents may arise only one time at a facility, e.g. from a decontamination activity or from a research experiment, and the volume of the generated effluent may vary from a few cm^3 up to several m^3. For those facilities like medical institutions using large amounts of radioactive materials and large research laboratories where nuclear applications are carried out more regularly, there will be regular liquid waste generation. For these facilities, decay storage of effluents should be arranged as a well-structured system, appropriately designed to meet the needs of the facility. Design of decay storage systems, for both regular and irregular effluent discharges, should aim to provide satisfactory radiation protection for workers, the public and the environment. Radiation protection principles should be applied in the same way for radioactive waste management as they would be for other applications.

The quality assurance programme for decay storage, which includes appropriate record keeping, begins as soon as the collection of liquid wastes commences. In addition, as a general rule, generation of the radioactive waste should be kept to a minimum and waste segregation should be applied.

1.2. OBJECTIVE

The objective of this report is to provide guidance on the administrative and technical issues for the management of low level radioactive effluents intended for discharge to the environment. This may or may not include a decay storage arrangement prior to discharge. This report is aimed at providing helpful advice to the operators of all types of medical and institutional facilities generating liquid radioactive effluents, irrespective of the frequency of generation and consistent with the volumes specified in the scope.

1.3. SCOPE

This publication covers options for the discharge of low level radioactive effluents generated from medical and other institutional applications. It is worthwhile to point out that the report deals only with liquid discharges and does not include gaseous effluents. It also concentrates on the aqueous liquids which is the vast majority of the discharge in most cases.

The scope only covers decay storage systems and does not include low level radioactive waste pre-treatment and treatment methods. In this connection, small quantities of organic liquid waste are not supposed to be discharged and they require some treatment prior to discharge or long term storage, which make it outside the scope of this publication. The principles and appropriateness of direct discharge to the environment are described. The circumstances whereby it is appropriate to store low level radioactive effluents for decay purposes are also described. The volumes considered in this report are ranging from irregular effluents of several cm^3 to regular effluents of several m^3/week.

1.4. STRUCTURE

Details of an administrative infrastructure relevant to the management of discharge of radioactive effluents to the environment are given in Section 2. The principles for such discharges are given in Section 3, with options for the management of direct discharge and storage for decay described in Section 4. Section 4 also includes cost-benefit analysis for the decision making process, optimization of radiation protection and a section on advantages and disadvantages of decay tank systems. In Section 5, the factors that might influence direct discharge to the sewage system are discussed and in Section 6, the design considerations and operation of a decay tank system are explained. Issues on effluent and environmental monitoring are given in Section 7, with emergency arrangements discussed in Section 8. Quality assurance arrangements are discussed in Section 9. In Annex I, an example of calculation method and a worked example are provided for the benefit of those who are faced with designing a decay tank system for the first time. Appendix I provides examples of decay tank systems.

2. FRAMEWORK AND INFRASTRUCTURE FOR LIQUID RADIOACTIVE DISCHARGES

Establishment of a regulatory infrastructure is essential for the safe management of radioactive waste including discharges of short lived radionuclides. Its establishment is dependent upon the provision of adequate financial, organizational, human, technical and advisory resources relevant to the needs of the country and the complexity of the proposed applications by medical, research and other institutions. A national policy for radioactive waste management is a fundamental cornerstone of a radioactive waste management system [1]. While the national policy should be created based on internationally accepted scientific principles, it should also consider local social conditions or cultural values and traditions. The national policy should generally be established at the highest level of government, usually at the national executive level. National policy should be developed with the contributions of stakeholders; however the responsibility for final approval rest with the government [2].

The principles of national regulatory requirements should be transcribed into national legislation. Guidance based on regulatory requirements should be made available by the Regulatory Authority and should ideally include the activity levels acceptable for discharges to the environment. Roles and responsibilities for both inspectors and the licensees should be defined by the national legislation. The regulatory infrastructure should make provision for enforcement arrangements for non-compliance through legislation which empowers inspectors to impose sanctions or to suspend operating licenses in cases of serious violation of the national legislation by operators. It is the responsibility of the operator to demonstrate to the regulatory body that he has all the necessary equipment for waste processing/management and environmental monitoring, and that it is suitable for the purpose.

The operator should apply for authorization to the regulatory body, fully describing the proposed application and providing an environmental impact study/assessment for all planned discharges. It is important that the environmental impact study/assessment is appropriately tailored to the complexity of the proposed system and the infrastructure of the country. The terms of the authorization will specify arrangements for the storage and discharge of the radioactive effluents and any requirement for environmental monitoring and sampling. Where the environmental impact of a proposed direct discharge to the sewers would be unacceptable, a proposal to mitigate the impact by construction of a decay tank system will facilitate obtaining an authorization for effluent discharges from the regulatory body. It might also facilitate the preparation of documentation required as part of the operating conditions of the authorization when making the discharge.

A suitable comprehensive record keeping system should be established and integrated in the operational procedures and submitted to the regulatory authority as required. Arrangements must be in place for storage of the records. Where records are stored electronically, arrangements must be in place to transcribe the data into a new format consistent with developments in technology so that the data will always be retrievable. Requirements for record keeping of the discharges to the environment are given in [3] and the records to be kept should be identified within a well-established quality assurance programme.

3. PRINCIPLES OF DISCHARGE OF RADIOACTIVE EFFLUENTS TO THE ENVIRONMENT

Low level radioactive waste generated from medical, research and other institutional applications should be managed in a safe manner in compliance with the requirements of the Regulatory Authority. The principal approaches to the management of low level liquid radioactive waste are 'delay and decay', 'concentrate and contain' and 'dilute and disperse [4]. 'Delay and decay' involves storing the low level liquid radioactive waste until the desired reduction in activity has occurred through radioactive decay, followed by discharging it into the sewage system without a requirement for further dilution. 'Concentrate and contain' means reduction of the volume and confinement of the radionuclide contents by means of a conditioning process to prevent dispersion in the environment and this approach is beyond the scope of this publication. 'Dilute and disperse' means discharging low level liquid radioactive effluent to the environment in such a way that environmental conditions and processes ensure that the concentrations of the radionuclides are reduced to such levels that the radiological impact of the released material is acceptable. In some circumstances the principle of 'delay and decay' may be combined with that of 'dilute and disperse'. An example of these combined principles is utilized in the medical sector with Iodine-131 decay tanks. Typically a patient produces 5 liters of effluent per day but this is diluted to 50 liters with toilet flushing by the time the effluent reaches the decay tank.

The maturity and complexity of the sewage system into which the radioactive effluent is being discharged is very important. Countries with a well-developed regulatory infrastructure and a mature and extensive sewage disposal network, that includes one or more sewage treatment plants, might reasonably allow direct discharges to the sewage system if no adverse impact is identified. For countries with cities constructed without any sewage system or where the sewage system is inadequate, the installation of an engineered decay tank system to reduce the impact of the effluents should be considered.

An essential principle for the discharge of effluents to the environment is to consider all possible impacts. These should be assessed using models accepted by the Regulatory

Authority as “fit for the purpose”. Important criteria to be considered during the study/assessment are the extent of dilution of the discharge and the fate of the discharge. The institution/establishment specific parameters of:

- The volume of the effluent generated;
- The frequency of the generation;
- The activity and/or the activity concentration of the generated effluents, and
- The physical and chemical characteristics of the effluents

will determine the way forward for their management. If the activity level of the effluent is below the authorized/generic discharge level, the effluent can be directly discharged to the sewage system. Alternatively, dilution with an acceptable amount of water consistent with the principle of ‘dilute and disperse’ may facilitate direct discharge into the sewage system.

Clearance and exemption levels are set by the Regulatory Authority and they could be generic or on a case by case basis. Regulatory Authorities grant discharge authorizations to the licensees and registrants, the process of which is clearly indicated in [3]. The ICRP noted that the term ‘clearance’ is sometimes incorrectly applied as a quasi-synonym to the concept of controlled discharges of radioactive effluents into the environment. Sometimes, Regulatory Authorities might define activity levels, in the process of authorization of discharges, at which no regulatory involvement is required in order to verify that the public are sufficiently protected during the release of radioactive effluents. In principle, the dose criteria applied for clearance may equally be applied to the analogous concept of defining an activity level at which no regulatory involvement is required to verify that the public are sufficiently protected during the release of radioactive effluents. ICRP does not recommend the equalization of these two concepts and states that the clearance concept could be misused for promoting the dilution of discharges in order to circumvent regulatory control. Further information can be found in the ICRP publication: “Scope of Radiological Protection Control Measures” [5].

Guidance on translating the principles of exemption from regulatory control into a practice in the context of the waste arising from medical and other institutional applications and guidance on the nature and scope of radiation dose calculations are given in TECDOC 1000 [6]. Moreover, generic levels expressed in terms of release rates of radionuclides to the environment or activity concentrations in solid materials, below which there is no need for further regulatory control for the waste arising from medical, research and industrial uses of radionuclides, are also given in [6].

Records of discharges to the sewage system should be made, kept and reported as might be required by the Regulatory Authority.

4. DISCHARGE OPTIONS FOR RADIOACTIVE EFFLUENTS

Options for the discharge of low level radioactive effluents considered within the context of this publication will be based on the two principles of ‘dilute and disperse’ and ‘delay and decay’. Operationally, this effectively provides for two options:

- Direct discharge to the sewage system; and
- Storage for decay prior to discharge to the sewage system.

Storage may involve the use of suitable containers to hold the effluent whilst it is held to decay in a secure radioactive waste storage area or may involve the installation of a decay tank system. The use of containers is best suited to conditions where the overall volume is small i.e. typically less than 0.5 m^3/yr and where the half-life of the radionuclide is less than 100 days.

It is widely acknowledged that there is rarely any justification to refuse the immediate discharge into the sewage system of excreta from patients administered diagnostic reference levels of Technetium-99m radiopharmaceuticals, whether discharged to the sewage system from their home or during their stay in the hospital. This is due to the low activity involved in diagnostic use and the short half-life. Whilst it is expected that most low level radioactive effluents will be discharged to the sewage system, either directly or after a suitable decay period, some effluents may need to be pre-treated to change chemical or physical composition. Treatment of radioactive effluents prior to discharge is beyond the scope of this report.

In deciding upon the best option for the discharge of low level radioactive effluents, the following factors should be considered:

- Population of the vicinity;
- Extent of development of the sewage system of the country;
- Number of establishments/institutions discharging to the same sewage system;
- Discharge requirements of the establishment/institutions;
- Frequency of generation of the proposed discharges;
- Volumes and activity levels of the proposed discharges;
- Number of operational sewage treatment plants serving the area;
- Impact on the environment of the proposed discharges;
- Acceptability of the doses to the representative person;
- Regulatory criteria.

The composition of radioactive effluents may cover a wide range, both with regard to the activity level and the presence of alpha and beta/gamma emitting radionuclides. Some waste streams may contain both. Many effluents contain specific groups of radionuclides, others may contain only one or two. For effluents containing mainly short lived beta/gamma activity, the effluents should be stored. After decay to a specific activity within prescribed limits, they can generally be safely discharged to the environment [2].

The waste discharge requirements of certain facilities, such as a hospital, could be very complex and may require a number of discharge options for their liquid effluents. Consider the situation of a large university hospital, with radiotherapy and diagnostic nuclear medicine services, which also has a comprehensive university research and teaching facility. Dependent upon evaluation of the essential parameters to decide upon the best management options, three different discharge options might be necessary:

- A series of decay tanks may be installed for collection of higher activity effluents (kBq to GBq per litre activity level) dependent upon whether from bathing water or urine, and larger volume Iodine-131 patient excreta, which will be held for a suitable period prior to discharge to the sewage system at authorized discharge levels. Such wastes may or may not be generated on a daily basis, dependent upon how many patients are treated at the hospital per month and the time period that they remain in hospital;

- The daily small volumes of liquid waste, typically Bq or kBq activity levels per litre i.e. from radioimmunoassay laboratories, will be decanted and discharged directly to the sewage system on a daily basis. The overall dilution within the sewage system before the waste leaves the hospital site will ensure that the authorized discharge activity levels will always be met;
- The infrequent generation of typically small volume but higher specific activity (MBq per litre, although in exceptional circumstances may be at GBq per litre level) liquid effluents from research laboratories or from medical radio-labeling procedures. These wastes most likely have no connection to the decay tank system and are unsuitable for direct discharge to the sewage system. A suitably labeled storage container and secure waste storage area must be available for decay storage of these wastes until they reach the authorized discharge activity level and can be decanted direct to the sewage system.

Although it is outside the scope of this report, it should be noted that if the radionuclide in the effluent will not decay within a reasonable time span, i.e. for radionuclides of half-life of greater than 100 days or with an initial high activity, the effluents should be routed to an alternative option for further management, and the regulatory body should be informed of this decision. Normally this kind of liquid effluent should be transferred to a centralized waste processing facility wherein further technical capabilities are available for its proper management. A suitable record keeping system must be in place to ensure such effluents are not retained beyond the required period of decay storage.

Irrespective of the selected option for discharge of radioactive effluents, suitable quality assurance arrangements must be put in place. Further information on quality assurance is provided in Section 9.

4.1. DIRECT DISCHARGE TO THE SEWAGE SYSTEM

Direct discharge to the sewage system is widely practiced as it is often the best option for disposal of very low activity radioactive effluents. For some diagnostic laboratories i.e. radioimmunoassay or radiotracer laboratories, the volumes and specific activities of the liquid radioactive effluents are generally low (Bq or kBq per litre) and are often produced on a daily basis with direct discharge to the sewage system, in full compliance with authorized discharge limits. Such discharges are usually made via designated sinks and sluices that are appropriately labeled, cleaned after the discharge and monitored to ensure there is no residual contamination.

Dilution, if applicable, during the discharge would reduce the activity concentration of the radioactive effluent. For small volumes of radioactive effluents, the tap should be turned on slightly prior to making the discharge and the water should be left running for a suitable time period afterwards to further dilute the effluent and to ensure it is adequately flushed from the pipes at the point of discharge into the sewage system. The integrity of the plumbing system should be checked periodically so as to avoid unwanted leakage of radioactive effluents from the pipe work or accumulation of radionuclide activity in the sink trap or pipes.

Although infrequent generation of liquid effluents is more commonly associated with small laboratories, larger facilities such as research establishments may also produce such effluents. The characteristics of the effluent being produced by many large facilities on a daily basis may not always be the same. Where the effluent is of low activity level and is compliant with the discharge limits, it should be discharged directly to the sewage system.

If effluents are regularly generated with radioactivity levels higher than the generic discharge limit, then an assessment should be made to show what the radiological impact of direct discharge of the effluents to the sewage system would be. Unacceptable impact will call for revision of management procedures and/or consideration of other management option. This assessment should be submitted to the Regulatory Authority as part of the application process for a specific discharge authorization.

4.2. STORAGE FOR DECAY

For facilities frequently producing large volumes (greater than 0.5 m^3/yr) of radioactive effluents with an activity level above the authorized discharge limit, the principle of 'delay and decay' is usually the best management option. This can be achieved in a number of ways based on the following options:

— Storage in suitable containers held to decay in a radioactive waste storage area;

— Storage in decay tank(s).

Occasionally small volumes of radioactive effluents containing higher concentrations of radionuclides may be generated, e.g. from research applications or decontamination of pipes and equipment. The activity levels and radionuclide content of these effluents are critical for deciding upon the discharge option on a case by case basis. The chosen option will usually involve a period of decay storage in containers prior to decanting to the sewage system. This will necessitate appropriate labeling of the waste container, record keeping and secure decay storage arrangements being in place. The period of storage for decay will be governed by the initial activity level of the radionuclide, its decay profile and the authorized discharge limit. It is essential that appropriate containers are selected for storage of effluents i.e. will not leak or corrode within the projected storage period and should facilitate minimization of spread of contamination during discharge. Radiation dose rate checks should periodically be carried out during the storage period of the radioactive effluents to ensure the doses are as expected. Periodic inspection of stored containers should be made to ensure detection of any leakage.

On occasions, larger waste volumes start to be generated at an existing facility where the best option would be to install decay tanks, but there is no available space for their construction, as may occur on hospital premises once new services of Iodine-131 therapy are introduced. To attempt construction within an existing hospital area might mean a reduction in essential services, so an alternative compromise solution must be found.

One such solution involves making further use of existing radioactive waste storage arrangements (often used only for solid waste) to incorporate a specific area for radioactive effluent decay storage. For this system to operate, it would necessitate that the patient undergoing treatment would collect his/her urine and transfer it into containers suitable for radioactive urine storage. Hospital staff would be required to assist with the transfer of urine into the container where the likelihood of contamination problems through spillage is high. Once the urine container is full, it should be sealed and placed in a shielded trolley for transfer to the radioactive waste storage area.

The urine collection containers should have a wide neck (for ease of transfer of the liquid without spillage), an approximate 5 liters capacity (typical maximum urine collection in a 24 hour period), and be of suitable construction. An appropriate amount of anti-microbial disinfection agent should be placed in the containers before use to reduce any biological hazards that might arise from prolonged storage of the filled containers. It will be necessary to construct a series of appropriately shielded bins in the radioactive waste storage area e.g. three or more, with each bin of sufficient capacity to hold all of the individual containers of radioiodine patient urine that will be produced in one month. Three labels, with suggested labeling of month one, two and three, with a magnetic rubber backing, could be used to rotate between the bins to identify how long their contents have been kept in storage. Such a system would avoid the need for repeated handling of the stored containers of urine after they are placed in the bins for decay.

Containers would only be removed at the end of the decay period when their contents would be suitable for decanting to the drain in compliance with authorized discharge limits. This type of system can also be adapted for radionuclides other than Iodine-131. For transport of the effluent in the container to the radioactive storage area, a suitably shielded bin on a trolley could be designed, so as to reduce the exposure of the worker during transfer to the storage bins in the radioactive storage area.

Installation of decay tank(s) might be required due to the large volume and high activity of the effluent that is produced, which if discharged directly to the sewage system might expose the operators of the sewage treatment plant to unacceptably high radiation levels. It is a well-known fact that sewage plant processes re-concentrate radionuclides in sewage sludge [7]. There exist a number of possible arrangements for the installation of a decay tank system to avoid such a situation:

(a) A single tank;

(b) A number of individual tanks each dedicated to specific waste streams;

(c) A number of connected tanks in series.

(a) The installation of a single decay tank is not widely used but might be appropriate for specific circumstances. A typical application would be for a research establishment utilizing a single radionuclide for an extended time period where the effluent generated is unsuitable for direct discharge. The effluent will be collected in the tank for the duration of the experiment. Thereafter it will be held to decay until it reaches the authorized limit when it will be discharged.

(b) One or more interconnected tanks is often the most suitable option for collection of a single radionuclide effluent for decay, whereas more complex arrangements may be required when multiple radionuclides of different characteristics are collected on a frequent or infrequent basis. A typical example may be a radiopharmaceutical manufacturing facility, where a whole range of alpha, beta and gamma emitting radionuclides, of half-lives ranging from hours to many years, may require management prior to discharge. For such an example, three independent tanks of different capacity might be the best option:

(i) A tank to collect short half-life (less than 100 days) mixed beta/gamma radionuclide liquid waste;

(ii) A tank to collect mixed beta/gamma waste of half-life greater than 100 days;

(iii) A tank for collection of alpha or mixed alpha/beta/gamma emitting radionuclides.

In this example, the tanks will have sampling ports and the facility will have access to extensive analytical measurement arrangements to quantify the mixed radionuclide content of the individual tanks. The discharge of the effluent to the sewage system can only be made when the results of the overall radionuclide content of the tank have been assayed to demonstrate compliance with the authorized discharge limits.

(c) Decay of relatively higher activities of radioactive effluent generated from medical, research and other institutional applications in decay tank systems is often the best option for the management of larger volumes of higher activity effluents that are unsuitable for direct discharge. A decay tank system is usually recommended for radionuclides with half-lives of less than 100 days. A decay tank system usefully reduces the radioactivity discharged to the sewage system [8][9], and often involves minimal intervention by the operator. For hospitals with a nuclear medicine/radiotherapy department, a series of connected tanks to collect Iodine-131 patient waste may be the selected option. Further information on the design and operation of decay tanks is provided in Section 6.

Many facilities, when faced with the prospect of drafting a radiological impact assessment to apply to the regulator for a case specific authorized discharge limit, would prefer a simpler option in terms of their work commitment. A case specific authorized discharge limit (which will be higher than the generic discharge limit) would of necessity also require some level of monitoring of the impact of the discharges. A simpler longer term solution that requires less work input from the operator is to design and install a series of decay tanks that will only discharge the liquid effluent to the sewage system once authorized discharge limits are achieved. Such a system is likely to require minimal work input by the nuclear medicine/radiotherapy staff and will possibly remove the need for monitoring of the discharge. The number of tanks in series and their capacities will be dependent on the volumes of waste produced. Further information on this subject is given in Section 6 and sample calculations are given in Annex I.

Due to the complexity of the design of a discharge system, however simple, examples have been provided in Appendix I. They provide for examples and design features that cover a wide range of design features and cover simple inexpensive systems as well as complex and costly ones. It should be mentioned here that all designs provide for acceptable solutions but with varying degree of flexibility and automation.

4.3. THE DECISION MAKING PROCESS

There are a number of key decision points in the establishment of a liquid waste management process. Once the liquid effluent management requirement is identified and quantified, the first decision is the option of direct discharge or a requirement for a decay storage system. The next stage is matching the suitability of design and operation of the storage solution to meet the requirements. The objective of effluent storage is to ensure that discharge limits can be met whilst protecting people and the environment.

Identification of the storage solutions must consider a number of factors:

- The volume of the effluent;
- Half-life of the radionuclide;
- Total and specific activity;
- Presence of other harmful contaminants;
- Chemical properties of the effluents e.g. corrosive;
- Dose rate and shielding requirements.

The flowchart given in Figure 1 provides guidance on some of the options available for effluent management based on the characteristics of the effluent e.g. the volume, half-life and activity. Table 1 supports the 8 options identified in the flowchart and identifies examples of possible solutions for each of the options and gives a suggested mechanism for its implementation. It should be noted that the examples presented here are not exhaustive.

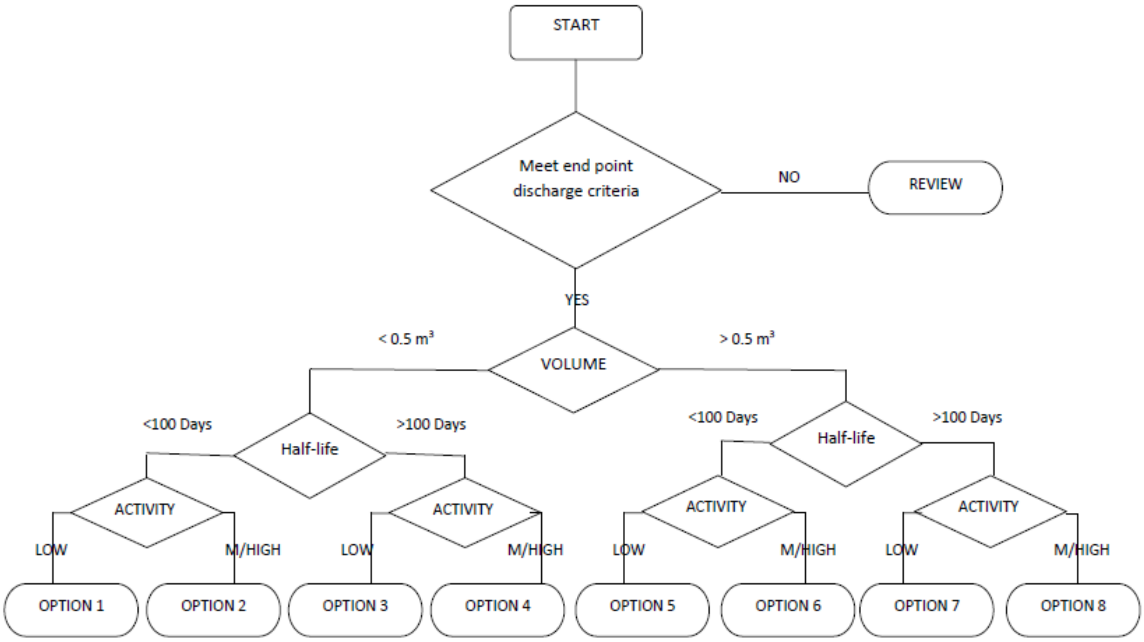


FIG. 1. Flowchart for the decision making process.

TABLE 1. OPTIONS AND SOLUTIONS AS IDENTIFIED IN FIG. 1 FOR THE DIFFERENT SITUATIONS [1]

OPTION	Possible Solution	System
1	Direct discharge if specific activity is below discharge limits	Direct discharge or collect in small container (~ 25 L maximum)
2	Store for decay in shielded container	Small container
3	Need to do environmental study/assessment to assess suitability for direct discharge	Direct discharge or collect in small container
4	Need to do environmental study/assessment to assess optimized period of decay storage	Collect in shielded small containers
5	Direct discharge via an interceptor tank if specific activity is below discharge limits, otherwise hold at the interceptor tank if decay storage is required	If decay required, transfer effluent from interceptor to a buffer tank
6	Requires decay storage	A fit for purpose decay tank system
7	Protracted period of decay storage likely due to long half live	Decay tank system to meet longer storage requirements
8	Store for decay; may need shielding	Several tanks in series
Non-conforming to Discharge Limits	Requires pre-treatment to remove unacceptable materials (toxic or organic solvent) prior to decay storage	The required pre-treatment procedure is beyond the scope of this report

There is no single option that would be suitable in all circumstances. The design of the system should be suitably tailored to match the prevailing conditions and the local infrastructure, taking due account of any projected discharge expansion or change in characteristics of the effluent. The local infrastructure should be given high priority in the decision making process. The installation of a very expensive highly automated decay tank system cannot be justified in a developing country with a basic infrastructure. Such a system is destined for failure as it is unlikely that the resources will exist to secure ongoing function of the system. Furthermore, the initial expenditure will be grossly disproportionate to the benefits gained from the operation of the decay tanks. It would be impossible to justify the cost of such a system.

4.4. COST-BENEFIT ANALYSIS FOR OPTION SELECTION

Cost-benefit analysis is a tool to find the best way of allocating resources. A proposed practice involving radiation exposure can be justified by considering its benefits and its costs [10]. The aim is to ensure a net benefit. As part of the options appraisal process, it is useful to carry out a cost-benefit analysis to ascertain that the cost expenditure is proportionate to the benefits in dose reduction to the representative person and/or protection of the environment that will be achieved. Recommendations of justified expenditure to save a mSv of dose to the

[1] Note: Low activity; Bq –kBq per liter and medium/high activity; kBq – GBq per liter.

critical group have previously been published [11][12] although their usefulness is less clear when considering the different economies of developing countries. Although cost-benefit analysis has its role to play in the overall decision making process, it is not unknown for other factors to be given priority when the final option is selected e.g. in developing countries where human resources are not a limiting factor, a less costly option might be selected that delivers the same level of radiation protection but where dose sharing amongst the workers can be used to reduce the exposure of the individual.

When looking at cost-benefit analysis, the subject of risk must also be factored in and whether the risk is acceptable and if the risk related activity provides benefit to the individual. Risk-benefit analysis is applied explicitly or implicitly to a wide range of problems. More formally, cost analysis is used, in which all the factors to be considered have some financial value attached. Three commonly used terms in cost-benefit analysis are total cost investment, fixed cost investment and operational costs. The total cost investment is the overall expenditure for the project and this is made up of two main components – the fixed cost investment which is the installation cost of the option and the ongoing operational costs.

There is no worldwide uniformly applicable financial value that can be applied to the factors considered in cost-benefit analysis due to the extremes of circumstances that exist. Nonetheless the generic value of this management tool in the decision making process should not be overlooked, but relevant factors need to be appropriately weighted or disregarded dependent on the prevailing circumstances.

The factors to be considered as part of cost-benefit analysis include:

- Magnitude of the dose if no action is taken relative to dose limits;
- Justification for the expenditure versus other competing expenditure demands;
- Design features to minimize exposure or facilitate ease of operation of the decay tank system e.g. may relate to materials or components;
- Operation and maintenance costs, including staff training;
- Environmental impact of various abatement options;
- Projected lifetime of the system to be installed;
- Future ease of decommissioning.

Other ethical issues, listed below, may influence the implementation of the optimized solution from the cost-benefit analysis, especially in government funded establishments where many other cost pressures are competing for limited financial resources.

- Magnitude of the risk relative to other risks e.g. expenditure to reduce/remove a low radiation health risk may appear an inappropriate spend when considered against the need to reduce the risk of infection or impact of war in an affected area;
- Voluntary and non-voluntary risk e.g. knowingly and willingly exposed versus no knowledge of the exposure or not agreed to it;
- Wealth and societal expectation e.g. wealth of the area and whether expenditure to reduce the risk could be justified and would be expected by the local population.

The basic notion in the application of cost-benefit analysis to decision making is very simple. An option is selected if the resulting net benefit exceeds that of the next best alternative and not otherwise. Searching for a value that meets this ideal solution i.e. optimization, involves an interplay of the cost of providing the best solution and the cost of the detriment if it is not implemented. Further information on cost-benefit analysis in the optimization of radiation protection can be found in ICRP 37 [13].

When designing a new facility that is likely to produce large volumes of liquid effluent that will require decay storage prior to discharge to the sewage system, it is wise to include a provision for the installation of suitable decay tanks. Retrospective installation of decay tanks at an existing facility will always be more costly and will often present difficult logistics problems due to unavailability of space or engineering limitations of the building.

Other related expenditures should not be overlooked. Operators will routinely consider any fees levied by the regulatory body when applying for an authorization, but the time spent preparing and reviewing the application and supporting documentation is often overlooked and not included as part of the overall costs. The regulators may charge for their service to review the initial application, and additional charges may be imposed where design modifications are required. Since such drafting and review requires experienced staff, these additional costs need to be considered as part of the overall cost analysis. A well designed decay tank system, where the possibility of failure has been appropriately considered as part of its design, can reduce the volume of additional documentation required both for the authorization application and routine operation, hence reducing costs.

To optimize radiation protection for a given practice, the incremental costs involved in reducing the collective dose, from a given level to a range of lower levels, are compared with the incremental health benefits that result. The ALARA value is that level of collective dose below which the cost of any additional radiation protection measures would exceed the worth of the reduction of health detriment. The method involves a differential cost-benefit analysis with the ALARA principle in mind. Further information can be found in Reference [10].

4.5. ADVANTAGES AND DISADVANTAGES OF DECAY TANK SYSTEMS

In considering advantages and disadvantages of decay storage, either in the form of containers or tank systems, what constitutes an advantage in one geographic location may represent a disadvantage in another, especially once economic circumstances are factored in. Something that appears to be an advantage when considered in isolation may be a disadvantage when utilized in a specific scenario e.g. use of stainless steel tanks in a high chloride environment where corrosion will be a problem or use of plastic tanks exposed to direct sunlight where they may become brittle. No aspect of design is likely to be advantageous in all situations, and care should be exercised to ensure that the advantages and disadvantages are considered in relation to the specific circumstances and the environment.

Manually operated decay tank systems may be an advantage in a developing country where labour supply is cheap and plentiful whereas automation may be preferred in a highly developed country where manpower costs are high. The infrastructure of the sewage system of the location might influence the design of the decay tank system. A leaking sewage system might necessitate the effluent is held for a longer period to ensure it is fully decayed prior to release so as to avoid the risk of ground contamination. Irrespective of whether a manual or an automatic system is the chosen option, there will be a need to decide whether a large system with infrequent discharges or a smaller system that requires more frequent discharges is installed. A combination of a manual and automatic system might be the most advantageous design in certain circumstances. Such an example is provided in Appendix I.3.

There are clear advantages in considering both the immediate decay storage requirements as well as project future requirements prior to making a final decision on the design and location of the decay tank system. If the construction is in a basement, it is likely that space may be at a premium and it may not be possible to increase the number of tanks in the future if the effluent volume to be managed increases. Prior to the initial design acceptance, a key decision needs to be made on whether to over-design the system at the outset to accommodate future demand. Clearly this can only be done if sufficient budget is available, although cost-benefit analysis will show that retrospective expansion of an existing system will always be more costly. In some instances e.g. a construction in a basement where no additional space is available, it may be necessary to construct a completely new tank system in another location once expansion is required.

Further considerations relate to the type of tank and whether to locate the tanks above or below ground. For tanks located below ground, there is a disadvantage in that there will be an on-going requirement for an active pump to discharge the effluent to the sewage system. This requires electricity, system redundancy and on-going maintenance costs. If the tanks are located above ground, the key advantage is that discharge will be reliant entirely on gravity. This is especially advantageous in countries where the supply of electricity is very spasmodic and unreliable. Where an open top design of tank is constructed in a basement, there will be the need to consider possible gas build up. To alleviate this, it will be necessary to have appropriate ventilation and extract systems, which again have an on-going cost for electricity and maintenance which could be disadvantageous. In such circumstances, it would be advantageous to construct the tanks above ground in a secure compound under an open canopy, so dilution to air can be utilized. Security for a decay tank system must be tailored relevant to the prevailing conditions and is an important factor in deciding the best location for the tank system. Other issues such as bacterial growth during decay storage of the effluent and possible radiation exposures consistent with avoidance of dose must also be factored into the decision making process.

Initial and on-going training requirements are likely to be higher where a sophisticated tank system is installed e.g. the highly automated decay tank system given in Appendix I.2. This could be disadvantageous in a developing country where the knowledge expectations of the workforce are lower. Monitoring requirements will be different for manual and automated systems, specifically where the automated design has been identified as an advantageous design feature to reduce human intervention. This is more likely to be advantageous in a country where labour costs are high or where reduced intervention is necessary as part of dose control methods. Where a larger workforce is available to participate in the monitoring programme, a manual tank system can be advantageous due to the initial lower installation costs and reduce maintenance costs of the tank system. Another important consideration is the availability of spare parts and the timeframe from ordering to receipt of the component. In developing countries where spare parts would have to be purchased from outside the country and protracted timeframes for their delivery are further exacerbated by import difficulties, a simple system where there is little likelihood for components of the system to fail is clearly advantageous. There is a distinct advantage in having a decay tank system where the necessary spares can be sourced locally. A schematic example of such a system is given in Appendix I.4.

It may be necessary that the decay tank system has to also combine the flexibility to accommodate effluent pre-treatment. Such an option can simplify the process by separating out certain radionuclides or toxic content to ensure that the effluent will meet discharge criteria after the defined decay storage period. The elimination of longer-lived radionuclides by extraction from the effluent as a pre-treatment prior to decay storage will simplify the operation. Such an example of pre-treatment availability prior to decay storage is given in Appendix I.1.

5. FACTORS INFLUENCING DIRECT DISCHARGE TO THE SEWAGE SYSTEM

Direct discharge to the sewage system is widely practiced as it is often the best option for disposal of very low activity radioactive effluents typically produced in laboratories from radiotracer techniques and other similar practices. Although the radioactive effluent discharge is made directly to the sewage system, it will be strictly controlled through an authorization process, which places conditions and discharge limits on the operator. The fate of the radioactive discharges must be clearly understood and their impacts appropriately assessed. The impacts should be assessed both for people and the environment, to ensure that the practice remains acceptable with reference to doses received by the representative person, and that it remains the best discharge option for the radioactive effluent. The assessment of the impact of direct discharges made to the sewage system should consider the representative person for dose calculation purposes. This may necessitate calculating doses for people working to maintain the sewers, the workers at the sewage treatment plant and for members of the public, especially where their lifestyle activities may bring them into contact with the diluted effluents e.g. persons consuming fish caught downstream of an effluent discharge point from the sewage treatment plant.

For patients administered radionuclides as part of medical diagnosis, their urine and faeces will often be contaminated with excreted radioactivity. As many of these patients return to their home soon after being administered the radionuclide, it is inevitable that radioactive excreta will be discharged directly to the toilet facilities in their home. Where inadequate domestic sanitation arrangements exist, as occurs in certain parts of the world, such direct discharge arrangements might be inadequate to provide sufficient protection to family members and other persons, as well as to the environment. In such circumstances, the practice of direct discharge should not be authorized. A number of factors need to be considered prior to selecting direct discharge of radioactive effluents as the most appropriate discharge option.

The factors influencing direct discharge to the sewage system, while not exhaustive, may include:

- Knowledge of the local population and their habits;
- Impact on animals used as a human food source that might ingest the effluent after discharge;
- The level of development of the sewage system;
- Number of establishments/institutions discharging to the same sewage system;
- Impact upon the environment of the proposed discharge;
- Doses to the representative person;
- Regulatory criteria.

Direct discharge of the radioactive effluent to the sewage system should be made in accordance with the terms and conditions of an authorization granted by the Regulatory Authority. In order to make an assessment of the discharges made to the sewage system, their pathways should be known and the sewage system should be modern and not leak sewage into the surrounding environment. Direct discharge of radioactive effluent will be further diluted by other effluents discharged to the same pipes within the boundary of the facility, and will achieve further dilution with wastes from other sources both en route to, and once the effluent arrives at, the sewage treatment works. Information on the dilution of effluents should be known as it will be required when modeling the impact of the discharges.

Conditions are usually specified in the authorization under which discharge of small volumes of radioactive effluents from laboratories can be decanted to the drainage system of a sink or sluice. To avoid the build-up of contamination in the drainage pipes, it is common for the tap water to be running for a suitable time period both before and after the liquid discharge is made to the drain. For most purposes, 10 minutes both before and after making the discharge might be sufficient.

Although individual facilities will assess the impacts of the discharges from their own site, it is important to remember that there may be many facilities discharging radioactive effluents that would be processed through the same sewage plant, hence their collective impact will also need to be considered and assessed by the regulatory body prior to specifying the authorized discharge limits permitted for a given facility. The excreta from patients undergoing treatment in nuclear medicine departments has been recognized as the most significant contributor to the radiation doses received by the sewage treatment plant workers [14]. A case by case assessment for individual hospitals usually demonstrates that the doses received by the sewage workers from the discharges from a specific hospital are below the dose limits set for a member of the public [14].

Work by Titley et al. [15] has indicated that if substantial activities of radioactive waste from a non-nuclear site are discharged directly to a sewage works, there is potential for sewage workers to receive significant doses. It is important to have an understanding of the fate of the radionuclide effluents once they are discharged. The fate of Iodine-131 discharged to the sewers has been modeled and quantified by Punt et al. [16]. Once discharged to the sewer, Iodine-131 will be transported to the sewage treatment works where it may become associated with sewage solids or discharges to surface waters with treated sewage effluent. During low flow periods, bio-solids settle out in the sewer and it is possible that some of the Iodine-131 will be retained in the sewage system. Approximately one third of the iodine activity received at the treatment works is believed to become associated with solids during initial sewage treatment and hence will not be discharged with treated effluent [16].

In natural aquatic systems iodine tends to remain predominantly in the dissolved form, primarily as iodide (I-) or the slightly more reactive iodate (IO_3) under oxygenated conditions, both species of which are generally repulsed from the negative charges on most sediments. However, sorption to organic material and clay sediments can occur, particularly as pH decreases. Iodine can also form organic complexes with humic substances [17] and this can prompt adsorption of iodine onto bio-solids in the sewage system and at the treatment works [18]. Therefore, when assessing possible doses from a site which directly discharges to a sewage system, it is important that the doses to sewage treatment plant workers are assessed. Account also has to be taken of the radiation doses that could arise from the disposal of the sewage sludge [19] which may be spread on agricultural land, hence generating further pathways for exposure of the public either directly or via the food chains.

In some circumstances, the pathways for exposure of the public other than sewage workers must also be considered. Where the outflow from the sewage treatment works discharges into a watercourse that is used by local fisherman, further exposure pathways must be considered e.g. local radiation background, ingestion of fish and accidental ingestion from falling in the water. Calculation of these parameters might identify that these members of the public are the critical group rather than the sewage treatment workers. Descriptions and guidance on radiological assessment for the disposal of radioactive waste from universities, hospitals and medical and industrial research establishments are given in [14].

6. ENGINEERED STORAGE OF RADIOACTIVE EFFLUENTS FOR DECAY

The radioactive effluents generated may vary in the volume and frequency of generation as mentioned in Section 4. However, if the amount of effluents generated is relatively high and the liquid waste is regularly produced, a specific system should be in place to store and decay the effluents as they are generated. Specific details of a storage arrangement, which involves designing a series of shielded storage bins to hold the waste containers for decay, are given in Section 4.2. Further information on the design and operation of decay tank systems is provided below. When designing a decay tank system, the licensee should make provision for the future decommissioning of the facility and identify any special features in the design to facilitate decommissioning.

6.1. DECAY TANK SYSTEM

A decay tank system consists of one or more tanks that are often connected together, and used to collect and store effluents. A decay tank system is usually the best option for decay storage when quantities or activities of radioactive effluents are above the authorized limits for direct discharge. Decay tanks may be used singly or connected in series and may have limited or extensive levels of automation for their operation. A technical drawing of a single decay tank is given in Figure 2. A picture of two tanks, which are part of an inter-connected series of four tanks installed in a hospital, is given in Figure 3.

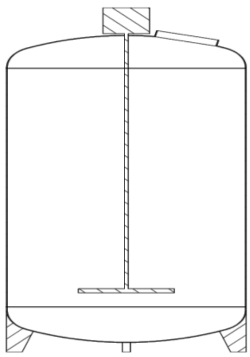


FIG. 2. Technical drawing of a decay tank with stirrer.

FIG. 3. A view of decay tanks installed in a medical establishment.

6.1.1. Design for a decay tank system

6.1.1.1. Suitability and sustainability of design

Suitability and sustainability of design are two essential considerations when designing a decay tank system for radioactive effluents. When deciding on the best option in a developing country, often contractors external to the country are engaged to design and construct the selected option e.g. decay tanks. It is essential that the contractor does not design to what he believes ‘might’ be required, based on knowledge from his own country or past experience, but instead designs a system that is appropriate for the present projected requirements of the facility, whilst allowing reasonable additional spare capacity. If the contractor has inadequate knowledge or understanding of the needs of the facility, which can occur due to inadequate data provided by the facility of what their projected waste storage requirements might be, he is likely to design a facility that is not suitable for the required purpose. This might result in the installation of an over- or under-sized tank system, or an over-engineered design, that makes it too difficult to operate and maintain, and therefore inappropriate to the needs of the facility. This may result in the tanks not being used because they fail to meet, or exceed, the requirements of the facility and hence are unsuitable for their intended purpose. An over-engineered or over-sized tank system will not be cost effective to operate.

Furthermore, the technology and availability of spare components to maintain the decay tank system, and the level of expertise of engineers within the developing country, might be such that they will be unable to maintain or repair the tanks system should it fail. This should be avoided by matching the technology of the system to the capabilities of the maintenance staff at the facility. This necessitates consideration of what increase in sustainable knowledge might reasonably be achieved by local staff from provision of a short training course on maintenance and operation of the tank system, usually provided by the contractor at the time that the tanks are installed. The management of the institute or the hospital should ensure that all relevant staff is familiar with the work procedures for operation and maintenance of the tank system and that compliance with the procedures is within their technical capabilities. The institute or the hospital should also set up a system that would preserve this knowledge for future staff members. Basic technical requirements and skill for the operational staff should be well defined, documented and adhered to when appointing new staff members. Prompt local availability of spare components for a suitable future time period, e.g. a period of ten years, should be ensured before such components are included in the design of the system.

Before entering the tender report stage for design of a suitable decay tank system, it is essential that a comprehensive data collection, relevant to the facility requirements is made. This should include all details of the radioactive effluents that might require storage in the tanks at the facility prior to discharge. Examples of the data that should be provided to the contractor might include:

- Details of all the radionuclides and their activities, specific activity and effluent volumes that are currently being discharged, either regularly or irregularly;
- Information of any projected new uses of radionuclides in the following 5-10 years, with estimates of what liquid effluents might be produced;
- Regulatory requirements for discharge;
- Constraints on the available space where the decay tank system is to be constructed.

This list is not exhaustive, but only gives an indication of the type of information that might need to be provided to the contractor.

This information should also include a forward look of what further increases in effluents for management might arise over the coming years of operation. Whereas it is essential that the decay tank system should allow capacity for increases in the discharges, it should not be over-sized such that it will not be used because it is uneconomic to operate. Ideally the area in which the tank system is to be constructed should allow sufficient floor space that would allow the installation of additional tank(s) in the future if required but should also facilitate ease of decommissioning.

6.1.1.2. Design considerations for the decay tank(s)

It is important to design a decay tank system with an optimum number of tanks to meet both the facility specific conditions and workload requirements. This will include consideration of issues such as effluent volume, radioactivity level, half-life of the radionuclides and effluent generation frequency. The cost of the system should be considered during the design stage and an optimization study should be carried out to achieve installation of the optimum number of tanks that will be cost-effective to operate. Decay tank systems are usually designed as two or more tanks in series, although in some cases, the tanks may also be installed in a parallel configuration. An example of a number of individual tanks, each collecting a different waste stream i.e. beta/gamma emitting radionuclides of half-lives less than 100 days, is included in Section 4.2. The design parameters and requirements of the facility determine the volume and number of the tanks to be installed. The decay tank system operates in such a way that one tank might be filling while the content(s) of the other(s) are decaying. The design of the tank system should meet the following general requirements [20]:

— It should be constructed of suitable materials e.g. stainless steel, concrete or high density polyethylene (HDPE), which should be of good quality that it will remain free of leakage for the entire lifetime of the decay tank system;
— It should have sufficient volume capacity to store current effluent production and be able to accommodate increases in volumes that may occur in the future. Additional volume capacity for the last tank in the system could be useful to prevent flooding or alternatively a separate buffer tank to hold any overflow of effluent could be installed;
— It should have ease of access for normal operation, maintenance and for emergency interventions;
— It should aim to minimize the workload of the operator. One method by way this can often be achieved is by ensuring an optimized number of tanks is installed, such that there is sufficient capacity to allow the contents of filled tanks to decay prior to discharge;
— It should have appropriate and adequate safety systems in place, to provide advance warning if the tanks are under threat of overflow e.g. level controllers;
— it should have an appropriate system of instrumentation and control valves to operate when the tank level is almost full to capacity, so that the effluent may manually or automatically be switched to the next tank or discharged if the content meets the regulatory criteria;
— It should have provisions for sanitary control;
— It should have appropriate warning signs;
— It must incorporate features to facilitate future ease of decommissioning.

The design of the tank system should also consider incorporating some or all of the following features [20]:

— It might be fitted with a secondary enclosure of sufficient volume to hold the contents in case of tank(s) failure. Where such a design feature is not incorporated on the tank, this objective must be addressed by appropriate features of the storage area;
— where tanks are constructed of concrete or metal, the tank might have an internal lining of a corrosion resistant material to minimize any possibility of internal corrosion/concrete degradation;
— It might have sampling points which allow sampling of its content;

— It might have a trap door to allow visual inspection to check for the build-up of any internal deposits e.g. scale, on the base and sides of the tank, and to allow access for cleaning if required;
— It might have a mechanical stirrer/agitator to keep the contents in motion during sampling and discharge, which would reduce the incidence of scale deposits;
— It might have a pressure relief valve to permit release of any gaseous build-up that might occur in the tank(s);
— It might be provided with an aeration system for septic control.

6.1.1.3. Design considerations for the storage area

Specific design requirements of the storage area to hold the tank system are often a regulatory requirement. The suitability of whether the tank system might be installed within an enclosed building, or outside under a canopy, depend upon a number of factors. These factors may include consideration of issues such as climatic conditions, topography of the area, control of public access and ability to implement adequate safety and security measures. The design of the storage area might be further constrained by prevailing conditions at the facility e.g. does a room already exist where the tank system is to be installed or must a new location be found to accommodate this new construction ?

It is recommended that the decay tank system is constructed above ground for ease of maintenance, for emergency interventions and to facilitate decommissioning. Where space above ground cannot be found, or when a tank system is to be installed as part of construction of a new facility, construction in the basement of the building might be the preferred option. Whereas design planning for a basement installation may adequately provide for routine operation and maintenance, including emergency interventions, problems are usually encountered when the facility requires decommissioning. The placement of tanks directly into a hole dug in the ground is to be discouraged under all circumstances.

A decay tank system could be installed inside a building or outdoors and the tanks could be configured as horizontal or vertical. Decay tanks should be located as far as possible away from where the public have access, and if placed external to the building, should be surrounded by security fencing. When considering if it is appropriate to construct a tank system external to the facility, it is important to consider the following factors:

— The suitability of the prevailing weather conditions;
— The cost effectiveness of this construction option;
— The ease of access for operation, maintenance and transport;
— The option to avoid the need for a ventilation system where foul odours require dispersal;
— The advantage of construction in a remote location to which the public will not have ready access, hence facilitating better security arrangements;
— The availability of additional space to facilitate construction of additional tanks to meet future needs.

Specific design requirements for a storage room to hold the decay tanks should include the following features:

— Dose rate monitoring capability, (manual or automatic);
— Impermeable finishes to the walls and floor for ease of decontamination;

- Arrangements to capture any effluent leakage and to provide adequate security e.g. Combination door locks;
- Appropriate warning signs;
- Ease of access for routine operations and maintenance and for emergency interventions e.g. Access for the fire service or to transfer stored effluents into temporary storage in a tanker;
- Additional floor space to facilitate future construction of an additional tank should this be necessary.

The design of the storage room might also include some or all of the following features:

- Closed circuit television (CCTV) cameras to provide improved security arrangements;
- A concrete up-stand around the perimeter of the decay tank system or provision of a perimeter drainage grill with an interceptor tank at the sub-floor level to hold any leakage, which can be later pumped out;
- A storage space to hold the spill kit required as part of emergency arrangements. Further information is provided in Section 8;
- A fire detection and alarm system.

Design requirements should be tailored to the relevant regulatory requirements of the country and not all of the above design requirements may be necessary. The design of the system with tanks with double wall cannot be over emphasized. This feature substantially enhances safety of the design, especially in a case of "single Tank" use.

An example of calculation for the design of a decay tank system is given in Annex I.

6.1.2. Operation of the decay tank system

The operation of a decay tank system consists of a number of activities. The first stage is collection of the effluent, which in the second stage, is stored for a pre-defined time period. The third stage may include sampling and analysis, although this may not always be necessary, as assurance that the effluent will be suitable for discharge may have been achieved through design of the operating system. The next stage is discharge of the effluent once authorized discharge limits have been achieved through decay. The final stage is completion of the required monitoring arrangements. Throughout the operation of the decay tank system, due consideration must be given to its maintenance.

The operation of a decay tank system should be carried out as part of a management system to include technical and administrative arrangements. The technical arrangements might include the operation, maintenance, effluent and/or environmental monitoring, recording and reporting. The administrative arrangements might include staff training, emergency planning and provisions for security of the decay tank system and the records. All of the above will be supported by a comprehensive quality assurance programme, which incorporates the work instructions and operational procedures.

A schematic for the design of a flexible operation decay tank system is given in Figure 4 and the figure illustrates how the tank system can be operated in two different ways. Firstly, the tanks can be operated in series, with suitable connections between the tanks. Secondly, by following the broken lines shown, it can be seen how the design of the system permits for the operation of each tank as a single unit since each tank has its own inlet and outlet.

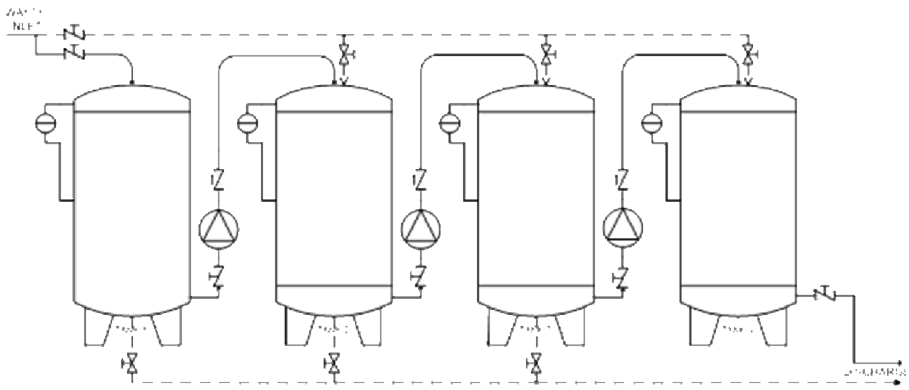


FIG. 4. Schematic for a decay tank system.

The control of operation of the decay tank system can be done via a manual or a computer aided system. Computer systems could be used to on-line control and view the status of the tank system via automated software, where the level of the tank(s) can be seen on-line and pump(s) and valve(s) can be automatically operated via a software interface. A picture showing an example of the software interface for a decay tank system is shown in Figure 5.

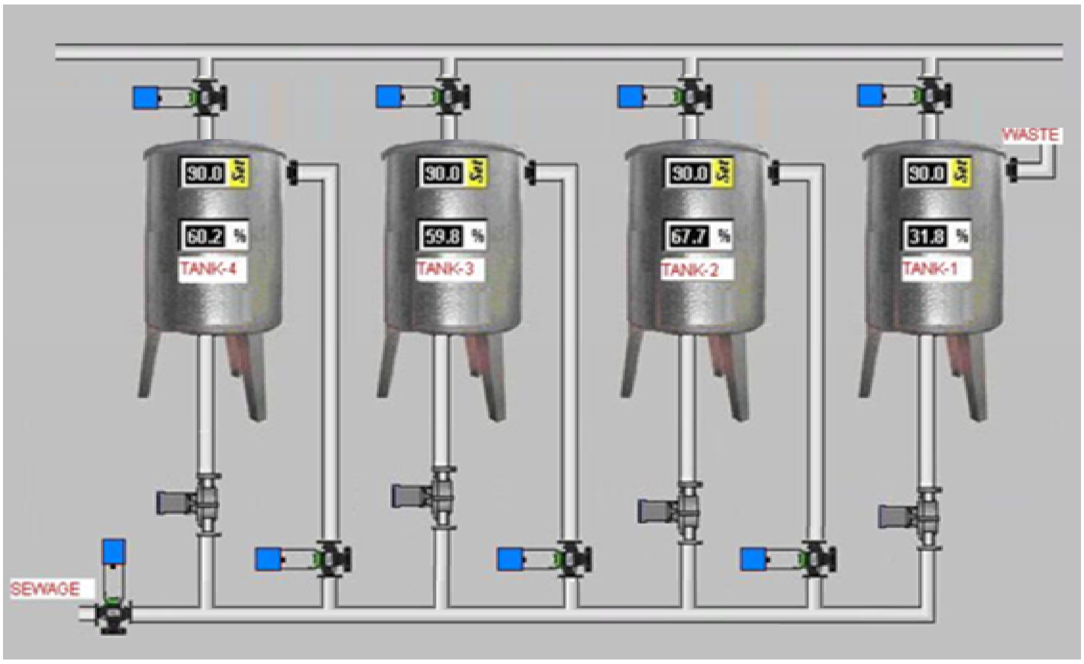


FIG. 5. A typical software interface showing the status of control of a decay tank system.

The pump system might consist of pump(s), level sensor(s) and a control board. The effluent level measuring system might consist of level meter(s), level sensor(s) and an alarm. The design should provide for the operator to switch on the pump [either manually or via a computer] for transfer of effluents between the tanks or to make a discharge. Computerized discharge needs radioactivity measurements for operational control.

As part of routine operation, measures should be implemented to prevent any overflow of the effluent from the tank systems. Visual inspections and radiation checks should be carried out periodically to assure that no leakage from the tanks, pipes or connecting instruments is occurring. A list of operational checks/tests to be carried out should be provided to the operator. A supply of disposable gloves, face mask, absorbent granules, hazard warning tape, and possibly a radiation detector should be available in the area.

Maintenance can be considered under several sub-categories:

- Routine maintenance, which will be carried out to a written routine schedule during normal operation of the decay tank system e.g. Checking the operation of the alarm system, lubrication of valves etc.;
- Planned preventative maintenance – which is often carried out to a pre-defined time schedule, but will not occur as frequently as routine maintenance. This may include periodic cleaning of the tanks to avoid unacceptable levels of scale depositing on the internals of the tank;
- Contingency maintenance – this will be carried out as a result of problems with the tank system, and usually is an unplanned activity as a result of failure of one or more aspects of operation of the decay tank system.

Provision for periodic maintenance, repairs, and area contamination checks in and around the decay tank system should be mandatory [21]. Checking of the plumbing system to ensure that it remains leak-free should also be carried out periodically. A copy of the emergency arrangements should be made available and accessible at an appropriate place in the vicinity of the decay tank system. More information on emergency arrangements is given in Section 8.

Security should be in-built for both the design and operation of the tank system. A key consideration is control of access, which can be addressed in a number of ways:

- Deterring unauthorized access to the tank system;
- Detecting intrusions e.g. using motion sensors, CCTV or security guards;
- Assessment of the extent of the intrusion;
- Delay of intruders;
- Effective response capabilities;
- Security management.

6.1.3. Radiation protection considerations

Radiation protection principles should be considered during the design and operation of the decay tank system. The aim is always to achieve dose minimization for the operators, and any other exposed persons, including members of the public. When considering dose minimization for the workers at the facility, the following items need to be considered:

- Dose reduction achieved through design of the decay tank system e.g. Ease of operation, level of automation and reduced maintenance requirements;
- Procedures and work instructions aimed at ensuring all doses remain as low as reasonably achievable;
- Training of staff and refresher training at appropriate intervals to ensure they remain up to date in their knowledge;

- A personnel monitoring programme with appropriate review to ensure ongoing dose reduction where achievable;
- Provision of relevant Personal Protective Equipment (PPE);
- Clear identification and signage of the entire drainage network carrying radioactive discharges for the benefit of site maintenance workers not directly involved with operation of the decay tank system e.g. plumbers who may open the interceptor tank remote from the decay tank system to deal with a blockage in the pipes carrying effluent that has been discharged. Such workers should only be allowed to carry out emergency maintenance in compliance with written procedures, supported by appropriate monitoring and wearing of suitable PPE to ensure minimization of their radiation exposure.

For computer controlled tank systems, the operator will receive a lower radiation exposure compared to a manually operated decay tank system, although this statement may not apply to the doses received from maintenance operations. An area monitor could be installed to monitor the dose rate in the area where the decay tank system is installed. The decay tank area may be designated as either a controlled or supervised area, such that the doses received by those working in the area are either directly measured or can be extrapolated from knowledge of time spent in the area and typical exposure rates.

Although radiation protection should be intrinsic to all aspects of work involving radiation, the doses to maintenance workers carrying out planned periodic maintenance of a series of decay tanks requires specific consideration. The design of an automated facility should be such that the requirement for an extensive monthly maintenance schedule, necessitating close proximity to the highly active storage tanks, will not be required. An example where the doses received by maintenance workers were unacceptable is given in Appendix I.2.

Radiation protection of the public requires consideration of all possible pathways of exposure. To minimize, or to ideally prevent the possibility of direct exposure of the public, the decay tank system should be in a secure location where the public will not have ready access. If the public may be able to access that part of the site, the decay tanks should be either located inside a secure building, or if constructed outside, close access should be prevented through construction of suitable security fencing. Any area where the public might reasonably be exposed to radiation if they were to make unauthorized access, or where background radiation doses are such that they should not linger in the area, should be clearly identified through appropriate radiation warning signs. The emergency arrangements for the facility must include actions to be taken in the event that unauthorized public access to the decay tank system results in contamination of a member of the public.

Another group that needs to be considered is workers whose employment does not involve work with radiation, but who may be occupationally exposed to radiation as a result of the activities of others e.g. sewage treatment plant workers exposed due to discharged radioactive effluents. For their protection, both the operator and the regulatory body have responsibility to ensure that discharges are only made at or below the authorized limits. Any modeling for the fate of radionuclides discharged should ensure sufficient margin of safety to provide for uncertainties in the assumptions that are made when estimating the doses to the representative person.

7. RADIOLOGICAL MONITORING DURING AND AFTER DISCHARGE

Radiological monitoring is a mean by which measurements and their interpretation assessed and utilized as part of the control of exposure to radiation. There are several purposes of a monitoring programme, and the most important one is to ensure exposures to the representative person are maintained at an acceptable level. This is achieved through the terms set by the regulatory authority in the authorization process. Provided that the requirements established by the regulator in granting a discharge authorization are satisfied, and in particular, that the assumptions about conditions in deriving the authorized discharge limits remain valid, permissible doses to the representative person will not be exceeded. The monitoring programme should enable exposures to the representative person to be assessed with the appropriate degree of confidence [3].

The Regulatory Authority may require the operator to monitor discharges, depending upon the selected discharge option. The scale and scope of the effluent monitoring and/or environmental monitoring programme and the methods of measurement used, should either be set by, or agreed with, the Regulatory Authority. Prior to discharging effluent, it may be necessary to carry out preliminary monitoring, which provides baseline information before any new discharge activity commences. The monitoring parameters for discharged liquid effluent, as a minimum, should consist of measurement of the volume, types of radionuclides present, and the activity level. Although outside the scope of this report, it may also be necessary to identify and measure any other hazardous chemicals which might be present in the discharged effluent that might be subject to other regulatory requirements.

Frequently, the monitoring and sampling requirements are specified within the terms of the authorization. For such circumstances, an appropriate monitoring programme should be established and executed. The monitoring programme might include effluent and/or environmental monitoring based on the radiological assessment carried out in support of the authorization. Guidance for determining whether an effluent and/or environmental monitoring programme is likely to be required is given in Reference [3]. The average activity level of the discharged effluent can be ascertained over an agreed representative period through routine monitoring, based on the pattern of discharges. If the discharge activity is below the exemption levels set by the regulatory authority, neither effluent monitoring nor environmental monitoring might be required. The degree of environmental monitoring required is linked to the assessed representative person dose. In some cases, only limited environmental monitoring for a defined time period will be required to support the assumptions made in the assessment of the impact of the effluent discharges. Any discharge exceeding an authorized limit should promptly be reported to the Regulatory Authority, who may require the operator to carry out additional environmental monitoring and provide a written report on the impact of the unauthorized discharge.

Environmental monitoring, which provides an additional opportunity to check for unexpected releases to the environment, might include methods such as sample collection, analysis and environmental surveillance. Effluent monitoring should be carried out to ensure that effluents are appropriately discharged to the sewage system. In some cases, the effluent may require on-line monitoring during discharge and if so, appropriate equipment should be installed to demonstrate that the regulatory criteria for discharge are being met. If discharge activity is very low, on-line measurements may not be sufficiently sensitive to meet regulatory discharge criteria and therefore sampling will be required.

Where the regulatory body requires the operator to carry out an environmental monitoring programme, its design should be consistent with its objectives. Measurements should be made and sampling carried out at appropriate locations outside the boundary of the facility that are accessible to the public. Sampling locations should be selected close to the points where the maximum radionuclide deposition is anticipated to occur [22]. Where an environmental monitoring programme is required, the records should be retained for the period required by the Regulatory Authority.

The plumbing systems should be periodically checked to assure that it is not leaking. Radiation levels around the decay tank system could also be monitored with an area monitor as part of the monitoring programme. The operator should keep appropriate records of the monitoring programme and report to the Regulatory Authority at approved intervals.

8. EMERGENCY ARRANGEMENTS FOR STORAGE OF RADIOACTIVE EFFLUENTS

Where large volumes of high activity liquids are stored within a confined area, whether in containers or a decay tank system, the full range of potential hazards must be identified and their potential consequences assessed e.g. fire, leakage, adverse weather conditions, explosion, sabotage and build-up of gases. Written emergency arrangements should be prepared for all reasonably foreseeable accidents or incidents, and these should be incorporated into the emergency plan for the facility. A copy of the emergency arrangements should be readily available by the tank system. Relevant staff should be trained in implementation of the emergency arrangements and any identified emergency equipment should be readily available in the effluent storage area and should be periodically checked to ensure it remains in good working condition.

Whereas the design of a decay tank system should include features to prevent the unplanned overflow of effluents from the tanks or for large spillages at the time of discharge, the possibility of failure of the sensors or level detectors on the tanks leading to accidental spillages should be anticipated. A detailed response plan on how to mitigate the effects of such a failure should be established and staff trained in its implementation. In case a decay tank starts to leak, the emergency arrangements should promptly be implemented to avoid further leakage of the effluent. A typical emergency arrangement might include the hire of a tanker vehicle suitable to transfer the effluent content into, as a means of temporary storage until the leaking tank can be repaired. Once repaired and checked for its integrity, the liquid will be pumped back into the decay tank from its temporary storage in the tanker vehicle. The possibility of a catastrophic tank failure that cannot be repaired must also be considered. In such circumstances, it might be necessary to use a tanker for storage of the effluent for the entire decay period. The emergency arrangements should include decontamination of the tanker vehicle before it is returned to regular operation. If implementation of the plan necessitates ready availability of a hired tanker into which the residual effluent must be transferred, a contract must be in place to ensure that the contractor will fulfill this emergency requirement.

Where decay tanks are in routine use, especially in hospitals, all potential scenarios that might lead to inadequate capacity for storage being available should be considered. This might include leakage of a tank that has to be taken out of use when the other tank(s) are already full. Where it is not possible to promptly repair the leaking tank, the ongoing excretion of radioactive excreta by patients in the hospital will continue even if tank capacity is not available for its storage. The emergency arrangements must provide for interim storage of such effluents in a safe way until normal services can be restored. This might typically involve the hire of a tanker.

For an automatic operation decay tank system, a serious fault in the electricity supply or catastrophic system failure may accidentally lead to the opening of the discharge valve at a time when the system is not appropriately prepared to discharge into the sewage system. Appropriate emergency arrangements must be in place to deal with such possibilities. An emergency power supply that automatically operates immediately after the domestic power supply fails might be necessary as part of the emergency arrangements.

For container storage of effluents in a suitable radioactive decay storage area, a copy of the emergency arrangements should be available. An emergency spill kit containing gloves, plastic aprons, face masks, absorbent wipes and granules, hazard warning tape, mop and bucket, supplies of containers for transfer of contents from leaking effluent containers etc. should be readily available in the effluent storage area. Again, staff should have been appropriately trained for implementation of the emergency arrangements, which should include a capability to restrict access to the effluent storage area until the leakage has been appropriately dealt with and the area has been declared free from contamination.

9. QUALITY ASSURANCE

Irrespective of the option utilized to manage effluents for discharge, it will be necessary to establish an appropriate quality assurance system to ensure that adequate measures are in place for addressing technical and administrative issues such as system operability, safety, health, environment, security, quality and economy of operation, including security of adequate finance. The programme should include planning, implementation, reviewing and actions that would result in a continual improvement, i.e. it should include assurance of each stage for the selected management option. Starting from the design stage, the intrinsic and desired properties that need to be qualified, monitored or otherwise assured have to be assessed for each step in the selected effluent management option. For the handling and storage operations, the requirements mainly concern the safety of the operators, security of the stored effluents from interference and the behavior of the storage containers and/or tanks under all possible conditions.

The quality assurance programme should include, but is not limited to the following;

(a) At the design stage:

- Adequacy of the system for the intended job;
- Compatibility of the system and its components with the processed material and the surrounding environment;
- Flexibility of the system for intended and unintended modes of operation;
- Suitability of the system for the expected technical level of operators.

(b) At the construction stage:

- Ensuring materials provided by suppliers for construction of the decay storage system are in accordance with the design and engineering specifications;

- Ensuring that the construction of the approved design of the decay tank system is fully compliant with the technical specifications, and where changes have been agreed , these are clearly documented;
- Final inspection, commissioning and acceptance of the decay tank system, with agreed timescales for correction of any problems identified that require rectification.

(c) During operation:

- Documenting written policies, plans, procedures and instructions (for both normal and emergency situation). It should identify the scope of the activities to be covered and provide for performing work under controlled conditions by designated qualified personnel;
- Carrying out of audits, at an appropriate frequency and the inspections to be made and recorded;
- Providing appropriate training to the workers based on their level of education and experience commensurate with the scope, complexity and nature of the work, as well as defining their roles and responsibilities;
- The operators who are responsible for completing the documentation and records to demonstrate compliance with the authorization conditions should be clearly identified and appropriately trained. All records from the design, construction, commissioning, operation of the decay storage system and monitoring of the discharged effluent have to be validated, verified and approved. These records should be safely retained for the required time period (records for design, construction commissioning need to be retained for the lifetime; operational records for a given period);
- addressing technical issues through independent verification and checking at all stages;
- Designating a responsible officer, who may also be the radiation safety officer to make the decision to discharge the stored effluent after a suitable decay period has elapsed. Where someone other than the radiation safety officer is authorized and trained to make the decision to discharge the effluents, the radiation safety officer should be informed when a discharge will be made;
- Identifying and recording non-conformances and their causes and implementing corrective measures to prevent or at least minimize their re-occurrence;
- At appropriate intervals, reviewing, updating and implementing new measures to meet regulatory requirements whilst ensuring their suitability and effectiveness. All activities that affect quality must be assessed, documented and reported to the management on a regular basis.

The quality assurance programme may also involve a number of components:

- The intrinsic quality of the process – the parameters measured or checks made as part of the quality assurance programme should be appropriately selected to match what needs to be assured. Examples are: sampling of the effluent at appropriate points to verify compliance to specific activity, ph or the chloride ion content to prevent corrosion, etc.;
- The rigorous implementation of the stages of the effluent management option so as to guarantee compliance throughout the process;
- The control of the effluent at the time of discharge to the sewage system to ensure conformity with the discharge limits and any agreed regulatory standards and criteria;

- The fulfillment of the quality assurance cycle through planning, implementation, reviewing and taking appropriate corrective actions that could lead to continual improvement.

In the planning stage, all administrative measures and relevant documents (i.e. Quality Manual, Procedures, Work Instructions and Forms) should be in place. In addition, there is a need to create awareness among the personnel through training in order for them to understand which requirements need to be fulfilled once the programme is implemented. At the implementation stage, the personnel should carry out the work in accordance with the approved procedures. Any non-conformance should be reported immediately, suitably logged and incorporated in the overall review of discrepancies. The last stage is to take necessary corrective actions, thus completing the cycle of quality assurance.

The quality assurance programme and audits should be tailored to match the simplicity or complexity of the effluent management option. Assurance of quality should not have to rely on exhaustive checking of the activity content of the final effluent prior to discharge – this should already have been guaranteed by the appropriate checks carried out during the various stages of the process.

As part of the overall decay storage arrangements an appropriate quality assurance programme should be established whenever an effluent and/or environmental monitoring programme is required. Measures to satisfy the following specific conditions should be incorporated into the quality assurance programme:

- Compliance to requirements relating to effluent and/or environmental monitoring and to obtain representative samples should be properly implemented;
- Determining appropriate samples to be collected and their sampling frequency;
- Establishing relevant procedures for the calibration and performance testing of measurement equipment;
- Establishing a programme of inter-comparison of measurements with other accredited measurement laboratories. This is particularly relevant where duplicate samples are provided to the regulator for independent measurement;
- Calibration of the measurements should be traceable to international standards;
- Analytical laboratories should be appropriately accredited;
- The record keeping system should be adequate.

The reporting procedure should be in compliance with that agreed with the regulatory body [3].

Appendix I

EXAMPLES OF THE DECAY TANK SYSTEMS

I.1. THE DESIGN AND OPERATION OF A LOW LEVEL EFFLUENT TREATMENT PLANT IN MALAYSIA

This plant has been designed to provide the operator with two options to operate the low level effluent treatment plant to manage active liquid effluent, namely:

(i) Decay storage and discharge;
(ii) Decay storage, treatment and discharge.

Liquid waste from all active sinks of the various laboratories is transferred into a central open $3m^3$ stainless steel tank located in a pit between four buildings. The effluent is then pumped to either of the two primary holding tanks, each of $5m^3$ capacity, located in the basement of the isotope production building, dependent on which tank is filling at that time. This effluent transfer can be done either automatically or manually. The primary holding tanks are equipped with stirrers. Once the first of the tanks is full, the valve will be closed and the effluent from the central pit will be transferred into the second tank. The effluent will remain in these tanks until the second tank is three quarters full. The retention period for decay in the primary holding tank is governed by the time it takes to fill the second tank to three quarters full. At this point, the effluent from the first tank will be released to one of the four collection tanks, each of capacity $20m^3$ (effective volume $17.5m^3$). The process of filling up the second collection tank begins as soon as the first tank is full. Similarly, the process continues with the third collection tank. As the filling of the third collection tank begins, the operator will take samples (at 3 sampling ports, top, middle and bottom) of the first tank for effluent quality analysis. This includes measurement of the required parameters: pH, total solids, suspended solids, biological oxygen demand (B.O.D.), chemical oxygen demand (C.O.D), and gross β/γ activity. The authorized discharge activity level for direct discharge of radioactive effluents containing mixed radionuclides was calculated using a worst case scenario based on the total activity present being Strontium-90. The authorized limit for direct discharge of the effluent is set by the regulatory body. If the results of the analyses of the effluent show that all measurement parameters are below the limits for authorized discharge, the effluent will be transferred directly to the holding tanks.

The second operational option for effluent management is implemented when the results of the analyses show that one or more of the measured parameter exceed the limits for discharge set by either of the two Regulatory Authorities (these discharges are subject to both authorized radioactive discharge limits set by the Atomic Energy Licensing Board, and separate discharge limits for the other chemical content of the effluent set by Department of the Environment). In such circumstances, it will be necessary to treat the effluent by means of a chemical flocculation-coagulation process. This process will be carried out on batches of the effluent, where after pH adjustment, aluminium sulphate solution (alum) and a coagulation agent are added. The treated effluent is then pumped into the flocculator, where the solid phase settles to the bottom and this solid settlement is later pumped into one of the settling tanks. The treated supernatant from the flocculator will be pumped into one of two retention tanks. When the first retention tank is full, samples are taken for analysis. If the analyses reveal that the effluent meets all relevant discharge criteria, it will be transferred to the final holding tank which has a capacity $100m^3$. Should analyses reveal that the effluent does not meet all of the discharge criteria it will be pumped back from the retention tank into the collection tank and will start the treatment cycle again.

The final stage of the process, when it has been demonstrated by analysis of samples that the effluent meets all of the discharge criteria, is to pump the effluent from the holding tank into the dilution pond. The dilution pond is a man-made lake within the boundary of the site. Transfer of the effluent from the holding tank into the dilution pond provides a further dilution factor of one thousand to the effluent. The man-made lake connects to a stream which eventually flows into the river, again providing further dilution of the effluent discharge.

The pictorial schematic below aims to demonstrate the dual operation options for this effluent management plant. The pictures do not include the initial stages of the stainless steel tank in the pit between the four buildings or the two primary holding tanks located under the laboratories. The picture only shows the main operational plant that has been constructed on a single area of the site which is bounded by a concrete up-stand to retain any effluent leakage, with the entire plant constructed under a roof canopy to provide protection from adverse weather conditions. The arrows indicate the two options for operation of the plant.

Although this effluent storage, treatment and discharge system was designed to deal with the effluents produced on a very large site, it could readily be adapted as suitable for the design of a centralized radioactive effluent processing facility to deal with the liquid wastes produced within a country.

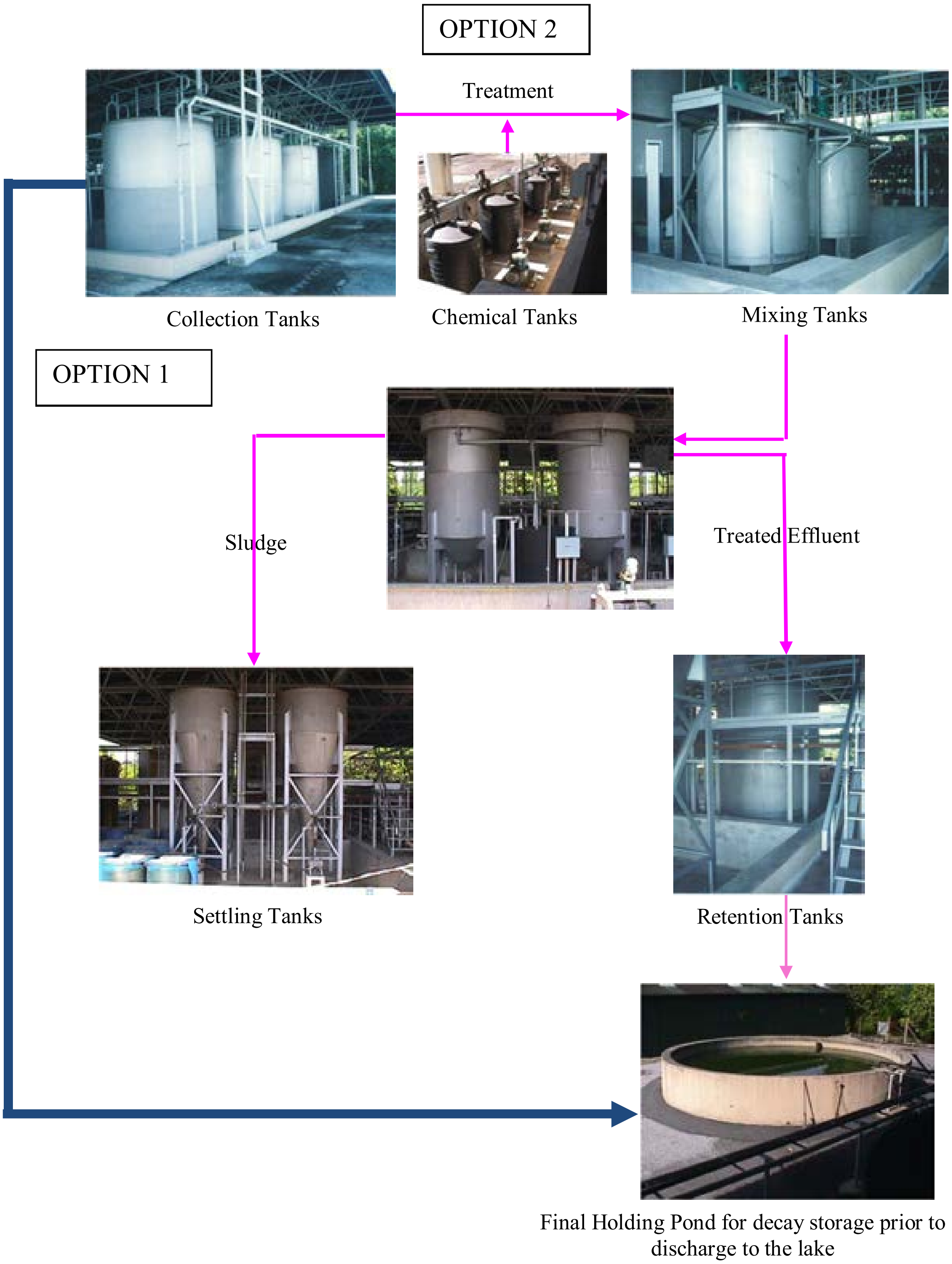


FIG.6. Decay storage system with pretreatment option.

I.2. DESIGN AND OPERATION OF A LIQUID WASTE DECAY TANK STORAGE SYSTEM AT A HOSPITAL IN THE UNITED KINGDOM

IAEA wishes to acknowledge the provision of pictures and data by Professor Peter Marsden to facilitate inclusion of this example of a highly automated decay tank system in this report.

A large multi-storey hospital in the UK was to be constructed with scheduled completion in 2005 and it was to incorporate extensive facilities for cancer diagnosis and treatment to meet the anticipated future demand, namely;

- 721 in-patient beds;
- 6 radiotherapy bunkers;
- 10 unsealed radiotherapy en suite bedrooms;
- 38 rooms with imaging equipment;
- 2 cardiac catheterisation laboratories;
- The hospital was built as a PFI (Private Finance Initiative) & cost £422 million to construct.

The hospital would have 10 in patient radionuclide therapy en suite bedrooms. A typical administration of 7.5 GBq of Iodine-131 is administered to the "average" therapy patient, but in some instances, much higher administration activities are required, which could be as high as 30 GBq. Based on 40 administrations of 7.5 GBq per month, assuming it is all excreted, 325 GBq Iodine-131 might be discharged per month from the toilet in these bedrooms. Once the higher administrations of up to 30GBq are factored in (as increasingly patients have a period of remission prior to a requirement for further treatment), an allowance for these higher activities resulted in an authorized discharge limit for Iodine-131 of 625 GBq per month being sought. Prior to granting an authorized discharge license, the regulator requires the operator to draft an environmental impact assessment to support the proposed discharge limits, having due regard to protection of people and the environment.

If the hospital was to discharge Iodine-131 liquid waste at the maximum level of 625 GBq per month (as being sought in the authorization) by direct release into the sewage system, the representative person of interest was identified as the sludge press workers at the local sewage treatment works, which is the largest sewage treatment works in Europe. An annual estimated radiation dose to these workers from direct discharge of the excreta of 40 patients per month treated with Iodine-131 would be of the order 185 µSv/year (see Figure 7). By installing a decay tank system to hold the waste for even a minimum time period of 30 days, this would reduce the impact of the discharge to the representative person to 6µSv, therefore it was a regulatory requirement that the new hospital was constructed with a series of decay storage tanks to achieve this dose reduction. Note that this tank system is designed to hold the effluent for between 30-40 days whereas many other tank systems for Iodine-131 hold the effluent for 3 months. The reason for this is that the dose to the representative person from discharging after approximately 30 days was less than 10µSv/year, which the regulators accept as being below regulatory concern for further abatement. Note also that radioactive discharges from sewage treatment works are not made into a water body from which drinking water is abstracted.

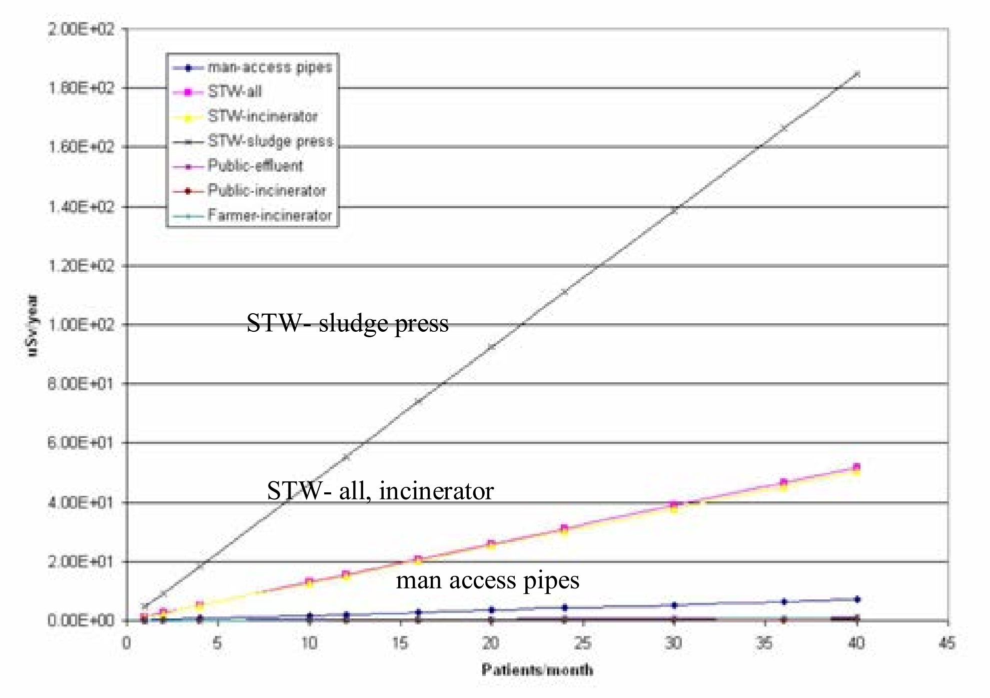


FIG. 7. Estimated doses in µSv per year to a range of workers due to direct patient discharges of Iodine-131 to identify the critical group.

A highly automated decay tank system was designed that consists of five 5000 litre tanks in parallel (Figure 8). When one tank is full, the level sensor in the tank detects it and the automated system will trigger the closing of the tank inlet valve. The system will then automatically switch to filling of the next tank. As the fifth tank starts to fill, the first tank will commence discharge of its contents. Because the tank system is located in the third level basement below ground, a peristaltic pump is required to pump the discharge from the tanks upwards to reach the main sewer. The whole system is software driven from a computer server (Fig. 9) although there is a manual override system panel (see Fig. 10). This panel also has a full series of warning lights to advise on the status of the individual tanks including the buffer tank. Should the level sensor in any of the five tanks fail, the tank would overfill and a pressure release valve would automatically open and drain the excess into the buffer tank (Fig. 11), located opposite to the five tanks in parallel. As soon as the buffer tank starts to fill, this will set off an alarm at the control panel.

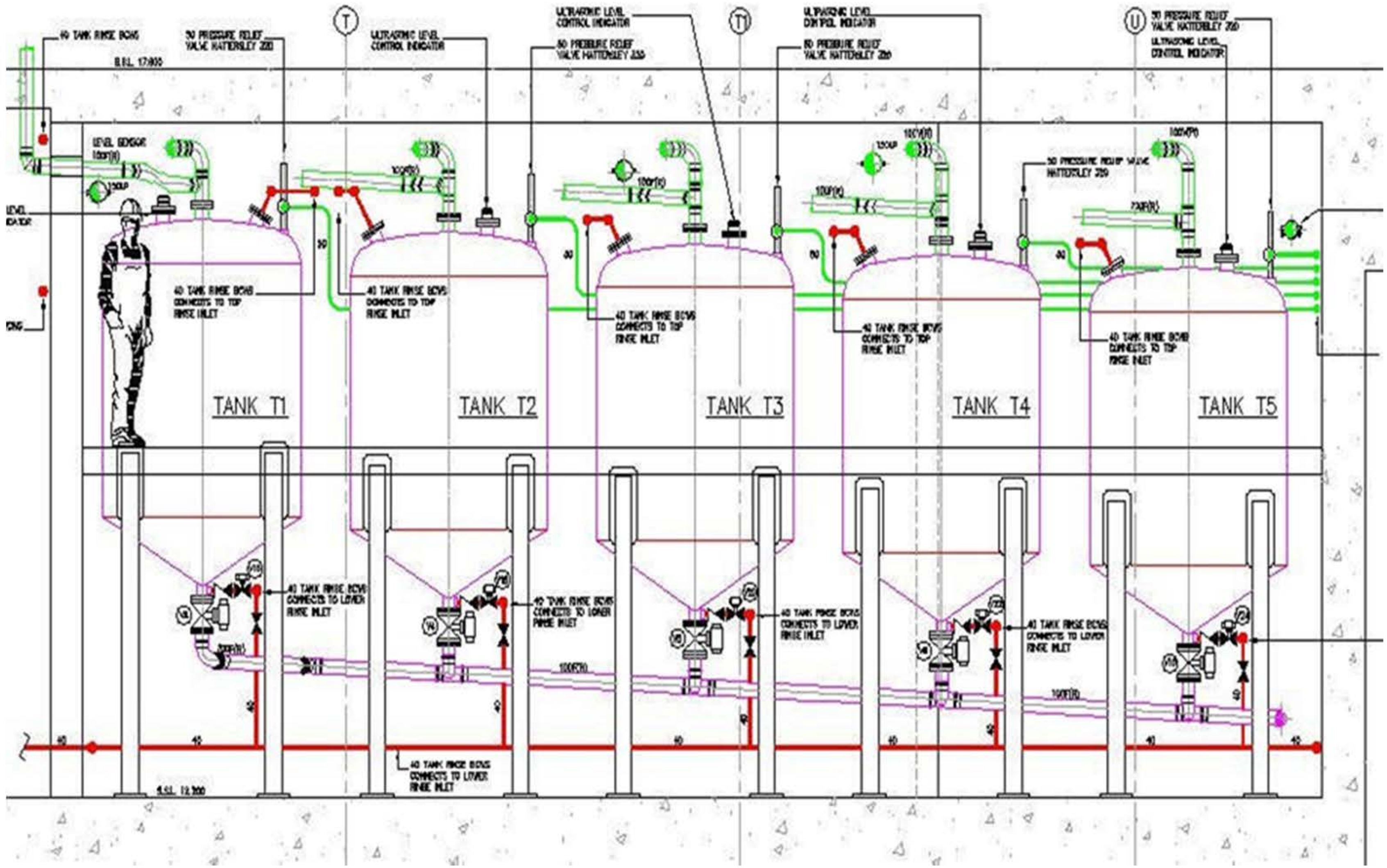


FIG. 8. Schematic of the constructed tanks, showing a worker on the inspection gantry used to access the top of the tanks for maintenance.

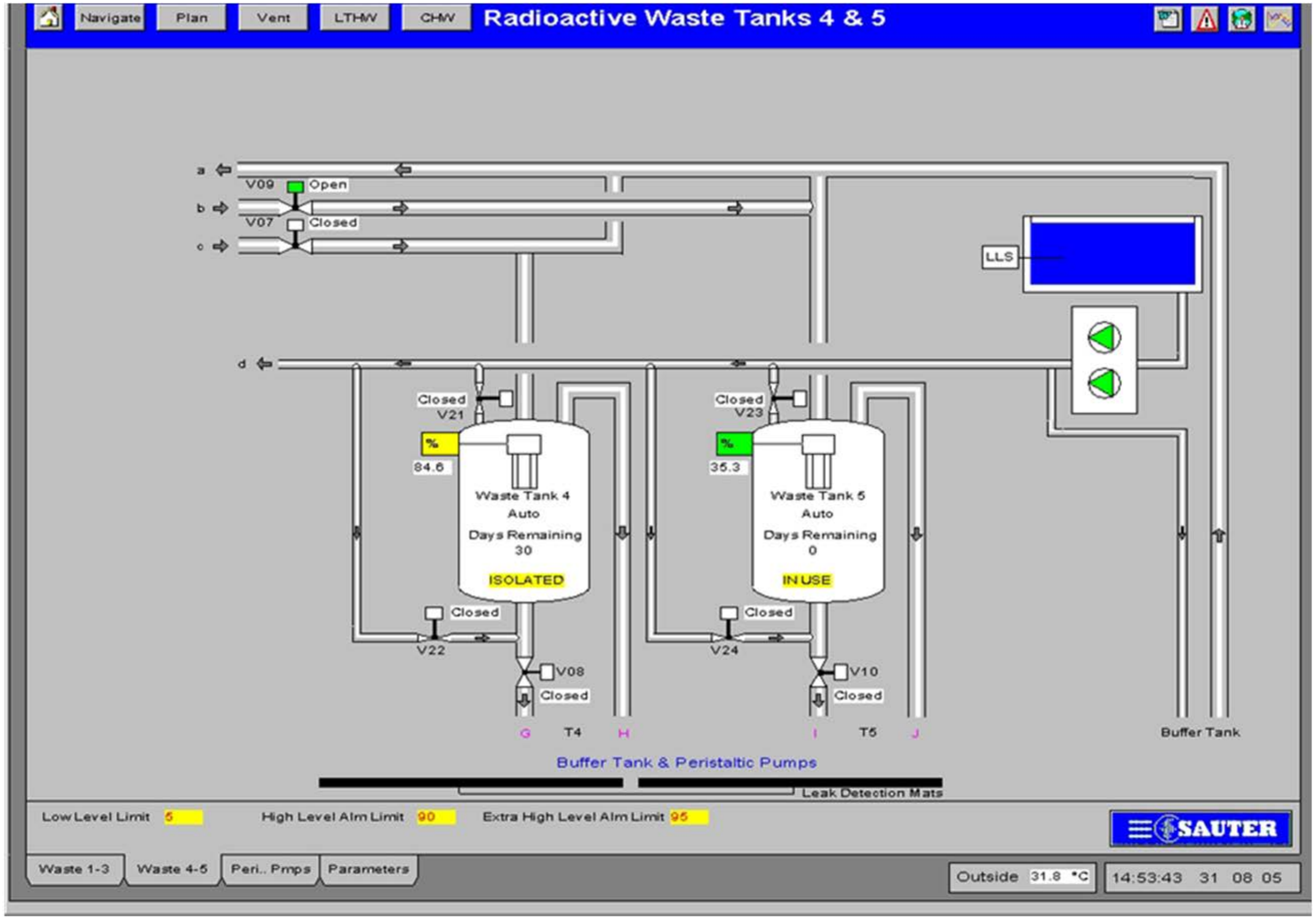


FIG. 9. Screen of the software from the server showing status of the operation of decay tanks 4 and 5.

FIG. 10. The control panel with key access manual override option.

The above figure is of the control panel where if necessary, the tanks can be manually controlled - opened and closed by pressing buttons after first inserting the key into the relevant key point. There are 16 sub-units to the control panel, arranged in four rows of four and six different key points. The top two central switches are the off and automatic control settings for the peristaltic pumps. Both pumps are currently set to auto.

The first two control sub-units on row two are for tank 1. On the first sub-unit, there are two red warning lights corresponding to the high level (90% full) and the extra high level sensors (95% full) for the tank. The key point beneath these lamps can be used to manually override operation of tank one, which will routinely be set to AUTO when operating as an automated system as per its design. Use of the key allows switching the operation of tank 1 to either manual (turnkey to the left) or the off position (turnkey to upright position). There are five paired sub-units on the control panel for override of the automatic system for each of the tanks. The bottom right two sub-units are for operation of the buffer tank.

Note that on the panel, the light in sub-unit one on the top left side of the panel is illuminated indicating normal operation of the panel. The high level warning light is illuminated on tanks 2 and 5 indicating both tanks are 90% full. There is a lamp illuminated on the second sub-unit for tank 4 showing that the inlet valve for this tank is opened i.e. the tank is currently filling.

To arrive at the volume and number of tanks to construct, it was estimated that each patient en suite toilet produces 50 litres of liquid waste per day (based on use of toilet with flushing). Based on treatment of about 10 patients per week (40 per month being the projected maximum), a 5000 litre tank will take approximately 10 days to fill. Having a series of 5 tanks, with the first tank discharging as the fifth tank is filling allows for an overall liquid retention time of between 30-40 days, which met the projected dose reduction from 185µSv/year to 6µSv/year to the sludge press workers.

There are 10 in-patient radiotherapy bedrooms with en suite bathroom located in the hospital. These bedrooms have been constructed to a suitably shielded design and are in pairs on five floors at levels 11, 12, 13, 14 and 15. The tanks are in direct line below the bedrooms at level 3 below ground (the lowest basement level) and the effluent from all the Iodine-131 reaches the tanks by a single lead shielded pipe (Figure 12). Figure 13 shows the five stop cocks (top) which are manually operated to open/close off the flow from the shielded pipe after it splits into five pipes each leading to tanks 1-5, and the valves (below) are the automatic controls to open and close the feed of Iodine-131 effluent into the relevant tank.

In the schematic below (Figure 11), the room to the right is where the two peristaltic pumps in parallel are located. The design is for each pump to be used in turn, so both are being used, but there is always a back-up pump in case the other fails. In this picture only tank 5 is seen but tanks 1-4 are in line behind tank number 5. The small buffer tank to the left of the picture is part of contingency arrangements for operation of the system. Should a level sensor in any of the five tanks fail, the tank would overfill and a pressure release valve would open and drain the excess into the buffer tank whilst simultaneously sending an alarm to the controller.

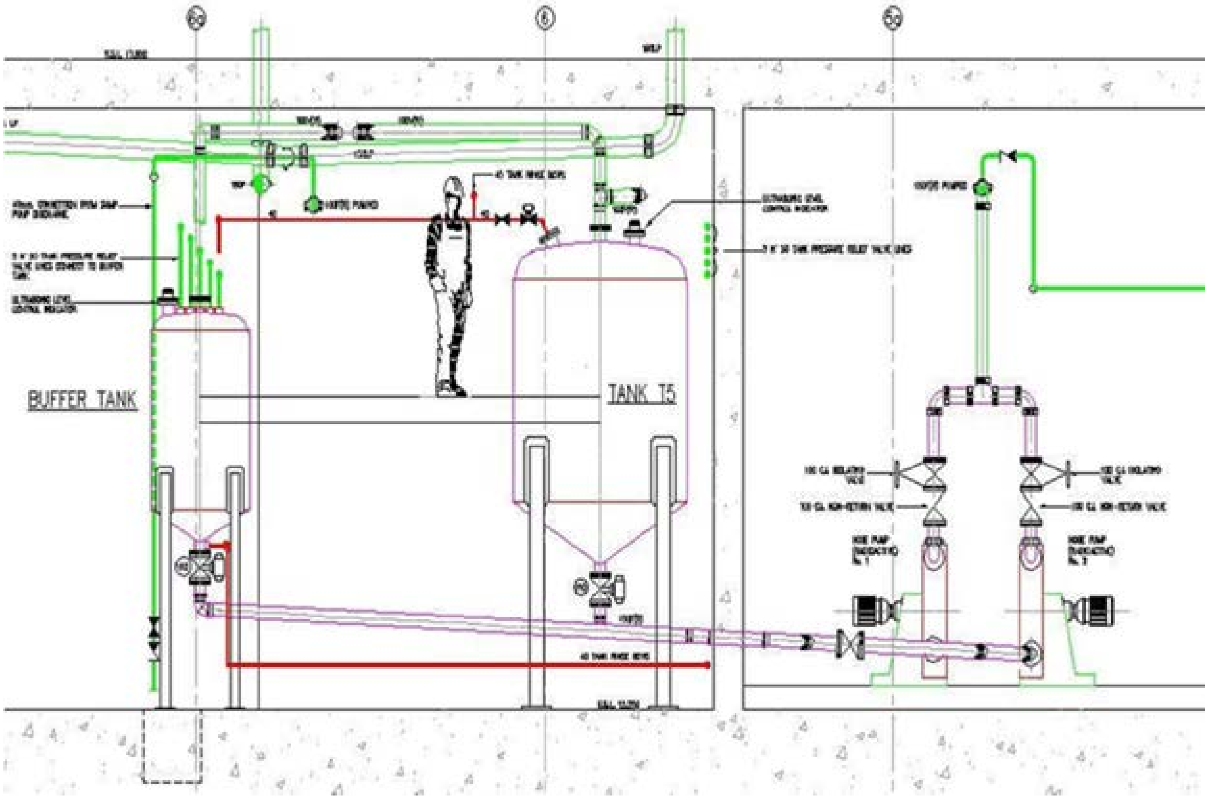


FIG. 11. A schematic showing tank 5 & the buffer tank.

FIG. 12. The pipe on the right is the main riser and the lead clad pipe on the left is carrying active waste to the tanks from the radiotherapy patient bathroom.

FIG. 13. The stop cocks (top) and the valves (below).

Gravity is used to fill the tanks although their filling is carefully monitored and controlled through the automated system, whose operation can be checked via the control panel and can be viewed on the software screen from information stored on the server. Figure 14 shows the two peristaltic pumps used to pump the liquid from the tank when it is due to discharge its contents. The pump is required to discharge the waste to the sewer because the tanks are located at basement level 3 below ground, hence liquid must be actively pumped upwards to reach the discharge sewer.

FIG. 14. The two peristaltic pumps used to pump the liquid from the tank.

FIG. 15. A water leak detector.

The water leak detectors are located on the bunded floor beneath the tanks (Figure 15). This is a simple box with a couple of pin projections. If a leak occurs, it will cause a circuit to be made hence setting off an alarm on the control panel and a display on the 4th floor computer screen.

Experience with operation of the system:

Once the system design was issued to the relevant hospital staff by the PFI Partner, who has control and ownership of the construction, the Radiation Protection Adviser (RPA) communicated with the design engineers to get information on the maintenance requirements. It was important to understand the level of maintenance and intervention that would actually be required by the hospital maintenance staff to keep the system operating efficiently. The worker would be standing on a gantry close to the tanks to carry out maintenance (Figure 16). Training on how to maintain and repair the system could be given prior to the system becoming operational, so maintenance staff could gain experience in exchanging defective components in the shortest possible time without the risk of radiation exposure. Suitable PPE was identified and made available for avoidance of spread of contamination onto skin when changing valve components etc. that would be contaminated with radioactive effluent at the time of replacement should they become defective after the system became operational.

FIG. 16. The upper part of the decay tanks viewed from the inspection gantry.

Whilst a highly automated design was intended to reduce the level of intervention and maintenance required to keep the system operating efficiently, hence keeping doses to the hospital maintenance workers as low as reasonably achievable/practical, it was not recognised until late in the design stage that potential radiation exposures to the in-house maintenance staff were going to be a problem. It was only when the design engineers provided information on what would be required each month to maintain safe performance of the decay tank system that the possible doses to these workers could be estimated.

The design engineers stated that approximately 15 visits per year would be necessary for routine monthly maintenance (2 hours per visit) or fault fixing (1 hour per visit). The hospital RPA calculated the radiation exposure to a maintenance worker relative to activity in the tank and distance away from the tank during maintenance or repair operations – see Figure 17. In the absence of shielding to the tanks, the following were considered as a means of dose reduction.

- There are five maintenance workers who could share these duties;
- One maintenance worker could realistically make three visits per year;
- Dose sharing as a means of controlling exposure is deemed low down in the hierarchy of acceptable control methods.

With no additional dose reduction intervention, the annual increase in the radiation dose to a hospital maintenance worker was estimated to be up to 1500 µSv. This dose increase to the maintenance workers needs to be balanced against the dose reduction to the identified critical group of sewage press treatment workers of 179µSv per year that will be saved due to operation of the delay for decay tanks.

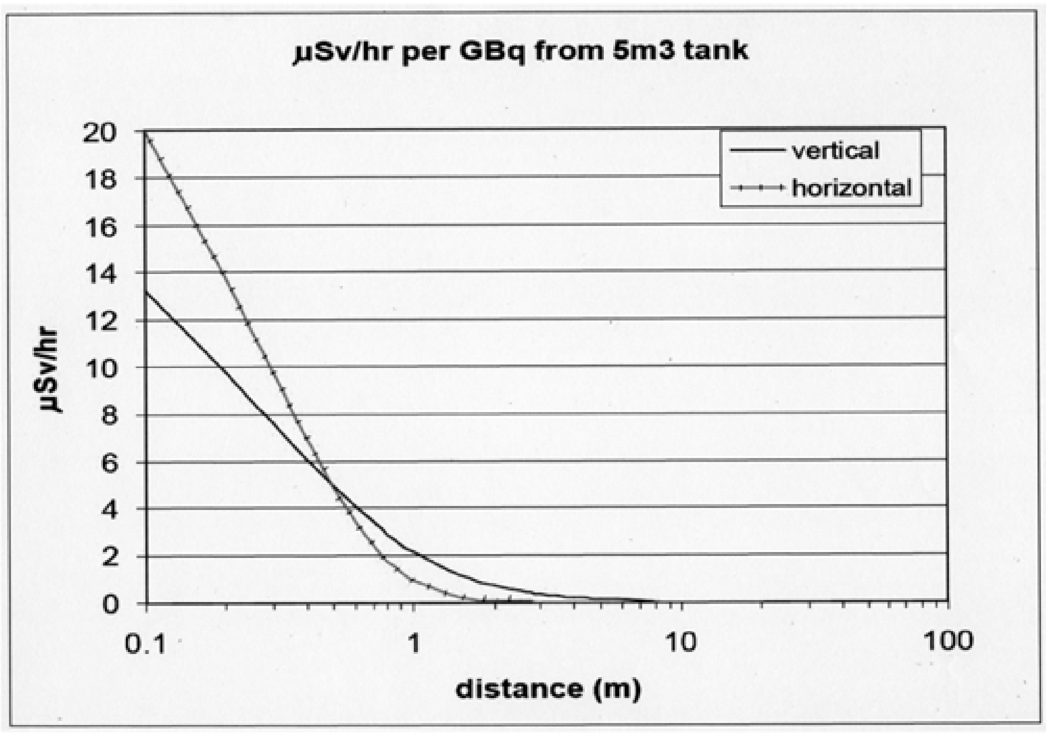


FIG. 17. Estimated radiation exposure of the maintenance worker based on distance from the tank per GBq of activity in the tank.

The costs to install and operate the decay tank system:

- The tanks cost £250 000;
- Installation and plumbing costs were estimated as an additional £250 000;
- No firm financial value is available for the maintenance of the system or the software control as this was all done in-house, but it is thought to be in the region of £500 000;

— Even if the dose to the in-house maintenance staff would not be increased, it was extrapolated that a spend of £5 million had been necessary to save a mSv of dose i.e. £1 million saved a dose of less than 200 μSv to the sludge press workers, therefore £5 million to save 1mSv.

Once it was identified that the radiation exposure of individual maintenance workers would be increased by up to 1500 μSv per year from work required to keep the tanks repaired or operating efficiently, the RPA liaised with the regulators and it was agreed that a by-pass system should be incorporated into the design of the tank system. The Regulatory Body, who had required the installation of the tanks as part of this "new build" to reduce the dose to the sewage treatment plant workers, acknowledged that these doses would be unacceptably high compared to the dose reduction achieved for the sewage treatment plant workers. After discussion with the regulatory bodies, it was agreed that a by-pass system should be fitted such that all of the tanks could be drained to provide access without the radiation exposure when a repair or routine maintenance is required.

Although a requirement for a by-pass system had been identified at the design stage, the PFI builders initially refused to finance the installation. With further support from the Regulatory Body, a by-pass system was installed as the BPM (Best Practical Means) case put to the regulators agreed this was the best option. The PFI Partner then went ahead and installed the by-pass system and once it was commissioned, it was taken into use.

At present, the system is being operated with the by-pass in operation all the time, although the tanks are occasionally being maintained and operated with clean water so that they will be in good working order once full operation of the system for decay storage of radioactive liquid waste is required. In the interim, the hospital is considering alternative interventions/modifications to reduce the doses to the maintenance workers below the current predicted levels by:

— Investigating if a less stringent maintenance regime can be implemented that still ensures peak performance of the automated system;
— Considering the options for shielding to minimise exposure to the maintenance worker.

In terms of cost-benefit analysis, this highly automated and very expensive tank system effectively cost £5 million to save a mSv of dose to the representative person. Unfortunately this expenditure had the adverse effect of causing a new group to be adversely affected to a much greater extent. Another issue highlighted from this project is that problems can occur when one legal entity has design and financial control over the installation of the decay tank system, but another entity will operate and maintain the system.

I.3. THE OPERATION OF A COMMERCIALLY AVAILABLE I-131 EFFLUENT SYSTEM DESIGNED FOR USE IN HOSPITALS

The administrated activity of I-131 in the nuclear medicine department of this hospital is 7 GBq/week and the hospital has a single room for therapeutic application which can accommodate a patient. A commercially available tank system with two tanks was installed. It was assumed that 80% of the total activity administered to the patient is excreted, and the waste activity to be collected during operation of the tanks is shown in Figure 18. The maximum amount of activity accumulated in the tanks was estimated to be

12.3 GBq. The tanks each have a volume of 12 m^3 and are positioned horizontally. The tanks are located in the basement and this location was selected due to it being an area of low occupancy. The tanks are made of stainless steel which is resistant to corrosion. The floor and side walls are covered with ceramic material to a height of about 50 cm for ease of decontamination. Radiation warning signs are placed on the tanks and at the entrance to the storage room. The two tanks are connected and level controllers are installed to control the effluent level in the tanks. The technical drawing of the tank system is given in Figure 19. Mixers are available in both tanks to ensure that the contents remain homogeneous. The transfer of effluent between the tanks and discharge to the sewage system can be achieved both automatically and manually via pumps integral to the system. A control panel is integral in the system from where the discharge can be automatically controlled as can the mixing operation. An area radiation monitor continually measures the background in the decay tank room and acts as a detection system for leakage. The tanks are designed with an upper removable lid to facilitate maintenance. The level of the tanks can also be checked via visual inspection of the level gauge. Records of discharges are kept and sent to the Regulatory Authority on an annual basis.

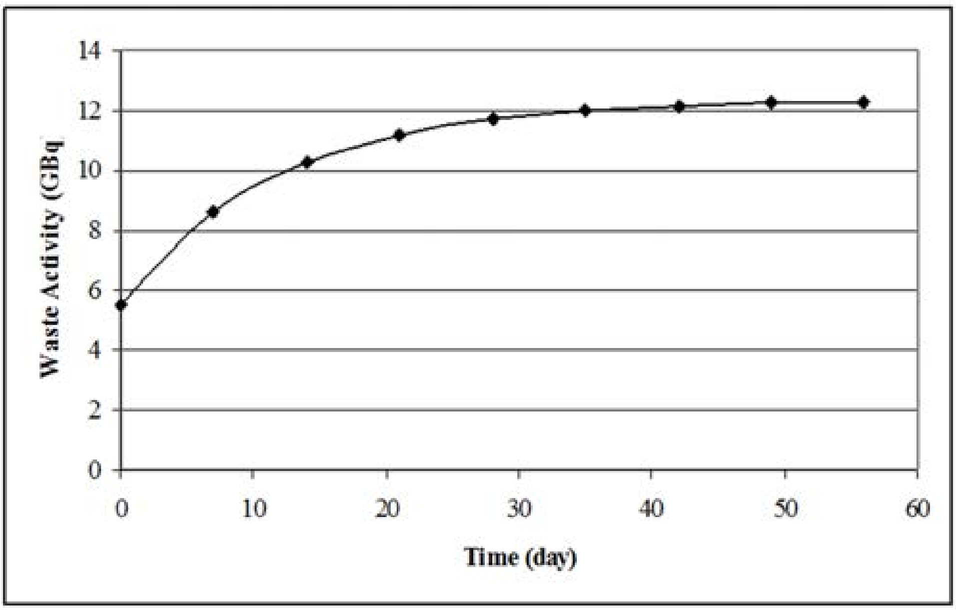


FIG. 18. Accumulation of waste activity in the tank.

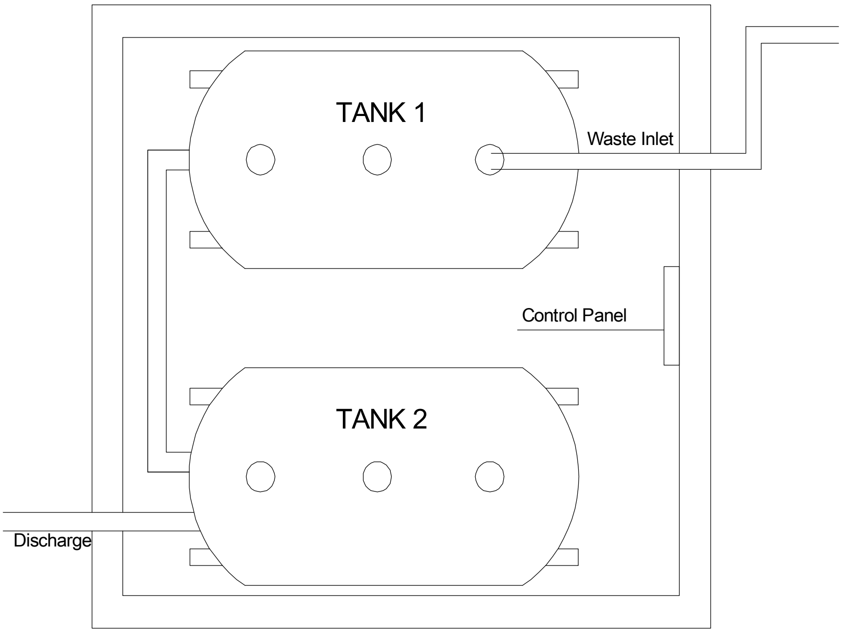


FIG. 19. Drawing of the tank system.

FIG. 20. View of tank systems installed in a medical establishment.

I.4. SCHEMATICS OF DECAY TANK SYSTEMS

(1) A dual tank system

The design of the decay tank examples 1 & 2 were provided by the Nuclear Research Institute Rez in the Czech Republic and have been in use since 1961. The tanks were designed for storage and decay of concentrated short-lived radioactive waste (RAW). The building is located below ground on three sides (see Figure 21). It contains two cylindrical tanks (length 9.5 m, diameter 3 m, weight approx. 10 metric tons), each with a capacity of 63 m^3. The decay tanks are made from structural steel jacketed by stainless steel inside the vessel. They are placed into two separate concrete bunkers located partially below ground. Above the bunkers, a building with tank inlet pipes and ventilation equipment is located.

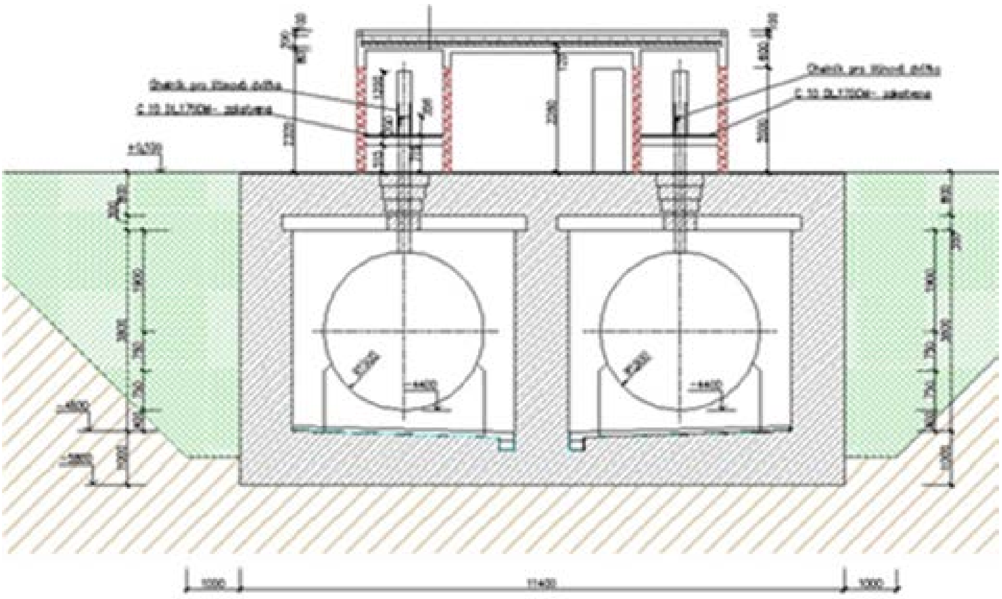


FIG. 21. Decay tanks (section).

(2) A triple tank effluent decay storage system

Three steel tanks are located in concrete underground bunkers (see Figures 22 & 23). The dimensions of the tanks are: length 9.5 m, diameter 3 m and each with a capacity of 63 m^3. The weight of each tank is approximately 10 metric tons. The tanks were designed to collect liquid RAW from a research reactor.

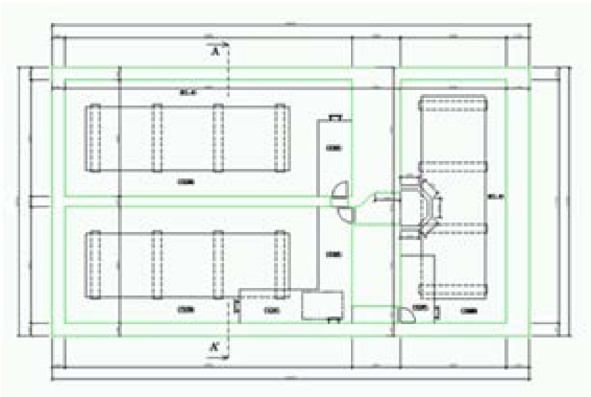


FIG. 22. Underground floor with the tanks.

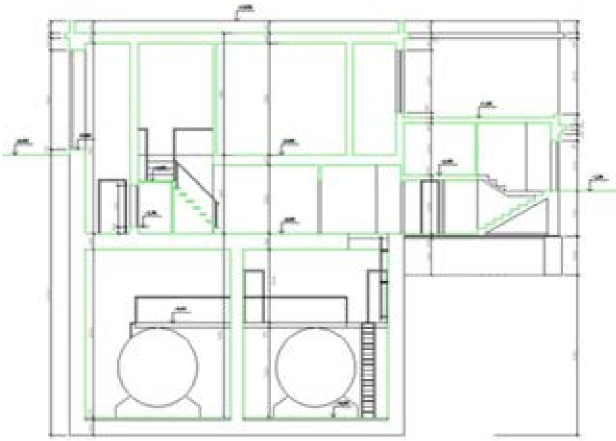


FIG. 23. Cross- Section of the building.

FIG. 24. Storage tank.

(3) A very low cost simple system with a single tank

This system design (Figure 25) can be appropriately modified to provide the ability to decay store liquid effluents at very nominal cost where the effluent volumes are not very large, the activity level is low and the half life is short. Its design utilizes everyday readily available materials and is largely a manually operated system. It is ideally suited to facilities that are producing effluents on an infrequent basis that require decay storage prior to discharge. A single tank could be filled and allowed to decay during the period that no further effluents for decay storage are being produced. Should a design of this type be installed and there is a need to store more effluent before the tank contents can be discharged, there is the option to either collect the new effluents directly into 200 litre drums or instead to divert the stored effluent into drums for further storage and then drain the newly produced effluent into the decay tank. This system has fixed storage capacity but could be modified and improved where larger yet limited volumes of effluent need to be managed.

The effluent drains by gravity into the tank which is set below the ground in an area that can be accessed via a hatch in the floor. The effluent flow into the system is controlled via a three way stop cock. Position one is closed, position two is to direct the effluent flow into the underground storage tank and position three is to divert the effluent into a 200 litre drum fitted with a tap at the base. Each drum will be located on a wheeled base, so that when it is full, it can be wheeled to a suitably secure radioactive waste storage area. A flexible pipe can be fitted to the tap at the base of the drum so that its contents can be discharged into the sewage system once the activity has decayed to the required level.

The effluent to be collected flows by gravity through a 5cm diameter pipe fitted with a non-return valve to enter the decay storage tank. At the base of the decay tank is a motorized valve. There is a manual switch on the wall by the tank which can be used to divert the discharge from the tank via the motorized valve either to the sewage system or to a drum for further storage. When the effluent in the tank is diverted to the drum, the effluent will pass through a gate valve to reach one of two pumps. The pump is required to pump the effluent upwards to meet the pipe that transfers the effluent into the drum. Only one pump is needed for routine operation to transfer the effluent to the storage drum (the duty pump) but a stand-by pump was incorporated in the design for redundancy.

After a suitable decay storage period, the contents of the tank should be sampled via the sampling port to ascertain if the effluent is at a suitable activity level for discharge.

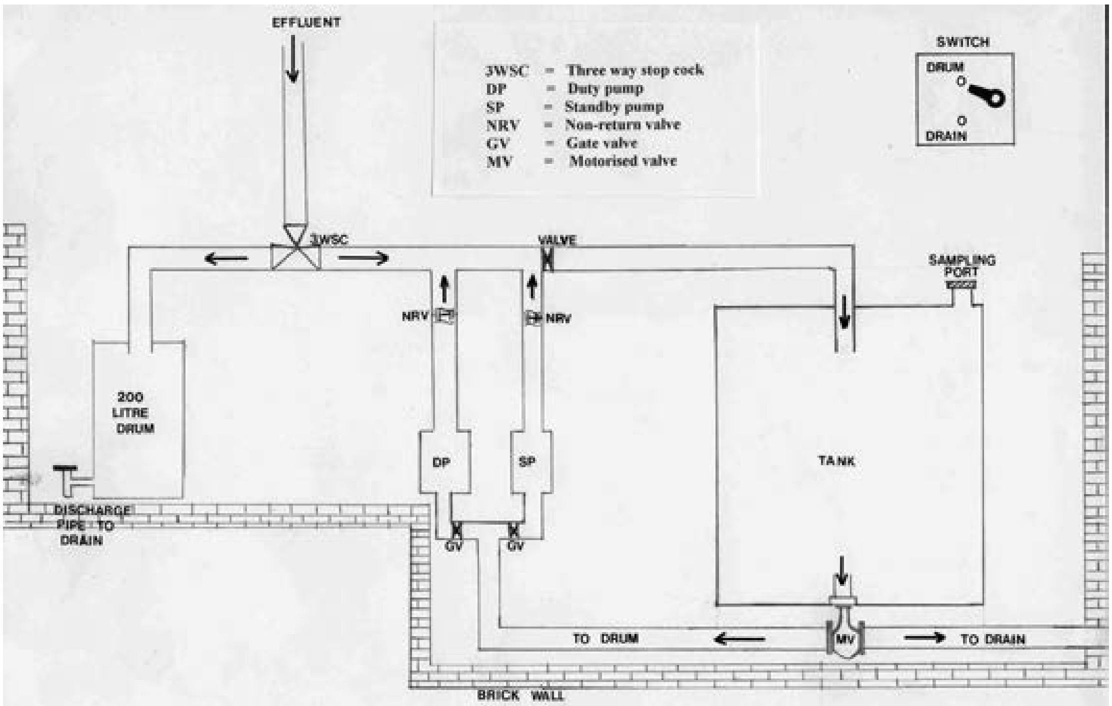
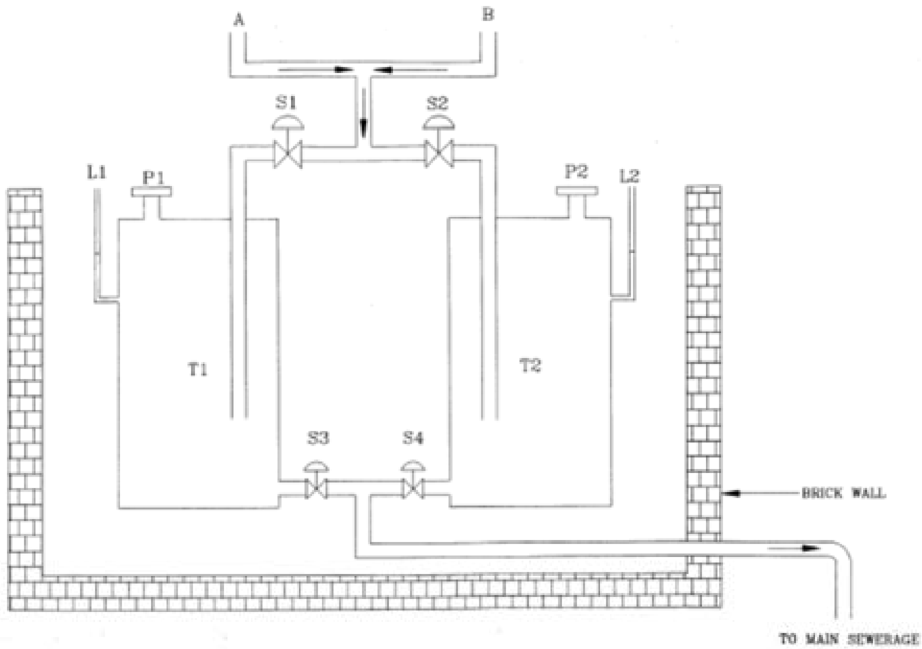


FIG. 25. A simple single tank system with overflow storage capacity utilizing 200 liter drums.

(4) A dual tank decay system for Iodine-131 effluent

Figure 26 shows a typical design of a dual tank decay system [21]. The optimum capacity of each decay tank should be decided on the basis of anticipated daily release of effluents from the ward. However, two tanks, each with a capacity of about 5 000 liters may be adequate for a two bedded radiotherapy ward. The decay tanks should be leak proof, corrosion resistant, and should have smooth surfaces inside. The outlets of the tanks should be at a higher level than that of the main sewerage line to avoid back flow of effluents. One tank at a time should be used for collecting effluents from the therapy ward. The tanks should have a warning device which operates when the tank is almost full so that the effluent outlet of the patient ward may be manually or automatically connected to the second tank. The collected and decayed contents of the first tank should be sampled (after an appropriate storage period) before discharging directly to the main sewage system. It will be necessary to ensure that the average monthly concentration of the activity at the discharge point does not exceed the limit laid down by the relevant regulatory authority. This method of waste disposal is currently being followed in India and has concurrence of the regulatory authority.



P1, P2 — Provisions for collecting samples/inserting probe for estimating radioactivity concentration;
S1, S2 — Inlet gate valves; S3, S4 — Outlet gate valves;
L1, L2 — Fluids level indicators;
T1, T2 — Storage tanks (preferably below ground level);
A,B — Outlets of toilets of ^{131}I therapy patient wards.

FIG. 26. A design for a dual tank Iodine-131 decay tank system suitable for a hospital.

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Annex I

GENERIC CALCULATION FOR DESIGN OF A DECAY TANK SYSTEM

Although a number of different methods exist to assess the design requirements for a decay tank system, the generic calculation given below may prove suitable in certain circumstances. Assuming the waste input occurs at regular intervals, with pulse activity input to an infinite tank and the activity is decayed for a period equal to the time between waste inputs, the accumulated radioactivity in the tank at the beginning of the period between the n^{th} and the $(n+1)^{th}$ waste inputs can be calculated via Equation 1 [23].

$$Tb(n) = A \times \sum_{i=0}^{i=n-1} e^{-i\lambda\Delta t} \to \frac{A}{1-e^{-\lambda\Delta t}} \quad \text{as} \quad n \to \infty \qquad \textbf{(1)}$$

where Tb is tank activity, Δt is the time period between waste inputs, λ is the decay constant and A is the waste activity regularly put into the tank. The activity that would be accumulated in tank (TA) quickly reaches saturation and it is one of the design parameters. The equation relating discharge activity (RA) and accumulated tank activity (TA) is given in Equation 2 [24] and RA is another design parameter.

$$RA = TA \times e^{-\lambda \times t} \qquad \textbf{(2)}$$

The decay period (t) required to reach RA for the tank can be expressed as [24]:

$$t = -(1/\lambda) \times \ln(RA/TA) \qquad \textbf{(3)}$$

Decay constant (λ) is the third design parameter. The time period (TP) from the beginning of the effluent accumulation until it is discharged to the sewage system is equal to the collection period (X) plus the decay period (t). The collection period (X) is a further design parameter**.** The total number of tanks required (TN) for the decay tank system can be expressed as in Equation 4. An example calculation for the decay tank system is provided below.

$$TN = 1 + \frac{\ln(RA/TA)}{-\lambda X} \qquad \textbf{(4)}$$

Figure I-1 shows the activity of Iodine-131 collected in an infinite tank for regular waste activity inputs for different activity input periods of 3, 5 and 10 days. The y-axis of FIG. I.1 is given as the dimensionless value of activity to be collected in the tank for the period of regular activity input to the tank. Moreover, average daily water usage of patients determines the required tank volume and is another design parameter for the decay tank system that must be known to the medical establishment. The final design has to take into consideration the residual activity for discharge (RA) and the volume of liquid waste generated.

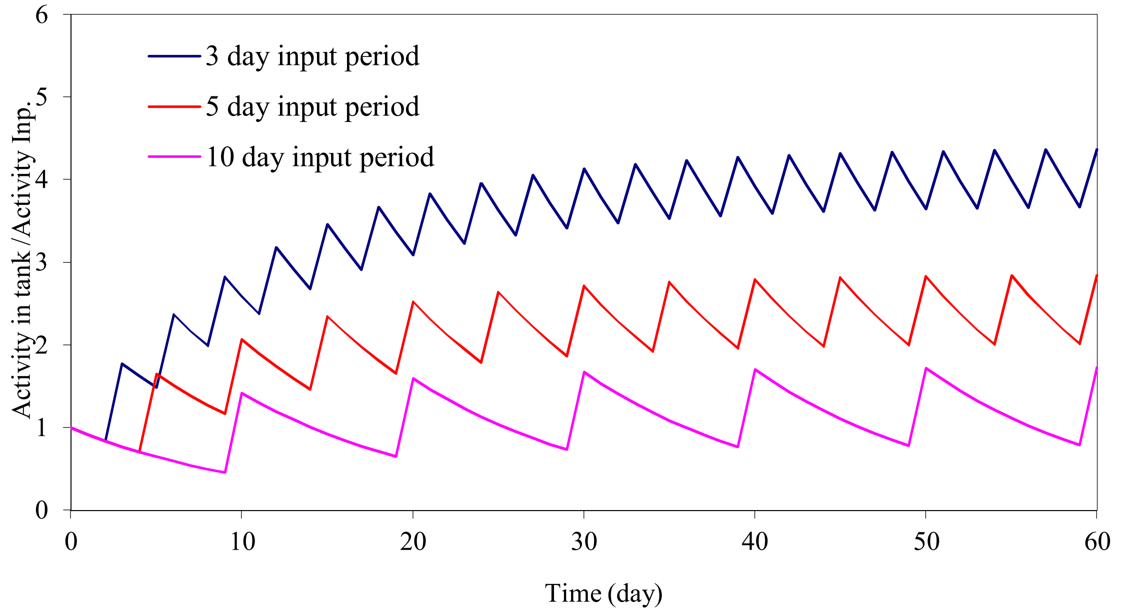

FIG. I-1. Activity of Iodine-131 to be collected in an infinite tank divided by the regular activity input to the tank for different waste activity input periods of 3, 5 and 10 days.

I-1. EXAMPLE CALCULATION FOR A DECAY TANK SYSTEM

The requirement to design a decay tank system may appear to be a rather daunting and onerous task to the novice. The following example provides information on the factual data that has to be collected in order to carry out the design calculations for a decay tank system for Iodine-131 and shows how the data is utilized as part of these calculations. The assumptions made are based on data from therapeutic applications. The example calculation could easily be customized by substituting the data for a given facility.

The following assumptions have been made for Iodine-131 therapy treatments - the period of residency in hospital is 5 days for each patient and a maximum of two patients are treated at the same time. It is assumed that two patients are continually undergoing treatment throughout the entire month as a worst case scenario; therefore the calculation assumes twelve patients per month undergo treatment. Each patient is administered 5.55 GBq Iodine-131, and it is assumed that 80% of the radioactive material (representing the most important component of radioactive waste from these treatments [23]) is excreted from the patient's body in urine in the first 24 hours. The remaining 20% is not considered for calculation purposes as this will either be retained in vivo or will have decayed. It was assumed that each patient produces 55 litres of effluent per day from excreted radioactivity and water used for toilet flushing.

Using the above data, the activity to be accumulated in an infinite tank is tabulated in Table I.1 and the maximum activity to be accumulated in an infinite tank was calculated to be 25.3 GBq utilizing Equation 1. The graph showing the activity accumulated in the tank is given in Figure I-2.

Data for six different collection periods (*X*), with the tank filling for periods between 10 and 60 days, is presented in Table I-2. The total tank activity can again be calculated for each scenario using Equation 1 and the release limit for I-131 was assumed to be the minimum annual limit of intake (ALI) for this radionuclide of 8×10^5 Bq [25].

In this example, the release activity is given in units of activity (Bq, MBq, GBq), and the release limit is given as an activity concentration (Bq/l, Bq/ml), therefore the dilution factor should be considered for the conversion from activity concentration to activity. The decay period can be calculated via Equation 3. The time period is the sum of the collection period (*X*) and the decay period (*t*). The number of tanks required can be calculated using Equation 4. Where the calculation does not yield a whole number i.e. 3.4 tanks required for a 50 days collection period, two possible options might then exist. Firstly, if sufficient funds are available to construct four tanks of the same capacity, the capacity constructed should be rounded to 4 tanks as an engineering judgment, which also serves to provide additional capacity for the future should the workload and hence the storage requirements increase. The second option is to build three tanks of the same size and a fourth tank having only 40% capacity compared to the other tanks. There should be a continuous flow arrangement existing between the four tanks. The fourth smaller tank should be constructed with an overflow arrangement whereby as effluent flows into the top of the fourth tank as part of the continuous flow arrangement between the tanks, some effluent will be displaced from the tank and will be discharged to the sewer.

In deciding on the number of tanks and the design that might be most appropriate, factors such as space available for the installation and cost should be considered in reaching a final decision. Further information on design of decay tank systems is given in Section 6 and information on cost-benefit analysis is given in Section 4.3.

TABLE I-1. TOTAL WASTE ACTIVITY ACCUMULATED IN THE TANK OVER TIME WITH INCREASING PATIENT NUMBERS

	Days																				
Patient numbers	**0**	1	2	3	4	**5**	6	7	8	9	**10**	11	12	13	14	**15**	**20**	**30**	**40**	**50**	**60**
1-2	**8.9**	8.1	7.5	6.9	6.3	5.8	5.3	4.9	4.5	4.1	3.7	3.4	3.2	2.9	2.7	2.4	1.6	0.7	0.3	0.1	0.1
3-4						**8.9**	8.1	7.5	6.9	6.3	5.8	5.3	4.9	4.5	4.1	3.7	2.4	1.0	0.4	0.2	0.1
5-6											**8.9**	8.1	7.5	6.9	6.3	5.8	3.7	1.6	0.7	0.3	0.1
7-8																**8.9**	5.8	2.4	1.0	0.4	0.2
9-10																	**8.9**	3.7	1.6	0.7	0.3
11-12																		5.8	2.4	1.0	0.4
13-14																		**8.9**	3.7	1.6	0.7
15-16																			5.8	2.4	1.0
17-18																			**8.9**	3.7	1.6
19-20																				5.8	2.4
21-22																				**8.9**	3.7
23-24																					5.8
25-26																					**8.9**
Σ Waste Activity (GBq)	**8.9**	**8.1**	**7.5**	**6.9**	**6.3**	**14.7**	**13.4**	**12.3**	**11.3**	**10.4**	**18.4**	**16.9**	**15.5**	**14.2**	**13.0**	**20.8**	**22.4**	**24.1**	**24.8**	**25.1**	**25.3**

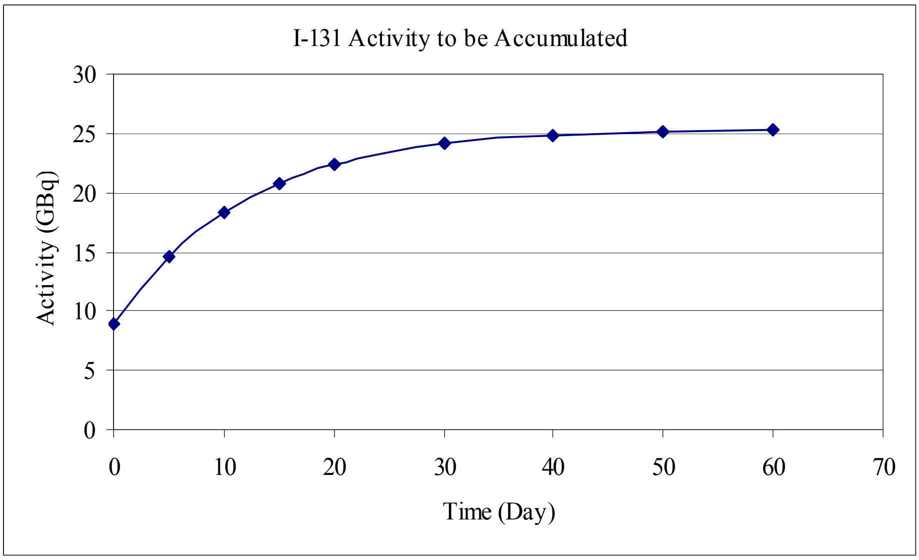

FIG. I-2. The activity over time accumulated in an infinite tank.

TABLE I-2. ALTERNATIVES FOR A DECAY TANK SYSTEM WITH DIFFERENT COLLECTION PERIODS

Alternatives	I	II	III	IV	V	VI
Collection Period (*X*) (day)	10	20	30	40	50	60
Tank Activity (*TA*) (GBq)	18.4	22.4	24.1	24.8	25.1	25.3
Release Activity (*RA*) (MBq)	0.8	0.8	0.8	0.8	0.8	0.8
Decay Period (*t*) (days)	116.5	118.8	119.6	120.0	120.1	120.2
Time Period (*TP=X+t*) (days)	126.5	138.8	149.6	160.0	170.1	180.2
Calculated number of tanks required (*TN=TP/X*)	12.6	6.9	5.0	4.0	3.4	3.0
Number of tanks to be constructed in the decay tank system	13	7	5	4	4	3
Tank Volume (L) (*V=XxPatient CapacityxDaily water usage*)	1100	2200	3300	4400	5500	6600

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