Storage Tanks for Liquid Radioactive Wastes: Their Design and Use
STORAGE TANKS FOR LIQUID RADIOACTIVE WASTES: THEIR DESIGN AND USE
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<td>Germany, Federal Republic of</td>
<td>Nigeria</td>
<td>Zambia</td>
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<tr>
<td>Ghana</td>
<td>Norway</td>
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May 1972
STORAGE TANKS FOR LIQUID RADIOACTIVE WASTES: THEIR DESIGN AND USE

A Guidebook prepared by

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Trombay, Bombay, India

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1972
STORAGE TANKS FOR LIQUID RADIOACTIVE WASTES:
THEIR DESIGN AND USE
IAEA; VIENNA, 1972
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FOREWORD

Much of the radioactive waste produced at nuclear establishments is in liquid form. Various types of tanks have been developed for the satisfactory long-term storage of such waste when it is of low or intermediate-level radioactivity.

When liquid waste is highly radioactive, as that resulting from the aqueous reprocessing of irradiated fuel to separate fissile and fertile material, the problems of treatment and ultimate disposal are greater. The only practical method available at the moment for handling this waste is its long-term storage in specially designed tanks. Nevertheless, storage of this type of waste in liquid form has some inherent disadvantages, and much is hoped from current research and development work to provide techniques for the safe ultimate disposal of these wastes.

The International Atomic Energy Agency, considering that a summary of present knowledge on the design of containers for liquid wastes of various levels of activity would be useful, have sponsored the present guidebook. It has been prepared chiefly for the benefit of Member States that are developing, are about to develop, or are planning to develop in the future, their own nuclear programs. It aims at assisting them to produce specifications for tank designs and supporting ancillary services, and to adequately assess the designs offered against those specifications. The book may also help personnel in radioactive waste management to understand some of the facets of the safe management of radioactive wastes.

The guidebook has been written by Mr. R.V. Amalraj, of the Bhabha Atomic Research Centre, Bombay, India. Mr. Edward D. Hespe of the IAEA organized and directed the work of preparation. The IAEA is also grateful to the atomic energy authorities of Belgium, Canada, France, India, the United Kingdom and the United States of America for providing the author with necessary information on their radioactive waste tank storage systems.
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1. INTRODUCTION

This Guidebook is intended primarily for the waste management specialists in those developing countries that have not the advantage of a well-developed engineering and technological background. The intention of the author is that the book should assist the specialist to (1) visualize the problems associated with the design of storage tanks, (2) prepare design briefs for such systems, and (3) evaluate resulting design proposals.

Thus the book discusses mainly the design criteria of radioactive waste storage systems. Since — for some time at least — specialists in this category are unlikely to be faced with the problem of managing self-heating wastes, storage facilities for this waste category are not dealt with.

2. NATURE OF RADIOACTIVE LIQUID WASTES AND THEIR STORAGE

2.1. General

A knowledge of the chemical and radiochemical composition of the wastes is of primary importance for the design and operation of the facilities required for their management. Radiochemical composition establishes the base for hazards control and the requirements for the removal of radiolytic gases, while the chemical composition directly influences corrosion rates. Processing of raw materials and normal operation of reactors give rise to large volumes of low-level radioactive liquid wastes. Slightly higher radioactive wastes are to be expected from reactors during off-standard operating conditions, research laboratories and isotope production plants.

2.1.1. Raw material processing

The waste produced in uranium and thorium processing contains large amounts of inactive chemical load. The radioactivity content of the waste is due to the presence of small amounts of uranium and its decay products. Isotopes of radium (some of them gaseous) are the most hazardous radio nuclides present in these streams. Fabrication of fuel elements does not give rise to any significant amount of radioactivity in the liquid wastes.

2.1.2. Reactor operation

One of the commonly used coolants in nuclear reactors is demineralized water which becomes the main source of waste. The radioactive contamination of the coolant is normally due to the neutron activation of the impurities in the coolant and of the corrosion products. Fission products are also found in the coolant due to the contamination of the cladding material by the fuel, or as a result of cladding failure. The cooling system is either of single-pass or of recirculating type. In the first type the problem of waste handling becomes more serious when the cladding ruptures. In the recirculating system the coolant is re-used after necessary filtration and demineralization. Liquid wastes from heavy-water reactors contain, besides other isotopes, large amounts of tritium. Leakages from pumps, valves, heat exchangers, etc. must also be treated as wastes. Regeneration of ion-exchange columns in the water purification systems produces
### TABLE I. WASTE FROM REACTOR OPERATION

<table>
<thead>
<tr>
<th>Designation</th>
<th>Type of reactor</th>
<th>Power rating (MW(e))</th>
<th>Volume collected (gal/yr)</th>
<th>Activity range before dilution ( (\mu\text{Ci/cm}^3) )</th>
<th>Percentage re-used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Rock Point (USA)</td>
<td>Boiling water</td>
<td>50</td>
<td>( 1 \times 10^4 )</td>
<td>( 10^{-4} - 10^{-2} )</td>
<td>80</td>
</tr>
<tr>
<td>Bradwell (UK)</td>
<td>Gas-cooled</td>
<td>300</td>
<td>( 1.2 \times 10^4 )</td>
<td>( 10^{-7} - 2 \times 10^{-1} )</td>
<td>Nil</td>
</tr>
<tr>
<td>Dresden-I (USA)</td>
<td>Boiling water</td>
<td>200</td>
<td>( 11 \times 10^4 )</td>
<td>( 10^{-5} - 10^{-2} )</td>
<td>84</td>
</tr>
<tr>
<td>Edf 1 (France)</td>
<td>Gas-cooled</td>
<td>70</td>
<td>About ( 10^8 \text{ m}^3/\text{yr} ) for the three reactors</td>
<td>( 10^{-5} - 10^{-1} )</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Edf 2 (France)</td>
<td>Gas-cooled</td>
<td>180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edf 3 (France)</td>
<td>Gas-cooled</td>
<td>475</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hinkley Point (UK)</td>
<td>Gas-cooled</td>
<td>500</td>
<td>( 3.6 \times 10^8 )</td>
<td>( 10^{-8} - 2 \times 10^{-2} )</td>
<td>Nil</td>
</tr>
<tr>
<td>Humboldt Bay (USA)</td>
<td>Boiling water</td>
<td>52</td>
<td>( 7 \times 10^5 )</td>
<td>( 10^{-4} - 10^{-2} )</td>
<td>Nil</td>
</tr>
<tr>
<td>Indian Point-I (USA)</td>
<td>Pressurized water</td>
<td>162</td>
<td>( 8.8 \times 10^6 )</td>
<td>( 3 \times 10^{-6} - 2 \times 10^{-2} )</td>
<td>Nil</td>
</tr>
<tr>
<td>Yankee (USA)</td>
<td>Pressurized water</td>
<td>165</td>
<td>( 8.5 \times 10^5 )</td>
<td>( 10^{-6} - 10^{-2} )</td>
<td>Nil</td>
</tr>
</tbody>
</table>

\( a \) Not including tritium.

\( b \) Average volume.
chemical wastes containing high concentrations of salts carrying some radioactive contamination. Other sources of chemical and radioactive wastes are liquids from decontamination operations, resin sluicing, etc.

The nature and quantities of liquid wastes generated in some of the operating power reactors are given in Table I [1].

Irradiated fuel elements are stored under water in fuel-storage canals or ponds to allow for the decay of short-lived activity. This water may be contaminated with fission products from the exposed ends of fuel elements; defective or ruptured cladding may also give rise to contamination. Generally, activity from the canal water is continuously removed by means of ion-exchange columns to facilitate re-use of the decontaminated water to the maximum extent. The regenerant from the demineralizing columns becomes a source of contaminated chemical radioactive waste. The activity level in the water and in the regenerant depends upon the nature of the fuel stored, the nature and status of the cladding material, the extent of irradiation of the fuel and the period of storage.

2.1.3. Research, isotope production and utilization

Liquid wastes arising from the production and utilization of isotopes, research and development activities and decontamination operations are unpredictable in nature and are liable to wide variations depending on the type of operations involved. The wastes resulting from isotope separation facilities are generally similar in composition to the raffinates from fuel reprocessing plants, but the activity levels are lower by several orders of magnitude. Wastes produced from hospitals and industries using radioisotopes generally contain small quantities of radionuclides, like $^{32}\text{P}$, $^{35}\text{S}$, $^{198}\text{Au}$, $^{131}\text{I}$, etc., which are short-lived. A large number of radioisotopes including alpha emitters may be present in effluents produced from research laboratories. The dissolved solids in the waste may range from 0 to 500 ppm depending upon the nature of the work. Complexing agents, detergents, organic materials and oxidizing agents are invariably present in the wastes from such laboratories. The wastes are variable with regard to volume, chemical composition and radioactivity. Liquid wastes resulting from decontamination operations may contain a wide spectrum of chemicals, detergents, soaps and other cleaning agents. Suspended solids and oxidizing agents are also likely to be present. Foam and lather formation is a particular property associated with the wastes from the operation of radioactive laundries. The volume and activity level of these effluents will differ from site to site.

2.2. Radioactive liquid waste categories

A mutually agreed definition of waste categories is very useful for proper communication and dissemination of information regarding their management.

Taking into consideration the different viewpoints put forward by some of the developed and developing countries, the International Atomic Energy Agency has made recommendations for categorizing radioactive liquid wastes as given in Table II [2] and this categorization has been adopted for use in the subsequent chapters.
TABLE II. PROPOSED CATEGORIES OF LIQUID WASTES

<table>
<thead>
<tr>
<th>Category</th>
<th>Activity level A ((\text{Ci} / \text{ml}))</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(A \leq 10^{-6})</td>
<td>Not normally treated</td>
</tr>
<tr>
<td>2</td>
<td>(10^{-6} &lt; A \leq 10^{-3})</td>
<td>Without shielding</td>
</tr>
<tr>
<td>3</td>
<td>(10^{-3} &lt; A \leq 10^{-1})</td>
<td>Shielding possible</td>
</tr>
<tr>
<td>4</td>
<td>(10^{-1} &lt; A \leq 10^{1})</td>
<td>Shielding necessary</td>
</tr>
<tr>
<td>5</td>
<td>(10^{1} &lt; A)</td>
<td>Cooling and shielding necessary</td>
</tr>
</tbody>
</table>

2.3. Facilities utilizing tank storage

The provision of adequate storage facilities is essential for the management of radioactive wastes. Figure 1 shows a few typical tanks generally associated with the various phases of nuclear operations and radioactive waste management.

Liquid wastes produced during refining of uranium and thorium require storage prior to their discharge for settling, treatment and monitoring. In reactor operations the active non-chemical wastes are stored in tanks before their treatment for re-use or discharge. The chemical wastes are treated after collection in site storage tanks.

All categories of liquid wastes, irrespective of their nature and composition, require storage for some length of time. This may be storage for activity decay, or storage for effecting dilution, or storage before and after treatment.

3. CONSIDERATIONS FOR DESIGN OF WASTE STORAGE TANKS

3.1. General

Considerations for the design of storage systems for radioactive liquid wastes are varied as compared to those in conventional industry, in view of the complexity of the problems encountered. Some of these wastes contain sufficiently high concentrations of fission products to cause special problems in the design of tanks for their safe storage. Also, as these wastes will be a potential hazard for a long period of time, the storage system should be so designed as to ensure safe handling, effective containment and environmental safety. On the other hand, wastes containing smaller concentrations of fission products do not pose such serious problems in their handling and storage.

3.2. Types of tanks and their sizing

Schemes for the management of category-2, -3 and -4 wastes employ storage tanks for their collection, treatment and disposal. The types and sizes of tanks used for these wastes are varied and hence only a few selected tank types and considerations for their sizing are discussed in this section.
FIG. 1. Typical tanks associated with various phases of nuclear operations and radioactive waste management.
3.2.1. Collection tanks

Collection tanks are provided for the segregation and storage of wastes at production sites prior to their monitoring for treatment or disposal. To facilitate gravity feed, the tanks can be advantageously housed below ground level in a basement area or in a vault with provision for collection of leakages or spills. The general arrangement of a set of hold-up tanks used for segregation and collection of wastes is shown in Fig. 2.

Collection tanks are sized up to provide sufficient hold-up capacity for each type of waste for economic management of transfer and treatment depending upon the quantities of wastes produced. These tanks are filled on a batch principle and a minimum of two tanks are provided so as to allow time for sampling and analysis. The same objective can be achieved by providing compartmented tanks.

3.2.2. Tanks used in treatment plants

Category-2 and -3 types of wastes are usually treated by chemical treatment and ion-exchange methods. Tanks are used for storage of wastes before and after treatment. Pretreatment storage is necessary for monitoring and conditioning of wastes. Storage after treatment facilitates the monitoring of waste prior to disposal or recycling for further treatment.
A set of three pretreatment tanks with provision for inter-transfer of wastes will facilitate uninterrupted operation of the plant. When one tank is used for feeding wastes to the treatment plant, the second tank, which is full, is used for sampling, analysis and conditioning of wastes, and the third tank is used for receiving wastes. Similar operational flexibility can be obtained by providing an equal number of post-treatment tanks. These are generally similar to the pretreatment tanks in their design and construction except that a stirring arrangement may not be necessary. It is preferable to route the treated wastes through a monitoring station before discharge where the quantity and the radioactivity of the wastes can be determined in order to account for the total release into the environment.

The general arrangement details of a set of pretreatment and post-treatment tanks associated with a chemical treatment/ion-exchange plant are shown in Fig. 3.

In sizing the pretreatment tanks, the following aspects have to be examined:

(a) Average production rate of wastes requiring treatment
(b) Surge loads of wastes expected during off-standard operating conditions and plant decontamination
(c) Planned shut-downs of the treatment plant.

FIG. 3. Pretreatment and post-treatment tanks associated with a chemical treatment/ion-exchange plant, Bhabha Atomic Research Centre.
The following points must be considered in sizing the post-treatment tanks from where wastes are directly discharged:

(a) Expected volume of the treated wastes
(b) Dilution water available, if any, in the general plant area
(c) The maximum permissible concentration stipulated for effluent discharge at the site.

Depending on their composition, category-3 and -4 wastes are generally evaporated to obtain volume reduction. As the waste volumes to be handled are not large, small tanks of metallic construction may be used as evaporator feed tanks. Provisions for secondary containment, leak detection, level measurement, etc. are necessary. The evaporator concentrates belonging to category-4 wastes are stored in large tanks located below ground level to take advantage of earth shielding.

The tanks storing category-4 wastes can be broadly classified into two types, i.e. free-standing tanks of metallic construction housed in a secondary container and concrete tanks with metal liners.

The storage tanks of the first type are cylindrical in shape, made of either stainless steel or carbon steel depending on the nature of waste stored. They are generally of flat or domed roof construction. The roof is designed to meet the structural and shielding requirements. The bottom of the tank rests on a thick concrete base. The bottom plate is generally curved up to join the shell so as to avoid accumulation of sludge around the corners. One or more tanks are housed in an enclosure which is normally a concrete vault with a metal liner. The height of the liner depends on the capacity of the largest tank in the vault.

The second type, i.e. concrete tank with metal liners, is used to a limited extent for storing category-4 wastes. These tanks are almost similar to the type of tanks described above except that the bottom and side walls of the tanks are of reinforced concrete with metal liners.

The sizing of a tank for storing category-4 wastes is based on the following considerations:

(a) Quantity of waste to be stored and its nature
(b) Geological and hydrological conditions prevailing at a site
(c) Useful capacity and spare capacity
(d) Cost.

After the capacity of the storage tanks has been fixed, the proportioning of their dimensions has to be carried out. For tanks storing category-2 and -3 types of wastes, various shapes are being adopted depending on the site conditions. For category-4 waste storage it is preferable to use tanks of cylindrical shape to help ensure tank integrity. Cylindrical tanks have the advantage of more uniform stress distribution under loading condition and less corrosion at corners as a result of accumulation of sludges, as compared to rectangular tanks. Most of the high-level radioactive waste storage tanks are cylindrical in shape. The dimensions of a storage tank are arrived at by optimizing the diameter-to-height ratio. The various factors which influence the cost of the tank are the cost of the foundation and of the land as well as that of the tank bottom, shell and roof. The optimum diameter-to-height ratio of the tank is selected to give the minimum total capital cost. Since very often the cost factors cannot be determined...
accurately until the tank is designed, the range of optimum proportions has
to be determined by successive approximations. The final tank dimensions
have to be selected after considering the various aspects that are peculiar
to the site, which include the shielding requirements, the level of the feed
pipe where gravity flow is used, etc. Methods to be followed for optimizing
the tank dimensions for various shapes are reviewed by Brownell and
Young [3].

3.3. Corrosion considerations

As category-2 and -3 waste storage tanks should be capable of receiving
liquids of diverse chemical nature, the effects of these on construction
materials have to be properly evaluated. The corrosion resistance of stain-
less steel is well known. However, wastes containing fluorides and chlorides
will destroy the protective oxide layer and bring about rapid attack. At
normal temperature, carbon steel is quite resistant to alkaline solutions.
Although general corrosion in alkaline waste storage tanks is quite low,
pitting and stress corrosion may affect the tank integrity.

As high radiation and temperature problems do not exist with the storage
of these wastes, suitable chemically resistant paints can be advantageously
used, wherever necessary, to minimize corrosion. Effluents containing
highly corrosive constituents, such as chlorides and fluorides, can be
safely stored in tanks by providing protective linings like isomeric rubber,
polyvinyl chloride (PVC) and epoxy fibre glass. It is desirable to segregate
chemical and non-chemical wastes and store them separately.

In selecting the construction materials for the storage of category-4
wastes special consideration is required for acid wastes containing sul-
phates or fluorides. Special stainless steel and also carbon steel lined
with lead or plastic materials can be used for storing these wastes. Though
neutralization of the acidic wastes reduces corrosion, the consequent pre-
cipitation, if any, and volume increase may have to be considered. Also,
the design of metallic containers for storing category-4 wastes should take
into account the long-term corrosion effects during storage. Pitting cor-
rosion is possible in tanks holding stagnant solutions and it is enhanced by
surface defects. Stress corrosion is mainly responsible for considerably
reducing the life of these tanks. Residual stress present in finished tanks
near the heat-affected areas, unstable thermal conditions during storage
and surface discontinuities should be avoided as far as possible, as these
are responsible for increased stresses which may lead to stress-corrosion
cracking. Studies on the choice of suitable construction materials for
category-4 waste storage tanks have been carried out by Marcus and
Omay [4].

It is desirable to carry out corrosion studies on materials likely to
be used for tank construction, simulating the conditions prevailing at a
particular plant. Based on the data collected, it should be possible to select
the construction material and to provide the required corrosion allowance.
Such studies should include the following:

(a) Evaluation of all promising materials; the welded samples repre-
senting the critical joints in the tank have to be included.
(b) Taking into account the storage conditions, such as waste com-
position and temperature.
(c) Collection of data for the liquid phase, the interphase and the vapour phase, if any.

The information should be based on prolonged trial runs with periodic evaluation. Care should be taken to maintain the properties of the test solution constant throughout the test period.

Actual corrosion data under operating conditions can be collected by using test pieces in the tank; such data can be useful for predicting the tank life and also for the design of future tanks.

3.4. Agitation

Agitation is necessary to ensure uniform mixing of different waste streams collected in tanks and their conditioning before treatment or discharge. Good mixing of tank contents is essential to obtain representative samples for monitoring purposes.

As the major portion of radioactivity may be associated with the settling sludge, its non-uniform distribution in a tank may give rise to problems in sampling and treatment. These problems can be reduced by dispersing the sludge in the tank by employing devices for agitation.

The selected agitation device should be such that it provides an effective, steady and mild mixing pattern in the tank. The entrainment of liquid droplets for a given mixing should be kept to a minimum. It should be possible to operate the agitation devices continuously so as to avoid maintenance problems.

For mixing category-2 and -3 types of wastes, recirculating pumps and mechanical agitators may be used. Recirculation by pumps is normally provided for small-capacity tanks. Recirculation is ineffective when fast-settling suspended solids are present in the waste. If mechanical agitators are used, they have to be run at low speed and there should not be any splashing of wastes. The design and location of the stirrer blades should be such as to ensure good and uniform mixing of the entire tank contents.

Air-lift agitators and spargers can be advantageously used for agitating category-4 wastes in tanks.

3.5. Sampling

It is essential, when sampling, to obtain the most representative samples in order to assess the characteristics of wastes for storage treatment or disposal. Sampling will enable the composition and activity level to be determined. If a large number of radionuclides are to be identified, or if the wastes contain very low concentrations of radioactivity, it may be necessary to collect a large quantity of a given sample. Thorough mixing of the tank contents before sampling is necessary and it should be possible to withdraw samples from different locations. Further, the construction materials of the sampling system should be such that they do not chemically react with the constituents of the sample.
3.6. Leak detection

In the event of a failure of a tank holding higher-level radioactive wastes it is essential to promptly detect the leak in order to take immediate corrective measures. This may be done by providing level gauges inside the tank and by installing radiation detection devices in adjacent bore holes or at collection points connecting the lateral channels constructed beneath the tank.

As waste transfer operations in tanks holding category-2 and -3 wastes are carried out frequently, spillage and overflowing may occur. The rooms or platforms where category-2, -3 and -4 waste storage tanks are located are generally provided with curbs and collection sumps and such other secondary containment devices as are useful to detect leakages. For underground storage tanks, where no secondary containment is provided, measurement of the liquid level in the tank and waste inventory control will indicate leakages. The level gauges should be very sensitive when large-sized tanks are used, as is generally the case when storing category-4 wastes. Also, the radiation measuring instruments employed should be sensitive to even small changes of radiation levels above the background. A static monitor, if not properly located, may become ineffective as there are chances of the liquid bypassing the instrument. Further, the determination of the nature and the activity level of the leakage is not possible if such detectors are used. An analysis of ground-water samples, periodically collected from monitoring wells around the tank, will provide the most reliable information on these factors.

3.7. Decontamination

Decontamination of tanks is necessary to facilitate maintenance and also to bring down the general radiation level, wherever necessary. As the tanks placed behind shielding walls or below ground level may not be readily accessible for decontamination it is desirable, particularly for higher-level wastes, to provide recirculation jets for the introduction of a measured quantity of decontaminating solutions with provisions for heating. The action of decontaminating solutions on the construction material of tanks has to be taken into consideration when selecting the cleaning reagents.

4. DESIGN AND CONSTRUCTION OF WASTE STORAGE TANKS

4.1. General

The special features in the design and construction of radioactive liquid waste storage tanks are the extra safety and the rigorous inspection and testing requirements to ensure quality control. As these features increase the cost, the degree of safety of the system should be justified by the service requirements. Depending on the nature of the services required, proper design, construction, inspection and testing procedures have to be adopted.
4.2. Design

Stress evaluation plays a predominant role in the assessment of tank integrity. The basic requirement for the design is to ensure that the stresses induced in the material do not exceed the maximum allowable stress for that material. Should they exceed a value which is safe for a particular design, modifications have to be incorporated by changing the dimensions, geometry, loading pattern, etc.

The various types of loading that have to be considered can be listed as follows:

(a) Static hydraulic loading
(b) Reactions at supports and piping systems
(c) Earth pressure and hydrostatic pressure from ground-water
(d) Seismic and other external loads
(e) Transient loads, if any.

In calculating the expected maximum hydrostatic pressure, possible changes in specific gravity have to be taken into account. The earth pressure will depend on the site conditions. Support reactions are predominant in the case of long, horizontal tanks resting on saddles, and vertical tanks installed on lug supports. The external loading on the tank can be high when shallow ground-water conditions prevail. The maximum expected ground-water pressure can be estimated by using hydrographs pertaining to the site. If tanks are located in seismic regions, the design should account for the expected earthquake loads. Similarly, external loads due to wind pressure, ice load, etc. have to be considered wherever applicable. The data required for such considerations may be obtained through the local meteorological centres. Transient loads due to temperature variations often call for the provision of additional safety factors. In evaluating thermal stresses, indeterminates such as the actual temperature gradients, the effect of thermal expansion, the magnitude of secondary stresses developed in walls due to restraints, have to be considered.

The stresses to be considered are the primary stresses developed by the imposed loading and the secondary stresses developed due to the constraints of a structure. Some national codes stipulate that a detailed stress analysis of structural components has to be carried out in order to ensure that the induced stresses do not exceed the allowable limits. In cases where codes and standards do not call for a rigorous stress analysis, the designer has to use his judgement for carrying out stress analysis for all critical components based on the requirements of the service conditions.

4.2.1 Steel tanks

Cylindrical types of tanks used for storing higher-level radioactive wastes possess greater structural strength. The stresses that may occur in the shell and which have to be determined are the longitudinal and circumferential stresses. The stress from superimposed loads should also be considered.

Longitudinal and circumferential stresses may be caused by hydrostatic load, internal vapour pressure, external loads and thermal gradients. Apart from these, stresses at the knuckle plates and shell-head junction should
be determined. For large-size tanks, stresses at the knuckle plates can be quite high. Supports and openings may impose detrimental loading. Methods for evaluating stresses induced in the shell by the supports are indicated by Brownell and Young (Ref. [3], p. 203).

In dealing with situations where design uncertainties exist it may be difficult to decide the safety factor to be provided. Considerations for assuming reasonable safety factors should take into account the method of design employed, the quality of materials used and the standards followed for fabrication including the service conditions of the tank.

As the welded joints in tanks are more susceptible to failure, the integrity of such joints has to be ensured. Whenever position welding is required, high-quality design and welding are essential. For critical service requirements, as may be the case in category-4 waste storage, it is desirable to carry out 100% radiographic examination of welds.

The salient structural details of a typical horizontal steel tank for a volume of 1500 m$^3$ of category-2 liquid wastes associated with a power reactor installation are shown in Fig. 4.

4.2.2. Concrete tanks

Bare concrete tanks are not generally used for storing radioactive wastes, as leak-tightness and corrosion resistance cannot be assured. Concrete tanks are invariably lined with suitable materials for preventing a leak path.

Reinforced concrete tank design takes into account the fact that tension cracks will develop. The reinforcing steel controls the size of the cracks while the structure is under tension.

Apart from the stresses due to the imposed loading, stresses that are induced in concrete produce 'shrinkage cracks'. The concrete shrinks against the action of steel during the curing period. But in course of time the plastic flow eliminates this stress.

Cylindrical tanks, though involving more cumbersome form-work, are advantageous as compared to rectangular tanks, as regards both the structure and the material economy. As the concrete walls are rigid, both the ring tension and the vertical beam action under hydrostatic head have to be considered. The dimensions of the tank and the types of restraints at the edges determine the proportion of the load resisted by ring tension and beam action. When the wall cannot deflect freely under the load, the maximum ring tension is found to occur not at the point of maximum hydrostatic pressure but at some point above this [5]. The circumferential stresses are caused by the internal hydrostatic pressure, earth pressure, external water pressure, and the surcharge from equipment used during construction and also thermal stresses, if any. The vertical stresses are due to the roof load, wall bending moment, temperature gradient, etc. The weight of the liquid is carried through the floor slab to the subgrade. The liquid load does not cause bending of the slab if the subgrade is quite firm. Reinforcements have to be provided against any settlement of soil causing bending of the slab. If hydrostatic pressure due to ground-water is expected, the base slab has to be designed to withstand this uniform upward pressure when the tank is empty. An ellipsoidal dome is a good shape to resist earth load and internal vapour pressure. It also reduces the amount
FIG. 4. Structural details of a steel tank to hold category-2 liquid waste, Rajasthan Atomic Power Plant.
of excavation and avoids the use of a heavy dome ring, as is necessary in the case of a segmental spherical shape.

The design of rectangular reinforced concrete tanks is generally based on similar considerations as discussed for cylindrical tanks. However, the uncertainty in evaluating restraints at corners and thermal stresses pose design problems. Therefore, rectangular tanks are not recommended for use in critical service.

In general, the design of concrete structures is often complicated since the stresses developed in the structure are not necessarily directly proportional to the load. The problems have to be solved by trial and error methods. However, a rough approximation can be made by simplified assumptions.

The structural details of a typical underground reinforced concrete tank with a metal liner used for collecting category-3 wastes from a research reactor are shown in Fig. 5.

4.2.3. Prestressed concrete tanks [6]

Critical designs for prestressed concrete tanks are generally based on model testing and studies on prototype structures. The principle involved in the design of prestressed concrete structures is that the pre-stressing permits the concrete to be used as a tension member while maintaining the concrete itself under compression. The tension-loaded steel is efficiently utilized and tensile cracks in concrete are virtually eliminated.

The advantages of using prestressed concrete may be summarized as follows:

(a) Ductile mode of failure and resealing capacity of the structure
(b) Under loading conditions, the effective stress on the concrete is kept at a minimum and hence deformation can be reduced
(c) Cable replacement and restressing are easy
(d) Substantial savings in cost are possible for large structures.

However, for prestressed concrete tanks the design has to take into account the following:

(a) Effects of temperature transients, if any
(b) Stress concentration due to bunching of cables at penetrations
(c) Necessity of special protection for high-tensile steel cables immediately after tensioning so that stress corrosion is avoided. In places liable to stress corrosion, the use of cold-drawn high-tensile steel wires is recommended.

In view of the inherent advantages with respect to cost and structural integrity, prestressed concrete structures are being used for storing non-heating radioactive liquid wastes, despite the disadvantages mentioned above.

Figure 6 gives the details of a typical prestressed concrete tank used for storing low-level radioactive waste solutions [7].
FIG. 5. Structural details of an underground reinforced concrete tank with a metal liner for category-3 wastes, Bhabha Atomic Research Centre.
4.2.4. Steel liners for concrete tanks

Both reinforced concrete and prestressed concrete tanks are generally provided with a metal liner which is compatible with the waste to be stored. The liner can be used as an inside form for the concrete.

Design and construction procedures to be followed for liners are basically similar to those adopted for steel tanks.

It is the usual practice to choose the thickness of the liner on the basis of the corrosion characteristics of the waste stored and also taking into account the different types of loads imposed on the liner.

The loads to be considered are [8]:

(a) Hydrostatic load during test
(b) External load from the concrete, if the liner is used as an inside form during construction
(c) Shrinkage stress transferred from the concrete causing circumferential compression
(d) Circumferential compression due to prestressing, if any.

The liner is anchored to the concrete by providing holdfasts at regular intervals. The buckling strength of each section of the liner should be evaluated and compared with the imposed load on that section. Yielding of the liner under compressive stress may not pose problems, as local adjustment within the section is possible.
4. 3. Construction

4. 3. 1. Steel tanks

With increasing structure dimensions and weight, a combined fabrication in shop and field appears to be advantageous. In such a case, the site should have facilities for welding, machining, stress-relieving, inspection, etc. The materials used should be properly identified with the necessary mill-test reports and coded markings to enable proper material selection and site assembly. As fabrication progresses, the edges of plates, openings and fittings have to be carefully examined for laminations, cracks or similar flaws. It is quite possible that the inspection of welds may not reveal some of the root-surface defects, and therefore the welding procedures followed for the fabrication should be clearly specified to avoid such defects. The best method to guard against effects of cold work and residual stresses in heat-affected areas is stress-relieving by heat treatment. If the stainless steel used is not stabilized, corrosion in the weld-affected areas of the tank is possible due to carbide precipitation and depletion of chromium. Heat treatment is the commonly accepted practice to restore chromium back to the impoverished zones.

4. 3. 2. Concrete tanks

For the preparation of a good concrete-mix it is necessary to find out the proper proportions of the ingredients to ensure a workable, dense and strong concrete. No uniform procedure can be laid down because of the large number of variables involved. The quality control procedures adopted for material, mix and construction must be very rigorous to ensure the structural integrity of the tanks.

The methods employed for the construction of concrete tanks have a marked effect on the integrity of the structure. It is essential to clearly specify all construction procedures in order to ensure homogeneity of the structure. Proper placement, compaction and formation of joints are some of the most important requirements. In the case of large-capacity tanks, where monolithic pour may be difficult, it is necessary to carefully prepare the concrete surfaces before successive pours to ensure good construction joints.

4. 4. Inspection and testing

4. 4. 1. Testing of raw materials

Inherent defects in the raw material and defects introduced during transport, storage and fabrication may cause failure conditions. Variations in the quality of raw materials used give rise to some uncertainties in predicting the performance of tank structures under service. Rigorous inspection for flaw detection, determination of the chemical constituents and proper handling of the material during transport and storage are some of the requirements for avoiding tank failure due to material defects.

Some of the common tests recommended for different construction materials are as follows:
Steel plates and structurals: visual inspection, radiography, magnetic particle and sonic techniques, liquid penetrant tests, etc.

Cement: test for soundness, setting time, tensile strength and compressive strength.

Sand: analysis for deleterious materials, sieve analysis and void test.

Aggregate: tests for deleterious materials, physical properties and alkali reactivity.

Concrete: consistency test, compression and expansion tests, estimation of water/cement ratio and test for setting shrinkage.

Reinforcing and prestressing cables: visual inspection, determination of yield and ultimate strength and creep test.

4.4.2. Testing of steel tanks

A hydrostatic test can be done on tanks which are supported or anchored safely. The corrosion allowance provided has to be taken into account for arriving at the test pressure. The pressure-holding time should be sufficient to enable inspection for leakage of all the parts. Almost all the tests specified for the inspection of steel plates and structurals are generally applicable for the inspection of welds.

4.4.3. Testing of concrete tanks

Concrete tanks are tested for leakage by filling them with water to the desired level. If the tank has a liner, this has to be tested hydrostatically before the concrete forms are placed in position.

5. DESIGN OF ACCESSORIES FOR WASTE STORAGE TANKS

5.1. General

To facilitate the proper storage and handling of radioactive liquid wastes it is essential to provide suitable accessories. In accordance with the various considerations discussed in section 4, special features have to be incorporated in the design of accessories to provide safe operating conditions.

5.2. Transfer systems

The transfer systems associated with radioactive liquid waste storage tanks essentially consist of pipes, pipe fittings and valves. Pumps are generally used to provide the required energy for the transfer of wastes. The degree of safety required for transfer systems will be dependent upon the specific activity of the liquid, the location of the equipment and the possible off-standard operating conditions.

5.2.1. Pipes and connections

The materials for pipes and connections have to be selected primarily with regard to the chemical nature of the liquid to be handled. Considerations like those of maintenance and decontamination should also be taken
into account. The use of carbon steel is limited in the nuclear industry, as it easily corrodes and its decontamination is difficult. Carbon steel may, however, be used in transfer systems carrying low-level radioactive wastes under alkaline conditions, where maintenance and periodic replacement of the piping do not pose problems. Stainless steel is the most versatile material that can be used for piping systems, particularly for cases where large variations in the chemical composition of wastes are expected. Also, it is advantageous to use stainless steel because the need for maintenance is reduced and decontamination is easier. Because of their corrosion-resistance properties copper pipes are commonly used in the form of embedded piping for transferring low-level radioactive wastes. Polyethylene is cheap, light, flexible and chemically inert and it is therefore an ideal material for drain pipes carrying laboratory wastes. Unplasticized polyvinyl chloride (PVC), which is the most rigid variety, is commonly used for radioactive waste piping, provided the recommended temperature limits are not exceeded. PVC is resistant to chemical action and it can be easily decontaminated.

The pipe fittings should be suitable to form perfectly leak-tight joints. It is preferable to use all-welded fittings for pipes carrying radioactive wastes. Flanged fittings are used for equipment connections and on pipe sections which require dismantling. Flanged connections should be kept to the minimum and threaded connections have to be avoided, except in the case of very low-level radioactive wastes.

5.2.2. Valves

The valves used for radioactive service are generally adaptations of the standard valves used in chemical plants. These special adaptations are for the purpose of precluding the possibility of trapping radioactive materials in the body of the valve and to facilitate remote operation, wherever required.

The gate-valve is mainly used as an on-off distribution valve because it does not permit easy control of flow. The gate-valve provides a clear, unrestricted flow-opening, resulting in a very low pressure drop. It is normally used on large-size pipes carrying wastes with low suspended solids. The globe-valve is used for coarse throttling service in the case of wastes containing low solids. The ball-valve is a quick-opening valve which can be used as an on-off distribution valve in pipes handling wastes containing very low suspended solids and sludges. The butterfly-valve is widely used in large-sized radioactive waste piping because of its economic design and ease of remote operation. However, this valve cannot control the flow accurately. The diaphragm-valve is used in radioactive waste systems for flow control because there is no leakage at the valve stem. It can also be used in pipe-lines carrying slurries.

A diversion box (Fig. 7) is commonly used in transfer systems for handling category-4 wastes. It consists of a rectangular concrete box with removable covers. A typical diversion box has a number of lines entering through one face of the box with nozzles on the inside face. On the opposite face, a number of nozzles are located leading through the wall of the box to various tanks. The nozzles on the opposite faces of the box can be connected to provide different routings by jumpers (rigid sections of pipes terminated in connectors) when waste transfer to a specific tank
FIG. 7. Typical diversion box used in transfer systems for handling high-level radioactive liquid wastes.
is required, or they can be blanked off when not in use. The box should contain a sump or an overflow leading to a catch tank from which it can be returned to a storage tank by means of a suitable jumper connection.

5.2.3. Pumps

The ideal method of effecting radioactive liquid transfer is by gravity flow. Since this method is not always practicable, pumps are used to provide the motive force for transferring liquids. The characteristics of pumps should satisfy the process requirements. The theory and complete details of design, selection and performance of pumps can be found in Refs [9,10].

Numerous types of pumps are being used for handling radioactive liquids. A few of the most commonly used types are discussed below.

Positive displacement pumps are not generally used for transferring radioactive liquid wastes, since the flow is not uniform and the maintenance poses problems. In certain cases, diaphragm pumps can be used, particularly for slurries. These pumps can be easily put into service and maintained. Centrifugal pumps give excellent service where flooded suction conditions are available. Self-priming pumps can be used with advantage in low-activity waste service where flooded suction conditions cannot be provided.

The pump best suited for handling higher-level radioactive wastes is a completely submersible pump. As such pumps may not be commonly available, a reasonable alternative is a submerged pump, powered by a motor which is installed outside the tank. A vertical submersible regenerative turbine pump can develop much higher heads than a centrifugal pump and is generally used for pumping small quantities of liquids. Deep-well turbine pumps are used for transferring solutions at high flow rates. They are commonly used for transfer operations from deep underground tanks.

Ejectors are increasingly being used for transferring higher-level wastes from storage tanks, as maintenance and leakage problems are minimized due to the absence of moving parts. They are of standard types using steam, air or water as motive fluids. Design data and general characteristics of ejectors can be obtained from manufacturers and handbooks (see Ref. [11]).

In pumping installations it may be necessary to use control systems. Some such controls are:

(a) Automatic pump trip in conditions like low liquid level in the tank, leakage of active liquid and high discharge pressure.
(b) Automatic pump start at high liquid level in the vessel. This should be considered particularly for unmanned collection tanks and sumps to avoid overflowing.
(c) Automatic change-over of stand-by pumps. This is often done to regulate wear and tear of pumps.

5.2.4. Design and installation of transfer systems

The calculation of pressure drops in pipe-lines is important for the sizing of pipes and the selection of pumps to perform the required service. Such calculations are also necessary for gravity flow piping for determining the required gradients and the pipe diameters. The methods followed for
estimating the pressure drops in pipe-lines are conventional and can be obtained from standard handbooks (see Refs [11,12], p. 377-90, 1430-35). The pipe diameters for transfer operations should be selected to provide the most economical design, with minimum total capital and operating costs. The capital cost of the pipes and fittings is directly proportional to the pipe diameter, whereas the cost of pumping, which is dependent on the flow rates and pressure drops, is inversely proportional to the pipe diameter. The economic pipe diameter can be determined by optimizing the above cost factors. Methods for optimizing pipe diameters are given in Ref. [13].

Apart from conventional design practices for piping systems, the following points have to be taken into account prior to designing radioactive waste transfer systems:

(a) Containment of possible leakages
(b) Shielding requirements
(c) Provision of spare piping and embedments
(d) Possibility for isolation of active streams
(e) Facility for flushing and decontamination of piping
(f) Ease of maintenance and replacements
(g) Provisions for remote operation
(h) Safety and environmental contamination.

The extent of safety precautions applied in the design of radioactive waste piping largely depends on the hazard potential of the waste and the cost considerations which vary from site to site. The piping systems for handling low-activity wastes are relatively simple in design and are similar to the piping systems employed in conventional chemical plants. The piping design is more involved for higher-level radioactive waste transfer, where even minor leakages can be very hazardous and the cost of rectification high. The following generally accepted methods of installation are recommended for piping systems handling higher-level radioactive wastes:

(a) Pipe-lines within buildings should be installed in pipe trenches or pipe galleries with provision for secondary containment.
(b) Piping systems outside the building should be underground and run in reinforced concrete trenches lined with asphalt on the inside. Alternatives, like concentric carbon steel pipes over waste lines and steel-lined concrete conduits, can be used with discretion. Exhaustive studies on this subject have been carried out at Hanford [14-16] and it has been recommended that encasements need to be provided only at buildings and heavy traffic areas; isolated pipes should be run in concentric pipes and the remaining piping provided with cathodic protection. These recommendations appear to meet the requirements with respect to safety and economy and may be suitable for most sites.
(c) In general, pipe-lines should be installed at an incline to facilitate easy gravity discharge of the contents when the lines are not in use.
(d) The trenches and other encasements for pipes should be sloped towards low points located at intervals along the pipe-lines to facilitate the collection of active waste from leakage. The low points should be provided with leak detectors, samplers and arrangements for removing the collected liquid.
(e) Since the radioactivity prevents easy maintenance of the pipes, it may be necessary to duplicate pipes or to provide alternative routings. In particular, the embedded pipes should be duplicated.

(f) Pipings with radioactive liquid wastes should be clearly isolated from non-radioactive parts. Seal-pots should be installed in pipes which are routed from radioactive to non-radioactive sections to prevent cross-contamination.

(g) Flushing facilities should be provided, particularly for pipe-lines which carry liquids with suspended solids. The flushing liquid should be treated as active waste.

(h) A regular monitoring and inspection program should be laid down to ensure prompt detection of leakages.

Failure of pipe-lines can generally be attributed to ineffective supports, neglected vibration and thermal expansion effects, inaccessibility of inside surfaces for inspection, etc. To ensure the integrity of the piping systems it is essential to inspect and test them periodically.

5.3. Gas-cleaning systems

The selection of gas-cleaning systems for waste storage tanks largely depends upon the nature of the wastes stored. In general, the gas-cleaning systems for the waste storage tanks consist of devices for removing liquid droplets and particulate matter. Salient details of some of the commonly used gas-cleaning equipment are briefly covered below.

5.3.1. Cyclones

Cyclones are commonly used as precleaning devices for removing liquid droplets entrained into the off-gas system. In a cyclone, the gas tangentially enters a cylindrical or conical chamber where the droplets collect at the periphery due to centrifugal action, and the clean gas leaves through a central opening. A cylindrical cyclone is more suitable as regards the problem of re-entrainment of the liquid droplets that is likely to occur in a conical cyclone; the design details of such a cylindrical cyclone with provision for de-entrainment are covered in Ref. [17]. Small-diameter cyclones are better suited for achieving high collection efficiency.

5.3.2. Scrubbers

The scrubbers are mainly used for removing and neutralizing corrosive vapours and mist. The design of a scrubber aims at effecting an intimate contact between the scrub liquor and the off-gases. Centrifugal spray scrubbers are found to be very effective for removing the contaminants [18]. As the scrubbing liquid is generally recirculated, the nozzles in the scrubbers must be capable of handling liquids with a fairly high solid concentration. Also, the scrub liquor should be filtered to overcome this problem.

5.3.3. Deep-bed filters

A deep-bed filter consists of an assembly of fibrous media packed in the form of a bed. Materials such as glass, asbestos and their combinations
in suitable proportions are generally used. Glass-fibre filters are widely employed in gas-cleaning systems associated with tanks because of their chemical inertness. The efficiency of such filters depends upon the packing density, the thickness of the bed, the mean fibre diameter and the face velocity of the gas. The decontamination factor that can be obtained with these filters can be evaluated by using empirical methods [19].

5.3.4. High-efficiency filters

Fibrous materials are formed into a lap and pleated to make a high-efficiency filter. This type of construction provides a large surface area to the air flow, thus reducing the overall pressure drop across the filter. Such filters, having a collection efficiency of 99.99% for particles of 0.3 μm, are commercially available and can be used in the final stage for removing the fine particles in the off-gases. The selection and installation of such filters should be based on the following considerations:

(a) The filter media and all the other components of the filter should be capable of withstanding the humid and corrosive conditions expected in the system
(b) The capacity should be such as to meet the maximum gas flow during adverse operating conditions.
(c) The filters should be so mounted in the filter frame as to provide a perfectly leak-proof assembly and to enable easy replacement without spread of contamination.

5.4. Agitators

Agitation will be normally required in most of the radioactive waste storage tanks. The equipments used for agitation in tanks are: recirculating pumps, mechanical agitators, air-lift circulators and spargers.

5.4.1. Recirculation pumps

Agitation by recirculation of wastes using pumps or ejectors is normally done in small-capacity tanks storing category-2 and -3 wastes. This is a method which can be conveniently used when simultaneous sampling is required. Recirculation of about five to ten volumes of the tank capacity, depending upon the nature of waste handled, will be necessary to ensure homogeneity of the waste. The pump which is used for transferring the waste from the tank can also be utilized for effecting recirculation. The capacity of such a pump should provide for the desired mixing in a reasonably short time.

5.4.2. Mechanical agitators

Various types of mechanical agitators are used for mixing category-2 and -3 wastes. The most common agitators used are the propeller and the turbine types.

Propeller mixers are inexpensive, simple and compact. The mixing is effected by revolving helical blades producing axial currents in the liquid. The efficiency of a propeller mixer is much dependent on its location and
the shape of the tank. The arrangement should provide sufficient turbulence. In circular tanks, the use of baffles or eccentric mounting of the impeller assembly is preferable. If the impeller is mounted vertically, the use of a draft tube will provide efficient mixing. Propeller mixers can be mounted directly on to the tank either from the top or from the side. Side-entering stirrers can be used for long horizontal tanks, but such a technique gives rise to a possible leak-path for the contained liquor through the stirrer shaft gland. Propeller mixers are quite efficient for suspending fine solids of low specific gravity wastes. Turbine-type agitators generate strong radial currents and are similar in construction to the impellers in centrifugal pumps. They provide efficient mixing of wastes containing suspended solids of high specific gravity. The initial outlay on turbine mixers is higher than for propeller mixers. Some of the common types of agitators and their mounting details are shown in Fig. 8.

FIG. 8. Common types of agitators and their mountings.
The use of a good stuffing box or mechanical seal and strong bearings is important. Also, the vibration transmitted to the tanks from agitators mounted directly on to the tanks has to be kept to a minimum to avoid stress corrosion in tanks.

The lack of accurate quantitative terms to describe agitation and of truly basic data has complicated the selection of agitators. The design of agitators is generally based on experience. A good guide for the selection of agitators and the estimation of power requirements can be found in standard literature (see Ref. [11], p. 1218 and 1226-27).

5.4.3. Air-lift circulators and spargers

Air-lift circulators are ideal for use in large tanks holding category-4 wastes for which mechanical agitators cannot be used because of the associated problems. They provide a slow and thorough turn-over of material at reasonable gas flow rates. A non-condensable gas, usually air, is used as the motive fluid.

The air-lift circulator (Fig. 9) consists of a simple vertical pipe with an air distributor at the bottom. Circulation of liquid is effected by formation of an aerated mixture of lower specific gravity. The motive force should be sufficient to overcome the frictional and acceleration resistances. To enable the efficient operation of circulators at varying liquid depths, two or three sets of circulators with different lengths have to be installed.

![Flow measurement lines to dp instrument purge meter](image)

**FIG. 9.** Air-lift circulator [20].
in the tank. Excellent work has been carried out by Cook and Waters [20] on the evaluation of the performance of submerged air-lift circulators.

Jet-spargers are long vertical tubes with nozzles at the bottom. Connections are provided at the top for compressed air and vacuum application. When in operation, the liquid in the cylinder is expelled through the nozzle by the air pressure and the jet sweeps the bottom of the tank. The cylinder is then allowed to refill with liquid by applying vacuum for a second purge and the operation is repeated in cycles.

Compressors for uninterrupted supply of air to the circulators and spargers are generally duplicated.

5.5. Samplers

Samples taken from tanks are transferred to the sample station. Samples of category-2 and -3 wastes stored in tanks can be obtained by lowering a bottle of suitable shape and capacity into the tank and drawing it out at a constant speed so that the bottle is just filled at the end of the operation. This provides a sample representing all the levels in the tank. Samples can also be obtained by lowering a stoppered bottle to various levels of liquid in the tank and releasing the stopper by remote operation to obtain liquid samples at different levels. It is important to control contamination during these processes.

Normally, air lifts and air jets are used to move the liquid samples from tanks holding category-4 wastes to the sampling station. The operating components of a typical high-active waste sampler (Fig. 10) include the following:

(a) One or two air-operated jet assemblies
(b) Suction and discharge piping to recirculate the liquid
(c) Sample pot
(d) Remote pipetting device
(e) Carriers for transporting samples.

For higher-level radioactive wastes the sample station, the operating components and the controls should be isolated by suitable shielding, which may be concrete or lead, or a combination of both. Sample jets, flow control valves and piping are housed in a concrete valve pit with removable covers. Lead glass windows or reflecting mirrors should be provided for viewing. The station should have an exhaust hood for preventing air contamination. The sample pot is placed in the suction line for mixing. Sample jet and pot assemblies are connected with the piping for the continuous flow of the liquid from the sampling point through the sample pot to the suction side of the jet. An air lift is used to assist in attaining reasonable recirculation rates if high lifts are required. A remote pipette is used for collecting a fixed amount of sample from the sample pot into the sampling bottle. The sample bottles can be transported to the laboratory by a system of conveyers.

Steam as a motive fluid for the jets dilutes the sample through condensation. The use of air lifts and air-operated jets is therefore more advantageous. The sampling lines should be suitably arranged and sloped to enable complete drainage of the system. They should be provided with
FIG. 10. Operating components of a typical high-level radioactive waste sampler.
a flushing arrangement for avoiding cross-contamination of samples and for keeping the lines clear, particularly when slurries are handled. The sampling system described above can also be used for low-active waste sampling. For this, the shielding, sample pot and remote pipetting may not be necessary.

5.6. Leak detectors

Leak detectors are used to detect the accidental leakages of radioactive wastes from hold-up tanks. They are generally either electrical conductivity probes or radiation detectors.

The electrical conductivity type of detectors consists of two conductors located very close to each other. They are mounted in a frame reasonably close to the floor. A potential difference is maintained between the two probes. Suitable current measuring devices and alarms are included in the circuit. Under normal conditions, the probes are insulated from each other and there is no flow of current. In the event of a leakage, the probes are short-circuited by the liquid, which results in a flow of current. This is detected and used to actuate an alarm. For these detectors it is necessary to ensure good insulation between the electrical conductors, the supports and the ground.

Radiation counters used for leak detection should be very sensitive and adequately shielded to reduce the background to a minimum. The assembly is placed near the floor with the window facing the floor of the secondary container or the collection sump. In the event of a leakage of radioactive liquid, the counts registered by the counter will increase, thus giving an indication of the leak. Particular care should be taken in selecting the inter-connecting wires in view of the high voltages involved and the likely adverse condition of high humidity.

5.7. Instrumentation

Instruments for measurement and control of variables like level, density, temperature, hydrogen-ion concentration, etc. may be required for radioactive waste storage systems. A brief description of some of the more important instruments used is given below.

5.7.1. Level measurement

A purge dip-tube system is most commonly used for level measurement in waste storage tanks (Fig. 11). Air at a pressure which is slightly higher than that required to overcome both the hydrostatic head of the liquid and the static pressure in the vapour phase of the tank is passed at a controlled rate through a purge tube submerged in the liquid, and a second air line is terminated at the top of the tank. The difference between the backpressures experienced by the air lines is proportional to the depth of the liquid above the purge tube. This differential pressure is either directly measured by a gauge near the tank or transmitted for remote measurement by using differential pressure transmitters.

The tip of the purge tube in the tank is tapered at an angle to prevent clogging and is located at a sufficient distance from the tank bottom to ensure a layer of homogeneous liquid free from sludges above it. The purge
tubes are so installed as to enable their easy removal for periodic inspection and cleaning.

The electrical conductivity type of level measurement can also be used in tanks where a qualitative indication of the liquid level is sufficient, i.e., whether the liquid level is above or below a set point or points. This method is very commonly used for automatic control and alarm systems. One or more electrical conductivity probes are installed at the desired depths in the tank and the indication of the liquid depth is obtained by making or breaking contact between the probes corresponding to the conductivity of the liquid.

Good insulation between the probes and probe supports should be ensured. An accumulation of sludges on the supports should be prevented, as it tends to increase the possibility of a current flow between the probes, even if the liquid level is below the probes, which results in erroneous indications.

5.7.2. Density measurement

The principle applied in density measurement is similar to that described above for level measurement. For each density measurement two purge tubes are used. The tubes are immersed in the liquid and are terminated at a known, fixed, vertical distance from each other. The difference in hydrostatic head at the tube openings depends on the density of the liquid and the vertical distance between the tubes. The latter being constant, the difference in pressure is proportional to the density. The pressures from the purge tubes are fed to a receiver gauge to indicate the density.
5.7.3. Temperature measurement

For temperature measurement in the tanks the sensing element is normally a thermocouple. A suitable 'well' made of material not likely to be affected by the tank liquid is used as a secondary containment for protecting the sensing element. The material selected should have high thermal conductivity. The signal from the sensing element is fed to a standard indicator or recorder. By locating measuring elements at various points the temperature at different levels in the tank can be determined. For ease of installation and servicing the 'well' should be straight and of uniform bore with the open end situated at an accessible place where the radiation level is within permissible limits.

5.7.4. pH measurement

The pH of the liquid in the tanks can be determined using commercially available immersion-type pH-electrode assemblies rated for the temperatures expected in the tanks. The assembly consists of a measuring electrode, a reference electrode and a temperature compensator mounted at the end of a long stainless-steel pipe. The electrodes are protected from mechanical damage by means of a wire cage. The pipe extends to the top of the tank from where leads are taken through a terminal box and connected to measuring instruments. The pH value is obtained after amplification of the electrical signal on a suitable meter.

Most of the commercially available electrodes have to be kept wet for reliable operation. Arrangements should be made to ensure that the probe is kept wet in the event of the tank liquid falling below the level of the electrodes. The solid particles in the liquid tend to adhere to the electrodes thus giving rise to erroneous readings. Regular and frequent cleaning of the electrodes is therefore essential. In the case of higher-level radioactive wastes it may be preferable to measure the pH by sampling.

5.7.5. Pressure measurement

Pressure gauges can be used in conjunction with pipes connected with tappings on the top of the tanks for measuring the pressure in the tanks. Air may be purged through the pipe to prevent infiltration of radioactive vapours from the tank. If air purge is not used and the indicator is remote from the tank it should be ensured that the air temperature in the line at the gauge is the same as that in the tank. Condensation of vapour in the line should be prevented by lagging and/or heating.

5.7.6. Flow measurement

The flow of the liquid through pipe-lines when entering or leaving a tank can be measured using head-flow meters. The venturi tube is the most suitable flow meter for waste containing suspended solids. The stream-lined construction of this device prevents the solids from sticking to the sides of the body. The differential pressure developed by the venturi tube is piped to a flow transmitter, the output of the transmitter being fed to a receiver gauge. As venturi tubes are expensive, in many cases orifice plates may serve the same purpose. The orifice plates create a
pressure difference and a measurement of this gives an indication of the flow. An orifice plate used in the slurry-carrying pipe-line should be eccentric to the bore at the bottom of the pipe in order to prevent build-up of sludges on the upstream side of the orifice. The tappings to the transmitter are taken from the sides of the pipe.

6. OPERATING TECHNIQUES

6.1. General

All the operations connected with a radioactive waste storage system should be carefully planned and controlled. Though the design of the system ensures reasonable safety, poor operational practice will lead to its failure. It is therefore necessary to ensure the integrity of the tanks at all times and to promptly detect spread of contamination. Any unforeseen occurrences during operation have to be properly evaluated and the findings recorded for future guidance. Based on the actual experience gained in the operation of the storage system, the operating procedures should be reviewed periodically and improved upon. If every item of expenditure incurred in the operation is carefully recorded in accordance with the accepted costing procedures, useful data will be available for future economic evaluation.

As the details of operating techniques are specific to a particular installation and generalization is not practical, only a few important aspects are summarized in the following.

6.2. Transfer operations

Category-2 and -3 wastes are normally stored in tanks for short periods and frequent transfer operations are required for treatment and disposal of these wastes. Wastes collected in site storage tanks are transported to treatment plants either by using tank trucks or through pipe-lines. Small volumes of wastes may be transported by tank trucks. Wastes are generally transferred into the tank truck by applying suction to the truck container. The pipes and hoses connecting the tank and the tank truck have to be leak-tight and preferably kept at an inclination so as to enable complete drainage of the liquid back to the tank at the end of the transfer operation. Tank trucks are emptied either by allowing the waste to flow by gravity or by pumping. If the waste is transported by pipe-lines it is advisable to remove the suspended matter near the point of origin to avoid sludge accumulation at low points. Whenever pipes, valves, etc. are blocked, they have to be cleared by passing air, water or steam at an appropriate pressure through the pipes. The method depends on the characteristics of the piping material and the system. Before any transfer operation is carried out it is desirable to mix the tank contents.

If a common transfer system serves a group of tanks in a system handling a variety of category-4 wastes, the transfer lines should be flushed before every change of the type of waste handled (see Ref. [4], p. 20). Before flushing, a volume of water equivalent to that of the remaining waste in the transfer line is first pumped in, so that the waste is completely replaced by water. The wash-water is collected separately and the pipeline is then thoroughly flushed. After completing the flushing operation,
the water in the pipe-line is replaced by the new stream of waste and the routing is changed to fill the waste storage tank. The use of activity monitors in the transfer line and the return flush line will help in controlling these operations. Such a practice will avoid cross-contamination of waste streams and dilution of wastes during flushing.

Hot concentrates coming from waste evaporators are cooled by using cooling arrangements provided for this purpose, so as to avoid vaporization in the pipe-lines. During evaporation it is important to control the waste concentration in such a way that solid formation by crystallization is avoided, and thus blockage of pipe-lines and enhanced erosion are prevented.

6.3. Analytical control

Analytical control is required for effecting a check on handling, disposal or storage of category-2, -3 and -4 wastes. The analysis of these effluents will help in deciding the treatment method to be adopted and the degree of decontamination to be achieved before they are discharged. Such a control will involve radiochemical and chemical analyses of a variety of liquids and sludges stored in tanks.

Radiochemical analysis generally includes the determination of gross activities and hazardous radionuclides like $^{90}\text{Sr}$, $^{137}\text{Cs}$, $^{226}\text{Ra}$, etc. Chemical analysis involves the determination of pH, solids content and amounts of various constituents like sodium, potassium, calcium, magnesium, phosphates, bicarbonates, etc., which have significant effect on the treatment methods to be adopted. An estimation of chlorides and polyvalent ions (such as ferric and chromic) present in the waste is of importance as they induce corrosion in the tanks. The chemical constituents may exist in several valency states in the form of complexes and colloids. It is necessary to determine the biological oxidation demand for wastes containing biodegradable materials that are released to sewage systems. Wherever applicable, it is also desirable to determine chemically toxic materials such as cyanides, chromium, beryllium, etc. in effluents before discharge.

The analytical methods to be followed are conventional and can be found in Refs [21, 22]. Their choice depends upon the purpose of the analysis, the required accuracy, the concentrations of active and inactive constituents and the available instruments.

In view of the high radiation levels involved in the analysis of higher-level radioactive wastes, the use of sophisticated analytical equipment with a high degree of automation may be necessary. Conventional sampling and laboratory analysis are time-consuming and at times may limit the waste-handling operations. The development of modern instruments has made it possible to obtain quantitative analytical data directly and virtually instantaneously. However, it is important to note that accuracy and precision depend on realistic estimates of the requirements.

6.4. Decontamination

Wherever necessary, the decontamination of waste storage tanks can be carried out by flushing the tanks with suitable decontaminating reagents. The composition and the concentration of the reagents employed depend
upon the tank material and the nature of contamination. Decontamination procedures and reagents used for various materials can be found in Ref. [23].

For most surfaces the initial decontamination step is usually a thorough wash with hot water. The decontamination solution is generally prepared in a separate vessel and pumped through spray nozzles located in the tank. Decontamination is made more effective by steam-heating and air-agitation. When large quantities of decontaminating solutions have to be used it is necessary to recirculate the solution to save costs on decontaminating agents. The spent reagent solution is drained to a collection vessel and the tank is flushed with hot water to remove the remaining chemicals. A small-capacity tank requiring a high degree of decontamination can be filled to its capacity with the decontaminating solution, heated for a few hours and finally flushed thoroughly with hot water. The used reagent solution and the wash-water have to be treated as radioactive waste.

6.5. Operational safety

Places where radioactive liquid wastes are stored should be treated as controlled areas and due attention is necessary to provide safe working conditions for the operating personnel both during normal operation and maintenance.

A proper record of the quantity and the activity level of the waste handled should be maintained so as to ensure adequate operational control. Sufficient spare capacity should always be provided in a tank installation to meet any peak demand during off-standard operating conditions. It is advisable to always keep the quantity of stored waste as low as is practicable. Special care should be taken while opening storage tanks holding wastes which may contain flammable solvents.

If contamination of the operating areas occurs due to accidental spillage of wastes from the tank or its accessories, immediate measures should be taken to prevent spread of contamination and exposure of the operating staff. The contaminated areas should be isolated and after properly assessing the nature and extent of contamination, clean-up operations should be carried out. The area may be declared safe only after the residual contamination is found to be within safe limits. A survey of external radiation and personnel contamination should be carried out regularly and suitable personal protective equipment should be made readily available to the persons engaged in operation and maintenance.

7. SHIELDING OF WASTE STORAGE TANKS

7.1. General

For tanks holding higher-level radioactive wastes, shielding is required for reducing the radiation field to an acceptable level. The design of tank shielding is usually based on standard methods described in literature.

7.2. Factors influencing shielding design

The storage tanks below ground are generally shielded with earth, whereas for the above-ground tanks concrete is used as the shielding
material. The calculation of the shielding requirements for storage tanks is complicated because of the large number of isotopes present in the waste and the extended source geometry involved.

The gamma flux distribution around the source has to be calculated in order to arrive at the desired thickness of the shielding material for reducing the gamma radiation to the acceptable limits. This requires a basic knowledge of the number of photons of a particular energy or of the effective energy of the gamma radiation emitted by the nuclides present in a unit volume of the waste. For the shielding design of waste storage tanks a calculation of the flux distribution around the tank along the line of maximum flux has to be carried out individually for each of the energies or the effective energies concerned.

7.3. Shielding design

The steps normally followed in the shielding design are:

(a) Estimation of concentrations of nuclides present in the waste
(b) Determination of the shielding constants
(c) Estimation of flux distribution along the line of maximum flux and selection of proper shield thickness.

The concentrations of gamma-emitting nuclides present in fission-product wastes depend upon the nature and type of the parent fuel, its burn-up, cooling history and the volume of the waste generated per unit weight of the fuel. It is difficult to estimate the exact distribution of the gamma radiation of various energy levels present in the waste because of the large number of isotopes present. In shielding calculations it has become common practice to divide them into discrete energy groups and estimate the concentrations of each group having a particular effective energy. From the energy released by each of the energy groups the concentrations of various nuclides in a unit weight of the fuel for each of the energy groups can be estimated [24].

For the specific type of shielding material the calculation of the flux distribution requires the knowledge of shielding constants such as attenuation coefficient and build-up factor. Because of the extended source geometry the shielding calculations for the storage tank should take into account the self-shielding provided by the source itself. This in turn will depend on the various constituents present in the stored waste. The shielding properties of earth and concrete vary with their composition. The total linear attenuation coefficient of a mixture is obtained by the summation of the linear attenuation coefficients of the various elements present in the mixture, and the estimation of the build-up factor is based on the effective atomic number [25]. Attenuation coefficients of the elements generally present in earth and concrete are given in Ref. [26]. Walker and Grotenhuis [25] have compiled data on the shielding constants for concrete. Because of the variations in the composition of wastes and the limited published data on the shielding constants the designer is often compelled to make approximations based on the available data.

Types of tanks that are often met in shielding calculations are those for holding higher-level wastes, which are generally cylindrical in shape. The flux distribution along the line of maximum flux along the radial side of a cylindrical tank is of interest in order to arrive at the shielding requirements for the above-ground tanks, while the flux distribution along the line
of maximum flux along the axial side will enable the estimation of the same for the underground tanks. Methods based on approximations to simple source geometries with due consideration of the self-shielding of the source provide the required accuracy for the shielding calculations. The method indicated by Rockwell (Ref. [24], p. 360) can be used to obtain the gamma flux distribution along the radial side of a cylinder. The flux along the axial side of a cylinder can be arrived at by approximating it to a large or small cone (Ref. [24], p. 401) to obtain the maximum and minimum values of the flux expected at the point of interest. The stacked disk solution is another method for a more accurate estimation of flux along the axial side. This method assumes the cylinder to be made up of a series of thin stacked disks [27].

To obtain the proper shielding thickness, the flux distribution along the line of maximum flux has to be calculated for different shielding thicknesses. The dose rates due to each of the energies or the effective energies have to be calculated and summed up to obtain a relationship between dose rates and shielding thickness. The required shielding thickness can be readily selected from the above relationship after fixing the allowable dose on the surface of the shielding, based on the occupancy factor.

8. ENVIRONMENTAL SAFEGUARDS

8.1. General

Environmental contamination due to release of tank contents can lead to serious consequences. The criteria for selecting sites for the location of tanks, particularly those holding higher-level radioactive wastes, should be carefully evaluated to ensure environmental safety and to devise suitable measures for control of contamination from a potential release of radioactive wastes from tanks.

8.2. Location of tanks and tank farms

The site selection criteria for locating nuclear facilities should take into account the associated radioactive waste management aspects. This is particularly important when higher-level radioactive waste storage facilities will be located at the site. For the selection of a suitable location of the tanks the movement of radioactivity through the ground in the case of its release needs proper evaluation.

8.2.1. Geological conditions

For locating tanks and tank farms for higher-level radioactive wastes, a regional geological survey of the area has to be made. Also, comprehensive microgeological studies, which should include subsurface exploration by drilling and investigations regarding hydrogeology of the site, are useful. It is desirable to select an area which has a compact bed rock, preferably without joints, faults and folded structures. Granites, quartzites and basalts are suitable as good basement rocks for the foundation of tanks. While some of the soft and friable formations like shales, slates, sand
stones, etc. are cheaper for excavation, the requirement for grouting of the basement and special water-proofing may increase the total cost.

8.2.2. Hydrological conditions

The hydrological conditions in the area depend upon the amount of rainfall it receives, the recharge area of the ground-water, the run-off and the thickness of the aquifer zone. Hydrological studies of the area will reveal the pattern of the movement of radioactivity in the ground. The complexity of microhydrological studies is mainly due to the heterogeneous nature of soils and weathered rock. Extreme care has to be taken in making predictions regarding the rate and direction of ground-water movement. Tracer techniques are often useful for this purpose. Even though some of these techniques are helpful for predicting the radioactivity movement pattern in the case of a tank failure and for taking preventive measures, it is a safer practice to locate the storage tanks holding higher-level radioactive wastes above the water table.

8.2.3. Movement of radioactivity in the ground

The movement of radioactivity and the extent of contamination of the surroundings of a tank due to leakage will depend upon the following factors:

(a) Nature of waste
(b) Type and composition of the soil
(c) Effective retention capacity of the soil for the radionuclides present in the waste
(d) Rate and direction of movement of ground-water
(e) Additional retention in the aquifer zone
(f) Dilution, if any, of the contaminated ground-water at the point of emergence.

When waste escapes from the tank it percolates through the surrounding soil, undergoes complex physico-chemical changes and joins the ground-water. During percolation, some of the radionuclides such as strontium, caesium, etc. are retained by the soil. The extent of such retention depends on the nature of waste and the type of the soil. Radionuclides like ruthenium, which are not readily retained by the soil, will contaminate the aquifer zone. Some of the radionuclides initially retained by the soil may, in course of time, be released due to leaching, which will also result in the contamination of the aquifer zone.

8.3. Environmental monitoring

Leakages from storage tanks are usually detected and contained at the source itself by providing suitable devices. Once the waste reaches the ground, the detection of radioactivity in the soil and in the ground-water is likely to be delayed and the recovery of the liquid waste is no longer possible. Continuous pumping and analysis of the ground-water from suitably placed monitoring wells will ensure the detection of possible contamination of the environment. A costly but more reliable alternative to this would be close placement of wells and analysis of the ground-water.
Analysis of soil and ground-water samples and determination of the rate and direction of ground-water flow provide satisfactory data to detect the movement of sub-surface radioactivity. These data are also useful for predicting the time it takes the radionuclides present in the waste to reach the boundaries of the controlled area.

8.4. Control measures

Some of the control measures that may be considered for decreasing the extent of environmental contamination are:

(a) Making the surrounding soil impermeable
(b) Installing 'tile-drainage systems'
(c) Providing protective barriers.

The surrounding earth can be made impermeable by pumping an asphalt emulsion into it. It has been reported that a 10% asphalt emulsion in water seals sand or sandy clay types of soil [28]. As the ground-water is the main carrier of radionuclides present in the waste, the ground-water movement through the tank farm area can be controlled by providing a suitable 'tile-drainage system' [29]. Naturally-occurring clay minerals like bentonite, clinoptilolite or expanded vermiculite may be provided as barriers in the tank farm area for the effective retention of some of the radionuclides. The absorption capacity of the soil can be increased by injecting suitable chemical reagents which react with silica present in the soil. At Mol Laboratories, Belgium, the system 'silica - hydrofluoric acid - antimony acid' has been used for the effective removal of strontium [30]. It is necessary to ensure long-term reliability and usefulness of the above-cited preventive measures for a particular site.

8.5. Emergency provisions

Conditions leading to emergency in a tank installation may arise due to failure of the tank itself or of any of its accessories. It should be possible to detect the failure without any delay so that remedial action can be taken. The secondary containment provided for a tank should have sufficient capacity to receive the entire contents of the tank in the case of tank failure. For tank installations holding higher-level radioactive wastes critical components that are likely to fail should be duplicated by independent controls to facilitate the isolation of the defective units thus assuring continued operation.

9. SUMMARY OF EXPERIENCE

9.1. General

Nuclear installations use a variety of tank designs, depending on the nature and quantity of waste produced, the purpose of storage and the prevailing environmental conditions. The design details of typical tanks that are being used at various installations, together with the operational experience (wherever reported), are summarized below.
Wastes resulting from the operation of nuclear reactors are being managed successfully by using suitable tanks for treatment or controlled discharge to the environment. The tank design at different installations does not vary much for similar types of reactors, as the methods adopted for their management have been more or less standardized.

Radioactive wastes arising from research laboratories are collected in tanks usually installed at the production sites of the wastes. As the nature, activity and volume of these wastes vary considerably from site to site, tanks of different types and capacities are being used.

9.2. Nuclear power stations [31]

9.2.1. Yankee Atomic Electric Co. (USA)

The liquid wastes from this pressurized-water reactor are segregated into hydrogen- and air-bearing waste streams. The hydrogen-bearing stream is collected in a primary drain collection tank (28.4 m$^3$) made of stainless steel. Waste from this tank is pumped to a stainless-steel-clad waste hold-up tank (284 m$^3$). The wastes produced during shut-down are pumped from a low-pressure surge tank to a stainless-steel-clad activity dilution tank (284 m$^3$). The chemical waste stream containing air, resulting from the decontamination of equipment, is stored in a stainless-steel monitoring tank (17.79 m$^3$).

Depending on their activity content, hydrogen-bearing liquids are either discharged through a disposable cartridge filter to the condenser cooling-water effluent or evaporated. The air-bearing wastes are collected in two stainless-steel tanks (5.19 m$^3$ each). Depending on the activity content, these wastes are either discharged at a controlled rate to the main condenser cooling-water discharge line or transferred to the gravity drain tanks for further treatment by evaporation. The wastes are processed in an evaporator in separate batches to prevent a possible air-hydrogen explosive mixture. The condensate is pumped to either of the two aluminium test tanks (30.43 m$^3$ each) having diaphragm seals. Based on the analysis of samples, the waste is transferred to primary-water make-up or discharged after dilution. Table III gives the design data of the tanks used in this installation [32].

9.2.2. Central Electricity Generating Board (UK)

Radioactive liquid wastes arising from Mark I (Magnox) Gas-Cooled Reactor (GCR) power stations are normally of low specific activity, ranging from about $10^{-5}$ to $10^{-2}$ Ci/m$^3$. The pH-values of wastes may vary from about 3 to 12.

The normal practice at Mark I GCR power stations is to provide an effluent treatment plant in which active effluent is collected in primary monitoring and delay tanks. The effluent is neutralized and, after passing through filters, held in final monitoring and delay tanks for sampling, analysis and final discharge from the station in the coolant water outlet, in which it is well mixed and diluted normally by a factor greater than $10^4$. The active effluent discharged from a typical Mark I GCR power station is of the order of 36 m$^3$/day.
Particulate matter is extracted by filters at all stations and collected by backwashing and settlement for accumulation at the site. In special cases, for example at Trawsfynydd, where the liquid effluent is discharged into a lake, an additional plant is provided to remove the soluble activity.

The effluent treatment plant tanks in Mark I GCR stations are normally lined to resist corrosion and have provision for containment and detection of leaks, usually by standing on an asphalt tray with tell-tale drains and sumps. The tanks are sized for estimated maximum daily arisings and are normally duplicated for use on alternate days. Facilities are provided for stirring or recirculation to minimize settlement, for neutralizing and for collecting representative samples. Final discharge pumps are normally capable of discharging the final monitoring and delay tanks in about two hours.

Design features of some of the effluent treatment plant tanks used at Mark I GCR power station at Sizewell 'A' are given in Table III [33].

9.2.3. Douglas Point Power Station (Canada)

This is a 200-MW(e) heavy-water natural-uranium type power reactor. The liquid wastes produced are segregated into potentially active, active/non-chemical and active/chemical streams.

The first two streams are released in a controlled manner into the environment, taking advantage of the dilution available at the plant site. The third stream is discharged after treatment. Also, provision is made to divert the low-active stream for treatment whenever the specific activity is higher or the plant effluent flow rate is not adequate to affect the discharge within the permissible limits.

The potentially active waste is directly sent to the plant coolant water through an in-line activity monitor. If the activity exceeds the monitor-set point, the waste is automatically redirected to a hold-up tank (31.62 m$^3$). The active non-chemical waste streams are received in a hold-up tank for decay and analysis. If the activity is low, the waste is diverted to a disposal tank (182 m$^3$). Two tanks are provided for this purpose. Remotely operated mechanical agitators are used for mixing. The pumping rate from this tank to the plant effluent line can be adjusted depending upon the dilution available. Also, provision is made for diluting the wastes to the desired level before pumping them into the plant coolant water. The higher-active streams are diverted for treatment.

The active chemical wastes are collected in a stainless-steel tank (9.09 m$^3$) and are treated on a daily basis. An agitator is provided in the tank for mixing; if the quantity handled is small, mixing is effected by recirculation. The acidic wastes are neutralized in this tank and treated, if necessary.

Salient design details of the tanks described above are given in Table III [34].

9.3. Research establishments

9.3.1. Oak Ridge National Laboratory, Tennessee (USA) [35]

The research and development work and the operation of nuclear reactors give rise to large quantities of wastes varying in nature and activity.
<table>
<thead>
<tr>
<th>Name of installation</th>
<th>Average activity level (Ci/m³)</th>
<th>Purpose of storage</th>
<th>Capacity of tank (m³)</th>
<th>Material of construction</th>
<th>General details</th>
<th>Important accessories</th>
<th>Salient safety features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yankee Atomic Electric Co. (USA)</td>
<td>$10^{-2}$</td>
<td>Gravity drain tank</td>
<td>17.79</td>
<td>Stainless steel</td>
<td>Underground cylindrical tank with dished head; shell and end-plates of 4.76 and 7.93 mm respectively</td>
<td>Level Indicator, high-level alarm, auto-pump start, etc.</td>
<td>61-mm-thick concrete provides shielding</td>
</tr>
<tr>
<td></td>
<td>$10^{-3}$</td>
<td>Primary drain collection tank</td>
<td>28.4</td>
<td>Stainless steel</td>
<td>Underground cylindrical tank with dished head; shell and end-plates of 6.35 and 7.93 mm respectively</td>
<td>Level and temperature indicator, auto-pump start, etc.</td>
<td>Same</td>
</tr>
<tr>
<td></td>
<td>$10^{-3}$</td>
<td>Waste hold-up and activity dilution decay tank</td>
<td>284</td>
<td>Concrete</td>
<td>Above-ground cylindrical tank clad with stainless steel; shell top and bottom plates of 9.52, 7.93 and 12.48 mm respectively</td>
<td>Sample valve, level and temperature indicator, etc.</td>
<td>Same</td>
</tr>
<tr>
<td></td>
<td>$10^{-7}$</td>
<td>Test tank</td>
<td>30.43</td>
<td>Aluminium</td>
<td>Above-ground cylindrical tanks; shell top and bottom plates of 4.76 and 6.35 mm respectively</td>
<td>Sample valve, level and temperature indicator, high-level alarm, etc.</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Monitored waste tank</td>
<td>5.19</td>
<td>Stainless steel</td>
<td>Above-ground cylindrical tank with dished bottom; shell and end-plates of 4.76 mm</td>
<td>Agitator</td>
<td>-</td>
</tr>
<tr>
<td>Central Electricity Generating Board, Sizewell 'A' (UK)</td>
<td>Active drain reception tank</td>
<td>20.45</td>
<td>Concrete</td>
<td>Above-ground tank on asphalt tray with sump</td>
<td>Same</td>
<td>Same</td>
<td></td>
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<td></td>
<td>Neutralization tank</td>
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<td>Carbon steel</td>
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<td>Same</td>
<td>Same</td>
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<tr>
<td>Other than tritium - $8 \times 10^{-4}$ Tritium - $2 \times 10^{-4}$</td>
<td>Final monitoring and delay tank</td>
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<td>Concrete</td>
<td>Above-ground concrete tank on asphalt tray with sump</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>Hold-up tank</td>
<td>31.82</td>
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<td>Above-ground cylindrical tank with shell and head-plates of 7.93 mm</td>
<td>Agitator, sample valve, monitor, recorder, level indicator, etc.</td>
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<td>Carbon steel</td>
<td>Above-ground cylindrical tank with shell and end-plates of 6.35 mm</td>
<td>Agitator, sampler, tank level alarm, in-line activity monitor, etc.</td>
<td>Internal vinyl coating, basement pit, etc.</td>
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Liquid wastes locally called intermediate-level wastes (ILW), ranging in activity level from $3 \times 10^{-3}$ to $3 \times 10^{2}$ Ci/m$^3$, are produced at an average rate of $20 \times 40$ m$^3$/d or about $1.1 \times 10^4$ m$^3$/yr. These wastes are collected by gravity flow through stainless-steel pipelines to 21 monitoring tanks, each located near a major source of waste. The purpose of the monitoring tanks is to provide a temporary hold-up of the waste for sampling and volume measurement prior to segregation and subsequent treatment or discharge. To protect the tanks, the transfer pipes and less corrosion-resistant equipment in the waste system, the waste in the monitoring tanks is made alkaline by adding caustic soda solution while the tanks are being filled.

The tanks vary in capacity from 2 to 10 m$^3$ each (to provide about two days' filling time). A typical monitoring tank installation is shown in Fig. 12. This is an underground stainless-steel tank (American Iron & Steel Institute, type 347) anchored to a concrete saucer that slopes towards a sump. A float type or a pneumatic bubbler type liquid level gauge is provided to indicate the quantity of waste in the tank. The tank is also provided with a recirculating type sampler, a means of agitating the tank contents, and a vent through a filter to the atmosphere or to the vessel off-gas system of the facility. The sump under the tank can be sampled through a 'dry well' extending to the surface to detect any leakage from the tank. Crushed stone is packed around the tank above the concrete saucer to the tank top. At least 1.3 m of earth is provided above the tank top to serve as shielding. The liquid levels in all the monitoring tanks are continuously telemetered to, and recorded at, the waste monitoring centre, where an operator is on duty at all times.

The ILW in the monitoring tanks is transferred by self-priming pumps or steam jets through 5-cm-diam. stainless-steel pipe-lines to an underground 645 m$^3$ concrete tank, which serves for temporary storage and provides surge capacity for accommodating the large volumes of waste that may arise from emergency operations. The choice between pumps and jets is determined by the elevation of the monitoring tanks and the length of the transfer lines. From the surge tank the waste is pumped in batches to the waste evaporator facility, where it is concentrated by a factor of 20 to 1 in a single-stage pot-type evaporator. The concentrate is sent to another 645 m$^3$ underground concrete tank identical to the surge tank, where it is stored temporarily (several months) before being pumped about 3.2 km through a 5-cm-diam. carbon steel pipe-line to the shale-fracturing site for ultimate disposal in deep (300 m) underground formations.

The two 645 m$^3$ underground concrete tanks previously mentioned are grouped with four other such tanks in two rows of three tanks spaced with their centres 20 m apart. The tanks are interconnected by a system of pipe-lines allowing the contents of any of the tanks to be transferred to another. Each tank is 15.4 m in diameter by 3.7 m deep, surmounted by a domed top having a maximum depth of 2 m. The tank bottoms are 7.6 cm thick, and the sides are 15.2 cm thick at the bottom and 12.7 cm thick at the top. The tank bottoms rest on concrete saucers placed on bed-rock at a depth of 5.5 m below the surface, each saucer having a slightly larger diameter than the tanks and a curb around the outer rim. Crushed stone is packed around the outsides of the tanks above the concrete saucers to the point of maximum liquid level in the tanks. Each tank bottom and saucer slopes 2% towards a low point from which a 15-cm-diam. terra-cotta pipe
FIG. 12. Monitoring tank at Oak Ridge National Laboratory [35].

conducts any drainage from the tank to a dry well that extends to the surface. All six dry wells drain to a leak detection system that is continuously monitored for radioactivity. The tops of the tanks are covered uniformly with 2 m of earth to provide shielding. Each tank is equipped with a pneumatic bubbler type liquid level gauge and a sampler and is vented through a filter to the atmosphere.

The tanks were constructed in 1943 by the Gunite process, by which a cement-sand mixture combined with water was discharged in the form of mortar from the nozzle of a cement gun. The minimum concrete strength
specified was 175 kg/cm\(^2\). The tank bottoms, sides and dome-shaped tops are reinforced with wire mesh and steel rods, each tank containing approximately 743 m\(^2\) of wire mesh and over 6 tonnes of reinforcing rod within the concrete. The inside surfaces of the tanks were coated with a bitumastic or asphaltic paint. These tanks were originally intended to store the ILW for an indefinite period, but the quantity of the waste soon exceeded the capacity of the tanks and they have since been used only for temporary storage (a few months).

9.3.2. Atomic Energy Research Establishment, Harwell (UK) [36]

The research carried out and the operation of experimental reactors produce an average estimated volume of 240 m\(^3\)/d of liquid wastes. The activity levels of these wastes vary from detection level to 10 Ci/m\(^3\) and the pH varies from 1 to 11.

Category-4 wastes (10\(^{-4}\) to 10 Ci/m\(^3\)) are stored in tanks of 10 m\(^3\) capacity made of either stainless steel or resin-bonded glass-reinforced laminate for retention prior to treatment in the high-level plant. Four such tanks are contained in a large, heavily shielded reinforced concrete (40 cm) outer tank which is lined with a brick outer lining and a tiled brick inner lining. Six such tanks are contained in their individual sumps made of reinforced concrete with an asphalt lining, which are large enough to hold the entire content of the tank. The category-4 waste treatment plant showing storage tanks is given in Fig. 13.

Category-3 wastes (10\(^{-3}\) to 10\(^{-1}\) Ci/m\(^3\)) received from hold-up tanks are stored in ten above-ground cylindrical tanks made of carbon steel and having a capacity of 88 m\(^3\) each. The wall and the bottom of the tanks are 0.65 and 1.3 cm thick respectively. Six of these tanks are used for liquids and four for storage of radioactive sludges. These tanks are housed in sumps to prevent contamination of the ground. The waste is mixed either by recirculation or by air sparging.

Category-2 wastes (10\(^{-3}\) Ci/m\(^3\)) are stored at production sites in gravity-fed delay tanks constructed of carbon steel (0.65 cm), engineering bricks (15 cm) or reinforced concrete (15 cm). These tanks are mostly rectangular in shape, only those of small volumes are cylindrical. Their capacity varies from 2.3 m\(^3\) to 45.4 m\(^3\) depending upon the quantity of wastes produced. All the steel tanks are painted on the outside for corrosion resistance. A hard-rubber lining at the inner surface has been found to be satisfactory. All tanks are contained in their own sump of asphalt-lined brick or concrete to prevent leakage to the ground. At least two tanks are provided in a building so that while one tank is being filled the other is available for sampling, monitoring and transfer to the pre-treatment tanks.

The two pretreatment tanks (1820 m\(^3\) capacity each) of reinforced concrete (30 cm) are constructed underground with an acid-resisting brick lining. Each is provided with six stirrers. The tanks have sloping bottoms with sumps for collecting the sludge. Samples are taken from several positions and mixed to give a representative sample. Leakage can be detected by level measurement.

The two post-treatment tanks used (1360 m\(^3\) capacity each) are similar to the pretreatment tanks and are constructed of reinforced concrete with a bitumen lining.
9.3.3. Nuclear Centre, Cadarache (France) [37]

The processing of fissionable materials, research activities and the operation of reactors produce radioactive liquid wastes ranging in activity from \(10^{-1}\) to \(10^{-3}\) Ci/m³ and varying in pH from 2 to 9. The estimated quantity of wastes produced is about 50 m³/d.

Three stainless-steel tanks of 25 m³ capacity each are used for interim storage of incoming effluents to facilitate analysis before transfer to the suitable pretreatment tanks. The pretreatment storage facility consists of eight stainless-steel and eight prestressed concrete tanks. The stainless-steel tanks are used for storing effluents containing alpha or very low beta-gamma activity. The prestressed concrete tanks coated internally with Epikote or isomeric rubber paints are used for storing effluents of higher-level radioactivity and also for effluents containing corrosive elements like fluorides.

The details of stainless-steel tanks are shown in Fig. 14. These tanks are of 250 m³ capacity each, with an inside diameter of 9.4 m and a height of 2.98 m. Four of the prestressed concrete tanks utilized are of 250 m³ capacity each, having a diameter of 8.5 m and a height of 4.5 m. The remaining four tanks, of 500 m³ capacity each, have a diameter of 12 m and a height of 4.5 m.
All pretreatment tanks are installed on concrete platforms which provide containment for leakage. A trapezoidal block made of compact soil, 8 m wide at the base and many metres high, provides shielding. At one side, a 0.4-m-thick concrete shielding wall is constructed between the storage facility and the treatment plant. The feed and transfer are assured by a group of centrifugal pumps which are installed in the operating gallery. The mixing is effected by recirculation with pumps having a flow rate of 25 to 30 m$^3$/h. Samples are drawn by pumping and tapping the effluents in a glove box. Conductivity type electrical probes are provided for leak detection with visual alarm in the control room. Instruments for level, temperature and pH measurement are also provided.

The post-treatment storage facility consists of prestressed concrete tanks of 500 and 1000 m$^3$ capacity. These tanks are constructed in a retention pit made of concrete. The treated effluents are stored in these tanks for analysis and discharge.
9.3.4. Bhabha Atomic Research Centre, Trombay (India) [38]

The research and development work carried out and the operation of experimental reactors produce large quantities of wastes of varying composition and activity levels.

Category-3 and -4 wastes ($10^{-4}$ to $10 \text{ Ci/m}^3$) are stored after neutralization in six underground cylindrical tanks of $227 \text{ m}^3$ capacity each. These are constructed of reinforced concrete and are lined with a carbon steel liner. They have a 1-ft-thick concrete ellipsoidal roof and a flat bottom. The neutralized wastes are fed by gravity flow through carbon steel pipelines or from a tank car. The tanks are provided with flow indicators, agitators and instruments for measuring pH, density, temperatures, level, etc. The tanks are vented through filters. After sufficient decay, these wastes are either concentrated by evaporation or chemically treated.

Category-2 wastes ($10^{-4} \text{ Ci/m}^3$) are stored in site storage tanks. Figure 15 shows the arrangement of three such underground tanks, similar in construction, used at one of the laboratories engaged in radioisotopes, radiochemistry and radiometallurgical research. One typical tank used is made of carbon steel with 3-mm-thick lining of fully banded polyvinyl chloride. The carbon steel plates used are 6.35 mm thick. The tank has a diameter of 1.67 m and a height of 1.5 m with an effective capacity of $2.27 \text{ m}^3$. The tank is painted externally with an epoxy-base paint (polyamine-cured) and is contained in a sump pit with a reinforced concrete wall and a removable concrete batch of 2.5 cm thickness. The liquid wastes are fed by gravity and the tank contents are mixed by using submerged pumps.

The wastes from the above tanks are transferred to a treatment plant. The pretreatment tank used is made of reinforced concrete ($675 \text{ m}^3$ capacity) lined with 6.35 mm carbon steel plates. The tank is divided into three compartments, each having a sloping bottom leading to a sump. Stirrers are provided for mixing the tank contents.

The post-treatment tank is similar in construction to the pretreatment tank except that stirrers are not provided. The treated wastes are discharged into the sea, through a central discharge facility after measuring radioactivity and flow.

10. COSTS

10.1. General

The degree of safety envisaged is the prime factor influencing the design and consequently the cost of a radioactive waste storage system. Each of the safety measures incorporated in the design has a direct bearing on the cost. Hence a balance must be struck between cost and safety. Once safety in respect of a particular installation is clearly defined, the design can be decided and the cost thereof estimated. Costing is essential for comparing alternative schemes and selecting the most economical and safe design. A large number of variables is involved in costing; costs of material and labour vary considerably from country to country and may differ in the same country from one region to another. Such factors render direct comparison of costs unrealistic.
FIG. 15. Arrangement of waste collection tanks for the radiological laboratory, Bhabha Atomic Research Centre [38].
This section summarizes the various factors which influence the cost of radioactive waste storage systems.

10.2. Costing procedures

The published cost data on radioactive waste storage systems are of limited use for cost comparison because of the differences in the procedures adopted for calculations and also because cost estimates at different sites may not include equivalent components. It is of prime importance that all cost components should be taken into consideration. This is particularly true for costs such as overheads, the components of which can become apparent only after a system has been in use for a sufficiently long period. For setting up a waste storage system the capital cost and the operating cost should be estimated with a fair degree of accuracy. The capital cost is the total amount required for setting up the system. The operating cost, which also includes depreciation and cost of maintenance, provides a good basis for arriving at the unit cost of storage and for comparing alternative schemes.

10.2.1. Capital costs

Some of the major items of expenditure which constitute the capital costs are:

(a) Land and site preparation
(b) Buildings and structural works
(c) Waste tanks including shielding, secondary containment, etc.
(d) Process piping, valves, valve pits and auxiliary process equipment
(e) Auxiliary facilities like electrical sub-station, water storage and distribution, sanitary and storm water systems, emergency power, roads, fencing, etc.
(f) Instrumentation
(g) Engineering design and inspection
(h) Construction overheads
(i) Contingencies.

Cost data in respect of most of the above items can be readily obtained for a particular site or estimated with reasonable accuracy. It is advisable to obtain the latest cost data from the manufacturer for the materials or equipment. Some idea of the cost of various materials and equipment can also be obtained from Refs [39-41].

However, due to the constant change in costs of materials, labour, taxes and plant overheads, the cost data may become rapidly obsolete. Therefore it is necessary to bring the cost data up to date. The method normally followed for updating such data is based on 'cost indices' which are costs with reference to a base year [42, 43].

The cost of an equipment \( C_A \) of capacity \( A \) can be approximated from the known cost \( C_B \) of a different capacity for the same equipment \( B \) from the following relationship [44]

\[
C_A = C_B \frac{A}{B}^{0.6}
\]
This relationship can be reliably used where the range of capacities is less than tenfold.

The cost factors based on conventional chemical plant costs evaluated by Stockdale (Ref. [41], p. 304) can be used for estimating radiochemical plant capital costs.

10.2.2. Operating costs

The cost elements to be taken into account for computing the total operating cost of a waste storage system are:

(a) Transport
(b) Storage
(c) Environmental monitoring
(d) Maintenance
(e) Emergency operations required, if any
(f) Depreciation
(g) Overheads
(h) Other costs.

To the cost of each of the above items have to be added the costs of labour, material, utilities and services. Though the costs of these items can be estimated by using costing procedures and the data available for conventional industries, the validity of the same for radioactive waste storage systems has to be fully established.

**Transport.** The cost of transportation depends mainly on the chemical nature, the activity level, the quantity of wastes and the load factor. It has been reported that for a volume of less than about 1200 m$^3$/yr of liquid waste the transport by tankers is more economical [45].

**Storage.** The cost of a radioactive waste storage system is dependent on the nature and quantity of waste, the period of storage, the method of filling the tank and the type of environment. Though the basic design features may not considerably change with increasing specific activity of the waste, the cost of shielding that may be required will increase the total cost.

**Environmental monitoring.** Environmental monitoring includes groundwater monitoring and air monitoring. The monitoring cost for long-term storage of higher-level radioactive liquid wastes can be a significant component of the operating cost, depending upon the site conditions.

**Maintenance.** The maintenance cost includes the cost of repairs, replacement, routine inspection, etc. The cost of maintenance varies widely with the status of the installation and its design features. Maintenance costs will normally vary from 5 to 10% of the cost of investment. For installations handling higher-level wastes the maintenance costs can even be higher if direct maintenance is involved.

**Emergency operations.** The operating costs should include estimates of the cost of emergency operations like decontamination of plant areas, emergency transfer of wastes, etc.
Depreciation. Depreciation provides for the recovery of the capital cost towards the replacement of equipment, buildings, etc. after their use for the expected length of useful service. The expected life varies for different items and is very much dependent on the design and construction. The best approach for estimating the life of an equipment is to base it on the actual experience gained with such equipment in similar plants.

Overheads. Overheads are costs which cannot be assigned to any specific operation. They include the costs of overall supervision, clerical staff, medical facilities, stores, security, insurance, etc.

Other costs. Expenditure incurred from applied research and interest on investment will have to be included in the operating costs. The cost of applied research should include the cost of work carried out to develop and improve the existing equipment or methods that are of direct use for the site. The interest on capital borrowed or invested can also be taken as an indirect cost. Such costs are worked out on a percentage basis for the capital involved.

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[34] SIMMONS, R.B.V., personal communication, 7 March 1969.
[38] GAD, V.M., personal communication, 19 March 1969.
# APPENDIX

## CONVERSION TABLE

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