A CRITICAL REVIEW OF MATERIALS SELECTED FOR HIGH INTEGRITY CONTAINERS

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ABSTRACT

Under consideration is the selection of materials for the manufacture of High Integrity Containers (HICs). A study has been conducted in this regard, including review of material properties and structural analyses. As a result of this study, conclusions were reached recommending against the manufacture and use of either all plastics or all metal HICs. HICs manufactured entirely from plastic have demonstrated structural limitations. Metal HICs are subject to corrosion and are not expected to satisfy containment requirements. As an alternative design a HIC is recommended which uses both materials, plastic for containment and metal for structure.

INTRODUCTION

A recognized method for disposing of low level nuclear waste is to place these materials in special containers and then bury the containers underground at an approved disposal site. These containers are known as high integrity containers (HICs). This paper addresses the selection of materials used in the manufacture of HICs.

There are a number of government regulations concerning HICs. These regulations control, within certain limits, what waste material can be placed into a HIC and how burial is to be managed. Federal regulations are compiled in 10CFR61 "Licensing Requirements for Land Disposal of Radioactive Waste"[1] and a supplementary publication, the U.S. Nuclear Regulatory Commission "Technical Position on Waste Form"[2]. There are also additional regulations promulgated by each of the states where burial sites are located[3,4]. Together the regulations set performance criteria for shipping, handling and burial. Material selection for fabrication of a HIC is left to the discretion of the design engineer, as long as compliance with regulations can be demonstrated.

The primary concern of this paper is the selection of a HIC material to survive burial underground. To be acceptable for burial, a HIC must have a demonstrated structural integrity and containment integrity sufficient for a 300 year life once it is buried. Manufacturers of HICs are required to establish performance criteria concerning structure and waste containment consistent with government regulations. The objective is to ensure that containers provide safe and secure disposal of nuclear waste products. Manufacturers and users of HICs must identify and account for all reasonably foreseeable waste forms and chemistries in the burial environment. This requires that careful attention be given to both the structural and environmental conditions at the burial sites.

Over the last three years the design requirements of HICs have been studied. In particular, this study has involved the selection of candidate materials from which HICs can be manufactured. Material properties and structural requirements have been reviewed. Effort has also gone into characterizing the nature of the waste products in terms of chemistry and form. As a result, it has become apparent that many factors which affect both structural integrity and containment integrity have not previously been fully and properly considered.

It is time to look more objectively at the issue of what constitutes good HIC design. From the onset, this has been the purpose of the study which underlies this paper. This paper includes a review of various factors, such as waste characterization and structural modeling, which significantly influence HIC design and material selection.

WASTE CHARACTERIZATION

Waste materials which are buried in HICs consist primarily of ion exchange resins and filter media. In addition, small amounts of free water (up to 1% of container volume) and small amounts of miscellaneous contaminants may be present with the waste.

Ion exchange resins used in nuclear power stations may be either bead-type or powdered resins, typically styrene divinyl benzene based resins. Bead or gel type resins are produced in small spheres approximately 0.5 mm in diameter (20-40 mesh) and contain approximately 50% water. Powdered resins are produced by grinding bead resins into fine particles typically 35-45 microns in size, which contain approximately 60% water by weight. This contained water may form "free" or pourable water if the resin structure breaks down.

The resin types used in power plants are nearly all strong-acid cation and strong-base anion or mixtures of these resins. In general, larger quantities of cation than anion resins are used due to ion exchange system design, resin capacity and applications typical of power stations. When placed into service, cation resins are typically in the hydrogen ion form while anion resins are typically in the hydroxide form.

In processing the wastes, the resins are converted to the ionic forms removed from the wastes. Although resins may be removed from service based on activity or radiation levels, radionuclides consume an insignificant portion of the resin capacity. As a result, resins are exhausted by *normal water constituents* such as sodium, magnesium, calcium, chlorides, sulfates and carbonates. These constituents may be found in the circulating or service water which provides the heat sink for the power cycle. The water leaks into the plant, is collected in a controlled drain system and consequently is processed as "radioactive" waste. It is not unusual, for example, to process wastes with high concentrations of sodium chloride at plants located on the seacoast. These ionic materials will be removed by the resins, then the resins are eventually placed into HICs and buried.

When the resins are removed from service, it is unlikely that all of the capacity has been exhausted. Unexhausted cation resin in the hydrogen form, for example, will produce low pH, acidic conditions while unexhausted anion will form high pH, alkaline conditions. For stainless steels, a highly corrosive environment will result when unexhausted cation resins in the hydrogen form are placed into a HIC with anion resin exhausted to the chloride form. Introduction of water to the resin during transfer to the HIC will form a dilute hydrochloric acid solution.

Irradiation of the resin results in resin breakdown by the release of functional groups and by changes in cross-linking[5,6]. The side affects of this process are identified as release of free liquid, reduction in pH and gas generation. As an example of this behavior, irradiation of hydrogen form cation resins to 7x10^7 rads resulted in pH values as low as 1.5 when 2.0 grams of this resin were placed in 10mm of water[7]. In general, research has shown that the range of radiation induced chemical by-products is varied and includes many products which would be aggressive in a container environment.

Characterization of the conditions inside a HIC is further complicated by biodegradation. Bacteria growth on the resins used in radioactive waste treatment is well documented but the effect of biodegradation products on HIC materials is unclear.

In summary, the conditions inside of the HIC cannot be precisely defined. Conditions vary depending upon density of the waste water processed, the type or mixture of resins, radioactivity loading on the resins, the amount of water available in the container and the presence of biodegradation. Selection of the HIC materials must consider all of these factors in order to meet the objectives of HIC design.

DESCRIPTION OF HICS IN USE TODAY

HICs in general use today are fabricated of either polyethylene or ferralium stainless steel. These containers range in size from 208 liter (55 gallon drum size) containers up to relatively large containers, 2 meters tall by 2 meters in diameter. A representative range of container sizes and capacities is shown in Fig. 1.

The polyethylene containers are rotationally molded with wall thickness ranging from 11 mm to 19 mm. The smaller containers are typically provided with flat tops while the large HICs have elliptical heads and flat or conical bottoms. No other provisions to support the container under burial are provided other than the polyethylene material itself.

A stainless steel container is now being manufactured using a specialty grade duplex material and employing conventional fabrication and welding methods[8]. The wall thickness is 6.4 mm. Information concerning thickness of the top and bottom is not available. There is no lining inside the container to protect against corrosive attack from the waste product within.

STRUCTURAL MODELING FOR UNDERGROUND BURIAL

Once radioactive waste product is placed in a HIC, the HIC now assumes the primary function of separating the waste from the surrounding environment. The ability of a HIC to perform this function is referred to herein as its "containment integrity". The HIC design should be such that containment integrity is insured during shipping, handling and burial.

Eventually the HIC is buried. When this occurs, it is now required to function as a structure, supporting soil. The ability of the HIC to perform this function is referred to herein as its "structural integrity". The properties of structural integrity and containment integrity are related. As a structure, a HIC is subject to failure by a variety of mechanisms which may cause cracking, rupture or damage resulting in a breach of containment. The importance of the structural function of the container must therefore be recognized in its fullest extent.

In this investigation, a HIC has been treated as a "buried structure". That is, an overburden of soil acts to create loads and pressures on the container. The container, in turn must be able to resist these loads and, in so doing, meet certain structural performance criteria[9,10]. There are, however, certain considerations in the design of a buried structure which are different from structures in general. The design should consider not only performance of the container-structure but also the behavior of the soil around the container. The interaction is known as soil-structure interaction.

Two models of burial conditions are defined. Each of these burial conditions are described in the following sections. In addition, comment is also made concerning burial technique at a disposal site as it relates to soil compaction.

Cluster Burial

A sketch depicting cluster burial is shown in Fig. 2. The model assumes that multiple containers are placed at the bottom of an excavated site at some repeated inter-container spacing, d. The distance d is such that a masonry arch develops over the soil located between containers. As a result, the container sees a vertical load due not only to a cylindrical column of soil over the container but also shares a portion of the soil load over the masonry arches which develop between itself and its neighbors. This model results in a vertical pressure on the container greater than otherwise developed by a cylindrical column of soil directly over the container. However, lateral pressure on the walls of the container would be non-existent. The following expressions for vertical and horizontal pressure would apply:

$$\begin{aligned} p_v &= C_o \lambda h \\ p_h &= 0 \end{aligned} \qquad (1)$$

where: p_v = vertical pressure on the container
p_h = lateral (horizontal) pressure on the container
λ = soil density
h = height of soil overburden
C_o = factor greater than 1.0 which accounts for increase loading due to development of masonry arches between containers

$$C_o = A_o/A_c$$

where: A_c =cross-sectional area of container
A_o =cross-sectional area of slug of soil supported by container

The exact intercontainer spacing d is outside the control of the designer. Ideally, the spacing would be minimized. However, soil conditions can develop a masonry arch between containers should less efficient arrangements be employed.

Isolated Burial

It is conceivable that conditions at the disposal site may result in the isolated disposal of a single container. Further, this model is considered herein to offer interpretation of the local conditions on a container at the periphery of a cluster burial arrangement.

Analysis has been conducted which compares the compressibility of a single isolated vertical container with the compressibility of the surrounding soil. The results indicate that, upon initial burial, a masonry arch does not develop over the container. Therefore the container must carry the burden of soil overhead. For this load condition, the expressions for vertical and lateral pressures are written as follows:

$$p_v = \lambda h$$
$$p_h = K \lambda (h + \ell/2) \qquad (2)$$

where: λ =soil density
h =height of soil overburden
ℓ =height of container
K =factor relating lateral pressure to vertical pressure and to a given overburden height (in this case a height equal to $(h + \ell/2)$ which gives an average lateria pressure on the container); K would be 0.5 for soils that have not been preloaded or preconsolidated[11] (uncompacted, as in the case at a disposal site).

Soil Condition Upon Burial

Disposal techniques are such that burial of HICs takes place without compaction. Under such circumstances, an engineering definition of soil condition upon disposal is difficult at best. Various design parameters upon which an analysis of loading due to soil-structure interaction is based cannot, therefore, be evaluated accurately. The reliability of the analysis is terefore decreased. Under such circumstances greater margins of safety are required than would otherwise be the case.

POLYETHYLENE HICs -- PROBLEMS

Polyethylene is a thermoplastic material commonly used in the shipping and storage of many chemicals. It is also inexpensive. Based on these criteria alone, PE is a candidate for a HIC material. However, the structural properties of unreinforced plastics, specifically polyethylene, are simply insufficient to handle the high external loads associated with burial. There is no assurance that survival to 300 years can be obtained unless structural features are added which make the container undesirably expensive and complex relative to other alternatives.

A major part of the study involved an attempt to design and justify an all plastic cylindrical container. This design was expected from the start to be similar to other plastic HICs in service. As a basis for design, a container having the dimensions 198 cm tall by 188 cm in diameter was selected. The attempt to design such a container proved unsuccessful. Plastic HICs, it was found, proved to have insurmountable structural limitations. The primary factors controlling design include environmental stress cracking, stress rupture and buckling of the container wall.

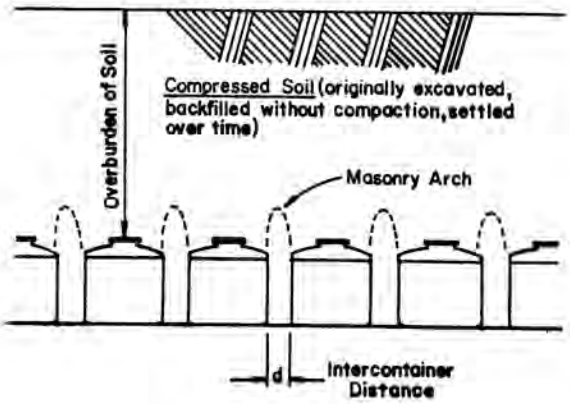

Fig. 2. Cluster Burial of High Integrity Containers.

Environmental Stress Cracking (ESC)

Although a variety of materials may be placed in a HIC, the predominant waste product is spent ion exchange resin. This material is wet when it is removed from service. Even though the resin is dewatered prior to placement in the HIC, the product is not totally dry. The bottom of the container is expected to collect what moisture is available due to (a) eventual settling out of residual moisture left behind in the resin after dewatering and (b) irradiation induced breakdown of the resin. The make-up of this liquid can be expected to contain ESC promoters such as surfactants. Further, the container is placed on an earthen base formed by simply scraping the bottom of the burial trench. Once buried, the bottom of the container will embed into the earthen trench thereby creating tensile stresses in the container bottom. Conditions for ESC are now in place due to the combination of tensile stress and the expected presence of harmful chemicals[12,13]. Exact predictions are not possible. In engineering design situations, a lack of information concerning an expected failure mechanism naturally biases judgment to the side of caution. A recommendation would therefore be made against such a design.

Stress Rupture

Plastics are viscoelastic materials and are subject to the time dependent effects of stress and deformation[13]. This factor must be considered as part of the design. Once placed in the ground and buried, the sidewalls of the container, the lid and the bottom are now stressed due to soil-structure interaction as described earlier in this paper.

Due to pressures developed by the surrounding soil the container lid and bottom are now deformed. At the depths HICs are buried, the soil loads and pressures are tremendous considering the relative strength and stiffness of polyethylene.

The best properties among polyethylene materials are obtained using high density polyethylene.

Regardless of density, the material is classified as viscoelastic. For such materials, when subject to a state of stress over a long period of time, the appropriate design criterion is stress rupture. Figure 3 shows stress rupture curves in generalized form. The term "rupture" implies just what it says, a tearing apart of material -- a structural failure. The stress rupture curve provides information to the design engineer concerning threshold levels of stress corresponding to structural failure as a function of time in service. Referencing Fig. 3, Curve B represents a material which exhibits a change in failure mechanism during its lifetime. The result of such a behavior is a lowered threshold stress level for failure at prolonged lifetime. Curve A represents a material which does not manifest this behavior.

For most viscoelastic materials, including polyethylene, stress rupture data is in limited supply. A required design life of 300 years further aggravates this problem. For example, it cannot be known whether the material will behave in a manner exhibited by Curve B. Recognizing that the container itself is irradiated during service, a real possibility exist that a behavior change could occur.

In the absence of limited data or no data at all, the development of a stress rupture curve or the extrapolation of existing data to longer service life, is an exercise in engineering judgement. The approach employed here involved bringing together what is known about the static properties of the material, available data for creep and stress rupture of polyethylene, stress rupture behavior for other viscoelastic plastics and knowledge of viscoelastic materials in general.

From a standpoint of failure by stress rupture, locations on the HICs subject to tensile stress would be the lid, the bottom, and locations of secondary stresses where the lid and bottom join to the container sidewall. The unrealistic nature of such a design becomes apparent when the stresses resulting from soil loads on the lid and bottom are compared with the allowable stress. Flat lids and bottoms up to 25 mm thick proved to be unsatisfactory. Various dome shaped lids were also examined and proved unsatisfactory.

Buckling

A HIC designed as a cylindrical shell and placed upright in a burial site experience pressure from the surrounding soil on the top and the bottom. For the case of an isolated container there exists horizontal pressure on the sides of the HIC as well. Under this condition of loading, the HIC is modeled as an externally pressurized cylinder. The sidewalls are subject to buckling.

Procedures for anlyzing sidewall buckling of externally pressurized cylinders are readily available[14]. The procedures involve specifying wall thickness and then calculating the soil overburden required to buckle the container. The relationships between soil overburden, p_h and p_v are established using Eqs. (1) for the case of cluster burial, and Eqs. (2) for the case of isolated burial.

Figures 4 and 5 represent, in part, the results of this analysis for isolated burial and cluster burial respectively. A controlling factor in resistance to buckling is not only the thickness of the sidewall but also the elastic properties (elastic modulus) of the material of construction. Figures 4 and 5 are plots of the sidewall thickness required to resist buckling as a function of soil overburden and elastic modulus of the HIC material. In both figures Curve A corresponds to a HIC made of high density polyethylene (elastic modulus = $7x10^2$ mPa). Curve B corresponds to a container made of stainless steel (elastic modulus = $2x10^5$ mPa). The difference in wall thickness required to resist buckling is very much a function of the material from which the HIC is made. This feature is strikingly evident in Figs. 4 and 5. It is also evident from these figures that the critical condition for buckling of the sidewall is the case of isolated burial, Fig. 4.

A word on factor of safety is appropriate at this point. Experimental results from tests on thin walled cylinders have shown that theretical analyses overstate the actual loads at which failure occurs. Failure is expected at loads 40-60% of what is predicted. Furthermore, there are differences between laboratory test results and conditions as they exist at the burial site. It has already been noted that the loads on the bottom of a HIC would not be expected to be uniform. Also, the backfill surrounding the HIC is not carefully compacted into place. Variations in burial conditions indicate a need to apply factors of safety in the range of 4.0 to 5.0 applied to theoretically calculated loading. It is evident that the required wall thickness of an unreinforced plastic container would be unacceptably high.

STAINLESS STEEL HICS -- PROBLEMS

As a result of a study of plastic materials, in particular polyethylene, the conclusion has been reached that an unreinforced all plastic HIC would not provide in all cases the required structural integrity necessary for burial. Various other possible materials were examined with an emphasis on metals. Fabrication of metal storage containers is established technology. Metals, of course, do not suffer from the structural problems of low strength and low stiffness exhibited by plastics. A conventional fabricated metal vessel of relatively thin wall would resist even the soil pressures developed upon burial in 16.8 meter trenches at the Richland site.

For reasons of economy and practicality, candidate metals were restricted to stainless steels. Other metals noted for corrosion resistance, such as titanium alloys and the noble metals were rejected outright on the basis of cost. Conventional structural steels were rejected due to an expected lack of corrosion resistance in the burial environment.

Considerations of Corrosion from Within

The most important consideration in using metals for fabrication of a HIC is corrosion. Corrosion may occur from outside the container due to the surrounding soil environment. However, the more severe corrosive environment exists inside the container. Corrosion of an all metal container from within is a serious problem.

Waste form was discussed earlier in this paper. For waste placed in a HIC, regulations limit total irradiation prior to disposal. These same regulations, however, place virtually no controls on the chemistry of the contents. A typical waste product is ion exchange resin, usually a mixture of cation and anion resins. The pH is often neutral and the quantity of potentially harmful chemicals often small. Unfortunately, there can be no assurance that this description of waste product is always going to apply. The range of waste product chemistry may never be known. However, as already described, it is probable and therefore foreseeable that waste product placed in a HIC can have a low pH and can have chemical contents, such as chlorine, at levels considered harmful to stainless steel, regardless of the grade of stainless steel involved. It is also probable that contents placed in a HIC will be more corrosive than surrounding soils. The difference in corrosiveness may be several orders of magnitude.

Stainless steel HICs in use as of this writing have been evaluated for corrosion in soils. However, the available literature does not address corrosion from within. Recognizing the increased potential from corrosion due to the container contents, attempts to qualify an all metal stainless steel HIC as offering containment integrity over a life of 300 years cannot be justified.

Consideration of Corrosion from Without

Regarding the corrosion behavior of stainless steel and soils reference is made to two studies conducted by the National Bureau of Standards[15,16]. The earlier of these two references concern data and conclusions available as a result of field tests conducted by NBS from 1910 to 1955. Many different materials were tested including nine different stainless steel exposed to different soils for 14 years. The later of the two references specifically concerned stainless steels. A greater variety of stainless steel grades and a variety of specimen treatment conditions were involved. Results of exposures up to eight years are reported. Together, these two reports are the best information available for assessing the corrosion behavior in soils of a stainless steel HIC.

For purpose of comparison, Table I has been prepared which lists the characteristics of test soils in the most recent of NBS studies. The table also includes corresponding characteristics of the backfill sands at both the Barnwell and Richland burial sites. An examination of the information in these tables reveals that the pH of backfill sand is within the range of pH of the test soils. Particular attention is given to Table I where it is seen that the chloride content of the backfill sands are noticeably less than the NBS test soils, in particular soil types C, E and G. Examination of the NBS results indicates that the aggressiveness of the soil is independent of pH in the range reported, but is distinctly related to the chloride concentration. In this sense, the soils at both burial locations are considered to have a very low potential as corrosive environments.

The following observations are based upon a consideration of all of the reported data in both NBS studies:

(a) Corrosion is not dependent on soil pH in the pH range observed.

(b) Corrosion is highly dependent upon the presence of chlorides and sulphates in the soil. On this basis, existing site backfill sands, regardless of the grade of stainless steel involved, would not be considered aggressive environments.

(c) There are a variety of grades of stainless steels for which very little corrosion would be expected in a backfill sand environment.

(d) Sensitization detracts from corrosion resistance[17]. In the NBS study, sensitization was produced by specially heat treating the steels to produce a sensitizied microstructure. Ordinary fabrication of containers from these metals results in sensitization due to a condition of inherent heat treatment in the heat affected zone surrounding a weld. For comparison, the NBS study tested welded samples as well as sensitized samples. In such cases, the corrosion behavior was similar.

(e) Manufacture of a HIC from stainless steel would necessarily involve welding. Today, grades of stainless steel are available through alloying which are routinely welded without sensitization.

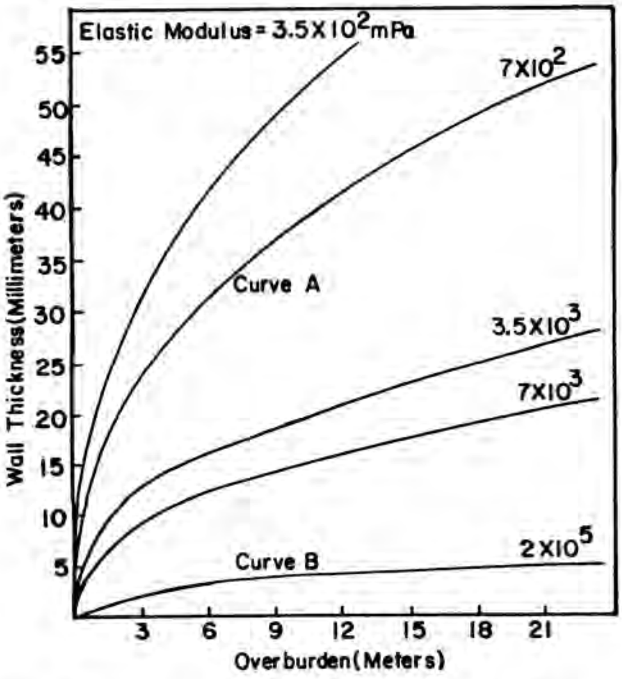

Fig. 4. Wall Thickness Required to Resist Buckling for a Container in Isolated Burial.

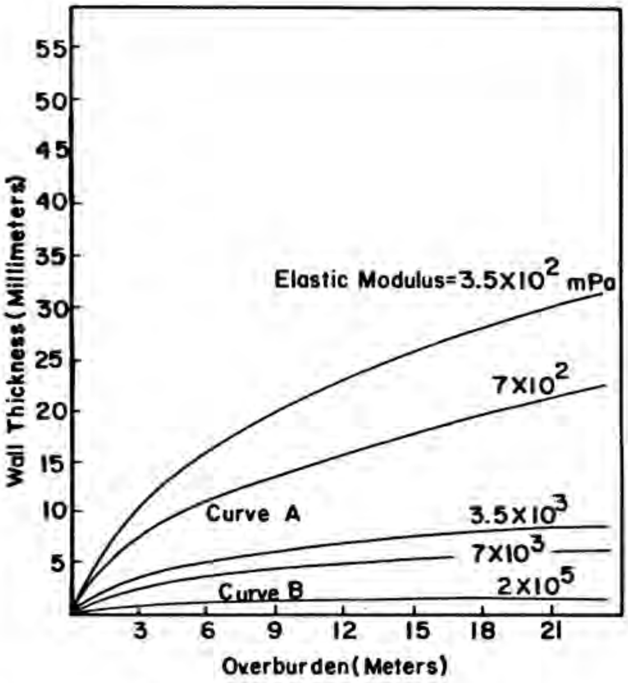

Fig. 5. Wall Thickness Required to Resist Buckling in Cluster Burial.

(f) There is a need to consider a 300 year life in comparison with the eight year life test data available. Fourteen year test data is reported in the earlier NBS study. These data show discernably small increases in weight loss and pitting over the eight year data taken from the later study. Further, the earlier NBS study demonstrates that corrosion damage in metals proceeds at a decreasing rate as exposure time increases.

The data available from NBS and an application of metallurgical principles of stainless steels virtually guarantees structrual integrity for the lifetime of a HIC manufactured from an appropriate grade of stainless steel. However, from the standpoint of containment integrity, the data also shows that, regardless of the grade of stainless steel involved, penetration of the container wall is possible. Corrosion of stainless steel in soils, when it occurs, is in the form of "pitting" and not in the form of "uniform attack". In other words, although total corrosion may be very minor, what does occur will tend to concentrate at isolated locations in the form of pits. Depending upon the wall thickness, pitting eventually results in performation. Such an event is possible, given wall thicknesses dictated by structural and economic requirements. Such an event extends to even the expensive specialty grades of stainless steels.

Structural integrity of a metal HIC is a relatively easy achievement. There are a number of choices of stainless steels, including relatively common and inexpensive grades which can be used to accomplish this task. Containment integrity, however, is another matter. Regardless of the stainless steel employed, a review of available data (or lack thereof) demonstrates that perforation of containers is expected. For an all metal HIC, structural integrity upon burial is a certainty. Loss of containment integrity due to corrosion is possible and is, therefore, a problem to be addressed.

Consideration of Hydrogen Related Damage

Slow general or localized corrosion of metals as well as the general breakdown of ion exchange resins due to irradiation are mechanisms accompanied by available hydrogen at exposed metal surfaces along the inside of an all metal HIC. For many metals, including many stainless steels, this situation is accompanied by diffusion of hydrogen into the metal and a potential for hydrogen embrittlement. The result could be premature failure[18].

The conclusion drawn from this investigation is that there is a basis to expect, given the evnironment within a container, a reasonable probability of hydrogen damage over a 300 year life in a stainless steel container fabricated as a welded structure. This expected problem of hydrogen damage is further reason to question the use of an all metal container.

DISCUSSION

An investigation of suitable thermoplastic materials has resulted in a conclusion that unreinforced plastics are unable to withstand soil pressures which develop upon burial. On the other hand, polyethylene offers the necessary corrosion and radiation resistance to conditions which are foreseeable in the waste material placed in a HIC. In other words, polyethylene is able to satisfy the requirement of containment integrity, but is not expected to economically provide structural integrity.

Investigation of suitable metals has resulted in a conclusion that metal HICs can be designed which provides the required structural integrity with a comfortable factor of safety. Modest wall thicknesses and conventional fabrication technology would be involved. To offer resistance to anticipated corrosive environments, metal HICs would be expected to be fabricated from stainless steels. However, analysis has also shown that a stainless steel HIC would not be expected to offer containment integrity in the long-term burial environment. Identified problems are corrosion and hydrogen embrittlement. Corrosive attack is most foreseeable at exposed metal surfaces along the inside of the container. Isolated perforation of the container due to corrosion from the surrounding soil environment is also a possiblity. In other words, an all metal HIC can be designed to satisfy the requirement of structural integrity, but is not expected to provide the containment integrity required.

Based on the study conducted, it has been concluded that neither polyethylene nor stainless steel alone would be suitable for use as HIC materials. However, the potential exists for the use of these materials together to take advantage of the better properties of both. This alternative is currently under investigation.

TABLE I
COMPARISON OF NBS TEST SOILS (REF. 16) WITH SOILS AT BURIAL SITES

NO.	TYPE	LOCATION	DRAINAGE	pH	Ca	Mg.	CHLORIDES	SULPHATES
	Barnwell Backfill Sand	Barnwell, SC	—	5.6	—	200ppm	5.2ppm	135ppm
A	Sagemoor Sandy Loam	Toppenish, WA	good	8.8	108ppm	23	330	216
B	Hagerstown Loam	Loch Raven, MD	good	5.3	—	—	—	—
C	Clay	Cape May, NJ	poor	4.3	540	754	3529	6768
D	Lakewood Sand	Wildwood, NJ	good	5.7	—	—	—	—
E	Coastal Sand	Wildwood, NJ	poor	7.1	302	329	5765	1133
G	Tidal Marsh	Patuxent, NJ	poor	6.0	140	165	3259	1709
	Richland Backfill Sand	Richland, WA	—	7.8	—	—	1 max	4 max

REFERENCES

1. Code of Federal Regulations, Title 10, Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste," (January 1, 1984).

2. "Technical Position of Waste Form," Nuclear Regulatory Commission, (May, 1983).

3. "Guide for High Integrity Container Topical Report Applications," Revision 1, DHEC/BRH/073085, South Carolina Department of Health and Environmental Control, (July, 1985).

4. "Criteria for High Integrity Containers," Washington State Radiation Control Program, (August, 1983).

5. Siskind, B., D.R. Dougherty, and D. R. MacKenzie, "Extended Storage of Low Level Radioactive Waste: Potential Problem Areas," NUREG-CR-4062, Brookhaven National Laboratory (December, 1985).

6. Piciulo, P. L., "Technical Consideration for High Integrity Containers for the Disposal of Radioactive Ion-Exchange Resin Waste," NUREG/CR-3168, Brookhaven National Laboratory, (October, 1983).

7. Pillay, K.K.S., "Radiation Effects on Ion Exchangers Used in Radioactive Waste Management," Pennsylvania State University, (October, 1980).

8. Temus, C.J., et al., "Development of Metallic High Integrity Containers," presented at the Symposium on Waste Management, Tucson, Arizona (February 27 - March 3, 1983).

9. Watkins, R.K., "Buried Structures," in Foundation Engineering Handbook, Ch. 23, ed. by H. F. Winterkorn and H. Fang, Van Nostrand-Reinhold, (1975).

10. Spangler, M.G. and R.L. Hardy, "Soil Engineering" Harper and Row, (1982).

11. Wu, T.H., "Retaining Walls," In Foundation Engineering Handbook, Ch. 12, ed. by H.F. Winterkorn and H. Fang, Van Nostrand-Reinhold, (1975).

12. Young, R.J., Introduction to Polymers, Chapman and Hall, (1981).

13. O'Toole, J.L., "Design Guide," in Modern Plastics Encyclopedia 1984-1985, McGraw-Hill, (1985).

14. Timoshenko, S.P. and J.M. Gere, Theory of Elastic Stability, 2nd ed. McGraw-Hill, (1981).

15. Romanoff, M., "Underground Corrosion," Pb-168 350, National Bureau of Standards, Circular 579, (April, 1957).

16. Gerhold, W.F, et al., "The Corrosion Behavior of Selected Stainless Steels in Soil Environments," NBSIR 81-2228, National Bureau of Standards, (February, 1963).

17. Samans, C.H., Metallic Materials in Engineering, Mac Millan (1963).

18. Failure Analysis and Prevention, Metal Handbook, 8th ed., Vol. 10, American Society for Metals, (1975).