MANAGEMENT OF SPENT ION-EXCHANGE RESINS FROM NUCLEAR POWER PLANTS
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In nuclear power plants employing light or heavy water as coolant as well as in most waste treatment plants, ion-exchange materials are widely used for the purification of various water streams. Since the spent resins retain radioactive nuclides as well as chemical impurities, they present a form of low- and intermediate-level radioactive waste which requires particular handling and treatment for their storage and disposal.

The International Atomic Energy Agency convened a Technical Committee Meeting in December 1976 to consider the management of spent ion-exchange resins with respect to their treatment and conditioning. The present report contains the information presented at this meeting as well as additional and updated information on this subject collected during 1977-1980. The report was compiled by Mr. Vladimir Morozov of the IAEA's Division of Nuclear Safety and Environmental Protection and updated and completed by his successor, Jorma Heinonen.

The report is a product of the IAEA's activities under the programme component on the management of low- and intermediate-level radioactive wastes. Its subject is closely related to other activities in this area such as the current preparation of reports on "The Conditioning of Low- and Intermediate-level Radioactive Waste Concentrates" and "Treatment of Low- and Intermediate-level Solid Radioactive Waste".

As research and development work on this subject is proceeding in many countries to improve the systems for managing spent ion-exchange resins, in particular in connection with the operation of nuclear power plants, the Agency also started a Co-ordinated Research Programme on the treatment of spent ion-exchange resins in 1979.
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1. INTRODUCTION

Ion-exchange processes are widely used at light and heavy water nuclear power plants to remove impurities from coolant and waste streams. These water clean-up processes leave radioactive nuclides as well as chemical impurities on the resins, and the spent resins are a form of low- and intermediate-level radioactive waste.

The important characteristics of spent resins, as a type of waste from nuclear power plants, are the relatively high specific activity (in some cases up to 1 Ci/l) and the chemically unstable nature of the expended beads of organic resins. These characteristics make it necessary to take special precautions when handling, treating and conditioning these materials for interim storage and disposal.

The treatment of spent resins, prior to conditioning, serves to reduce the volume and/or to the resin properties preparation for conditioning itself.

The main purpose of conditioning is to convert the spent resins to forms which have:

- an adequate chemical stability and physical ruggedness,

- a leach resistance to ensure that the release of radionuclides will be slow even in contact with flowing water.

Conditioning preferably involves immobilisation which, in more specific terms, means processing the spent resin from its original form or after pre-treatment into a monolithic solid by mixing or incorporating it with a suitable material, such as cement, bitumen, organic polymers, and other materials or a combination of them. Processes to reduce resin volumes prior to immobilisation include de-watering by drying and by other means, as well as decomposition by incineration or chemical digestion.

The objective of this report is to describe the currently available processes, methods and technologies for the treatment and conditioning of spent ion-exchange resins from nuclear power plants. An attempt has been made to present a progress report on the present state-of-the-art. Besides describing the treatment techniques on the basis of operating experiences, the report introduces some new promising methods. The scope of the report is mainly technical, but one chapter
deals with the economic aspects as well. Although resin disposal falls outside the essential scope, the current and prospective status of this ultimate waste management step is briefly discussed as well.
2. USES OF ION-EXCHANGE PROCESSES IN NUCLEAR POWER PLANTS

Ion-exchange resins remove radioactive material from liquid wastes through the exchange of ions between the liquid phase and the solid ion-exchange resin.

The major types of organic ion-exchange resins commonly used in nuclear power plants are fully described elsewhere [1, 2, 5] and can be broadly summarised as follows:

- strong acid cationic exchangers based on styrene - DVB (gel and macroporous types)
- strongly basic anionic exchangers based on styrene - DVB and medium basic resins using acrylic copolymers.

Large capacity ion-exchangers are either in deep-bed form using bead resins capable of regeneration, placed in a large vessel with an inlet and outlet or in filter form using powdered ion-exchange materials which are directly discharged to waste without regeneration. The resins are used as separate single-bed units or as mixed bed units containing anion and cation resins in a mixture, or they can be used as a pre-coat in filters.

In some cases, resins are used in replaceable cartridge form. Equipment design is related to the type of resins employed and the need for regeneration. In principle, it is possible to operate a nuclear power plant without regenerating the ion-exchange resins used in purification systems depending on economic, technical and environmental considerations.

The use of inorganic ion-exchange materials for some special applications is already possible and according to the recent results, the views for further development are promising [6,7,8].

2.1 Application to liquid waste processing

Ion-exchange resins are used for purification of water streams within nuclear power plants, which is essential for chemical control and removal of radioactivity. Uses vary in different reactor systems but can be summarised as follows:

1) Continuous clean-up of reactor coolant in BWRs, PWRs and HWRs.
2) Purification of condensate or feedwater in BWRs.
3) Control of reactivity, e.g. by boron removal in heavy water moderate reactors and PWRs.

4) Purification of various effluent streams from other reactor systems. This includes water streams from chemical processes, e.g. decontamination and laboratory drains and detergent-bearing wastes from personnel decontamination as well as floor chains, etc.

5) Clean-up of spent fuel storage pools.

In reactor coolant circuits for BWRs, PWRs and HWRs, the ion-exchange material picks up the radioactive nuclides (activation and fission products) while performing its primary function of coolant chemistry control. This control is necessary to:

(a) minimise corrosion of coolant circuit materials;
(b) minimise the circuit crud inventory and resultant deposition problems;
(c) provide reactivity control (e.g. for boron in PWRs).

While the removal of radioactive products from coolant is a secondary function, it minimises deposition of activity on out-of-core surfaces and reduces build-up of gamma fields around the reactor.

Ion-exchange materials are also used to purify turbine condensate to minimise carry over of impurities in feedwater. These impurities arise from:

(a) carryover of trace constituents from the boiler water in steam to the turbine;
(b) corrosion of circuit materials by steam and condensate;
(c) leakage of chemical impurities from condenser cooling water into the condensate.

After a period of reactor operation, it has been found necessary to decontaminate the coolant circuits of LWRs to reduce the radiation exposure to maintenance personnel. The procedures used for decontamination vary and are under development in several countries. The objective of these procedures is to minimise corrosion of sensitive coolant circuit materials and remove accumulated radioactivity. It is also necessary to minimise the volume of effluents from such operations. Ion-exchange resins are expected to be a widely used approach for concentration of activity removed during decontamination.
Ion-exchange resins are also used in the moderator circuits of heavy water reactors (HWRs, SGHWR) to control chemistry conditions in the D$_2$O circuit and the level of soluble reactor poison (e.g., natural boron or B-10). In PWR boron recovery systems, ion-exchangers are operated in the boron-saturated mode upstream of the system evaporators to reduce activity levels.

In many water reactor systems, ion-exchange, as well as evaporation and filtration, are used for the clean-up of miscellaneous waste liquid effluent streams. These wastes arise from system leakage, floor drains, equipment drains, laboratories and component decontamination. Detergent-bearing active effluents from personnel decontamination may also require purification by processes which include ion-exchange. The ion-exchangers in the liquid waste sub-system are often used as a back-up to evaporators in cases of:

(a) high liquid waste arisings in excess of the evaporator capacity;
(b) evaporator outage;
(c) sizeable quantities of low conductivity wastes.

In PWRs, evaporation is mostly the primary treatment method in the liquid radwaste system because of the relatively small quantities of waste arising (about 10 m$^3$ d$^{-1}$) and the high dissolved solids content (mostly boric acid). The DFs and capacity of the ion-exchangers are important but not critical because of their back-up function. In BWRs where waste streams are currently expected to be recycled to a large extent and discharged only in very limited amounts, the DFs again are important but not as critical as when wastes are discharged to the environment.

In the steam generator circuit of PWRs blowdown is normally treated by ion-exchange. Here the importance of DFs and capacity of the ion-exchanger is dependent on the extent and duration of steam generator leakage, the latter allowing activity and coolant treatment additives to contaminate the secondary steam generator system.

Fuel storage pools at nuclear power plants provide interim storage facilities before irradiated fuel is shipped to central storage facilities or reprocessing plants. Fuel surfaces are likely to be contaminated with
active deposited crud which may be released to the pool water during storage. If defective fuel is present, fission products can also be released. Both insoluble crud and soluble impurities must be removed from pool water to provide a non-corrosive environment for fuel cladding during storage and to maintain water clarity. This is usually achieved by filtration followed by mixed-bed ion-exchange processes.

2.2 Resin consumption and activity levels

The quantities of radioactive spent resins arising at reactor sites are variable and depend not only upon the reactor size but also on the application of either bead or powdered resin systems as well as an operational history of the plant. The content and level of radioactivity is strongly variable depending as well on, for example, the fuel failures, and naturally on time when the activity is determined. Compilation of the radioactivity of spent resins from a 1000 MWe BWR plant is presented Table I [4].

### TABLE I

<table>
<thead>
<tr>
<th>Type of waste</th>
<th>Specific activity x) Ci/m³</th>
<th>Total activity Ci/a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fresh</td>
<td>old</td>
</tr>
<tr>
<td>Resins:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- granular from prim. circuit</td>
<td>10 - 10³</td>
<td>1 - 10²</td>
</tr>
<tr>
<td>- powder from condensate</td>
<td>1 - 10²</td>
<td>10⁻⁴ - 10⁻¹</td>
</tr>
<tr>
<td>- granular or powder from other sources</td>
<td>10⁻⁵-1</td>
<td>10⁻⁶ - 10⁻¹</td>
</tr>
<tr>
<td>Resins together</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filters</td>
<td>10⁻³-1</td>
<td>10⁻⁴ - 10⁻¹</td>
</tr>
<tr>
<td>Sludges (mainly evap. bott.)</td>
<td>10⁻¹-10⁻²</td>
<td>10⁻² - 10⁻³</td>
</tr>
<tr>
<td>Wet, total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

x) Fresh waste: stored less than 1 year, possibly some days

Old waste: stored 5-10 years.
A detailed review by ERDA - Ref. [3] of optimal waste management technologies provides details on predicted waste resin arisings and likely activity levels arising at LWRs. Some data is also available from operational nuclear power plants. For example, Swedish BWR plants expect 25 m$^3$ bead resin and 110-165 m$^3$ powdered resin sludge (~10% dry residue) per 1000 MW-year, about 90% of the radioactivity is contained in the bead-type resins.

Some comparative figures for waste arisings and the associated activity levels were presented in the Technical Committee Meeting. These figures are shown in Table II.

2.3 **Operational considerations**

In non-regenerative systems, resins are transferred at the end of their useful life from the column or filter to an interim storage tank as a slurry. The useful life does not necessarily coincide with ion-exchange capacity exhaustion; increased pressure drop across the system caused by fouling of the bed by insoluble impurities or high levels of absorbed activity also require bed changes. Separate filters or precoats are frequently employed upstream of the ion-exchanger to prevent physical fouling and to extend useful bed life. On the other hand, powdered resin units act as filters and ion-exchangers. Expended resins are transferred hydraulically after fluidisation by backwashing. Air sparging is also used. Resin contamination can be estimated by sampling after fluidisation and during transfer operations. Several samples are required in order to minimise the errors associated with impurity segregation within the resin bed. Because the insoluble crud particles retained by the bed are partially released from resin surfaces and then behave differently in the transfer medium, it is difficult to design an accurate sampling arrangement. The discharge stream of fluidised resin should preferably be diverted into a sampling by-pass loop without interrupting the main flow of spent resin.

Where ion-exchange resins are used to clean-up heavy water systems, D$_2$O must be recovered by dedeuterisation before transfer and disposal. These resins are contaminated by activation and fission nuclides and especially the possibility of tritium contamination should be taken into account. The fate of tritium retained by the waste resins should be considered in any subsequent handling or processing operation.
### TABLE II

**SPENT ION-EXCHANGE RESIN WASTE ARISING FROM OPERATING NUCLEAR POWER PLANTS**

<table>
<thead>
<tr>
<th>Country</th>
<th>Reactor type</th>
<th>Power output MW(e)</th>
<th>Type of ion-exchange resins</th>
<th>Quantity m³/yr</th>
<th>Specific activity Ci/m³</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany, Federal Rep. of</td>
<td>PWR</td>
<td>1300</td>
<td>bead resins</td>
<td>3</td>
<td>(10^2 - 5 \times 10^2)</td>
<td>Generalised aver. data</td>
</tr>
<tr>
<td></td>
<td>BWR</td>
<td>1300</td>
<td>powdered resins</td>
<td>115</td>
<td>(2 \times 10^{-2} - 10^{-1})</td>
<td>Condensate cleaning</td>
</tr>
<tr>
<td></td>
<td>BWR (Lingen)</td>
<td>240</td>
<td>(\sim)</td>
<td>35²</td>
<td>10-20</td>
<td>Reactor water clean.</td>
</tr>
<tr>
<td></td>
<td>BWR (Oundremingen)</td>
<td>237</td>
<td>(\sim)</td>
<td>4.5</td>
<td>400</td>
<td>Reactor coolant</td>
</tr>
<tr>
<td></td>
<td>BWR (Wirtgassen)</td>
<td>640</td>
<td>(\sim)</td>
<td>2</td>
<td>70</td>
<td>Liquid effluents</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\sim)</td>
<td>0.5</td>
<td>10</td>
<td>Fuel storage pond</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\sim)</td>
<td>10</td>
<td>1</td>
<td>Condensate cleaning</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\sim)</td>
<td>1</td>
<td>50</td>
<td>Reactor coolant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bead resins</td>
<td>4</td>
<td>2</td>
<td>Liquid effluents</td>
</tr>
<tr>
<td></td>
<td>PWR (Stade)</td>
<td>622</td>
<td>(\sim)</td>
<td>0.4</td>
<td></td>
<td>Reactor coolant clean.</td>
</tr>
<tr>
<td></td>
<td>PWR (Biblis)</td>
<td>1200</td>
<td>(\sim)</td>
<td>0.65</td>
<td>100-200</td>
<td>Reactor coolant treat.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\sim)</td>
<td>0.5</td>
<td></td>
<td>Fuel storage pond</td>
</tr>
</tbody>
</table>

* These data were presented at the Technical Committee meeting.
<table>
<thead>
<tr>
<th>Country</th>
<th>Reactor type</th>
<th>Power output MW(e)</th>
<th>Type of ion-exchange resins</th>
<th>Quantity m³/yr</th>
<th>Specific activity Ci/m³</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>BWR</td>
<td>620</td>
<td>Bead resins</td>
<td>14</td>
<td>3.5 - 35</td>
<td>- condensate demineralisation - fuel storage pond - waste collector - Rx clean-up</td>
</tr>
<tr>
<td></td>
<td>(Nine Mile Pt.)</td>
<td></td>
<td>Powdex and/or solka floc</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>BWR</td>
<td>670</td>
<td>Bead resins</td>
<td>14</td>
<td>10 - 100</td>
<td>-&quot;- -&quot;- -&quot;-</td>
</tr>
<tr>
<td></td>
<td>(Oyster Creek)</td>
<td></td>
<td>Powdex and/or solka floc</td>
<td>75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* These data were presented at the Technical Committee Meeting.
In the short-term, spent resins are stored under water in suitably resistant tanks in a contained environment. However, because of the possible high levels of activity associated with the resins and their chemical and mechanical stability, degradation of the functional groups and resin matrix itself could occur in the foreseeable future and even in the operational lifetime of the reactor. The handling and interim storage of spent organic resins must be performed with caution. Chemical stability of organic anion resins is one of the crucial points that depends on the type of resin and on its chemical form. The resins should not be stored for long periods in strong nitric acid or in strong sodium hydroxide solution, particularly at a raised temperature or in static flow conditions. In general, anion exchange resins in nitrate form are more stable towards chemical attack than those in hydroxide form. However, the decomposition of nitrate form resins is exothermic and temperature dependent. If the amount of resin material is larger when it is insulated so that the heat cannot dissipate, the result may be a violent reaction \[9\]. Thus for safety reasons, the following aspects should be taken into account:-

- the resins should be kept wet during transport and storage,
- anion resins should be converted to hydroxide forms before decanting and/or drying,
- the amount of anion resins in one vessel should be limited to prevent undue chemical reaction.

REFERENCES


3. TREATMENT AND CONDITIONING OF SPENT ION-EXCHANGE RESINS

Expended ion-exchange resins are a form of low- and intermediate-level radioactive waste that must be treated and conditioned for storage and/or disposal. The methods used for conditioning and treatment can accomplish several purposes. The primary object is, however, to improve the safety and economics associated with the further handling, storing and disposal. The treatment prior to the conditioning step may reduce the volume of the waste, e.g. by dewatering resin slurries. Besides volume reduction, the treatment may also alter the physico-chemical properties of the waste in a way which facilitates the conditioning, i.e. processing the waste to make it suitable for storage and disposal. This purpose can be reached, e.g. by chemical adjustment while combustion of organic resins serves both volume reduction and change of the waste properties. One traditional method used for conditioning of ion-exchange resins is to dewater and pack them with or without absorbents into containers for storage or even for disposal. The method generally preferred at present is to include immobilisation in the conditioning.

Immobilisation involves processing radioactive waste in a liquid (resin slurry) or particulate solid form (dry resin) to a solid monolithic matrix in incorporating it with a suitable material such as fluid concrete or bitumen. The nature and extent of the two process steps can vary much depending on the technique applied. It is possible to combine both volume reduction and immobilisation in one process as subsequent operational steps, as it is done in many bituminisation methods. The recently developed slagging incineration technique fulfills the need for the reduction of volume as well as conditioning of waste to a form suitable for storage and disposal simultaneously in one process.

This chapter discusses the different processes which are in various stages of application and development.

3.1 Volume reduction techniques

The volume reduction of all forms of radioactive wastes has increased in importance during recent years. The reasons are mainly economical due to the increased need for storage capacity, and consequently increased storage costs. The volume of ion-exchange slurries containing free water can be
reduced by methods such as filtering, centrifuging, decanting, drying and combustion. The residues from the certain reduction processes, dry powder or ash, are in some cases considered suitable for storage. In other cases, the material is immobilised with, for example, cement, bitumen or polymers. Care must be taken that the immobilisation agent is compatible enough with the residue.

3.1.1 Decanting

Decanting involves filling a vessel with the slurry to be decanted and allowing it to remain still so that the solids will settle at the bottom of the vessel. The free liquid is pumped out of the top of the vessel. The method is not very effective for the removal of free water. However, it can have a remarkable practical importance for example in the interim storage of spent resins in tanks and silos [1].

3.1.2 Filtration

Filtration can be used at different points in a sequence of liquid waste treatment operations to remove insoluble particulate matter. The process aims at volume reduction by dewatering resin slurries prior to further conditioning steps.

Two main filtration techniques are applied: pressure filtration and vacuum filtration.

At the power plant in Ringhals, Sweden, powdered resins are partially dewatered before cementation by precoat filtration and blowing pressurised air through the filter valves [2].

A technique has been developed at the Institute of Nuclear Research, Swierk, Poland, which involves dewatering of resin slurry by means of vacuum filtration and drying in a stream of heated air [3].

3.1.3 Drying

The technology for drying sludges is well established in the conventional industry. Application of the treatment of nuclear wastes, however, implies engineering and design work as well as adaptation for the subsequent process steps from the nuclear waste management point of view [5].

A number of processes to reduce the volume of wet ion-exchange resins by drying have been developed or proposed. Drying can be accomplished by controlled heating to temperatures of 120–150°C under normal pressure.
drying has been proposed as well [31]. With both processes, care must be taken to prevent dust explosions from the dry fires in air. Passages of inert gas \( \text{N}_2 \) through the drying apparatus or applying a vacuum below 0.2 bar would overcome this problem [32].

3.1.4 Centrifugation

In this technique, centrifugal force is used to separate suspended solids from the liquids. It can be well applied for dewatering of ion-exchange resins as well.

In spite of the fact that centrifugation is relatively widely used, at nuclear power plants [1, 6] and research centres, in connection with applying chemical flocculation processes, the filtration process generally takes preference. This is mainly due to cost and maintenance factors.

3.1.5 Incineration

The incineration process involves the thermal oxidation of the organic compounds and transforms them into off-gases, which can be released after appropriate gas-cleaning. The residue of the process is ash containing the non-combustible fraction and to a large extent, the radioactivity present. Incinerators are employed to reduce the volume of all types of combustible wastes including organic ion-exchange resins. Numerous incinerators are described in detail in the available literature [5, 7, 8].

There are some particular problems involved in the incineration of resins. Special attention has to be given to the composition of the feed waste when burning ion-exchange resins. For example, the resins have a tendency to melt at high temperatures and the molten product is not easily burnable. One way to overcome this problem is to mix the resins with other forms of solid waste before incineration. This kind of dilution will also reduce the activity in the furnace, which might be profitable in some cases since many incinerators are designed to process low-activity material only.

The air flow through the furnace has to be controlled very exactly to prevent a flowing-out of non- or half-burned resin particles from the incinerator unit with the off-gas stream. In addition, the off-gases, resulting from incineration of resins, are corrosive, and the off-gas system must be designed accordingly. A process for incineration of resins has been successfully demonstrated at the Nuclear Research Centre at
Two companies in the USA viz. Newport News and Energy Incorporated have developed a fluidised bed incinerator which can burn for example, spent ion-exchange resins. There is no commercial installation of this system in existence. A full-scale pilot plant, however, has been in operation since 1977 [4, 5]. Burning of spent resins by fluid bed technique has been studied in Sweden and Finland in a laboratory and pilot scale as well [9].

The promising new technique, quite suitable for ion-exchange resins as well, is the high temperature slagging incinerator. The basic differences of that technique from the conventional ones are: high operation temperature (1200 - 1600°C), the feed must contain a substantial amount of non-combustible, fusible materials, the process results in a crystalline amorph residue with high stability and low leachability. In 1975 at Mol, Belgium, a 100kg/h system was installed at the Belgian Nuclear Research Centre S.C.K./C.E.N., for incinerating low-level radioactive waste. The unit has been in radioactive test operation since 1977 [10, 11]. At Rocky Flats, USA, a demonstration plant employing rotary kiln technique, will be installed in 1980. That plant will be capable of burning ion-exchange resins as well [12]. This implies also the slagging pyrolysis incinerator (SPI) which would be in operation at Idaho Falls in 1987 [13].

3.1.6 Wet combustion - chemical digestion

The acid digestion process is a method that traditionally utilises the dehydrating action of concentrated sulphuric acid to carbonise solid organic materials and to oxidise the carbon by means of nitric acid. Also the mixture $H_3PO_4/\text{HNO}_3$ has been used successfully [33, 34]. The big advantage of this technique is that the risk of loss of radioactive components is less than with incineration. The essential application area of wet combustion is alpha-bearing waste, but the method can, in principle, be used to reduce the volume of ion-exchange resins as well. In Karlsruhe, the oxidation of ion-exchange resins by acid digestion has been investigated [14]. It has been shown that resins are fit for this type of treatment. Respective experiments have also been made, e.g. Hanford Engineering Development Laboratory at Richland, USA [15] as well as at KEMA in Arnhem, Netherlands [16].
Although this process has been investigated in laboratory and bench scale test units, it has not yet reached the stage of practical application in nuclear power plants.

3.2 Immobilisation techniques

Immobilisation implies a treatment designed to reduce the mobility of radioactive materials in the wastes to ensure safe transport, storage or disposal. One traditional method used for conditioning of ion-exchange resins is to dewater and pack them, with or without absorbents, into containers for storage or even for disposal. The preferred immobilisation method, however, is to process the resin in a monolithic solid form with low leachability, by mixing or incorporating it with a suitable material. This kind of process is commonly called immobilisation or solidification.

The materials which are most commonly used for immobilisation are cement, bitumen and organic polymers. Each of these materials has its benefits but also specific physical and chemical limitations which have to be taken into account. One of the most important aspects is the compatibility between waste and solidification media. This refers to the ability of a given waste/solidification agent mixture to form a solid free-standing monolithic matrix having reasonable compressive strength. The selection of the immobilisation materials and technique commercially available depends to an extent on national circumstances, e.g. the waste management policy and strategy adopted, economic conditions, etc.

3.2.1 Cement

Incorporation of ion-exchange resins into cement-based materials has been practised for many years in many countries, throughout the world. The technique in itself is simple, and it is based on large experience in civil engineering. Consequently, the chemical and physical properties of cement and concrete are well known. However, knowledge of the effect of mixing cement with ion-exchange resins is still limited, and experimental work is often necessary to optimise cement–waste–water–additives formulations in relation to product properties desired. As a general rule, it can be stated that mechanical strength is inversely proportional to resin loading[17].

The major step in the process is mixing the four ingredients. Mixing can be accomplished in the disposable container or prior to placement in
the container. Pre-treated resin slurries are mixed with dry cement or "dry" resins can be added to pre-mixed cement grout or all ingredients can be mixed simultaneously.

The process can be performed with two principal methods:

1) In-drum or in-container mixing.

The drums are prepared with a cement/additive mixture filled with the proper amount of resin slurry, capped, and put on a tumbling or rolling station where the contents are thoroughly mixed. Another way is to have an external agitator lowered into the drum to blend the waste and cement, either after or during filling. The mobile cement solidification plants DEWA and MOWA imply this type of process as well [18, 19].

2) External mixing.

Continuous in-line mixers which allow small hold up and easy cleaning, as well as batch mixers of various types, can be used for blending wastes and cement prior to leading the storage drum.

The typical flow sheets for the said methods are shown in Figures 1 and 2.

The method of mixing the cement and waste is important for the homogeneity of the final product. Care must be taken in mixing to avoid air entrainment as the desire is to produce an end product with the highest possible density.

The processes used to date can yield a dry, incombustible, solid matrix with reasonable mechanical strength and a fair leach resistance acceptable for storage and disposal. The general tendency might be towards maximum waste loadings, but on the other hand, the mechanical strength is of great importance in certain conditions as well.

In actual power plant practice, where ion-exchange slurries can be contaminated by other waste streams as well, care should be taken to determine waste chemistry before mixing since acidic waste, as well as borate contaminants from other waste streams will retard cement hardening. In immobilisation or solidification of power plant wastes by cementation, the spent resins have turned out to be the most problematic. One of the potential problems is the swelling of resin grains after solidification due to the humidity. This can lead to a considerable decrease of mechanical strength of the
the concrete product. The phenomena, which in particular implies cation exchangers and its consequences are studied, for example, in Sweden [20].

Several additives have been used to improve the setting properties, fission product retention, volumetric efficiency and to eliminate problems attendant to waste chemistry. These include absorbents like vermiculite and other clay minerals, baryte, hematite, and sodium silicate, etc. Sodium silicate is said to provide a good set for boric acid solution and to lower the volume increase factor. A Portland cement sodium silicate system has been developed by a company in the United States. This system should considerably lower the volume increase factor as compared with conventional cement formulations [17, 22]. The numerical data given for cementation in Chapter 4 suit to that system.

It should be emphasised that the sodium silicate formulations are intended to optimise the volumetric efficiency not mechanical strength.

Another company in the United States has recently added disposal demineraliser vessels to its products. They are designed for in-site cement solidification of resins [23]. Coating materials, such as bitumen, can be applied to cement to cover the pores and thus lower the leachability[17]. The studies with polymer-impregnated cements have given promising results, because of the good product properties; low leachability, good mechanical strength, etc. This technique has been investigated in Brookhaven National Laboratory, USA [21], and in Casaccia, France [22] a pilot plant facility has been constructed.

A system using a mixture of cement and bitumen as emulsion has recently been developed in France as well [22].

3.2.2 Bitumen

The term "bitumen" covers mixtures of high molecular weight hydrocarbons. A variety of bitumen types are generally produced in the petrochemical industry. Those which are used, or considered for use, in radwaste immobilisation can be grouped, according to their production origin, into the following 3 main categories:

- direct distillation bitumen;
- blown or oxidised bitumen;
- cracked bitumen.
EXAMPLE OF IN-DRUM MIXING PROCESS

FIG. 1.

EXAMPLE OF EXTERNAL MIXING PROCESS

FIG. 2.
As a matrix material for the incorporation of radioactive wastes, bitumen has a number of advantages, e.g. insolubility in water and high resistance against diffusion in water, which leads to end products with low leachability. Furthermore, the bitumen possesses high incorporation capacity which leads to high volumetric efficiency. There are also a number of disadvantages which can be of importance, e.g. the bitumen is combustible although not easily inflammable, chemical interactions with certain waste components are possible, and finally bitumen has a limited radiation stability which might be of importance in the long term after incorporation of certain ion-exchange resin [24]. The inconveniences of the material can be counter-balanced by careful selection of the bitumen type as well as operational conditions such as:-

- appropriate pre-treatment of wastes to be incorporated; one recommendation is to incinerate ion-exchange resins prior to incorporation into bitumen [17];
- to use low operational temperatures, i.e. those which are considerably lower than decomposition temperatures;
- to apply fireproof installations and provision for fire-fighting [22].

Processes to immobilise low-level waste in a bitumen (asphalt) are widely used. Most of the experience with these systems involves liquid waste where volumes are reduced but several operating systems have also processed resins. The basic process operates at elevated temperature, 130–230°C, and liquid bitumen is continuously mixed with the resin slurry. During the process most of the excess water is evaporated but some residual water remains in the product. Products obtained at the lower temperatures still contain up to 10% water.

Bitumen technology is applied with several different types of systems. The systems with most experience use a twin screw extruder evaporator [35] or thin film evaporator [36]. Other systems use rotating cylindrical dryers or batch-type pot dryers. Figure 3 shows a flow chart for a system using the screw extruder. Resins are preheated to adjust pH and a slurry is then introduced into the extruder inlet. Liquid bitumen is simultaneously introduced and the slurry-bitumen mixture is progressively heated as it passes through the extruder into a disposal container. Hardening takes place in the container.
SCREW EXTRUDER EVAPORATION PROCESS

FIG. 3.

TURBULENT-FILM EVAPORATION PROCESS

FIG. 4.
Release of Amines from 200 kg Bitumen Product Drums

Remarks:
Results from labscale experiments on 0.1 kg samples with the following composition:
50 wt.% bitumen E.15
475 wt.% loaded mixed-bed ion exchange resins
2.5 wt.% residual water

FIG. 5.
Vapours produced during the process are cleaned before return to liquid waste storage. Figure 4 shows a flow chart for a system using a film evaporator. In this system, the resins are preheated, ground, and dehydrated before transfer to the evaporator. Mixing is accomplished in the evaporator at a constant temperature as opposed to the progressive temperatures in the screw extruder system. The provisions in both systems for bitumen storage and feed, and vapour clean-up are similar. The twin screw extruder also includes an oil-tar separator.

At higher temperatures, anionic resins are decomposed with formation of amines, thus precise temperature control is necessary. At normal operating temperatures of 160-180°C relatively large amounts of amines are formed leading to the potential information of explosive off-gases. Reduction of temperature to about 130°C eliminates this problem (see Figure 5), but lower temperatures result in higher water content in the product.

3.2.3 Organic polymers

A number of immobilisation techniques using different types of polymers have been developed as alternatives for the bituminisation and cementation methods with a view to improve the products and/or process.

A few of the techniques employing polymers have reached the stage of full-scale radioactive operation and commercial availability.

3.2.3.1 Urea-formaldehyde

Systems using commercially available urea-formaldehyde as a solidification agent have been developed in the United States. The urea-formaldehyde prepolymer is mixed with wet waste, resin slurry, and an inorganic acidic catalyst is added to this mixture. The catalyst is either a weak acid, such as NaH₂SO₄, H₃PO₄, or dilute solutions of strong acids, such as HNO₃, H₂SO₄. The pH range required is from 1.0 to 2.0. Under the right conditions, the polymerisation starts by adding the catalyst and is completed within about 30 minutes. The cross-linked polymeric structure entraps the resin particles and any free water.

The systems which use urea-formaldehyde are fairly simple. Various techniques are used for mixing the three ingredients. For in-container systems, mixing is accomplished mechanically with a disposable blade or air sparging. Catalyst is added after the resins and binder are thoroughly mixed. For continuous systems, mixing is accomplished with static or dynamic mixers which
first mix resin slurry with the binders. Catalyst is added through a second mixer or dispersion plate close to the disposable container. Figure 6 is a flow diagram for static mixing technique.

The process is very sensitive to waste chemistry and even under ideal conditions, the reaction between the mono- and dimethyl-ureas results in the release of free water which is acidic. The amount of free water depends on the age of the binder, the temperature and composition of the waste, and the specific proportions of waste, binder, and catalyst. The volume of free water is never less than one per cent of the mass even under ideal conditions.

Due to the chemistry and free water problems, urea-formaldehyde processes have been refined to using new types of urea-formaldehyde formulations [17].
But, due to the condensation of acidic water in the course of the further solidification process over a period of several hours, a one-step process cannot be employed. Additional additives of absorbents, e.g. cement, vermiculite, etc. are required to meet the no free-standing water criteria. The low pH 1 to 2 required for the polymerisation reaction is a remarkable drawback for the use of the common carbon steel container. Due to the above problems, the urea-formaldehyde systems which have been in common use in the United States are gradually losing ground in relation to other immobilisation techniques [22].

3.2.3.2 Polystyrene - divinyl benzene

A polymerisation process using a mixture of styrene and divinyl benzene as a solidification material and azoisobutonitrile as a catalyst has been developed in the Federal Republic of Germany [37]. Substitute products such as acrylic acid, types of acrylates and heterocyclic compounds as pyridine derivatives can be used for the styrene. Many divinyl compounds can be substituted for the divinyl benzene. The process is exothermic and temperature is controlled by precisely metering the catalyst. Reaction times are intentionally lengthened with solidification occurring in about 2 days. Complete hardening is obtained after 6-12 days.

A mobile unit [Fig. 7] using the process has been operational in the Federal Republic of Germany since 1975 [38]. Figure 8 shows a flow chart for this system. The unit consists of a dosing vessel, a mixing vessel to mix the binder ingredients and the catalyst, storage tanks for ingredients, and a vacuum device. By flushing with water, resin slurries are sluiced to the dosing vessel, transferred by vacuum to the disposable container (200 l drum), and dewatered. The polymer solution and catalyst are mixed in the mixing vessel and then transferred to the disposable container. With the exception of filling the measuring vessel, all transportation of the material inside the unit is done by vacuum.
Mobile unit "Fama" for incorporation of spent ion-exchange resins into polystyrene (STEAG).

FIG. 7.

The final product forms a hard, solid block with good mechanical properties in which the resins are uniformly distributed. The thermal properties and leach rates are good. The unit can handle spent bead resins with radioactivities of up to 1000 Ci/m$^3$. The capacity is 1–2 m$^3$ of resins per day. The specialised mobile unit FAMA can serve a large number of PWR's, i.e. reactors producing bead resins in significant amounts [18]. Up to 1979, approximately 100 m$^3$ of spent resins were solidified.

3.2.3.3 Thermo-setting resins

A polymerisation process where resins are uniformly dispersed in a fluid solution of polyester (for example, polyester and styrene) has been developed in France [31]. Polymerisation is accomplished without external heating by the controlled addition of a catalyst. Process reaction heat is sufficient to harden the mixture. Solidification takes place in 2 to 10 hours dependent on the volume of the mixture and the amount of catalyst and accelerator.
Scheme of the Mobile Unit "Fama" for Incorporation of spent Ion Exchange Resins into Polystyrene (STEAG)

FIG. 8.
FIG. 9. INCORPORATION INTO THERMALLY HARDENED PLASTICS (POLYESTERS)

A flow chart for this system is shown in Figure 9. Resins are chemically pre-treated to ensure saturation of free ion-exchange sites and prevent interaction with the catalyst. Pre-treatment consists of percolating an alkaline solution of constant pH until uptake of cations by the resins is eliminated. Treated resins are then transferred to a metering pot and de-watered. Excess water is reused to prepare treatment chemicals. Pre-treated resins, with a moisture content of 40-60%, are then placed in the disposable container. Polyester solutions and other additives are transferred to the
FIG. 10. Overall view of a 2001 cylindrical block containing 50% spent ion-exchange resins solidified by thermo-setting plastics. The steel drum has been cut off and withdrawn.

disposable container in the following order: (1) polyester, (2) polystyrene in alpha methyl-styrene, (3) silica powder (1% by wt.), (4) catalyst and (5) accelerator. Continuous mixing ensures homogeneity and viscosity is used to monitor the reaction. The materials are mixed for about 20 minutes after the addition of the accelerator. Figure 10 shows a cylindrical block containing 50% spent ion-exchange resins solidified by thermo-setting plastics.

Besides the good volumetric efficiency, the process products are supposed to be homogenous, with good leach resistance and mechanical properties. Since 1976, waste concentrates of the Nuclear Research Centre of Grenoble have been treated with this process. At the Nuclear Power Plant of Ardenne, a PWR facility is also in operation [25]. Instead of polyester, it is also possible to use epoxies.
3.2.3.4 Polyethylene

Ion-exchange resins have been satisfactorily incorporated in polyethylene in a power plant in the Federal Republic of Germany, and also studied at the Oak Ridge National Laboratory in the United States [18, 21, 22]. Commercially-available polyethylene was used, the properties of which are similar to those of bitumen. Thus, similar equipment can be used in the process as for bituminisation. The present economical conditions might not favourise polyethylene in relation to bitumen.

3.2.3.5 Dow process

A vinyl ester-styrene polymer system has been composed of a commercially-modified vinyl-ester product, in the United States. Polymerisation is achieved by an addition mechanism using a promoter-catalyst system which permits curing without external heat. Wastes are entrapped in the polymer matrix. No chemical reaction takes place between the waste and binder materials. Solidification takes place in 5 to 20 minutes dependent on the volume and the amount of catalyst and promoter.

The system uses in-container mixing techniques with a disposable mixing blade. Pre-treated resins are added to the container and dewatered. Binder and promoter-catalyst are sequentially added and mixing is accomplished with a high torque mechanical agitator.

Much of the information about this system is proprietary. The Dow binder has a low ignition temperature (100°C) and added precautions must be taken during storage. The process is relatively insensitive to waste chemistry but sensitive to waste stream temperature. Waste temperatures are limited to about 55°C due to the temperature increases, 33-44°C, that occur during the exothermic gelling process to prevent boiling off. This temperature sensitivity should not affect resin processing.

The resultant product is a liquid-free solid that immobilises the resins homogeneously, prevents significant leaching, has good physical integrity and resistance to impact, and can withstand a high temperature.

A number of test operations have been carried out using Dow process to solidify radioactive wastes, including spent ion-exchange resins, generated in power plants. In 1979, several utilities in the United States installed the Dow process in their plants [26].
3.2.4 Other techniques

Many types of solid waste, granular or in powdered form, such as inorganic ion-exchangers or ashes, can be compacted, sintered or pelletised, either alone or mixed with an inorganic binding agent. The compacts or ceramic pellets can be coated further with different materials and encapsulated in an appropriate way for disposal. According to the studies made, different kinds of pressing techniques can be applied, e.g. various cold-pressing techniques, hot-pressing techniques and isostatic pressing techniques.

Extensive laboratory studies concerning different methods have been made in the United States. One company, Newport News Corporation, has developed not only a fluidised bed calciner/incinerator applicable for spent resins, but also a pelletisation solidification system which is particularly suited for immobilising the solids and ashes resulting from calcination and/or incineration [27].

In Sweden, laboratory work has been done on elution of mixed bed resins, starting with the long-lived fission products $^{132}$Cs and $^{90}$Si. The eluted nuclides are then sorbed on inorganic exchangers, zeolites or titanates, which are finally sintered by the hot isostatic pressing process. The reduced activity of the resins after elution renders it possible to incinerate them by using fluidised bed technique exactly like the experiments done in Sweden [22, 28]. Respective studies have been performed in the U.K. as well [22].

3.3 Summary of the treatment and conditioning technology

In the foregoing section, a brief description has been presented of several established and developing processes for treatment and conditioning of spent ion-exchange resins.

It is plain that safe disposal of radioactive wastes generated by nuclear power plants is dependent on the preceding management steps, treatment and conditioning. The main function of treatment prior to conditioning is still preparation, pre-conditioning, i.e. to make the spent resins suitable for conditioning, interim storage or transport. However, more emphasis is being placed on reduction of volume of all types of low- and intermediate-level wastes. Thus, techniques with substantial volume reduction capacity, such as incineration or acid digestion, are rising in interest.
Final conditioning, which involves immobilisation of spent resins, should provide protection against dispersal of radioactivity in adverse events. Thus, the conditioned waste form should have adequate thermal and chemical stability, physical ruggedness and low leachability. The properties of immobilised waste products are related to the immobilisation medium used as also, to some extent, to the applied process. A few immobilisation systems, i.e. processes and product properties are briefly discussed below.

3.3.1 Systems

Table I presents the current status of immobilisation processes as a function of medium and process type. For convenience, status has been divided into the following three categories:-

Current Practice (CP) - the process and agent have been used with radioactive material at an operating nuclear power plant.

New Technology (NT) - the process and/or agent have been demonstrated with full-scale pilot plant operations and will be installed at an operating nuclear power plant in the near future.

Developmental (D) - the process and agent are presently being investigated on a pilot plant basis but have not yet been finalised for nuclear power plant installation.

Most of the experience has been obtained from the systems using cement or bitumen. With regard to organic polymer techniques employing urea-formaldehyde, polystyrene-divinylbenzene, thermo-setting resins(polyesters and epoxies) and polyethylene have already been used in nuclear power plants, whilst the Dow process (modified vinyl-ester product) is just being installed in some power plants in the USA. The various pressing processes - many of them often utilise inorganic binders as additives - are still mostly under development. For example, pilot tests will be performed in Sweden in the near future. The only technique in this category which is supposed to be mature for power plant use is the pelletisation system offered by the US company Newport News.
## TABLE I

### Summary - Immobilisation Techniques

#### Process Types

<table>
<thead>
<tr>
<th>IMMobilisation Media</th>
<th>CONTINUOUS PROCESSES</th>
<th>BATCH PROCESSES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static mixing</td>
<td>Dynamic mixing</td>
</tr>
<tr>
<td>Cement with or without additives</td>
<td>—</td>
<td>CP</td>
</tr>
<tr>
<td>Bitumen</td>
<td>NT</td>
<td>CP</td>
</tr>
<tr>
<td>Urea-formaldehyde</td>
<td>CP*</td>
<td>CP</td>
</tr>
<tr>
<td>Polystyrene-divinylbenzene</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Thermo-setting plastics (polyester epoxies)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>—</td>
<td>CP</td>
</tr>
<tr>
<td>Dow process (vinyl-ester)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Pressing processes with and without inorganic binders</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

### Legend

- **CP** - current practice
- **NT** - new technology
- **D** - developmental
- *** - mobile systems also in operation**
3.3.2 Properties of the conditioned products

The physical and chemical properties of conditioned ion-exchange resins have been the subject of numerous investigations. A number of the most relevant properties in view of the further management steps, viz. handling, transport, storage and disposal, are listed in the attached Table II. The table compiles the data from Reference 39, giving information on important properties of products resulting from three solidification media, viz. bitumen, cement and styrene-divinylbenzene. One can argue the representativeness of the numerical values given, like concerning the column "Waste incorporated quantities". The figures presented for cement are high according to some references [72, 21, 22, 29, 30]. Nevertheless, the data presented in the table were found by the Committee as illustrative for the three techniques referred to.

The most important criterion of judging the solidified products is how well the radioactive materials remain in the final product. Thus, a property of decisive importance is the low leachability. Mechanical ruggedness is very important, in particular during transport and handling. The importance of long-term chemical stability and radiation resistance depends on the characteristics of waste incorporated and on the disposal circumstances.

Neither of the two principal solidification techniques, cementation and bituminisation, is ideal for incorporation of spent ion-exchange resins. One of the main potential problems is the swelling of incorporated ion-exchange particles during storage or disposal. This is due to adsorption of water and it can markedly reduce the mechanical and consequently leaching properties of both bituminised and concrete products.

Leachability, low-volumetric efficiency, and in some cases unsatisfactory mechanical properties are the potential problem areas concerning the most applied immobilisation method for ion-exchange resins, viz. cementation. For improvement of the products, encouraging results have been reported in using additives, e.g. sodium silicate, polymer and impregnation or bitumen coating of the concrete products. The pre-treatment of resins, such as incineration, might also be a method for overcoming the above problems, which also applies to bituminisation.

With regard to organic polymers, e.g. styrene divinylbenzene as immobilisation media, many product properties are comparable to those of bitumen, e.g. radiation stability. However, the amount of data available is still very limited.
<table>
<thead>
<tr>
<th>Properties</th>
<th>Main characteristics</th>
<th>Bitumen</th>
<th>Cement</th>
<th>Styrene-divinylbenzene</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical Properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leachability ((g/cm^2 \cdot d^{-1}))</td>
<td>(10^{-5} \div 10^{-4})</td>
<td>(10^{-3} \div 10^{-2})</td>
<td>(\sim 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>Release of explosive, flammable, corrosive, poisonous gases</td>
<td>Release of radiolysis gases</td>
<td>Releases of radiolysis gases</td>
<td>At (90^\circ) - release of (N_2O), At (400^\circ) - matrix destruction</td>
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</tr>
<tr>
<td>Hazard of explosion</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>a. against radiation</td>
<td>b. Possible but rare</td>
<td>b. Possible, but rare</td>
<td>b. Possible</td>
<td></td>
</tr>
<tr>
<td>b. bacterial attack</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compatibility with storage media</td>
<td>Good</td>
<td>Good (in dry condition)</td>
<td>Good (in dry condition)</td>
<td></td>
</tr>
<tr>
<td><strong>Mechanical Properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density ((g/cm^3))</td>
<td>Upto 1.4</td>
<td>1.7 (\pm) 2.4</td>
<td>1 (\pm) 1.1</td>
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</tr>
<tr>
<td>Mechanical strength ((kg/cm^2))</td>
<td>Plastic deformation</td>
<td>(&gt;150 \div 650)</td>
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<tr>
<td>Brittleness</td>
<td>At low temperature</td>
<td>Possible</td>
<td>Possible</td>
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<td><strong>Thermal Properties</strong></td>
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<tr>
<td>Softening point (^\circ C)</td>
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<td>(&gt;1000)</td>
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<tr>
<td>Flash point (^\circ C)</td>
<td>More than 250</td>
<td>no</td>
<td>As for ion-exchange resins</td>
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</tr>
<tr>
<td>Property</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------------</td>
<td>------------------------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>Thermal decomposition (°C)</td>
<td></td>
<td></td>
<td>350 ± 400</td>
<td></td>
</tr>
<tr>
<td>Thermo conductivity (W/mK)</td>
<td>0.31</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Specific heat (J/kgK)</td>
<td>1700</td>
<td>900</td>
<td>-</td>
<td></td>
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<tr>
<td>Phase transition</td>
<td>No (under normal</td>
<td>&gt; 1000°C</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td>storage conditioning)</td>
<td></td>
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<td></td>
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<tr>
<td>Radiation Stability</td>
<td></td>
<td></td>
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<tr>
<td>Stability</td>
<td>Change of visco-elastic</td>
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<td>properties, swelling</td>
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</tr>
<tr>
<td></td>
<td>of volume 25% at 100 M</td>
<td></td>
<td>No change</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rad (10 NeV electron)</td>
<td></td>
<td>material up to 10⁹ rad.</td>
<td></td>
</tr>
<tr>
<td>Max. tolerance integral</td>
<td>~ 10⁸</td>
<td>10¹⁰</td>
<td>10⁸</td>
<td></td>
</tr>
<tr>
<td>doses (rad.)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Radiolysis</td>
<td>0.5cm³(H₂)/g by 100 M</td>
<td>Till 0.02cm³(H²)/g</td>
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<tr>
<td></td>
<td>Rad.</td>
<td>0.7 (0.2 per g product)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>by 100 M Rad.</td>
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<tr>
<td>α- irradiation resistance</td>
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<td>Under investigation</td>
<td>Under investigation</td>
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</tr>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Special</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>properties</td>
<td></td>
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</tr>
<tr>
<td>Homogeneity</td>
<td>Depends on mixing</td>
<td>Depends on mixing</td>
<td>Depends on mixing</td>
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<tr>
<td>Segregation tendency</td>
<td>At heating</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Waste incorporated</td>
<td>50%</td>
<td>Bead and powdered</td>
<td>60 ± 65% Vol of IX</td>
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</tr>
<tr>
<td>quantities</td>
<td></td>
<td>resins</td>
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<tr>
<td></td>
<td>20 ± 30 kg/2001</td>
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</tbody>
</table>
REFERENCES


4. ECONOMIC ASPECTS

Ion-exchange is used as the primary method for water treatment in nuclear power plants. The way in which ion-exchange media are used and treated further up to the disposal have a significant impact on capital and operative costs. This section generally discusses the economic factors associated with the use, treatment, packaging and disposal of ion-exchange resins. It is emphasised that the actual importance of the said factors are in relation to country and even to plant specific circumstances, and they depend on the whole waste management system applied. Thus, the figures and numerical values as well as actual comparisons between different treatment methods, which in fact are still in a developing state, have to be considered with great caution. The purpose of discussing them is to serve as an example of the methodology of an appropriate economic evaluation.

4.1 General economic considerations

The economics associated with the use of ion-exchange media must be evaluated in the context of the entire sequence of events that the resins are exposed to from initial purchase through ultimate disposal. For new plants, this evaluation can be conducted in two phases: (1) evaluation of ion-exchange processes compared to other water treatment processes such as evaporation or filtering plus (2) evaluation of alternate techniques to condition and prepare a particular form of ion-exchange media for disposal. For operating plants which already have installed equipment, this evaluation is confined to the second phase.

The objective is to select an approach that will satisfy the criteria for storage and disposal in the country of origin that is also the lowest operating cost solution. However, since a plant must also handle other forms of radioactive waste, the lowest cost solution for resins is not necessarily optimum when other waste loads are considered. Relative comparisons can be made when the following elements of operating costs are considered.
1. Labour
The actual cost of plant-operating personnel, including benefits and overhead, for the manpower required to operate, maintain equipment used for resins throughout their on-site cycle, and handle them.

2. Materials
The costs of fresh ion-exchange media, treatment/regenerative chemicals, immobilisation agents, disposable containers, and other expendables.

3. Depreciation
The annual charge for amortisation of the facility and equipment allocated to resin processing and handling.

4. Disposal services
The cost for transportation, cask rental, and any charges assessed by the operator of the ultimate disposal site.

Figure 1 presents a flowchart of the activities that should be considered to evaluate resin disposal alternatives. Once a water treatment process is selected and the criteria for disposal are established, consideration of these factors will permit an economic evaluation of most approaches. This figure can be divided into two major categories (1) treatment system selection and (2) packaging system selection. These two categories are discussed separately below.

4.2 Treatment system
The processes selected for water treatment will determine the specific characteristics of the radioactive waste material the plant will produce. From Figure 1, this includes the form, volume, specific activity, and physical characteristics of the waste.

Favoured types of treatment and resultant waste forms are shown in Table I. The primary forms of material are powdered and/or deep bed resins. Some processes also generate secondary waste forms consisting of regenerative solutions and/or spent filter cartridges.

Regenerative solutions represent a fairly high volume of low specific activity material which must be converted to a form acceptable for disposal. Regeneration will reduce resin disposal requirements and
activity level dependent expenses resulting from resins. It will increase capital investment, operating expenses, and disposal costs.

Expendable filter cartridges used as demineraliser pre-filters represent a high activity, low volume source of material. Additional capital investment and operating expense is offset by improved resin performance. Their relatively small volume does not significantly increase disposal costs but their high activity does result in increased radiation exposure expense.

4.2.1 Resin volume, type, and activity level

The volume of resins generated by a particular system is the dominant factor in evaluating disposal economics. Expected volumes dictate both equipment and facility requirements and thus increase capital investment and operating expenses. Disposal costs are also a direct function of resin volume.

The importance of resin activity level is second only to volume when considering disposal costs. Generally, the curies of activity removed from a particular process stream by ion-exchange will not vary significantly with mode of operation. There are economic tradeoffs that can be made between volume and activity level. High volume, low activity modes of operation decrease capital investment in structural shielding and radiation exposure expenses but increase process equipment investment and disposal costs. The opposite is true for low volume, high activity modes of operation. Radiation exposure expenses can be reduced by the use of more sophisticated designs for maintenance access, and handling. This is the present trend in the United States.

The forms of the resins, i.e. deep bed or powdered, will determine the methods used to prepare the material for ultimate disposal and effects capital investment and operating expenses. Powdered resins usually require more sophisticated approaches to subsequent processing and hence higher capital investment and operating costs. Generally though, the form of the resin material does not have a significant impact on overall disposal costs.
FACTORS AFFECTING RESIN DISPOSAL COSTS

FIGURE 1


<table>
<thead>
<tr>
<th>WATER TREATMENT METHODS</th>
<th>RESIN FORM</th>
<th>OTHER WASTE FORM</th>
<th>ACTIVITY LEVEL(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PWR STATIONS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Boron recovery system</td>
<td>Deep bed</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>2. Liquid waste system</td>
<td>Deep bed</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>3. Steam generator blowdown</td>
<td>Deep bed</td>
<td>None</td>
<td>Negligible to low</td>
</tr>
<tr>
<td>4. Condensate clean-up</td>
<td>EITHER Deep bed</td>
<td>Regenerative solutions</td>
<td>Negligible to low</td>
</tr>
<tr>
<td></td>
<td>Powedered</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td><strong>BWR STATIONS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Floor and equipment drains</td>
<td>Deep bed</td>
<td>None</td>
<td>Low</td>
</tr>
<tr>
<td>2. Radwaste clean-up</td>
<td>Deep bed</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Deep bed</td>
<td>Regenerative</td>
<td>Med</td>
</tr>
<tr>
<td>3. Condensate clean-up</td>
<td>EITHER Deep bed</td>
<td>Regenerative</td>
<td>Med</td>
</tr>
<tr>
<td></td>
<td>Powedered</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

High-radiation levels in excess of 20 rem/h

Med-radiation levels from 200 mrem/h to 20 rem/h

Low-radiation levels up to 200 mrem/h

(*) The definition of activity level is an example only serving the purpose of this Chapter. It has been made according to the above classification.
4.2.2 Volume reduction

Since volume is the dominant factor in overall disposal costs, volume reduction methods may be evaluated. Volume reduction methods applied to resins can be expected to decrease resin volume by a factor of about two. To achieve this reduction, additional capital investment and increased operating expenses are incurred. Radiation exposure expenses are increased, and the reduction process may produce additional gaseous waste streams which will require treatment.

Volume reduction has significant merit in processing low solids content liquid wastes like regenerative solutions and should be considered in an overall system evaluation.

4.2.3 Physical characteristics

The physical characteristics of the resin material are determined by upstream treatment processes. After use as an ion-exchange media, resins are sluiced to a hold-up tank. Further processing is used to reduce volumes before they are made available for packaging.

Dewatering is a favoured approach and the methods used are dependent on the immobilisation process used. Where immobilisation processes require water, such as cement, dewatering is accomplished in the hold-up tank to yield a 40-60 weight percent slurry that is pumpable. To obtain higher solids content waste streams, a centrifuge or other continuous mechanical dewatering process is used. The resultant material is a moist cake, moved by mechanical means to the packaging area. Generally, the higher the solids content, the more cost effective the process even though water might have to be added during the packaging process.

Generally, where other volume reduction processes are used the material changes significantly from its generic form. Drying reduces volume by a factor of two and yields a powdery material. Incineration yields a dry ash and chemical digestion yields a wet liquid.

In all cases, the interfaces between each process step must be carefully evaluated for operating implications.

4.3 Packaging systems

Upstream processes determine the characteristics of the material available for packaging. To complete the disposal cycle, subsequent operations must be carefully evaluated to ensure compatibility with the
form(s) of material received. The steps in Figure 1 that warrant further consideration include conditioning, immobilisation, encapsulation, transport, interim storage, and ultimate disposal. The economic factors associated with these steps are discussed below.

4.3.1 Pre-treatment

This step is necessary in some processes to ensure chemical compatibility between the resin and the immobilisation agents. A major consideration is the extent of resin depletion, particularly when a chemical immobilisation agent is used.

Most agents, except asphalt, require waste chemistry in the neutral PH range. The addition of chemicals to increase or decrease PH must be factored into the economic evaluation. Highly acidic materials will not perform well with cement while highly basic materials will not perform well with urea formaldehyde or some other chemical agents.

Where asphalt is used, a resin grinding process is usually used to ensure dispersion of the materials during the immobilisation process. Drying requires the addition of a chemical poison to prevent resin expansion when exposed to moisture.

These pre-treatment steps must be considered on an individual basis. They all add to the total cost of the process.

4.3.2 Immobilisation

The processes used to immobilise resins should be designed to convert the resin into a relatively inert form that satisfies criteria for further treatment and disposal. These processes will also affect overall costs since the selected process will determine the resin volume in the matrix that will be encapsulated.

The generic materials presently used on a commercial scale for resin immobilisation include cement, bitumen (asphalt), urea formaldehyde, and polyester resins. These materials are used in their generic form or with additives which enhance the physical and/or chemical characteristics of the resultant matrix. The capital investment in processing equipment and facilities also varies with the type of immobilisation agent. Generally, batch-type processes require less facility space and equipment investment than continuous processes. On the other hand, continuous processes
offer operating cost advantages over the batch-type processes. The primary consideration is compliance with the criteria for management and disposal.

The amount of material that can be processed per unit time varies with the process and system type. A second criteria for selection is ensuring that the system throughput is adequate to handle the total waste (resins and other waste streams) load of the station under normal conditions of operation, and realistic peak load conditions. Generally, lower throughput systems result in higher manpower related operating costs.

All systems require maintenance. The expenses for maintenance manpower and material as well as the potential exposure due to maintenance should be considered.

The performance characteristics of these agents also vary. Table II presents a particular example of ratios of ingredients for some of the more common agents. This table also shows the respective packaging efficiencies, a critical parameter when evaluating alternate agents. The higher the packaging efficiency, the more cost effective the agent.

Cost data for the more common agents is shown in Table III. Relative operating costs per unit volume of waste are also shown. This parameter is developed from the mixing ratios, materials cost and packaging efficiency for each waste type.

4.3.3 Encapsulation

After resins are mixed with an immobilisation agent, the mixture is placed in a disposable container. The resins and agent are allowed to set or solidify in this container, usually before transfer from the packaging area.

The type of disposable container used varies with the immobilisation process, the packaging facility layout, and the remotely operated process, the packaging facility layout, and the remotely operated equipment available for container closure and subsequent handling. Selection of container size(s) and type is a critical consideration because it governs ultimate disposal costs, manpower requirements, and radiation exposure.

Throughout the world a variety of container types are used. The most common type is a 55 gallon or 0.2 m³ steel drum. The most recent trend is toward the use of larger containers made of steel, concrete, and in some cases fibreglass or plastic.
The following examples illustrate the effect of container size, manpower requirements, and personnel exposure on unit cost.

**EXAMPLE: Container costs**

Figure 2 shows unit costs, in dollars per $m^3$, as a function of container volume for typical steel disposable containers in the United States. As shown, the 55 gallon drum is the most cost effective container due to its widespread use in non-nuclear applications. The larger containers are often specially fabricated in relatively small lots (100's) and must conform to nuclear safety-oriented criteria. Generally, these containers become more cost effective with increased size. Care must be taken to ensure compatibility between size, radiation level, and transport weight constraints that apply in most countries.

**Figure 2**

![Graph showing disposable container costs](image)
TABLE II

MIXING RATIOS AND PRODUCT DENSITIES

<table>
<thead>
<tr>
<th>WASTE AGENT TYPES</th>
<th>WASTE/AGENT WEIGHT RATIO</th>
<th>WASTE PRODUCT DENSITY g/cm$^3$</th>
<th>PACKAGING (1) EFFICIENCY %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. BEAD RESIN SLURRY (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asphalt</td>
<td>1</td>
<td>1.05</td>
<td>100$^{(3)}$</td>
</tr>
<tr>
<td>Cement</td>
<td>2.4</td>
<td>1.35</td>
<td>93</td>
</tr>
<tr>
<td>Polymer (4)</td>
<td>1.8</td>
<td>1.05</td>
<td>67</td>
</tr>
<tr>
<td>Urea formaldehyde (5)</td>
<td>2.6</td>
<td>1.13</td>
<td>79</td>
</tr>
<tr>
<td>2. POWDERED RESIN SLURRY (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asphalt</td>
<td>1</td>
<td>1.05</td>
<td>100$^{(3)}$</td>
</tr>
<tr>
<td>Cement</td>
<td>1.8</td>
<td>1.23</td>
<td>73</td>
</tr>
<tr>
<td>Polymer (4)</td>
<td>1.4</td>
<td>1.05</td>
<td>60</td>
</tr>
<tr>
<td>Urea formaldehyde (5)</td>
<td>2.0</td>
<td>1.18</td>
<td>73</td>
</tr>
</tbody>
</table>

(1) Packaging efficiency = \( \frac{\text{Initial waste volume}}{\text{Waste product volume}} \times 100 \)

(2) 50% resin by weight in water – bead slurry density 1.05 g/cm$^3$; powdered resin slurry density 1.08 g/cm$^3$

(3) Water in slurry is removed in process

(4) A vinyl ester styrene – typical

(5) Free liquid amounting to several percent of waste product volume results from process

(6) The figures given refer to a particular technique under certain conditions
### Table III

**Immobilisation Agent Characteristics**

*(Cost data in U.S. dollars - 1977)*

<table>
<thead>
<tr>
<th>Agent</th>
<th>Density</th>
<th>Cost $/lb.</th>
<th>Operating Cost $/gal. waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>1.05</td>
<td>0.06</td>
<td>0.26&lt;sup&gt;(2)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cement</td>
<td>1.5</td>
<td>0.03</td>
<td>0.11</td>
</tr>
<tr>
<td>Polymer</td>
<td>1.1</td>
<td>0.90</td>
<td>4.38</td>
</tr>
<tr>
<td>Urea formaldehyde</td>
<td>1.3</td>
<td>0.20</td>
<td>0.68</td>
</tr>
</tbody>
</table>

<sup>(1)</sup> Based on incoming waste as slurry form cost calculated from Table II mixtures

<sup>(2)</sup> Equivalent cost since process removes water from slurry
EXAMPLE: Manpower requirements

Handling of a container after packaging is dependent on facility layout and available handling equipment. For a particular facility container sizes can be compared.

After filling, a container must be removed from the packaging area to a storage area, and from there to a shipping cask/transport vehicle for shipment. Generally, the manpower required to handle a 0.2 m$^3$ drum is the same as that required to handle a larger container. The following table illustrates a unit cost comparison for a situation where two men are required for two hours to handle a container in the facility.

<table>
<thead>
<tr>
<th>Container volume (m$^3$)</th>
<th>Unit handling times (mh/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>1.4</td>
<td>14.3</td>
</tr>
<tr>
<td>4.8</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Thus, from a handling viewpoint, the larger containers are more cost effective than drums.

EXAMPLE: Radiation exposure

The radiation exposure for a container with the same curie content does not vary significantly with container volume. The more containers a crew handles with the same type of equipment, the more radiation exposure they will receive. From a handling viewpoint, larger containers are more radiation exposure effective than drums.

4.3.4 Interim storage

At most plants, waste is stored after encapsulation and provisions must be made within the facility for handling and storage. In the U.S., most plants include storage facilities equivalent to several months' waste production. In other countries, storage facilities are sized for up to five years' storage. There is some merit to storing material to reduce activity levels but once the short-lived nuclides have decayed, about three months, there is no economic advantage to extending the storage period.

Ideally, the storage facility should be close to the processing facility and shipping area to reduce the manpower required for handling and the radiation exposure incident to handling.
4.3.5 Transport

At present while the times contemplated for interim storage at the power plant site vary, it is an interim measure and ultimately the stored material must be removed to a final disposal site. Transport is accomplished by truck, rail, or barge. For each of these transport modes the cost is more a function of distance than payload. Thus, each transport mode should be used with payloads which correspond to the maximum allowable to minimize the cost of transportation. This criteria favors the use of the largest container size practicable in the light of the other constraints on the overall disposal approach. Additionally, the manpower and radiation expenses incident to preparing these encapsulated materials for transport decrease with increases in container size.

To compare the economics of transport alternatives, cost should be reduced to unit costs. The following example illustrates how transport unit costs vary with payload configuration and distance to the ultimate disposal site.

EXAMPLE: Transport costs

A favored truck shipping cask in the U.S. is a lead/steel shielded right circular cylinder with an internal volume of about 5 m$^3$. It conforms to legal weight limits when loaded and allows the shipper to transport either fourteen (14) 0.2 m$^3$ drums or a single 4.8 m$^3$ steel disposable container. The allowable radiation levels for each type of container are comparable.

Figure -3 shows the unit costs in U.S. dollars per m$^3$ of payload as a function of distance in kilometers to the disposal site. As expected, unit costs increase with distance, and the higher payload configuration is the least costly.

4.3.6 Disposal

In most cases, the encapsulated resins will be shipped off-site to a disposal facility. The costs associated with this last step in the management chain will vary from country to country.

In the U.S., wastes are interred in land burial sites. The land is owned by either a State or Federal Government entity and the site is operated by private contractors. A wide range of variables enter into
the cost structure for disposal at these facilities, but the dominant factors are (1) volume of the container, (2) radiation level, and (3) the amount of handling to unload each shipment. Figure 4 shows the cost structure for a typical cask shipment to a U.S. land burial site.

This particular shipping configuration illustrates the cost variances with container size. Where the cask arrives with 14 drums, multiple handling operations are necessary and the resultant personnel exposure is high. The same cask with a single container requires a single handling operation with less exposure and is thus less costly. The data takes into account the larger crane necessary to handle the heavier container.

Thus, at U.S. land burial facilities, the cost structures in effect favour containers larger than the standard 55 gallon drum. This economic advantage increases markedly as the radiation level increases.

4.4 Case study

Selection of the most cost effective approach to resin disposal involves the evaluation of a wide range of inter-dependent factors. Each plant must consider these factors in the context of plant and country specific circumstances. A thorough evaluation will, however, yield the most cost effective approach.

To illustrate how the factors discussed in this section enter into an evaluation, a hypothetical example case study for a U.S. plant was considered. Some of the conditions have been simplified for convenience. All expenses are initially reduced to unit costs, i.e. U.S. dollars per m³ of container. Total expenses are finally reduced to true unit cost, U.S. dollars in 1977 per m³ waste.

Assume the station is a twin 1000 MWe PWR with non-regenerative deep bed ion-exchangers located 400 km from a disposal facility. The annual requirement for disposal is 300 m³ of resin in the 10–25 Rem/hr range. The plant includes facilities for packaging with cement or urea formaldehyde and drums or large containers are being considered. The values used in U.S. conditions referring to the particular exemplary methods. Those are not aimed to be typical of the two techniques, viz. immobilisation with cement and urea formaldehyde.
NOTE: Both types of containers are transported in the same shipping cask - 14 0.2 m³ drums vs. a single 4.8 m³ container.
TYPICAL COSTS FOR SHALLOW LAND BURIAL AT A US FACILITY (US DOLLARS)

NOTE: BOTH TYPES OF CONTAINERS ARE TRANSPORTED IN THE SAME SHIPPING CASK

FIGURE 4
4.4.1 Depreciation

Depreciation is a function of equipment and installation costs and the time period over which these capital investments are amortised. These capital expenditures also vary with system and container type. Typical installed costs for the equipment considered will vary from $1,000,000 (U.S. dollars) for a urea formaldehyde system using drums to $1,400,000 for a cement system using large containers. Installed cement systems are about $200,000 more costly than urea systems. Installed handling equipment for large containers is about $200,000 more costly than drum equipment due to the larger capacity crane and heavier transfer equipment.

Table IV presents annual depreciation expenses for each system/container type based on a 30-year lifetime. This table also shows depreciation as a unit cost based on annual resin requirement of 300 m$^3$.

**TABLE IV**

<table>
<thead>
<tr>
<th>System/container type</th>
<th>Annual cost (US dollars)</th>
<th>Unit cost ($/m$^3$ container)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement/drum</td>
<td>40,000</td>
<td>124</td>
</tr>
<tr>
<td>Cement/large containers</td>
<td>47,000</td>
<td>146</td>
</tr>
<tr>
<td>Urea/drum</td>
<td>33,300</td>
<td>88</td>
</tr>
<tr>
<td>Urea/large containers</td>
<td>40,000</td>
<td>105</td>
</tr>
</tbody>
</table>

(1) Data corrected by packaging efficiency: 0.93 for cement and 0.79 for urea formaldehyde.

4.4.2 Labour

Each alternative results in different operating labour costs for system operation, maintenance, and container handling. Some typical differences in this cost element at a labour rate of $15 per man/hour are:

(a) **System operation** — Preparation of resins for packaging are essentially the same for both types of systems. Throughput, i.e. the amount of waste material packaged per unit time, varies with container size.

Studies have shown that a typical drum facility can process a drum in $\frac{3}{4}$ hour while a larger 170ft.$^3$ container can be processed in 1.5hrs. On this basis unit costs are:

Drum: $0.5 \text{ hr} \times 15\$/\text{hr} \div 0.2\text{m}^3 = 37.50\$/\text{m}^3$

Large container: $1.5 \text{ hr} \times 15\$/\text{hr} \div 4.8\text{m}^3 = 4.70\$/\text{m}^3$
(b) **Maintenance** - The mechanical equipment in a cement system requires more maintenance than a urea formaldehyde system. A good estimate is an additional 1000 manhours for an annual expense of $15,000. At 300 m³ of resin per year, this corresponds to a $50/m³ advantage for urea formaldehyde systems. When corrected for a 0.79 urea packaging efficiency this advantage is $40/m³ of container volume.

(c) **Handling** - Labour costs for handling involve movement of the packaged waste to storage and from storage to a shipping cask. These relative costs are container size dependent. Drums require about $\frac{1}{3}$ an hour to complete the handling cycle while the large container requires about 2.5 hours for the same cycle. On an unit cost basis, considering two operators, the relative units costs are:

\[
\text{Drums: } 2 \text{ men} \times \$15/\text{mh} \times 0.5 \text{ hr} = \frac{75}{0.2m^3}
\]

\[
\text{Large containers: } 2 \text{ men} \times \$15/\text{mh} \times 2.5 \text{ hrs} = \frac{15.60}{4.8m^3}
\]

(d) **Labour summary** - Relative total labour costs for both alternatives are:

<table>
<thead>
<tr>
<th>Container type</th>
<th>Systems type</th>
<th>Cement ($/m³)</th>
<th>Urea formaldehyde ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operation</td>
<td>37.50</td>
<td>37.50</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>40.00</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Handling</td>
<td>75.00</td>
<td>75.00</td>
</tr>
<tr>
<td></td>
<td>TOTALS</td>
<td>152.50</td>
<td>112.50</td>
</tr>
<tr>
<td>Large containers</td>
<td>Operation</td>
<td>4.70</td>
<td>4.70</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>40.00</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Handling</td>
<td>15.60</td>
<td>15.60</td>
</tr>
<tr>
<td></td>
<td>TOTALS</td>
<td>60.30</td>
<td>20.30</td>
</tr>
</tbody>
</table>

**4.4.3 Materials costs**

Materials costs include containers and solidification agents. From Table 3, cement costs $0.11/gallon or $29/m³ and urea formaldehyde costs $0.60/gallon or $180/m³.
Container costs are shown on Figure 2. A drum costs $90/m³ and the median for a 170 ft³ container is $260/m³.

4.4.4 Disposal costs

These cost elements include transportation, cask rental, and burial or ultimate disposal.

Figure 3 shows relative transportation costs. At a distance of 400 km, the unit cost is $230/m³ for drums and $140/m³ for large containers.

The cost of shipping casks must also be considered. If casks are owned by the plant, amortisation and maintenance is included in depreciation and operating costs. If casks are rented, costs are included under disposal. This case study assumes casks are rented at the rate of $100 per day and each shipment requires 5 days. The unit cask costs are:

\[
\begin{align*}
\text{Drums} & \quad \frac{500}{14 \text{ drums} \times 0.2 \text{m}^3} = \$178.60/\text{m}^3 \\
\text{Large containers} & \quad \frac{500}{4.8 \text{m}^3} = \$104.20/\text{m}^3
\end{align*}
\]

The costs of burial or ultimate disposal are shown in Figure 4. At a radiation level of 10–25R/hr, the unit costs is $400/m³ for drums and $220/m³ for large containers.

4.4.5 Cost summary

The cost elements presented above can be summarised to determine the least cost alternative for the assumed conditions. This summary is presented Table V. As shown, the most economical approach is cement with large containers and the least economical one is urea formaldehyde and drums.

The final step in the evaluation is to determine true unit cost, i.e., cost per unit volume of waste the plant must ship off-site for disposal. To do this, the data shown in Table V must be divided by the packaging efficiencies shown in Table II. This correction factor yields the following results:
<table>
<thead>
<tr>
<th>System/container type</th>
<th>True unit cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement/drums (0.93)</td>
<td>1296</td>
</tr>
<tr>
<td>Cement/large containers (0.93)</td>
<td>1032</td>
</tr>
<tr>
<td>Urea formaldehyde/drums (0.79)</td>
<td>1620</td>
</tr>
<tr>
<td>Urea formaldehyde/large containers (0.79)</td>
<td>1304</td>
</tr>
</tbody>
</table>

( ) Packaging efficiency

### TABLE V

UNIT COST SUMMARY - CASE STUDY

<table>
<thead>
<tr>
<th>Major cost element</th>
<th>Cement-$/m³(2)</th>
<th>Urea formaldehyde-$/m³(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drums</td>
<td>Large containers</td>
</tr>
<tr>
<td>1. DEPRECIATION</td>
<td>124</td>
<td>146</td>
</tr>
<tr>
<td>2. LABOUR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Operation</td>
<td>38</td>
<td>5</td>
</tr>
<tr>
<td>(b) Maintenance</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>(c) Handling</td>
<td>75</td>
<td>16</td>
</tr>
<tr>
<td>TOTAL</td>
<td>153</td>
<td>61</td>
</tr>
<tr>
<td>3. MATERIALS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Agent</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>(b) Container</td>
<td>90</td>
<td>260</td>
</tr>
<tr>
<td>TOTAL</td>
<td>119</td>
<td>289</td>
</tr>
<tr>
<td>4. DISPOSAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Transport</td>
<td>230</td>
<td>140</td>
</tr>
<tr>
<td>(b) Cask rental</td>
<td>179</td>
<td>104</td>
</tr>
<tr>
<td>(c) Burial</td>
<td>400</td>
<td>220</td>
</tr>
<tr>
<td>TOTAL</td>
<td>809</td>
<td>464</td>
</tr>
<tr>
<td>5. TOTAL ALL COSTS</td>
<td>1205</td>
<td>960</td>
</tr>
</tbody>
</table>

(1) All figures shown previously are rounded to nearest dollar.
(2) All figures are in cost per unit container volume. Final analysis must consider packaging efficiencies of agents.
The least cost approach is still the same but consideration of the packaging efficiency favours the cement systems.

The purpose of this case study is to illustrate a methodology for conducting an evaluation on a hypothetical basis. The present consideration cannot give any reason to favour a particular system or solidification agent. Each evaluation must be performed for the valid conditions of a particular plant taking into account all the relevant factors, e.g. W.M. policy and criteria, the system applied as well as all types of wastes to be treated, etc.

5. INTERIM STORAGE AND DISPOSAL

Current practices concerning the final disposition of spent ion-exchange resins vary from country to country and within each country. The reasons for these varying practices are the absence of specific criteria for ultimate disposal as well as the availability of ultimate disposal sites or facilities. It was proven that underwater storage for several years is possible. After extended storage time, a caking together and consequently difficulties when rinsing it out are possible. In Sweden, moist exchangers have been stored for 16 years and could be conveyed hydraulically afterwards. Exchangers cause corrosion on certain metallic container materials. Concrete containers appear to be fit for storage of moist exchangers (Sweden). Due to possible gas evolution (e.g. radiolysis), storage containers for wet-exchangers should not be tightly sealed (welded) because the radiation causes bonds to be broken in the polymer chains. This reduces their possibility to produce an inner pressure, which balances the osmotic pressure. At the same time, radiation will produce chain fragments and other molecules that can increase the osmotic pressure. As a result, pressure against the concrete walls surrounding the grains can theoretically increase to several tenths of bars during the periods of high humidity and, thus, destroy the product. Cation exchangers seem to cause the worst trouble. This chapter discusses the alternatives available for disposal in the context of current and proposed practices in countries to satisfy these needs.

Figure 1 shows three alternative approaches to disposal. These alternatives represent current practice in most countries.

5.1 Current and proposed practices

The practices followed for disposal of resins depend on the needs of nuclear power plants in each country and the timing of these needs. Some countries are committed to disposal approaches, while others provide for long-term interim storage at plant sites until national programmes are defined and implemented. A summary of the current and prospective practices in countries which have operating nuclear power plants is presented below.
5.1.1 US.A.

In the past, there were no uniform criteria for spent resin disposal at existing shallow land burial sites, except that resins be dewatered and in solid form. Some land burial sites required immobilisation and others did not. Resins had to be encapsulated prior to transport and the methods
of encapsulation were uniformly defined for all burial sites. Many early US plants did not include systems and facilities for low-level waste immobilisation. Most shallow land burial sites did not require immobilisation and resins were usually dewatered and encapsulated prior to disposal.

Due to the relatively high activity levels of the resins, retention at the power plant site was not desirable, so materials were encapsulated and shipped almost immediately. At least one early plant, a BWR, included relatively large underground interim storage tanks which were used to store resins for up to 5 years. Some difficulties were encountered with resin packing since both powdex and deep bed resins were stored in these tanks. However, two 5-year batches of resins have been successfully removed from these tanks, immobilised with systems brought on site for this specific application, and transported to shallow land burial sites. This approach is unique in the context of practices at other US plants but has been successfully implemented.

At other operating plants, the practices vary with reactor-type and the criteria for disposal at the closest shallow land burial site. The relatively large volumes of powdex produced at BWR's require that these materials be encapsulated regularly. Where the selected burial facility requires immobilisation, resins are traditionally immobilised with cement or urea formaldehyde. At present, bituminisation and Dow process facilities are under installation as well. The approach to disposal of deep bed resins at both types of plants is similar. Volumes are small relative to other low-level waste loads and the activity is generally high. Thus, it is customary to store resins in relatively small (1000-2000 gallon) plant storage tanks and arrange for shipment when the tank is near capacity. Again, resins are immobilised only if required by the shallow land burial site. Shipment is made shortly after encapsulation. Figures 2, 3 and 4 show preparation procedures for shipment of low-level radioactive wastes and transportation truck.

These practices are currently undergoing changes. New plants are required to have immobilisation systems and older plants are required to incorporate them in existing or new facilities. Additionally, the criteria for disposal at shallow land burial sites have and are undergoing change.
Several shallow land burial sites have closed - West Valley, New York, Morehead, Kentucky, and Sheffield, Illinois. At the three remaining sites, only one will accept de-watered resins for disposal. This one site, Barnwell, South Carolina, will undoubtedly require immobilisation of resins in the near future. Thus, the trend is toward immobilisation of all forms of low-level wastes.

While all of the alternatives on Figure 1 are still practiced, in the future plants will have to immobilise and encapsulate resins. These changing requirements coupled with prospective unavailability of shallow land burial sites, have led to another trend - consideration of relatively long-term (3-5 year), on-site storage of immobilised and encapsulated resins. This approach will undoubtedly be practiced at some power plant sites as part of our overall strategy to handle low-level waste disposal needs.

5.1.2 France

Prior to transport to burial sites, spent resins are immobilised. A typical twin 900 mwe unit will include a 9m³ tank for on-site storage prior to immobilisation. Shortly after transfer to this storage tank, a matter of weeks, resins are immobilised and encapsulated. Encapsulated resins are stored for weeks or months prior to transport.

Since 1969, INPRATOME has started operations on shallow land burial of low- and medium-active wastes near to the La Hague centre. Only solidified wastes, which are encapsulated in steel drums or in cement blocks, can be stored at the site. Such a centralised storage centre is intended for burial for almost all types of wastes produced by nuclear power plants.

5.1.3 Federal Republic of Germany

All nuclear power plants are equipped with storage tanks for spent ion-exchange resins. In these tanks, resins are stored without any pre-treatment. The storage capacity often is for about 5 years. After interim storage, resins are incorporated into a non-soluble matrix material, usually cement or polystyrene.

The final product is transported to the final storage site which actually was the Asse salt mine. For acceptance at the Asse mine, the resins cannot be in a loose form but have to be incorporated into a non-soluble matrix material. The material meets the specifications for low-level waste disposal.
if by concrete or other shielding the dose rate is limited to 200 mR/h at
the surface. Otherwise, it is considered as medium-level waste. The Asse
mine had a time-limited license which ran out entirely at the end of 1978.
The license has not yet been extended.

5.1.4 United Kingdom

A programme for ultimate disposal of low-level waste has not yet been
selected. The preferred treatment method to condition resins prior to
disposal is still under consideration.

Thus, the present policy is to provide for on-site storage of
untreated resins at each nuclear power plant. These on-site resin
storage facilities, large tanks, are designed to have a capacity to
serve at least 5 years' storage need. This practice has been in existence
since 1968. At Winfrith, about 80m³ of resins, primarily powerred, are
stored underwater in fined concrete storage tanks with a total capacity
of about 800m³. No problems have arisen and the 80m³ currently stored
contains about 500Ci, mostly Co60.

5.1.5 India

A programme for a disposal method has not yet been selected.

At operating BWR's, present practice is to place de-watered resins
in steel drums and transport off-site for storage. No treatment or
conditioning is done. A new practice is to use relatively large tanks
for on-site storage of resins. A 1m-thick concrete 225m³ tank is used.
The tank would be partially below ground and resins can be de-watered
by decantation and be stored for an indefinite period. It is proposed
that one more such tank will be constructed [2].

At the heavy water reactor, resins are immobilised with cement,
placed in drums and shipped off-site for disposal.

REFERENCES


5.2 Ultimate management steps

The disposal of spent ion-exchange resins from nuclear power plants is not yet an established procedure on a world-wide basis. The methods applied, possessing the largest experience, are shallow ground disposal and dumping into the deep sea.

On the basis of substantial investigations made in several countries, the disposal into geological formations is seen as one of the most promising alternatives. The most remarkable experience gained up to now from this area originates from Asse salt mine. Various other types of geological disposal modes have been studied as well, e.g. underground caverns, natural or man-made, at different depths, in different rock formations, such as hard rock, sediments including clays, anhydrite, etc.
As seen in the previous chapters, the conditioning of spent resins for the back-end of management chain, viz. transport, storage and disposal has been an object of an intensive study as well. The consecutive barriers created by the conditioning together with the relative favourable radioactivity content (relatively low-level activity with relatively short-lived nuclides) of spent resins from NPPs, render it possible to approach the task of disposal in a flexible way. The spent resins, for example, can be safely and easily stored in engineered storage facilities, even during longer periods of time, viz. 100-200 years.

LARGE QUANTITY SHIPPING CASK FOR SHIPMENT OF HIGHLY ACTIVE RESINS—USA

FIGURE 3
TYPICAL SHIPPING CASK, TRAILER AND REACTOR CONFIGURATION (USA)

FIGURE 4
6. CONCLUSIONS AND RECOMMENDATIONS OF THE TECHNICAL COMMITTEE

A number of different techniques reviewed in this report are successfully applied to the treatment and conditioning of spent ion-exchange resins from nuclear power plants. However, there is still a need for technical improvements in many respects.

The incorporation of spent organic resins into cement and bitumen, the immobilisation media mostly used, can still be somewhat problematic and should be performed with particular care. A clear improvement for the situation might be achieved by applying advanced immobilisation methods which use, for example, organic polymer as solidification agent. Further possibilities would be in the combustion of organic resins by incineration or acid digestion. Up to now, the experiences from both of those techniques are somewhat restricted.

There is also a need for criteria set to the relevant properties of conditioned waste. Those criteria would be necessary for the harmonisation of the different waste management steps viz. conditioning in relation to storage and disposal. The existence of that kind of criteria would demonstrate the maturity of waste management technology as a whole.

The different aspects related to the treatment and conditioning of spent resins were thoroughly discussed in the Technical Committee Meeting in 13–17 December, 1976. The summary of discussion is given below.

- It is not possible to remove radionuclides from ion-exchange resins so completely that they can be disposed of as inactive waste. It is also questionable if it is appropriate to transfer radionuclides from the resins, where they are fixed relatively well, into a soluble intermediate state. Since a complete elution is not possible, the total waste volume is even increased, because the regenerating solution arises in addition to the still active exchangers.

- Regeneration of ion-exchange resins and subsequent solidification of the regenerating solutions can possibly cause a higher radiation dose to the operating personnel than solidification of the resins.
- It appears that no necessity exists to regenerate ion-exchangers at NPP with the sole aim of reducing the amount of waste. The amount of solidified regenerating solutions will be comparable with the amount of solidified resins. The decision for regeneration must be based on economical considerations.

- In principle, the general efforts should be to keep the volume of radioactive residues as small as possible. Taking into account relatively small volumes of spent ion-exchange resins arising at NPP, an urgent necessity for volume reduction of ion-exchangers by "decomposition" methods at NPP does not exist (with the possible exception of Powdex resins).

- As far as high- and low-level active ion-exchange resins are treated or stored separately, the volume of the high-activity exchangers can be reduced to one-half by separating the anion and cation exchangers (by stirring up), since generally only the cation exchangers have a higher activity level.

- A general recommendation to incorporate all spent ion-exchange resins into a matrix material could not be given. It depends largely on whether or not an additional barrier against release of radionuclides is provided at the final storage.

- The development of new methods for treatment of spent ion-exchange resins could be advantageous; however, an urgent need for this does not exist.

- The knowledge about the behaviour of spent ion-exchangers and of the final products made from them is not yet sufficient. This is especially true for the long-term behaviour. The methods of investigation should be improved and standardised.
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