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Greater-Than-Class C Low-Level Radioactive Waste Characterization

Appendix H: Packaging Factors for Greater-Than-Class C Low-Level Radioactive Wastes

Greater-Than-Class C Low-Level Waste Management Program

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DOE/LLW-114H

GREATER-THAN-CLASS C LOW-LEVEL WASTE CHARACTERIZATION

Appendix H: Packaging Factors for Greater-Than-Class C Low-Level Radioactive Wastes

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ABSTRACT

This report develops and presents estimates for a set of three values that represent a reasonable range for the packaging factors for several waste streams that are potential greater-than-Class C low-level radioactive waste. The packaging factor is defined as the volume of a greater-than-Class C low-level waste disposal container divided by the original, as-generated or "unpackaged," volume of the wastes loaded into the disposal container.

Packaging factors take into account any processes that reduce or increase an original unpackaged volume of a greater-than-Class C low-level radioactive waste, the volume inside a waste container not occupied by the waste, and the volume of the waste container itself. The three values developed represent (a) the base case or most likely value for a packaging factor, (b) a high case packaging factor that corresponds to the largest anticipated volume of waste for disposal, and (c) a low case packaging factor for the smallest volume expected.

Three categories of greater-than-Class C low-level waste are evaluated in this report: activated metals, sealed sources, and all other wastes. Estimates of reasonable packaging factors for the low, base, and high cases for the specific waste streams in each category are shown in Table H-1.

Table H-1. GTCC LLW packaging factors to be used in volume projections

Potential GTCC LLW Waste Stream	Base Case	High Case	Low Case
Activated Metals			
BWR Operations			
Control Rod Blades	5	10	4
Incore Instruments	5	10	3
PWR Operations			
Thimble Plug Assemblies	20	30	10
Incore Instruments	5	10	3
Primary Sources	1	1	1
BWR Decommissioning			
Core Shroud	2	3	1.4
PWR Decommissioning			
Core Shroud	2	3	1.4
Core Barrel	2	3	1.4
Sealed Sources	380	1,000	2
All Other GTCC LLW			
Decontamination Resins	1	2	0.2
Cartridge Filters	2	4	0.1
Aqueous Liquids	0.2	3	0.1
Solidified Liquids	1	1.6	0.8

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1. INTRODUCTION

This report develops and presents estimates for a set of three values that represent a reasonable range for the packaging factor (PF) for several waste streams that are potential greater-than-Class C low-level radioactive waste (GTCC LLW). The PF is defined as the volume of a GTCC LLW disposal container divided by the original, as-generated or "unpackaged," volume of the wastes loaded into the disposal container. The PF will be used to determine the packaged volume of GTCC LLW that the U.S. Department of Energy (DOE) will receive from commercial waste generators.

The method for determining a PF considers the unpackaged volume of a potential GTCC LLW prior to any treatment and packaging for disposal. A PF estimates what that unpackaged volume will become when the wastes are actually processed (if processed at all) and packaged into a waste disposal container for final disposal in the future.

A PF for a specific GTCC LLW waste stream is the number of times an unpackaged volume will be increased or decreased to take into account predisposal treatment (if any) and packaging for disposal. Packaging factors take into account any processes that reduce or increase an original unpackaged volume of a GTCC LLW, the volume inside a waste container not occupied by the GTCC LLW, and the volume of the waste container itself.

A set of three values is proposed as the range for a reasonable PF estimate for potential GTCC LLW streams. These values are determined by considering existing low-level radioactive waste processing, handling, packaging, and transportation technologies, and the uncertainties in forecasting which technologies will be used later when GTCC LLW is treated, packaged, and transported for disposal. The three values represent (a) the base case or most likely value for a PF, (b) a high case packaging factor that corresponds to the largest anticipated volume of waste for disposal, and (c) a low case packaging factor for the smallest volume expected. The high and low cases are not proposed as worst case values, but rather as reasonable values for the range of the base case or most likely value for the PF.

PF is the reciprocal of packaging efficiency (PE). Packaging efficiency is an unpackaged volume of GTCC LLW inside a waste disposal container, divided by the volume of the outside dimensions of the waste disposal container. The assessments of reasonable PFs are developed below by determining the PEs and then taking the corresponding reciprocals.

The three categories of GTCC LLW evaluated in this report are: (a) activated metals, (b) sealed sources, and (c) all other wastes. The specific types of materials evaluated in each category and the generators are listed in Table H-2.

Table H-2. Potential GTCC LLW and generators

Potential GTCC LLW Waste Stream	Generator Nuclear Power Plants
Activated Metals	
BWR Operations	
Control Rod Blades	
Incore Instruments	
PWR Operations	
Thimble Plugs	
Incore Instruments	
Primary Sources	
BWR Decommissioning	
Core Shroud	
PWR Decommissioning	
Core Shroud	
Core Barrel	
Sealed Sources	Manufacturers and Users
All Other GTCC LLW	
Decontamination Resins	Nuclear Power Plants
Cartridge Filters	Nuclear Power Plants
Aqueous Liquids	Industrial and Academic Users
Solidified Liquids	Fuel Testing and Bburnup Evaluation Facilities and Industrial Users

2. ACTIVATED METALS

PFs for activated metal GTCC LLW are developed in this section. The large components, core barrels and core shrouds, are evaluated in Section 2.1. The small components, BWR control rod blades, incore instruments, etc., are considered in Section 2.2. For each type of component, background information and assumptions on the scenarios for packaging of such materials are presented. The calculational models are then described and results provided. Estimates of the base, high, and low cases for reasonable PFs to be used in disposal volume projections are made after evaluating the results.

An important consideration in the analyses is the assumption that different waste streams of GTCC LLW are **not** mixed in the same waste disposal container. This assumption does not reflect the current practices for the packaging of LLW for burial at commercial LLW disposal sites. Within the guidelines acceptable at each disposal site, various small-size activated metal components are normally mixed together and disposed of as commercial LLW. While the acceptability of this practice for commercial and DOE disposal in the future will influence the types and quantities of potential GTCC LLW that ultimately are disposed of as GTCC LLW, this study purposely ignores the possibility that activated metal waste streams will be mixed in determining the reasonable PFs for each specific waste stream examined.

In using this approach, a higher PF will result for each individual waste stream than would be the case with mixing (i.e., more containers of GTCC LLW will be predicted than would actually be generated). This is because the mixing of different streams would enable small components to be placed into containers with pieces of large components, filling in some of the void spaces in those waste containers. Taking advantage of mixing to reduce costly disposal volume seems a reasonable practice that would be applied to GTCC LLW in the future.

However, by not considering mixing, the PFs for unmixed waste streams are expected to be only slightly higher than for the cases where mixing would be performed. As will be seen by the range of PF values in the results, such a small difference should not affect the usefulness of the values proposed for the PFs. Also, this approach is helpful since it allows computer modeling of an individual waste stream and prevents the problem of mathematically treating the many possibilities that arise if waste streams were evaluated as mixed.

2.1 Large Activated Metal Components

2.1.1 Background Information and Assumptions

The large activated metal components (LAMC) considered in this study are the boiling water reactor (BWR) and pressurized water reactor (PWR) core shrouds and the PWR core barrels. These LAMC are expected to be generated as potential GTCC LLW when nuclear power plants are decommissioned. Previous estimates of the PFs for LAMC are assumed to have been based on requirements (current at that time) for limiting the curies in waste disposal containers sent to commercial low-level waste burial sites. The relatively low amount of total curies allowed in a single disposal container compared to the high concentration of curies predicted to be in typical LAMC meant that large components would have needed to have been cut into many small pieces and distributed into many waste containers. Hence, low PEs and correspondingly high PFs were estimated. In contrast to the previous estimates, no constraint is placed on the total amount of curies in a disposal container of LAMC. Although the waste acceptance criteria for disposal have not been established by DOE for GTCC LLW, a limit on curies in containers of LAMC is not a reasonable assumption for this study.

In evaluating reasonable PFs for LAMC, the unpackaged volume of the pieces that can be loaded into potential disposal containers is determined by the shapes and sizes of those pieces which can be cut to fit into the container being considered. Since the sizes of the LAMC at the reactor sites vary, and the size (or sizes) of the waste containers acceptable to DOE is not fixed, many combinations of component and container sizes are possible for future packaging configurations for LAMC. By looking at the range of the possible combinations, a reasonable estimate of the most likely or base case PF is determined. Similarly, the high and low cases are based on the spread of values for the PFs for the many combinations.

In using this approach to determine PFs for LAMC waste containers, an additional consideration enters into determining the acceptable sizes. The container's dimensions must be near the sizes considered for either truck or rail casks.

In the calculations, the size of the cylindrical waste container is fixed, and sections of the lower core barrel (LCB) are added to the inside as long as the next piece fits into the waste envelope or, for large waste containers, until an entire LCB is in a single waste container.

Model TITAN Truck Cask. The description of the calculational model for the model TITAN truck cask is the same as is used in these calculations except that the number of sections of LCB loaded into the waste container is not limited by the weight constraint of the TITAN cask. In these cases, the number of sections is increased until no additional section can fit into the waste container.

The results of the calculations are provided in Table H-14 in Appendix A for the TITAN truck cask design. The results show the effects on PEs as the inside diameter and thickness of the LCB are varied for cylindrical, volume-constrained waste containers. The PEs for an entire LCB vary from a low value of 0.567 to a high value of 0.711. Figure H-3 in Appendix A shows graphically the reason for the high PEs for the case with an LCB with an inner diameter of 148 in. and thickness of 2.5 in. For this case, the weight of the LAMC would be 15,407 pounds, and a total payload weight of 16,992 pounds must be accommodated by the cask. The total number of waste containers needed to package an entire LCB varies from three to five containers.

Model IF-300 Rail Cask. The description of the calculational model for the Model IF-300 rail cask is based on the fact that the number of sections of LCB loaded into the waste container is not limited by the weight constraint of the IF-300 cask. In these cases, the number of sections is increased until no additional sections can fit into the waste container or until an entire LCB is in a single waste container.

The results of the calculations are provided in Table H-15 in Appendix A for the IF-300 rail cask design with cylindrical waste containers. The results show the effect on PEs as the inside diameter and thickness of the LCB are varied for cylindrical, volume-constrained waste containers. The PEs for an entire LCB vary from a low value of 0.419 to a high value of 0.786. The total number of waste containers needed to package an entire LCB is one to two containers.

Model 125-B Rail Cask. The description of the calculational model for the Model 125-B rail cask is based on the fact that the number of sections of LCB is not limited by the weight constraint of the 125-B cask. In these cases, the number of sections is increased until no additional section can fit into the waste container or until an entire LCB is in the waste container.

The results of the calculations are provided in Table H-16 in Appendix A for the Model 125-B cask with cylindrical cross section waste containers. The results show the effect on PEs as the inside diameter and thickness of the LCB are varied for cylindrical cross section, volume-constrained waste containers. The PEs for an entire LCB vary from a low value of 0.421 to a high value of 0.726. The total number of waste containers needed to package an entire LCB is one container.

Volume-Constrained Square Cross Section Waste Containers. The calculational model for square cross section containers considers three variations of transport packages. In the calculations the size of the waste container is fixed, and sections of the LCB are added to the inside as long as the next piece fits into the waste envelope or, for large waste containers, until an entire LCB is in the waste container.

PWR Spent Fuel Casks. Any of the spent fuel casks existing or under development with baskets for PWR spent fuel assemblies have a square cross section cavity into which a waste container of sections of an LCB could be placed for transport by either truck or rail mode. The square cross section cavity is assumed in these calculations to be 8.75 in. on a side and deep enough to accept the waste container. A clearance of 0.25 in. is allowed between each inside surface of the square cavity and the outside surface of a waste container for loading it into and removing it from the cask.

The nominal outside dimensions of a square cross section waste container are 8.25 in. on a side and 164.5 in. in overall length. These outer envelope dimensions are used in calculating the volume of the waste container. The length is based on the length of a section of the LCB of 160.5 in., an axial clearance of 1 in., a bottom plate thickness of 1 in., and a top plate thickness of 2 in. The wall thickness of each side is assumed to be 0.25 in. These values may be reduced in thickness after analyzing for adequate structural strength during lifting. The axial space in the cask cavity not filled with the waste container is assumed to be filled by a lightweight spacer of the appropriate length.

A clearance of 0.25 in. is allowed between each inside surface of the square cross section cavity of the waste container and the outside surface of a waste envelope for loading sections of the LCB into the waste container. The waste envelope thus has a square cross section of 7.25 in. on a side and a length of 161.5 in. inside the waste container.

The results of the calculations are provided in Table H-17 in Appendix A for casks with PWR fuel baskets. The results show the effect on PEs as the inside diameter and thickness of the LCB are varied for square cross section waste containers. The PEs for an entire LCB vary from a low value of 0.498 to a high value of 0.614. Figure H-4 in Appendix A shows graphically the reason for the average PEs for the case with an LCB with an inner diameter of 148 in. and a thickness of 2.5 in. For this case, the weight of the LAMC would be 1,910 pounds, and a total payload weight of 2,103 pounds must be accommodated by the cask for each cavity in the spent fuel basket. The total number of waste containers needed to package an entire LCB varies from 21 to 36 containers.

Model GA-4 Truck Cask. A newly designed truck cask, the Model GA-4, has a square cross section cavity with 18 in. on a side and a length of 167.25 in. Using the same approach as outlined above, the dimensions for these cases are:

Cask cavity side length = 18 in.

Clearance between inside surfaces of the cask cavity and outside surfaces of the waste container = 0.25 in.

Outside dimensions of the waste container:
Side length = 17.5 in.
Overall height = 164.5 in.

Wall thickness of the waste container = 0.25 in.

Clearance between the inside surfaces of the waste container and the outside of the waste envelope = 0.25 in.

Outside dimension of the waste envelope:
Side length = 16.5 in.
Height = 161.5 in.

The results of the calculations are provided in Table H-18 in Appendix A for the GA-4 truck cask design without a fuel basket. The results show the effect on PEs as the inside diameter and thickness of the LCB are varied for square cross section, volume-constrained waste containers. The PEs for an entire LCB vary from a low value of 0.665 to a high value of 0.795. The total number of waste containers needed to package an entire LCB varies from four to seven containers.

Model 125-B Rail Cask. An existing rail cask, the Model 125-B, has a cylindrical internal cavity of 51.25 in. inside diameter and is 190 in. in depth. The inner containment vessel is assumed to be removed and replaced by a new design basket that has a square inscribed in the circular cavity. A square cross section waste container would be placed into the special basket for transport. A radial clearance of 0.625 in. would be allowed between the inside surface of the cask cavity and the outside surface of the special basket. The outer diameter of the special basket would then be 50 in. Assuming a 0.5 in.-thick wall for the special basket would result in an inside diameter of 49 in. The side of a square inscribed in the inside diameter would be 34.64 in. A square cross section cavity of 34.5 in. is assumed.

Using the same approach as outlined above, the dimensions for these cases are:

Cask basket cavity side length = 34.5 in.

Clearance between inside surfaces of the cask cavity and outside surfaces of the waste container = 0.25 in.

Outside dimensions of the waste container:
Side length = 34 in.
Overall height = 167.5 in.

Wall thickness of the waste container = 0.375 in.

Clearance between the inside surfaces of the waste container and the outside of the waste envelope = 0.25 in.

Outside dimension of the waste envelope:
Side length = 32.75 in.
Height = 161.5 in.

The results of the calculations are provided in Table H-19 in Appendix A for the Model 125-B rail cask with an inner containment vessel replaced by a basket for square cross section waste containers. The results show the effect on PEs as the inside diameter and thickness of the LCB are varied for square cross section, volume-constrained waste containers. The PEs for an entire LCB vary from a low value of 0.417 to a high value of 0.781. The total number of waste containers needed to package an entire LCB varies from one to three containers.

2.1.2 Packaging Factor Estimates for LAMC

A total of 117 cases were evaluated, which represent nine different sizes of LCBs loaded into spent fuel casks in 13 weight or volume-constrained waste containers. The resulting PE for each case represents a possible loading of LAMC into a waste container. Based on the many PEs that were determined and are summarized in Table H-20 in Appendix A, the proposed base case for PFs for LAMC is a factor of 2 or a PE of 0.5. This value reflects the considerable number of uncertainties that will affect the actual PFs. These include the actual diameters and thicknesses of existing LCBs, the effect of flanges and protrusions that may be present on LCBs, the tolerances to which the sections of an LCB can be cut remotely underwater, the clearances that will be required between sections of an LCB for loading into a waste container, the types of casks to be used for transport, and the sizes of the waste containers that will be used. While some reactor sites may achieve a PF higher than 2, others will likely not achieve even this high a value. For the overall LAMC waste stream from all reactor sites, an average of all the possibilities will likely most fairly characterize the PF actually to be realized.

A PF of 2 (PE of 0.5) is slightly higher than the average value of all the results for the PE for an entire LCB. This value appears to be the most reasonable for a base case PF without additional information to reduce some of the uncertainties that are included in establishing the ranges of the values for the variables in the study. A slightly higher-than-average value appears warranted since the lowest PE cases correspond to cask cavity filling, weight-constrained waste containers that are less likely to be used than cask cavity inefficient, weight-constrained waste containers. If spent fuel casks are to be used in the future, the void need only be in the cask cavity and not in both the cask cavity and the waste container (which is in the cask cavity).

A value for the PF of 3 or a PE of 0.33 is proposed for the high case for the range of PFs. This value represents the largest volume of LAMC that would be expected for disposal. Neglecting some of the lowest PEs noted above for cask cavity inefficient, weight-constrained waste containers, several of the cases that had a PE this low or lower represent combinations of variables that individually are considered reasonable. Since these combinations of variables are possible, they may determine actual PFs. If these cases represent many of the LCBs in existence, a PF of 3 might be realized.

A value for the PF of 1.4 or a PE of 0.71 is proposed for the low case for the range of PFs. This value represents the smallest volume of LAMC that would be expected for disposal. Several of the cases had PEs this high or higher for the PE for an entire LCB, and many more were higher for the fully loaded waste containers. A value as high as the highest PE generated was not selected, since the theoretical aspects of this evaluation have not been tested against the real-world problems of cutting large components remotely to fit into tolerances as tight as those that were used in the calculations.

However, these values for the base, high, and low ends of the range for PFs should be reasonable estimates even if larger tolerances for remote cutting and handling are found to be necessary. The reduction of the length of each of the sections in a waste container by an inch would not change the values for the proposed PFs since these are not at the extremes of the values resulting from the calculations.

Conversely, the results from the many combinations of variables that were evaluated show that there are certain combinations where the geometry of the waste containers and the geometry of the LCB sections (e.g., LCB inside diameter and thickness) combine to tightly pack the sections into the waste container. There may be combinations of sizes of waste containers and LCBs where reducing clearances slightly would improve PFs further for the volume-constrained cases. That is, an additional section of an LCB may be able to fit into a waste container if the clearance allowed for the waste envelope were used.

As noted previously, the assumption that mixing will not be permitted would tend to overestimate the packaged volume of LAMC if such mixing is allowed, since small parts of other components could be used to fill the void spaces in containers of large pieces. Perhaps more significant, pieces of other components could be used to complete the filling of the last waste container only partially filled with pieces of a large component. As the data shows, the PEs for a single fully loaded waste container filled with sections of the LCB are higher than the overall PE for an entire LCB when the last filled waste container is only partially filled. The low PE of the last, partially filled waste container brings down the average for the group of waste containers. The smaller the number of waste containers in the group, the larger this effect becomes. Just utilizing the space in the last, partially filled container would thus raise the overall PE for all activated metals from a site.

2.2 Small Activated Metal Components

2.2.1 Background Information and Assumptions

The small activated metal components (SAMC) considered in this study are BWR control rod blades and incore instruments as well as PWR thimble plugs, incore instruments, and primary sources. These SAMC are expected to be generated as potential GTCC LLW during nuclear power plant operations and at decommissioning. Previous estimates of the PFs for SAMC for current operations are not published and are based on the practice of mixing pieces of SAMC in waste disposal containers sent to commercial LLW disposal sites.

In contrast to the LAMC, which are characterized by a single large item with well-defined geometry and volume requiring disposal, the SAMC consist of many small items generated during on-going operations without a definite generation rate. The volume requiring disposal is therefore not as determinate as for the LAMC. Also, since each item of the SAMC is small compared to the internal volume of the waste containers previously considered for the LAMC, there is a possibility that an insufficient amount of a specific SAMC waste stream will be available to fill the volume available in a single waste container.

Calculational Model and Results. The PFs for each of the SAMC materials are based on calculational models or engineering judgements as described below. Each specific SAMC waste stream is discussed individually. The models are based on filling a single waste container with a specific waste stream. This assumes a sufficient volume of the waste stream will be available to fill the container.

BWR Control Rod Blades. A BWR control rod blade (CRB) consists of long thin metal plates in the shape of a cruciform. The plates sandwich a neutron poison material that controls the operation of the BWR plant. A CRB is almost 10 in. across, and the width of the metal plate sandwich is about 0.3 in. A CRB is approximately 175 in. long, and the end not inserted into the reactor core has a cylindrically shaped velocity limiter integral to the CRB assembly. A CRB is activated by neutrons when it is inserted into the core. Since not all of a CRB is inserted, there is a "hot end" and a "cold end."

Base Case--The evaluation of the base case PF assumes that the velocity limiter on the cold end is cut off and disposed of as commercial LLW. The hot end is flattened between rollers and then placed into a cylindrical cross section waste container. The volume of the hot end of the CRB is approximately 0.6 ft^3. The envelope dimensions of the flattened CRB are assumed to be 2 in. by 10 in. by 160 in. Two sizes of cylindrical waste containers are evaluated for the base case. One is for transport in a Model TITAN truck cask, and the other is for the IF-300 rail cask.

A new-design truck spent fuel cask under development, the Model TITAN, will have interchangeable baskets for PWR or BWR spent fuel assemblies. With the basket removed, there is a cylindrical cavity into which a waste container with CRBs could be placed for transport by truck. The cylindrical cavity is 23.75 in. inside diameter and 180 in. deep. A radial clearance of 0.25 in. is allowed between the inside surface of the cask cavity and the outside surface of a waste container for loading it into and removing it from the cask.

The nominal outside dimensions of a cylindrical waste container are 23.25 in. on a side and 164 in. in overall length. These dimensions are used in calculating the outer envelope volume of the waste container. The length is based on a length of a hot end of a CRB of 160 in., an axial clearance of 1 in., a bottom plate thickness of 1 in., and a top plate thickness of 2 in. The wall thickness of each side is assumed to be 0.25 in. These values may be reduced in thickness after analyzing for adequate structural strength during lifting, storage, and disposal. The axial space in the cask cavity not filled with the waste container is assumed to be filled by a lightweight spacer of the appropriate length.

A clearance of 0.25 in. is allowed between the inside surface of the cylindrical cavity of the waste container and the outside surface of a waste envelope for loading CRBs into the waste container. The waste envelope has a cylindrical cross section of 22.25 in. in diameter and a length of 161 in. inside the waste container.

Figure H-5 in Appendix A shows an arrangement of boxes (2 in. by 10 in.) that represent the envelope dimensions of flattened CRBs in the waste container. The 13 CRBs in the container have a displaced volume (not envelope dimension volume) of 7.8 ft^3. With a waste container outer volume of 40.29 ft^3, the PE for this size container is 0.19.

An existing rail cask, the Model IF-300 with the basket removed, has a cylindrical cavity with a 37.5 in. inside diameter and a depth of 180.25 in.

Using the same approach as outlined above, the dimensions for these cases are:

Cask cavity inside diameter = 37.5 in.

Clearance between inside surface of the cask cavity and outside surface of the waste container = 0.375 in.

Outside dimensions of the waste container:
Outside diameter = 36.75 in.
Overall height = 164 in.

Wall thickness of the waste container = 0.375 in.

Clearance between the inside surface of the waste container and the outside of the waste envelope = 0.25 in.

Outside dimensions of the waste envelope:
Diameter = 35.5 in.
Height = 161 in.

Figure H-6 in Appendix A shows an arrangement of boxes that represent the flattened CRBs in the waste container. The 37 CRBs in the container have a displaced volume (not envelope dimension volume) of 22.2 ft^3. With a waste container outer volume of 100.67 ft^3, the PE for this size container is 0.22.

From these two results, the base case for the PE for BWR control rod blades is 0.2, or a PF of 5.

Low Case--The evaluation of the low case PF assumes the velocity limiter on the cold end is cut off and disposed of as commercial LLW. The hot end is flattened between rollers and then placed into a square cross section waste container. The volume of the hot end of the CRB is approximately 0.6 ft^3. The envelope dimensions of the flattened CRB are assumed to be 2 in. by 10 in. by 160 in. Two sizes of square cross section waste containers are evaluated for the low case. One is for transport in the Model GA-4 truck cask, and the other is for the Model BR-100 rail cask.

The Model GA-4 cask under development has a square cross section cavity into which a waste container with CRBs could be placed for transport by truck. The square cross section cavity is 18 in. on a side and has a depth of 167.5 in. A clearance of 0.25 in. is allowed between each inside surface of the square cavity and the outside surface of a waste container for loading it into and removing it from the cask.

The nominal outside dimensions of a square cross section waste container are 17.5 in. on a side and 164 in. in overall length. These outer envelope dimensions are used to calculate the volume of the waste container. The length is based on the length of a hot end of a CRB of 160 in., an axial clearance of 1 in., a bottom plate thickness of 1 in., and a top plate thickness of 2 in. The wall thickness of each side is assumed to be 0.25 in. These values may be reduced in thickness after analyzing for adequate structural strength during lifting, storage, and disposal.

A clearance of 0.25 in. is allowed between each inside surface of the square cross section cavity of the waste container and the outside surface of a waste envelope for loading the flattened CRBs into the waste container. The waste envelope has a square cross section of 16.5 in. on a side and a length of 161 in. inside the waste container.

Figure H-7 in Appendix A shows an arrangement of boxes that represent the flattened CRBs in the waste container. The 11 CRBs in the container have a displaced volume (not envelope dimension volume) of 6.6 ft^3. With a waste container outer volume of 29.06 ft^3, the PE for this size container is 0.23.

A new rail cask currently under development, the Model BR-100, has a cylindrical internal cavity of 58.5 in. inside diameter and 180 in. in depth. For these cases, the basket for spent fuel assemblies is assumed to be removed and replaced by a new design basket that has a square inscribed in the circular cavity. A square cross section waste container would be placed into the special basket for transport. A radial clearance of 0.75 in. would be allowed between the inside surface of the cask cavity and the outside surface of the special basket. The outer diameter of the special basket would then be 57 in. Assuming a 0.5 in. radial dimension for the structure of the special basket would result in a usable inside diameter of 56 in. for the waste container. The side of a square inscribed in the inside diameter would be 39.6 in. A square cross section cavity of 39.5 in. is assumed.

Using the same approach as outlined above, the dimensions for these cases are:

Cask basket cavity side length = 39.5 in.

Clearance between inside surfaces of the cask cavity and outside surfaces of the waste container = 0.25 in.

Outside dimensions of the waste container:
Side length = 39 in.
Overall height = 164 in.

Wall thickness of the waste container = 0.375 in.

Clearance between the inside surfaces of the waste container and the outside of the waste envelope = 0.25 in.

Outside dimension of the waste envelope:
Side length = 37.75 in.
Height = 161 in.

Figure H-8 in Appendix A shows an arrangement of boxes that represent the flattened CRBs in the waste container. The 63 CRBs in the container have a displaced volume (not envelope dimension volume) of 37.8 ft^3. With a waste container outer volume of 144.35 ft^3, the PE for this size container is 0.26.

From these two results, the low case for the PE for BWR control rod blades is 0.25 or a PF of 4.

High Case--The evaluation of the high case PF for CRBs assumes the velocity limiter on the cold end is not cut off, and the entire CRB unit is disposed of as GTCC LLW. Also, the hot end is not flattened between rollers. The CRB unit, as removed from the reactor, is placed into a square cross section waste container. The volume of the CRB unit is approximately 0.64 ft^3. One size of square cross section waste container is evaluated for the high case PF. The square cross section waste container for transport in the Model GA-9 cask is similar to the previously described GA-4 cask. The GA-9 cask also has a square cavity 18 in. on a side but is 178 in. in length, which accommodates the full length of the CRB unit.

Figure H-9 in Appendix A shows an arrangement of CRB units in a waste container. The four CRBs in the container have a displaced volume (not envelope dimension volume) of 2.56 ft^3. With a waste container outer volume of 31.89 ft^3, the PE for this size container is 0.08. Based on this result and the likelihood that most CRBs would be flattened, the high case PE for CRBs is 0.1 or a PF of 10.

BWR and PWR Incore Instruments. Incore instruments for both BWR and PWR reactors consist of long, thin-walled metal tubes. The tubes contain neutron detectors that monitor operations of BWR and PWR reactors. An incore instrument tube is approximately 0.4 in. to 0.7 in. in diameter and can be over 100 ft long. An incore instrument tube is activated by neutrons when part of it is inserted into the core. Since not all of an incore instrument tube is inserted, there is a hot end and a cold end.

Base, High, and Low Cases--The evaluation of the PFs assumes the cold end is cut off and disposed of as commercial LLW. The hot end is placed into a square cross section waste container. The displaced volume of the metal tube is approximately 0.005 to 0.2 ft^3, depending upon wall thickness of the metal tube. The small displaced volume and envelope dimensions of the incore instrument tube relative to the volume of the waste container require rather gross estimates for the base, high, and low case PFs.

The base case PF is estimated to be 5 or a PE of 0.2. This value is, however, no more than about the center of the range for the high and low cases. The high case PF is estimated to be 10 or a PE of 0.10. The low case PF is estimated to be 3 or a PE of 0.33. These proposed values consider the following calculations:

- The number of incore instrument tubes in the smallest size waste container was determined for several sets of variables. The smallest size container is one transported in a spent fuel cask for PWR assemblies as described above. The outside length of the square side of the container is 8.25 in., and the length of the side of the waste envelope is 7.25 in.

- The sets of variables considered the outer diameter (OD) of the incore instrument tubes, their wall thickness (THK), and the gap between the tubes. The gap represents the volume in a container that can not be efficiently used due to the difficulty in loading the tubes in a triangular pitch array in a waste container remotely underwater. The larger the gap between tubes, the fewer number of tubes that the container will hold.

- A PE of 0.34 results from tubes 0.7 in. in OD, 0.12 in. THK, with a small gap between tubes. A total of 108 tubes would be in the container. If the gap increases to 0.2 in. between tubes, the number of tubes in the container would drop to 64, and the PE would drop to 0.20.

- A PE of 0.28 results from tubes 0.4 in. in OD, 0.06 in. THK, with a small gap between tubes. A total of 358 tubes would be in the container. If the gap increases to 0.2 in. between tubes, the number of tubes in the container would drop to 144, and the PE would drop to 0.11.

These results show the sensitivity of the PE to the amount of volume not used for incore instrument tubes due to the difficulty in loading them remotely. Small changes in assumed wall thickness likewise result in substantial changes in PEs. The three proposed values for the PFs should, however, account for the possible combinations and be reasonable estimates of the PFs for incore instrument tubes.

PWR Thimble Plugs. PWR thimble plugs or orifice rod assemblies resemble PWR control rod assemblies except that the rods attached to the flat plate or spider that rests on top of a PWR fuel assembly are much shorter than control rods. The rods are only a few inches long. A thimble plug has an envelope dimension of approximately 6 in. square cross section by 11 in. overall height. The thimble plugs are activated by neutrons since they are inserted into the core at the top of a PWR assembly. The entire assembly is activated and considered "hot," although the inconel spring is the activated part that causes a thimble plug to become GTCC LLW.

Base, High, and Low Cases--The evaluation of the PFs assumes that the thimble plug (or orifice rod assembly) is removed from the PWR fuel assembly and disposed of as a unit. The unit is placed into a square cross section waste container. The displaced volume of the unit is approximately 0.02 to 0.03 ft^3. The small displaced volume and relatively large envelope dimensions of a thimble plug result in low estimates for the base, high, and low case PFs.

The base case PF is estimated to be 20, or a PE of 0.05. This value is, however, no more than about the center of the range for the high and low cases. The high case PF is estimated to be 30, or a PE of 0.03. The low case PF is estimated to be 10, or a PE of 0.1. These proposed values consider the following calculations:

- The number of thimble plugs in a square cross section waste container for the GA-4 truck cask was determined for several packaging configurations for the thimble plugs. The outside length of the square side of the container is 17.5 in., and the length of the side of the waste envelope is 16.5 in.

- The packaging configurations considered the units both as removed from the fuel assembly and with the rods flattened to be parallel to the top plate rather than perpendicular to it. The envelope dimensions in the flattened condition are 6 in. by 7 in. by 12 in. The unflattened units can either be unnested or nested.

- The unnested configuration in a container is due to the difficulty in loading the units remotely underwater as boxes based on their envelope dimensions in a waste container. The unnested configuration approximates a random dropping of units into a waste container.

- A PE of 0.09 results when thimble plugs are assumed stacked into a container standing on end as if in a fuel assembly. The rods in one plug should nest into the coupling of the plug below it and rest on the plate of the lower plug. In this type of nested stacking, there would be 23 layers of four plugs each, or a total of 92 plugs per container. If the displaced volume is 0.03 ft^3, the PE would be 0.09. In comparison, if the displaced volume is 0.02 ft^3, the PE would drop to 0.06.

- A PE of 0.06 results when thimble plugs are assumed to be stacked into a container lying horizontally. The rods of one plug would not be nested into another plug. In this type of nested stacking, there would be 27 layers of two plugs each, or a total of 54 plugs per container. If the displaced volume is 0.03 ft^3, the PE would be 0.06. In comparison, if the displaced volume is 0.02 ft^3, the PE would drop to 0.04.

- A PE of 0.09 results when thimble plugs are assumed to be stacked into a container lying horizontally and are nested with the rods from one plug nested into the coupling or rods of another plug. In this type of nested stacking, there would be 23 layers of four plugs each, or a total of 92 plugs per container. If the displaced volume is 0.03 ft^3, the PE would be 0.09. If the displaced volume is 0.02 ft^3, the PE would drop to 0.06.

- A PE of 0.11 results when thimble plugs are assumed flattened and then stacked into a container. The flattened rods are assumed to point up out of the container and are alternately all against the wall of the container in one layer and in the center of the container in the next layer. In this type of nested stacking, there would be 27 layers of four plugs each, or a total of 108 plugs per container. If the displaced volume is 0.03 ft^3, the PE would be 0.11. In comparison, if the displaced volume is 0.02 ft^3, the PE would drop to 0.07.

These results show the lack of sensitivity of the PF to the arrangement of the thimble plugs. The difficulty in loading them remotely will likely cause the PEs to be lower rather than higher. The three proposed values should, however, account for the possible random or stacking configurations and be reasonable estimates of the PFs for thimble plugs.

PWR Primary Sources. A PWR primary source is a neutron source material located in two rods in a burnable poison rod assembly. A burnable poison rod assembly without a primary source is not GTCC LLW. The rods containing a primary source can be cut off the assembly and then constitute a very small volume of as-generated GTCC LLW. With a displaced volume from 0.002 to 0.016 ft^3 per rod and only a few rods per reactor, the packaged volume would be very large if the rods are placed into any of the previously described waste containers by themselves. Primary rods are the one waste stream that does not warrant a waste stream-specific PF. These items should be mixed into waste containers with other types of GTCC LLW. For purposes of the model to predict packaged volumes, a PF of 1 should be used for the base, high, and low cases. This value will ensure that primary sources are not ignored as a specific waste stream. Also, the small value of the unpackaged volumes times a PF of 1 will result in a small contribution for this waste stream in comparison to the other activated metal components.

3. SEALED SOURCE

This section on sealed source GTCC LLW describes the types, quantities, and packaging factors for the major contributors of sealed source material. The principal references of data for this section are provided by the NRC survey[a] on surplus sources and direct input from manufacturers and users of sealed sources within the industry.[b] The section provides the current best estimate of GTCC LLW sources under Specific Licenses (>27,000) and General Licenses (>65,000). Also included are the major types of sources and the sizes specific to the sources; the devices; and the packages provided for handling, transport, and storage. To simplify the process in determining packaging scenarios and packaging factors based on the significantly large number of sealed source configurations (>2000), the sources and devices were characterized under three categories. The three major categories are moisture/density gauges, well logger units, and fixed/test gauges. These three types of sources are analyzed and modeled to determine the scenarios for the best estimate base case packaging factor as well as the high and low cases.

3.1 Background

Previous estimates of packaging factors for surplus sealed sources ranged from encapsulating nonreusable sources (currently ≈ 3,700) with cement in 55-gal containers (packing factor of 6,600) to extracting and consolidating unshielded sources in separate HLW canisters (packaging factor of 14.5). The high case encapsulation scenario was based on stabilization requirements for commercial disposal of Class C LLW waste and therefore was not considered appropriately applicable to the GTCC LLW projections. Additionally, these previous cases did not specifically consider the practical condition of some surplus sources contained in devices, gauges, and deployment units and the potential return of such devices to DOE in the original package and transport containers.

The NRC survey concluded that over 92,500 GTCC sources currently exist. Approximately 6% of these GTCC sources and devices are currently awaiting disposal or transfer to a storage location. The predominant source materials contain americium-241, cesium-137, curium-244, and plutonium-238 and -239. Of the inactive sources, some have been returned to the manufacturer for storage, but the majority are being held by the users because of cost constraints and/or manufacturers' refusal to accept returns. The users predominantly store these sources and devices in their original receiving configuration. Of those returned to the manufacturers, the majority of devices and source gauges have been disassembled to the extent practical to remove the electronics and ancillary equipment for optimum storage and consolidation.

The majority of GTCC sources and devices are transported from the manufacturer in 7A (type A) containers. However, some sources have been transported in type B containers due the higher

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a. U.S. Nuclear Regulatory Commission, NRC Sealed Source Survey, December 1990.

b. Information derived from Troxler Electronic Labs, Inc., Cornwallis Road/Alexander Drive, Research Triangle Park, NC 27709; Nuclear Environmental Engineering, Inc., Registry of Sealed and Device Sources, Amersham/Searle, personal communication with Brian Baker; Parkwell Laboratories, Inc., Registry of Sealed Sources and Devices; New England Nuclear, Registry of Sealed Sources and Devices; CPN Company, 2830 Howe Road, Martines, CA 94533; Monsanto Research Corporation, Dayton Laboratory, Dayton, Ohio.

specific activity and associated dose rate/transport index (TI) and special shielding requirements. The majority of the type A containers are retained by the users, while the type B containers are usually returned to the manufacturer. Generally, the users and manufacturers retain the shipping containers for storage and transport of the devices/sources.

3.2 Types, Quantities, and Sizes of Seal Sources

The NRC survey represented a sampling (≈25%) of their licensed users and manufacturers of sealed sources. These sample data were than extrapolated for both specific and general licensed users, including those under Agreement State licensing, to project the current estimate of GTCC source quantities. The NRC survey was focused primarily on the users who maintain a specific license for use of sealed source material. General license projections were based on NRC knowledge and data base records. The best estimate of quantities of GTCC sealed sources and devices that are currently in use or inactive is in excess of 92,500. The uncertainty of these results is projected to be within 10%. Table H-3 provides a summary of the major quantities of GTCC sealed sources and devices.

Table H-3. Major GTCC LLW sealed sources and devices

TYPES	SPECIFIC LICENSE (> 27,500)	GENERAL LICENSE (>65,500)
TRU-bearing Sources		
Well Logger Units	≈ 2,000	-
Density/Moisture Gauges	≈ 14,200	< 1 %
Gamma Gauges	≈ 200	< 1 %
Pacemakers	≈ 130	-
X-Ray Fluorescent	< 1 %	-
Smoke Detectors	-	< 1 %
Non-TRU-bearing Sources		
Test Gauges (Industrial/Analytical)	≈ 3,300	> 45 %
Fixed Gauges (Gamma/Beta, Thickness)	≈ 800	> 45 %
Calibration Sources	≈ 480	< 1 %
Category I Sources	≈ 450	-
Irradiator Sources Cat. II, III, IV	≈ 440	-

The major quantity of sealed sources and devices currently in use under specific licenses is identified with well logger units, density/moisture gauges, fixed/test gauges. The major sealed sources under the general (broad) license are of the fixed/test gauge type.

Sealed sources and devices present a problem, because most sources are small but require much larger containers for shielding, handling, deployment, storage, and eventual disposal. The actual

A typical moisture/density gauge source contains Cs-137 and americium-241. The maximum activities typically are 10 mCi of Cs-137 and 60 mCi of Am-241. The maximum threshold activity used by the NRC to determine these types of sources as GTCC LLW is 27 mCi for Am-241 and other transuranics and 910 mCi of Cs-137. A typical moisture/density source is 1.5 cm in length and 1.0 cm in outside diameter ($\approx 1.2\ cm^3$).

A typical oil well logger source contains Am-241, Pu-238, and Cs-137. The maximum activities range from 10–60 Ci of transuranic material and 20 mCi of Cs-137. The sizes of oil well logging sources are larger than the other types of sources and typically are 2.54 cm in diameter and 7.5 cm in length ($38.6\ cm^3$).

A typical GTCC test/fixed gauge source contains Cs-137, Sr-90, Am-241, and CM-244. The sources, for the most part, are smaller and contain significantly smaller quantities of source material than the oil well logger sources. The test/fixed gauges typically are 0.8 cm in length and 4 cm in outside diameter, with a total volume of 10 cm^3. Appendix B provides a detailed description of the major sources currently used for analytical and industrial applications. The range in sources sizes is identified below.

Packaged sealed sources are normally contact handled, but the sealed source capsule or jacket is not normally contact handled. The source is usually located within a container or device that is shielded to provide direct contact handling. The size of these devices is usually a function of the type of source, the shielding and containment requirements, and the manner in which the unit is to be deployed. These devices are usually transported in special cases or packages provided by the manufacturers to protect the devices. Table H-4 is a summary of the range of sizes for the individual source, the shielded container, the device, and the transport package for each of the major sealed sources identified within the NRC survey.

Table H-4. Source and package size ranges

MOISTURE/DENSITY GAUGES (≈ 14,000)			
Source size	0.75 cm^3	-	4.6 cm^3
Shield size	3,670 cm^3	-	4,140 cm^3
Gauge size	14,680 cm^3	-	20,700 cm^3
Package size	96,500 cm^3	-	104,950 cm^3

FIXED/TEST GAUGES (≈ 4,100 + 66,000+)			
Source size	4.24 cm^3	-	13.5 cm^3
Shield size	198 cm^3	-	655 cm^3
Gauge/Container size	5,678 cm^3	-	9440 cm^3
Package size	20,600 cm^3	-	32,180 cm^3

OIL WELL LOGGING UNITS (≈ 2,000)			
Source size	14.3 cm^3	-	38.6 cm^3
Shield size	1073 cm^3	-	1442 cm^3
Container size	3,785 cm^3	-	5,680 cm^3
Package size			
Type A	20,600 cm^3	-	32,180 cm^3
Type B	71,800 cm^3	-	71,800 cm^3

3.3 Sealed Source Transport to DOE

The identified sealed sources and devices (i.e., moisture/density gauges, fixed/test gauges and well logging units) represent over 90% of the potential surplus sources to be shipped to DOE. These sources could be transported to DOE in three potential configurations. The choice of configuration would be influenced by DOE requirements for acceptance, U.S. Department of Transportation/NRC transport regulations, and the cost of source disassembly.

The smallest practical size of a source/device unit that requires transport to the DOE could be represented by a stripped down, shielded/contact-handled configuration. This configuration would require the source owner to use a vendor/manufacturer's service in completely dismantling the source to the extent that only the shielded container would remain. This would eliminate all electronics and support components of the sealed source. This disassembly could reduce the total volume of a device/source unit by as much as a factor of 25. While this may be the smallest practical size possible for handling purposes, some difficulty may exist in qualifying or demonstrating this component suitable as a type A package for transport. The requirement for some additional overpack for meeting the Transport Index and related requirements is probable. However, this configuration would minimize additional handling and disassembly at the DOE site prior to storage.

with all external deployment/ancillary equipment removed. This would require some vendor/manufacturer service effort but could also significantly reduce the size of the source equipment transported to DOE. This configuration should be readily acceptable as a type A package with minimal requirements for overpacks, etc. Based on size comparison, it is estimated that the volume of sealed source equipment shipped in the minimum device/source configuration would be reduced by a factor of 5 when compared to the original fully packaged equipment.

The third configuration is a that of a fully packaged source in the original transport package. This configuration, while acceptable for receipt and transport requirements, would possibly represent the most inefficient volume of material for storage and handling purposes and require substantial disassembly for optimum storage and eventual disposal.

3.4 Sealed Source Packaging Factors and Scenarios

The development of a simplified packaging factor for all sealed sources and devices is difficult at best because of the range of sizes and configurations represented by diverse types of surplus sources that exist. By narrowing down the predominant types of sources in the previous section, it is possible to develop a weighted packaging factor for modeling purposes.

3.4.1 Base Case Scenario

In the base case scenario, all sealed sources and devices will be loaded into high-level waste (HLW) or equivalent canisters in the smallest shielded/contacted-handled configuration practical. This base case is highly probable in that no remote handling should be required to process the sources, and substantial volume reduction is accomplished. As sources are accumulated, each canister will be loaded completely to minimize any void volume.

The packaging factor for this scenario is developed based on the ratio of shielded source volume to the unshielded source volume and any additional voids created in the package. Since three sources are considered as the major contributors, a weighted value was used to determine the average packaging factor, shown in Table H-5.

Table H-5. Base case scenario packaging factor

$$PF = \{VOLUME_{Shielded} / VOLUME_{Source}\}\{1 / VOID_{Fraction}\}$$

Weighted Values:

Moisture/Density	× # of Units	=	Volume Units
4140 /4.6 = 900	14,000		12.6 E06
Fixed/Test Gauges			
655/13.5 = 48.5	70,000		3.39 E06
Well logger			
1442/38.6 = 37.4	2,000		.07 E06
TOTALS	86,000		16.06 E06

$$VOL_{Shielded} / VOL_{Source} = 16.06\ E06/.086\ E06 = 190$$

Void Fraction is estimated to be ≈ 45 % to 50 % based on small cylindrical and spherical-shaped sources with shields having no significant wall effects due to the relatively large high-level waste canisters (0.057 m by 0.45 m).

$$PACKAGING\ FACTOR_{BASE\ CASE} = \{190 \times 1 / 0.5\} = 380$$

3.4.2 Low Case Scenario for Sealed Sources

In the low case scenario, all sealed sources and devices will be loaded into HLW canisters or their equivalent in their smallest unshielded conditions. This assumes that all contacted-handled units established in the base case scenario are further volume reduced by extracting the capsuled source from the shielded device. This scenario is also considered probable because some vendors-/manufacturers (moisture/density and well logger devices) have disassembled units down to the source/capsule size for both recycling and storage while awaiting disposal options.

The packaging factor for this low case scenario is based on the loading of small (0.75 cm^3 to 38.6 cm^3) cylindrical sources into the relatively larger cylindrical HLW canister. It is assumed that the loading is done with no special orientation of the source. The PF will therefore be primarily influenced by the void fraction created by the random loading of the canister. As with the base case scenario, no special factors for wall effect voids are considered likely. The void fractions are expected to be ≈ 45 % to 50 %.

$$Packaging\ Factor = \{1 / VOID_{FRACTION}\} = 1/0.5 = 2$$

3.4.3 High Case Scenario for Sealed Sources

The high case scenario considers options ranging from direct loading of the devices and holders in storage and disposal containers (very inefficient) to selective loading of contact-handled sources and devices in special containers for transport. One vendor/manufacturer[a] is currently developing a method/process of loading multiple sources into a 7A drum (55 gal) that has special pipe sleeves and shielding for collecting surplus sources. The container design varies as a function of the source (i.e., neutron, gamma, etc.) and the associated shielding/Transport Index considerations. Based on nominal sealed source considerations, it is expected that from 10 to 20 sources may be loaded in this configuration. The immediate value to DOE is that these transport containers could be used as temporary storage containers and reduce the initial handling and storage impact at the receiving facility.

The high case scenario is defined as the loading of sources into a modified transport and storage container that can be transported and used by DOE for storage and eventual downloading to an HLW canister. This scenario is also highly probable and applicable to the three major source configurations identified in Table H-6.

The packaging factor is based on loading up to 20 sources in a 55-gal drum. The sources can be loaded in an unshielded condition with added shielding to the container or a shielded condition requiring minimal shielding by the drum.

Table H-6. High case scenario for sealed sources packaging factor

$$PF_{\text{High Case}} = \{Drum_{Vol} / \# \text{ of Sources} \times Vol_{Source}\} \{ \text{Weight Factor}\}$$

Moisture/Density	× # of Units	= Volume Units
208,206/ 20 × 4.6 = 2,263	14,000	3.17 E0
Fixed/Test Gauges		
208,206/ 20 × 13.5 = 771	70,000	5.4 E07
Well logger		
208,206/ 20 × 38.6 = 270	2,000	0.05 E07
TOTALS	86,000	8.62 E07

$$PF_{\text{High Case}} = 8.62\text{ E07} / .086\text{ E06} = 1000$$

The NRC staff recommended that an additional high case scenario be considered based on the return of the sealed sources in their original package configuration. The scenario appears appropriate when considering the majority of the fixed/test gauges are encased in steel cases with the sources and primary shields retained within. The shielding for this configuration includes both the case body and the shielded source within the case. An assumption was made based on measured

a. Personal communications with Bill Walker, Troxler Electronics, Inc., January 1991.

package scenario was developed for loading these source device cases in either a 55-gal drum or a standard box design. The drum configuration identified a maximum of 12 cases per drum. The comparable volume box configuration would hold 22 cases per box. The packaging factor of 12 cases of sources per drum is 1285 (208,206/ 12 × 13.5). The packaging factor of 22 cases per box is 700 (208,206/22 × 13.5). The average PF of these two configurations is 990. These packaging factors bound the range for the high case scenario and demonstrate that the weighted average approach should be acceptable for modeling purposes in determining sealed source package volumes for DOE projections.

4. ALL OTHER GTCC LLW

The volume of GTCC LLW generated by commercial facilities will not be the volume disposed of by the DOE. The volume of the waste containers into which the GTCC LLW will be placed will constitute the disposal volume. Empty volume in a waste container will be minimized by the generators if minimization is made cost-effective compared to costs for storage and disposal of the empty space. Although costs for DOE acceptance of GTCC LLW are not firm, a high cost per unit volume of waste container will tend to move generators toward minimizing void volume in a waste container for most GTCC LLW forms.

Since many GTCC LLW forms are similar to Class A, B, and C wastes that can be disposed of in licensed disposal facilities, and since disposal costs at such facilities are high enough to require waste generators to pursue volume reduction operations, the current industry practices for volume reduction of Class A, B, and C wastes will likely be considered for treatment of GTCC LLW. If there is a relatively higher cost for disposal of GTCC LLW by the DOE than for commercial disposal of low-level wastes, additional technologies for volume reduction of GTCC LLW that are cost-effective would likely be introduced in the future. Likewise, some currently available but uneconomical technologies may become cost-effective in the future.

A generic base case for a packaging factor for all other GTCC LLW is a factor of 1.0. This value reflects the uncertainty in the volume reduction technologies that can be used for GTCC LLW and in the amounts of the different types of materials that will be generated. From current projections of all other unpackaged GTCC LLW, the mix of such wastes will be primarily compactible and noncompactible materials. A reasonable assumption appears to be that the volume decrease from compaction, incineration, and other volume reduction technologies will offset the volume increase from packaging noncompactible materials into waste containers. With this assumption, the gains from volume reduction technologies would offset the historical increase in the overall volume of wastes just due to the packaging of the wastes.

The generic low value for the packaging factor for all other GTCC LLW is 0.5, or a prediction that a net reduction will occur from the amount generated to the amount disposed. This value reflects the significant advances in supercompaction and radioactive waste incineration that have recently become available for low-level waste treatment in the United States. With volume reduction factors of 300 to 1 for incineration and 10 to 1 for supercompaction, treatment of significant amounts of the GTCC LLW by these methods would bring the packaging factor down considerably. The proposed value reflects that these new technologies will be available and used to some extent by the GTCC LLW generators.

The generic high value for the packaging factor for all other GTCC LLW is expected to be 1.5, or a packaging efficiency of 0.67. This value represents an inability to use volume reduction technologies to a significant extent for GTCC LLW due to the radionuclide concentrations that make the waste GTCC LLW in the first place. Commercial treatment centers may be unwilling to allow treatment because of the potential for significant contamination of expensive equipment. Also, GTCC LLW generators may not have the volume of GTCC LLW to justify installation of volume reduction equipment. The proposed value reflects the unique nature of this waste and the potential difficulty in processing it economically.

4.1 Decontamination Resins

The two principal sources of decontamination resins include those generated in purification demineralizers for PWR and BWR reactor coolant systems and processing resins for major system and component decontamination solutions. The reactor coolant system purification resins are not normally GTCC LLW. However, if significant levels of failed fuel exist and resins systems are operated until resin exchange capacity is exhausted, then GTCC LLW resins are possible. Normally, these resin systems are replaced because of high differential pressure or high radiation fields, which normally preclude this as GTCC LLW.

The other principal source of GTCC LLW ion-exchange resins is from processing highly concentrated chemical decontamination solutions. These solutions contain oxidizers and chelating agents that readily remove the activated corrosion products (i,e., Ni-58 and Nb-94) from the surface oxides of the metals. The resins act as a concentration mechanism to highly concentrate these relatively long-lived corrosion products.

In determining the packaging scenarios and related packaging factors, the following assumptions are considered valid. First, the generators will use those economic incentives to maximize volume reduction technologies once it is concluded that the ion-exchange resins are determined to be GTCC LLW. Secondly, operational constraints on maximum concentration limits, capacities, and transport packages (Type B) will not restrict, influence, or constrain loading decisions. Thirdly, the packaging scenario will be directly influenced by the treatment method and any associated volume reduction, which will provide greater or lesser package loading efficiency. The following represents the best reasonable estimate of packaging scenarios/factors for spent resins.

4.1.1 Packaging Factors for Spent Resins (Base, High, and Low Case)

Unless driven by high cost, waste generators would normally be expected to minimize processing and handling of GTCC LLW spent resins. The primary requirement for transporting and receiving wet solids, which is consistent with current requirements, would be to dewater the resins and load them into a high-integrity container (HIC). This effort would only require a sluicing system and dewatering system with minimal requirements at the generator site. Typically, this is done with most resin operations identified in the industry. The loading into a high-integrity container satisfies most isolation and stabilization requirements and should be suitable for DOE acceptance. The loading efficiencies of this type of operation are only influenced by the resins' packaging efficiency and are not affected by the size of the container. The void fraction for small spherical bead resin is approximately 40-50%. Since the volume of resins identified in the source projection studies included the void volumes, a base case projection for spent resins was assumed to be dewatered resins with a volume packaging equivalent to unity.

$$\text{PACKAGING FACTOR}_{\text{Base Case}} = 1 \quad \text{(Dewatered Resins)}$$

The high case scenario assumed that requirements for stabilizing the resins other than in a high-integrity container would be imposed. Options for stabilizing the material with no volume reduction could include cementation or solidification by encapsulation with polymer materials. The technology for organic encapsulation typically shows no volume change relative to the dewatered resin volume. For cementation, the typical volume ratio of resins to cement ranges from 1:1 to 1:0.6. A reasonable high case scenario for expected packaging factors would be a solidified resin matrix with volume increase of 2.

PACKAGING FACTOR $_{\text{High Case}}$ = 2 (Dewatered and Solidified Resins)

The low case scenario assumes that substantial economic incentives exist to maximize volume reduction (VR). This scenario concluded that the latest technology would be used to sinter the resins with compaction to a VR of 10:1. The resins would then be stabilized through encapsulation or cementation, with a volume increase to 2:1. The resultant packaging factor for the low volume case would be a net volume change of 0.2.

PACKAGING FACTOR $_{\text{Low Case}}$ = 0.2 (Sintered and Cemented Resins)

4.2 Cartridge Filters

The principal sources of filter cartridges are BWR and PWR control rod drive filters, seal water injection and return filters, fuel pool, reactor coolant makeup, and purification system filters. Typically, filters range in size from 0.1 ft^3 (4 in. OD by 12 in. length) to 1.0 ft^3 (8 in. OD by 3 ft length). The predominant radionuclide contaminates are activated metals (C^{14}, Nb^{94}, Tc^{99}) and TRU sources (Cm^{242}, Pu^{241}, other traces transuranics). Cartridge filters generally contain metal endcaps for stability which are retained with the discarded filter.

4.2.1 Packaging Factors for Cartridge Filters (Base, High, and Low Case)

Generator decisions on packaging and transport to DOE will be influenced by least cost/impact processes for volume reduction, handling, and packaging. Cartridge filters do not require any special processing for collection and handling other than dose and contamination control. Consistent with current practices, it is reasonable to conclude that spent filters would be dewatered and packaged in high integrity containers with no consideration of volume reduction. Currently, highly contaminated filters (e.g, Class B or C) are randomly placed (dumped) in open HICs with flange closure lids. The loading efficiency with these various-sized filters in a relatively larger HIC container would be expected to range from .25 to 0.5. This scenario is considered the most likely (base case) because of minimal cost and accepted practice for storage and disposal.

Packaging Factor $_{\text{Base Case}}$ = 2 (Dewatered Filters/No VR)

In the high volume case, where encapsulation (e.g., cementation or equivalent) might be a requirement, it was assumed that the encapsulation material would be used to fill the voids created by the filter cartridges. The packaging efficiency for this scenario is considered to be the worst case, (0.25) with a PF of 4.

Packaging Factor $_{\text{High Case}}$ = 4 (Encapsulated Filters/No VR)

In the low volume case, it is assumed that significant economic incentive exists for the generator to look at available technologies and service organizations to volume reduce and package the waste filters. Current technology services available include shredding and encapsulation. A volume reduction of 10:1 or greater is expected.

Packaging Factor $_{\text{Low Case}}$ = 0.1 (Shredding and Encapsulation)

4.3 Aqueous Liquids

The primary sources of aqueous liquids include americium salts and UO_2 dissolved in nitric acid and hydrofluoric acid. These liquids generally contain both transuranic and activated/fission product components. The treatment and processing considerations for transport, storage, and disposal usually require solution neutralization and solidification. The transuranic activities in these liquids influence their GTCC LLW classifications. Since GTCC LLW liquids cannot be easily transported, the generators will usually use best available technologies for volume reduction and stabilization. These technologies and treatment services include ion-exchange processing (similar to treatment of decontamination solutions), evaporation, and direct solidification. These aqueous liquids, after pH adjustment (neutralization), are readily amenable to all demonstrated treatment technologies.

4.3.1 Packaging Factors for Aqueous Liquids (Base, High, and Low Case)

One current method for concentrating and stabilizing the aqueous liquids is the use of ion-exchange resins. These resins could be processed as discussed in Section 4.1. Based on the expected high dissolved salt content and the associated resin capacity, the volume reduction in this process would not be expected to be much greater than 10:1. Because of the relatively high concentration loading of TRU and salts, it may be expected that these resins would be placed into an HIC or solidified by cementation. The volume increase with cementation is ≈ 1.6, and the overall processing/packaging volume reduction would be expected to be ≈0.2. The container used to solidify the material would be the same as the disposal container, and therefore the packaging factor would be 0.2.

PACKAGING FACTOR $_{\text{Base Case}}$ = 0.2 (Ion-Exchange/Solidified Liquids)

The high volume case for processing liquids assumes that a base solution neutralization step will be required, which could double the volume of the waste liquid prior to further processing. This step would then be followed by a cementation process, which could increase the volume by 1.6. The net increase in volume for the high volume scenario is 3:1.

PACKAGING FACTOR $_{\text{High Case}}$ = 3.0 (pH Adjusted/ Solidified)

The low volume case scenario assumes that the liquids will be evaporated to near-dryness and then solidified in cement. Because the acid and dissolved salt content is relatively high (1–2 wt%), the concentration factor for evaporation would be less than 100. The cementation step would increase the volume, with a net volume reduction of approximately 10.

PACKAGING FACTOR $_{\text{Low Case}}$ = 0.1 (Evaporation/Solidified Liquids)

4.4 Solidified Liquids

The sources of GTCC LLW solidified liquids include TRU bearing solids from fuel fabrication facilities and highly concentrated process liquids from BWR and PWR facilities. It is assumed that no additional requirement exists for processing this material. Additionally, no special restrictions exist for packaging, transporting, storage, and disposal of this material. The physical form of this material is considered as a solidified monolith or as solid granular material.

4.4.1 Packaging Factors for Solidified Liquids (Base, High, and Low Case)

Since this material exists in a solid form, there may be no economic incentive to further process and volume reduce this waste form. The most probable packaging and handling scenario would be to leave this material in the existing transport package or transfer this material into transport containers and load to the maximum extent practical. The material would be expected to fill each container with minimal voids and loading inefficiencies. The packaging volume would be similar to the source projection volume.

PACKAGING FACTOR $_{\text{Base Case}}$ = 1 (Dry with No Further Processing)

The high volume case assumes that the solid form of material will be encapsulated because of stablization requirements. Consistent with previously used methods, this could include cementation, with a volume increase factor of 1.6. The waste form would be formed in the storage, transport, and disposal container with minimal voids.

PACKAGING FACTOR $_{\text{High Case}}$ = 1.6 (No Volume Reduction/ Encapsulation)

The low volume case assumes the use of the best available and demonstrated technology. It is also assumed that the solid material is not amenable to incineration or similar processes. The low case scenario considers the vitrification/melting of solidified liquids, with a potential volume reduction of 20%. The waste form would be formed in the storage and disposal container, with optimum packaging efficiency.

PACKAGING FACTOR $_{\text{Low Case}}$ = 0.8 (Vitrification)

APPENDIX A

Figures and Tables for Activated Metals

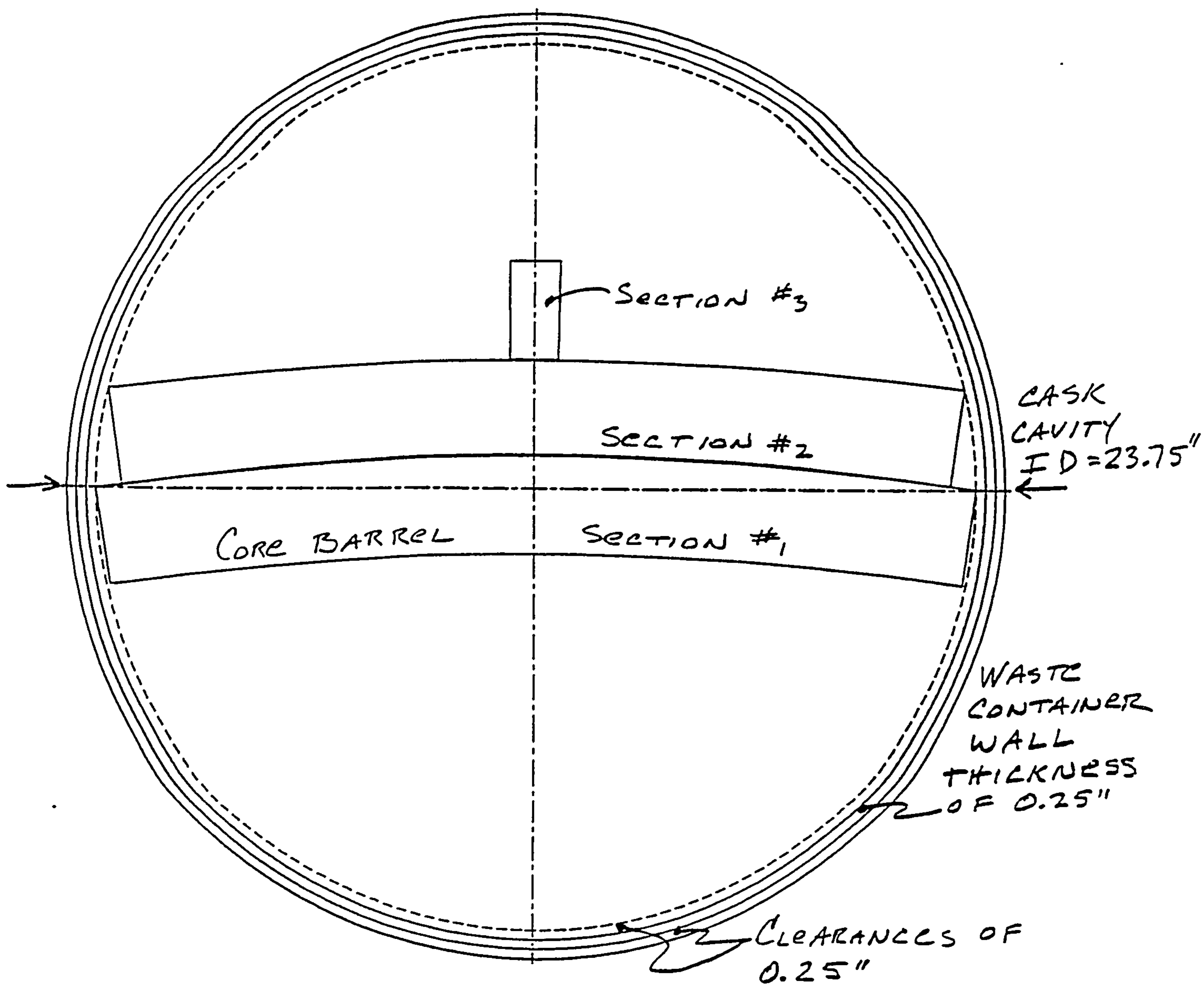

Figure H-1. Arrangement of LCB sections in a weight constrained, cylindrical cross section waste container.

Example: Model TITAN truck cask without basket
CB dimensions: ID = 148 in. Thk = 2.5 in.

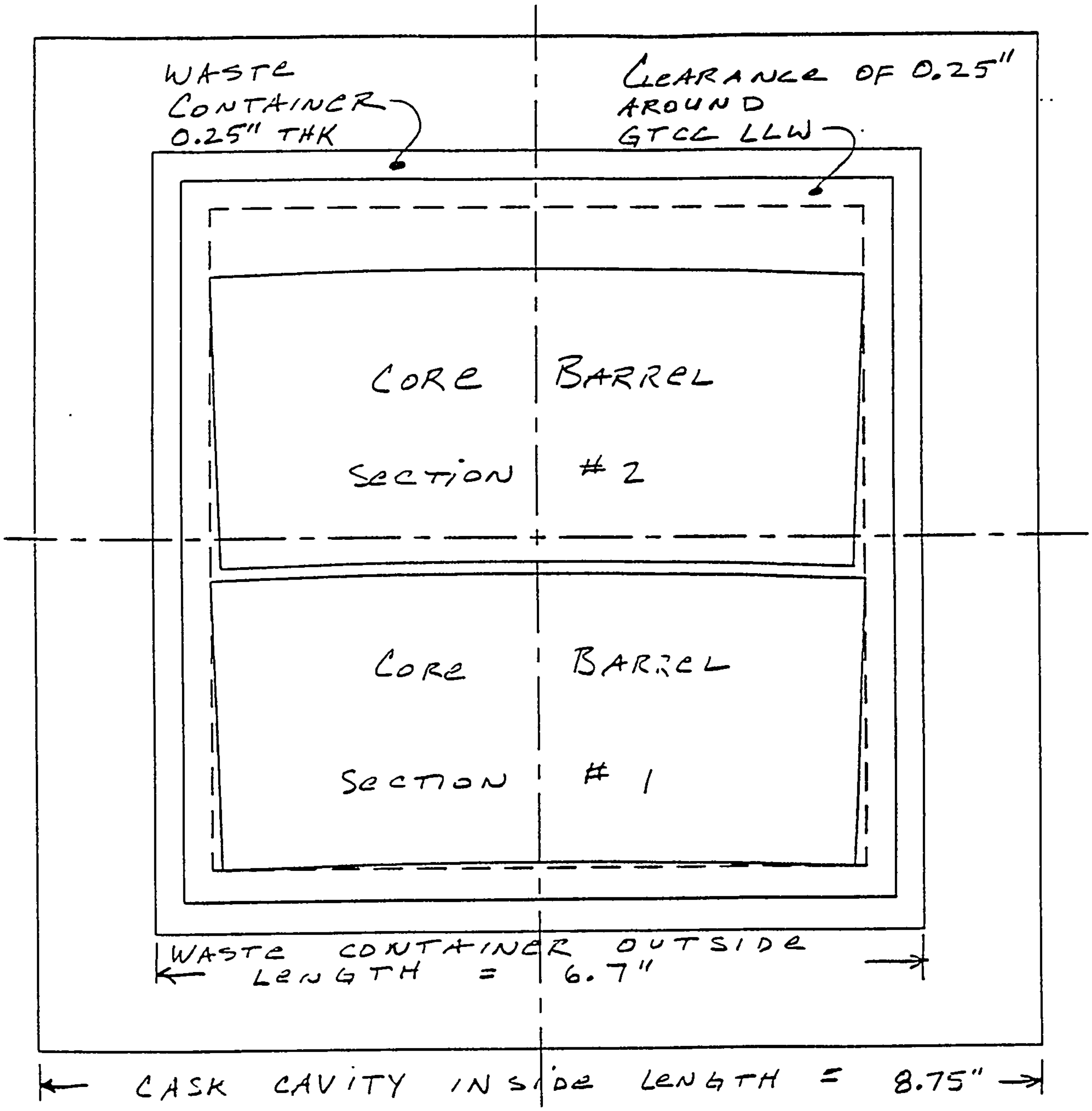

Figure H-2. Arrangement of LCB sections in a weight-constrained, square cross section waste container.

Example: PWR spent fuel cask with basket in place
CB dimensions: ID = 148 in. Thk = 2.5 in.

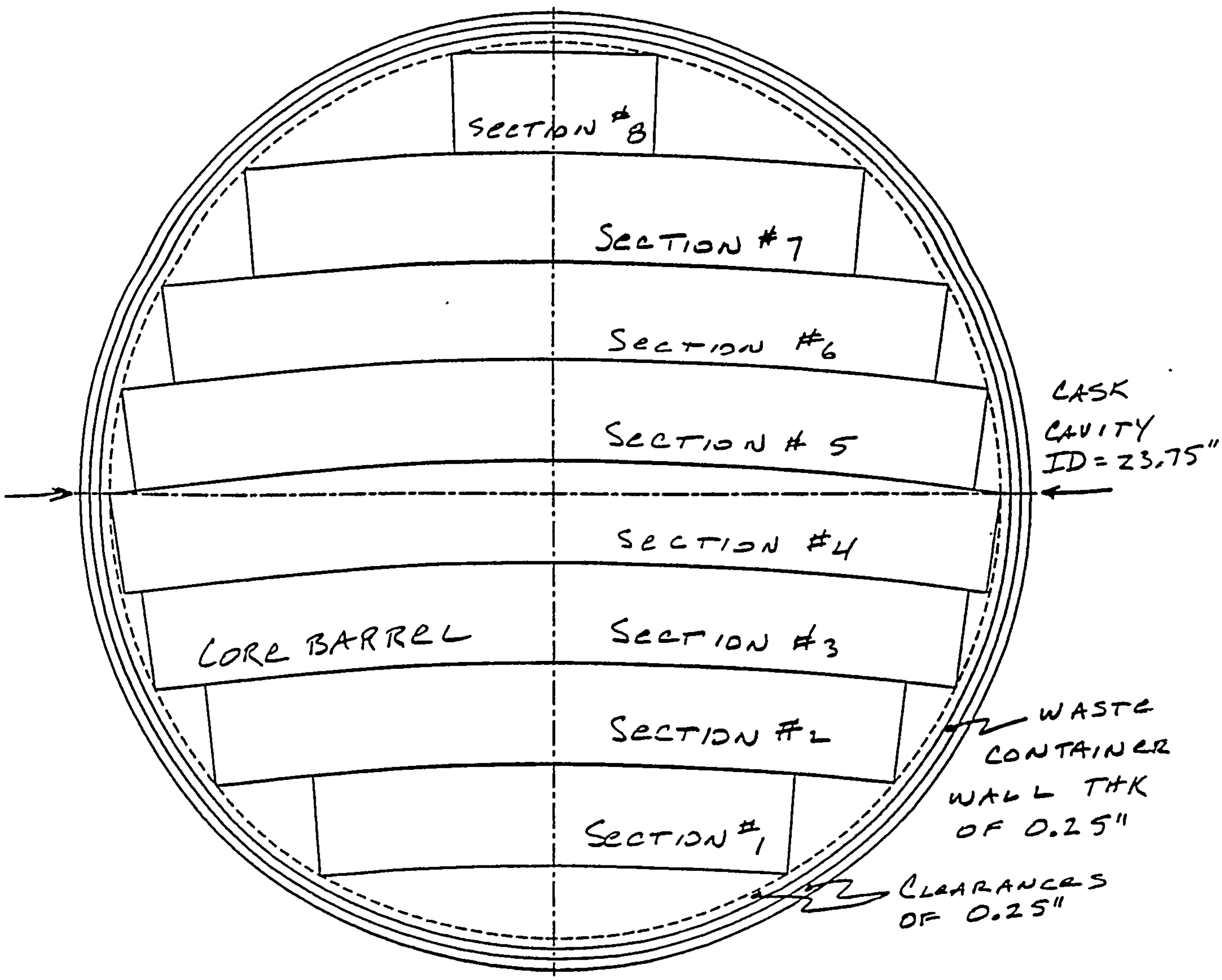

Figure H-3. Arrangement of LCB sections in a volume constrained, cylindrical cross section waste container.

Example: Model TITAN truck cask without basket
CB dimensions: ID = 148 in. Thk = 2.5 in.

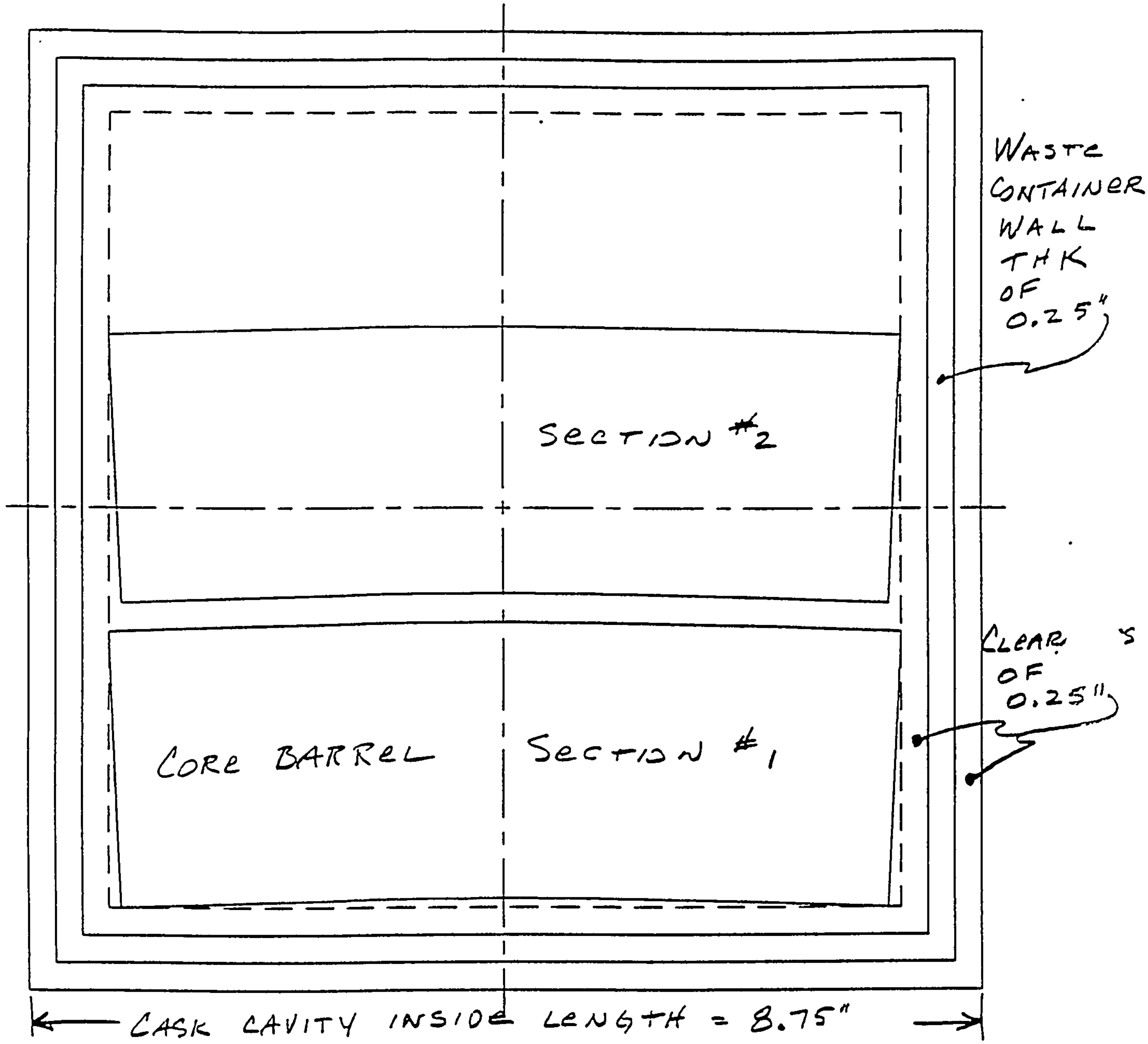

Figure H-4. Arrangement of LCB in a volume constrained, square cross section waste container.

Example: PWR spent fuel cask with basket in place
CB dimensions: ID = 148 in. Thk = 2.5 in.

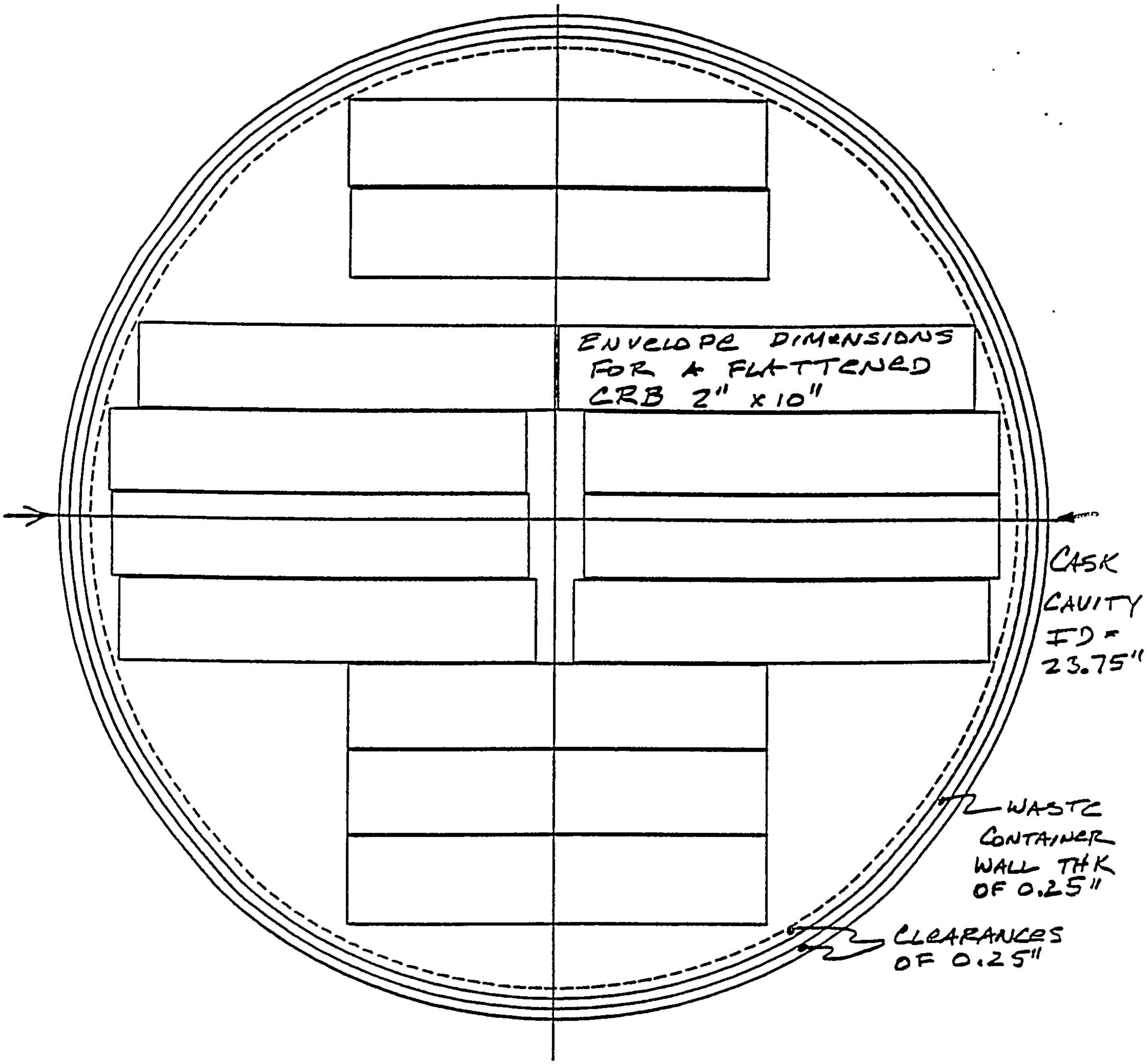

Figure H-5. Arrangement of BWR control rod blades in a cylindrical cross section waste container.

Example: Model TITAN truck cask without basket
Flattened CRB envelope dimensions: 2 in. by 10 in.

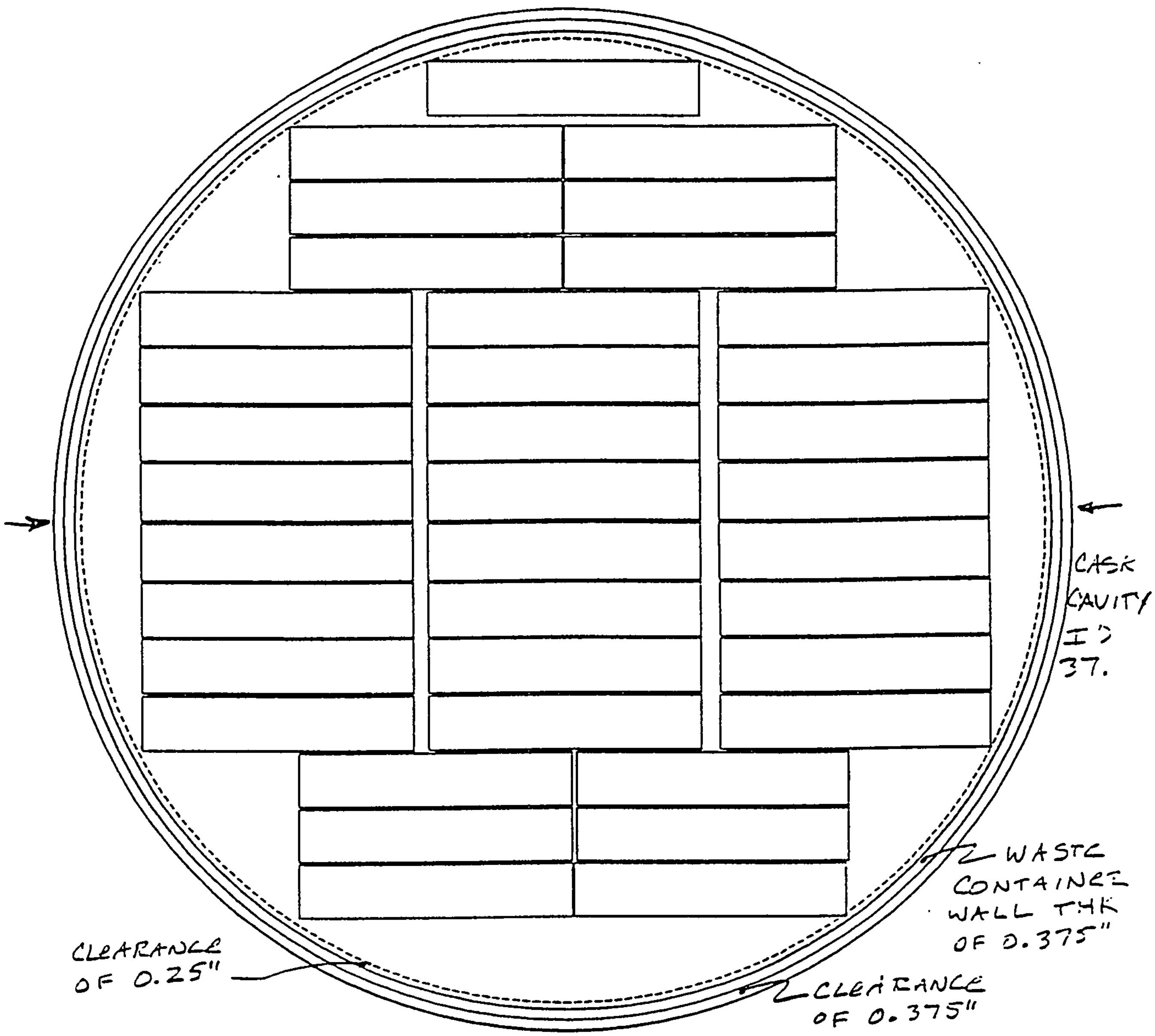

Figure H-6. Arrangement of BWR control rod blades in a cylindrical cross section waste container.

Example: Model IF-300 rail cask without basket
Flattened CRB envelope dimensions: 2 in. by 10 in.

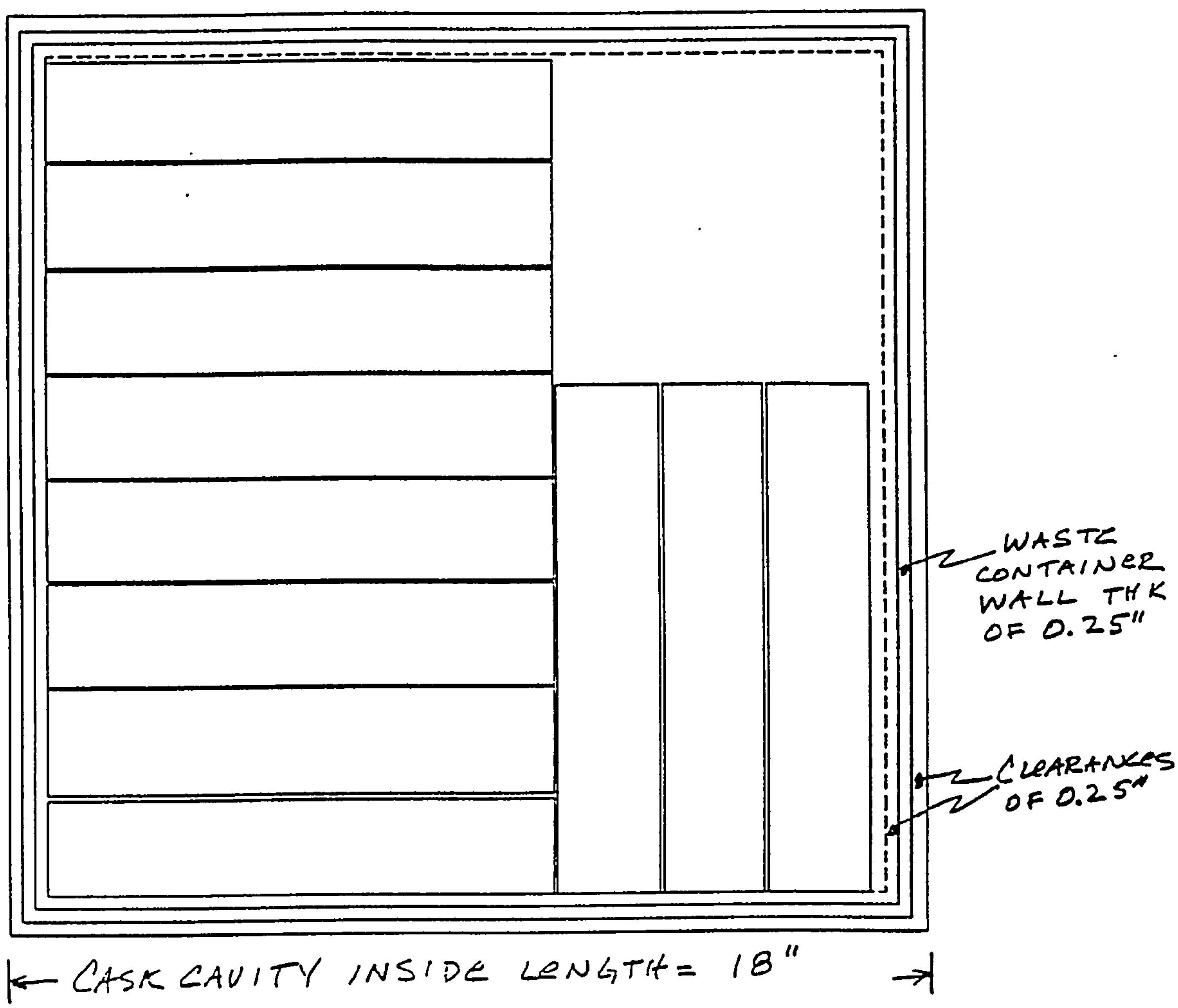

Figure H-7. Arrangement of BWR control rod blades in a square cross section waste container.

Example: Model GA-4 truck cask without basket
Flattened CRB envelope dimensions: 2 in. by 10 in.

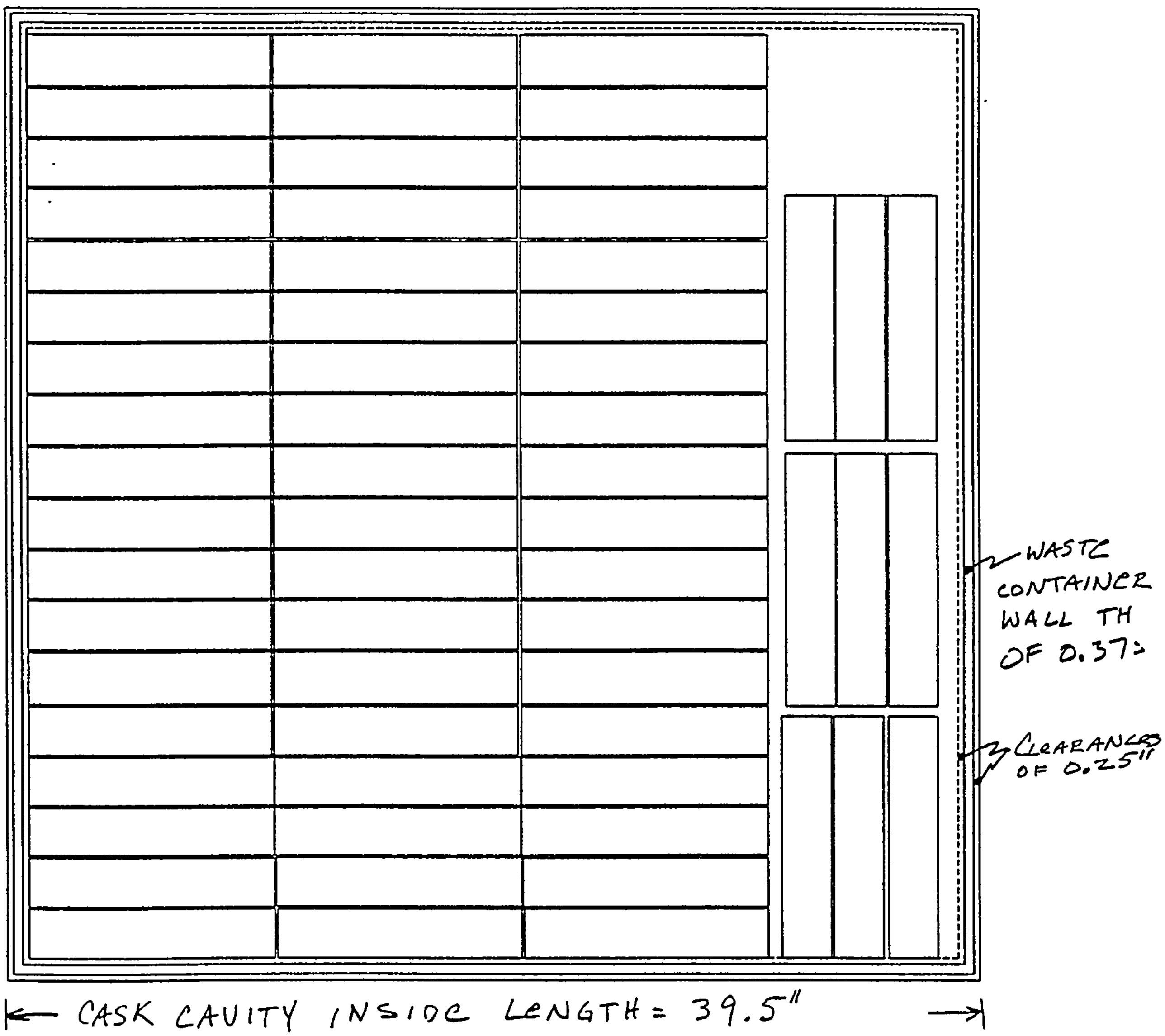

Figure H-8. Arrangement of BWR control rod blades in a square cross section waste container.

Example: Model BR-100 rail cask without basket
Flattened CRB envelope dimensions: 2 in. by 10 in.

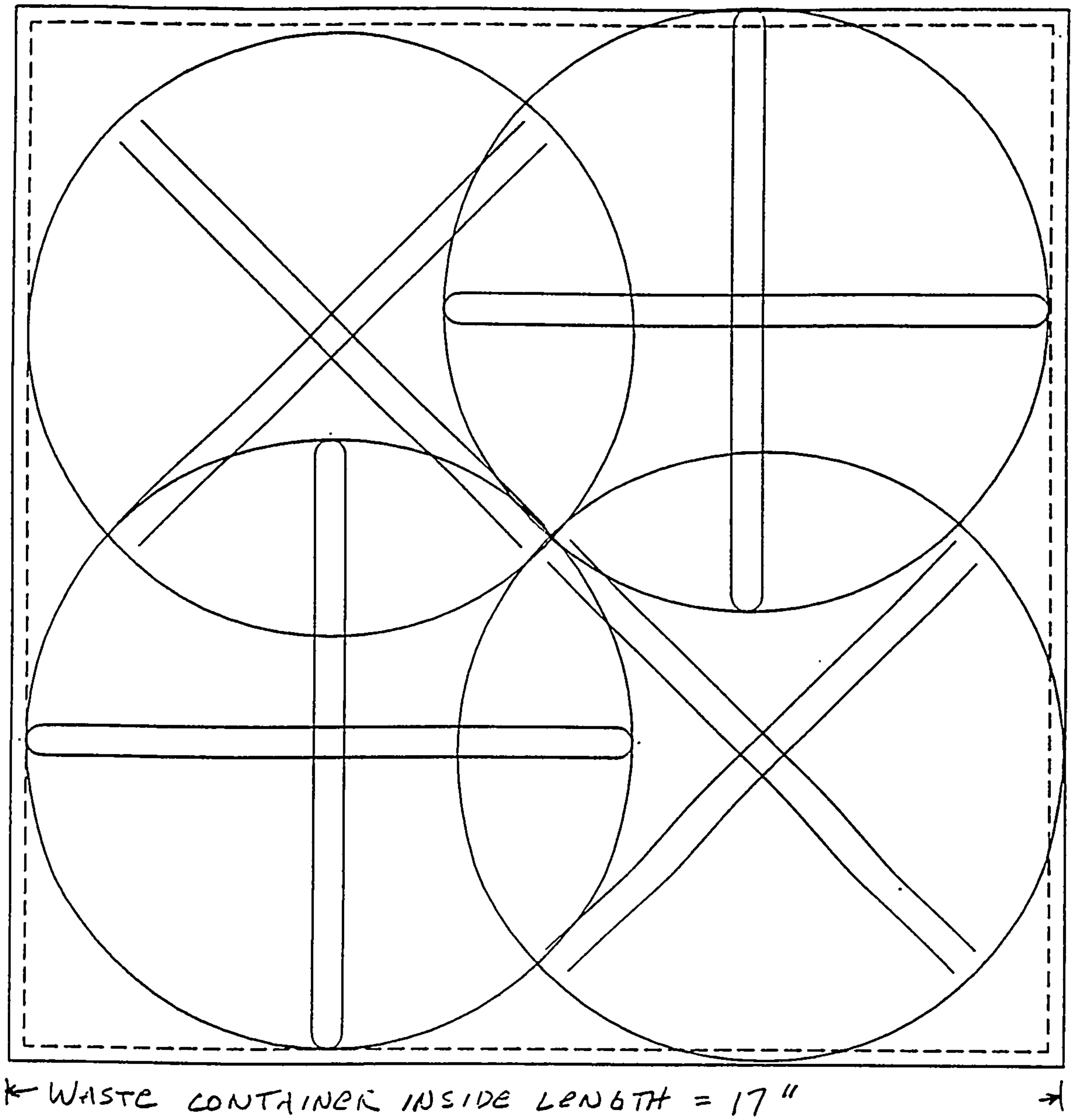

Figure H-9. Arrangement of BWR control rod blades in a square cross section waste container.

Example: Model GA-9 truck cask without basket
CRB envelope dimensions: 10 in. diameter

Table H-7. Packaging efficiences for the Model TITAN Truck Cask without a spent fuel basket

Packaging Efficiencies for the Model TITAN Truck Cask without a Spent Fuel Basket

Weight Constrained — Cylindrical Waste Containers

Payload weight is maximized up to 6,235 pounds limit for the cask

Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Weight of a full waste container pounds
1	153	148	2.5	0.222	12	0.225	6,235
2	152	148	2	0.213	10	0.225	6,235
3	154	148	3	0.214	15	0.225	6,235
4	163	158	2.5	0.219	13	0.225	6,235
5	162	158	2	0.206	11	0.225	6,235
6	164	158	3	0.214	16	0.225	6,235
7	143	138	2.5	0.208	12	0.225	6,235
8	142	138	2	0.221	9	0.225	6,235
9	144	138	3	0.214	14	0.225	6,235

Table H-8. Packaging effeciences for the Model IF-300 Rail Cask without a spent fuel basket

Packaging Efficiencies for the Model IF-300 Rail Cask without a Spent Fuel Basket

Weight Constrained — Cylindrical Waste Containers

Payload weight is maximized up to 21,000 pounds limit for the cask

Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Weight of a full waste container pounds
1	153	148	2.5	0.267	4	0.333	21,000
2	152	148	2	0.284	3	0.333	21,000
3	154	148	3	0.321	4	0.333	21,000
4	163	158	2.5	0.285	4	0.333	21,000
5	162	158	2	0.303	3	0.333	21,000
6	164	158	3	0.274	5	0.333	21,000
7	143	138	2.5	0.332	3	0.333	21,000
8	142	138	2	0.265	3	0.333	21,000
9	144	138	3	0.300	4	0.333	21,000

Table H-9. Packaging efficiences for the Model 125-B Rail Cask without an inner containment vessel

Packaging Efficiencies for the Model 125-B Rail Cask without an Inner Containment Vessel

Weight Constrained — Cylindrical Waste Containers

Payload weight is maximized up to 57,565 pounds limit for the cask

Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Weight of a full waste container pounds
1	153	148	2.5	0.283	2	0.527	57,565
2	152	148	2	0.451	1	0.451	50,119
3	154	148	3	0.340	2	0.527	57,565
4	163	158	2.5	0.302	2	0.527	57,565
5	162	158	2	0.481	1	0.481	53,043
6	164	158	3	0.363	2	0.527	57,565
7	143	138	2.5	0.264	2	0.527	57,565
8	142	138	2	0.421	1	0.421	47,194
9	144	138	3	0.318	2	0.527	57,565

Table H-10. Packaging efficiencies for casks with PWR spent fuel baskets

Packaging Efficiencies for Casks with PWR Spent Fuel Baskets

Weight Constrained — Square Cross-section Waste Containers

Payload weight is maximized up to 1,515 pounds limit for each cask cavity position

Case Number	Lower Core Barrel Dimensions ------inches------ Outer Dia.	Inner Dia.	Thck	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Length of the side of a waste container inches	Weight of a full waste container pounds	Number of sections of LCB per full waste container
1	153	148	2.5	0.597	43	0.609	6.7	1,498	2
2	152	148	2	0.469	40	0.472	7	1,306	2
3	154	148	3	0.350	81	0.352	7	1,025	1
4	163	158	2.5	0.609	45	0.610	6.7	1,499	2
5	162	158	2	0.466	43	0.472	7	1,307	2
6	164	158	3	0.351	86	0.352	7	1,026	1
7	143	138	2.5	0.600	40	0.609	6.7	1,497	2
8	142	138	2	0.461	38	0.471	7	1,305	2
9	144	138	3	0.348	76	0.351	7	1,024	1

Table H-11. Packaging efficiencies for the GA-4 Truck Cask without a spent fuel casket

Packaging Efficiencies for the GA-4 Truck Cask without a spent fuel basket

Weight Constrained Square Cross-section Waste Containers

Payload weight is maximized up to 8,760 pounds limit for the cask

Case Number	Lower Core Barrel (LCB) Dimensions ------inches------ Outer Dia.	Inner Dia.	Thck	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Length of the side of a waste container inches	Weight of a full waste container pounds	Number of sections of LCB per full waste container
1	153	148	2.5	0.704	7	0.734	15.3	8,755	5
2	152	148	2	0.663	6	0.711	15.2	8,392	6
3	154	148	3	0.610	9	0.678	15.9	8,762	4
4	163	158	2.5	0.657	8	0.735	15.3	8,762	5
5	162	158	2	0.708	6	0.712	15.2	8,397	6
6	164	158	3	0.659	9	0.682	15.8	8,710	4
7	143	138	2.5	0.657	7	0.733	15.3	8,747	5
8	142	138	2	0.619	6	0.711	15.2	8,387	6
9	144	138	3	0.641	8	0.677	15.9	8,753	4

Table H-12. Packaging efficiencies for the 125-B Rail Cask with an inner containment vessel replaced by a special square cavity basket

Packaging Efficiencies for the 125-B Rail Cask with an Inner Containment Vessel replaced by a Special Square Cavity Basket

Weight Constrained Square Cross-section Waste Containers

Payload weight is maximized up to 51,808 pounds limit for the cask or cavity size (34")

Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Length of the side of a waste container inches	Weight of a full waste container pounds	Number of sections of LCB per full waste container
1	153	148	2.5	0.490	2	0.807	34	48,533	12
2	152	148	2	0.781	1	0.781	34	47,065	15
3	154	148	3	0.590	2	0.805	34	48,384	10
4	163	158	2.5	0.522	2	0.807	34	48,537	12
5	162	158	2	0.417	2	0.810	34	48,678	15
6	164	158	3	0.629	2	0.805	34	48,397	10
7	143	138	2.5	0.457	2	0.807	34	48,532	12
8	142	138	2	0.729	1	0.729	34	44,142	14
9	144	138	3	0.551	2	0.804	34	48,372	10

Table H-13. Packaging efficiencies for the BR-100 Rail Cask with a spent fuel basket replaced by a special square cavity basket

Packaging Efficiencies for the BR-100 Rail Cask with a Spent Fuel Basket replaced by a Special Square Cavity Basket

Weight Constrained — Square Cross-section Waste Containers

Payload weight is maximized up to 40,000 pounds limit for the cask

Case Number	Lower Core Barrel (LCB) Dimensions, inches: Outer Dia.	Inner Dia.	Thck	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Length of the side of a waste container inches	Weight of a full waste container pounds	Number of sections of LCB per full waste container
1	153	148	2.5	0.605	2	0.818	30.6	39,882	11
2	152	148	2	0.498	2	0.788	30.1	37,291	13
3	154	148	3	0.700	2	0.785	31.2	39,925	9
4	163	158	2.5	0.645	2	0.818	30.6	39,892	11
5	162	158	2	0.532	2	0.848	30.1	39,961	14
6	164	158	3	0.747	2	0.786	31.2	39,942	9
7	143	138	2.5	0.565	2	0.817	30.6	39,873	11
8	142	138	2	0.465	2	0.788	30.1	37,290	13
9	144	138	3	0.654	2	0.785	31.2	39,909	9

Table H-14. Packaging efficiencies for the Model TITAN Truck Cask without a spent fuel basket

Packaging Efficiencies for the Model TITAN Truck Cask without a Spent Fuel Basket

Volume Constrained — Cylindrical Waste Containers

Case Number	Lower Core Barrel (LCB) Dimensions inches: Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container
1	153	148	2.5	0.667	4	0.747
2	152	148	2	0.709	3	0.713
3	154	148	3	0.642	5	0.715
4	163	158	2.5	0.711	4	0.750
5	162	158	2	0.567	4	0.600
6	164	158	3	0.685	5	0.716
7	143	138	2.5	0.662	3	0.744
8	142	138	2	0.623	4	0.719
9	144	138	3	0.600	5	0.713

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Table H-15. Packaging efficiencies for the Model IF-300 Rail Cask without a spent fuel basket

Packaging Efficiencies for the Model IF-300 Rail Cask without a Spent Fuel Basket

Volume Constrained — Cylindrical Waste Containers

Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container
1	153	148	2.5	0.493	2	0.812
2	152	148	2	0.786	1	0.786
3	154	148	3	0.593	2	0.793
4	163	158	2.5	0.526	2	0.812
5	162	158	2	0.419	2	0.821
6	164	158	3	0.633	2	0.795
7	143	138	2.5	0.460	2	0.810
8	142	138	2	0.734	1	0.734
9	144	138	3	0.554	2	0.790

Table H-16. Packaging efficiencies for the Model 125-B Rail Cask withoug an inner containment vessel

Packaging Efficiencies for the Model 125-B Rail Cask without an Inner Containment Vessel

Volume Constrained — Cylindrical Waste Containers

Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container
1	153	148	2.5	0.565	1	0.565
2	152	148	2	0.451	1	0.451
3	154	148	3	0.681	1	0.681
4	163	158	2.5	0.603	1	0.603
5	162	158	2	0.481	1	0.481
6	164	158	3	0.726	1	0.726
7	143	138	2.5	0.526	1	0.526
8	142	138	2	0.421	1	0.421
9	144	138	3	0.636	1	0.636

Table H-17. Packaging efficiencies for casks with PWR spent fuel baskets

Packaging Efficiencies for Casks with PWR Spent Fuel Baskets

Volume Constrained — Square Cross-section Waste Containers

Case Number	Lower Core Barrel (LCB) Dimensions inches: Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Length of the side of a waste container inches	Weight of a full waste container pounds	Number of sections of LCB per full waste container
1	153	148	2.5	0.498	34	0.511	8.25	1,910	2
2	152	148	2	0.614	22	0.616	8.25	2,248	3
3	154	148	3	0.600	34	0.612	8.25	2,235	2
4	163	158	2.5	0.502	36	0.512	8.25	1,911	2
5	162	158	2	0.600	24	0.616	8.25	2,250	3
6	164	158	3	0.604	36	0.612	8.25	2,238	2
7	143	138	2.5	0.510	31	0.511	8.25	1,908	2
8	142	138	2	0.600	21	0.615	8.25	2,247	3
9	144	138	3	0.595	32	0.611	8.25	2,233	2

Table H-18. Packaging efficiencies for the GA-4 Truck Cask without a spent fuel basket

Packaging Efficiencies for the GA-4 Truck Cask without a Spent Fuel Basket

Volume Constrained — Square Cross-section Waste Containers

Case Number	Lower Core Barrel (LCB) Dimensions inches: Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Length of the side of a waste container inches	Weight of a full waste container pounds	Number of sections of LCB per full waste container
1	153	148	2.5	0.748	5	0.775	17.56	12,072	6
2	152	148	2	0.746	4	0.829	17.56	12,871	8
3	154	148	3	0.751	6	0.772	17.56	12,035	5
4	163	158	2.5	0.665	6	0.775	17.56	12,081	6
5	162	158	2	0.795	4	0.829	17.56	12,878	8
6	164	158	3	0.686	7	0.773	17.56	12,046	5
7	143	138	2.5	0.698	5	0.774	17.56	12,062	6
8	142	138	2	0.696	4	0.828	17.56	12,863	8
9	144	138	3	0.701	6	0.771	17.56	12,023	5

Table H-19. Packaging efficiencies for the 125-B Rail Cask with an inner containment vessel replaced by a special square cavity basket

Packaging Efficiencies for the 125-B Rail Cask with an Inner Containment Vessel replaced by a Special Square Cavity Basket

Volume Constrained — Square Cross-section Waste Containers

Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container	Length of the side of a waste container inches	Weight of a full waste container pounds	Number of sections of LCB per full waste container
1	153	148	2.5	0.490	2	0.807	34	48,533	12
2	152	148	2	0.781	1	0.781	34	47,065	15
3	154	148	3	0.590	2	0.805	34	48,384	10
4	163	158	2.5	0.522	2	0.807	34	48,537	12
5	162	158	2	0.417	2	0.810	34	48,678	15
6	164	158	3	0.629	2	0.805	34	48,397	10
7	143	138	2.5	0.457	2	0.807	34	48,532	12
8	142	138	2	0.729	1	0.729	34	44,142	14
9	144	138	3	0.551	2	0.804	34	48,372	10

Table H-20. Packaging efficiencies for all cases sorted in descending order of packaging efficiency for the entire LCB

Packaging Efficiencies for all cases

Sorted in descending order of packaging efficiency for the entire LCB

Table Number	Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container
12	5	162	158	2	0.795	4	0.829
9	2	152	148	2	0.786	1	0.786
6	2	152	148	2	0.781	1	0.781
13	2	152	148	2	0.781	1	0.781
12	3	154	148	3	0.751	6	0.772
12	1	153	148	2.5	0.748	5	0.775
7	6	164	158	3	0.747	2	0.786
12	2	152	148	2	0.746	4	0.829
9	8	142	138	2	0.734	1	0.734
13	8	142	138	2	0.729	1	0.729
6	8	142	138	2	0.729	1	0.729
10	6	164	158	3	0.726	1	0.726
8	4	163	158	2.5	0.711	4	0.750
8	2	152	148	2	0.709	3	0.713
5	5	162	158	2	0.708	6	0.712
5	1	153	148	2.5	0.704	7	0.734
12	9	144	138	3	0.701	6	0.771
7	3	154	148	3	0.700	2	0.785
12	7	143	138	2.5	0.698	5	0.774
12	8	142	138	2	0.696	4	0.828
12	6	164	158	3	0.686	7	0.773
8	6	164	158	3	0.685	5	0.716
10	3	154	148	3	0.681	1	0.681
8	1	153	148	2.5	0.667	4	0.747
12	4	163	158	2.5	0.665	6	0.775
5	2	152	148	2	0.663	6	0.711
8	7	143	138	2.5	0.662	3	0.744
5	6	164	158	3	0.659	9	0.682
5	7	143	138	2.5	0.657	7	0.733
5	4	163	158	2.5	0.657	8	0.735
7	9	144	138	3	0.654	2	0.785
7	4	163	158	2.5	0.645	2	0.818
8	3	154	148	3	0.642	5	0.715
5	9	144	138	3	0.641	8	0.677
10	9	144	138	3	0.636	1	0.636
9	6	164	158	3	0.633	2	0.795
6	6	164	158	3	0.629	2	0.805
13	6	164	158	3	0.629	2	0.805
8	8	142	138	2	0.623	4	0.719
5	8	142	138	2	0.619	6	0.711
11	2	152	148	2	0.614	22	0.616
5	3	154	148	3	0.610	9	0.678
4	4	163	158	2.5	0.609	45	0.610
7	1	153	148	2.5	0.605	2	0.818
11	6	164	158	3	0.604	36	0.612
10	4	163	158	2.5	0.603	1	0.603
11	5	162	158	2	0.600	24	0.616
1[illegible]	8	142	138	2	0.6[illegible]	21	0.615
	3	154	148	3	0.6[illegible]	34	0.612

Table H-20. continued

Packaging Efficiencies for all cases

Sorted in descending order of packaging efficiency for the entire LCB

Table Number	Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container
4	7	143	138	2.5	0.600	40	0.609
8	9	144	138	3	0.600	5	0.713
4	1	153	148	2.5	0.597	43	0.609
11	9	144	138	3	0.595	32	0.611
9	3	154	148	3	0.593	2	0.793
13	3	154	148	3	0.590	2	0.805
6	3	154	148	3	0.590	2	0.805
8	5	162	158	2	0.567	4	0.600
10	1	153	148	2.5	0.565	1	0.565
7	7	143	138	2.5	0.565	2	0.817
9	9	144	138	3	0.554	2	0.790
6	9	144	138	3	0.551	2	0.804
13	9	144	138	3	0.551	2	0.804
7	5	162	158	2	0.532	2	0.848
9	4	163	158	2.5	0.526	2	0.812
10	7	143	138	2.5	0.526	1	0.526
13	4	163	158	2.5	0.522	2	0.807
6	4	163	158	2.5	0.522	2	0.807
11	7	143	138	2.5	0.510	31	0.511
11	4	163	158	2.5	0.502	36	0.512
11	1	153	148	2.5	0.498	34	0.511
7	2	152	148	2	0.498	2	0.788
9	1	153	148	2.5	0.493	2	0.812
6	1	153	148	2.5	0.490	2	0.807
13	1	153	148	2.5	0.490	2	0.807
10	5	162	158	2	0.481	1	0.481
3	5	162	158	2	0.481	1	0.481
4	2	152	148	2	0.469	40	0.472
4	5	162	158	2	0.466	43	0.472
7	8	142	138	2	0.465	2	0.788
4	8	142	138	2	0.461	38	0.471
9	7	143	138	2.5	0.460	2	0.810
6	7	143	138	2.5	0.457	2	0.807
13	7	143	138	2.5	0.457	2	0.807
10	2	152	148	2	0.451	1	0.451
3	2	152	148	2	0.451	1	0.451
10	8	142	138	2	0.421	1	0.421
3	8	142	138	2	0.421	1	0.421
9	5	162	158	2	0.419	2	0.821
6	5	162	158	2	0.417	2	0.810
13	5	162	158	2	0.417	2	0.810
3	6	164	158	3	0.363	2	0.527
4	6	164	158	3	0.351	86	0.352
4	3	154	148	3	0.350	81	0.352
4	9	144	138	3	0.348	76	0.351
3	3	154	148	3	0.340	2	0.527
2	7	143	138	2.5	0.332	3	0.333
2	3	154	148	3	0.321	4	0.333
3	9	144	138	3	0.318	2	0.527

Table H-20. continued

Packaging Efficiencies for all cases

Sorted in descending order of packaging efficiency for the entire LCB

Table Number	Case Number	Lower Core Barrel (LCB) Dimensions inches Outer Diameter	Inner Diameter	Thickness	Packaging Efficiency for entire LCB	Number of waste containers needed	Packaging Efficiency for a full waste container
2	5	162	158	2	0.303	3	0.333
3	4	163	158	2.5	0.302	2	0.527
2	9	144	138	3	0.300	4	0.333
2	4	163	158	2.5	0.285	4	0.333
2	2	152	148	2	0.284	3	0.333
3	1	153	148	2.5	0.283	2	0.527
2	6	164	158	3	0.274	5	0.333
2	1	153	148	2.5	0.267	4	0.333
2	8	142	138	2	0.265	3	0.333
3	7	143	138	2.5	0.264	2	0.527
1	1	153	148	2.5	0.222	12	0.225
1	8	142	138	2	0.221	9	0.225
1	4	163	158	2.5	0.219	13	0.225
1	9	144	138	3	0.214	14	0.225
1	3	154	148	3	0.214	15	0.225
1	6	164	158	3	0.214	16	0.225
1	2	152	148	2	0.213	10	0.225
1	7	143	138	2.5	0.208	12	0.225
1	5	162	158	2	0.206	11	0.225

APPENDIX B

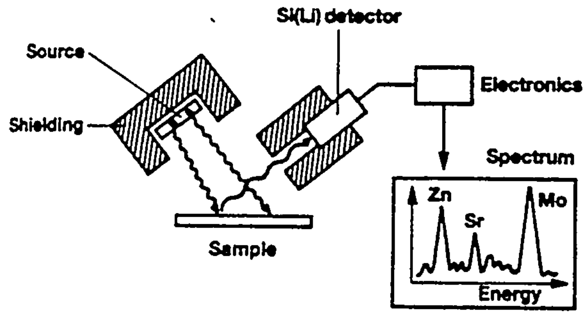
Description of Sealed Sources and Devices

X-ray fluorescence

Technique

Primary radiation from the radioisotope source excites atoms of the elements present in the sample, removing electrons from the sub-shells round the nucleus. X-rays characteristic of each element are emitted as electrons from the outer shells and move to fill the gaps created in inner shells. The shell from which the electron is removed determines the series of X-rays produced. The intensity of the X-ray is indicative of the concentration of the particular element in the sample. Since radioisotopes emit specific radiations, a limitation results on the range of elements whose characteristic X-rays can be excited. Thus a series of nuclides is employed in order that excitation of all elements from silicon to uranium can be achieved.

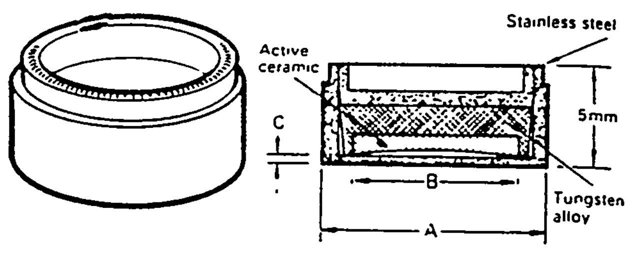
Geometry



Applications

- Alloy analysis for checking stock, scrap sorting and checking components.
- In mining, analysis of material excavated from pits, and cores, chippings and slurries from drilling operations.
- Analysis of electroplating solutions.
- General chemical analysis.

Source



Capsule dimensions and Safety performance testing

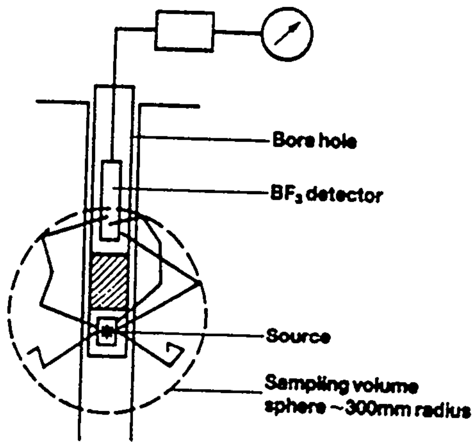
Capsule	Overall diam. 'A' mm	Active diam. 'B' mm	Window thickness 'C' mm	Safety performance testing ANSI/ISO Classification	IAEA special form	NRC model no.
X 10/2	8	4 2	0 2–0 25	77C64545	GB/3/S	AMC D2
X 11	10 8	7 2	0 2–0 25	77C64444	GB/4/S	AMC D3
X 11/1	10 8	8 0	0 2–0 25	77C64444	GB/4/S	AMC D3

Moisture gauging

Technique

Fast neutrons emitted by the source are moderated by collision with hydrogen atoms in moisture contained in the material. These moderated or thermal neutrons are detected by a neutron detector (usually a boron trifluoride (BF_3) proportional counter) to give a measure of the concentration of hydrogen atoms.

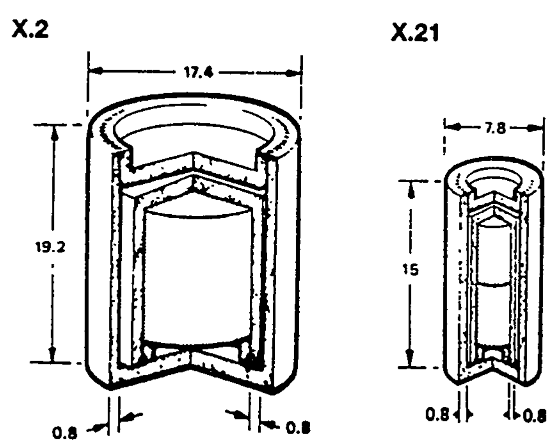
Geometry



Applications

- Soil moisture content for agricultural and construction use.
- Moisture content of materials in silos.
- Continuous moisture content gauging in raw material supplies e.g. gravel, wood chips etc.

Source



Safety performance testing

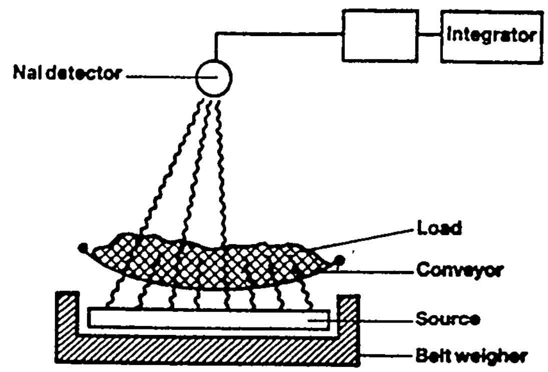
Capsule	ANSI/ISO classification	IAEA special form	NRC model no.
X 2	77E66544	GB/8/S	AMN PE1
X 21	77C65545	GB/43/S	AMN PE5

Thickness gauging

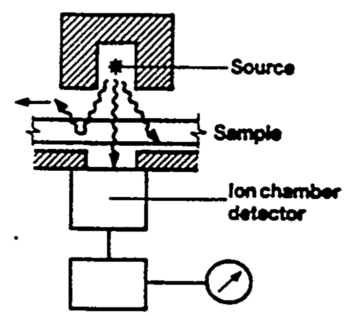
Transmission thickness technique

The source and the detector are placed on opposite sides of the material to be measured. Gamma or beta radiation transmitted through the sample is then directly related to the sample thickness, provided the density of the material is constant.

Geometry



Gamma transmission



Beta transmission

Applications

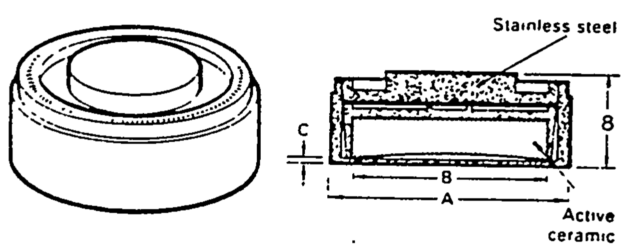
Gamma gauging

- Thickness gauging of sheet metal, glass, plastic, and rubber at thickness too large for beta sources, e.g., greater than 500mg/cm².
- Belt weighing, giving mass (kg/m²) flowing on conveyor belt.

Beta Gauging

- Thickness gauging of thinner plastics, thin sheet metal, rubbers, textiles and paper, e.g., 1 – 1000mg/cm².
- The weighing of cigarettes
- Measurement of dust and pollutant levels on filter paper samples e.g., 0.1 – 200 mg/m³ dust.

Source



Capsule dimensions and Safety performance testing

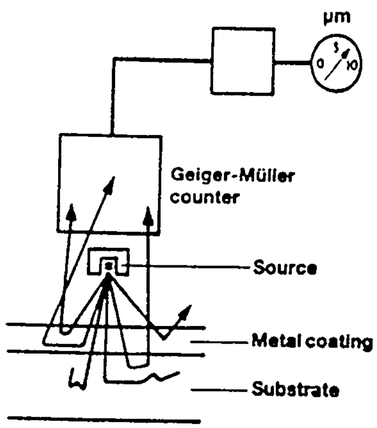
Capsule	Overall diam. 'A' mm	Active diam. 'B' mm	Window thickness 'C' mm	Safety performance testing ANSI/ISO classification	IAEA special form	NRC model no.
X 94	36	31	0 25–0 3	77E64444	GB/107/S	AMC 30
X 95	45	40	0 25–0 3	77E64444	GB/121/S	AMC 50

Thickness gauging

Beta backscatter thickness technique

The intensity of beta radiation which is scattered back from thin samples is related to sample thickness and atomic number.

Geometry



Beta backscatter thickness gauging

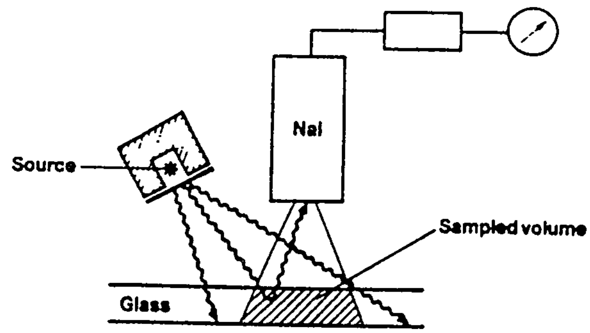
Applications

- The thickness gauging of paper, plastic and rubber on steel rolls.
- The measurement of a coating thickness on a substrate, virtually any coating/substrate combination providing there is sufficient difference in density or atomic number. Coating range < 1–100µm depending on source and materials.

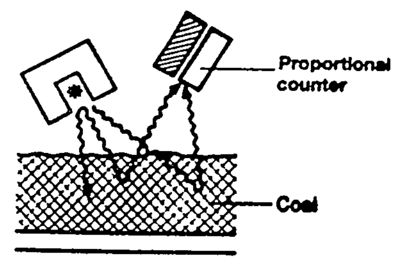
Gamma backscatter thickness technique

The intensity of backscattered radiation from the sample is measured to give sample thickness or mean atomic number. Used for the measurement of substances of low Z for which transmission measurements are not sufficiently sensitive.

Geometry

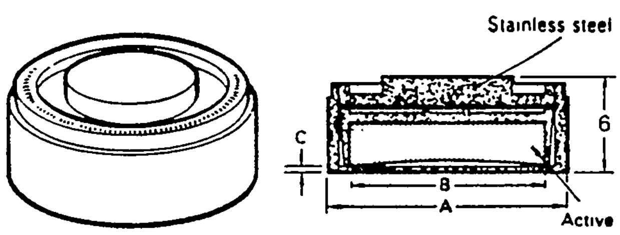


Gamma backscatter thickness gauging



Mean atomic number (Z) gauging (ie where thickness is known).

Source



Capsule dimensions and Safety performance testing

Capsule	Overall diam. 'A' mm	Active diam. 'B' mm	Window thickness 'C' mm	Safety performance testing ANSI/ISO classification	IAEA special form	NRC model no.
x 91	10 8	7 5	0 2–0 25	77C64444	GB/38/S	AMC 16
X 92	15	12	0 2–0 25	77C64444	GB/39/S	AMC 17
x 93	30	25	0 2–0 25	77C64444	GB/40/S	AMC 19
X 97	22	18	0 2–0 25	77C64444	GB/41/S	AMC 18

Applications

Thickness gauging

- Measurement of light alloys, glass, plastics, rubbers for which beta sources are not suitable e.g., greater than 500 mg/cm², and access only available from one side.

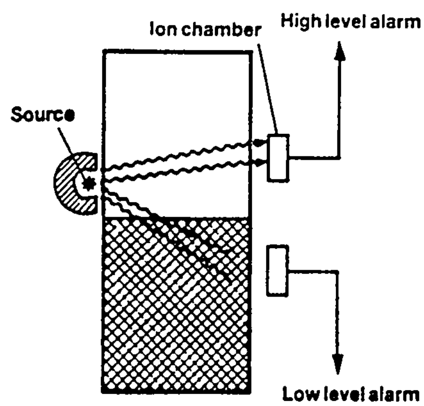
e.g., tube wall thickness gauging

Level gauging

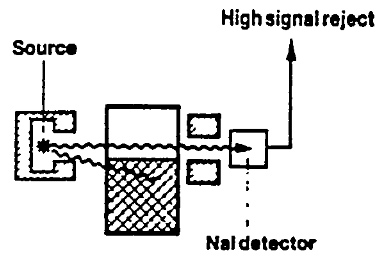
Gamma switching technique

The transmission of gamma radiation through a container is affected by the level of the contents. The intensity of the transmitted radiation is measured and used to activate switches when pre-set intensity levels are reached.

Geometry



Storage hopper level control



Can/package contents monitoring

Applications

Storage hopper level control

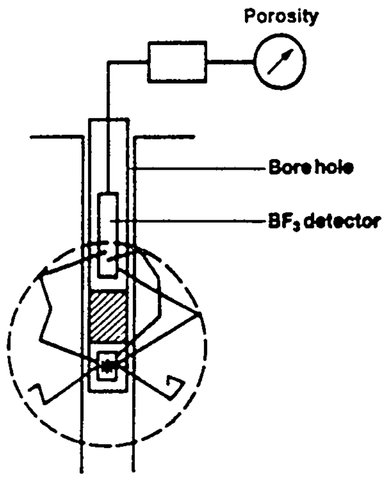
● Switch can be used to operate high level and low level alarms or pump switch control.

Oil well logging

Neutron porosity logging technique

Fast neutrons emitted by a neutron source are slowed down by the formation and may undergo three interactions: 1) inelastic scatter, 2) elastic scatter, 3) absorption. Therefore, by collision with hydrogen atoms in the formation the neutron will be moderated to thermal or epithermal energies where it is soon captured by hydrogen nuclei and emits a secondary gamma ray. The detection of these three interactions by using different types of neutron detectors (BF_3 (thermal), ^3He (epithermal)) can be used to determine the hydrogen content of the formation. Since the majority of hydrogen in a formation generally exists within the pore space, the neutron flux will then be related to the porosity.

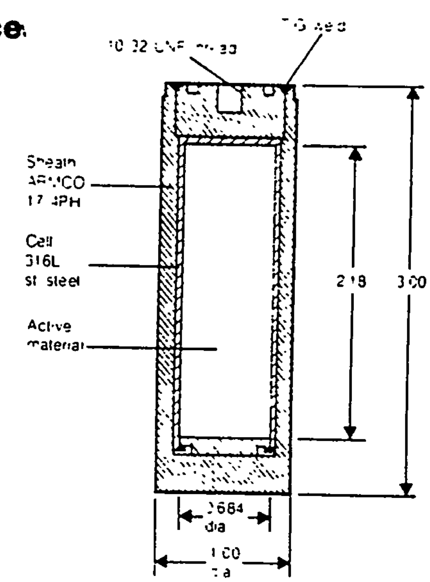
Geometry



Applications

- Determination of formation hydrogen content
- Formation porosity for oil and mineral logging

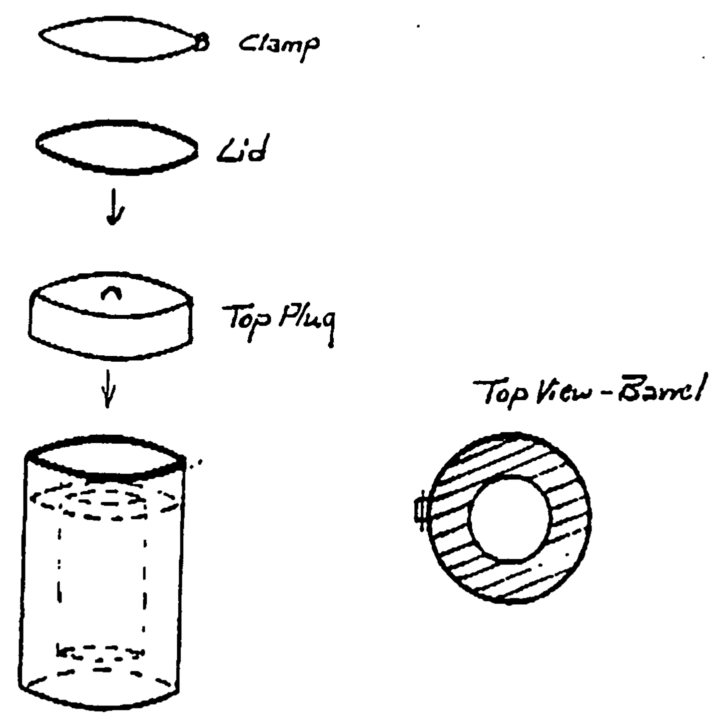
Source



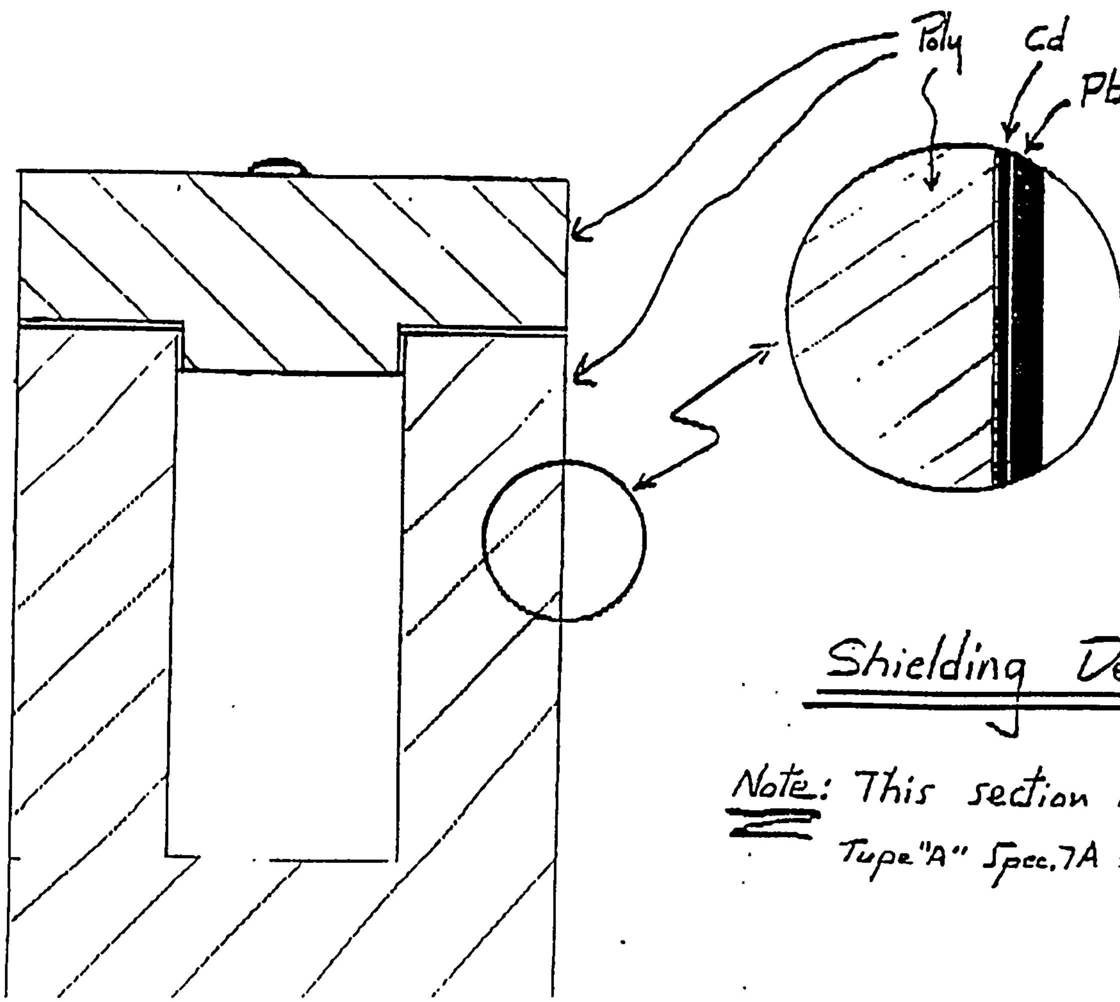
APPENDIX C

Description of 55-Gal Drum for Sealed/Device Source for Storage and Transport

(Design Concepts by Bill Walker, Troxler Electronics Inc.)

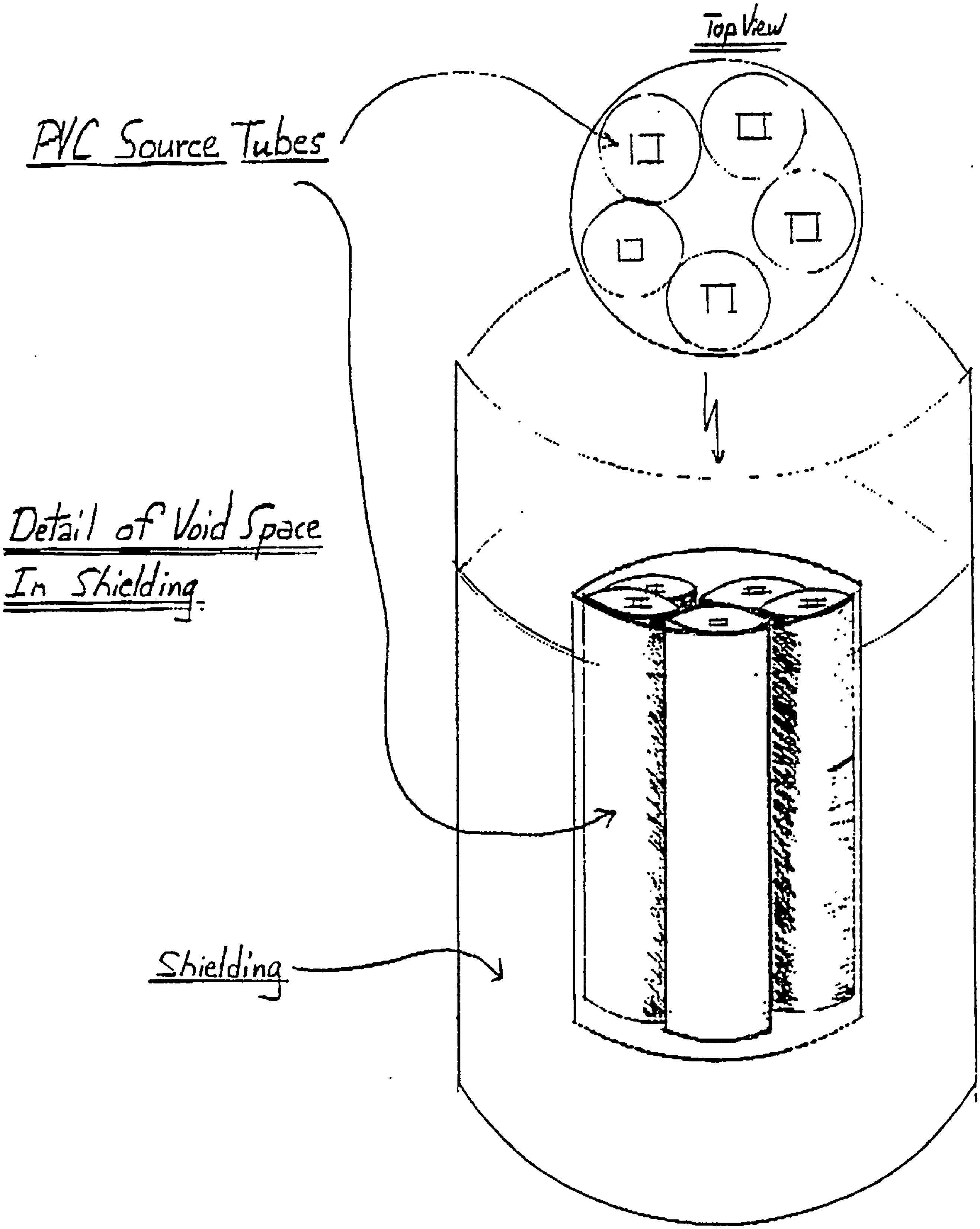


DOT TYPE "A"
SPEC 7A
55 Gal Drum

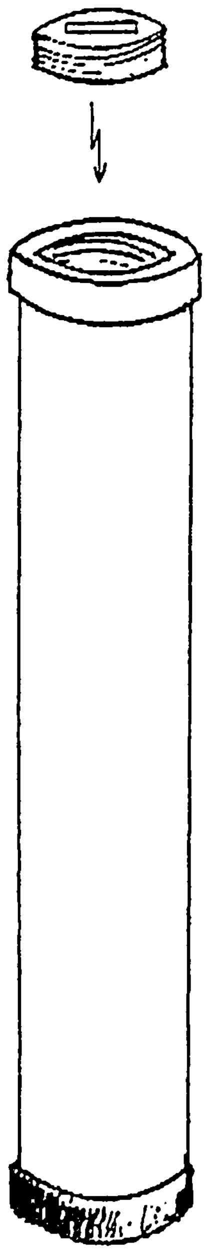


Shielding Detail

Note: This section made to fit Type "A" Spec. 7A 55 gal Barrel



Top View
PVC Source Tubes
Detail of Void Space
In Shielding
Shielding



Detail
PVC Source Tube

Note: 1) Like sources inserted in tube & logged.

2) Metal Canister ld be of similar des - Normal Form Sources