ALTERNATIVE NUCLEAR WASTE SOLIDIFICATION PROCESSES

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INTRODUCTION

The increasing emphasis upon environmental considerations as they relate to nuclear power plants has focused additional attention upon the disposal of radioactive waste material generated in the operation of a nuclear station. These wastes include liquid process wastes and drains, evaporator concentrates, spent ion exchange resins, filter precoat and cake materials, and cartridge filter units. Additional contaminated waste materials generated in plant operation such as tools, rags, clothing, and equipment components are not considered in this paper since they are normally disposed of by compaction in suitable containers for direct burial. Radioactive gaseous wastes generated in the plant are subject to different treatment processes and also are excluded from the scope of this discussion.

The early nuclear plants generally disposed of a portion of the liquid wastes by dilution of the waste liquid stream in the plant's condenser coolant effluent stream. In some cases the waste evaporator concentrates were solidified. (1,2).[1] These discharges were generally a small fraction of the 10CFR20 limits for the release of radioactive materials to the environment and met the then current licensing requirements. Solid waste materials were generally disposed of either in the dewatered form or by solidification in a 55-gal DOT drum with Portland cement.

With the adoption by the Atomic Energy Commission of the "as low as practicable" requirement for the release of radioactive materials from nuclear power plants, the direct disposal of liquid radioactive wastes from the plant is no longer considered to be acceptable. (3)

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[1] Numbers in parentheses designate References at end of paper.

Experience in some of the already operational nuclear power plants has shown that these plants generate considerably more waste materials than had initially been expected in the design of the plants. As a result of these considerations and increasingly severe restrictions placed upon the disposal of wastes at the commercial burial sites, considerable interest has been developed in the last several years in various systems which have been proposed or are being utilized for the solidification of liquid and solid radioactive wastes from nuclear power plants for offsite transportation to disposal sites. Currently, all of the systems which are in use in the United States for this purpose utilize either Portland cement or an organic polymer, urea formaldehyde, as the basic solidification material. It is the purpose of this paper to review the use of these alternative materials as they are affected by the characteristics of the waste materials to be solidified and their effect upon the ultimate cost of disposal of the solidified wastes. This paper will also review some of the features of the equipment used in the waste solidification process and discuss several of the current problems facing this portion of the nuclear industry.

The radioactive wastes generated in a nuclear power plant will vary significantly in composition, levels of radioactivity, and quantity in the different types of power reactors. The type of primary or secondary coolant cleanup system which is selected for a typical plant will also have a significant impact upon the wastes generated by the plant. Table 1 provides a tabulation of typical waste streams for pressurized water reactors and boiling water reactors. The data provided in Table 1 represent a composite summary of the waste streams specified for a number of different reactor plants and are not necessarily indicative of the actual or expected waste streams for a particular plant. The actual waste quantities generated in a particular plant will also vary substantially with the amount of condenser and steam generator leakage experienced in that plant.

TABLE 1 - TYPICAL YEARLY VOLUMES OF RADIOACTIVE WASTE MATERIALS FOR VARIOUS TYPES OF NUCLEAR POWER PLANTS (1)

WASTE MATERIAL	PWR-HIGH ANNUAL VOLUME OF WASTES	PWR-LOW ANNUAL VOLUME OF WASTES	BWR POWDEX CONDENSATE SYSTEM	BWR DEEP BED RESIN SYSTEM
	cuft	cuft	cuft	cuft
Deep Bed Demineralizer Resins 50% moisture, 45#/ft^3 bulk density	416	250	704	1,951
Powdered Demineralizer Resins (2) 50% moisture, 42#/ft^3 bulk density	---	---	4,602	2,817
Diatomaceous Earth 60% moisture, 27-32#/ft^3 bulk density	---	---	1,244	847
Concentrated Liquids, 10% borates, pH 9, 64.9#/ft^3	8,400	1,500	---	
Concentrated Liquids, 25% sodium sulfates, 75.5#/ft^3	36,500	---	2,385	15,000
TOTAL	45,316	1,750	8,935	20,615

(1) Values are typical for 1000-1200 MWe plants and do not necessarily apply to a specific plant.

(2) Resin sludges are mixture of resin and filter precoat material.

The two most commonly utilized solidification materials, urea formaldehyde and Portland cement, have substantial differences as to the type of waste they can effectively solidify. In order to overcome some of the deficiencies encountered with the use of Portland cement, a process has been developed which utilizes sodium silicate as an additive, which substantially improves the flexibility of a Portland cement solidification system. A summary of the results of an extensive laboratory program performed by United Nuclear Industries which studied the solidification properties of a number of materials is presented in Table 2. A review of these data indicates that no one solidification material provides a fully satisfactory solution for the solidification of all types of wastes.

TABLE 2 - COMPARISON OF SOLIDIFICATION PROPERTIES OF VARIOUS WASTE SOLIDIFICATION MATERIALS

PROPERTY	UREA FORMALDEHYDE	PORTLAND CEMENT PLUS SODIUM SILICATE	PORTLAND CEMENT
Shipping efficiency	High	Highest	Low
Tolerance for variations in proportion of liquid waste	Good	Good	Poor
Fluid mixes	Excellent	Excellent	Poor
Residual water	Occasionally	Never	Occasionally
Tolerance for chemical composition of waste:			
Boric acid wastes	Good	Good	Poor
Basic wastes	Reduced shipping efficiency	Best	Good
Regenerant wastes	Good with quality control on UF or additive	Best	Good
Decon and laundry wastes	Problems	Problems	Problems
Physical Properties	Good	Best	Variable
Shelf life	Good below 85F Poor above 85F	Excellent	Excellent

WASTE SOLIDIFICATION SYSTEMS PROCESS DESCRIPTION

The waste solidification systems supplied for many of the early PWR and BWR types of reactors used Portland cement as the solidifying agent with vermiculite added in some cases as a liquid absorbant with mixing of the dry or liquid wastes with Portland cement accomplished either by a drum roller or an in-drum agitator mixing system. This type of mixing system, illustrated in Figure 1, performed its mixing on a batch basis and had a limited throughput capability. The resultant solidified mixture produced was less than a full waste container due to void filling in the cement and dry waste material by the liquid waste.

Several Portland cement solidification systems have been developed by equipment suppliers which are of the in-line or continuous process type. These systems have the advantage of making full use of the available shipping volume of the waste container and provide a flexibility in the size of container selected for use. This basic type of system as illustrated in Figure 2 provides a number of advantages over the in-drum batch type mixing system in terms of volumes of cleanup wastes, processing efficiency, and throughput capability. However, its effectiveness in terms of packaging efficiency is limited by the inherent ratio of Portland cement to water required for solidification.

A competitive system has been developed and is supplied by several firms which provides several advantages over the in-line Portland cement system. This system, based on the use of urea formaldehyde as the solidifying agent, provides a higher packaging efficiency for most wastes that is achievable with a Portland cement system and avoids the problems which may be encountered with the in-plant use of a dry bulk material such as Portland cement by the use of liquid materials. The urea formaldehyde is reacted with a catalyst to produce a reasonably hard, free standing solidified mass. The solidifying material, urea formaldehyde, is available from a number of chemical suppliers under various trade names and, among

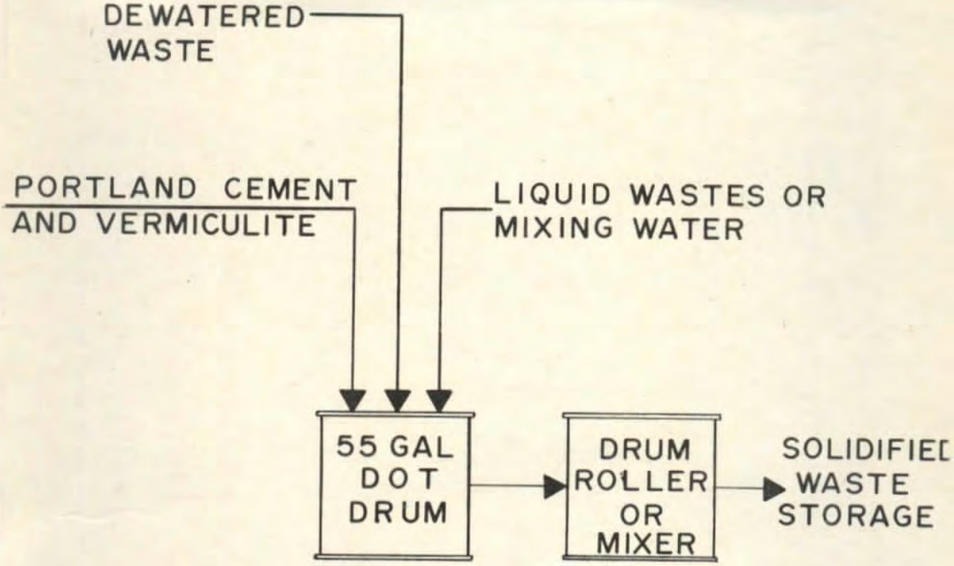

FIGURE I

PORTLAND CEMENT
DRUM MIXING SOLIDIFICATION SYSTEM

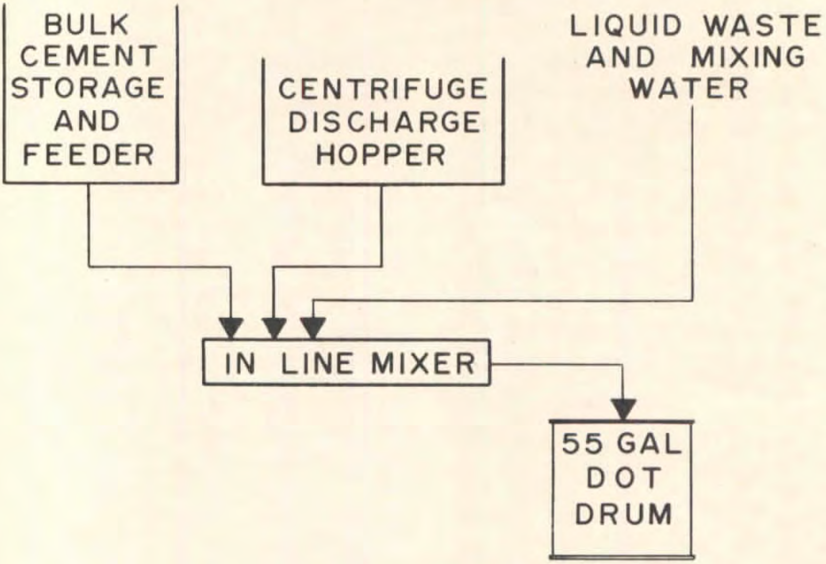

FIGURE 2

PORTLAND CEMENT
IN LINE MIXER SOLIDIFICATION SYSTEM

other uses, is commonly used for rock grout or sealant, plywood manufacture, and household glue. The catalyst used to achieve solidification is commonly a weak acid such as sodium bisulfate ($NaHSO_4$) or phosphoric acid (H_3PO_4) or dilute sulfuric acid (H_2SO_4). The selection of the catalyst material is dependent upon the pH of the waste stream to be solidified and the process requirements of the system. A system of this type is shown diagrammatically in Figure 3.

A study of the advantages and shortcomings of each of the systems described earlier has led to the development of an improved Portland cement solidification system which uses sodium silicate as an additive to the waste-Portland cement mixture. This system provides significantly improved waste packaging efficiencies over that available with Portland cement while at the same time taking advantage of the reduced solidification material costs provided by a Portland cement based system. A solidification system of this type is shown in Figure 4.

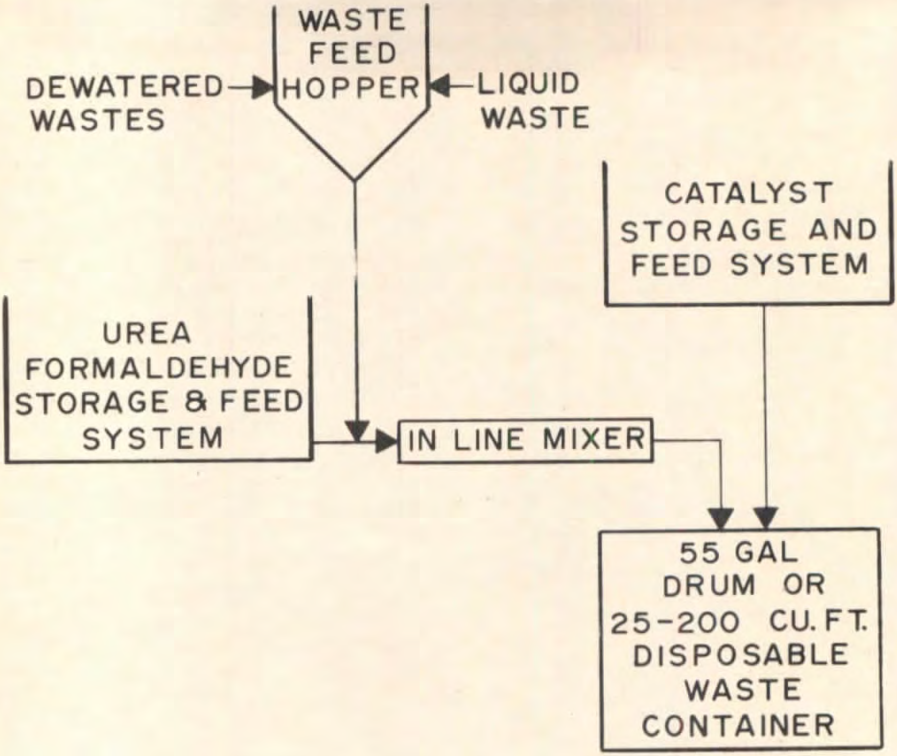

FIGURE 3

UREA-FORMALDEHYDE
WASTE SOLIDIFICATION SYSTEM

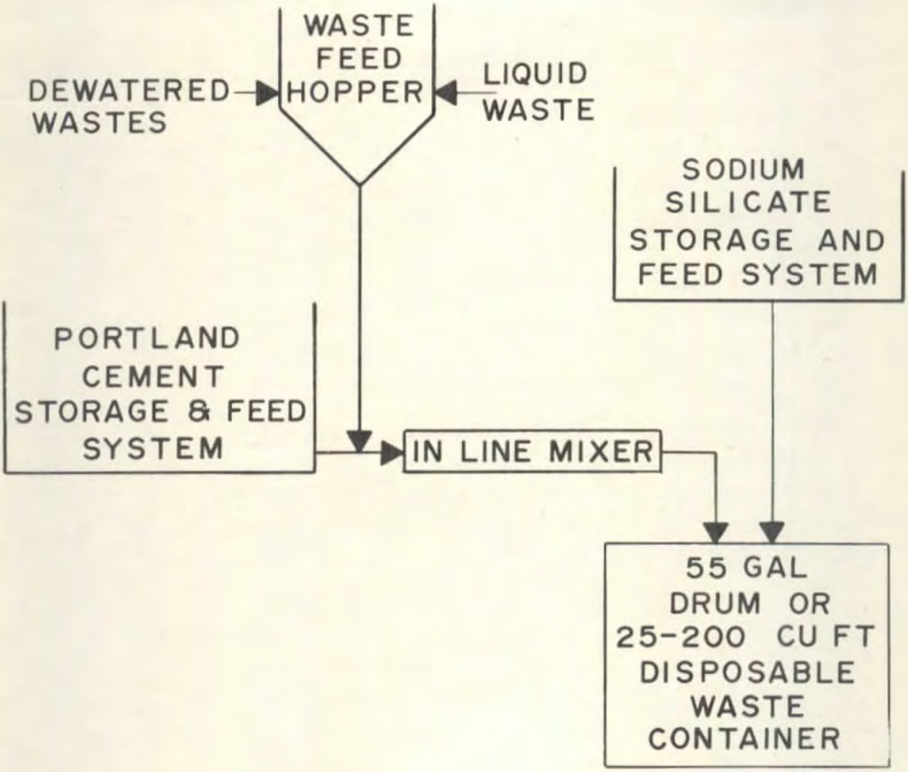

FIGURE 4

PORTLAND CEMENT
WASTE SOLIDIFICATION SYSTEM

PROCESS REQUIREMENTS

Currently, Department of Transportation and Atomic Energy Commission regulations only require that solidified waste materials be suitably packaged for transportation (4,5) and place no limitations upon the physical properties of the dry or solidified waste material. However, it is considered by many that some additional requirements regarding the properties of the packaged wastes may be developed in the future.

Waste material transportation and disposal costs are generally based on a volume basis with cost adders for increased weight and radioactivity levels. Generally the current practice is to package the maximum quantity of wastes in a given volume of solidified wastes so long as other packaging and handling requirements are met since activity levels are relatively low for the bulk of the wastes processed. Currently, many specifications for waste solidification systems require the production of a water free, reasonably hard, free standing solid. These requirements can be generally met by any of the solidification processes described earlier, with varying degrees of packaging efficiencies and effectiveness. The packaging efficiency of a particular process is defined as the bulk volume of radioactive waste which is contained in a unit volume of solidified waste, expressed as a percentage.

PROCESS CONSIDERATIONS

The reaction of urea formaldehyde leading to the production of a crosslinked gel and solidification proceeds only under acid conditions. Basic wastes may be mixed with acid wastes to produce a neutral or acid solution or sufficient catalyst is added to neutralize wastes. The reaction between the mono- and dimethylolureas leading to crosslinked gels releases water. Thus, as solidification proceeds, some water is released from the urea formaldehyde, the temperature and composition of the waste, and the specific proportions of waste and solidifying agents. In tests, where water which is slightly acidic has been released, the amount is small compared with the volume of the solid and can be readily absorbed by several available methods.

Each solidifying agent, Portland cement or urea formaldehyde, commonly used to solidify wastes from nuclear plants may react chemically with one or more of the waste products causing a retarding of the setting time or destroying the setting properties completely. For example, concentrated sodium borate or sodium chloride wastes destroy the setting properties of Portland cement. The addition of sodium silicate produces a good solid with Portland cement and concentrated sodium borate solutions. Concentrated sodium sulfate waste is an example of a waste that causes erratic setting of urea formaldehyde. Satisfactory solidification can be achieved by following recommended quality control procedures for the urea formaldehyde, by dilution to less than 10 percent sodium sulfate or by adding a small amount of calcium chloride. The calcium chloride addition provides a predictable, solid product with good shipping efficiency over a wider range of properties of the urea formaldehyde. Because of the almost infinite number of combinations of chemicals that may be present in the wastes, particularly in decontamination solutions or other miscellaneous plant wastes, it is impossible to predict with complete certainty the chemical reactions that may occur when mixed with a solidifying agent.

SHIPPING EFFICIENCIES

The shipping efficiency achievable with a given waste-solidifying agent formulation will have a significant impact upon the overall cost of disposing of the waste from a nuclear plant. A tabulation of achievable shipping efficiencies is shown in Table 3 for the three processes being discussed in this paper. The term shipping efficiency is used in this evaluation since it is a common measure of the quantity of waste actually contained in the packaged, solidified waste and permits a direct comparison between the various solidification processes. The shipping efficiency values tabulated in Table 3 are based upon waste solidification formulations developed for use in waste solidification systems supplied by UNI. These formulations were initially developed in a laboratory testing program and subsequently confirmed either by equipment operation or in pilot plant development programs. These efficiencies represent mix formulations which will repeatedly provide solidified waste samples having acceptable physical properties. Formulations which differ from these will produce a solidified waste product whose properties will differ from those utilized as a basis for this analysis. Thus, other evaluations of this subject may provide differing shipping efficiencies; however, the relative efficiency of the various processes will remain constant.

TABLE 3 - SOLIDIFICATION OF RADWASTES WITH PORTLAND CEMENT AND UREA FORMALDEHYDE

	SHIPPING EFFICIENCY		
WASTE	PORTLAND CEMENT + SOFIUM SILICATE	UREA FORMALDEHYDE	PORTLAND CEMENT w/o ADDITIVES(3)
Deed bed demineralizer resins, bulk density 45 #/cuft	95(1)	96	100
Powdered resins, bulk density 42 #/cuft	97(1)	93	84
Diatomaceous earth, bulk density, 27 #/cuft	130(1)	130	65
Concentrated liquids			
Borates, pH 7.5	68.7	70.8	52(2)
pH 9	68.7	64.7	52
Sulfates - 25% Na_2SO_4	75	60.4	52

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(1) Concentrated liquid waste may be added to primary waste to substantially improve packaging efficiency.

(2) Solidification will not occur without additives or dilution of waste concentrates, although free water will be absorbed.

(3) Based on in-line processing system efficiencies in container filling.

These data show that either the urea formaldehyde-phosphoric acid or Portland cement-sodium silicate provides substantially higher shipping efficiencies that the Portland cement system. Although either of the two preferred systems produce excellent shipping efficiencies, the Portland cement-sodium silicate system demonstrates a slight edge over the urea formaldehyde-phosphoric acid system. The Portland cement-sodium silicate system is definitely superior if concentrated sulfate wastes must be solidified. For plants with powered resins and precoat filters, considerable advantage is gained by adding concentrated liquid waste to the dewatered solid waste. Even more concentrated liquid waste could be disposed with the dewatered solids "almost for free" if a centrifugal discharge type filter and air drying are used to achieve greater dewatering of the solid wastes.

In Table 4, the annual quantities of waste generated and after solidification are tabulated for two types of PWR's. The Type A PWR with very high annual volumes of wastes is of recent vintage and the estimate of waste quantities appears to be based, in part, upon actual plant operating experience. The Type B PWR with low annual volume of wastes is typical of early specifications issued for solidification systems. If the new PWR designs are generating the high volume of wastes shown for the Type A plant, additional effort is clearly warranted to reduce waste volumes. These high quantities of waste volumes represent, in part, the addition of secondary coolant system condensate treatment systems which are being added as a result of the steam generator leakage experienced in some of the currently operating plants.

TABLE 4 - RADWASTE SOLIDIFICATION - PWR

	Type A, High Annual Volume of Waste				Type B, Low Annual Volume of Waste			
	Annual Volume - cuft				Annual Volume - cuft			
Waste	Not Solidified	PC + SS	UF	PC w/o Additives	Not Solidified	PC + SS	UF	PC w/o Additives
		SOLIDIFICATION				SOLIDIFICATION		
Deep bed demineralizer resins; moisture 50% bulk density 45 #/cuft	416	437	433	416	250	263	260	250
Concentrated liquids:								
10% borates	8,400	12,227	11,864	16,153*	1,500	2,183	2,118	2,885*
25% sodium sulfate	36,500	48,667	60,430	70,192				
TOTAL	45,316	61,331	72,727	86,761	1,750	2,446	2,378	3,135

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*Solidification will not occur without additives or dilution of waste concentrate, although free water will be absorbed.

NOTE: PC = Portland Cement SS = Sodium Silicate UF = Urea Formaldehyde

In Table 5, the annual quantities of waste generated and those after solidification are tabulated for a BWR reactor system.

The data in Tables 4 and 5 indicate that the quantities of waste material to be disposed of from a nuclear power station are relatively large. The disposal of the materials in a manner which will avoid a significant environmental impact will require considerable attention, both in the initial design of the plant and in its subsequent operation. It should be noted that these wastes are relatively low level - short half life wastes. They are not the highly radioactive - long lived wastes generated in the fuel reprocessing plants, which currently are the subject of considerable study and discussion.

ECONOMICS

The estimated costs of operating a nuclear power station waste disposal system are tabulated in Tables 6 and 7 for PWR and BWR types of reactor systems respectively. These costs include estimates of disposable containers, plant labor, solidification materials, and shipping and burial charges. These cost data show that the yearly operating cost of the Portland cement sodium silicate system are substantially lower than for the other types of systems. The cost of operating these systems may be surprisingly large to some who are not familiar with the systems; however, they are generally proportional to the waste volumes produced. The economics of a particular plant are necessarily dependent upon the waste composition and volume for the plant. Recent studies have shown that the cost of the waste containers will be substantially reduced if 55-gallon drums are used in preference to the larger 35-200 cuft disposable containers due to current large increases in the cost of fabricated large steel containers. The cost data in these tables are based upon the use of a 35 cuft disposable concrete container.

TABLE 5 - RADWASTE SOLIDIFICATION - BWR

	POWDEX CONDENSATE SYSTEM				DEEP BED RESIN SYSTEM			
	Annual Volume - cuft				Annual Volume - cuft			
Waste	Not Solidified	PC + SS	UF	PC w/o Additives	Not Solidified	PC + SS	UF	PC w/o Additives
		SOLIDIFICATION				SOLIDIFICATION		
Deep bed demineralizer resins Moisture 50% Bulk density, 45 #/cuft	704	741	733	704	1,951	2,053	2,032	1,951
Powdered demineralizer resins Moisture 50% Bulk density, 42 #/cuft	4,602	4,744	4,948	5,478	2,817	2,904	3,029	3,354
Diatomaceous earth Moisture 60% Bulk density, 27 #/cuft	1,244	957	957	1,914	847	652	652	1,303
Concentrated Liquid 25% sodium sulfate Density 75.5 #/cuft	2,385	3,180	3,949	4,587	15,000	20,000	24,834	28,846
TOTAL	8,935	9,622	10,587	12,683	20,615	25,609	30,547	35,454

TABLE 6 - ESTIMATE OF ANNUAL OPERATING COSTS FOR RADWASTE SOLIDIFICATION - PWR

	ESTIMATED COST - DOLLARS					
	TYPE A, HIGH WASTE VOLUME			TYPE B, LOW WASTE VOLUME		
	PC + SS	UF	*PC w/o Additives	PC + SS	UF	*PC w/o Additives
35 and 50 cuft disposable containers	$350.000	$424,000	$503,500	$ 14,000	$ 14,700	$ 19,300
Labor	39,500	48,000	56,500	1,600	1,700	2,200
Solidification materials	38,000	252,000	112,000	1,800	7,900	4,500
Shipping and burial	210,000	246,000	301,000	17,000	18,000	24,000
TOTAL	$637,500	$970,000	$973,000*	$34,400	$42,300	$50,000*

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*Includes borated wastes which cannot be fully solidified. by Portland cement system without additives or dilution.

Note:
PC = Portland cement
SS = Sodium silicate
UF = Urea formaldehyde

TABLE 7 - ESTIMATE OF ANNUAL OPERATING COST
RADWASTE SOLIDIFICATION - BWR

	PORTLAND CEMENT PLUS SODIUM SILICATE	UREA FORMALDEHYDE	PORTLAND CEMENT w/o ADDITIVES	PORTLAND CEMENT PLUS SODIUM SILICATE	UREA FORMALDEHYDE	PORTLAND CEMENT w/o ADDITIVES
Cost of containers	$ 55,000	$ 61,000	$ 72,500	$146,000	$175,400	$202,600
Labor	6,200	6,800	8,200	16,500	19,800	22,900
Solidification Materials	4,800	30,100	11,200	13,200	101,500	40,100
Shipping & burial	53,000	56,400	68,100	89,400	102,500	118,400
TOTAL	$119,000	$154,300	$150,000	$265,100	$399,200	$384,000

WASTE DISPOSAL REQUIREMENTS

The current NRC and DOT regulations regarding the shipment of radioactive waste materials place primary emphasis upon the packaging of the waste materials for shipment (4,5). Similar regulations have been developed by the International Atomic Energy Authority and are in common use overseas (6). These IAER regulations generally follow the same regulatory approach as that in the DOT regulations, with one significant exception. This exception is a requirement regarding the leachability of the solidified waste in water. Unfortunately, the IAEA regulations do not clearly specify a test procedure or method which is directly useable by different investigators to provide quantitative comparison of results.

A recent paper by Dr. J. H. Leonard of the University of Cincinnati reported the results of a series of leach tests upon samples of various solidified wastes (7). These results indicate that all waste solidification processes currently in use will have difficulty in complying with a stringent leachability test requirement. UNI has also performed a series of leach resistance tests, which provided results qualitatively similar to those obtained in Dr. Leonard's work. There is work under way by several investigators regarding the use of additives which would improve the leach resistance of the various solidified wastes. However, the need for the establishment of a standard test procedure for leach testing of waste materials is felt to be necessary if a regulatory requirement for this characteristic is to be established. A representative of the DOT recently stated that it was planned to adopt the IAEA regulations in the near future. If this occurs, the need for a standardized test procedure is imperative.

In this discussion, the emphasis has been upon the packaging and shipping regulations which are the responsibility of Federal agencies. Regulations regarding the actual disposal of the wastes are most generally the responsibility of the individual states which issue the permits or licenses for the burial sites.

PROCESS SYSTEM TRENDS

The high volume of wastes being generated in some of the nuclear power stations has created considerable interest in methods of reducing these waste quantities. One of the approaches being given serious attention in a number of plant designs is the use of wiped film or other types of waste evaporators which can reduce the liquid wastes to concentrations of 50 weight percent solids or greater in place of the more commonly used 25 percent concentration. Waste evaporators are available from several suppliers which can provide this degree of concentration. UNI has developed solidification systems which can successfully process and solidify these highly concentrated wastes. It is expected that increasing emphasis will be placed on the use of these high concentration units in the future, as well as drying of the liquid waste material to a dry solid.

Among the other approaches being utilized to reduce the volume of resin regeneration wastes and waste resins is the use of ultrasonic cleaning of waste particulate matter from ion exchange resin beds. This technique is expected to obtain increasing acceptance as additional operating experience with the equipment is obtained.

WASTE PROCESSING EQUIPMENT ARRANGEMENTS

Due to the large number of physical arrangements encountered in various nuclear power stations due to plant size, type, site conditions, etc., most waste solidification systems are custom designed to fit a particular installation. In most cases, the space required for the actual waste processing equipment is relatively small compared to storage space required for the processed wastes. Figure 5 illustrates one system arrangement which utilizes a remotely operated crane for the handling of the solidified waste containers. Due to the current emphasis which is placed upon minimizing the radiation exposure of plant personnel, it is necessary that all process equipment, as well as the handling of processed wastes, be performed remotely with relatively heavy shielding provided for the operating gallery.

A typical waste solidification system control panel which is utilized for process control of the system is shown in Figure 6.

The equipment utilized for the processing of these wastes is relatively small but comparatively complex due to the various engineering requirements for the system. Figure 7 illustrates a process waste mixing skid, and Figure 8 illustrates a chemical addition equipment skid which is normally located in a non-radioactive area.

FIGURE 5

RADWASTE SOLIDIFICATION SYSTEM

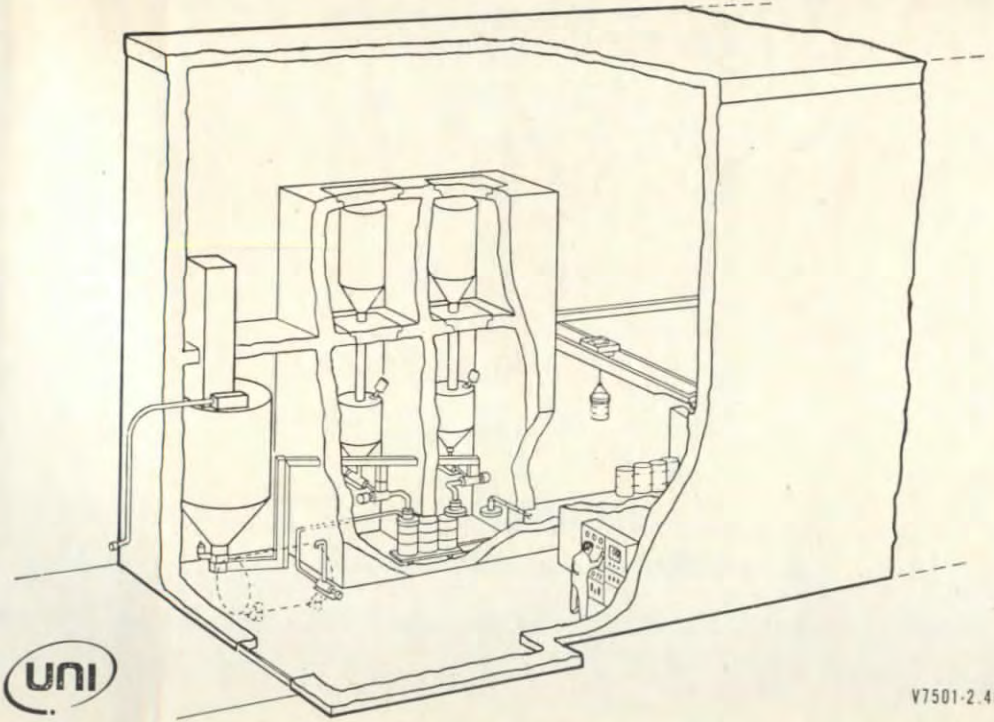

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Fig 6

WASTE SOLIDIFICATION SYSTEM CONTROL PANEL

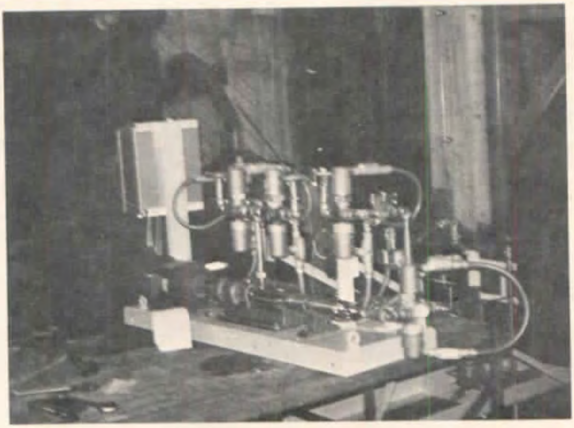


FIG 7

PROCESS WASTE MIXING SKID

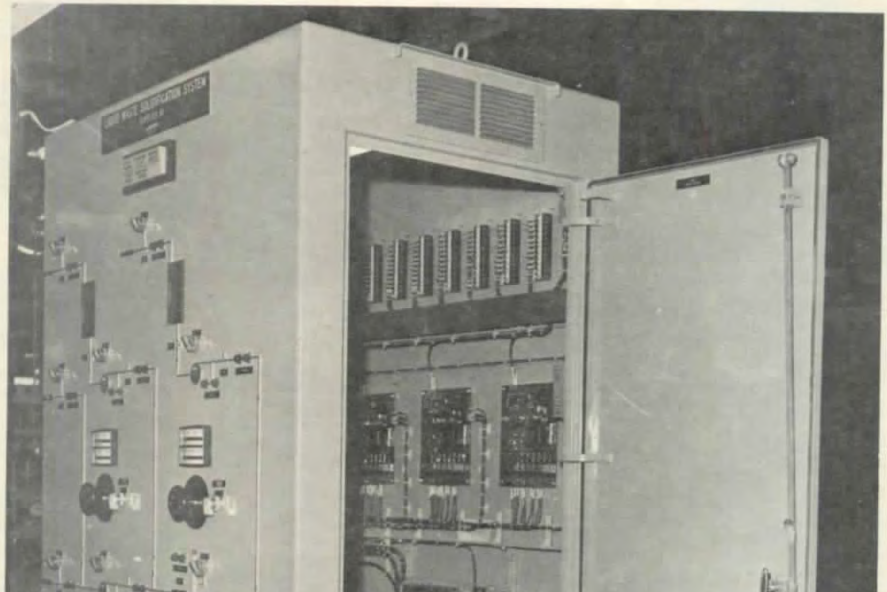
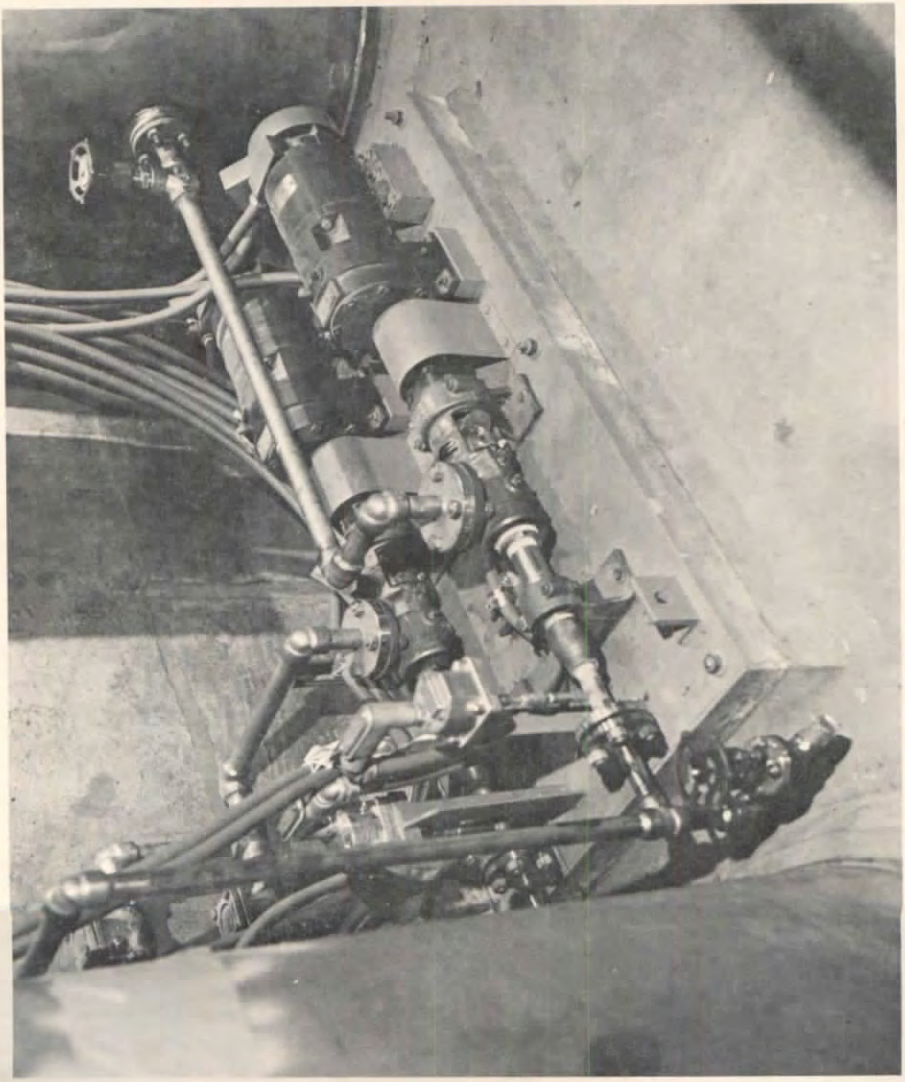


FIG 8

CHEMICAL ADDITION EQUIPMENT SKID



CONCLUSIONS

The treatment, handling and disposal of the nuclear power plant process wastes has become a substantially larger factor in the plants than had been originally anticipated. The process requirements, systems and regulatory requirements for these systems have been evolving rapidly and are receiving increasing emphasis in the later plant designs. Each of the solidification processes described has particular advantages in a given plant system and represents an evolving technology and improvements of the processes and equipment designs.

In the reactor systems where large quantities of wastes are anticipated to be generated, the cost of solidifying and disposing of the solidified wastes will become a significant plant operating cost and careful consideration needs to be given to the achievable packaging efficiency in the selection of a solidification system.

The types of wastes which will be present will also have a substantial impact upon the selection of the most advantageous processing system, together with consideration of system complexity and ease of operation and maintenance.

Careful attention must be given in the design of the waste solidification portion of the processing system to insure that adequate space is provided for material handling and storage as the quantities of wastes being generated in the plants substantially exceed the volumes contemplated in many of the early plant designs.

REFERENCES

1 Schwieger, R. G., "Controlling Radioactive Discharges from Water-Cooled Reactors," Power, August 1972.

2 Jason, R. H., and Ward, J. E., "Nuclear Waste Management Practices and Trends," Presented at the American Power Conference, April 21-23, 1970.

3 U. S. Atomic Energy Commission, "Final Environmental Statement Concerning Proposed Rulemaking Action: Numerical Guides for Design Objectives and Limiting Conditions for Operation to meet the Criterion 'As Low as Practicable' for Radioactive Material in Light-Water Cooled Nuclear Power Reactor Effluents," WASH-1258, Volume 1, July 1973.

4 Code of Federal Regulations, 10, Energy, Part 71, "Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions," January 1, 1974.

5 Code of Federal Regulations, 49, Transportation, Part 173.393, "General Packaging Requirements," October 1, 1973.

6 International Atomic Energy Agency, Vienna, "Regulations for the Safe Transport of Radioactive Materials," IAEA Safety Standards, Safety Series No. 6, 1973 Revised Edition.

7 Leonard, J. H., and Gablin, K. A., "Leachability Evaluation of Radwaste Solidified with Various Agents, Presented at ASME Winter Annual Meeting, November 17-22, 1974.