Safety Guide 100

DESIGN GUIDE FOR PACKAGING AND OFFSITE TRANSPORTATION OF NUCLEAR COMPONENTS, SPECIAL ASSEMBLIES, AND RADIOACTIVE MATERIALS ASSOCIATED WITH THE NUCLEAR EXPLOSIVES AND WEAPONS SAFETY PROGRAM

CHAPTER 4.0

CONTAINMENT ASPECTS

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FIGURES

TABLES

ACRONYMS

AA	Arithmetic Average
AISI	American Iron and Steel Institute
AL	Albuquerque Field office
ALARA	As Low as Reasonably Achievable
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
AWS	American Welding Society
B&PVC	Boiler and Pressure Vessel Code
CFR	Code of Federal Regulations
DOE	Department of Energy
DOT	Department of Transportation
DP	Defense Program
EBW	Electron Beam Welding
EGW	Electrogas Arc Welding
FCAW	Flux Cored Arc Welding
FRW	Inertia and Friction Welding
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HAZ	Heat-Affected Zone
IAEA	International Atomic Energy Agency
MNOP	Maximum Normal Operating Pressure
NDE	Nondestructive Evaluation
NRC	Nuclear Regulatory Commission

OFW	Oxyfuel Gas Welding
PAW	Plasma Arc Welding
PQR	Procedure Qualification Record
PV	Pressure Volume
QA	Quality Assurance
RMS	Root Mean Square
SAE	Society of Automotive Engineers
SAM	Submerged Arc Welding
SAR	Safety Analysis Report
SARP	Safety Analysis Report for Packaging
SD	Supplemental Directive
SER	Safety Evaluation Report
SERP	Safety Evaluation Report for Packaging
SMAW	Shielded Metal Arc Welding
SSR	Safe-Secure Railcar
SST	Safe-Secure Trailer
STP	Standard Temperature and Pressure
SW	Stud Welding
TSRA	Transportation System Risk Assessment
WPS	Welding Procedure Specifications

4.0 CONTAINMENT ASPECTS

4.1 INTRODUCTION

This design guide addresses containment systems to aid in the identification and documentation of compliance issues with respect to 1) the Nuclear Regulatory Commission (NRC), Type B, performance-based packaging requirements delineated in the appropriate sections of 10 CFR 71;[1] 2) the applicable standards set forth in the American National Standards Institute (ANSI) document, *Leakage Tests on Packages for the Shipment of Radioactive Materials,* ANSI N14.5;[2] and 3) the specific requirements set forth in applicable Department of Energy (DOE) orders. Generic guidance has been provided for the validation of containment designs including numerous methods and techniques that can be used for the verification of containment. Specific guidance has also been provided, intended as an aid toward the identification of specific containment issues that must be documented in the Containment Section of the Safety Analysis Report for Packaging (SARP). Although much of the guidance provided has been directed toward the shipment of dispersible forms of fissile materials, substantial guidance has also been provided for the shipment of tritium.

4.1.1 Scope

As noted above, this design guide has been compiled to aid in the identification of design and operational issues associated with the packaging and safe transport of radioactive materials, components, and special assemblies in support of the Defense Program (DP). The information provided herein should not be used to document the safe movement of nuclear weapons or nuclear explosives; guides will be developed for these types of packaging and transportation operations.

4.1.2 Background

The operations guidance forwarded is prepared to the requirements of DOE and is consistent with federal regulations and national standards implemented by DOE under DOE Order 5610. 12,[3] *Safety Requirements for Packaging, Storage, and Offsite Transportation of Components, Special Assemblies, and Radioactive Materials associated with the Nuclear Weapons Program.* In accordance with DOE Order 5610.12, as revised, the DOE, Office of Assistant Secretary for Defense Programs (DP-1) is responsible for assuring the safe packaging and off-site transportation of nuclear explosives, nuclear weapon and explosive components, special assemblies (i.e., weapon-like assemblies) and radioactive materials. These off-site transportation activities are conducted employing only the DOE Transportation Safeguard System (i.e., Safe Secure Trailer (SST), Ross Aviation, etc.), which includes conveyance for both ground and air transport of hazardous cargo. It is DOE policy to avoid transporting plutonium or parts containing plutonium by air, and restrictions to this effect are stipulated in DOE Order 5610.12.

Under the direction of the DOE, Office of the Deputy Assistant Secretary for Military Applications (DP-20), the Department of Energy, Albuquerque Field Office (AL) is delegated the responsibility to technically evaluate both the design and operational safety of packaging and transportation system used to convey hazardous materials transported in support of national defense activities within the DOE transportation safeguard system when such cargo is moved between DOE DP production and laboratory sites and between the DOE DP sites and Department of Defense sites (i.e., first military destination).

Under DOE Order 5610.12, as implemented by the AL Supplemental Directive (SD) 5610.12, *Packaging and Off-site Transportation of Components and Special Assemblies Associated with the Nuclear Weapons Program*[4] as revised, DOE requires that the transportation of hazardous material meet or exceed requirements detailed in applicable Federal Regulations (i.e., 49 CFR 170-189[5] and 10 CFR 71). In accordance with 49 CFR 173.7, *National Security Exception*, DOE is authorized to develop and self-regulate the packaging and transportation of hazardous cargo transported in support of the national security interest, provided that such activities are conducted only by public conveyance (i.e., SST) and provided that each transportation operation is evaluated quantifying the risk to the public, workers, and the environment to as low as reasonably achievable (ALARA). DOE public conveyances meet the federal regulation standard for "exclusive use carrier"; however, all hazardous material shipments should be first evaluated against the criteria for nonexclusive use in order to not unduly burden the DOE transportation system.

DOE requires that a SARP be prepared. It is recommended that the SARP be prepared in general conformance with NRC Regulatory Guide 7.9[6] as revised. DOE requires that a packaging quality assurance program be documented in conformance with DOE Order 5700.6C,[7] consistent with accepted national standards [i.e., ANSI/American Society of Mechanical Engineers (ASME) NQA-1,[8] ANSI N14.5, etc.]. Each SARP documents, as applicable, the structural, thermal, containment, radiation shielding, criticality safety, safe operating procedures and associated maintenance and fabrication acceptance criteria essential to assure safe and repeatable packaging design and hypothetical accident design response. Each SARP must adequately and clearly demonstrate to DOE that the packaging (including the transportation system, if necessary) containing authorized contents and transported within the DOE Transportation Safeguard System complies with the requirements of 10 CFR 71, or clearly delineates areas of technical deficiency such that DOE may consider the application for an exemption under 49 CFR 173.7(b), *National Security Exemption*, and seek authorization for such an application in accordance with the stipulations of DOE Order 5610.12. All requests for off-site transportation authorization to ship under 49 CFR 173.7(b) must document to DOE the imperative for the shipment and be supplemented with a shipment specific transportation system risk assessment (TSRA). Further discussion of shipments made utilizing a TSRA may be found in DOE DP Guide SG-20[9] and AL SD 5610.12.

Regardless of method of shipment or type of authorization, each petitioner for package certification or transportation authorization must have, in addition to a SARP, a DOE approved quality assurance program, of which the packaging or transportation system quality program is a subpart. Before fabrication of packaging, all key vendors must be qualified to the quality assurance requirements stipulated and accepted by the DOE certifying authority. The packaging must be fabricated in accordance with the DOE quality assurance program. The applicant should assure compliance with this DOE requirement prior to package testing. The packaging fabrication acceptance criteria should be submitted as part of the SARP. Both federal regulations and DOE orders require that operation of packaging and transportation system be conducted in accordance with the DOE-approved quality assurance program.

This guide describes methods that are acceptable to DOE for complying with the regulations of 10 CFR 71. It shall be the objective of DOE to first pursue a performance-based packaging design solution and document the safety of the transportation system using engineering methods and rely on methods of assessment of risk when no other avenue is deemed practical. This guide shall not be construed as detailing the minimum documentation and technical information requirements; additional information may be required depending on the system forwarded and possible problems the reviewer might perceive.

It is expected that this guide will be revised periodically to include information gained from experience. Operating contractors, national laboratories, and department personnel are invited to submit recommendations for improvement in the scope and content. When other methods or means are proposed to meet the intent of the federal regulation or DOE policy, these proposals should be forwarded along with justification to the DOE certifying official for consideration.

4.1.3 Definition of Terms

The definitions provided in this section have been derived from the information presented in the references presented in Sect. 4.7 Supplemental Definitions, i.e., generic definitions, and/or definitions proposed for use in this document have not been referenced.

A_1 - The maximum activity of "special form radioactive material" permitted in a Type A package.

A_2 - The maximum activity of radioactive material, other than "special form radioactive material," permitted in a Type A package.

Accident Conditions of Transport - See Hypothetical Accident Conditions.

Allowable Test Leakage Rate - The more restrictive of L_A or L_N, taking into consideration the differences between test and transport conditions.

Allowable Test Release Rate - The more restrictive of R_A or R_N, taking into consideration the differences between test and transport conditions.

Carrier - A person engaged in the transportation of passengers, or property, by land, or water as a common, contract, or private carrier, or by civil aircraft.

Certificate of Compliance - A certificate issued by DOE, or the NRC, as appropriate, approving for use, with specified limitations, a specific packaging for radioactive materials exceeding A_1/A_2 quantities, as defined in DOE/NRC regulations.

Components - Nuclear Materials and/or Hazardous Materials that comprise and/or are associated with the nuclear weapons program. Nuclear Components - Weapons components that contain fissile and/or radioactive materials. Hazardous components - Components that contain hazardous materials, other than fissile and/or radioactive materials, as defined in 49 CFR 172.101.

Containment System - The components of the packaging intended to retain the radioactive material during transport.

Contractor - The person/persons managing, or operating, government-owned, or leased, property on behalf of DOE.

Conveyance - Any vehicle, aircraft, vessel, freight container, or hold, compartment, or defined deck area of an inland waterway craft or seagoing vessel.

D-38 - See Depleted Uranium.

Depleted Uranium - Uranium containing less Uranium-235 than the naturally occurring distribution of uranium isotopes. (See also the definition for natural uranium.)

DOE Transport - Conveyance within a DOE-owned transportation system, e.g., an SST, a Safe-Secure Railcar (SSR), and/or DOE-owned aircraft and vehicles.

Enriched Uranium - Uranium containing more Uranium-235 than the naturally occurring distribution of uranium isotopes. (See also the definition for natural uranium.)

Equivalent Protection - Alternative measures that will achieve a level of safety equal to or greater than the measures specified in the regulations for which the alternative is sought, which will be consistent with the public intent and which will provide adequate protection against risks to life and property.

Exclusive Use - The sole use of a conveyance, by a single consignor, and for which all initial, intermediate, and final loadings and unloadings are carried out in accordance with the direction of the consignor, or consignee. Exclusive use applies only to transport by SSTs, or SSRs. (See also the definitions for Full Use and/or Sole Use.)

Fissile Materials - Materials that are composed of any of the following radionuclides: uranium-233, uranium-235, plutonium-238, plutonium-239, plutonium-241, or any combination of these radionuclides, including trace amounts of heavier radionuclides in the actinide series. Unirradiated natural uranium and depleted uranium and natural uranium/depleted uranium that has been irradiated only in thermal reactors are not included in this definition.

Fissile Radionuclides - See Fissile Materials.

Fluid - The substance or material that is intended to be retained by the sealing surfaces of the containment vessel. As used in this document, the term "fluid" may be a liquid, a gas, or a mixture of both. The use of the term "fluid" may also extended to include powders and solids, as well. (Note: The term medium, the plural of which is media, is often used with the same meaning.)

Full Use - See Exclusive Use

Hazardous Materials - Substances or materials that have been determined by the Secretary of Transportation to be capable of posing an unreasonable risk to health, safety, and property when transported in commerce and has been so designated in 49 CFR 172.101.

Hypothetical Accident Conditions - The Hypothetical Accident Conditions of transport defined in 10 CFR 71.73.

Leak - Any opening through a containment system that permits the escape of the contents. Note: It is considered conservative to assume that slurries and powders behave as a liquid and aerosols behave as gases; i.e., the predicted leakage rate will be greater than the actual leakage rate.

Leaktight - A leakage rate less than or equal to 1×10^{-7} standard cc/sec of dry air, at an upstream pressure of 1 atmosphere absolute and a downstream pressure of 0.01 atmosphere absolute or less, irrespective of the form of the radioactive contents. A leakage rate of 1×10^{-7} standard cc/sec is equal to 4.09×10^{-12} g-moles per sec of dry air or helium and is equivalent to a helium leakage rate, under the same conditions, of 1.96×10^{-7} cc/sec. (Note: Also see the definition of standard cc/sec.)

Maximum Normal Operating Pressure - The maximum gage pressure (psig) that could develop in the containment system, in a period of one year under the test conditions specified in 10 CFR 71 .71(c)(1) in the absence of venting, external cooling by ancillary systems, or operational controls during transport.

Maximum Permissible Leakage Rate - The maximum permissible leakage rate for the medium present during transport.

Maximum Permissible Release Rate - The radioactive content release rates that are equivalent to the appropriate packaging containment requirements specified in Table 4.1.

Media/Medium - See Fluid.

Natural Uranium - Uranium with the naturally occurring distribution of uranium isotopes (approximately 0.711 wt% uranium-235 and the remainder essentially uranium-238).

Normal Conditions of Transport - The Normal Conditions of Transport defined in 10 CFR 71.71.

Package - The packaging together with its radioactive contents as presented for transport. Fissile material package - A fissile material packaging together with its fissile contents. Type B package - A Type B packaging together with its Type B radioactive contents. On approval, Type B package design is designated by the NRC or the DOE as B(U) unless the package has a maximum normal operating pressure of more than 700 kilopascals (100 lb/in.^{2}) gage or a pressure-relief device that will allow the release of radioactive materials to the environment under the tests specified in 10 CFR 71.73 (Hypothetical Accident Conditions), in which case it will be receive a designation B(M). B(U) refers to the need for unilateral approval for international shipments; B(M) refers to the need for multilateral approval. There is no designation made in how packages with these designations may be used in domestic transportation. To determine their designation for international transportation, see the

Table 4.1. Containment requirements for Type B packages

Condition	Criterion	Maximum permissible release rate
Normal Conditions of Transport Accident Conditions of Transport	Regulatory Requirement R_N Regulatory Requirement R_A	A_2[a] × 10^{-6} per hour A_2 in one week, except 10,000 Ci for ^{85}Kr in one week

[a] A_1/A_2 values are specified in Tables VII, Regulations for the Safe Transport of Radioactive Materials, IAEA, Safety Series No. 6,[10] and in Table A1 of 10 CFR 71, Appendix A.

regulations defined in 49 CFR 173. A Type B package approved prior to September 6, 1983, was designated only as Type B. Limitations on its use are defined in 10 CFR 71.13.

Packaging - The assembly of components necessary to ensure compliance with the packaging requirements of 10 CFR 71 and/or DOE Order 5610.1. It may consist of one or more receptacles, absorbent materials, spacing structures, thermal insulation, radiation shielding, and devices for cooling or absorbing mechanical shocks. The vehicle, tie-down system, and auxiliary equipment may be designated as part of the packaging.

Permeation - The passage of a fluid through a solid barrier (which has no "holes") by adsorption-diffusion-desorption processes. (Note: Permeation should not normally be considered as leakage or a release unless the fluid itself is hazardous or radioactive.)

Quality Assurance - Preplanned and systematic actions necessary to provide adequate confidence that a facility, structure, system, or component will perform satisfactorily and safely in service. The goal of quality assurance is to ensure: 1) that research, development, demonstration, scientific investigations, and production activities are performed in a controlled manner; 2) that components, systems, and processes are designed, developed, constructed, tested, operated and maintained according to engineering standards, quality practices, appropriate technical specifications, and appropriate operational safety requirements; and 3) that the resulting technological data are both valid and retrievable. Quality assurance includes quality control, which comprises the actions necessary to control and verify the features and characteristics of a material, process, product, or service to specified requirements.

Quality Assurance Plan - A document that contains or references quality assurance elements established for an activity, group of activities, or a project. The quality assurance plan describes how conformance with the appropriate requirements is to be assured for structures, systems, computer software, components, and their operation commensurate with 1) the scope, complexity, duration, and importance to satisfactory performance; 2) the potential impact on the environment, safety, and health; and 3) the requirements for reliability and continuity of operation.

Quality Assurance Program - A systematic program of controls and inspections applied by any organization or body involved in the transport of radioactive materials to provide adequate confidence that the standard of safety prescribed in the regulations is achieved in practice.

Radioactive Material - Any material having a specific activity greater than 0.002 uCi/g of material.

Reference Air Leakage Rates - The maximum permissible leakage rates converted to standard cc/sec of dry air. (See definition of “standard cubic centimeter per second.”)

Release Rate - The quantity of radioactive contents per unit time that escapes through a leak.

Safe-Secure Railcar (SSR) - A specially designed railcar which has protective and deterrent systems that are used in a special train to transport nuclear explosives or special nuclear materials.

Safe-Secure Trailer (SST) - A specially designed trailer which has protective and deterrent systems that are used with a special tractor to transport nuclear explosives or special nuclear materials.

Safety Analysis Report (SAR) - Formal documentation that systematically describes a system and that systematically identifies and assesses associated hazards/risks for the purpose of demonstrating adequate safety.

Safety Analysis Report for Packaging (SAIRP) - Formal documentation that provides a comprehensive evaluation of the container and its contents to demonstrate safety compliance in accordance with DOE Order 5610.12.

Safety Evaluation Report (SER) - A document that provides the evaluation of and the recommendations made by the review team of the SAR supporting the request for certification.

Safety Evaluation Report for Packaging (SERP) - A document that provides the evaluation of and the recommendations made by the review team of the SARP for the packaging design.

Sensitivity (of a Leakage Detector) - The minimum usable response of the detector to tracer fluid leakage, i.e., the leakage rate that will produce a repeatable change in the detector reading.

Sensitivity (of a Leakage Test Procedure) - The minimum detectable leakage rate that the test procedure is capable of detecting. Note that a more sensitive test has a smaller numerical value of sensitivity. The sensitivity of the procedure accounts for the sensitivity of the detector and the variables of the procedure that are external to the detector, such as pressure differential, time, and fluid type. The sensitivity of the leakage test procedure will determine the degree of agreement between the measured value and the true value.

Simulated Radioactive Material - A material that is not necessarily radioactive but that has pertinent physical, chemical, dispersal, diffusion, or dissolution properties similar to those of the radioactive material to be shipped.

Sole Use - See Exclusive Use.

Special Assemblies - Major assemblies of nuclear weapons components that do not comprise a complete nuclear explosive and, therefore, are not capable of producing a nuclear detonation.

Specific Activity - The radioactivity of the radionuclide per unit mass of that nuclide. The specific activity of a material in which the radionuclide is essentially uniformly distributed is the radioactivity per unit mass of the material.

Standard Cubic Centimeters per Second (std cm^3/s) - Leakage rates referring to the standard conditions for dry air at 1 atmosphere (atm) absolute pressure (i.e., 101 kPa) and 298 K (i.e., 25°C). (Note that a leakage rate value of 1 std cm^3/s, as used in this document, differs slightly from the chemical definition of "Standard Temperature and Pressure (STP)," for which the predefined conditions are 1 atm absolute pressure (101 kPa) and 273 K (i.e., 0°C).

Tracer Fluid - The gas or liquid that is used to detect leakage or measure leakage rates.

Type A Quantity - A quantity of radioactive material, the aggregate radioactivity of which does not exceed A_1 for special form radioactive material or A_2 for normal form radioactive material, where A_1 and A_2 are given in appendix A of 10 CFR 71, or may be determined by the procedures described in Appendix A of 10 CFR 71.

Type B Quantity - A quantity of radioactive material greater than a Type A quantity.

4.2 REGULATORY REQUIREMENTS FOR CONTAINMENT AND LEAKAGE TESTING

4.2.1 General

The subparts and parts of 10 CFR 71 that are particularly germane to the subject of containment can be found in Subpart A, Part 71.4 *(Definitions),* Subpart E, Parts 71.43, 71.51, and 71.63 *(General Standards for all Packages, Additional Requirements for Type B Packages,* and *Special Requirements for Plutonium Shipments,* respectively), and Subpart G, Part 71.85 *(Preliminary Determinations).* Because the appropriate subject matter from the Definitions section of 10 CFR 71.4 is presented in Subsect. 4.1.3, the appropriate material from each of the remaining Sections is reproduced below.

Dimensions are expressed primarily in metric units. The approximate English equivalents, given in parentheses, are provided for informational purposes only.

4.2.2 10 CFR 71, Subpart E

4.2.2.1 Part 71.43 - General standards for all packages

The regulatory requirements specified in 10 CFR 71.43 read as follows:

a. The smallest overall dimension of a package must not be less than 10 cm (4 in.).

b. The outside of a package must incorporate a feature, such as a seal, which is not readily breakable, and which, while intact, would be evidence that the package has not been opened by unauthorized persons.

c. Each package must include a containment system securely closed by a positive fastening device which cannot be opened unintentionally.

d. A package must be of materials and construction which assure that there will be no significant chemical, galvanic, or other reaction among the packaging components or between the packaging components and the package contents, including possible reaction resulting from inleakage of water to the maximum credible extent.

e. A package valve or other device, the failure of which would allow radioactive contents to escape, must be protected against unauthorized operation and, except for a pressure relief device, must be provided with an enclosure to retain any leakage.

f. A package must be designed, constructed, and prepared for shipment so that under the tests specified in 10 CFR 71.71 (Normal Conditions of Transport) there would be no loss or dispersal of radioactive contents, no significant increase in external radiation levels, and no substantial reduction in the effectiveness of the packaging.

g. A package must be designed, constructed, and prepared for transport so that in still air at 38°C (100°F) and in the shade, no accessible surface of a package would have a temperature exceeding 50°C (122°F) in a nonexclusive use shipment or 82°C (180°F) in an exclusive use shipment.

h. A package must not incorporate a feature which is intended to allow continuous venting during transport.[1]

4.2.2.2 Part 71.51 - Additional requirements for Type B packages

The regulatory requirements specified in 10 CFR 71.51 read as follows:

b. A Type B package, in addition to satisfying the requirements of 10 CFR 71.41 through 10 CFR 71.47 must be designed, constructed, and prepared for shipment so that under the tests specified in:

1. Part 71.71 (Normal Conditions of Transport): there will be no loss or dispersal of radioactive contents, as demonstrated to a sensitivity of 10^{-6} A_2 per hour, no significant increase in external radiation levels, and no substantial reduction in the effectiveness of the packaging.

2. Part 71.73 (Hypothetical Accident Conditions): there will be no escape of krypton-85 exceeding 10,000 Ci in one week, no escape of other radioactive material exceeding a total amount A_2 in one week, and no external radiation dose rate exceeding one rem per hour at one meter from the external surface of the package.

b. Compliance with the permitted activity release limits of paragraph (a) of this section must not depend on filters or upon a mechanical cooling system".[1]

4.2.2.3 Part 71.63 - Special requirements for plutonium shipments

The regulatory requirements specified in 10 CFR 71.63 read as follows:

a. Plutonium in excess of 20 Ci per package must be shipped as a solid.

b. Plutonium in excess of 20 Ci per package must be packaged in a separate inner container placed within outer packaging that meets the requirements of Subparts E and F for packaging of material in normal form. If the entire package is subjected to the tests specified in Part 71.71 (Normal Conditions of Transport), the separate inner container must not release plutonium, as demonstrated to a sensitivity of 10^{-6} A_2 per hour. If the entire package is subjected to the tests specified in Part 71.73 (Hypothetical Accident Conditions), the separate inner container must restrict the loss of plutonium to not more than A_2 in one week. Solid plutonium in the following forms is exempt from the requirements of this paragraph: reactor fuel elements; metal or metal alloy; and other plutonium bearing solids that the Commission determines should be exempt from the requirements of this section.[1]

4.2.3 10 CFR 71, Subpart G

4.2.3.1 Part 71.85 - Preliminary determinations

The regulatory requirements specified in 10 CFR 71.85 read as follows: Prior to the first use of any packaging for the shipment of licensed material:

a. The licensee shall ascertain that there are no cracks, pinholes, uncontrolled voids, or other defects which could significantly reduce the effectiveness of the packaging.

b. Where the maximum normal operating pressure will exceed 34.3 kilopascal (5 psi) gauge, the licensee shall test the containment system at an internal pressure at least 50% higher than the maximum normal operating pressure to verify the capability of that system to maintain its structural integrity at that pressure.[1]

4.3 REGULATORY GUIDES AND STANDARDS FOR CONTAINMENT AND LEAKAGE TESTING

4.3.1 General

In order to provide the translational mechanism between the regulatory requirements and real-world applications, the Office of Standards Development of the NRC has developed a series of Regulatory Guides (Reg Guides). With respect to the subject of containment and leakage testing criteria for the packaging and shipment of radioactive materials, guidance can be found in NRC Reg Guide 7.4, *Leakage Tests on Packages for Shipment of Radioactive Materials,*[11] and in ANSI N14.5.[2] Excerpts from both documents are presented in Subsects. 4.3.2 and 4.3.3.

4.3.2 NRC Regulatory Guide 7.4 - General

The material presented in Subsects. 4.3.2.1 through 4.3.2.4 contains paraphrased versions of the material presented in Sects. A through C of NRC Reg Guide 7.4. For the most part, the material presented has been taken directly from the Reg Guide. Where appropriate, however, the text has been modified to fit within the confines of this report.

4.3.2.1 Section A - Introduction

The NRC regulation, 10 CFR Part 71, *Packaging and Transportation of Radioactive Material,* applies to licensees of the NRC who transport licensed material or who deliver licensed material to a carrier for transport. Certain standards and requirements in 10 CFR 71 prescribe that there will be no release, or limited release, of radioactive materials from a package or component of a package under certain conditions. Part 71.71, for example, requires that there be no release of radioactive material from the package containment vessel under the specified Normal Conditions of Transport. Part 71.85 *Preliminary Determinations,* as another example, requires that the package containment vessel not leak at an internal pressure 50% higher than the maximum normal operating pressure. This regulatory guide identifies a leak test standard acceptable to the NRC staff for use in demonstrating that packages of radioactive material comply with these containment requirements.

4.3.2.2 Section B - Discussion

Subcommittee N14.5, Leakage Tests on Packages for Shipment of Radioactive Materials, of ANSI has prepared a standard (ANSI N14.5) that specifies:

1. Minimum leakage test requirements for package containment systems
2. Methods for relating leakage test procedures to package containment requirements
3. Minimum requirements for leakage test procedures

ANSI N14.5 is related directly to the package containment requirements of the International Atomic Energy Agency (IAEA), Safety Series No. 6, as modified. The IAEA requirements specify containment in terms of maximum leakage of radioactive material per unit time. ANSI N14.5 describes methods for converting those containment requirements to maximum permissible leakage rates for the tracer fluid, usually a gas, of a leakage test procedure. While 10 CFR 71 does not generally specify containment in terms of permissible leakage rates, it is recognized that no system provides absolute containment.

4.3.2.3 Section C - Regulatory position

The guidance contained in ANSI N14.5, *Leakage Tests on Packages for Shipment of Radioactive Materials,* constitutes a procedure generally acceptable to the NRC staff for assessing the containment properties of a radioactive material package to satisfy the provisions of 10 CFR 71.

4.3.3 ANSI N14.5 - General

Leakage test requirements that pertain to the containment of radioactive materials during shipment are delineated in ANSI N14.5. Section 4 of the standard describes how it should be used. Section 5 of the standard defines the "Package Containment Requirements and Maximum Permissible Leakage Rates;" Sect. 6 defines the "Containment System Test Requirements;" and Sect. 7 defines the "Test Procedure Requirements."

Also included in ANSI N14.5 is a set of non-mandatory Appendices: Appendix A describes a series of accepted leakage test procedures and how they should be used; Appendix B describes the subject of leakage, in general, using a series of equations and examples. Although the information presented in the Appendices is not part of the standard, it is included in the standard for informational purposes. (See Appendix B of this document for additional guidance.)

The information presented in Subsects. 4.3.3.1 through 4.3.3.4 contains paraphrased versions of the material presented in Sects. 4, 5, 6, and 7 of ANSI N14.5. For the most part, the material presented has been taken directly from the ANSI Standard. Where appropriate, however, the material has been paraphrased to fit within the context of this report.

4.3.3.1 Section 4 - How to use the standard*

Using the flowchart in Fig. 4.1 as a guide, the following procedures shall be used for this standard:

1. Determine the package containment requirements for both normal and accident conditions as provided in Subsects. 4.3.3.2.1 and Table 4.1;

2. Determine either the maximum permissible release or leakage rate in accordance with Subsects. 4.3.3.2.2 and 4.3.3.2.3, respectively, for the appropriate transport conditions;

3. If a gas is used as the tracer fluid, then the reference air leakage rate shall be determined as in Subsect. 4.3.3.2.4;

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* This material is reproduced with permission from American National Standard, *Leakage Tests on Packages for Shipment of Radioactive Materials, ANSI N14.5*, copyright 1987 by the American National Standards Institute. Copies of this standard may be purchased from the American National Standards Institute at 11 West 42nd Street, New York, NY 10036.

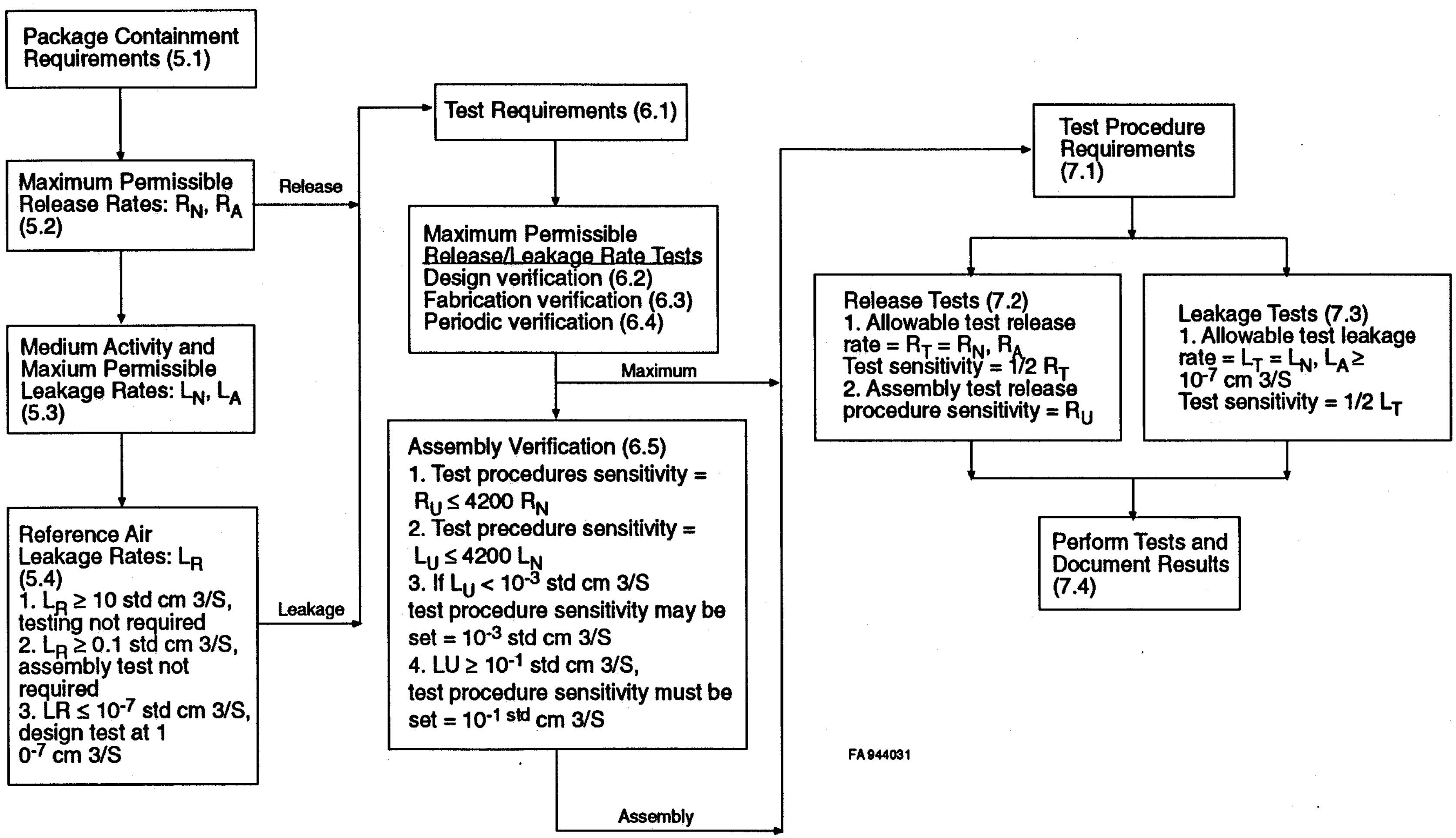


Fig. 4.1. Flowchart for using ANSI N14.5.

4. Determine the tests required by the rules given in Sect. 4.3.3.3 for the following situations:

   a. Design verification
   b. Fabrication verification
   c. Assembly verification
   d. Periodic verification

5. Determine the allowable release or leakage test rate and sensitivity as required in Subsect. 4.3.3.4 for each of the tests required in Step 4, above;

6. Select appropriate test procedures for each of the test situations and sensitivities determined in Step 5, above; and

7. Perform the required tests, and document the results that demonstrate compliance with this standard, as required in Subsect. 4.3.3.4.4.

4.3.3.2 Section 5 - Containment requirements and maximum permissible leakage rates

4.3.3.2.1 General

Compliance with package containment requirements shall be demonstrated either by determination of the radioactive contents release rate or by measurement of a tracer material leakage rate. All measured leakage rates shall be correlated to relate the measurement to the potential release of the contained material by performance of tests on prototypes or models, reference to previous demonstrations, or reasoned arguments.

The package containment requirements shall be determined from Table 4.1 and the applicable subsections of 10 CFR 71 and IAEA Safety Series No. 6. The maximum permissible release or leakage rate shall be determined according to Subsect. 4.3.3.2.2 or 4.3.3.2.3.

4.3.3.2.2 Maximum permissible release rates

The maximum permissible release rates shall be determined from Table 4.1, and shall be designated as RN and RA, respectively, where

R_N = maximum permissible release rate for normal conditions of transport, Ci/hr (curies per hour)

R_A = maximum permissible release rate for accident conditions of transport, curies in one week. A time-averaged value may be used

When a package contains a mixture of radionuclides, the maximum permissible release rate shall be determined for the radionuclides according to the applicable documents cited in Subsect. 4.3.3. Methods for calculating aggregate A_2 values can be found in Appendix A of this document and in Section B16, in Appendix B of ANSI N14.5.

Compliance with the release limits specified in Table 4.1 and this section may be demonstrated by direct measurement of the radioactive release for the appropriate normal and accident conditions of transport.

4.3.3.2.3 Maximum permissible leakage rates

The package containment system will contain the radioactive contents and, generally, a medium that might be capable of transporting the radioactive contents through any leaks that might exist in the package containment system. Before the maximum permissible leakage rate can be established, the following shall be determined for both normal and accident conditions of transport:

1. The maximum permissible release rates, R_N and R_A
2. The activity that could escape from the containment system

The activity in the medium that could escape from the containment system shall be designated as C_N and C_A, where,

C_N = the activity per unit volume of the medium that could escape from the containment system for normal conditions of transport, Ci/cm^3 (curies per cubic centimeter

C_A = the activity per unit volume of the medium that could escape from the containment system for accident conditions of transport, Ci/cm^3

C_N and C_A shall be determined by the performance of tests on prototypes or models, reference to previous demonstrations, calculations, or reasoned argument. Consideration shall be given to the following:

1. The chemical and physical forms of the materials within the containment system

2. The possible release modes such as diffusion of gases, airborne transportation of powders or particulates, reactions with water or other materials present in the system, and solubility

3. The maximum temperature, pressure, vibration, and the like to which the contained material would be subjected for normal and accident conditions of transport. These shall be determined by the performance of tests on prototypes or models, reference to previous demonstrations, calculations, or reasoned argument.

The maximum permissible leakage rates for the medium present during transport shall be determined from Equations 1 and 2:

$$L_N = R_N/(C_N) \times 1/3600 \qquad (1)$$

where

L_N = the maximum permissible leakage rate for the medium under Normal Conditions of Transport, cm^3/s (cubic centimeters per second) and

R_N and C_N = the appropriate values for normal conditions determined from above;

and

$$L_A = R_A/(C_A) \qquad (2)$$

where

L_A = the maximum permissible leakage rate for accident conditions of transport, cm^3 in one week

R_A and C_A = the appropriate values for accident conditions determined from above

For an averaged value of L_A,

$$L_A = [R_A/(C_A)] \times 1.65 \times 10^{-6} \text{ cm}^3/\text{s} \quad (3)$$

4.3.3.2.4 Reference air leakage rate

The reference air leakage rate, L_R, which is expressed in standard cubic centimeters per second and which is equivalent to the maximum of L_N or L_A, shall be established by calculation. See Appendix B and ANSI N14.5 for instructions to determine and use L_R in design, test, and assembly verification testing. The determination of the reference air leakage rate shall account for the following:

1. The relationship between the leakage rate of air and that of a different gas, liquid, aerosol, and the like

2. The relationship between the leakage rates at different sets of pressure and temperature conditions

(With respect to condition 2 above, it should be noted that the definition of "standard cubic centimeters per second," as used in ANSI N14.5 differs slightly from the chemical definition of STP, for which the predefined conditions refer to a temperature of 273.15 °K, or 0°C. See the comparable note in Subsect. 4.1.3.)

The calculated reference air leakage rate (L_R) is used as follows:

1. If L_R is greater than or equal to 10 std cm^3/s for both normal and accident conditions, the package is exempt from the required testing in Subsects. 4.3.3.3.2 through 4.3.3.3.5.

2. If L_R is greater than or equal to 0.1 std cm^3/s for both normal and accident conditions, the package is exempt from assembly testing described in Subsect. 4.3.3.3.5.

3. If LR is less than or equal to 10^{-7} std cm^3/s for either normal or accident conditions, the tests described in Subsects. 4.3.3.3.2, 4.3.3.3.3, and 4.3.3.3.4 need only demonstrate that the measured leakage rate does not exceed $l0^{-7}$ cm^3/s (that is, the package is considered to be leaktight, as defined in Subsect. 4.1.3 of this document). Assembly verification shall be performed as required in Subsect. 4.3.3.3.5.

The reference air leakage rate is also helpful in comparing and selecting an appropriate test method and procedure from Appendix A (of ANSI N14.5) or information in Subsect. 4.5.5.

4.3.3.3 Section 6 - Containment system test requirements

4.3.3.3.1 General

Type B package containment systems shall be leakage- or release-tested and evaluated according to Subsects. 4.3.3.3.2 through 4.3.3.3.5, by procedures that comply with the requirements of Subsect. 4.3.3.4. Packages determined in Subsect. 4.3.3.2.4 to have a reference air leakage rate equal to or greater than 10 std cm^3/s for both normal and accident conditions of transport are exempt from this requirement.

4.3.3.3.2 Design verification

Compliance with package test requirements may be demonstrated by one of the four methods described in this section. For these tests, the radioactive contents may be simulated by nonradioactive contents. The choice of method will depend on the package design; variation from the methods discussed below is acceptable, provided that the intent of this standard is met. When testing is performed, only one specimen of a particular design need be tested. Guidance for the use of scale-model leakage tests is beyond the scope of the ANSI Standard and this safety guide.

If full-size prototypical containment systems and packages are to be tested, they shall be assembled as for shipment, subjected to normal and accident conditions of transport, and tested to show that they are either leaktight or have leakage or release rates less than or equal to the maximum permissible rates of Subsect. 4.3.3.2.2 or 4.3.3.2.3. Consideration should be given to the possibility that transient conditions during the thermal test may be the most limiting.

If full-size models of containment systems, closures, or related individual components are to be tested, they shall be an adequate representation of the actual package. The model shall be assembled as for shipment, subjected to normal and accident conditions of transport, and tested as described in Subsect. 4.3.3.3.2.

If the adequacy of a containment system design is to be shown by comparison, a suitable, previously verified, and essentially equivalent design shall be used for the comparison. Limited testing may be used to supplement the comparison.

If a demonstration test is to be performed, the actual release or leakage rate of the assembled containment system shall be determined under some known test condition. This shall be accomplished by one of the methods discussed in Subsect. 4.3.3.3.2, or by reference to the appropriate technical literature.

A demonstration shall then be performed. This demonstration shall consist of calculations, tests, or other techniques which show that, for normal and accident conditions of transport, the closure parts are not abnormally deformed or excessively displaced, temperature limits for the closure parts are not exceeded, and therefore the maximum permissible release or leakage rates of Subsect. 4.3.3.2.2 or 4.3.3.2.3 are not exceeded.

4.3.3.3.3 Fabrication verification

Before first use, each reusable containment system shall be assembled as for shipment, except that the radioactive contents may be simulated by nonradioactive contents, and tested to show that it is either leaktight or has a release rate or leakage rate less than or equal to the maximums shown in

Subsects. 4.3.3.2.2 or 4.3.3.2.3. To the extent possible, all joints and seams on the containment system shall be tested in the fully assembled state. In some cases, the testing of the joints and seams may have to be performed at the subassembly or component level to permit adequate access to and testing of the area.

Single-trip containment systems shall be tested to the same requirements as reusable systems, except that 1) the sample size may be less than 100 percent and 2) the testing shall have been completed during the preceding 12-month period. The sample size specified shall consider lot size, the maximum acceptable percentage of defects, and confidence level. The terminology and procedures used should be equivalent to the terminology and procedures described in the references noted above and below. The package need not be subjected to normal and accident conditions of transport before the test.

When components of reusable Type B package containment systems are modified, or when replacement is made of components not routinely replaced, the affected portion of the containment system shall be tested according to Subsect. 4.3.3.3.3. Leakage testing is not required following modification or replacement of parts not affecting the containment system.

4.3.3.3.4 Periodic verification

A shakedown period shall be specified for reusable Type B package containment systems (normally the first three uses) and shall be tested according to Subsect. 4.3.3.3.3. In addition, before use for shipment, they shall have been tested according to Subsect. 4.3.3.3.3 within the preceding 12-mo period. Periodic verification of the containment system need not include the testing of inaccessible joints and seams but shall include all components such as closures, valves, pipe fittings, and burst disks.

4.3.3.3.5 Assembly verification

As part of the preparation for each shipment, the containment system of each Type B package shall be assembled and tested, as indicated in Subsect. 4.3.3.3.5, to verify that it has been properly assembled and that the containment function has been established. The required test depends on the Normal Conditions of Transport.

Assembly shall be performed in accordance with a written procedure that includes a checklist for verifying that all containment system parts comply with the applicable requirements, are in place, and are properly secured. Parts that typically fall into this category are gaskets, flanges, seals, and the like.

When a release test is to be performed, the assembly test procedure sensitivity, L_u, in Ci/hr, need only to be 4200 × R_N to verify the proper assembly of the package.

When a leakage test is to be performed, the assembly test procedure sensitivity, L_U, in std cm^3/s, need only to be 4200 × L_N to verify the proper assembly of the package; the test need not be more sensitive than 10^{-3} std cm^3/s but shall be at least 10^{-1} std cm^3/s. Packages determined in Subsect. 4.3.3.2.4 to have a reference air leakage rate greater than 0.1 std cm^3/s are exempt from this requirement.

4.3.3.4 Section 7 - Test procedure requirements

4.3.3.4.1 General

Leakage test procedures shall be compatible with the test item and, when applied to the containment system, shall have sufficient sensitivity to demonstrate compliance with the test requirements of Subsects. 4.3.3.3.2 through 4.3.3.3.5. Allowable test release or leakage rates and test sensitivities shall be determined from Subsects. 4.3.3.4.2 or 4.3.3.4.3 to satisfy the requirements of Subsects. 4.3.3.3.2 through 4.3.3.3.4. Assembly test procedures are determined in Subsect. 4.3.3.3.5.

The tests shall be designed to preclude false acceptance. For leakage tests, this might include assuring the presence of a tracer material and a driving pressure. For release tests, this might include the collection of, and the accounting for, all escaped material. A variety of appropriate test procedures is described in Appendix A of ANSI N14.5. All necessary safety precautions shall be implemented.

4.3.3.4.2 Release tests

Except for assembly verification testing described in Subsect. 4.3.3.3.5, the adequacy of the sensitivity of each test procedure shall be demonstrated in accordance with the procedures outlined below:

1. An allowable test release rate, R_T, in Ci/h, for the radioactive contents or a simulated radioactive material shall be determined. This rate shall be equivalent to the maximum permissible release rate of Subsect. 4.3.3.2.2. Account shall be taken of the difference between test and transport conditions. Appendix B of the standard recommends guidelines for these differences.

2. The sensitivity of each release test procedure, as determined by reference to the applicable literature, or the performance of tests shall be considered adequate when it does not exceed one-half of the maximum permissible release rate for the radioactive material, as determined in the previous paragraph.

4.3.3.4.3 Leakage tests

Except for assembly verification testing, as described in Subsect. 4.3.3.3.5, the adequacy of the sensitivity of each leakage test procedure shall be demonstrated in accordance with the requirements of the following sections:

An allowable test leakage rate, L_T, in std cm^3/s for the tracer fluid (i.e., argon, helium) of each leakage test shall be determined. This rate shall be equivalent to the maximum permissible leakage rate, as described in Subsect. 4.3.2.3. Account shall be taken of the following:

1. The relationship between the leakage rates for different gases

2. The relationship between the leakage tests that are conducted at different pressure/temperature conditions

3. When the calculated maximum permissible leakage rate is 10^{-7} std cm^3/s or less, it need only be demonstrated that the actual leakage rate does not exceed 10^{-7} std cm^3/s.

Appendix B of ANSI N14.5 recommends the following guidelines for these relationships:

1. The sensitivity of each leakage test procedure, as determined by reference to applicable literature or the performance of tests, shall be considered adequate when it is less than or equal to one-half of the allowable test leakage rate for the tracer material, as determined in the previous section. In order to demonstrate that a packaging is leaktight, the sensitivity of the leakage test procedure shall be 5×10^{-8} std cm^3/s or better.

2. Consideration shall be given to the leakage test procedure as it is applied to the test item. For example, gas pressure drop tests and gas pressure rise tests are dependent on the gas volume under test and, therefore, the sensitivity of these tests shall be adjusted for volume as well as time. In many cases, the sensitivity of a leakage test procedure can be varied extensively by changing volume, pressure, mixture composition, or time. Leakage test procedures performed under well-controlled laboratory conditions will normally be more sensitive than the same procedures performed under field conditions.

4.3.3.4.4 Testing

Testing shall be performed in accordance with Subsects. 4.3.3.4.1 through 4.3.3.4.3, as applicable, and documented. If, during any test, it is found that the leakage or release is greater than the maximum permissible, the leakage or release shall be reduced to the acceptable level before shipment.

4.4 CONTAINMENT BOUNDARY DESIGN CONSIDERATION

4.4.1 General

The containment vessel, closure lid, valve penetrations, attachment hardware and gaskets or seals constitute (in most cases) the containment boundary. The vessel usually provides most of the volume to accommodate the radioactive contents and it is usually cylindrical in shape. At least one end of the vessel will provide a flange for attaching a removable lid which incorporates some form of a sealing interface. Although a seal can be defined as a means to prevent leakage through a joint, it can also be used to describe the sealed joint itself. Valve penetrations, which may be needed for operational purposes, shall fall under the same scrutiny as the other components of the containment system. While each of these components is discussed separately, they constitute the containment system and are subject to compatibility constraints if the containment is to maintain its integrity. In Subsect. 4.4.2, we will examine the design, material selection, and fabrication techniques associated with the containment vessel, closure lid and attachment hardware. In Subsect. 4.4.3, we will examine the seal design from the standpoint of the properties of the 1) closure method, 2) sealing surfaces, and 3) seal materials. Although the fundamentals of a seal design must also be examined from the standpoint of the properties of the radioactive contents, this subject will be examined in detail in Sect. 4.6. Prior to beginning this discussion, it should be noted that the bulk of the material presented in Subsect. 4.4.3, has been adapted primarily from one of two sources: 1) SAND88-1015, a 1988 Sandia Report entitled *Compilation of Current Literature on Seals, Closures, and Leakage for Radioactive Material Packagings,*[12] and 2) the *Parker O-ring Handbook.*[13] Although the material contained in both source works has for the most part proved invaluable, it should also be noted that the material presented may not always be correct under all circumstances. Where appropriate, therefore, additional information has been provided, particularly with respect to those areas where design caution must be used. In Subsect. 4.4.4, we will examine the design requirements associated with valve-type penetrations into the containment boundary.

Currently, no national codes or standards are dedicated to the design and construction of Type B packaging. However, the NRC has developed numerous regulatory guides to provide design recommendations for the spent fuel casks used by the nuclear utilities. These regulatory guides, where relevant, serve as a set of suitable guidelines for DOE packaging design. NRC has adopted the design philosophy of applying stricter requirements and higher margins of safety to packages with higher levels of radioactivity. For example, Type B Fissile Class III packages must meet stricter requirements and require higher margins of safety than Type A, Fissile Class I packages. NRC Reg. Guide 7.11[14] defines three categories of Type B packages according to the levels of radioactivity in the content. For a specific radioactive isotope, Category I includes the highest curie level and thus requires the highest margin of safety, whereas Categories II and III include the medium and low activity levels and therefore require lower margins of safety.

To facilitate the design of any containment boundary, the following procedure is recommended as good business practice:

1. Establish the size, weight, form, and the nuclide constituents of the contents to be shipped.

2. Determine the A_1 or A_2 values for the contents (see Appendix A).

3. Using the information from items 1 and 2 above, determine the appropriate category for the containment boundary, shielding, and criticality safety hardware (see Fig. 4.2).

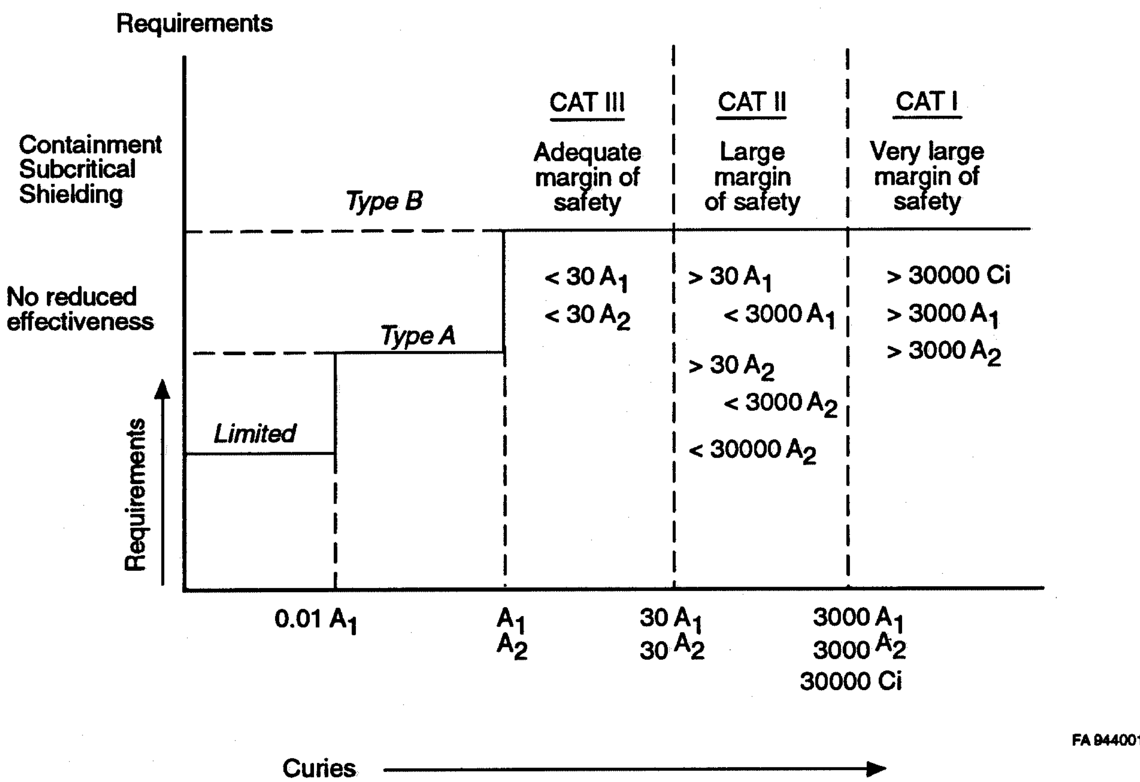


Fig. 4.2. Packaging types and activities of contents.

4. Using the category determination in item 3, determine the acceptable quality criteria for the design and manufacturing phase (see Table 4.2).

5. Determine the overall size, shape, and number of containment boundaries and appropriate closure methods based on internal supports, assembly, operational, and special requirements of certain contents.

Given the initial criteria established by this procedure, the design shall then incorporate the environmental impacts as specified in 10 CFR 71 and as stated previously in Sect. 4.2 of this guide. Even though the regulations do not impose any specific requirements on any structural components in terms of stress allowables or deformation limits, the containment boundary will be compromised if the structural components are over-stressed or grossly distorted. Therefore, the structural components should be designed according to a well-established design standard such as the ASME Boiler and Pressure Vessel Code (ASME Code)[15] as recommended by Reg. Guide 7.6. From experience, large factors of safety are incorporated in the ASME Code. Other codes and standards can be used as design criteria provided that they can be justified as conservative as the ASME Code. All of the loadings from the normal and accident conditions should be considered and combined as recommended by Reg. Guide 7.8 (Table 4.3). Figure 4.3 outlines a procedure for identifying and combining loads, classifying stresses, and comparing the stress results with the acceptance criteria specified by Reg. Guide 7.6. Section III of the ASME Code permits different design approaches to be used for the design which are "design by formulae" and "design by analysis." The design-by-formula approach is the cookbook method. General formulae are provided for vessel, pump, valve and piping designs. The designs are done according to step-by-step rules and the allowables for the design-by-formulae approach are necessarily conservative. By contrast, the design-by-analysis approach requires detailed analyses; therefore, the allowables can be set higher. Designs that are not qualified using the design-by-formulae approach may qualify with the design-by-analysis

Table 4.2. Structural design criteria (based on ASME Code)

Component Safety Group	Container contents		
	Category I	**Category II**	**Category III**
Containment	Section III Subsection NB	Section III Subsection ND	Section VIII Division I
Subcriticality	Section III, Subsection NG		
Shielding and other	Section III, Subsection NF		

Table 4.3. Summary of load combinations for normal and hypothetical accident conditions of transport

Normal or accident condition	Applicable initial condition							
	Ambient Temperature		Insolation		Decay Heat		Max. internal pressure	Max. weight of contents
	100°F	-20°F	Max	0	Max	0		
Normal Conditions								
Hot environment- 100°F ambient temp.			X		X		X	
Cold environment- -40°F ambient temp.				X	X		X	
				X		X	X	
Minimum external pressure	X		X		X		X	
		X		X	X		X	
Vibration and shock- Normally incident to the mode of transport	X		X		X		X	
		X		X	X		X	
		X		X		X	X	
Free drop- 1-ft drop	X		X		X		X	X
		X		X	X		X	X
		X		X		X	X	X
Accident Conditions								
Free drop- 30-ft drop	X		X		X		X	X
		X		X	X		X	X
		X		X		X	X	X
Puncture- drop onto bar	X		X		X		X	X
		X		X	X		X	X
Thermal- fire accident	X		X		X		X	

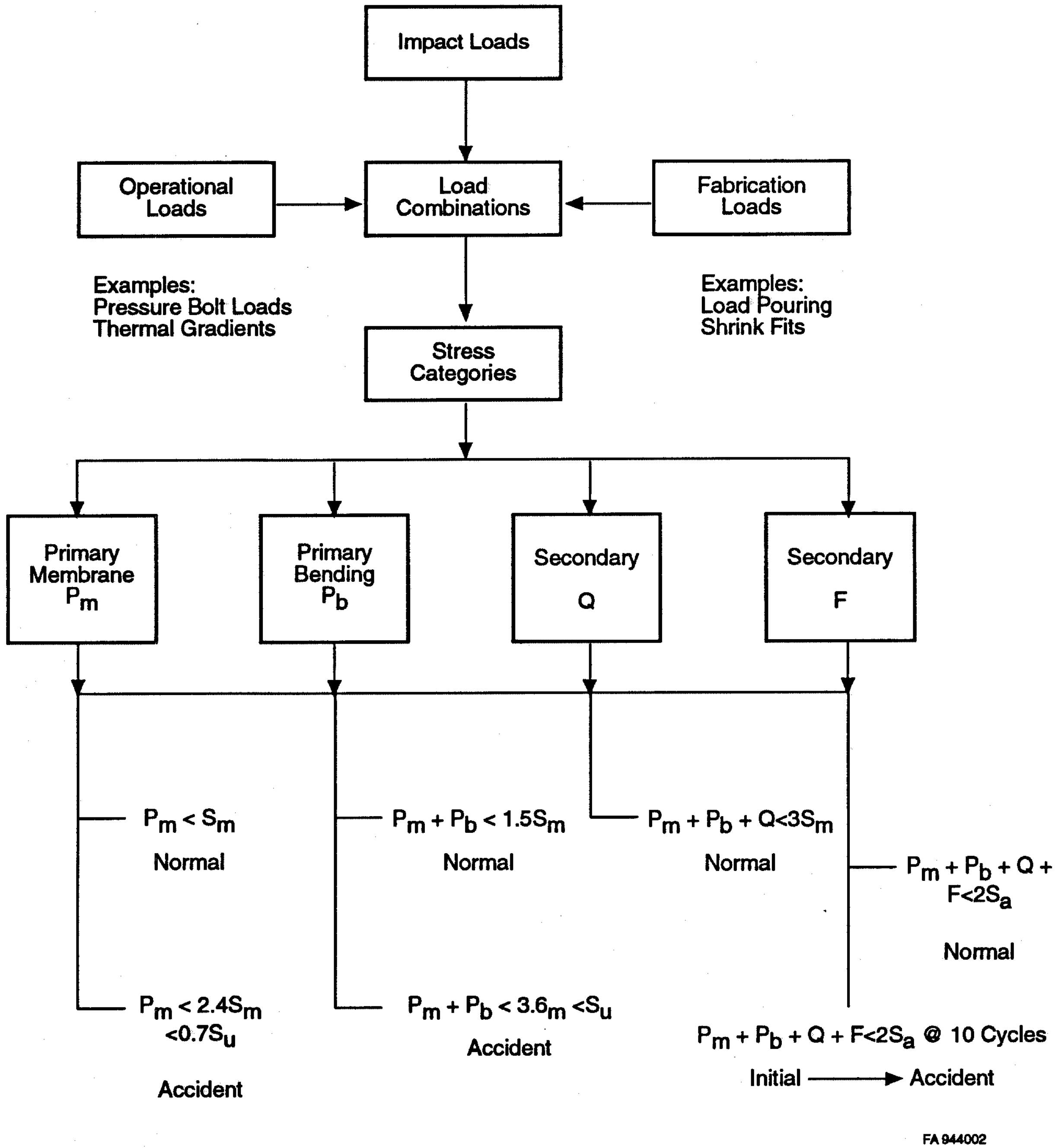


Fig. 4.3. Load combinations and stress intensity limits.

approach. Once the design approach is decided, all of the rules in that approach should be followed and the design must be consistent within the given design approach.

With advances in analytical and experimental techniques, the design-by-analysis approach has become more attractive than the design-by-formulae approach in yielding a well-balanced design for critical safety components. Additionally, it has become possible to determine local stresses in a structure in detail. It is therefore unreasonable to retain the same allowables throughout the structure because high local stresses do not constitute a global structural failure. The rationale of assigning different allowables for different types of stress is, "A calculated value of stress means little until it is associated with its location and distribution in the structure and with the type of loading which produced it. Different types of stress have different degrees of significance and must, therefore, be assigned different allowable values. For example, the average hoop stress through the thickness of the wall of a vessel due to internal pressure must be held at a lower value than the stress at the root of a notch in the wall."[15] Likewise, thermal stress allowables can be higher than those due to dead weight or pressure. Therefore, the design-by-analysis approach requires dividing stresses into categories and assigning different allowable values to different groups of categories.

Section III of the ASME Code divides stresses into three groups: primary stress (P), secondary stress (Q), and peak stress (F). "Primary stress is a stress developed by the imposed loading which is necessary to satisfy the laws of equilibrium between external and internal forces and moments. The basic characteristic of a primary stress is that is not self-limiting. If a primary stress exceeds the yield strength of the material through the entire thickness, the prevention of failure is entirely dependent on the strain-hardening properties of the material."[15] The primary stress can be further divided into three types of stresses according to spatial distributions: general primary membrane stress (P_m), local primary membrane stress (P_1), and primary bending stress (P_b). Examples of primary stress are stresses due to impact loads, internal pressure, and bolt loads. The stress state caused by these loads is divided into membrane and bending components.

"Secondary stress is a stress developed by the self-constraint of a structure. It must satisfy an imposed strain pattern rather than being in equilibrium with an external load. The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the discontinuity conditions or thermal expansions which cause the stress to occur."[15]

"Peak stress is the highest stress in the region under consideration. The basic characteristic of a peak stress is that it causes no significant distortion and is objectionable mostly as a possible of fatigue failure. "[15]

The basic philosophy of the design by analysis approach is based on linear elastic analysis. Failure by the maximum shear stress theory of failure is used as the basis for stress allowables. Stress categories are calculated as "stress intensity" before they are compared with the allowables which are called "stress intensity limits" in the code. Stress intensity is defined as twice the maximum shear stress at a point. If the principal stresses are Sl, S_2, and S_3, while $S_1 > S_2 > S_3$ (algebraically), the maximum shear stress is $(S_1 - S_3)/2$. Therefore, the stress intensity is then equal to $(S_1 - S_3)$ and it is required to be less than or equal to the stress intensity limit for a given or combined loading condition. Stress allowables, that is stress intensity limits, are not expressed in terms of the yield strength of the material, but rather as multiples of S_m. S_m is the stress intensity limit for general primary membrane stress and values of it for various metal alloys are tabulated in Sect. III, Appendix I of the code.

Yield strength is not a sufficient criterion in determining the allowable stress because of a big range of ductility and strain-hardening properties in materials. To prevent unsafe designs in materials with low ductility and in materials with high yield-to-tensile ratios, the ASME Code requires the stress allowable to be equal to or less than the smaller of 2/3 of the yield strength or 1/3 of the ultimate tensile strength. Table 4.4 summarizes the basic stress intensity limits and the multiples of yield strength and ultimate strength that these limits do not exceed for four stress categories: general primary membrane, local primary membrane, primary membrane plus primary bending, and primary plus secondary.

The stress limit for each stress category is related to the potential failure mode. The primary stress limits aim to prevent plastic deformation and to give a nominal factor of safety on the ductile burst pressure, whereas the primary plus secondary stress limits are intended to prevent excessive plastic deformation and collapse. Finally, the peak stress limit is intended to prevent fatigue failure as a result of cyclic loadings. The stress limits for P_m are more conservative than for $P_m + P_b$. Since most stress states in a package component are a combination of membrane and bending stresses, these stresses must be separated into different parts. In general, the maximum membrane stress occurs at the neutral axis where the bending stress is zero and the maximum membrane plus bending stress occurs at the extreme fibers. A conservative approach for evaluating stresses is to use the P_m limits for all stress states without separating them into membrane and bending components. In some cases, this approach may not be appropriate and the P_m and $P_m + P_b$ limits must be used.

In the ASME Code, all subsections in Sect. III and Sect. VIII, *Rules for Construction of Pressure Vessels,* Division 1 have provisions for the design-by-formulae approach. The design-by-formulae approach requires less rigorous analysis than the design-by-analysis approach. For less critical safety components, the design-by-formulae approach may be preferred because of its simplified procedures for the design. One advantage in using the design-by-formulae is that direct stresses, not stress intensities, are used to compare with the stress allowables. Stress intensity calculations and the determination of stress categories are omitted completely in the design-by-formulae approach. The stress allowables (S),

Table 4.4. **Basic stress intensity limits**

Stress category	Stress limit	Allowable stress intensity: Based on yield S	Allowable stress intensity: Based on tensile S
General primary membrane (P_m)	S_m	2/3 S_y	1/3 S_u
Local primary membrane (P_1)	1.5 S_m	S_y	1/2 S_u
Primary membrane plus primary bending ($P_m + P_b$)	1.5 S_m	S_y	1/2 S_u
Primary plus secondary ($P_m + P_b + Q$)	3.0 S_m	S_y	S_u

which is different from stress intensity allowables (S_m), for various metal alloys, are also tabulated in Sect. III, Appendix I of the code.

4.4.2 Containment Vessel, Closure Lid, and Attachment Hardware

4.4.2.1 Containment vessel

4.4.2.1.1 General design criteria

The design of the containment vessel is at best an iterative process dependent upon the allowable release rates as well as the environmental impacts imparted by the surrounding components of the shipping package when subjected to the requirements and tests stipulated in 10 CFR 71. The major loads are heat, internal pressure, and impact. In many cases, these loads act simultaneously and all effects should be analyzed. The principal design features to be considered are the overall shape characteristics of the vessel, wall thicknesses and provisions for positive fastening and sealing methods. Careful attention must be given to each design feature if failure of its function would lead to the release of radioactive material or an inleakage of water.

This design guide recommends Sect. III of the code in the areas of design stress selection, fatigue analysis and buckling for Categories I and II containment vessels, and Sect. VIII for Category III vessels. While Section III provides rules for the prevention of nonductile (brittle) fracture in Appendix G, the NRC issued its own guidelines for ferritic steels in Reg. Guide 7.11.

4.4.2.1.2 Cylindrical vessel sizing

The minimum cylindrical containment vessel thickness may be established in accordance with the following sections of the ASME Boiler and Pressure Vessel Code:

1. Category I - Rules of Sect. III subarticles NB-3320 or NB-3640 dealing with design for internal pressure;

2. Category II - Rules of Sect. III subarticles ND-3130 for external pressure and ND-3320 for internal pressure or ND-3640 for pipe type applications; and

3. Category III - Rules of Sect. VIII, Division 1 dealing with design for internal pressure and external pressure subparagraphs UG-27 through UG-3 1 and Appendix I.

For Category I packages, this only accounts for the circumferential primary membrane stress. Table NB-3217-1 in Sect. III, NB-3000 tabulates the specific classification of stress intensity associated with the various components of a pressure vessel. The constraints produced by the end closures will result in local bending stresses which are secondary in nature. The magnitude of these local bending stresses depends upon the shape and thickness of the head or end closure. Spherical closures provide the smallest discontinuity stresses while flat plates provide the largest. It is possible that these local stresses may exceed the yield strength upon pressurization. If upon relieving the pressure, the residual stress in compression is elastic, subsequent repressurization will result in elastic stresses provided the original pressure is not exceeded. This is the result of "elastic shakedown" where, provided the total stress range does not exceed twice the yield strength, relatively few cycles of stress have little effect upon the performance of the vessel. In cases where there will be many cycles of stress or where the stress range is such that the yield strength is exceeded in both tension and compression, a fatigue analysis should be performed to compare the computed number of cycles to failure with the number of cycles anticipated over the design life of the vessel.

4.4.2.1.3 End closure design

The shape of the end closure is normally dictated by the shape of the contents or a required volume of internal cushioning supports. Depending on the shape selected, the required wall thickness will vary based on a given internal or external pressure. For a Category Ill-type containment vessel, this point is illustrated further by applying the design by formula method in accordance with Sect. VIII, Division 1 depicted below. Figure 4.4 shows some of the more commonly used shapes for head or end closure.

In simplistic terms, the wall thickness required for each shape shown in Fig. 4.4 is determined by formulae given in UG-32, -33, and -34. To show how the shape plays an important part in the thickness and useable internal support volume for a given set of conditions, assume an internal pressure of 200 psig, an 18 in. inside diameter S = 13750 psi, and a weld efficiency E = 0.60 for a circumferential butt weld between the form closure and the cylindrical portion of the containment vessel. Applying the formulae and rules of paragraphs UG-32, -33, and -34 of Sect. VIII, Division 1, Table 4.5 shows the corresponding thicknesses of the closure wall. Similar formulae for Category II components are listed in Sect. III, ND-3000.

To determine the appropriate thicknesses, the design-by-analysis approach, previously described, must be followed for Category I components.

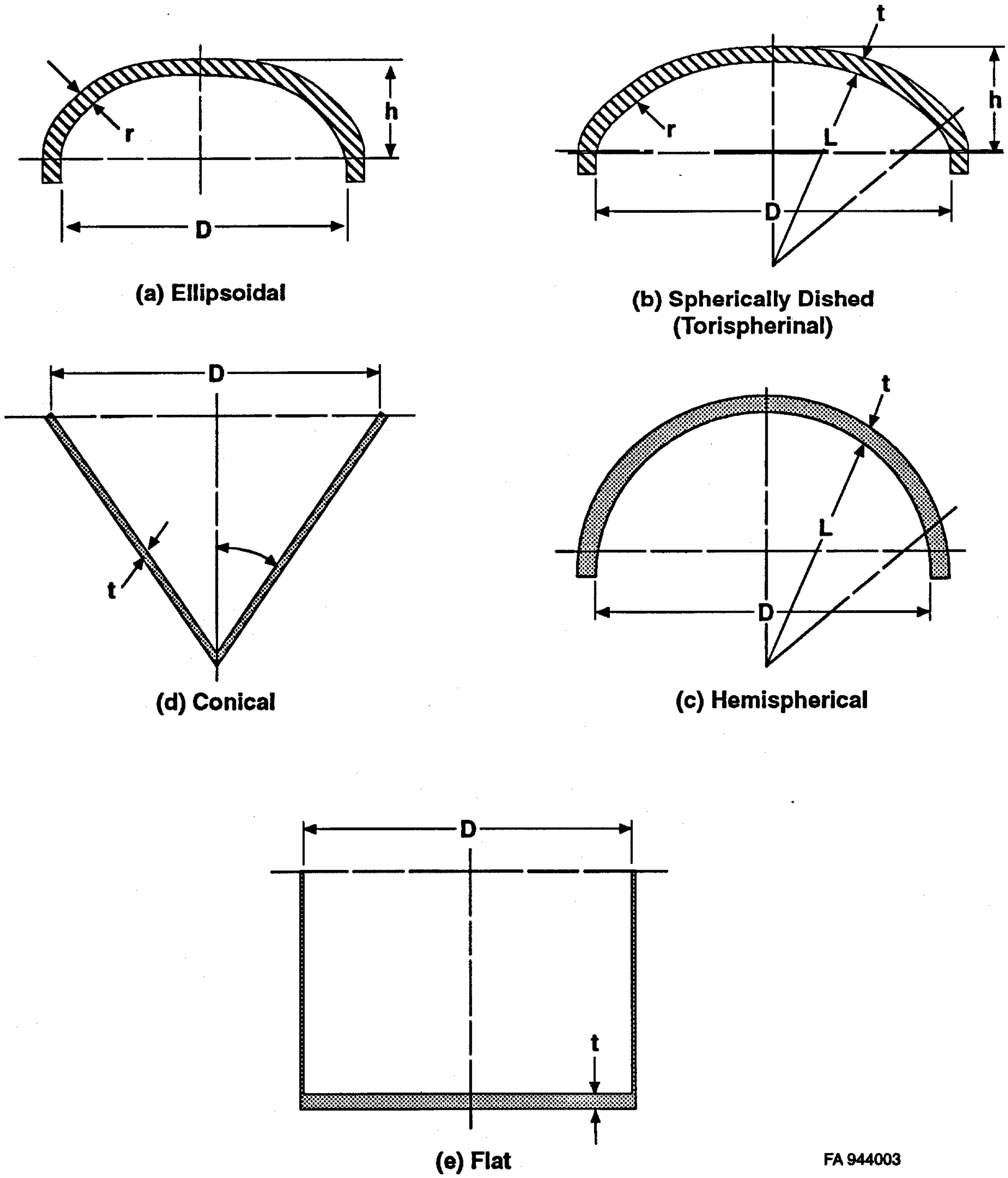


Fig. 4.4. Principle dimensions of typical heads.

Table 4.5. End closure geometry characteristics

Shape function	Formula	Wall thickness (in.)
Ellipsoidal	$t = \dfrac{P \cdot D}{2 \cdot S \cdot E - 0.2 \cdot P}$	0.219
Torispherical	$t = \dfrac{P \cdot L \cdot M}{2 \cdot S \cdot E - 0.2 \cdot P}$	0.387
Hemispherical	$t = \dfrac{P \cdot L}{2 \cdot S \cdot E - 0.2 \cdot P}$	0.109
Conical	$t = \dfrac{P \cdot D}{2 \cdot \cos\alpha (S \cdot E - 0.6 \cdot P)}$	0.313 for 45° half angle
Flat	$t = d \cdot \sqrt{\dfrac{C \cdot P}{S \cdot E}}$	1.609

From the assembly and packaging standpoint, the flat bottom containment vessel is the most preferred (Fig. 4.5). The major drawback to the flat bottom is the additional weight required to maintain an acceptable stress level for a given pressure.

The shape characteristic of the vessel is not always determined solely on internal or external pressure but on how the vessel maintains its integrity when subjected to the dynamic loads of drop testing.

4.4.2.1.4 Load combinations impact on vessel design

The subparts and sections of 10 CFR 71 that are particularly germane to the design of the containment boundary are paragraphs 71.71, *Normal Conditions of Transport,* and 71.73, *Hypothetical Accident Conditions.* Evaluation of each containment vessel design must include a determination of the effects on the design of each of the following conditions and tests as depicted in Table 4.3;

1. Hot environment - Ambient temperature 38°C (100°F) with solar insolation and decay heat added.

2. Cold environment - For the response of the package to extremely low temperature conditions, an ambient temperature of -40°C (-40°F) in still air and shade is assumed with and without the decay heat input and including the maximum normal operating pressure.

3. Reduced external pressure - Assess the vessel for the effects of external pressure equal to 3.5 psia for the case where the ambient temperature is 100°F, solar insolation, maximum normal operating pressure, and decay heat load. Also assess the vessel at the reduced external pressure

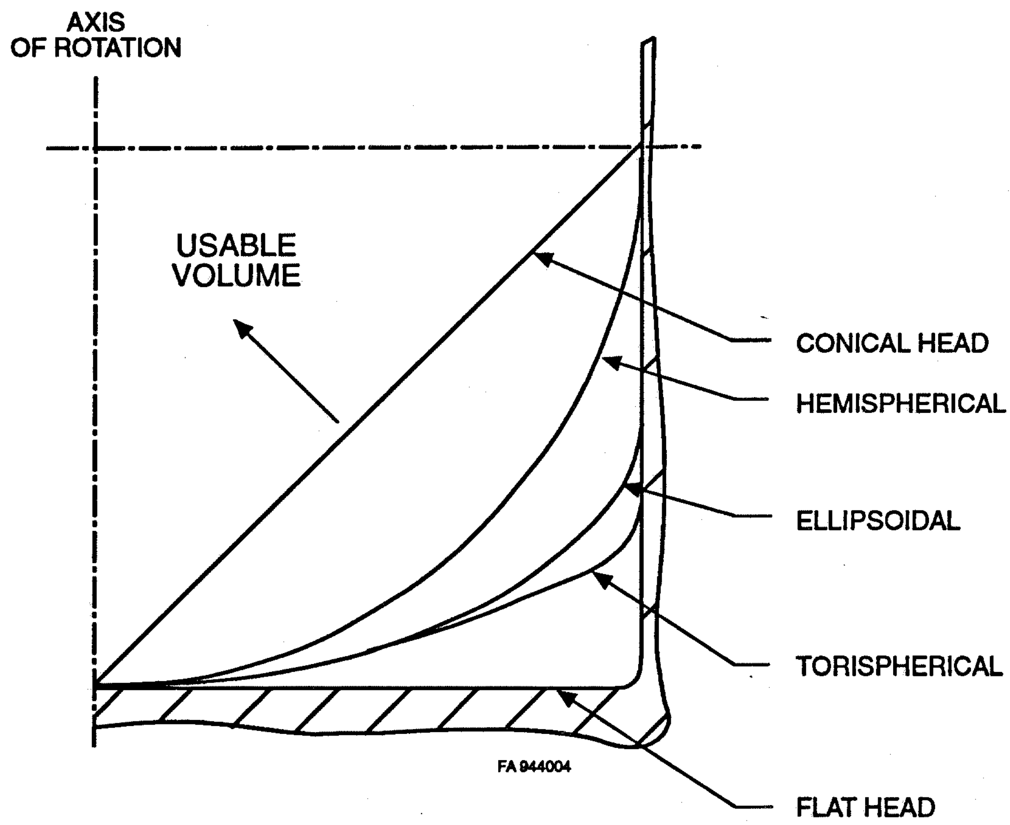


Fig. 4.5. Volumetric comparison of closure styles.

for the condition where the ambient temperature is -20°F, maximum normal operating pressure and decay heat load added.

4. Vibration - The containment vessel's design shall assess the effects of vibration and shock environment normally incident to transport.

5. Water spray - Test specimens of the total package design must be subjected to a water spray that simulates exposure to rainfall of approximately 5 cm (2 in.) per h for at least 1 h.

6. For Fissile Class II containment, a free drop from a height of 0.3 m (1 ft.) on each corner or quarter rim of a cylindrical package with the initial conditions as depicted in Table 4.3.

7. Between 1 1/2 and 2 1/2 h after the conclusion of the water spray test, a free drop through the distance specified in 10 CFR 71 .71(c)(7) onto a flat, essentially unyielding horizontal surface, striking the surface in a position for which maximum damage is expected.

8. Compression - For packages weighing up to 5000 kg, the package must be subjected to a compressive load applied uniformly to the top and bottom of the package for a period of 24 h in a position in which the package would normally be transported. The compressive load must be the greater of the following: the equivalent of five times the weight of the package or a load equivalent to the product of 12.75 kPa (1.85 lb/in.^{2}) and the vertically projected area of the package.

9. Penetration - Impact of the hemispherical end of a vertical steel cylinder of a 3.2 cm (1 1/4-in.) diam and 6 kg (13-lb) mass, dropped from a height of 1 m (40 in.) onto the exposed surface of

the package which is expected to be most vulnerable to puncture. The long axis of the cylinder must be perpendicular to the package surface.

The containment vessel must be designed and constructed so that under these criteria there will be no substantial reduction in the effectiveness of the vessel to withstand the Hypothetical Accident Condition testing. Evaluation for Hypothetical Accident Conditions is to be based on sequential application of the tests specified in this section, in the order indicated, to determine their cumulative effect on a package or array of packages. An undamaged specimen may be used for the water immersion test.

10. Free Drop - A free drop of the specimen through a distance of 9 m (30 ft) onto a flat, essentially unyielding horizontal surface, striking the surface in a position for which maximum damage is expected with the initial conditions as shown in Table 4.3.

11. Puncture - A free drop of the specimen through a distance of 1 m (40 in.) in a position for which maximum damage is expected, onto the upper end of a solid, vertical, cylindrical mild steel bar mounted on an essentially unyielding, horizontal surface under the initial conditions as shown in Table 4.3.

12. Thermal - Exposure of the whole specimen for not less than 30 mm to a heat flux not less than that of a radiation environment of 800°C (1475 °F) with an emissivity coefficient of at least 0.9. For the purpose of calculation, the surface absorptivity must be either that value which the package may be expected to possess if exposed to a fire or 0.8, whichever is greater; in addition, when significant convective heat input must be included on the basis of still, ambient air at 800°C (1475 °F). Artificial cooling must not be applied after cessation of external heat input, and any

combustion of materials of construction must be allowed to proceed until it terminates naturally. The effects of solar radiation may be neglected prior to, during, and following the test.

13. Immersion - Fissile Materials: In those cases where water has been assumed not present for criticality analysis, an undamaged specimen must be immersed under a head of water of at least 0.9 m (3 ft) for a period of not less than 8 h and in the attitude in which maximum leakage is expected.

14. Immersion - All Packages: A separate undamaged specimen must be subjected to water pressure equivalent to immersion under a head of water of at least 15 m (50 ft) for a period of not less than 8 h. For test purposes, an external pressure of water of 147 kPa (21 psi) gage is considered to meet these conditions.

The designer must evaluate the impact on the overall design of the containment vessel in accordance with the above criteria. To enhance the designer's understanding, the impact from each condition will be briefly discussed in the following paragraphs.

Applying the condition of item 1, the internal pressure will increase inside the container and reduce the allowable stress limits of the vessel structural material, thereby possibly increasing the required wall thickness of the shell. If the contents produce any decay heat, this source of heat should also be included in determining the overall pressure and vessel temperature. The maximum normal operating pressure by definition is the maximum gage pressure that would develop in the containment vessel in a period of one year under the heat test (solar insolation) specified in 10 CFR 71 .71(c)(1) in the absence of venting, external cooling by an ancillary system, or operational controls during transport. To illustrate, the following example is given:

1. Assume the containment vessel is assembled at 70°F with plutonium contents with some level of decay heat.

2. The container is purged and backfilled with 10 psig argon gas.

3. The final vessel temperature is 160 °F, taking into account the solar insolation input and decay heat generated.

Assuming the gas behaves according to the ideal gas law, the following simple calculation will determine the final pressure developed under condition 1:

$$\frac{P_1 \cdot V_1}{T_1} = \frac{P_2 \cdot V_2}{T_2}$$

where

P_1 = containment vessel pressure at assembly (absolute)

T_1 = containment vessel temperature at assembly

$V_1 = V_2$ assuming constant volume final containment vessel temperature

T_2 = final containment vessel temperature

Expressing temperature in degrees Rankine, the final containment pressure (P_2) can be determined by the following equation:

$$P_2 = \frac{P_1 \cdot V_1 \cdot T_2}{V_2 \quad T_1}$$

P_2 = 14.7 psia · 629.6 R / 529.6 R

P_2 = 17.2 psia

This simplified example does not take into account the increased pressure or temperature associated with chemical reactions or outgassing from internal support features that might occur due to the increase in temperature of an enclosed containment vessel. If a situation exists, where these other inputs will occur, then their impact must be included. The following features must be evaluated based on this pressure differential:

1. Stress levels in the containment vessel
2. Recalculate or check leakage requirements
3. Preload and stress in closure components (discussed in later sections)
4. Seal compression reduction, flange separation
5. Material differences in coefficient of thermal expansion

Under the conditions of item 2 and utilizing the above simplistic ideal gas law, the lowering of the ambient temperature will lower the pressure inside the containment vessel. This normally is not the worst pressure differential, but the material characteristics in terms of ductility and fracture toughness must be evaluated. Also differences in the coefficient of thermal expansion should be considered if the bolting material is not the same as the containment vessel and lid. O-ring or gasket sealing material’s survivability should also be investigated for this condition.

Under the conditions of item 3, the maximum internal pressure due to solar insolation and decay heat is assumed with an external pressure of 3.5 psia. Stresses in the containment vessel are then calculated using this pressure differential and are compared with the material allowable at the elevated temperature. If a lower internal pressure consistent with the ambient temperature in the range of -20°F and 100 °F is more unfavorable then the calculation are conducted at that set of conditions. Again, coefficient of thermal expansion should be considered if the materials of construction and bolting are different.

Condition 4 requires the evaluation of the package for vibration normally incident to transport. This type of vibration is usually nonperiodic in that there is no pattern to either frequency or amplitude. What must be provided as a "load" is usually a spectral density for the excitation. This is based upon test data for the roads and vehicles associated with transporting the packages. Random vibration methods for determining the maximum response are then used. The responses to the containment vessel must be evaluated under the ambient temperature in the range of -20 to 100°F with and without decay heat input and at the maximum normal operating pressure (MNOP) determined previously. Normally, with proper cushioning from internal supports, the containment vessel is isolated from the vibration responses. This is not always the case when evaluating the closure lid and attachment method. This will be discussed in more detail in sections on attachment methods.

The most severe loading conditions that the containment vessel must survive comes from the impact imparted by the drop test simulating accident conditions. Conditions and tests under items 5, 6, and 7 normally have little impact on the design of Type B containment vessels: However, since the leakage requirements for the normal condition of transport are more severe than those of the hypothetical accident condition, the tests must be conducted to comply fully with the requirements stipulated in 10 CFR 71.71.

Typically, the containment vessel is surrounded by some form of impact limiting material, Under the compression test of item 8 and the puncture of item 9, the loads are absorbed by this material and the containment vessel is not impacted.

Impacts may occur at any orientation and should be checked for that which can result in maximum damage. Some mitigation is provided by impact limiters which will require consideration of their nonlinear and inelastic response. In addition to the primary impact, the effect of rigid body motion and secondary (slap-down) impact should be evaluated. To obtain a detailed stress pattern or to model accurately nonlinear behavior such as plastic deformation or buckling, a dynamic finite-element analysis should be used. In this method, each component of the containment system can be modeled separately with its specific materials, geometry, and interfaces. While expensive and time consuming, dynamic finite-element analysis methods provide the most accurate and detailed estimates of containment response to impact loads.

The deformations that occur as a result of differential thermal expansion are self-limiting and the corresponding stresses are classified in the ASME Code as secondary. Normally the range of primary plus secondary stresses should not exceed three times the stress intensity limit (3S) for the material. If thermal stresses are involved, this limit may be exceeded if a multiplying factor is used with the calculated stress range to enter the design fatigue curve. This method is conditional upon limiting the stress range, excluding stress concentrations and thermal stresses, to $3S_m$.

Since there is a requirement to consider external pressure on the vessel due to immersion illustrated by tests 13 and 14, it should be designed so that the stress intensity limits in compression are not exceeded and that buckling is not a possible failure mode. Suggested rules for determining the maximum allowable pressure for the design of the vessel for Categories I, II, and III are given in Paragraph NB-3 133 of Sect. III, Paragraph ND-3133 of Sect. III, and UG-32, UG-33, and UG-34 of Sect. VIII, respectively, of the ASME Code.

4.4.2.2 Closure lid and attachment methods

4.4.2.2.1 General design criteria

The function of the closure device is to allow loading and unloading of the containment contents and to provide the mechanism along with the containment vessel of minimizing leakage of the radioactive contents. When attached, the containment closure is an integral part of the containment system and is subject to the same loads as described in Subsect. 4.4.2.1.1. Various shapes of the closure lid can be employed and are similar to those postulated for the ends of the containment vessel. The closure lid is normally more complicated than the simple end shapes because of the incorporation of leak check ports, valve penetrations, and the attachment method to the containment vessel. But, in general, the analysis criteria for the removable closure shapes are the same as those previously mentioned for the end closures of the containment vessel except for the local bending moments at the attachment points.

Several attachment schemes can and have been employed in the design of containment boundaries for the transportation of weapon components. It is assumed that applicants have the appropriate analytical knowledge and tools to evaluate each attachment method for their own particular set of conditions and compliance with the requirements of 10 CFR 71. Figure 4.6 illustrates the various uses of bolting, V-band clamping, threaded ring clamping, and key or spline attachment in the exposed and protected mode. This guide will try to highlight and describe the various design features of each and the appropriate load conditions that affect the sizing of the closure components.

A protected closure is one that is protected by the containment vessel structure such that no transverse component of the impact force can be transmitted from the impact limiting material to the edge of the lid. In contrast, the lid of an exposed closure system does not have this inherent protection. The

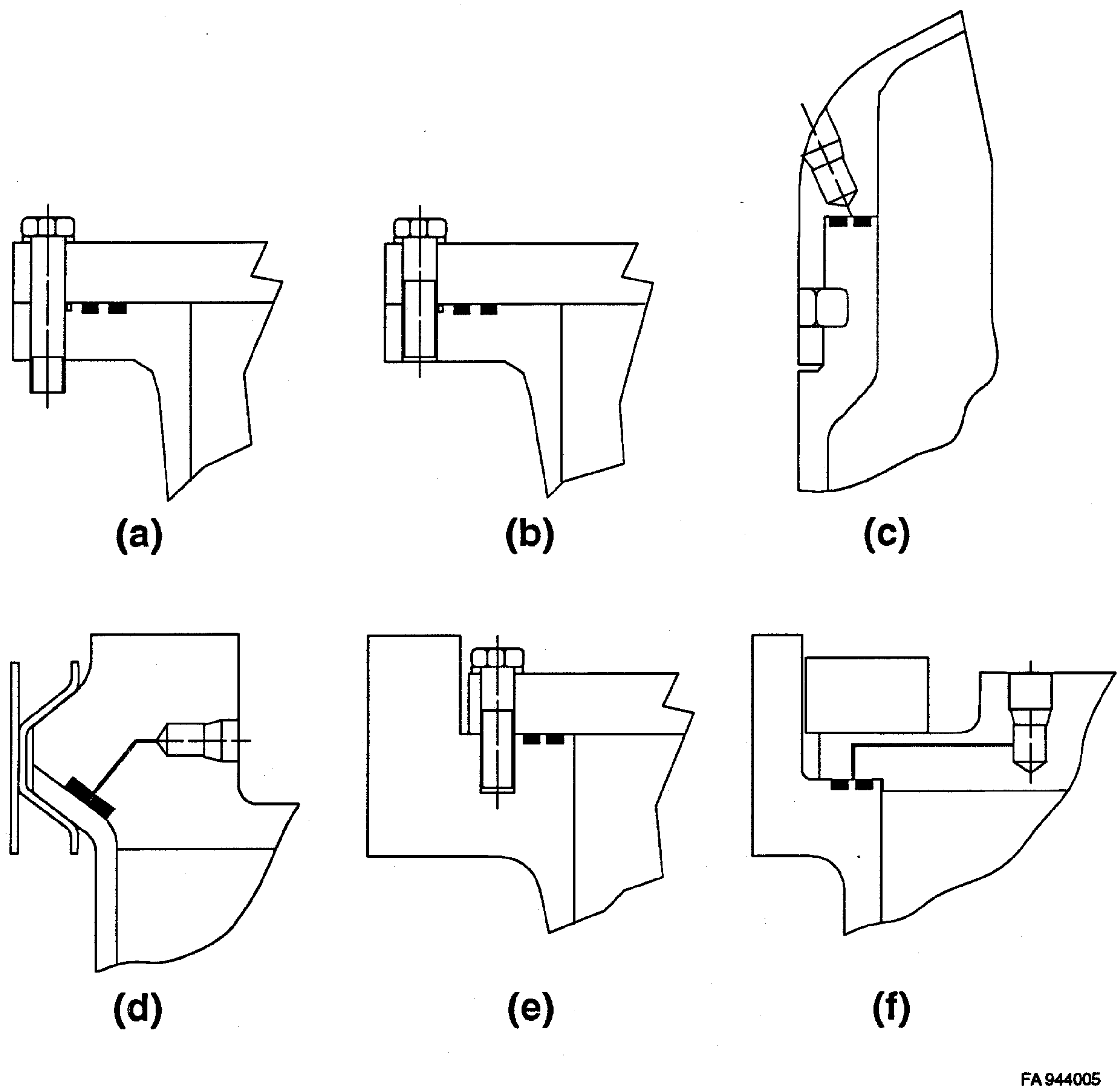


Fig. 4.6. Typical attachment methods.

protected closure method is recommended but not mandated. If the exposed closure method has further protection provided by the impact limiting material surrounding the containment boundary or the fastening method has been adequately designed and analyzed to react these additional impact force, then this type of closure is acceptable.

Parts 10 CFR 71.71 and 71.73 specify all the loading conditions that the closure lid and attachment hardware should be designed for under the Normal Conditions of Transport and under the Hypothetical Accident Conditions. In stress calculations, the loads or stresses on these components can generally be grouped into the following categories in accordance with the source of these loads:

1. Preload tension and torsion
2. Pressure loads
3. Thermal loads
4. Impact loads
5. Vibration and shock loads
6. Fabrication induced stresses

4.4.2.2.2 Bolted attachment method

The most often employed method of lid attachment is the use of a through bolt and nut [Fig. 4.6 (a)] or a bolt through the lid and threaded into a tapped hole in the containment vessel flange [Fig. 4.6 (b),(e)]. As shown in each sketch, seals or gaskets are employed to prevents leaks. Two types of seal arrangements, with and without metal-to-metal contact, are considered and their affects on the analysis of the bolted joint are discussed.

In the case of a closure system without metal-to-metal contact, a certain preload in the bolts is required to compress the gasket material to a level to prevent leakage. Any load from external forces will stretch the bolts and decompress the seal, possibly reducing the effectiveness of the closure to prevent leakage. Since all applied external forces will be carried almost completely by the bolts, including transverse impact loads, the following precautions are recommended:

1. The protected closure mode should be utilized.

2. The materials used for bolting and the corresponding flange materials should be closely match in coefficient of thermal expansion.

3. Uses of the seal method should be limited to small perturbations in pressure.

4. Special precautions must be incorporated to prevent vibration loads from loosening the attachment bolts.

For closure methods incorporating a bolted joint with an self energizing seal (e.g., an elastomeric O-ring) effective performance is maintained through metal-to-metal flange contact. The preload must be such that for the maximum force due to all external forces the metallic surface will remain in contact. If the joint components are infinitely stiff relative to the bolts, this preload is equivalent to the maximum external forces including those associated with thermal expansion. If this is not the case, then the preload must be made less than the maximum external force as not to overstress the bolts when the maximum external load is applied. There are two sources of axial thermal stress associated with the bolted joint. One is the axial stress in the bolt due to differential thermal expansion due to the hypothetical fire condition and the other is caused by the steady-state temperature distribution in the vessel under Normal

Conditions of Transport. If a differential thermal expansion exists between the lid and the containment vessel in the radial direction, a shear load on the bolts may occur. The axial load in a bolt due to temperature change in the bolt and its surrounding environment can be calculated as follows:[16]

$$P = K_b K_j (a_j - a_b) L d_T / (K_b + K_j)$$

where

P = axial bolt load due to differential thermal expansion of the bolt and the lid and vessel wall in the axial direction of the cask

L = thickness of the mating flanges (approximate) for the through bolt and thickness of the lid for the tapped hole application

a_j = coefficient of thermal expansion of the joint

a_b = coefficient of thermal expansion of the bolt

K_j = stiffness of the joint

K_b = stiffness of the bolt

d_T = change in temperature from initial temperature

A simple and conservative formula can be obtained from the equation below by assuming that the joint is rigid, i.e.,

$$P = (a_j - a_b) d_T E_b A_b$$

where A_b and E_b are the cross-sectional area and the modulus of elasticity of the bolt, respectively. Note that, in above equation, there is no need to calculate K_b and K_j.

The bolt load calculated with these equations can be added directly to other loads in the load combinations to calculate the total bolt load. In order to develop the stress intensity in the bolt due to axial load and shear from preloading the bolt, the initial tension from torquing (F_Q) is calculated as follows:

$$F_Q = Q/kD$$

where

Q = input torque applied (in.-lb)

k = the "torque coefficient" or the "nut factor"

D = nominal bolt diameter (in.)

The stress due to direct tension (S_Q) is:

$$S_Q = F_Q/A_T$$

where

A_T = tensile stress area at the thread root

The shear stress due to torquing can be calculated as follows:

$$S_S = 5.093(M_T)/(D_s)^3$$

where

M_T = torsional bolt moment (in.-lb)

D_S = diameter used to determine A_T above (in.)

The stress intensity value S_I is calculated by combining the tensile stress and the shear stress gives as follows:

$$S_I = [(S_Q)^2 + 4(S_s)^{1/2}$$

The major functions of the preload in closure bolts are to join the contact surfaces and to provide an environment in which the gaskets will function properly so that containment or dispersal requirements of 10 CFR 71.51 are met. In determining the number of bolts or fasteners to use, proper sizing of the flange should be conducted. The deflection and deformation between bolts should be limited so that no separation of the mating flanges will occur. Preload is also helpful in preventing vibration loosening, fatigue failure, and joint slippage. The joint will not slip or vibrate loose if the force generated from the preload, taking into account the temperature extremes, multiplied by the coefficient of friction between the lid and containment vessel is large enough to withstand the acceleration forces induced from the Normal Conditions of Transport.

See the appendices of Chap. 2, Structural Aspects, for an illustration of the procedures and the analysis used in designing a containment vessels with a bolted closure method according to the requirements of a Category III vessel.

4.4.2.2.3 Clamping attachment method

As shown in Fig. 4.6 (d), the V-band clamp method can be implemented to provide closure. Some of the advantages of this method compared to the bolted assembly are:

1. It provides for timely assembly and disassembly functions when limiting exposure of contents to personnel.

2. It allows remote maintenance application.

3. When the lid is designed in this fashion, the leak-check or fill port is protected from impact load generated from various drop orientations.

4. A V-band clamp arrangement can be designed to apply constant pressure to the entire circumference of the lid and vessel interface.

To develop the proper preload and to design the V-band clamp to withstand the conditions and test of 10 CFR 71, the use of finite-element analysis is recommended. Matching of materials in terms of thermal expansion and galling characteristics is also warranted.

4.4.2.2.4 Retaining ring attachment method

The screwed retaining ring type of joint [Fig. 4.6 (f)] has the advantage of eliminating the need for bolts, threaded studs, or the like. Compression of the O-ring seal and metal-to-metal contact is maintained by torquing the threaded external ring to the required value. In this concept, the lid and leak-check or fill ports are protected from transverse load due to various drop orientations. The major areas to be concerned is in the development of the torque required to fully set the O-rings and preclude loosening due to impact loads or vibration. Again, the use of finite-element analysis is recommended.

4.4.2.2.5 Spline key attachment method

The final attachment scheme shown in Fig. 4.6 (c) is the incorporation of a key or spline to provide the mechanism to prevent separation of the mating closure surfaces. Applications utilizing this type of attachment may be utilized in the remote maintenance domain. Joint slippage across the face seal is prevented by close tolerance machining of the mating radial surfaces. To a certain extent the load generated from the circumferential spline key equally loads the O-rings around their periphery. Disadvantages of this method are first, close tolerances in the spline cavity related to the mating gasket surfaces are required to properly seat the sealing material; second, proper matching of material in terms of galling characteristics and coefficients of thermal expansion is required.

4.4.2.3 Material selection

In selecting the appropriate material for the construction of the containment vessel, the designer must take into account the mechanical and thermal properties that affect the structural and the thermal response of the package as well as the potential for effects such as loss of ductility, brittle fracture, unintended chemical or galvanic reactions, fatigue, creep, and stress-corrosion cracking. 10 CFR 71.33(a)(5) requires that information regarding materials of construction be furnished in sufficient detail to provide a basis for evaluation of packaging. In order to assure a high level of quality, 10 CFR 71.37(b) requires, in part, that the designer must identify any established codes and standards proposed for use in package design. These regulatory requirements force the applicant to provide material property data that are thorough and of high quality. If possible, materials that are described by standard specifications should be used. This assures that the material properties that serve as a basis for the various safety analyses will be uniform. The applicant must adequately characterize any specified materials that are not described by authoritative standards.

The most predominant materials used for containment vessels in the shipment of Type B weapon components and special assemblies have been the 300 series of stainless steels: Through the years, thorough characterization of these material have been conducted and documented. Stainless steels exhibit increased strength and very little loss of ductility and adequate fracture toughness at the low temperatures specified for use by 10 CFR 71.

Material used for bolts should be selected based on loading requirements as well as ductility and fracture toughness. The use of well-established standards with published minimum values and certified material test reports will guarantee parts of high quality.

4.4.2.4 Fabrication methods

4.4.2.4.1 Forming techniques

Several methods can be employed for the fabrication of a cylindrical containment vessel with a bottom closure and provisions for a positive removable head closure. Due to the diversity of the applications, there is no correct or incorrect path to follow assuming the appropriate rules of construction, quality assurance criteria, and compliance with the requirements of 10 CFR 71 are adhered. As was previously stated in Subsect. 4.4.1, the category of the containment vessel should be determined early in the design process. It is recommended but not mandated that the appropriate sections of the ASME Code associated with each category be administered.

The selected fabrication process may have a direct influence on the mechanical proprieties of the original material selected for construction. Some of the most widely used containment vessel fabrication processes and their impact on material properties and limitations will be discussed in the following paragraphs.

Casting is performed by pouring molten metal into a mold and allowing the metal to cool and solidify, retaining the shape of the mold. The casting may be made in approximately the desired final shape or a continuous process such as tubes or rods that are cut into lengths as the casting emerges from the casting machine. The casting may also be a bulk form that will later be manufactured into a different shape. The advantage of using castings to form the total vessel shape is in the reduction of cost over the other fabrication process that requires subprocesses as rolling, welding, and additional machining. The disadvantages of casting lies in the cost of tooling and molds required to produce the desired shape and the possibility of a weaker, more porous material structure. The additional cost of molds can be reduced if a large quantity of vessels is required. The process of solidification of the casting tends to produce coarse, elongated grains, compositional variations, and structural flaws. Unless special care is taken, castings have very heterogeneous microstructures and heterogeneous mechanical properties.

Forging is a group of operations that work and shape metals by a hammering action where the metal has been heated to the appropriate temperature. The advantage of using forging as a fabrication process is that it permits working in more than one direction, eliminating the problem of directional properties associated with other fabrication processes. Forging may also eliminate additional subprocesses in obtaining the final shape as in the case of casting. In most forging operations, the workpiece rests on an anvil and is struck by a hammer to shape the metal into final or intermediate forms. The major disadvantage is the tooling and mold cost and the heating operation associated with developing the proper shape.

Pressing is a group of operations similar to that of forging except that the metal is forced into shape by a slowly applied pressure, usually with a hydraulic press. The advantage of this process is the more thorough kneading of the metal in all directions. This pressing force tends to work the interior of a large ingot more effectively than by the forging method. The major disadvantage again is the tooling cost, mold cost, and the heating operation associated with developing the proper shape.

Rolling is the process used to reduce hot ingots to plates, sheets, bars, and structural shapes. The ingot is passed through a series of rollers, producing a successively longer and thinner shape. In the case of the containment vessel, rolling is a fast and relatively inexpensive operation used primarily to form the cylindrical portion. The one disadvantage of rolling is that rolling refines the grains and elongates inclusions in the direction of rolling. This tends to give the shape good strength in the rolling direction, but less strength in the transverse directions.

An operation similar to rolling, called spin forming or spinning, is used to form axisymmetric parts such as pressure vessel heads. A metal disk is rotated rapidly and pressed against a chuck-former by a forming tool.

Extrusion is a means of producing extended lengths of material with a uniform cross section. Simply described, an extrusion process begins with a hot cylindrical billet inside a cylindrical container having a die at one end. The billet is compressed by a ram at the other side of the container, causing the billet to squirt or extrude through the die.

4.4.2.4.2 Welding and brazing techniques

4.4.2.4.2.1 Welding

Welding is a process where a localized coalescence of metals is produced either by heating the materials to suitable temperature, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler materials.

Problems associated with welding may potentially become major impediments to the certification of Type B DP transportation packages. Design information on welds, including required inspection and acceptance criteria must be thoroughly described in the SARP. Review drawings must include symbols for all welds per accepted standards.[17] Additional necessary information to fully describe the weld may be supplemented on the drawing by "notations," which are referenced to the particular welding symbol. The scope of the included information on each weld should cover design, certification of the welding procedure specifications (WPS), and required inspection/acceptance criteria. The effective strength and reliability of a weldment are dependent on the sound metallurgical characteristics of 1) the weld, 2) the heat-affected zone (HAZ), and 3) the base metal. Process/metallurgical variables that may affect the integrity of this weldment "system," include the following:

1. The size and geometry of the weld and resulting HAZ, which are determined by the weld process selected and the WPS

2. The chemical composition and solidification behavior of the melted region. These are determined by a multitude of process and materials factors, which include composition of the base metal, filler metal, fluxes and/or shielding gases utilized, and the mixing/dilution dynamics of the weld pool.

3. The weld thermal cycle and resulting residual stress

Microstructural features which may affect the strength and reliability of the weldment include alloy elements and hardness, grain size and orientation, brittle metallic phases, microfissures, and inclusions.

The criteria for welding for the various categories of package content activities are based on the requirements of the ASME Code. The general areas covered in the ASME Code relative to weld certification are materials, joint preparation and design, procedure/welder qualification, heat treatment, acceptance criteria, and nondestructive evaluation (NDE). A breakdown of the applicable ASME Code sections/subsections relative to weldment type and category are given in Table 4.6. Key welding elements are also presented in Table 4.6, referring the reader to the appropriate ASME Code section and paragraphs, where requirements can be found. The following are the principle welding processes addressed in the ASME Code:

Table 4.6. Detailed breakdown of pertinent ASME Code Section III and Section VIII articles relative to weldment type (from NUREG/CR-3019)

Weldment type	Category I weld	Category II weld	Category III weld
	Section III, Subsection NB	Section III, Subsection ND	Section VIII-Div. 1 as appropriate, Section III, Subsection NF
Base Materials	NB-2000 (except NB-2300) NB-4100, and applicable code cases	ND-2100, ND-2200, ND-2500, ND-4100 and applicable code cases	
Welding and brazing materials	NB-2400	ND-2400	Section VIII, Div. 1, Subsection A, General
Joint preparation	NB-4200	ND-4200	Requirements; appropriate parts of subsection
Welding	NB-4400	ND-4400	Section B, Methods of
Brazing	NB-4500	ND-4500	Fabrication; and Subsection C
Heat treatment	NB-4600	ND-4600	Classes of Materials
Qualification of procedures and personnel	NB-4300	ND-4300	As appropriate, Section III, Subsection NF.
Examination	NB-5000	ND-5000	
Quality assurance	Subpart H in Title 10, Code of Federal Regulations, Part 71		
Fracture toughness	Paragraph 1.10 of NUREG/CR-3019		

1. Oxyfuel gas welding (OFW)
2. Shielded metal arc welding (SMAW)
3. Submerged arc welding (SAW)
4. Gas metal arc welding (GMAW)
5. Flux cored arc welding (FCAW)
6. Gas tungsten arc welding (GTAW)
7. Plasma arc welding (PAW)
8. Electrogas welding (EGW)
9. Stud welding (SW)
10. Electron beam welding (EBW)
11. Inertia and friction welding (FRW)

WPS defines all details of welding methodology and material preparation required to consistently produce metallurgically sound welds. WPS may be in any format, written or tabular, to fit the needs of each manufacturer or contractor as long as every essential, nonessential, and supplementary essential (when required) variable is included or referenced, as outlined in the ASME Code, Sect. IX, QW-250 through QW-280: Acceptable ranges of these variables must be defined for the WPS user. The essential variables relative to a particular welding process as detailed in the ASME Code, Section IX may include the following:

1. Joint design
2. Base metal/filler
3. Allowable welding positions
4. Preheat, interpass temperature, postweld heat treatment
5. Shielding gas

6. Electrical characteristics, including metal transfer mode
7. Technique

Essential variables are process/design features that will alter the weld properties when changed and are addressed in the ASME Code, Sect. IX, Paragraph QW-250 for all weld processes listed above.

The following constitutes a "checklist" of items to consider in the WPS:

1. Scope the design

2. References; i.e., ASME, American Welding Society (AWS), military specifications and standards

3. Quality Assurance (QA) program-associated procedures

4. Essential, nonessential, and supplementary essential variables as defined in the ASME Code, Sect. IX

5. Detailed sketches/drawings of joint configurations

6. Allowable welding positions

7. Welding data sheets with descriptive information, which includes allowables for the following: base metals, filler metals, welding process, shielding gas characteristics, electrical characteristics, welding technique, and heat treatment (see ASME Code, Sect. IX, Form QW-482)

8. Material specifications

9. Tests and examinations with acceptance criteria

10. Supporting procedure qualification records (PQRs)

Table 4.6 includes a summary of ASME Code articles where the requirements for metallurgically sound welds may be found. Design requirements include selection of base and filler materials; design of the appropriate weld joint configuration; qualification of the WPS for the particular weldment design (including thermal cycle restrictions); and NDE and acceptance criteria requirements for production and activities management of all fabrication activities through administrative and technical procedures maintained in the QA Program.

4.4.2.4.2.2 Brazing

Brazing is a group of welding processes that join materials by heating to a suitable temperature and by using a filler metal having a liquidus above 840°F and below the solidus of the base metal. The filler metal is distributed between the closely fitted surfaces of the joint by capillary action. A similar process, soldering, uses a filler metal having a liquidus below 840°F. Brazing may be used to join dissimilar metals including clad metals. It also offers a simple means for achieving extensive joint areas or joint lengths while preserving the metallurgical characteristics of the metals.

Joining in a brazing process is a surface effect. The filler metal adheres to the base metals either by a mechanical bond or by diffusion and alloying.

Successful joining requires:

1. Careful precleaning of parts
2. A flux to prevent oxidation or to dissolve oxides
3. Proper part alignment of the parts throughout heating and cooling
4. Heating to the brazing temperature
5. Cooling and possibly post-cleaning

Some of the brazing processes commonly used are:

1. Gas torch brazing
2. Furnace brazing
3. Induction brazing
4. Resistance brazing
5. Dip brazing

Braze filler metals must have melt temperatures above 840°F but below the melt of the base metals being joined. The filler metal must wet the base metals and make a strong bond. Fillers are often in the form of rings, washers, strips, slugs, rod, wire, or powder. There are six classification groups of filler metals:

1. Aluminum-silicon used mainly for joining aluminum alloys

2. Copper-phosphorus used mainly for joining copper alloys

3. Silver used for joining ferrous and nonferrous metals except aluminum, magnesium, and other low-melt metals

4. Copper and copper-zinc used for various ferrous and non-ferrous metals

5. Magnesium used for joining magnesium alloys

6. Nickel used for joining stainless steels and high-nickel alloys

The requirements for qualification of brazing processes and operators are covered in detail in the ASME Code, Sect. IX, Part QB.

4.4.3 Properties of the Closure Method

One of the initial decisions that must be made pertains to the type of closure method that will be used. In general, closures can be welded, brazed, or a removable gasket can be used to effect the seal. Because the overwhelming majority of packagings used for the shipment of components, special assemblies, and radioactive materials fall into the latter category, the bulk of the information presented in Subsects. 4.4.3.1, 4.4.3.2, and 4.4.3.3 will focus on the properties of the sealing surfaces themselves and the properties of a variety of seal materials. The subject of welded (or brazed) containment closures will be discussed in Subsect. 4.4.3.4.

4.4.3.1 Gasket type seal designs - theory of operation

In principle, the theory behind the use of a gasket-type seal depends on a mechanical barrier created by the yielding of a softer material wholly or partially confined between two harder, mating surfaces. Through the selective use of applied external forces (i.e., the tightening of nuts and bolts, clamps, etc.), the softer material is forced to flow into the clearances and imperfections of the sealing surfaces, effecting a positive block to the gases, liquids, or solids being sealed. In practice, however, the use of a gasket-type seal becomes heavily dependent on the properties of the surface finish, most notably, roughness, waviness, and lay. In addition, the possible inclusion of inherent flaws must also be considered.[15]

4.4.3.1.1 Surface finish

Surface finish is used to denote the general quality of a surface. For a given sealing force, the smoother the initial surface the lower the leakage rate, because the total number of potential leakage paths are either fewer, or smaller, or both.

Surface texture is the technical term used to describe the characteristics of a surface. Surface texture is defined as the repetitive or random deviations from the nominal surface which form the three-dimensional surface topography (see Fig. 4.7). ANSI/ASME Standard B46.1 (1985) describes, standardizes, and specifies the measurement instrumentation for surface textures.[18] In addition, the ASM Metals Handbook defines the four basic elements of a surface texture as roughness, waviness, lay, and flaws.[19]

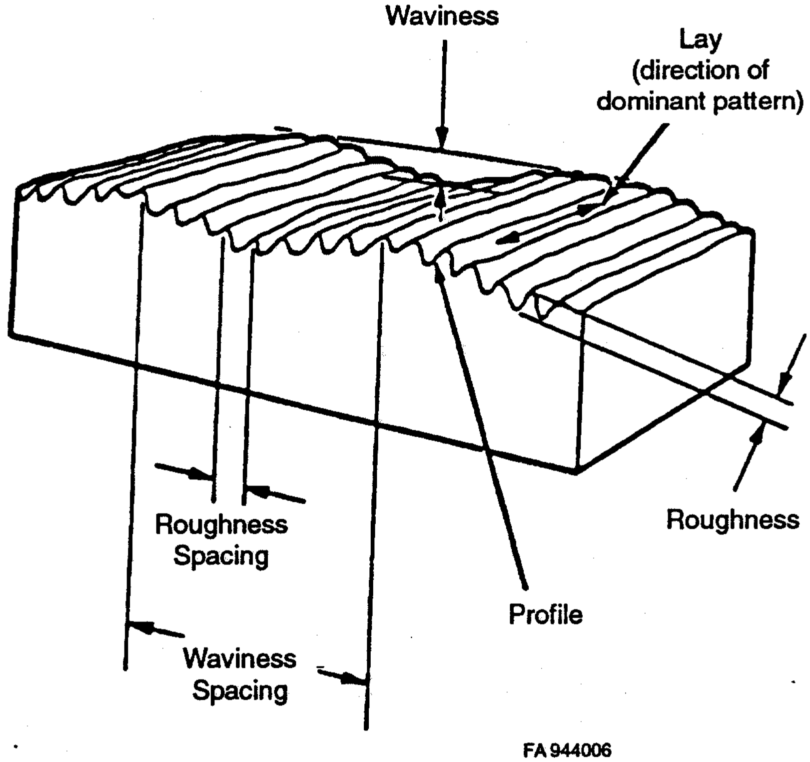


Fig. 4.7 Surface texture of a sealing surface. [15]

4.4.3.1.1.1 Roughness

Roughness consists of the finer irregularities that generally result from actions inherent in the production process. These include transverse feed marks and other irregularities within the limits of the sampling length. For the most part, the measured parameter of surface roughness is expressed in terms of R_a, which is the arithmetic average (AA) deviation of the surface from the roughness centerline. The units are typically expressed in micrometers or microinches. In some cases, however, the term R_q is still used as the primary measure of surface roughness. In these cases, R_q is used to define the average deviation from the roughness centerline in terms of the root mean square (RMS) value. When expressed in the same units, R_q is approximately equal to 1.11 R_a.

The inverse of surface roughness is sometimes also expressed in terms of smoothness, and, in general, the smoothness of the surface required will be dependent on the type of gasket material that is to be used. The use of metallic gaskets, for example, will typically require a smoother surface finish than that required for elastomeric gaskets. In generic order of increasing smoothness, the production processes that must be considered are planing or shaping, spark machining or milling, boring or turning, grinding, honing and buffing, lapping and polishing, and super finishing. It should be noted, however, that the actual value of the surface roughness (smoothness) achieved will also be dependent on the material and tooling details. [15]

4.4.3.1.1.2 Waviness

Waviness includes all irregularities whose spacing is greater than the roughness sampling length and less than the waviness sampling length. Roughness, therefore, may be considered to be superimposed on a "wavy" surface. Waviness may result from machine or work deflections, chatter, vibration, heat treatment, or cutting tool runout.[15]

4.4.3.1.1.3 Lay

Lay is the direction of the predominant surface pattern. Lay is primarily a function of the type of production used.[15]

4.4.3.1.1.4 Flaws

Flaws are unintentional irregularities which occur at one place or at relatively infrequent or widely varying intervals on the surface. Flaws include cracks, blow holes, inclusions, checks, ridges, scratches, etc. Unless otherwise specified, the effects caused by flaws are not normally included in the roughness average measurement. Where flaws are to be restricted or controlled, a special note as to the method of inspection should be included on the drawings and/or added to the specifications.[15]

4.4.3.1.2 Effects of surface finish on sealing capability

Because relatively rough surfaces can be expected to produce an unending series of relatively large leakage paths, an effective seal will require considerable flow of the gasket material of choice in order to create the mechanical barrier alluded to in Subsect. 4.4.3. Relatively smooth surfaces, on the other hand, can be expected to produce much smaller leakage paths which, in turn, can be expected to offer relatively high resistance to leakage flow and require much less plastic flow at the gasket surfaces.

When the mating surfaces of the flanges have significant waviness and the flanges are bolted together with a gasket material superimposed in between, the compressive strength on the gasket will not be uniform around the circumference of the seal. The stress on the gasket will be higher in the regions corresponding to the flange wavepeaks, and lower in the regions corresponding to flange wave troughs. When subsequent internal pressures reduce the compressive stress on the gasket, the initially low-stress regions of the gasket will approach the condition where the residual stress is insufficient to prevent leakage. Although the usual response would be to tighten the bolts in an attempt to increase the compressive stress on the gasket, such a response can only work when the bolts are still elastic, the flanges are not already completely in contact with each other, the flanges are sufficiently rigid to transfer the force to the regions of the gasket where it is most required, and when the mechanical properties of the gasket material can still allow for such an increase in compression.

It is more difficult and it requires greater compressional force to effect a seal when roughness from machining marks or flaws cross the line of the sealing contact area rather than run parallel to the seal. There is also a greater chance that a continuous passage will exist from one side of the gasket contact area to the other, thus increasing the chance of an excessive leakage rate. A piece of dirt, for example, or a single hair, can easily create an unsealed path that will allow for leakage rates on the order of 10^{-6} standard cm^3/s, or higher. It should also be noted that it will be easier to effect a seal when the machining marks are wide and shallow, as opposed to their being narrow and deep.

As the depth-to-width ratio of a flaw or surface defect increases, the gasket material has to be subjected to increasing compression in order to force the gasket material into the flaw. Given a sufficiently deep flaw, and/or the unexpected inclusion of extraneous materials such as dirt, hairs, or other materials, the available maximum compressive stress may be insufficient to extrude the gasket material into the flaw. Under these types of circumstances, it can be expected that the joint will leak.

(The concept of the assembly verification leakage test described in Subsect. 4.3.3.3.5, for example, assumes that scratches or other flaws introduced into the surfaces of a packaging will be detectable by visual inspection or will cause a leakage rate greater than that which is allowable.)

4.4.3.1.3 Effects of hardness on sealing capability

The material of the flanges (i.e., the sealing surfaces) must be locally harder than the gasket material. The harder the sealing surfaces, the less likely it will be that the manufacturing processes or routine operational processes will cause scratches.[13] Methods used for measuring the hardness of elastomers are described in Subsect. 4.4.3.2.2.4.

4.4.3.1.4 Properties of an idealized gasket

The properties required of an idealized gasket material to satisfactorily perform its sealing function can be described as follows:

1. The surface layers of the gasket should be plastic, whereas the internal structure remains elastic.

2. Under compression, the time-dependent creep properties should be very low and should remain unaffected by changes in temperature.

3. The gasket material should not be porous in the compressed state.

4. The inherent properties of the gasket should not be degraded by the material being sealed.

5. The gasket material should not tear or rupture easily under extensive compression.

6. The gasket material should be relatively inert (i.e., the material should not contribute to the corrosion of the flange faces).

7. The gasket material should be readily available and economical.

In a joint containing an idealized gasket, the plastic surface layers of the gasket material help ensure that the imperfections in the flange surfaces will remain properly sealed. In addition, a resilient inner structure helps ensure that the gasket material will be able to track small movements at the flange faces. Such an ability can be very important, since it is this ability that helps ensure that the compressive stress on the gasket will be maintained at an adequate level in spite of the potential for flange deflection under pressure or impact. Initial internal resilience alone, however, cannot be relied upon to guarantee a satisfactory seal, for it is also important that internal stress relaxation of the gasket material should be relatively low since this, in turn, helps ensure that the material does not unduly relieve itself of the stress that is imposed on it.[13]

4.4.3.1.5 Requirements imposed by 10 CFR 71

The requirements of 10 CFR 71 specify a wide range of environmental conditions over which the seals and closures of the packaging must function reliably for the useful lifetime of the packaging. For both normal and accident conditions of transport, these environments include:

1. Maximum normal operating temperature conditions that range up to 38°C (100°F) in ambient air combined with any additional heating considerations that might be derived from solar insolation and the addition of heat generated by the decay of the radioactive contents

2. Minimum normal operating temperature conditions that range down to -40°C (-40°F)

3. External pressures that range from 3.5 to 20 psia

4. Internal pressures that range up to the maximum normal operating pressure of the packaging

5. Vibrational conditions that might be encountered as a result of Normal Conditions of Transport

6. Shock conditions that might be encountered as a result of both normal and accident conditions of transport (i.e., the free drop and the drop onto a puncture bar)

7. Resistance to the radiative heat flux that might be encountered as a result of accident conditions involving a fire

8. Resistance to the influx of water under both normal and accident conditions

9. Radiation resistance

10. Chemical resistance to the material(s) that must be contained

4.4.3.1.6 Requirements imposed by operations and maintenance

In addition to the characteristics of an idealized gasket noted in Subsect. 4.4.3.1.4 and the variety of environmental requirements noted in Subsect. 4.4.3.1.5, operational and maintenance consideration must also be factored into the design of all reusable containment enclosures. These additional considerations further suggest that the closure design must also be capable of providing for:

1. Access to the cavity of the packaging

2. Installation of the gasket and lid by hands-on or by remote handling techniques

3. Reasonably uniform sealing forces in order to achieve a seal and maintain a leakage rate which less than that which is allowable for Normal Conditions of Transport

4. Maintenance of the allowable accident leakage rate with the forces and temperatures imposed on the closure design by the drop and thermal testing requirements

4.4.3.2 O-Ring type seal designs - theory of operation

4.4.3.2.1 General

Because there is no single type of gasket material that possesses all of the desirable characteristics of an idealized gasket noted in Subsect. 4.4.3.1.4, and because there are few, if any, gasket-type seal designs that can meet all of the requirements imposed by 10 CFR 71, the majority of the packaging currently in use by DOE tend to make use of O-ring type seal designs. Compared with a simple, flat gasket installed between two flat metal surfaces, O-ring type seal designs become a slightly more complex method used for closing off a passageway to prevent the unwanted escape or loss of a fluid.

The seal itself consists of an O-ring which is installed in a "gland." The combination of both elements (i.e., the O-ring and the gland) comprises a typical O-ring seal.

An O-ring is exactly that — a circular ring which is made from a material that has a cross section that is also a circle (see Fig. 4.8). O-rings are most commonly made from elastomers. O-rings, however, can also be made from Teflon, or other plastic materials, and they can also be made of metals and composites, both hollow and solid. The gland is a cavity (usually within a metal) into which the O-ring is placed (see Fig. 4.9).

Fundamentally, an O-ring should be considered as an incompressible, extremely viscous fluid that has a tremendously high surface tension under a wide variety of conditions. Whether by mechanical pressure from the surrounding structure (the gland), or by pressure transmitted by hydraulic forces, the extremely viscous fluid is forced to flow into and around the gland to produce an internal block to the flow of the less viscous fluid being sealed. Ideally, the inherent integrity of the O-ring material tends to absorb the stack-up of tolerances of the unit, and the inherent memory of the O-ring material tends to maintain the sealed condition. (See Figs. 4.10 and 4.11.) When the pressures transmitted by the hydraulic forces become too great and the material selected for the O-ring construction is no longer capable of absorbing the stack-up of tolerances from the unit, however, O-ring seals tend to fail, usually catastrophically. (See, for example, Fig. 4.12)

Because the overwhelming majority of containment schemes used by DOE for the transport of components, special assemblies, and radioactive materials tend to make use of elastomeric O-ring seal

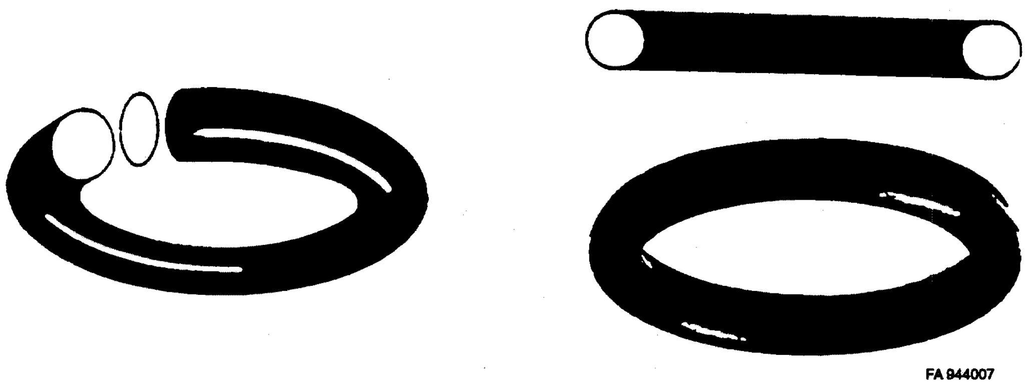


Fig. 4.8. Standard O-ring configuration.[13]

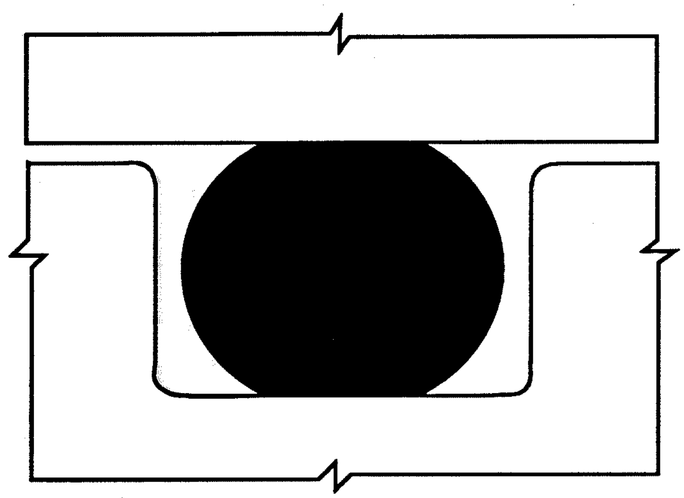


Fig. 4.9. Typical O-ring installed in a gland.[13]

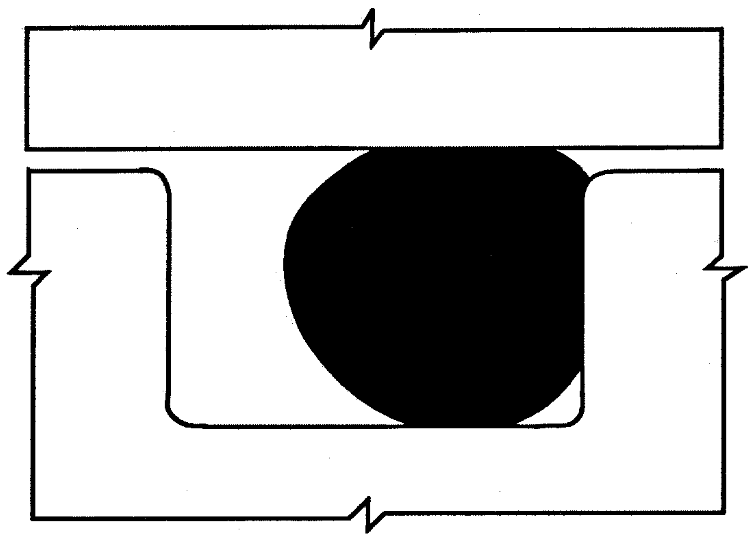


Fig. 4.10. Typical O-ring under pressure.[13]

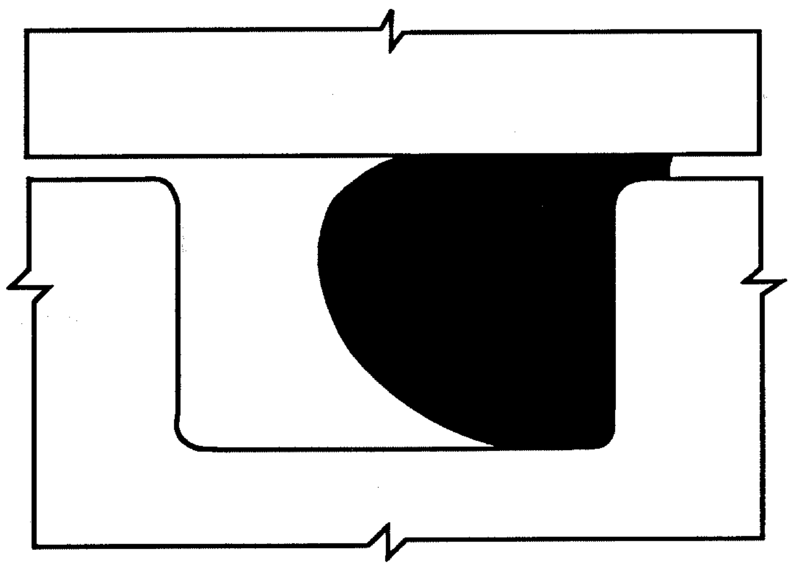


Fig. 4.11. Typical O-ring extruding.[13]

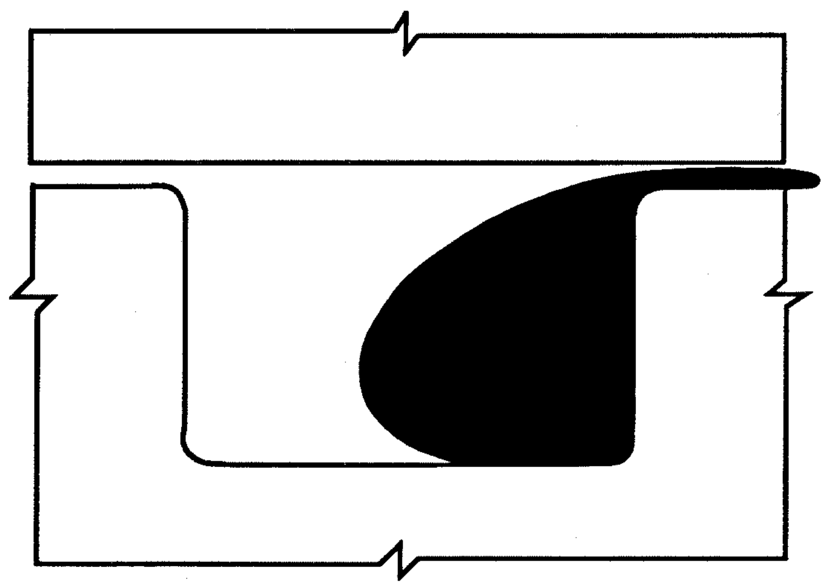


Fig. 4.12. Typical O-ring failure.[13]

designs, the material presented in this section will focus on the basic properties of elastomeric O-rings (including plastics). A comparable discussion on the use of metallic and/or composite O-rings can be found in Subsect. 4.4.3.2.3.

4.4.3.2.2 Elastomeric seal designs

In the design of an elastomeric O-ring seal, it is recommended that the O-ring material type be determined early. The chemical compatibility of the O-ring material should be determined first with respect to the fluid that is intended to be contained; the physical properties of the O-ring material should be considered next in terms of its compatibility with the overall gland design, i.e., the waviness, roughness, and lay of the pattern created by the sealing surface noted above, in Subsect. 4.4.3.1.1. Consideration should then be given to the expected maximum and minimum operating conditions for temperature and pressure, both internal and external.

Having narrowed the field with respect to the basic criteria of compatibility, temperature, and pressure, additional consideration can then be given to the inherent material properties of the O-rings themselves (i.e., the properties of hardness, compression set, squeeze, permeability, radiation resistance, etc.). An expanded review of each of these criteria is presented below.

4.4.3.2.2.1 Chemical compatibility

The chemical compatibility between an elastomer and the fluid (or fluids) to be contained should be one of the first considerations of the design. If, for example, the material to be contained might have an adverse effect on the elastomer (i.e., one or more chemical reactions which might produce surface destruction, loss of strength, dissolution, or a marked change in the physical properties of the elastomer in a relatively short amount of time), there would be little advantage in proceeding with the design until this particular problem is solved. If more than one fluid is involved, both the sequence and the time of contact should be considered.

Chemical compatibility can initially be determined by referring to the recommendations of the manufacturer, such as the fluid compatibility table presented in Appendix B of the *Parker O-ring Handbook.* [13] In the final analysis, however, chemical compatibility can best be determined by direct testing.

4.4.3.2.2.2 Temperature

In high-temperature environments, all elastomeric materials are subject to degradation. The properties most affected by heat are volume change, compression set, and hardness.

The first effect of increased temperature is to soften the compound. This is a physical change and will usually reverse itself when the temperature drops back into the normal range. It must be considered, however, in high-pressure applications because a compound that is sufficiently hard to resist extrusion at room temperature may begin to flow through the clearance gaps as the temperature rises due to this softening effect.

With increasing time at elevated temperature, chemical changes begin to occur. Initially, these types of changes can be expected to cause an increase in the hardness, followed by the volume and compression set changes noted above. Changes in tensile strength and elongation may also be involved. Being chemical in nature, these types of changes are usually not reversible.

The changes induced by low-temperature environments are primarily physical in nature and, in most cases, are completely reversible when the O-ring is warmed back up to its normal operating temperature environment. During the temperature excursions, however, it can be expected that hardness will be the property that is most immediately effected (i.e., when the temperature decreases, hardness increases). [13]

For low-temperature applications, the time at temperature must also be considered because in addition to the changes for hardness temporary changes in the flexibility, resilience, compression set, and brittleness of the material can be expected.

The data presented in Fig. 4.13 show the nominal temperature ranges for several types of elastomeric compounds that are routinely used for sealing applications. For higher temperature applications (i.e., temperatures that range from room temperature to over 900°F), the data presented in Fig. 4.14 provide a relatively simple method for estimating the expected seal lifetime at temperature.[16] For the most part, operational experience has shown that the data presented in both of these figures are relatively reliable, provided that the exposure times at temperature are not exceeded.

For lower temperature applications (i.e., temperatures that range from room temperature down to -70 °F), the data presented in Fig. 4.15 provide a relatively simple method for estimating the changes in hardness as a function of temperature.[13] With respect to these data, however, it should be noted that hardness is only one of the factors that must be considered for operations down into these temperature regimes and that other design considerations may dominate. As part of a series of experiments, for example, the lower temperature performance ratings of a series of elastomers was evaluated against the manufacturer's performance ratings. Under one set of circumstances, one group of experimenters concluded that the minimum experimental leaktight temperature was equal to, or less than, the

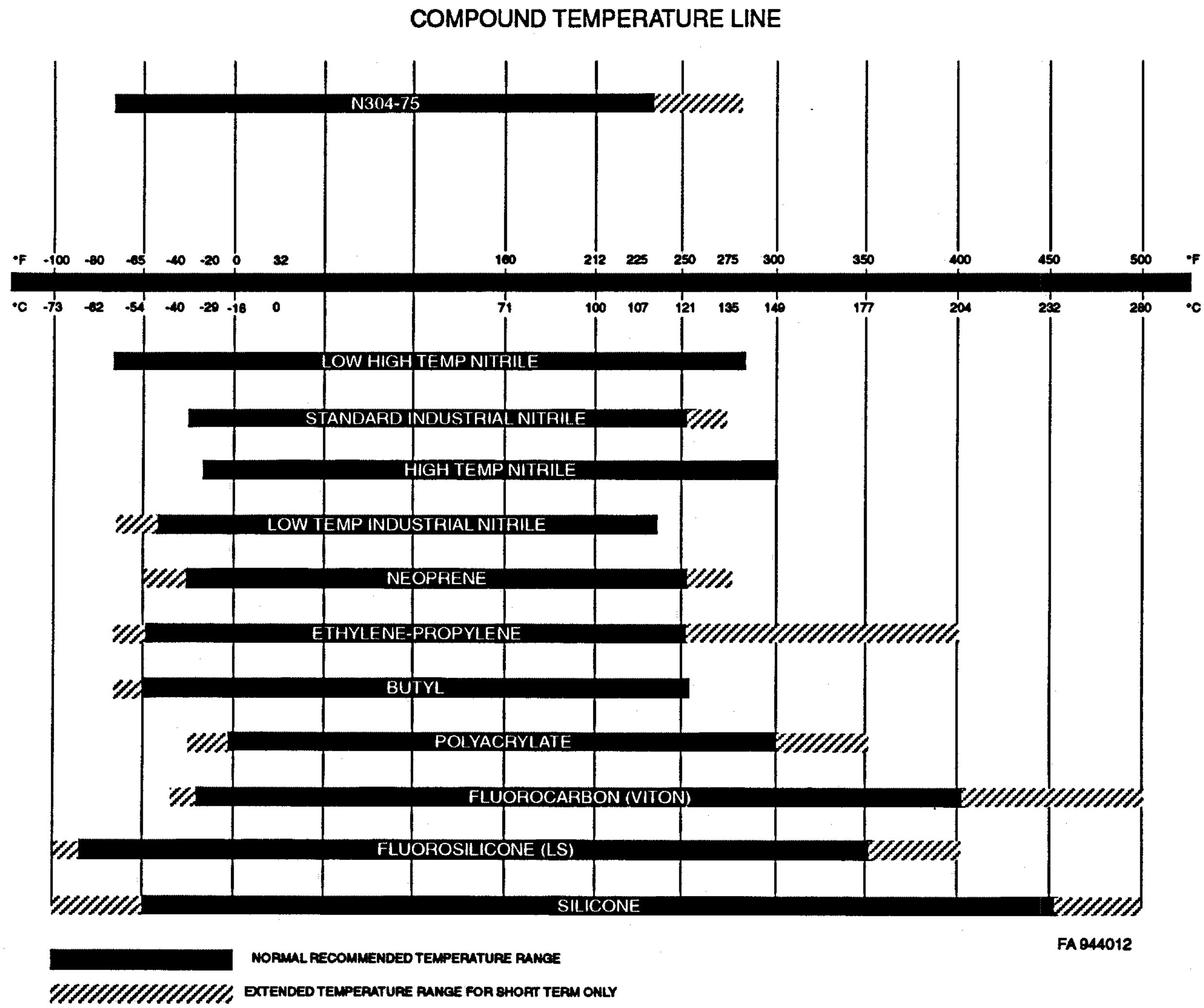
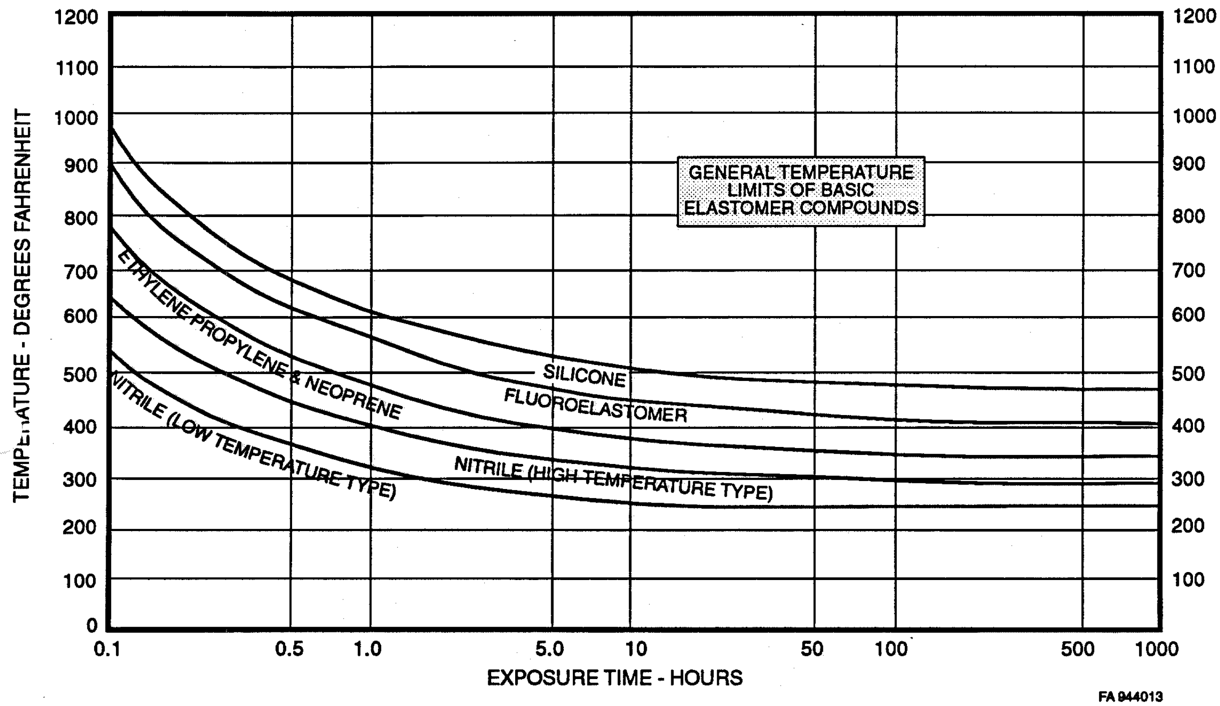


Fig. 4.13. Temperature capabilities of principal esastomers employed in seals.[13]



This chart is intended only as a rough guide. It cannot be used for precise predictions of seal life. Results will vary with a compound and fluid medium.

Fig. 4.14. Seal life vs. exposure time at temperature.[13]

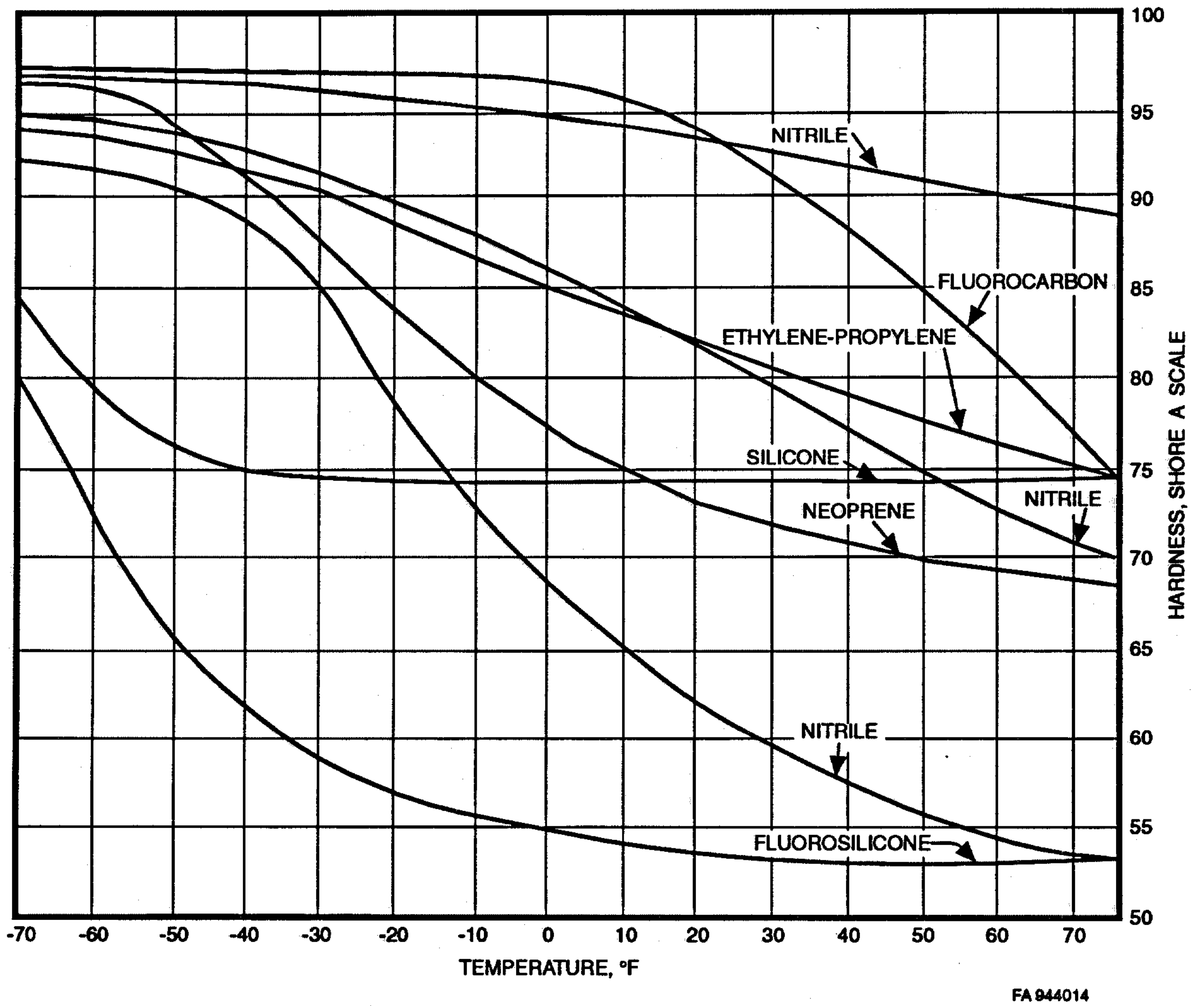


Fig. 4.15. Effects of temperature on O-ring material hardness.[13]

manufacturer's recommendations[20] (see Fig. 4.16). Under a slightly different set of circumstances, however, a similar group of experimenters concluded that the seal materials tested were not leaktight at the manufacturer's lower temperature ratings.[21] Thus, as with the previous cautionary note with respect to chemical compatibility, it is recommended that all seal designs be tested, at temperature, to ensure functionality.

4.4.3.2.2.3 Pressure

Because all elastomers are permeable to some extent (see Subsect. 4.4.3.2.2.6 below), gases under pressure tend to penetrate into all elastomeric seal materials. As can be expected, the greater the pressure the larger the quantity of gas forced into the material. When the gas pressure around the seal is released after an extended soak period, the gases trapped inside the seal material tend to expand. The trapped gases may expand harmlessly into the atmosphere or they may form blisters on the surface of the O-ring. Depending on the circumstances, some of the blisters may rupture, leaving cracks or pits on the O-ring surface. This phenomenon is called "Explosive Decompression" (see Fig. 4.17).

For the most part, the severity of the damage varies with the pressure; the gas, the type of compound selected, the size of the cross section, and other factors. Although this type of seal damage is rarely seen at pressures below 400 psi, elevated temperatures tend to increase the damage, as does a rapid rate of pressure drop.[13]

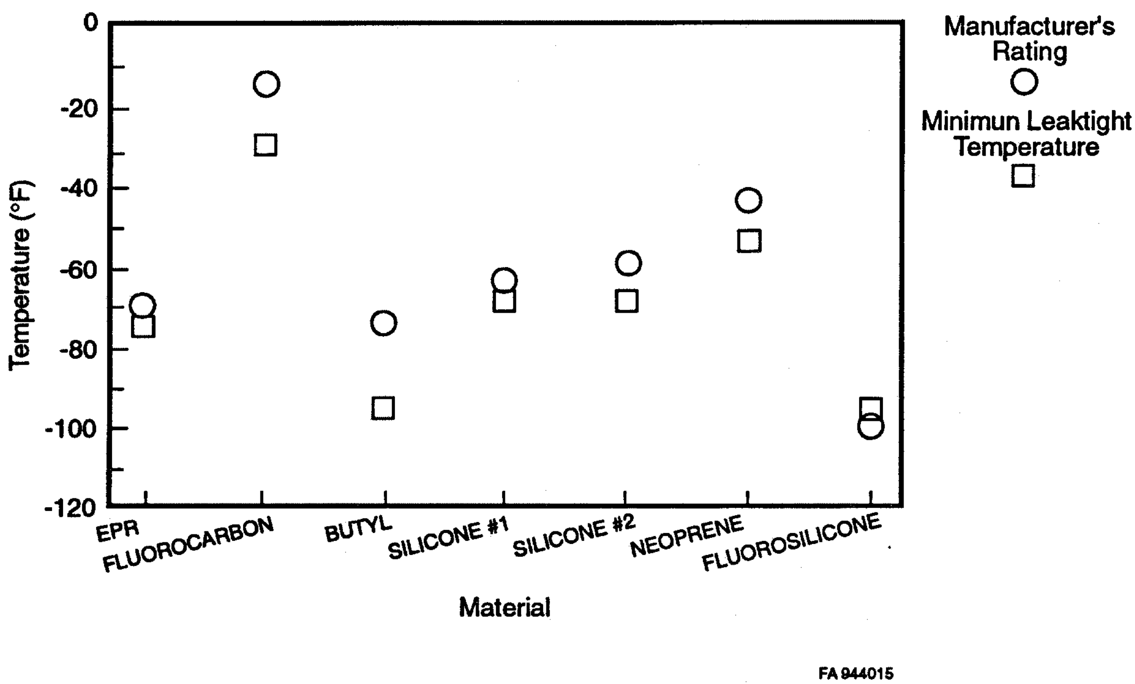


Fig. 4.16. Low temperature performance vs. manufacturer's ratings.[20]

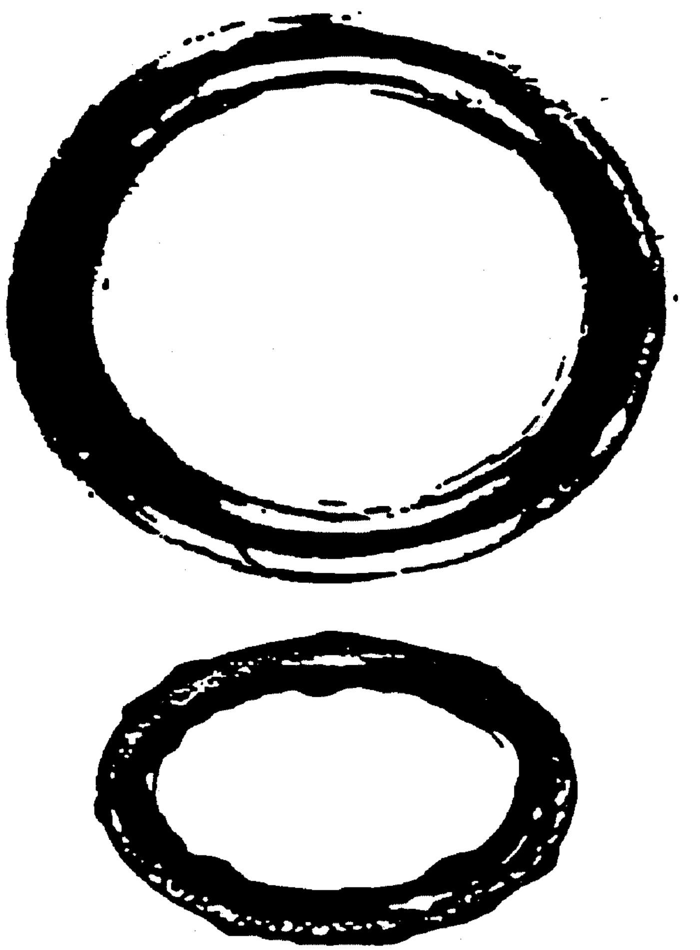


Fig. 4.17. Pitting and failure due to explosive decomposition.[13]

4.4.3.2.2.4 Hardness

Throughout the seal industry, the Type A durometer is the standard instrument used to measure the hardness of most elastomeric compounds. The durometer has a calibrated spring that forces an indenter point into the test specimen against the resistance of the material.

There is an indicating scale on which the hardness is read directly; it is calibrated to read 100 when there is no penetration, such as on a flat glass or steel surface.

Normally, durometer hardness is referred to in increments of five or ten, e.g., 60 durometer, 65 durometer, 70 durometer, etc. This practice is based on 1) the fact that hardness ratings are generally called out in specifications with a tolerance of $\pm$ 5 (i.e., 65 $\pm$ 5, 70 $\pm$ 5, etc.), 2) the inherent variations from batch to batch of a given elastomeric compound due to slight differences in raw materials and processing techniques, and 3) the inherent variations encountered in reading the durometer measurements.

Hardness effects play a very important role in the gland design from the standpoint that when the elastomer of choice is relatively soft, the sealing surfaces do not require a very high degree of finish. Conversely, it can also be expected that when the elastomer of choice is relatively hard, the sealing surfaces can be expected to require a relatively high degree of finish.[13] As was noted in Subsect. 4.4.32.2.2, however, temperature effects must also be considered because the hardness properties of most elastomeric seals tends to be affected by changes in temperature. (See Subsect. 4.4.3.2.2.2 and Fig. 4.15.)

4.4.3.2.2.5 Squeeze and compression set

Compression set is generally determined in air and is normally reported as the percent of deflection by which the elastomer fails to recover after a fixed time under specified squeeze and temperature conditions. Expressed in this format, 0% indicates that no relaxation has occurred, whereas 100% indicates total relaxation, i.e., the seal material just contacts the mating surfaces against which it no longer exerts any force. Compression may also be reported as a percentage of the original thickness. However, percent of original deflection is more common.

Although it may be desirable from a theoretical standpoint to use O-ring compounds that have relatively low compression set ratings, design considerations for this particular property must be balanced against the additional conditions defined by other in-service variables such as chemical compatibility, shrinkage, and radiation resistance. For example, one set of conditions that should be avoided is the combination of relatively high compression set and shrinkage, since this combination can be expected to lead to seal failure unless exceptionally high squeeze techniques are employed.[13]

The data presented in Fig. 4.18 provide a graphical description of the definition of compression set in terms of the percent of original deflection.

The tendency of an O-ring to return to its original shape when its cross section has been distorted over time is one of the fundamental reasons that O-ring types of seal designs tend to be preferred over all others. When used as a static seal, the maximum recommended squeeze for most elastomers is 30%. In radial types of seal designs (i.e., plug seals — see below in Subsect. 4.4.3.2.4.2); however, amounts as great as this may cause assembly problems. In face seal design situations, on the other hand, a 30%

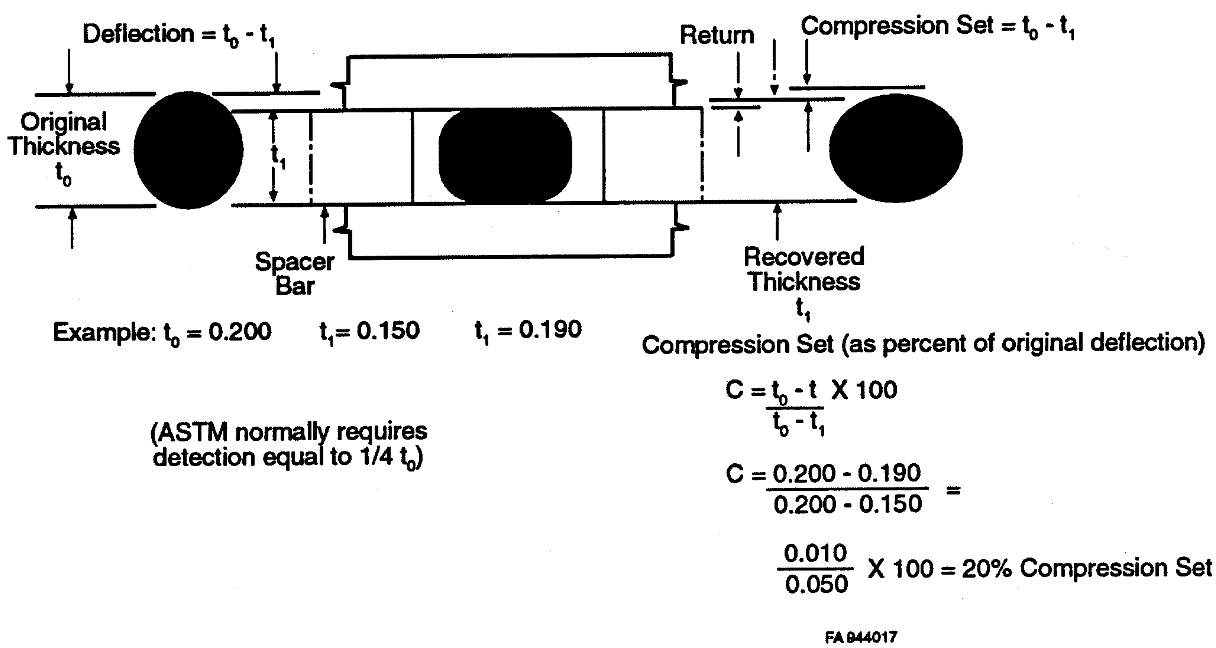


Fig. 4.18. Compression set.[13]

squeeze is often beneficial because recovery tends to be more complete and the seal may function better at lower temperatures.

The minimum recommended squeeze for all O-ring type seals, regardless of cross section should be about 0.007 in. The reason is that with a very light squeeze most elastomers tend to assume a 100% compression set. At the opposite end of the spectrum, however, it should also be noted that most elastomers should not be squeezed by more than 30%, because the additional internal stresses induced may contribute to premature seal deterioration.[13]

4.4.3.2.2.6 Permeability

Permeability can be defined as the tendency of a fluid to flow through a material as a result of the chemical combination of solubility and diffusivity. The mechanics of permeability should not be confused with leakage, which has been defined as the tendency of a fluid to flow through passages left open by the seal.

Permeability may be of prime importance in operations that involve vacuum service and in all applications that involve extended storage. For purposes of discussion, it should be noted that permeability increases (exponentially) with temperature. It should also be noted that different gases have different permeability rates. Note that the more a seal is compressed, the greater its resistance to permeability.[13]

A more extensive discussion on the subject of permeability can be found in Subsect. 4.5.5.1.

4.4.3.2.2.7 Radiation resistance

As noted in Subsect. 4.4.3.2.2.5, one of the more important properties of an elastomer used as an O-ring seal is its resistance to compression set. On exposure to gamma radiation, studies have shown that it is compression set that is most severely affected. After experiencing 10^8 rads, for example, all elastomers tested had taken over 85% set, which is enough loss of memory that leakage would be expected in all cases. At 10^7 rads, there were big differences between compounds, whereas at 10^6 rads, the effects on all compounds tested were minor. It is, therefore, in the range of 10^7 rads that an O-ring compound must be selected with care: At higher levels they should probably not be considered at all; at lower levels, factors other than radiation will probably be more significant.[13]

4.4.3.2.2.8 Material Selection

In addition to the basic design considerations that must be given to the properties noted above, generic consideration should also be given to the dynamic and electrical properties of the elastomer. Where appropriate, other inherent properties such as abrasion resistance, acid resistance, flame resistance, oil resistance, ozone resistance, tear resistance, water and steam resistance, weather resistance, and tensile strength should also be considered. Each of these factors, in turn, can then be weighed against the cost and availability of many different elastomers that are commonly used in the seal industry. In alphabetical order, the list includes elastomeric O-rings made from butadiene, butyl, chlorinated polyethylene, chlorosulfonated polyethylene, epichlorohydrin, ethylene acrylic, ethylene propylene, fluorocarbon, fluorosilicone, isoprene, natural rubber, neoprene, nitrile (Buna N), phosphonitrilic fluoroelastomeric, polyacrylate, polysulfide, polyurethane, SBR (Buna 5), and silicone compounds which are available from many different manufacturers.

The data presented in Table 4.7 provides a generic comparison of the properties of the commonly used elastomers. Presented in relative terms, i.e., in terms of Poor, Fair, Good, and/or Excellent; data such as these can be used to help select, or eliminate, possible candidate materials. It should be noted, however, that the data presented in Table 4.7 have been adapted from the material contained in the *Parker O-ring Handbook*.[13] Differences in compounding between one manufacturer and another may make a difference in the final selection.

4.4.3.2.2.9 Assembly considerations

Since cleanliness can be important for proper seal action and long seal life, every precaution should be taken to ensure that all mating parts are clean at assembly. Foreign particles in the gland such as dirt, chips, hairs, etc., may cause leakage directly attributable to unsealed passages and/or indirectly attributable to physical damage to the O-ring. Since both conditions can be expected to produce a reduction on the overall seal life, consideration should be given to the written version of the assembly procedures so that these types of occurrences can be avoided.

The seal assembly must be made with care in order to prevent damage to the O-ring as the O-ring is installed. Some of the more important assembly considerations should include:

1. The O-ring should be properly placed in the gland to insure that the O-ring will not be damaged when the seal is closed.

2. The internal dimensional stretch of the O-ring, as installed in the gland, should not be greater than 5%.

Table 4.7. Comparison of properties of commonly used elastomers[26]

PROPERTIES

Material Type	Abrasion Resistance	Acid Resistance	Chemical Resistance	Cold Resistance	Dynamic Properties	Electrical Properties	Flame Resistance	Heat Resistance	Impermeability	Oil Resistance	Ozone Resistance	Set Resistance	Tear Resistance	Tensile Strength	Water/Steam Resistance	Weather Resistance
Butadiene	E	FG	FG	G	F	G	P	F	F	P	P	G	GE	E	FG	F
Butyl	FG	G	E	G	F	G	P	G	E	P	GE	FG	G	G	G	GE
Chlorinated Polyethylene	G	F	FG	FP	G	G	GE	G		FG	E	F	FG	G	F	E
Chlorosulfonated Polyethylene	G	G	E	FG	F	F	G	G	G	F	E	F	G	F	F	E
Epichlorohydrin	G	FG	G	GE	G	F	FG	FG	GE	E	E	PF	G	G	F	E
Ethylene Acrylic	F	F	FG	G	F	F	P	E	E	F	E	G	F	G	PF	E
Ethylene Propylene	GE	G	E	GE	GE	G	P	E	G	P	E	GE	GE	GE	E	E
Fluorocarbon	G	E	E	FP	GE	F	E	E	G	E	E	GE	F	GE	FG	E
Fluorosilicone	P	FG	E	GE	P	E	G	E	P	G	E	GE	P	F	F	E
Isoprene	E	FG	FG	G	F	G	P	F	F	P	P	G	GE	E	FG	F
Natural Rubber	E	FG	FG	G	E	G	P	F	F	P	P	G	GE	E	FG	F
Neoprene	G	FG	FG	FG	F	F	G	G	G	FG	GE	F	FG	G	F	E
Nitrile or Buna N	G	F	FG	G	GE	F	P	G	G	E	P	GE	FG	GE	FG	F
Phosphonitrilic Fluoroelastomer	F	P	G	E	F	FG	G	E	G	E	E	G	FP	F	F	E
Polyacrylate	G	P	P	P	F	F	P	E	E	E	E	F	FG	F	P	E
Polysulfide	P	P	G	G	F	F	P	P	E	E	E	P	P	F	F	E
Polyurethane	E	P	F	G	E	FG	P	F	G	G	E	F	GE	E	P	E
SBR or Buna S	G	F	FG	G	G	G	P	FG	F	P	P	G	FG	GE	FG	F
Silicone	P	FG	GE	E	P	E	F	E	P	PG	E	GE	P	P	F	E

P – Poor F – Fair G – Good E – Excellent

3. The internal dimensionsal expansion to reach the gland during assembly should not exceed 100%. (Note: For very small diameter O-rings, it may be necessary to exceed this recommendation. When this type of situation is encountered, however, sufficient time should be allowed for the O-ring to return to its normal diameter before closing the gland).

The following items represent good design and assembly procedures when O-rings are use in the containment vessel:

1. Twisting of the O-ring should not be allowed during installation.

2. O-rings should not be forced over sharp edges or corners such as those that might be encountered over threads, keyways, slots, splines, ports, etc. In order to assist in the installation of O-rings during these types of situations, the use of mandrels, thimbles, supports, or other arrangements should be employed.

3. Closure of the gland must not pinch the O-ring at the groove corners.

4. Closure of the gland should be accomplished using relatively straightforward, longitudinal motions. (Rotary/oscillatory motions tend to cause a bunching of the O-ring, which, in turn, tend to contribute to the cutting of the seal).

Assembly considerations should also be given to the subject of lubrication of the O-ring seals. In some cases, for example, design engineers specifically require that there be no usage of O-ring lubrication whatsoever; in other cases, the use of lubricants tends to be preferred.

Taking the side of the latter, the information presented in the *Parker O-ring Handbook* specifically recommends the use of lubricants for all types of O-ring seals. In particular, the information presented goes on to suggest that the use of a lubricant can be extremely important from the standpoint of assembly.[13]

4.4.3.2.3 Metallic (composite) seal designs

Metallic seals encompass two types of sealing devices, metal O-rings (or gaskets) and composite O-rings (or gaskets) that are composed of both metals and nonmetals such as carbon fibers. The principle advantage of these types of seals is their ability to withstand large fluctuations in temperature without degradation of their sealing properties. The principle disadvantages, however, are 1) metallic O-rings and gaskets require precision machining on the flange faces because the O-ring material does not have the ability to accommodate imperfections in the sealing surfaces; 2) the plastic deformation that results from their compression typically requires that the seals be replaced after each use; and 3) additional efforts may be required during maintenance and assembly in order to maintain the surface finish and cleanliness. When properly installed, however, metallic O-rings and gaskets typically result in sealed joints with very low leakage rates, i.e., typically on the order of 10^{-8} std cm^3/s, or smaller.

Composite O-rings (and gaskets) usually incorporate metallic strips with nonmetallic fillers. The nonmetallic filler provides the elastic characteristics that permit compression of the gasket without permanent deformation of the metallic elements. The primary advantages to the use of these types of seals is that they tolerate extremely high temperatures (i.e., up to 2000°F), and that they tend to be resistant to corrosion and acid attack. Some designs of this type of seal tend to be susceptible to permeation (see Subsect. 4.5.3.1).

4.4.3.2.4 General seal designs

Seal designs can be characterized as being either face seals or plug seals, with either or both having a single or a double O-ring. In addition, it should also be noted that combinations of face seal and plug seal designs are possible. The configuration of the glands for the O-rings (or gaskets) should follow the vendor’s recommendations to take advantage of the extensive experience that the vendors have developed in specifying the size and roughness of the gland surfaces. The optimum amount of compression will be dependent on the O-ring or gasket material, as will be the surface roughness of both the bottom of the O-ring gland and the mating surface. Some elastomeric O-rings provide a better seal if there is a specific amount of roughness to provide additional local compression on the O-ring within the gland. Knowledge of such characteristics can be obtained only through experience with different types of O-ring materials.

4.4.3.2.4.1 Face seal designs

A face seal design is a design in which the gasket or O-ring is captured between the flanges on the body and the lid of the containment vessel. An example of this type of design, using a double O-ring configuration, is shown in Fig. 4.19. For this type of design, the O-ring glands are typically located in that portion of the vessel that will be the lower of the two mating surfaces when the vessel is being loaded. This type of design serves to minimize the difficulties associated with inserting O-rings in the upper glands and having them fall out while the closure is being put into place. One of the major advantages of this type of design is that the forces that maintain closure on the lid also maintain compression on the O-rings. One of the major disadvantages, however, is that the vessel lid may be moved radially or horizontally along or across the O-ring surfaces during assembly. These types of motions tend to distort the O-ring within the gland, placing stresses on the O-ring material beyond the

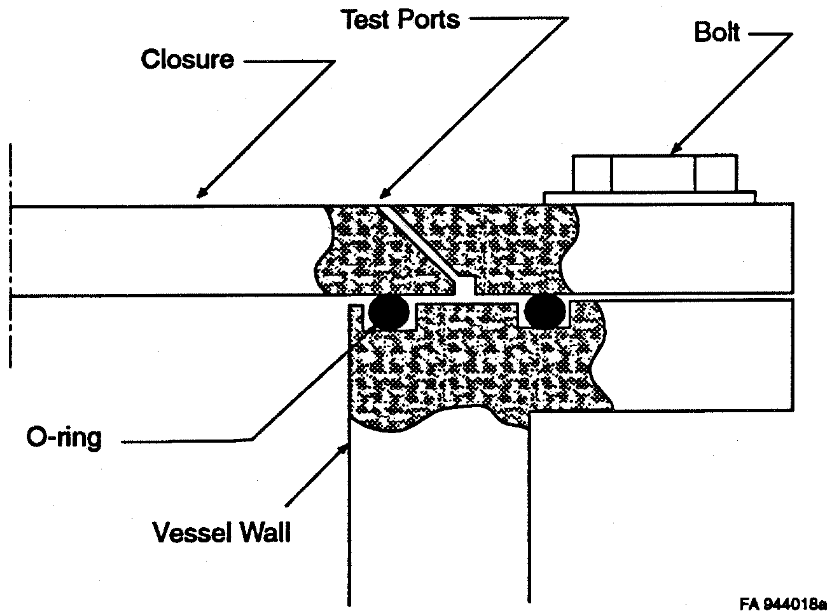


Fig. 4.19. Typical face seal design with double O-ring configuration.

stresses that are desirable to effect a proper seal (see Subsect. 4.4.3.2.2.9). For these types of situations, therefore, other design configurations should be considered.

4.4.3.2.4.2 Plug seal designs

The primary alternative to the face seal design is a plug seal (also known as a bore seal or radial seal) of the type shown in Fig. 4.20. This type of design typically makes use of a tapered plug with O-rings installed in circumferential glands in the plug portion of the containment vessel lid. With plug seal designs, the compressive forces on the O-rings are derived almost entirely from the mating geometries of the plug and the containment vessel body. As a consequence, the tolerances on the fabrication of the components for this type of design are very important to the proper functioning of the seal. One of the major differences between face seal and plug seal designs is that, as opposed to the face seal design, the O-ring glands that are most often used in plug seal designs are cut into that part of the containment vessel that will be the uppermost portion when the two mating surfaces are brought together during assembly. Because the installation of the O-rings will require that they be stretched in order to fit into their respective glands, the assembly considerations noted in Subsect. 4.4.3.2.2.9 can be of particular importance for the use of this type of seal.

4.4.3.2.4.3 Single seal vs double seal designs

As shown in Subsect. 4.3.3.3, ANSI N145 requires that all containment seal designs be tested upon completion of fabrication and at periodic intervals (e.g., annually) in order to demonstrate that the design criteria for the required containment can be satisfied.[2] From an operational standpoint, however, the testing of a containment vessel that has a single seal invariably requires the use of a vacuum/pressure type of bell jar and the subsequent evacuation/pressurization of the interior of the package to determine

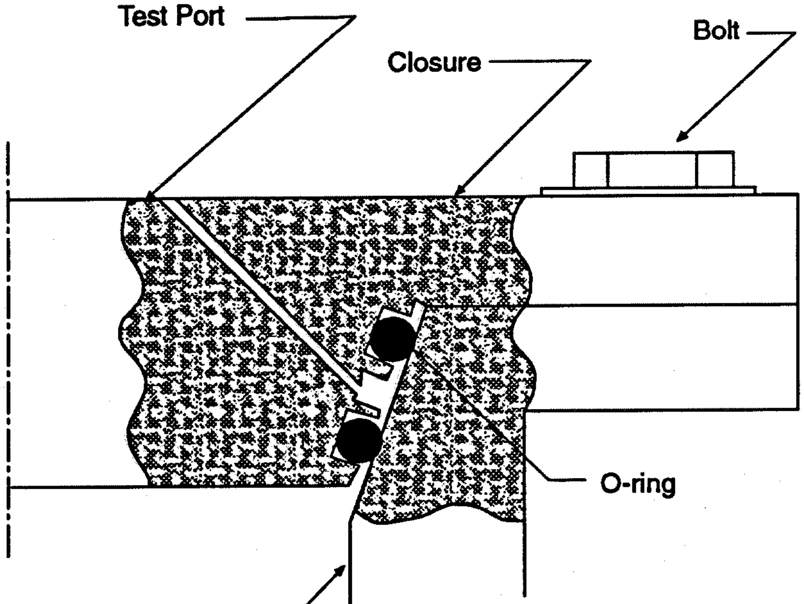


Fig. 4.20. Typical plug seal design with double O-ring configuration.

the conditions on both sides of the seal that will permit the detection of tracer gases as they attempt to pass by (or through) the seal. For the most part, these types of tests can be awkward and difficult to conduct, due to the various sizes of the bell jars required and the need to create a seal between an assortment of bell jars and different portions of the packagings. As a consequence, most of the packagings that are currently in use tend to make use of double-seal design concepts that allow for the independent testing of multiple seals without the use of a bell jar.

For the most part, the use of double-seal designs should not be confused with the concept of redundant seal designs, since truly redundant seal designs can only be obtained when there are two, independent pairs of sealing surfaces, with each pair of surfaces being sealed by independent sets of O-rings.

4.4.3.3 Metal-to-metal seal designs

Metal-to-metal seals can be defined as seal joints formed without the use of a gasket material that is capable of deforming to fill any leakage paths created by surface imperfections in the flanges. Metal-to-metal seals are typically associated with leakage rates on the order of 10^{-2} to 10^{-3} std cm^3/s. Metal-to-metal seals require great care in the finish of the flanges and are very susceptible to a loss of sealing capability due to scratches or the presence of particulate matter (i.e., dirt, sand, etc.). Metal-to-metal seals are most often used where the primary function of the seal is to provide confinement for relatively large objects such as ingots, fully encapsulated forms of radioactive materials, etc. Metal-to-metal seals should not be considered for use when the contents are in readily dispersible forms, such as gases, powders, aerosols, etc.

4.4.3.4 All welded (all brazed) construction

For many applications, it may be possible to place the contents into a container that can be seal-welded (or brazed) to obtain the final closure. Examples of these types of containers typically range from the simplicity of a threaded piece of pipe, with threaded pipe caps attached that are welded at both ends to the complexity of a tritium reservoir. For most applications, however, the use of all-welded (or all brazed) containment systems tends to be reserved for single-use types of containment systems, since the process of opening the container usually results in the destruction of container, itself.

Additional design considerations for the use of all-welded or all-brazed containment systems should also include the following:

1. Because welding and brazing are final fabrication processes, there is usually no mechanism available to pressure test the item to the 150% test requirements noted in 10 CFR 71.85(b) after the fabrication has been completed;

2. ANSI N14.5 requires that single-use containment systems be tested to the same requirements as multiple-use containment systems, as per the requirements shown in Subsect. 4.3.3.3.3;

3. Post welding (post brazing) inspections may be difficult to conduct due to the emission of the radiation and/or heat generated by the contents; and

4. It may be difficult to characterize the temperature profiles of the gases inside the container during/after the welding (brazing) process, which, in turn, may lead to relatively large uncertainties in the estimate of the final pressure.

In spite of these difficulties, however, the use of an all-welded or all-brazed containment system represents the optimum in a containment boundary design. There are no moving parts, and the entire containment boundary becomes part of the body material, which, when properly selected becomes relatively impervious to the effects of radioactive contents.

4.4.3.5 Double containment vs single containment

Prior to the design of the shipping package, a decision on the number of containment boundaries must be made based on the requirements as stipulated in 10 CFR 71.55(b) and (c). According to these requirements,

(b) Except as provided in paragraph (c) of this section, a package used for the shipment of fissile material must be designed and constructed and its contents so limited that it would be subcritical if water were to leak into the containment system or liquid contents were to leak out of the containment system so that, under the following conditions, maximum reactivity of the fissile material would be attained: (1) The most reactive credible configuration consistent with the chemical and physical form of the material; (2) Moderation by water to the most reactive credible extent; and (3) Close reflection by water on all sides.

(c) The Commission may approve exceptions to the requirements of paragraph (b) of this section if the package incorporates special design features that ensure that no single packaging error would permit leakage, and if appropriate measures are taken before each shipment to ensure the containment system does not leak.

In essence, if the inleakage of water creates a criticality issue or if leakage of the contents external to the primary containment boundary is possible, then the shipping package must include two separate and verifiable containment boundaries or vessels. To ensure that no single packaging error would jeopardize the integrity of the shipping package, each boundary must be designed, fabricated, and tested according to the necessary criteria established for a single containment boundary. These criteria are dependent on the materials to be transported and must be evaluated on a case-by-case basis. In either case, single or double containment, the boundary is identified by the closure vessel, lid and by any valve type penetrations.

4.4.4 Valve Penetrations

To enhance operational procedures and leak checking capabilities, penetrations into the containment boundary are often required. Certain applications require the containment vessel and closure to be fill with an inert gas. Fill valves with positive closure mechanism provide this feature. Since they may influence the total release rate of contaminants, these features must be designed, fabricated, inspected and tested to the same scrutiny as the primary containment vessel and closure.

Valve mechanisms must be evaluated to the load combinations shown in Table 4.3. Sufficient preload must be developed in the seating/sealing feature to preclude the effects from all external loads. Structural shielding of the valve should be incorporated in the design to enhance survivability from regulatory drop testing.

Prior to the decision to use a sampling valve or any other type of connection that opens directly into the containment vessel, the requirements of 10 CFR 71.43(e) must be factored into the design (see Subsect. 4.2.2.1). With respect to the current NRC interpretation, the implementation of

10 CFR 71.43(e) requires that all penetrations into the containment vessel must be provided with a cover and that the leakage testing requirements for the cover assembly must be the same as those required for the basic containment.

Category I packaging designs must include a pressure tap into the enclosure volume for leak checking of the enclosure at final package assembly. Leak-testing of the enclosure must be to the same requirements and standards as the primary containment boundary. After completion of the leak-testing procedures, the pressure tap must be plugged with a double sealing device. The double sealing device used to plug the pressure tap must be protected against unauthorized removal.

4.4.5 Quality Assurance and Nondestructive Examination

4.4.5.1 Material certification

Upon conclusion of the design and analysis phase in development of a certifiable containment boundary, the designer must specify the means of assuring that the mechanical and thermal properties used will be maintained throughout the useful life of the hardware. This is normally handled by specifying and using materials controlled by well known codes such as ASME, ASTM, Society of Automotive Engineers (SAE), and American Iron and Steel Institute (AISI).

It is recommended but not mandatory that materials utilized in the fabrication of the containment vessel meet the specifications from Sect. II of the ASME Code. The actual specifications are dependent on the material grade and form of the material employed. In addition to using well-developed material specifications, written certification from the manufacturer should be provided.

The following items as a minimum should be furnished to the fabricator in the production of Category III components:

1. Heat number traceability to mill

2. Chemical analysis of the material or heat

3. Mechanical properties including ultimate tensile strength, yield strength, percent elongation, percent reduction in area, and hardness

4. Description and process records of all heat treatments, if applicable, traceable to heat treat lot

5. Seamless or welded construction, if applicable

Additional requirements may be exercised if the category of the contents warrants a more inclusive material control. For categories I and II components Sect. III, NB-2000 and ND-2000 with references to the material specification in NCA subsections should be used for the various forms and types of material. Special provisions of ASME Code should be incorporated if the material is found defective and is repaired by welding.

4.4.5.2. Fabrication quality assurance

4.4.5.2.1 General

There are several steps that should be pursued in order to assure the fabrication and repeatability of a high-quality containment boundary. The initial step in providing quality assurance during the fabrication phase is the documentation of minimum acceptable requirements in terms of tolerances, chemical and physical properties of materials used, and inspection and testing criteria. These requirements are normally documented on drawings, specifications, and technical data sheets by the design engineer. It should be noted that these minimum requirements must be in accordance with those used in the analysis and testing phase of the design process and should not be degraded by the fabrication method employed. The second step is the development of a manufacturing plan to ensure that the process can comply with drawing requirements and can provide repeatability of the process. At this stage, qualified personnel are identified for the appropriate fabrication method. The third step is the development of an inspection plan. Although similar to step 2, this plan verifies the key elements in the fabrication of the containment boundary in the areas of material certification and drawing adherence. At this stage, the need for in-process inspection can be identified and the acceptance criteria formulated. Finally, a plan should be developed to handle deviations or nonconformances to drawing requirements highlighted during the inspection phase. These deviations should be documented and appropriate personnel identified to adequately evaluate the impact on the design.

4.4.5.2.2 Qualification of welding procedures specifications and welders

The WPS qualification process is summarized as follows:

1. Test coupons are prepared and welded according to the WPS by a qualified welder.

2. Tests, as required by the ASME Code, Sect. IX, are conducted on specimens machined from the test coupons. This testing must be performed by an independent laboratory.

3. The cognizant welding engineer evaluates the overall preparation, welding, and testing results. Implementation of possible changes to the WPS and retesting of new weld coupons would follow if required. When the desired results have been achieved, the WPS is qualified.

4. All welding data are recorded on a PQR, as described in the ASME Code, Sect. IX, QW 200.2.

5. The WPS is implemented in overall QA plan to control production operations.

A similar process is provided in the ASME Code, Sect. IX for the qualification of welders/weld operators.

To reduce the number of qualifications required for welding procedure specifications, base metals have been assigned P-Numbers in Sect. IX, Paragraph QW-420. These assignments are based essentially on comparable base metal characteristics, such as composition, weldability, and mechanical properties, where this can logically be done for base metals. These assignments do not imply that base metals may be indiscriminately substituted for a base metal which was used in a qualification test without consideration of compatibility from the standpoint of metallurgical properties, postweld heat treatment, design, mechanical properties, and service requirements. Where notch toughness is a consideration, it is presupposed that the base metals meet the specific requirements.

The following is a summary of base metal groupings as defined in the ASME Code, Sect. IX:

1. P-1 through P-11 - Steel and steel alloys
2. P-21 through P-25 - Aluminum and aluminum-base alloys
3. P-31 through P-35 - Copper and copper-base alloys
4. P.41 through P47 - Nickel and nickel-base alloys
5. P-51 through P-52 - Titanium and titanium-base alloys
6. P-61 through P-62 - Zirconium and zirconium-alloys

F-Number groupings of electrodes and welding rods discussed in Paragraph QW-430 are based essentially on the "usability characteristics," which fundamentally determine the ability of welders to make satisfactory welds with a given filler metal. These groupings are made to reduce the number of welding procedure and welder performance qualifications required, where this can logically be done. The groupings do not imply that base metals or filler metals within a group may be indiscriminately substituted for a metal which was used in the qualification test without consideration of the compatibility of the base and filler metals from the standpoint of metallurgical properties, postweld heat-treatment design and service requirements, and mechanical properties.

The following is a summary of electrodes and welding rod groupings as defined in the ASME Code, Sect. IX:

1. F-1 through F-6 - Steel and steel alloys
2. F-21 through F-24 - Aluminum and aluminum-base alloys
3. F-31 through F-37 - Copper and copper-base alloys
4. F-41 through F-45 - Nickel and nickel-base alloys
5. F-51 - Titanium and titanium-base alloys
6. F-61 - Zirconium and zirconium-alloys
7. F-71, F-72 - Hard-facing weld metal overlay

Weld metal chemical composition for ferrous alloys is grouped by A-Numbers in the ASME Code, Sect. IX, Paragraph QW-440.

The following is a summary of tests for procedures and performance qualification as given in the ASME Code, Sect. IX:

1. Mechanical tests
    a. Tension tests (QW-150)
    b. Guided-bend tests (QW-160)
    c. Fillet-weld tests (QW-180)
    d. Notch-toughness tests (QW-171 and QW-172)
    e. Stud-weld test (QW-466.4, QW-466.5, QW-466.6)
2. Macro-examination (QW- 183, QW- 184, QW- 191, QW- 192.4)
3. Liquid penetrate examination (QW- 195)
4. Radiography (QW-191)

Requirements for test coupon and specimen preparation are given in the following ASME Code, Sect. IX paragraphs:

1. Qualification thickness limits and the type and number of tests required: QW-450 through QW-452

2. Detailed information for fabrication of test specimens: QW-462 through QW-463

3. Suggested test jigs: QW-466

Requirements for qualifications of welders/welding operators per the ASME Code, Sect. IX are summarized as:

1. They must demonstrate their ability to make sound welds using a qualified WPS.

2. Qualification tests are not intended to assess an individual's skill in actual production of hardware, but to assess whether he/she has a minimum required skill level.

3. Test specimens will be tested by independent laboratories, and evaluated by a cognizant welding engineer/CWI.

4. See Article III of ASME Code, Sect. IX for Welding Performance Qualification general requirements.

AWS has a certification program that is appropriate for most noncontainment welds. Applicable AWS standards are:

1. QC-3, standard for AWS certified welders
2. QC-4, standard for accreditation of test facilities for AWS certified welder program
3. QC-1, standard for AWS certification of welding inspectors
4. Standard welding procedure specifications—Example: B2.1.002, GTAW of carbon steel

4.5 LEAKAGE TESTING CONSIDERATIONS

4.5.1 General

In addition to the seal design considerations noted in Sect. 4.4, design considerations must also be extended to the ability to prove that the containment vessel in question does indeed have the capability to meet the appropriate leakage testing requirements. Accordingly, the information presented in Subsect. 4.5.2 discusses the pros and cons of valve inclusions for leakage testing and/or long-term sampling. Permeation and outgassing considerations are discussed in Subsect. 4.5.3. Leakage testing procedures and leakage testing methods are discussed in Subsects. 4.5.4 and 4.5.5, respectively.

4.5.2 Valve Inclusions

The typical face seal and plug seal design configurations shown in Figs. 4.19 and 4.20 show the inclusion of a test port that communicates with an independent gland that is positioned between each of the two independent O-rings. The purpose of this test port is to allow for the independent testing of each of the O-ring seals. In the preliminary design stages of any new container, serious consideration should be given to the permanent installation of a valve at this location to help facilitate leak testing.

In addition to the installation of a valve at the leak testing port, however, serious consideration should also be given to the installation of a second valve. Ideally, this valve would be positioned such that, when open, it would allow for direct communication with the interior of the containment vessel. The purpose of this valve is to allow for sampling of the containment vessel before it is opened during disassembly. For health physics purposes, the use of a permanently installed sampling valve becomes particularly important for the design of shipping containers used for tritium. The use of a permanently installed sampling valve should also be considered for use in any containment system that may be used for long-term storage.

Prior to the decision to use a sampling valve, or any other type of connection that opens directly into the containment vessel, the requirements of 10 CFR 7 1.43(e) must be factored into the design (see Subsect. 4.2.2.1.). According to these requirements,

> "A package valve or other device, the failure of which would allow the radioactive contents to escape, must be protected against unauthorized operation and, except for a pressure relief device, must be provided with an enclosure to retain any leakage."

With respect to the current NRC interpretation, the implementation of 10 CFR 71.43(e) requires that all penetrations into the containment vessel must be provided with a cover and that the leakage testing requirements for the cover assembly must be the same as those required for the basic containment.

4.5.3 Permeation and Outgassing

4.5.3.1 Permeation

Gases have the property of being able to pass through some apparently solid barriers, even when the openings present are not large enough to permit continuous flow. The passage of a gas into, through, and out of a solid barrier having no holes large enough to permit more than a small fraction of the gas to pass through any one hole is known as permeation. The steady-state flow rate under these conditions is called the permeability coefficient or, more simply, the permeability. Permeability is typically expressed in cubic centimeters of gas flow per second, at STP, through a one square centimeter cross section, per millimeter of wall thickness, per torr of differential pressure.

Initially, the process of permeation involves the adsorption/absorption of the gas onto/into the outermost surface layer of the barrier where the gas pressure is highest. After being dissolved into the outermost surface through the solid, the gas moves through the solid by the process of diffusion. Concentration gradients then drive the gas out of the inner surface, into the lower pressure side, by the process of desorption.

As noted in Subsect. 4.4.3.2.2.6, permeability may be of prime importance in any operation that involves vacuum service and in all operations that involve extended storage. The data presented in Fig. 4.21, for example, show the measured permeation rates, at room temperature, for helium through a set of three, metallic/high-density composite Q-rings.[13] Since these data show clearly that the measured leakage rate (i.e., the measured permeation rate) increased by about four orders of magnitude over a time span of about one hour, the data further suggest that for the selection of an appropriate leakage test, design considerations must also be extended to the time duration of the leakage test required.

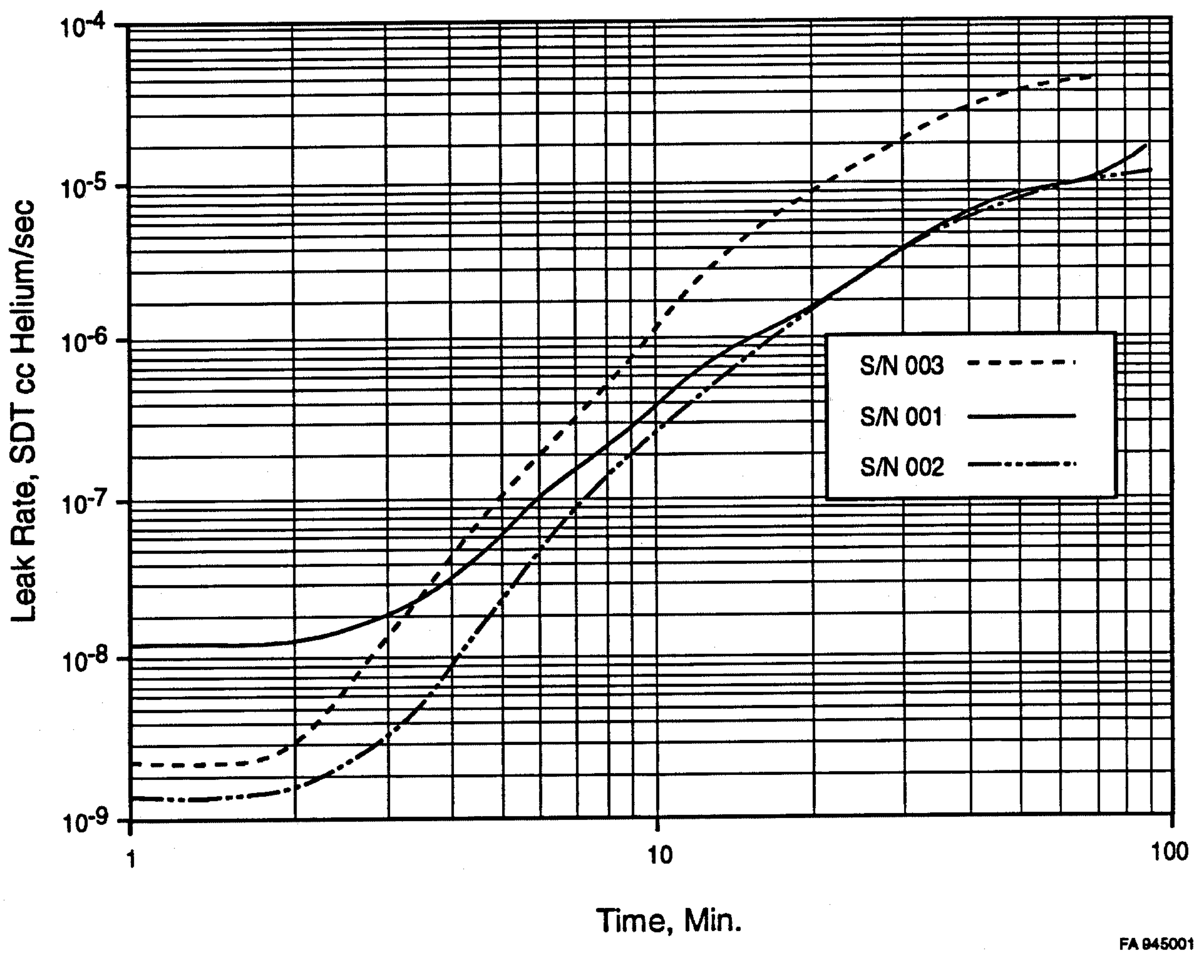


Fig. 4.21. Permeation rates as a function of time.

4.5.3.2 Outgassing

When a material is placed into a lower pressure environment (e.g., a vacuum), the gases and vapors that were previously adsorbed (or absorbed) onto (or into) the surface layers begin to desorb; that is, they begin to leave the surface layers of the material. Generically; this process is known as outgassing. The process of outgassing tends to be influenced by pressure differentials, temperature differentials, the shape of the material, the composition of the absorbed gas, and the type of solid material.

Depending on the leakage testing sensitivity required, the process of outgassing may, or may not, be a problem. For those applications where it must be considered, refer to Subsects. 4.5.4 and 4.5.5.

4.5.4 Leakage Test Procedures

The comments and precautions in the following sections should be applied to the appropriate leakage test procedures. The user alone is responsible for verifying that the selected procedure meets or exceeds the sensitivity requirement for the particular situation and that the test is applied correctly.[2]

4.5.4.1 Pressure-volume energy considerations

For test items with high design pressures, large volumes, or both, precautions should be taken to minimize the possibility of pressure-volume explosive hazards. It may be necessary, for example, to hydrostatically proof test the item to help ensure safety. Even with modest differential pressures, such as one atmosphere (i.e., 1 atm), large-volume systems may be hazardous. It is recommended, therefore, that pressures should be reduced to known safe values or that the internal volumes of test items be filled with a liquid or solid so that only a small gas volume remains for testing. When a liquid is used, caution should be taken to ensure that the liquid does not interfere with the leakage test.

Leakage testing may be conducted at pressures and temperatures different from the actual operating conditions if the effects of the difference on the containment system geometry and performance are negligible and/or if the actual operating conditions do not provide a pressure differential that would be large enough to provide meaningful results. The leakage test flow directions should be the same as in operation; flow in the reverse direction must be justified.[2]

4.5.4.2 Tracer material requirements

Tracer materials used must be clean and free of contaminants that might effect the test results. Care must be taken to ensure that a known representative tracer mixture reaches the containment boundary being tested. In addition, care must also be taken to ensure that there are no adverse reactions that might affect either the containment system contents or the leakage testing properties of the tracer.[2]

4.5.4.3 Additional considerations

In addition to the generic leakage test considerations provided above, consideration should also be given to the following:

- For leaks expected to be smaller than 10^{-6} std cm^3/s, wetting of the test item before the test begins should avoided whenever possible. When wetting cannot be avoided, the item must be dried thoroughly before the test.

- The partial pressure of the tracer gas in the test mixture must be at least 10% of the total pressure and must be known.

- When the normal operating conditions of the containment system are with positive pressure, justification must be provided for leakage testing performed under vacuum conditions.

4. All leakage tests are to be performed by qualified operators[2]

4.5.5 Leakage Test Methods

4.5.5.1 General

Practical leak testing techniques for the measurement of leak rates from radioactive materials packagings have been developed and utilized in the industry. Detailed procedures have been developed for the recommended methods, with emphasis on factors relevant to particular types of containers. The data presented in Table 4.8 lists these methods, along with their respective nominal sensitivities. For the most part, however, it should be noted that the actual test sensitivity will have to be calculated for each application, since it is a function of pressure, volume, temperature, time, and gas properties.[2]

The test methods shown in Table 4.8 have been subdivided into quantitative and qualitative leak-test methods. The quantitative test methods shown provide for the measurement of total leakage, whereas the qualitative test methods provide for the detection of individual leaks. Where appropriate, leak rates determined from the use of qualitative leak tests should be cross checked using calibrated leaks.[2]

Table 4.8. Recommended leak-test methods[21]

Test method	Nominal test sensitivity [a] std cm^3/s	Notes
Quantitative methods		
Gas pressure drop	10^{-1} to 10^{-5}	1,2
Gas pressure rise	10^{-4} to 10^{-5}	1,2
Gas-filled envelope with gas detector	10^{-3} to 10^{-9}	3
Evacuated envelope with gas detector	10^{-3} to 10^{-8}	3
Evacuated envelope with back pressurization	10^{-3} to 10^{-8}	3
Qualitative methods		
Gas bubble techniques	10^{-3}	3,4
Soap bubble techniques	10^{-3}	3,4
Tracer gas sniffer techniques	10^{-3} to 10^{-6}	3,4
Tracer gas spray techniques	10^{-3} to 10^{-6}	3,4

[a] For comparison purposes only. The values listed are referred to a common standard of dry air at 25°C and a differential pressure of 1 atm. Bubble test sensitivities are for 1 atm differential pressure except for the hot water bubble, which is at 0.25 atm differential.

Notes:

1. Depends on the volume tested, test time, and instrument sensitivity to pressure differentials.

2. The listed sensitivity is typical. The actual test sensitivity will have to be determined according to the equations in Appendix B of ANSI N14.5 and/or the ISO Standard.[2], [21]

3. The sensitivity listed applies to test methods under normal field conditions. Under favorable, well-controlled conditions, the test sensitivity could be increased by a factor of 10, or more.

4. For tests involving a liquid-gas interface, consideration must also be given to the effects of surface tension and the hydrostatic head of the liquid bath. See Appendix B of ANSI N14.5 and/or the ISO Standard for the appropriate equations.[2], [21]

The test methods shown in Table 4.8 are described in more detail in Subsects. 4.5.5.2 and 4.5.5.3. For each of the test methods, a schematic representation of the test set-up has been provided. A text description for each of the tests has also been provided showing how each of the tests should be performed. Appropriate information is also presented on test precautions, test applicability, and potential hazards.

4.5.5.2 Quantitative test methods

4.5.5.2.1 Gas pressure drop

This procedure, shown schematically in Fig. 4.22, applies to test items with pressure tap connections. The volume of the test item can be relatively large (e.g., the container volume); or it may be relatively small (e.g., the volume associated with interspaces between double O-ring seals).

The test sensitivity is primarily dependent on the test volume, the test duration, and the accuracy of the test equipment. With large volumes, the technique is relatively insensitive, but with small interspace volumes and accurate instrumentation, test sensitivities of 10^{-5} std cm^3/s can be achieved. It should be noted that the total test volume includes the volume associated with the container plus the volume associated with the test equipment.

The total leakage rate (from all leaks in the container) is calculated from the pressure drop over a given period of time from a known container volume, a known initial pressure, and for a particular ambient temperature. If the test duration is long, corrections may have to be made for changes in temperature.

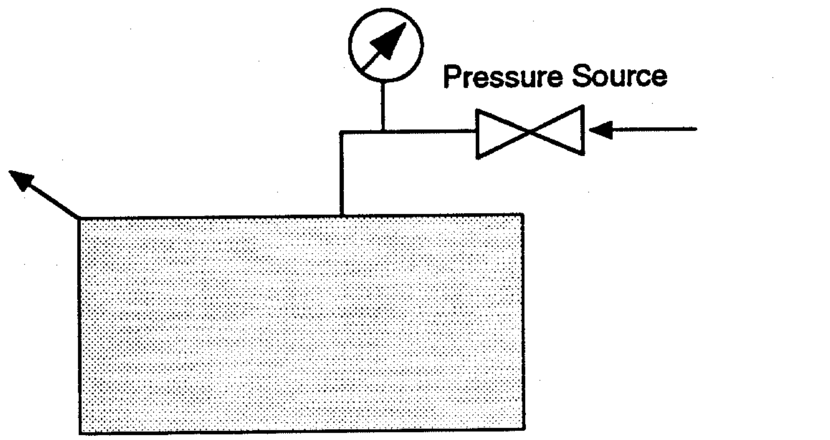


Fig. 4.22. Gas pressure drop test method.

Pressure measurements should be accurate to within ± 1% or better of full scale of the measurement devices. The pressure measurement devices should measure absolute pressure and should have a range between 1 1/2 and 4 times the specified pressure. Temperature measurements must be accurate to ± 1 °C. Test objects should be at or near to thermal equilibrium before the measurements are taken, otherwise errors in determining the average temperature may hide leakage effects.

4.5.5.2.2 Gas pressure rise

This procedure, shown schematically in Fig. 4.23, is similar to the gas pressure drop test described above and applies to test items with pressure tap connections. It has the advantage of being less affected by temperature changes than the pressure drop method, but it may require that all or part of the leakage flow be in the direction opposite to that encountered in normal operations.

The test sensitivity is primarily dependent on the test volume, the test duration, and the accuracy of the test equipment. The method can be used with relative ease to measure leak rates down into the 10^{-5} std cm^3/s region. The total leakage rate is calculated from the pressure rise in a known volume over a given period of time from a known initial pressure and for a particular ambient temperature. If the test duration is long, corrections may have to be made for changes in temperature.

Pressure measurements should be accurate to within ± 1% or better of full scale of the measurement devices. The pressure measurement devices should measure absolute pressure and have a range between 1 1/2 and 4 times the specified pressure. Temperature measurements must be accurate to ± 1 °C. Test objects should be at or near to thermal equilibrium before the measurements are taken.

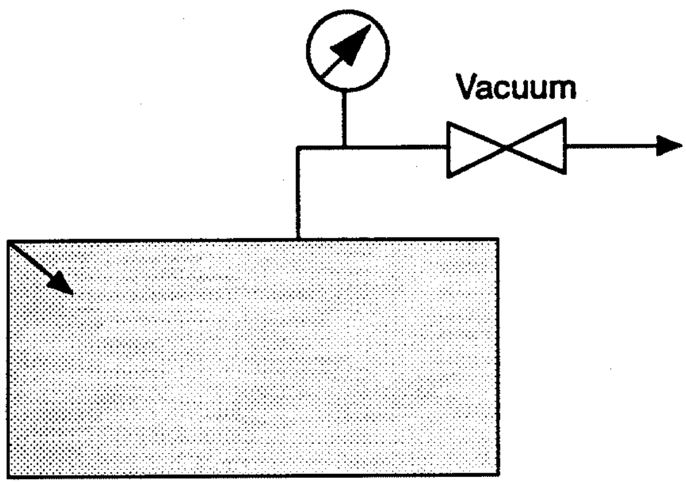


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Fig. 4.23. Gas pressure rise test method [21]

One of the fundamental problems associated with this procedure is outgassing, i.e., the release of gases from the internal surfaces of the test item when the test item is evacuated (see Subsect. 4.5.3). Keeping the test item clean and dry will reduce outgassing. The effect of outgassing can be minimized by operating with a relatively high pressure inside the test object.

4.5.5.2.3 Gas filled envelope - gas detector

This procedure, shown schematically in Fig. 4.24, is used on containers which can be surrounded by an envelope of tracer gas. Where only a single flange joint is being tested, it may be possible to reduce the envelope size to enclose only the flange area. Common tracer gases used are helium and halogen compounds.

The test sensitivity is primarily dependent on the test gas used, and to a lesser degree on the pressure differential and the method of detection. For halogen gas systems using gases such as dichloro-difluoromethane (R-12), sulphur hexafluoride (SF_6), or perchloro-methane, sensitivities of 10^{-3} to 10^{-8} std cm^3/s are achievable. Similar sensitivities are achievable using helium as the tracer gas in conjunction with mass spectrometer type detectors.

Although the use of helium in conjunction with a mass spectrometer type of detector is relatively straightforward and nontoxic, the same cannot be said for the use of halogen gas systems. For example, halogen gas should be used with stainless steel systems only after it has been determined that the selected halogen compound will not cause detrimental corrosion in the stainless steel by intergranular attack. In addition, halogen leakage testing requires a work space that is free from smoke (such as tobacco smoke) and other possible sources of halogen vapors such as a leak in a building refrigeration system. Halogen leakage testing should not be conducted in the proximity of high temperatures because the tracer gas in

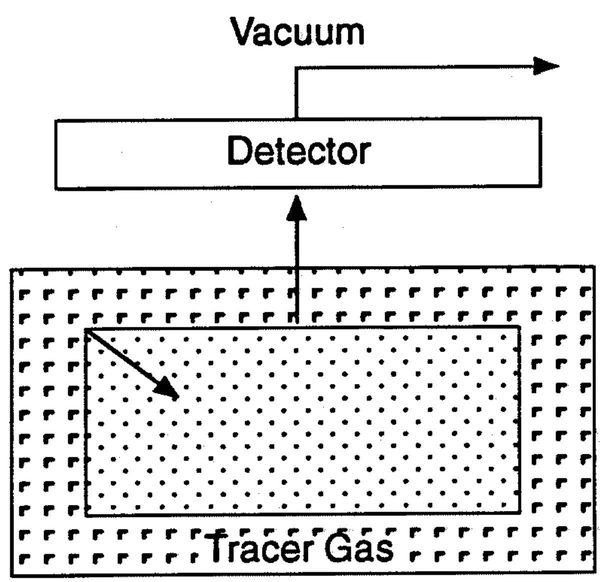

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Fig. 4.24. Gas filled envelope test method - with gas detector.[21]

question could break down into highly toxic compounds. Some of the halogen tracer gases themselves may be toxic, requiring test areas that are well ventilated.

4.5.5.2.4 Evacuated envelope - gas detector

This procedure, shown schematically in Fig. 4.25, involves pressurizing the container with a tracer gas and subsequently placing the container in an evacuated envelope connected to a tracer gas detection system. Where only a single flange joint is being tested, it may be possible to reduce the envelope size to just enclose the flange area. If a double O-ring seal joint is being tested, the tracer gas detector can be connected to a vacuum system which, in turn, is connected to the space between the two O-rings. Common tracer gases used are helium and halogen compounds.

The test sensitivity is primarily dependent on the test gas used, the pressure differential, and the method of detection. For halogen gas systems using gases such as dichloro-difluoromethane (R-12), sulphur hexafluoride (SF_6), or perchloro-methane, sensitivities of 10^{-3} to 10^{-8} std cm^3/s are achievable. Similar sensitivities can be achievable using helium as the tracer gas in conjunction with mass spectometer type detectors.

The typical test method would proceed as follows: 1) pressurize the container with the tracer gas to the desired test pressure; 2) evacuate the envelope surrounding the container or, if testing a flange with a double O-ring seal, the interspace; and 3) monitor the response of the detector fitted to the vacuum system.

If the container cannot be filled with tracer gas, the test item can be placed in a secondary chamber and externally pressurized with the tracer gas for a fixed period of time (see Subsect. 4.5.5.2.5).

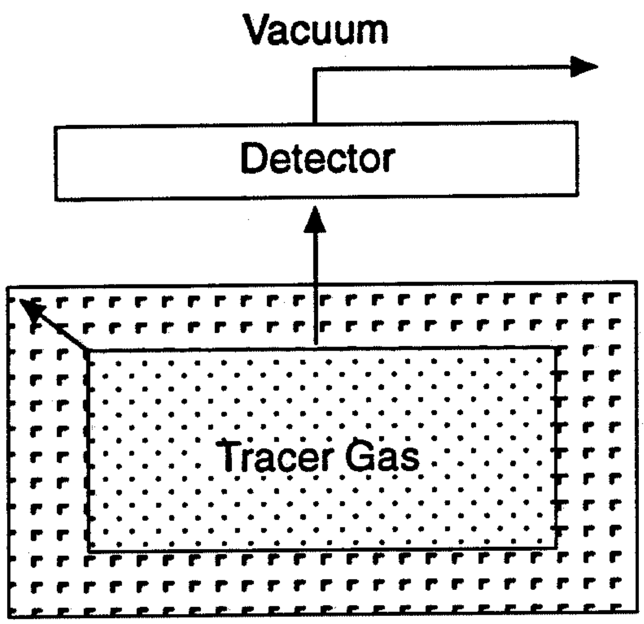

Fig. 4.25. Evacuated envelope test method - with gas detector.[21]

The external pressure can then be reduced and the item transferred to the primary envelope prior to evacuation. (Note: This method should only be used on items capable of withstanding relatively high external pressures.)

For the use of halogen gas test systems, the precautions noted in Subsect. 4.5.5.2.3 should be followed.

4.5.5.2.5 Evacuated envelope - with back pressurization

This procedure, shown schematically in Fig. 4.26, applies to test items without pressure taps and sealed sources that cannot be filled with helium during final closure. The test items must be able to withstand relatively high external pressures without damage. When appropriate mass spectrometers are available, gases other than helium can be used. The test sensitivity is dependent on the mass spectometer used, but is typically in the region of 10^{-6} to 10^{-8} std cm^3/s. It should be noted, however, that the overall test sensitivity may be affected by the rate of initial outgassing from the outer surface of the test item.

From an operational standpoint, the test item is placed in a suitable chamber and externally pressurized with helium for a predetermined period of time. Typical values are 3.0×10^6 Pa (about 30 atm) for one hour. The pressure is relieved and the item is immediately transferred to a test chamber which is connected to a mass spectrometer leak detector. This test chamber is then evacuated to the appropriate operating pressure, and the mass spectrometer leak detector is operated in accordance with the manufacturer's instructions.

In principle, helium from the external pressure source enters the test item through any leaks and is subsequently detected when the test item is placed in a vacuum allowing the helium to flow out again

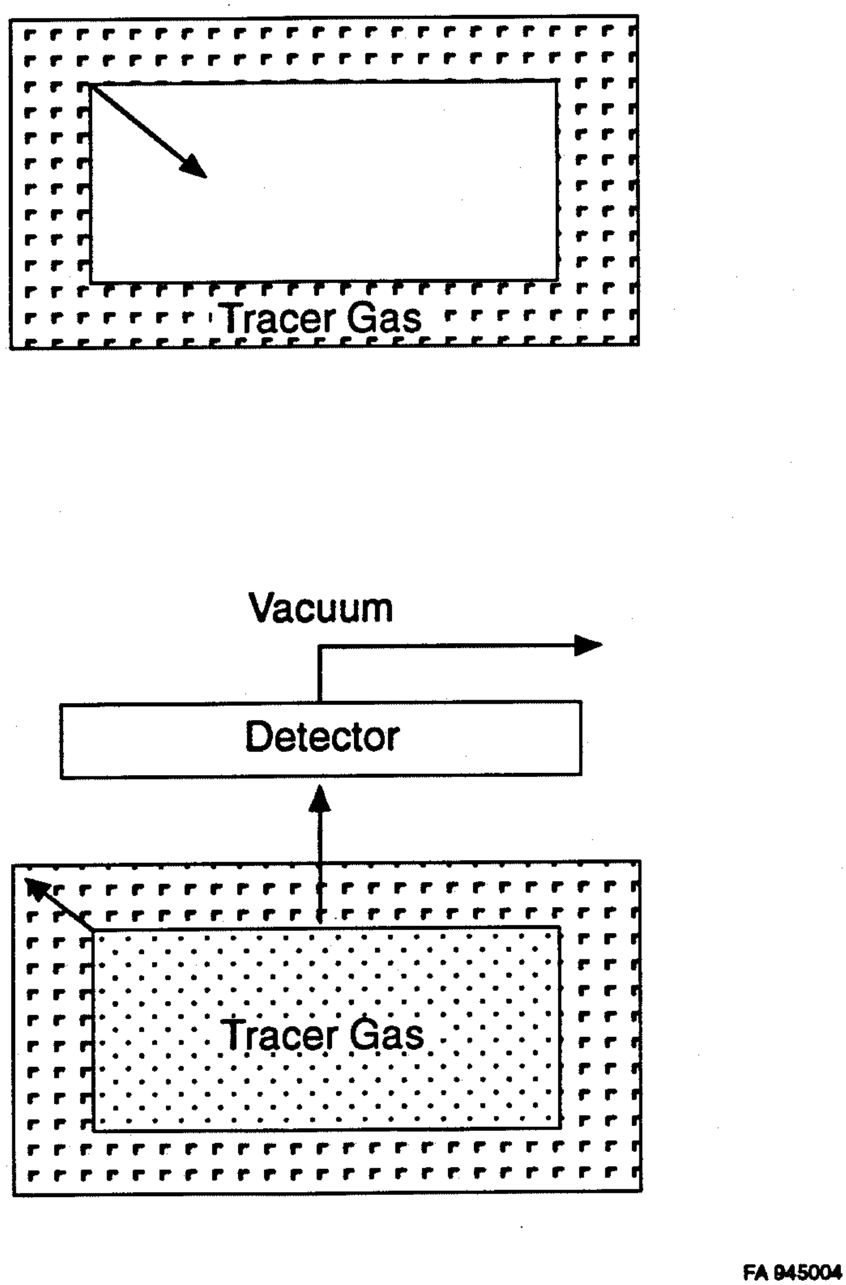

Fig. 4.26. Evacuated envelope test method - with back pressurization.[21]

through the leaks. This procedure can be very useful for testing several small samples at a time, provided that they can all be tested for leakage quickly in the evacuation chamber. In cases where the samples are delicate, it may be possible to use a lower pressurizing pressure for a longer period of time.

4.5.5.3 Qualitative test methods

4.5.5.3.1 Gas bubble techniques

These procedures, shown schematically in Figs. 4.27, 4.28, and 4.29, apply to small items, usually without pressure tap connections, which must be of a size to be conveniently lifted into and out of a tank which allows for close observation of the liquid. These methods can also be used for test items with pressure tap connections, or where the required pressure differential may be obtained by the use of a partial vacuum over the liquid in the tank, or by the use of a hot liquid in the tank. Individual leaks are indicated by gas bubble streams through the test liquid. The use of gas bubble techniques provides a qualitative result, with an absence of bubbles through the test liquid indicating a test sensitivity of 10^{-3} to 10^{-6} std cm^3/s, depending on the test liquid used. A variety of liquids such as water, alcohol, mineral oil, silicone oil, and glycols can be used in conjunction with a variety of tracer gases to improve the test sensitivity. Caution should be exercised, since gas bubbles may stream for a few seconds and then cease. Such streams could be due to gases trapped on the exterior surface of the test item and do not necessarily indicate a leak.

- The pressurized cavity bubble test method is shown schematically in Fig. 4.29. This method involves pressurizing the test item and, while the item is still pressurized, immersing the item into the liquid bath and searching for bubble streams.

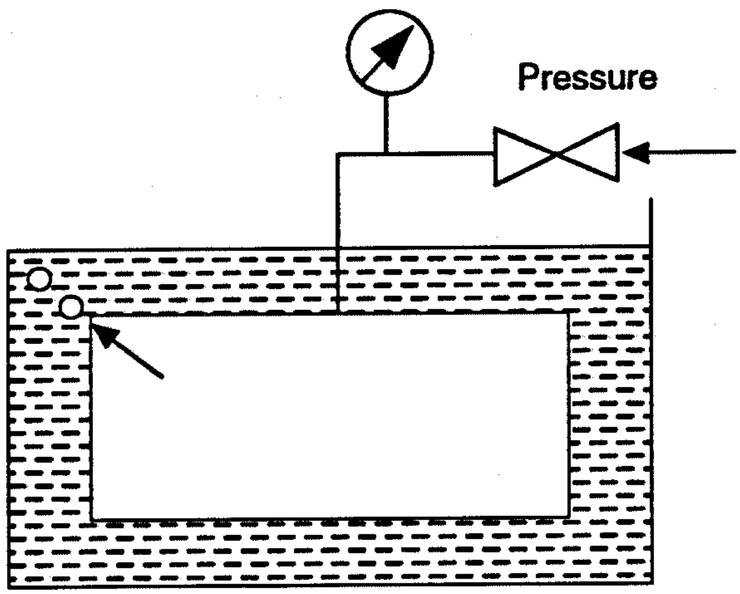

Fig. 4.27. Pressurized cavity bubble test method.[21]

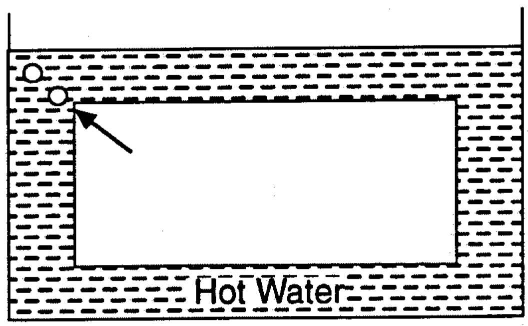

Fig. 4.28. Hot water bubble test method.[21]

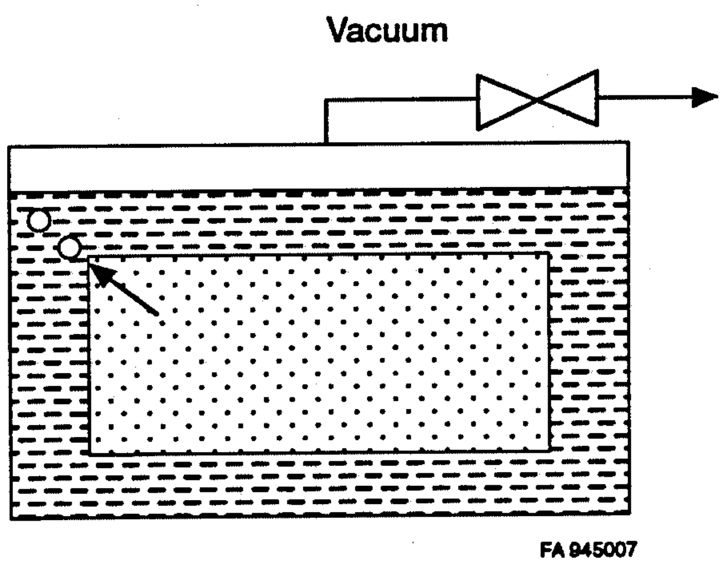

Fig. 4.29. Vacuum bubble test method.[21]

- The hot water bubble test method is shown schematically in Fig. 4.30. In this method, the test item (which is initially at room temperature) is immersed in a hot liquid bath which raises the internal pressure of the test item. The resultant increase in pressure allows for the detection of leaks that may have been too small to detect at room temperature. The test duration must be long enough to allow the test item and its contents to reach thermal equilibrium with the hot liquid bath.

- The vacuum bubble test method is shown schematically in Fig. 4.29. In this method, the test item is immersed in a liquid bath and the space above the liquid is evacuated to a suitable pressure. As with the previous two test methods, leakage is indicated by the presence of a stream of gas bubbles. The immersion liquid should possess a low surface tension and a low vapor pressure, and should be easily removed from the test item after the test has been completed.

4.5.5.3.2 Soap bubble techniques

This method, shown schematically in Fig. 4.30, applies primarily to containers with pressure tap connections. Individual leaks are indicated by the presence of gas bubbles forming in a liquid soap solution, or other commercially available liquid, that has been brushed or sprayed over the outer surface of the test item. This type of test gives a qualitative result, with an absence of bubbles through the soap solution indicating a leakage rate of less than about 10^{-3} std cm^3/s. The sensitivity may be increased by increasing the test pressure. Where possible, the method should be checked through the use of a calibrated leak of the sensitivity required for the containment.

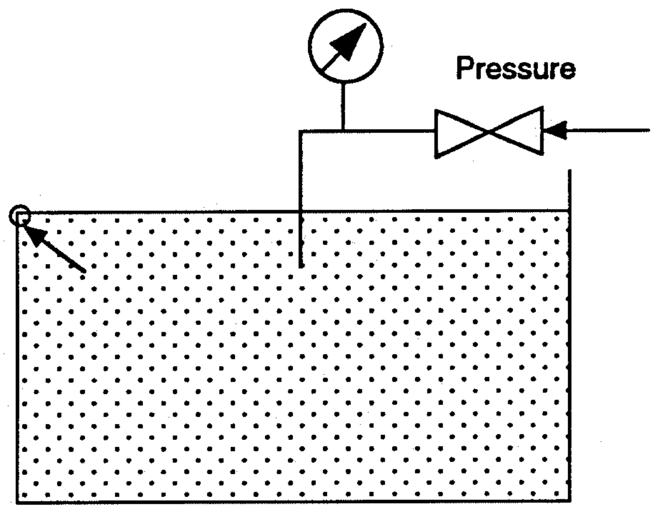

Fig. 4.30. Soap bubble test method.[21]

One of the major disadvantages of this type of test is that the soap solution used must bridge all potential leakage areas or joints to be effective. Where seals are not readily accessible, or joint gaps are such that they cannot be bridged or flooded, this method becomes unreliable.

4.5.6.3.3 Tracer gas sniffer techniques

This method, shown schematically in Fig. 4.31, is best used on large containers or sources where the area of a potential leak, e.g., a weld or seal, is clearly visible. There must be some facility for supplying tracer gas to the open sides of the seal. Provisions must also be made for the attachment of a tracer gas detector to the other side of the seal. Typical gases used are helium and halogen compounds. Leakage is indicated by the detector, which measures the concentration of the tracer gas. Although routine test sensitivities typically fall into the 10^{-3} to 10^{-6} std cm^3/s region, overall test sensitivities may be increased by as much as two orders of magnitude, depending on the skill of the operator.

For the use of halogen gas test systems, the precautions noted in Subsect. 4.5.5.2.3 should be followed.

4.5.6.3.4 Tracer gas spray methods

This method, shown schematically in Fig. 4.32, is best used on large containers or sources where the area of a potential leak, e.g., a weld or seal, is clearly visible. There must be some facility for supplying tracer gas to the open sides of the seal. Provisions must also be made for the attachment of a tracer gas detector to the other side of the seal. Typical gases used are helium and halogen compounds.

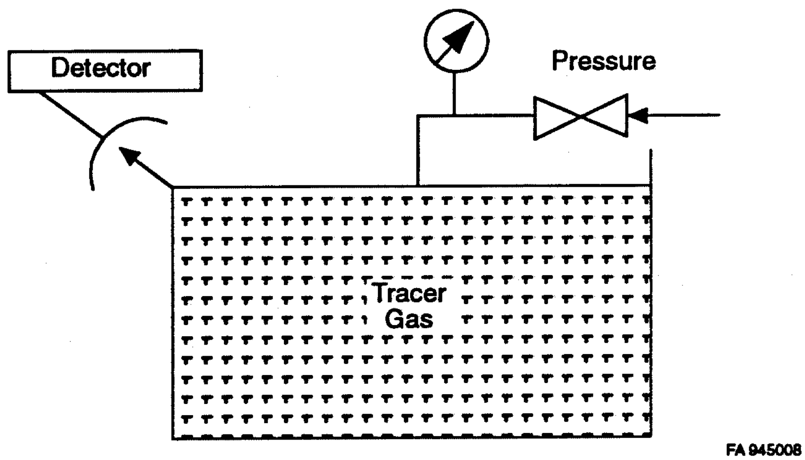

Fig. 4.31 Tracer gas sniffer test method.[21]

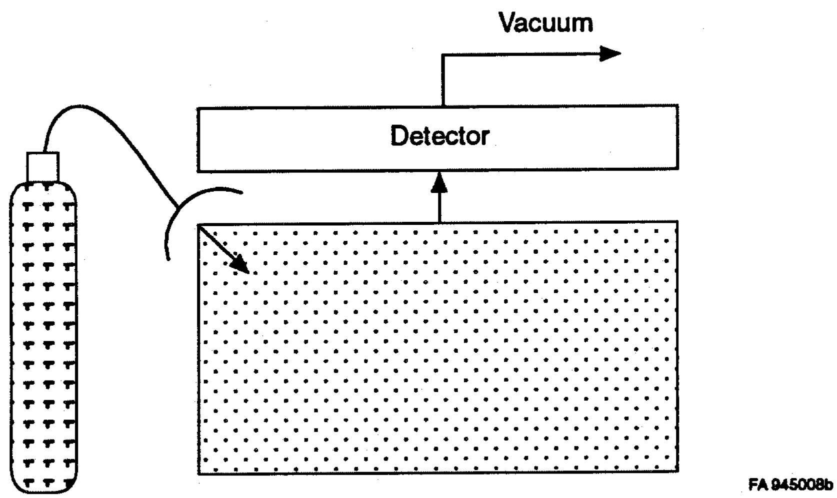

Fig. 4.32. Tracer gas spray test method.[21]

Leakage is indicated by the detector which measures the concentration of the tracer gas. Although routine test sensitivities typically fall into the 10^{-3} to 10^{-6} std cm^3/s region, overall test sensitivities may be increased by as much as several orders of magnitude, depending on the skill of the operator.

For the use of halogen gas test systems, the precautions noted in Subsect. 4.5.5.2.3 should be followed.

4.6 CHEMICAL AND ISOTOPIC CONSIDERATIONS

4.6.1 General

The bulk of the information presented in this chapter has been primarily concerned with 1) regulatory requirements; 2) the fundamental of basic seal designs from the standpoint of the properties of sealing surfaces, the properties of seal materials, and the properties of closure methods; and 3) the types of problems that may be associated with proving that the seal design selected will, in fact, perform as expected. One additional factor that must be considered, however, pertains to the chemical and physical properties of the radioactive materials that are intended to be contained. Because a detailed discussion of all possible combinations would be beyond the scope of this report, a generic overview is presented below.

4.6.2 Tritium

The lightest of the naturally occurring radionuclides, tritium is normally thought of as a gas. For purposes of containment during transport, however, tritium could just as easily be chemically compounded into the form of a hydride. For these types of situations, therefore, many of the considerations that would have been factored into the design of a containment vessel that had initially been intended for use with gases might have to be reconsidered with respect to its intended usage with powders, particulates, and/or solids.

4.6.3 Uranium

The lightest of the elements considered to be fissile, uranium is normally thought of as a solid. For purposes of containment during transport, however, uranium could just as easily be chemically compounded into the form of a halide (e.g., UF_6). For these types of situations, many of the considerations that would previously have been factored into the design of a containment vessel that had initially been intended for use with solids might have to be reconsidered with respect to its intended use with extremely corrosive gases, which, depending on the temperature, may also involve additional containment considerations for powders, and/or particulates.

4.6.4 Plutonium

The design considerations associated with containment vessels for plutonium, however, represent yet a third set of problems, primarily from the standpoint of isotopic compositions. Gram-for-gram, for example, the decay heat generated from plutonium-238 is much more intense than the decay heat generated from plutonium-239, due to major differences in their respective decay schemes. For these types of situations, therefore, most of the considerations that would previously have been factored into the design of a containment vessel that had initially been intended for use with plutonium-239 would have to be reconsidered with respect to its intended usage with plutonium-238.

4.7 SAFETY ANALYSIS REPORT FOR PACKAGING (SARP) PREPARATION

DOE requires that a SARP be prepared. It is recommended that the SARP be prepared in general conformance with NRC Regulatory Guide 7.9 as revised. The information provided in the containment section of each SARP document, as applicable, must adequately and clearly demonstrate to DOE that the packaging (including the transportation system, if necessary) containing authorized contents and transported within the DOE Transportation Safeguard System, complies with the requirements of 10 CFR 71, or clearly delineates areas of technical deficiency such that the DOE may consider the application for an exemption under 49 CFR 173.7(b), *National Security Exemption*, and seek authorization for such an application in accordance with the stipulations of DOE Order 5610.12. SARP review checklists have been developed to aid the applicant in providing the necessary information to show compliance with the appropriate paragraphs of 10 CFR 71. Therefore, it is recommended that:

1. The information provided in the containment section of each SARP follow the format as stipulated in Regulatory Guide 7.9

2. As a minimum and as applicable, each checklist item be addressed

4.7.1 NRC Regulatory Guide 7.9

The purpose of the Standard Format and Content of Part 71, Applications for Approval of Packaging for Radioactive Material (hereinafter "Standard Format"), is to indicate the information to be provided in the application and to establish a uniform format for presenting the information. Use of this format will help ensure the completeness of the information provided, will assist the reviewing organization and others in locating the information, and will aid in shortening the time needed for the review process. Application for approval with different formats will be acceptable if the applicant provides an adequate basis for the findings requisite to the approval of packaging. However, because it may be more difficult to locate needed information, the review time for such applications may be longer. The applicant should strive for clear, concise presentation of the information provided in this application. Confusing or ambiguous statements and unnecessarily verbose descriptions do not contribute to an expeditious technical review. Claims of adequacy of designs or design methods should be supported by technical bases, i.e., by an appropriate engineering evaluation or description of actual tests. Terms as defined in the packaging and transport regulations must be used.

4.7.2 SARP Checklist

At the present time, a checklist has developed by the Stone and Webster Engineering Corporation of Albuquerque, New Mexico. This document has been used recently in the evaluation of various Type B shipping packages. The checklist has addressed all paragraphs of 10 CFR 71, all Regulatory Guide 7.9 requirements, and most of the issues stipulated in UCID-21218 *(Packaging Review Guide for Reviewing Safety Analysis Reports for Packagings).* To provide the necessary technical foundation for determination of a safe and secure containment boundary, the following information must be presented in the SARP:

1. The containment boundary must be identified including complete documentation of vessel constituents' material, fabrication, and inspection procedures.

2. Identification of all boundary penetrations, seals, and closure methods must be provided with adequate documentation to support the claim of meeting containment requirements of 10 CFR 71.

3. Adequate documentation of analysis, source terms identified, and test performance in compliance with the requirements of Normal Conditions of Transport must be provided to demonstrate that there would be no loss or dispersal of radioactive contents to the appropriate sensitivity.

4. Adequate documentation of analysis, source terms identified, and test performance in compliance with the requirements of Hypothetical Accident Conditions must be provided to demonstrate that there would be no loss or dispersal of radioactive contents to the appropriate sensitivity.

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4.8 REFERENCES

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APPENDICES

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APPENDIX A

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APPENDIX A

A_2 DETERMINATION

A.1 GENERAL

In order for the designer to determine the proper containment boundary design, fabrication, test and quality assurance criteria, the A_2 of the contents and the total quantity A_2 being shipped must be ascertained through calculations or measurements. As presented in Sect. 4.1 of this document, the following procedure should be conducted in the initial design process:

1. Establish the size, weight, and form of the radionuclidests to be shipped;

2. Determine the A_2 and the total contents activity value (see Sect. A.4) for the contents

3. Using the information from items 1 and 2 above, determine the appropriate category for the containment boundary hardware (see Fig. 4.1);

4. Using the category determination in item 3, determine the acceptable quality criteria for the design and manufacturing phase (see Table 4.1).

5. Determine the overall size, shape and number of containment boundaries and appropriate closure methods based on internal supports, assembly, operational and special requirements of certain contents.

A graphical depiction, in the form of a matrix, is illustrated in Table Al of the material presented in 10 CFR 71, Appendix A. Example calculations of the more frequently encountered contents constitutes are provide in this appendix. The symbols inside of the brackets refer to the particular section covering the topic in Appendix A, of 10 CFR 71; i.e. [II(1)] refers to section II, paragraph (1) of Appendix A.

A.2 SINGLE RADIONUCLIDE

A.2.1 Known Identity and Activity [I(1)]

The A_2 of a single radionuclide is determined by simply extracting the data from Table A-1, Appendix A of 10 CFR 71. The designer must know the form of the contents, i.e. gas, solid liquid, in order to select the appropriate A_2. The example below using Tritium illustrates this point.

Symbol or radionuclide	**Element and atomic number**	**A_1 (Ci)**	**A_2 (Ci)**	**Specific activity (Ci/g)**
T (uncompressed)*	Tritium (1)	1000	1000	9.7×10^3
T (compressed)*		1000	1000	9.7×10^3
T (activated luminous paint)		1000	1000	9.7×10^3
T (adsorbed on solid carrier)		1000	1000	9.7×10^3
T (tritiated water)		1000	1000	9.7×10^3
T (other forms)		20	20	9.7×10^3

* For the purpose of Table A-1, compressed gas means a gas at a pressure which exceeds the ambient atmospheric pressure at the location where the containment system was closed.

Table A1

CONTENTS FORM	CONDITIONS OF CONTENTS: KNOWN IDENTITY KNOWN ACTIVITY	KNOWN ACTIVITY KNOWN IDENTITY (NOT LISTED)	KNOWN IDENTITY UNKNOWN ACTIVITY	DETAILED ANALYSIS NOT CONDUCTED	IDENTITY UNKNOWN UNKNOWN ACTIVITY
SINGLE RADIONUCLIDE	TABLE A-1 [I(1)]	DETERMINE PER INSTRUCTIONS GIVEN IN [I(2)]			ATOMIC NUMBER < 82 A_1 = 10 Ci A_2 = .4 Ci [I(3)] ATOMIC NUMBER > 82 A_1 = 2 Ci A_2 = .002 Ci [I(3)]
SINGLE RADIONUCLIDE WITH DAUGHTER PRODUCTS	TABLE A-1 [II(2)]	DETERMINE PER INSTRUCTIONS GIVEN IN [I(2)]			
MIXTURE OF RADIONUCLIDES	TABLE A-1 [II(3)]		DETERMINE PER INSTRUCTIONS GIVEN IN [II(4)] OR [II(5)]	A_1 = 10 Ci A_2 = .4 Ci [II(1)]	

A_1 & A_2 DETERMINATION MATRIX

APPENDIX A, 10 CFR 71

A.2.2 Known Identity But Not Listed in Table A-1 [I(2)]

The designer should refer to the appropriate section in Appendix A, 10 CFR 71 for further instructions on determining the correct A_2 for this situation.

A.2.3 Activity and Identity Unknown [1(3)]

If the atomic number of the radionuclide is known but the identity is unknown and has an atomic number less than 82, the A_2 is taken to be 0.4 Ci. If the atomic number is greater than or equal to 82, then the A_2 value is taken to be 0.002 Ci.

A.3 MIXTURE OF RADIONUCLIDES

A.3.1 Known Identity and Activity [II(3)]

If the identity and activity of each radionuclide in a mixture is known, the following simple spreedsheet can be used to determine the A_2 value of the mixture. It is important to note, that in the case of radioactive decay chains, daughter nuclides with half-life either longer than 10 days or greater than that of the parent nuclide, must be considered in the mixture calculations.

A.3.2 Detailed Analysis Not Conducted

The A_2 of a mixture of radionuclides is 0.4 Ci when a detailed analysis of the mixture has not been performed.

A.3.3 Known Identity with Unknown Activity [II(4) or II(5)]

The following example illustrates the use of an activity balance to determine the A_2 value when the identity of the radionuclides is known but the exact activity of each is not known.

A container is used to ship 1 *kg* of Uranium oxide ($U0_2$) as a powder. The uranium is enriched to 95 wt% ^{235}U. The maximum temperature and pressure for Normal Conditions of Transport are T = 50°C and a container pressure, P = 1.2 abs atm of air. Determine the A_2 value for this content.

Let SA = specific activity of each radionuclide.

Radionuclide	A_2 (Curies)	SA (Curies/gram)
^{234}U	0.1	6.2 E-3
^{235}U	0.2	2.1 E-6
U(95% 235)	To Be Determined	9.1 E-5
^{238}U	Unlimited	3.3 E-7

In order to determine the activities (or mass fractions of the three constituents, an activity balance must be evaluated as follows:

assuming f_i = mass fraction of each radionuclide

$$SA_{mix} = 9.1\text{ E-5 Ci/g} = (.95)(2.1\text{ E-6}) + (f_{u238})((3.3\text{ E-7}) + (f_{u234})(6.2\text{ E-3})$$

also:

$$.05 = f_{u238} + f_{u234} \quad \text{or} \quad f_{u234} = .05 - f_{u238}$$

Substituting for f_{u234}:

$$9.1\ E\text{-}5 = (.95)(2.1\ E\text{-}6) + (f_{u238})(3.3\ E\text{-}7) + (.05 - f_{u238})(6.2\ E\text{-}3)$$

and solving:

$$f_{u238} = .035646,\ f_{u234} = .0143537 \text{ and } f_{u235} = .95$$

Using the spreedsheet, as shown in Table A2, along with these mass fractions, the A_2 of the mixture is determined as follows:

Nuclide	mass	Sp. Act	Aci	A2	f(i)	f(i)/A2
	(g)	(Ci/g)	(Ci)	(Ci)	(Ci/Ci)	(1/Ci)
U-238	3.565E+01	3.300E-07	1.176E-05	1.000E+50	1.293E-04	1.293E-54
U-235	9.500E+02	2.100E-06	1.995E-03	2.000E-01	2.192E-02	1.096E-01
U-234	1.435E+01	6.200E-03	8.899E-02	1.000E-01	9.779E-01	9.779E+00
SM(B) =	1.000E+03					
		SM(D) =	9.100E-02		SM(G) =	9.889E+00
A2 of mix	= 1/SM(G)	=	1.011E-01	curies		

Table A2

(A)	(B)	(C)	(D)	(E)	(F)	(G)
Nuclide	mass	Specific	Act.(i)	A2	f(i)	f(i)/A2
(i)	(g)	Activity	(Ci)	(Ci)		(1/Ci)
		(Ci/g)				
			(B)*(C)		(D)/SM(D)	(F)/(E)
Pb210	3.110E-10	8.800E+01	2.737E-08	2.000E-01	1.977E-08	9.884E-08
Po210	5.290E-12	4.500E+03	2.381E-08	2.000E-01	1.719E-08	8.597E-08
Ra223	2.440E-11	5.000E+03	1.220E-07	2.000E-01	8.812E-08	4.406E-07
Ra226	2.500E-07	1.000E+00	2.500E-07	5.000E-02	1.806E-07	3.612E-06
Ra228	3.930E-15	2.30E+02	9.039E-13	5.00E-02	6.529E-13	1.306E-11
Ac227	1.730E-08	7.200E+01	1.246E-06	3.000E-03	8.997E-07	2.999E-04
Th227	4.010E-11	3.200E+04	1.283E-06	2.000E-01	9.269E-07	4.634E-06
Th228	1.950E-05	8.300E+02	1.619E-02	8.000E-03	1.169E-02	1.461E+00
Th230	5.550E-03	1.900E-02	1.055E-04	3.000E-03	7.617E-05	2.539E-02
Th232	2.330E-05	1.100E-07	2.563E-12	1.000E+50	1.851E-12	1.851E-62
Th234	1.470E-06	2.300E+04	3.381E-02	1.000E+01	2.442E-02	2.442E-03
Pa231	1.850E-04	4.500E-02	8.325E-06	2.000E-03	6.013E-06	3.007E-03
U232	7.630E-04	2.100E+01	1.602E-02	3.000E-02	1.157E-02	3.858E-01
U234	2.000E+02	6.200E-03	1.240E+00	1.000E-01	8.957E-01	8.957E+00
U235	1.900E+04	2.100E-06	3.990E-02	2.000E-01	2.882E-02	1.441E-01
U236	8.070E+01	6.300E-05	5.084E-03	2.000E-01	3.672E-03	1.836E-02
U238	1.010E+05	3.300E-07	3.333E-02	1.000E+50	2.407E-02	2.407E-52
SM(B) =	1.203E+05				1.000E+00	
		SM(D) =	1.384E+00		SM(G) =	1.100E+01
A2 of Mix	= 1/SM(G)	=	9.093E-02	curies		

A.3.4 Swipe Test Method

A sealed product can is to be used for shipping of plutonium oxide. The product can is to be held within a primary containment vessel already shown to satisfy containment criteria for normal and accident conditions. Swipe testing has been chosen as the most practical way to demonstrate containment for accident conditions for the product can containing the plutonium. Furthermore, natural uranium oxide is to be used as a surrogate for the plutonium oxide. From these results, the acceptability of the product can for containment of various isotopic mixtures of plutonium oxide will be determined.

The swipe test set-up is designed and efficiencies for the swiping and counting are found to be 10 and 40 percent, respectively. The overall counting efficiency (surface to counter) is thus $0.1 \times 0.4 = 0.04$. The product can is filled with the surrogate UO_2, cleaned, swiped, and loaded into a thoroughly cleaned primary container. The entire package is then subjected to the accident test sequence. After 168 hours, the package is disassembled with each component being swiped. Only the outside of the product can and the inner surfaces of the primary container yield any significant counts. The count rate which results from swiping all the contaminated surfaces is 300 counts per minute (c/m).

The corrected surface count, correcting for the overall efficiency, is 300/0.04 = 7500 disintegrations per minute on the surface, which is equal to 7500/60 = 125 disintegrations per second.

One Curie of activity represents 3.7×10^{10} disintegrations per second (dps). Thus the surface activity, and hence the activity which escaped the product can, is given by:

$$125\ (c/s)/(3.7 \times 10^{10})\ ((c/s)/Ci) = 3.4 \times 10^{-9}\ \text{Curies.}$$

The specific activity of natural uranium is given as 7.06×10^{-7} Ci/gm in Table A-4 of 10 CFR 71.

Thus, the mass of uranium released in a week is calculated as:

3.4×10^{-9} Ci/7.06×10^{-7} Ci/gm = 4.82×10^{-3} gm.

Assume now, that uranium is an adequate surrogate for plutonium under these test conditions; in that case the release rate of plutonium is also 4.82×10^{-3} g.

To prove adequate containment, the assumed equivalence between the behaviors of the uranium and plutonium oxides must be demonstrated, and the A_2 quantity for the plutonium isotopes to be shipped must be no more than that calculable from the measured 4.82×10^{-3} grams.

Just as a matter of interest, assume uranium and plutonium equivalence in this case, and from the data in Table A-l of 10 CFR 71 calculate the maximum permissible release amounts per week for the fissionable plutonium isotopes listed there. See Table A3.

Thus, this hypothetical product can provides a release rate which is low enough to meet the criteria for only the least active plutonium isotope.

Table A3

Plutonium isotope	Max grams per week
^{238}Pu	0.018×10^{-3}
^{239}Pu	32.26×10^{-3}
^{241}Pu	0.909×10^{-3}

A.4 TOTAL ACTIVITY OF CONTENTS

Thus far, this appendix has shown the designer methods of determining the A_2 of the mixture or of a single radionuclide. In order to determine the appropriate design, fabrication and quality assurance criteria, the total activity of the contents may be calculated as follows:

$$\text{Total Content Activity} = \frac{\text{Total Activity of Mixture}}{A_2 \text{ of Mixture}}$$

Using this value, Fig. 4.1 and Table 4.1, the designer can establish the appropriate criteria for designing the containment boundary.

A4.5 ANSI N14.5-1987 REVEIW EXAMPLE

The A_2 value of the mixture in this example with be used in Sect. A.2. A containment vessel must be designed to transport 16.628 *kg* of highly enriched uranium with the source terms of the isotopes as defined in Table A4 below.

<u>ORIGIN-S Results</u>. The source terms of the isotopes in the mixture (Table A4) were evaluated using the ORIGIN-S[1] computer program. The mass values for the parent and daughter products are presented in Table AS for the time interval of 0 to 30 years.

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[1] C.V. Parks, *SCALE 4.1 - System Module to Calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms*, Volume 2, Section F7, NUREG/CR-200, Radiation Shielding Information Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December 1984.

Table A4. Isotopic mass and weight percent for 16,628 grams of high enriched uranium

Nuclide	Weight Percent	Mass(gm)
U232	0.000004	0.000665
U234	1.000000	166.2800
U235	94.00000	15630.32
U236	0.400000	66.51200
U238	4.599996	764.8873
Total	100.0000	16628.00

Table A5. Mass values of parent and daughter products for 16,628 grams of uranium (grams)[a]

Nuclide	0 Year	2 Year	5 Years	10 Years	15 Years	20 Years	30 Years
Pb210	0.00E+00	2.18E-12	3.34E-11	2.58E-10	8.40E-10	1.92E-09	6.04E-09
Po210	0.00E+00	1.87E-14	4.17E-13	4.39E-12	1.43E-11	3.26E-11	1.03E-10
Ra223	0.00E+00	8.69E-13	5.28E-12	2.00E-11	4.29E-11	7.28E-11	1.49E-10
Ra226	0.00E+00	8.33E-09	5.20E-08	2.08E-07	4.67E-07	8.30E-07	1.86E-06
Ra228	0.00E+00	1.74E-16	9.67E-16	3.26E-15	6.28E-15	9.67E-15	1.70E-14
Ac227	0.00E+00	6.15E-10	3.73E-09	1.42E-08	3.04E-08	5.14E-08	1.06E-07
Th227	0.00E+00	1.43E-12	8.67E-12	3.30E-11	7.06E-11	1.20E-10	2.45E-10
Th228	0.00E+00	9.13E-06	1.45E-05	1.62E-05	1.58E-05	1.51E-05	1.37E-05
Th230	0.00E+00	9.22E-04	2.31E-03	4.61E-03	6.91E-03	9.22E-03	1.38E-02
Th232	0.00E+00	3.87E-06	9.67E-06	1.93E-05	2.90E-05	3.87E-05	5.81E-05
Th234	0.00E+00	1.11E-08	1.11E-08	1.11E-08	1.11E-08	1.11E-08	1.11E-08
Pa231	0.00E+00	3.02E-05	7.56E-05	1.52E-04	2.27E-04	3.02E-04	4.54E-04
U232	6.65E-04	6.52E-04	6.33E-04	6.02E-04	5.73E-04	5.45E-04	4.94E-04
U234	1.66E+02	1.66E+02	1.66E+02	1.66E+02	1.66E+02	1.66E+02	1.66E+02
U235	1.56E+04	1.56E+04	1.56E+04	1.56E+04	1.56E+04	1.56E+04	1.56E+04
U236	6.70E+01	6.70E+01	6.70E+01	6.70E+01	6.70E+01	6.70E+01	6.70E+01
U238	7.64E+02	7.64E+02	7.64E+02	7.64E+02	7.64E-02	7.64E+02	7.64E+02
Total	1.66E+04	1.66E+04	1.66E+04	1.66E+04	1.66E+04	1.66E+04	1.66E+04

[a] Only daughter products whose half-life exceeds 10 days or the half-life of the parent are included in this analysis. The data are generated by the ORIGIN-S computer code.

The A_2 value of the mixture at 10 years of decay is calculated and presented in Table A6. The tenth year of decay represents the smallest value of A_2 and thus the smallest allowable mass leak rate within the time interval examined. A summary of the content activity and the A_2 value of the mixture are given in Table A7.

Results:

The containment criteria analysis for the content indicates that the uranium oxide must be shipped in a Type B material package since the activity is greater than the A_2 value. Table A7 gives the A_2 values for the mixture in the 0- to 30-year time interval. The smallest A_2 value for the uranium mixture occurs after about 10 years of the decay (0.0866 curie).

Table A6. A_2 Calculation at Tenth Year

(A)	(B)	(C)	(D)	(E)	(F)	(G)
Nuclide	mass	Specific	Act.(i)	A2	f(i)	f(i)/A2
(i)	(g)	Activity	(Ci)	(Ci)		(1/Ci)
		(Ci/g)				
			(B)*(C)		(D)/SM(D)	(F)/(E)
Pb210	2.580E-10	8.800E+01	2.270E-08	2.000E-01	2.077E-08	1.039E-07
Po210	4.390E-12	4.500E+03	1.976E-08	2.000E-01	1.808E-08	9.038E-08
Ra223	2.000E-11	5.000E+03	1.000E-07	2.000E-01	9.150E-08	4.575E-07
Ra226	2.080E-07	1.000E+00	2.080E-07	5.000E-02	1.903E-07	3.806E-06
Ra228	3.260E-15	2.30E+02	7.498E-13	5.00E-02	6.861E-13	1.372E-11
Ac227	1.420E-08	7.200E+01	1.022E-06	3.000E-03	9.355E-07	3.118E-04
Th227	3.300E-11	3.200E+04	1.056E-06	2.000E-01	9.663E-07	4.831E-06
Th228	1.620E-05	8.300E+02	1.345E-02	8.000E-03	1.230E-02	1.538E+00
Th230	4.610E-03	1.900E-02	8.759E-05	3.000E-03	8.015E-05	2.672E-02
Th232	1.930E-05	1.100E-07	2.123E-12	1.000E+50	1.943E-12	1.943E-62
Th234	1.100E-08	2.300E+04	2.530E-04	1.000E+01	2.315E-04	2.315E-05
Pa231	1.520E-04	4.500E-02	6.840E-06	2.000E-03	6.259E-06	3.129E-03
U232	6.020E-04	2.100E+01	1.264E-02	3.000E-02	1.157E-02	3.856E-01
U234	1.660E+02	6.200E-03	1.029E+00	1.000E-01	9.417E-01	9.417E+00
U235	1.560E+04	2.100E-06	3.276E-02	2.000E-01	2.998E-02	1.499E-01
U236	6.700E+01	6.300E-05	4.221E-03	2.000E-01	3.862E-03	1.931E-02
U238	7.640E+02	3.300E-07	2.521E-04	1.000E+50	2.307E-04	2.307E-54
SM(B) =	1.660E+04				1.000E+00	
		SM(D) =	1.093E+00		SM(G) =	1.154E+01
A2 of Mix	= 1/SM(G)	=	8.665E-02	curies		

Table A7. Activity, activity to A_2 value, A_2 value for the mixture, and allowable leakage mass for uranium contents

Year	Activity (Ci)	Activity/A_2	A_2-Mixture (Ci)	Leakage mass (g)
0	1.08E+00	1.09E+01	.0987	1.52E+03
2	1.09E+00	1.19E+01	.0915	1.40E+03
5	1.09E+00	1.24E+01	.0877	1.34E+03
10	1.09E+00	1.26E+01	.0866	1.32E+03
15	1.09E+00	1.26E+01	.0869	1.32E+03
20	1.09E+00	1.25E+01	.0873	1.33E+03
30	1.09E+00	1.23E+01	.0882	1.35E+03

APPENDIX B

ANSI N14.5 REVIEW

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APPENDIX B

ANSI N14.5 REVIEW

This Appendix aids the calculation of leak test requirements for Type-B shipping containers using ANSI N14.5-1987. Additional information has been compiled to clarify the application of the leakage flow equations. After some discussion on the theory and function of the leakage flow equations an example problem will guide a designer through the calculations.

Most shipping containers have a cover gas like air, argon, or helium that covers the material being shipped. When the container's internal pressure builds up the cover gas could escape through a crack, pin hole, or improperly seated O-ring seal. As the gas leaks out of the container it could carry radioactive particles. 10 CFR part 71.51 and ANSI N14.5-1987 have radioactive activity release limits which must be met. These radioactive activity release limits are used to calculate the regulatory requirements for acceptance leakage testing. This appendix will focus on the O-ring seal, but this calculation could be done on welds to determine the container's integrity.

A review of the compressibility effects of gas is helpful to understand the logic used when calculating the leakage flow rates in ANSI N14.5-1987.

The Ideal Gas Law;

$$PV = nR_oT$$

$$(\text{atm})\ (\text{cm}^3) = (\text{gmol})\ (\text{atm-cm}^3/\ \text{gmol-}^\circ\text{K})\ (^\circ\text{K})$$

P (atm),	Absolute Pressure
V (cm^3),	Volume
n (gm mole, gmol),	Moles of gas
$R_o = 8.31 \times 10^7$ (erg-cm^3/ gmol-°K),	Universal gas Constant

R_o = 82.0562 (atm-cm³/ gmol-°K), Universal gas Constant
T (°K = 273 + °C), Absolute Temperature in degrees Kelvin

Dividing the Ideal Gas Law by time, generates a molecular leakage flow rate;

$$(PV = nR_oT) \,/\, \text{time}$$
$$(\text{atm})\ (\text{cm}^3/\text{sec}) = (\text{gmol/sec})\ (\text{atm-cm}^3/\ \text{gmol-}^\circ\text{K})\ (^\circ\text{K})$$

ANSI N14.5 uses this equation in the following form;

$$Q = PL = \dot{n}R_oT$$
$$(\text{atm})\ (\text{cm}^3/\text{sec}) = (\text{gmol/sec})\ (\text{atm-cm}^3/\ \text{gmol-}^\circ\text{K})\ (^\circ\text{K})$$

Q (atm-cm³/sec), Mass-like Leakage
P (atm), Absolute Pressure
L (cm³/sec), Volumetric Leakage
$\dot{n}$ (gmol/sec), Moles of gas / time

A mass flow rate can be found by rearranging the equations;

$$\dot{n} = \dot{m} \,/\, M$$
$$(\text{gmol/sec}) = (\text{gm/sec}) \,/\, (\text{gm/gmol})$$

$$Q = PL = (\dot{m} \,/\, M)R_oT$$
$$(\text{atm})\ (\text{cm}^3/\text{sec}) = (\text{gm/sec}) \,/\, (\text{gm/gmol})\ (\text{atm-cm}^3/\ \text{gmol-}^\circ\text{K})\ (^\circ\text{K})$$

$\dot{m}$ (gm/sec), Mass Flow Rate
M (gm/gmol or gm/gm-mole), Molecular Weight

ANSI N14.5 assumes the gas properties, both temperature and viscosity are constant at the upstream conditions for all leakage calculations. With a constant temperature, Q will be proportional to $\dot{m}$.

Q (atm-cm^3/sec),	Constant Mass-like Leakage Rate
P_c (atm),	Pressure at a condition
L_c (cm^3/sec),	Leakage rate at a condition
L_R (std-cm^3/sec),	Standard Leakage for Air at;
	T=298 °K, P_u= 1.0 atm, P_d = 0.01 atm

For a constant mass-like flow rate (Q), the volumetric flow rate (L) expands because the pressure in the leak path is reduced from the upstream pressure (high) to the downstream pressure (low). Since the volumetric leakage flow rate (L) is expanding all of the volumetric leakage rates must be defined at a specific pressure condition.

For testing purposes ANSI N14.5-1987 defines the conditions of a reference air leakage rate (L_R std-cm^3/sec) at; T=298 °K, P_u= 1.0 atm, P_d=0.01 atm. L_R is defined by a standard temperature and pressure but depending upon the size of the leakage, the flow regime could be Continuum (UnChoked) or Sonic (Choked). The UnChoked and Choked flow leakage equations are based on a different exit pressures and flow conditions.

The following is a list of different conditions of pressures that generate different flow leakages used in ANSI N14.5-1987.

Condition	Leakage	Pressure
upstream	L_u	P_u
downstream	L_d	P_d
average	L_a	P_a
Normal transport	L_N	P_e
Accident transport	L_A	P_e
Reference	$L_R = L_u$ or L_a	P_u or P_a
mixture	L_m	P_u or P_e or P_a
exit	L_e	P_e or P_d

unknown	L	P_u or P_e or P_a
Test leakage	L_T	P_u or P_a

ANSI N14.5 Assumes that the leak path is a perfect tube with:

D = diameter (cm), a = path length (cm)

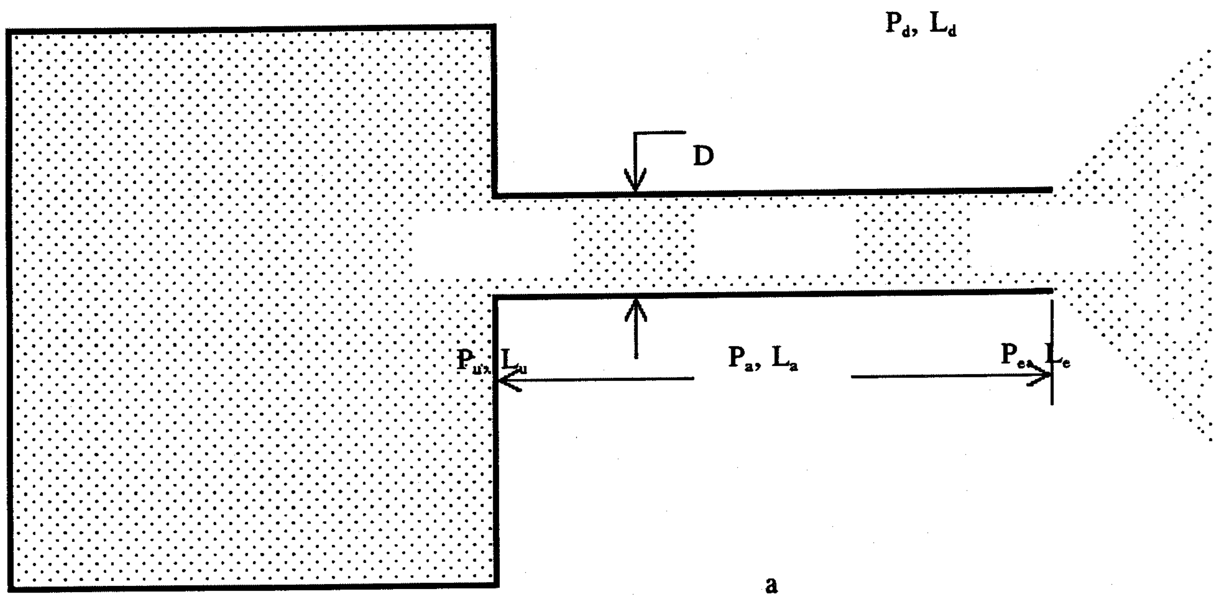


Fig. B1

The average pressure is used to calculate the leakage (L_a) based on UnChoked flow.

$$P_a = (P_u+P_d) / 2$$ Average Pressure

The leakage flow regime equations are evaluated with a ratio of downstream to upstream pressures. As the downstream pressure is reduced, the pressure ratio (P_d / P_u) gets smaller and more fluid flows through the leak until the leak path becomes choked. When the leak path is choked the exit pressure and flow leakage become constant, independent upon any further reduction in the downstream pressure. When the leak path becomes choked the pressure ratio is called the critical pressure ratio (r_c).

For UnChoked Flow, the exit pressure is the downstream pressure

$P_e = (P_d/P_u)(P_u)$, When $(P_d/P_u) > r_c$

$P_e = P_d$

For Choked Flow

$P_e = (r_c)(P_u)$, When $(P_d / P_u) \leq r_c$ and $r_f \geq 1$

When the pressure ratio is less then or equal to the critical pressure ratio the flow regime could be molecular (small) or sonic (large). A Flow Conductance Ratio (r_f) in ANSI N14.5 equation B5, is used to determine if the leakage flow regime is molecular (UnChoked) or sonic (Choked). For all leakage flow rates the flow conductance ratio (r_f), must be calculated using (ANSI N14.5, Eq B5) for both Choked and UnChoked leakages to verify that the proper flow regime equation is used. Each of these leakage equations must be evaluated at the proper leakage condition as specified above.

The fluid viscosity is required to calculate r_f (ANSI N14.5, Eq B5), but not used in the Choked leakage flow equation (ANSI N14.5, Eq B7). To obtain the proper viscosity at the upstream temperture use data from a reference, like the Handbook of Chemistry and Physics. An important part of these calculations is the viscosity of the gas which will change over 54 percent for air at 530°F compared to air at 72°F as shown in the example problem.

ANSI N14.5 FLOW EQUATIONS

Constant Mass-like Leakage Rate

$$Q = P\ L \quad (atm \cdot cm^3/s) \qquad \text{(Eq B1)}$$

Molecular and Continuum Flow L_a at P_a, UnChoked

$$L_a = (F_c + F_m)(P_u - P_d) \quad (cm^3/s) \qquad \text{(Eq B2)}$$

Continuum Flow Conductance

$$F_c = 2.49 \times 10^6\ D^4 / (a\ \mu) \quad (cm^3/atm \cdot s) \qquad \text{(Eq B3)}$$

Molecular Flow Conductance

$$F_m = 3.81 \times 10^3\ D^3 \sqrt{(T/M)}\ /\ (a\ P_a) \quad (cm^3/atm \cdot s) \qquad \text{(Eq B4)}$$

Flow Conductance Ratio

$$r_f = F_c / F_m = 654\ D\ P_a / (\mu \sqrt{(T/M)}\ ) \qquad \text{(Eq B5)}$$

Critical Pressure Ratio

$$r_c = \left[\frac{2}{k+1}\right]^{k/(k-1)} \qquad \text{(Eq B6)}$$

Sonic Flow L_u at P_u, Choked

$$L_u = \frac{\pi D^2}{4} \sqrt{\left[\frac{2kR_oT_u}{M(k+1)}\right] \times \left[\frac{2}{k+1}\right]^{1/(k-1)}} \quad (cm^3/s) \qquad \text{(Eq B7)}$$

These equations are related to the values given in Table B1.

Table B1. ANSI N14.5 Flow Equation Matrix

Flow Equation	Flow Regimes	Approximate Leakage*	Pressure Ratio	Conductance Ratio
UnChoked	Continuum	$L_a > 10^{-3}$	$P_d / P_u > r_c$	$r_f \geq 1$
UnChoked	Combination	$10^{-6} < L_a < 10^{-3}$	$P_d / P_u > r_c$	$r_f < 1$
UnChoked	Molecular	$L_a < 10^{-6}$	$P_d / P_u \leq r_c$	$r_f < 1$
Choked	Sonic	$L_u > 10^{-4}$	$P_d / P_u \leq r_c$	$r_f \geq 1$

*For leakage path length; a = 1.0 cm

TRANSITIONAL FLOW ZONES

I. When r_f is much larger then 1, and (P_d / P_u) approaches r_c the leakage flow rate jumps because the equations switch from; (UnChoked, Continuum) to (Choked, Sonic) flow.

II When (P_d / P_u) is much smaller then r_c, and r_f approaches 1 the leakage flow rate jumps because the equations switch from; (UnChoked, Molecular) to (Choked, Sonic) flow.

Data Table B2 was generated to illustrate the leakage flow regime transition from UnChoked, molecular to Choked, Sonic flow when (P_d / P_u) is much smaller then r_c. A fixed leakage path length of 1 cm long and different leakage diameters were used to generate reference air standard leakage rate (L_R) in std-cm^3/sec. This standard leakage rate is used in ANSI N14.5-1987 to determine the proper testing criteria. The mass-like flow rate varies because of the different exit pressures.

This data is plotted on in Figs. B2 and B3. Figure B2 is a plot of the reference leakage equations, notice that for any diameter or r_f of a leak path thier is at least two possible solutions to the leakage equations. Figure B3 applies the second criteria in the flow equation matrix Table B1 and plots the acceptable solutions of the leakage flow equations using the flow conductance ratio.

Table B2

(Q and L_R) vs (r_f and D)
For
Standard Air at; T=298 °K, P_u=1.0 atm, P_d=0.01 atm

r_f	diameter	Q UnChoked	L_a	QChoked	L_u
0.10000	1.79686E-5	7.71627E-11	1.52797E-10	5.07399E-6	5.07399E-6
0.12915	2.32072E-5	1.70640E-10	3.37910E-10	8.46381E-6	8.46381E-6
0.16681	2.99735E-5	3.79910E-10	7.52300E-10	1.41187E-5	1.41187E-5
0.21544	3.87116E-5	8.52560E-10	1.68825E-9	2.35506E-5	2.35506E-5
0.27825	4.99977E-5	1.93168E-9	3.82512E-9	3.92844E-5	3.92844E-5
0.35938	6.45757E-5	4.42606E-9	8.76447E-9	6.55327E-5	6.55327E-5
0.46416	8.34032E-5	1.02708E-8	2.03383E-8	1.09316E-4	1.09316E-4
0.59948	1.07718E-4	2.41723E-8	4.78659E-8	1.82347E-4	1.82347E-4
0.77426	1.39124E-4	5.77687E-8	1.14393E-7	3.04175E-4	3.04175E-4
1.00000	1.79686E-4	1.40296E-7	2.77813E-7	5.07399E-4	5.07399E-4
1.29154	2.32072E-4	3.46311E-7	6.85763E-7	8.46381E-4	8.46381E-4
1.66810	2.99735E-4	8.68726E-7	1.72025E-6	1.41187E-3	1.41187E-3
2.15440	3.87116E-4	2.21264E-6	4.38146E-6	2.35506E-3	2.35506E-3
2.78250	4.99977E-4	5.71609E-6	1.13190E-5	3.92844E-3	3.92844E-3
3.59380	6.45757E-4	1.49571E-5	2.96181E-5	6.55327E-3	6.55327E-3
4.64160	8.34032E-4	3.95749E-5	7.83662E-5	1.09316E-2	1.09316E-2
5.99480	1.07718E-3	1.05710E-4	2.09326E-4	1.82347E-2	1.82347E-2
7.74260	1.39124E-3	2.84653E-4	5.63669E-4	3.04175E-2	3.04175E-2
10.00000	1.79686E-3	7.71627E-4	1.52797E-3	5.07399E-2	5.07399E-2

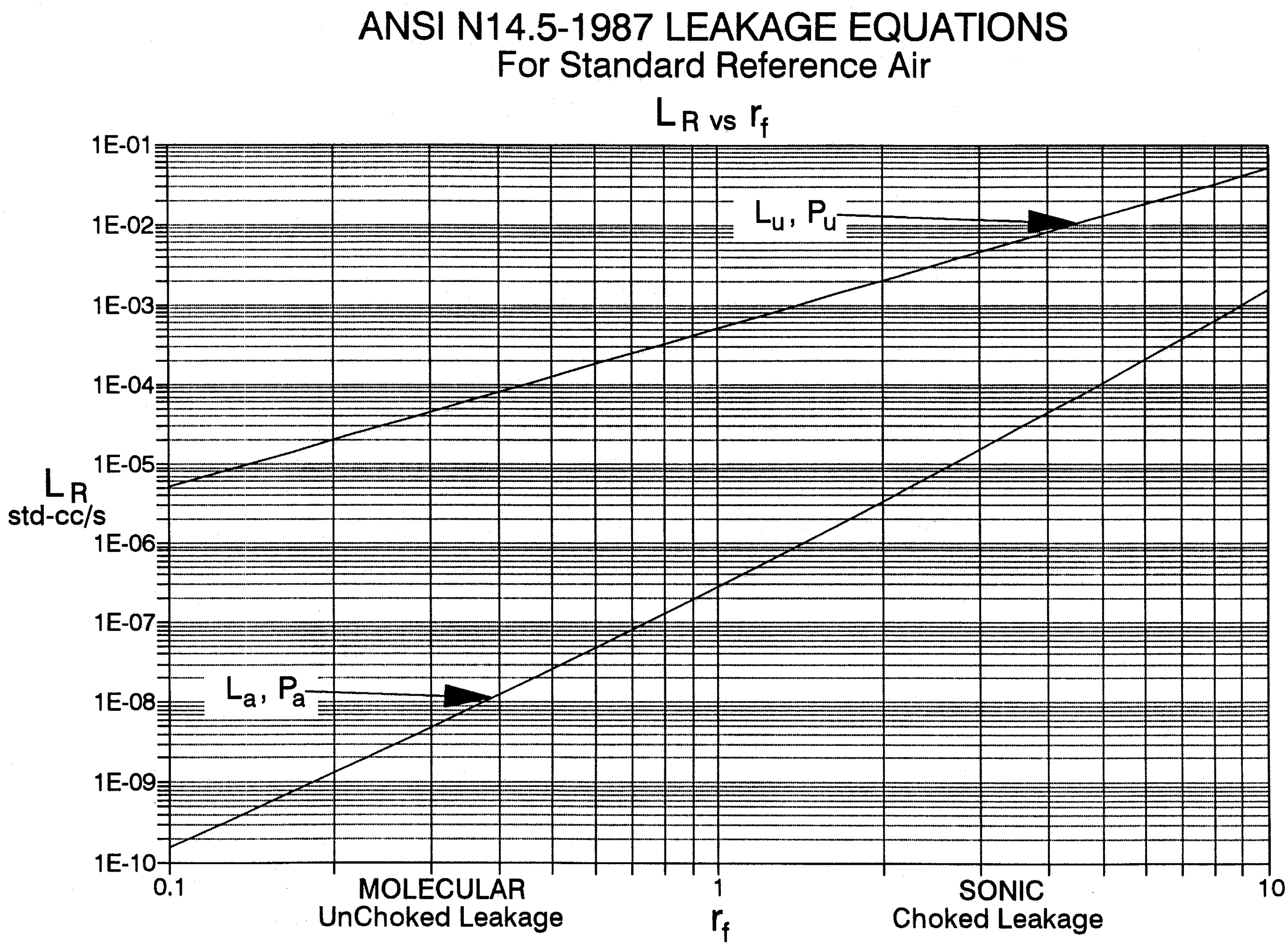
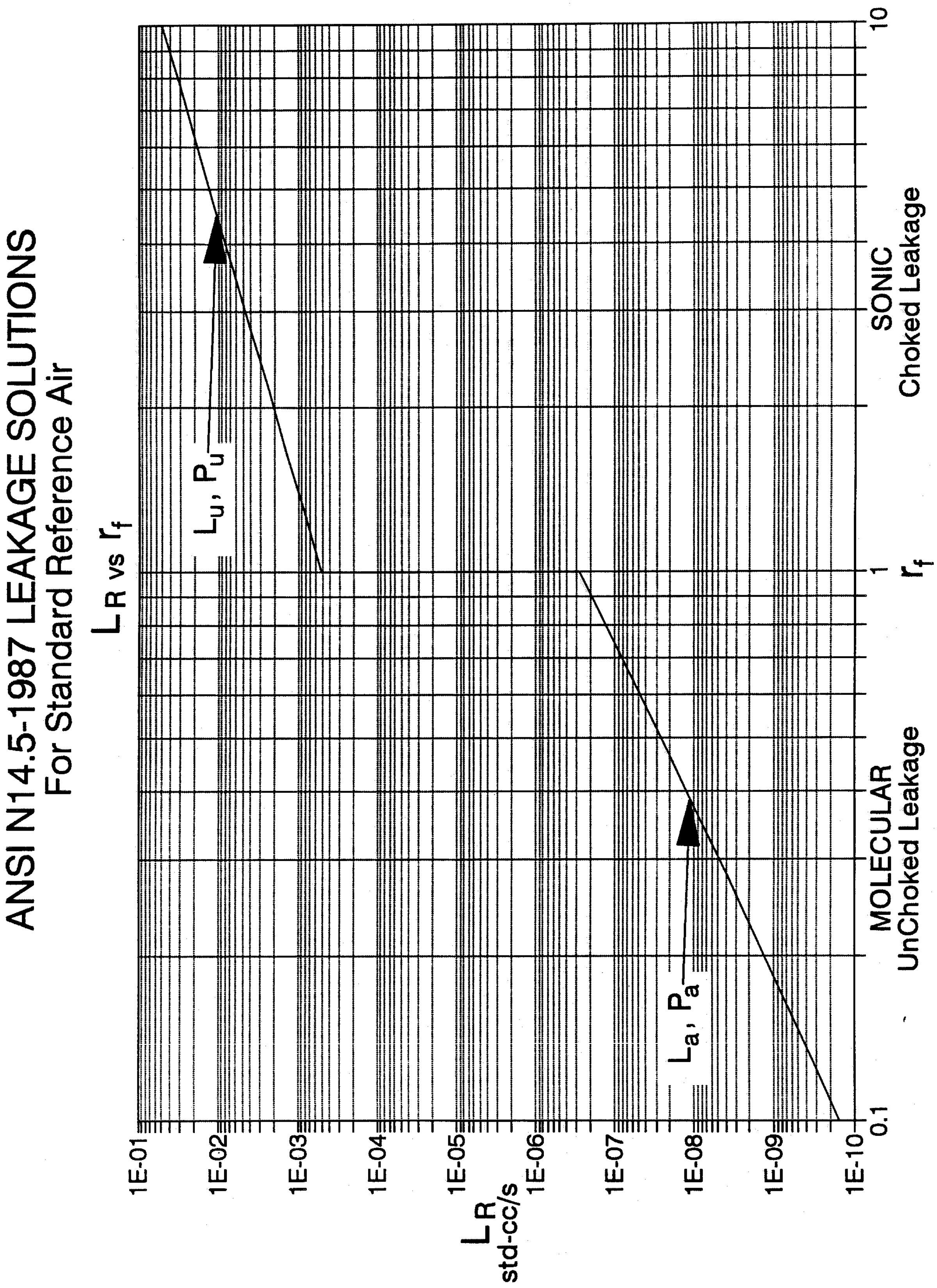

ANSI N14.5-1987 LEAKAGE EQUATIONS
For Standard Reference Air
L R vs rf
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E-09
1E-10
L R
std-cc/s
Lu , Pu
La , Pa
0.1
1
10
MOLECULAR
UnChoked Leakage
rf
SONIC
Choked Leakage

Fig. B2.



ANSI N14.5-1987 LEAKAGE SOLUTIONS
For Standard Reference Air
L_R vs r_f
L_u , P_u
L_a , P_a
L_R
std-cc/s
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E-09
1E-10
0.1
1
10
r_f
MOLECULAR
UnChoked Leakage
SONIC
Choked Leakage

Fig. B3.

Figure B3 shows that for any value of flow diameter or r_f a unique value for L_R can be calculated. When r_f transitions between 0.999999 and 1.0, the value of L_R changes from 2.77813×10^{-7} to 5.07399 x 10~ std-cm^3/sec (see Tables Bi and B2). For a given leakage La or La that is between these transition leakage flow values NO FLOW diameter can be calculated that satisifies all of the ANSI N14.5-1987 leakage flow equations.

This transitional flow zone between UnChoked, Molecular and Choked, Sonic leakage flow is further compounded when more then one gas is used in the leakage equations. If the conditions of transport have a cover gas that is not air and/or the leak testing is done with a different gas like helium. Then a transition zones may be crossed for each gas used in the leakage flow calculations.

Shown in Fig. Bl the volumetric leakage that could leak out of a container is the exit leakage (L_e). An exit leakage is at the exit pressure, which is the only detectable leak. This leak is measured at the entrance of a leak detection system. The reference leakage (L_R) either L_u or L_a is calculated at a higher pressure then the exit pressure, therefore L_e is larger than L_R. Since L_R is the allowable test leakage rate (L_T), and L_T will be the measured exit leakage (L_e). ANSI N14.5-1987 has a built in conservatism factor.

For standard air testing conditioins lets assume that we have;

$L_e = 1.9 \times 10^{-4}$ exit Leakage

$Q = P_e L_e$ (ANSI N14.5, Eq B1)

For UnChoked flow; $P_e = P_d$

$Q_2 = P_d L_e$ (ANSI N14.5, Eq B1) for UnChoked flow

$Q_2 = (0.01)(\text{atm})\ (1.9 \times 10^{-4})(\text{cm}^3/\text{s})$

$Q_2 = 1.9 \times 10^{-6}\ (\text{atm-cm}^3/\text{s})$ Mass-like leakage rate (if UnChoked)

Using Q_2, Find the average leakage L_a at P_a,

$Q_2 = P_a L_a$, (ANSI N14.5, Eq B1) for UnChoked flow

$L_a = Q_2 / P_a = 1.9 \times 10^{-6}\ (\text{atm-cm}^3/\text{s}) / (0.505)(\text{atm})$

$L_a = L_R = 3.76 \times 10^{-6}\ (\text{std-cm}^3/\text{s})$, Average Leakage Rate (if UnChoked)

For Choked flow; $P_e = P_u r_c$

Q_7 shall be the Mass-like Leakage found for Choked flow using the exit leakage L_e at P_e,

$Q_7 = P_u r_c L_e$, (ANSI N14.5, Eq B1) for Choked flow

$Q_7 = (1.0)(\text{atm})\ (0.5283)\ (1.9 \times 10^{-4})(\text{cm}^3/\text{s})$

$Q_7 = 1.00 \times 10^{-4}\ (\text{atm-cm}^3/\text{s})$, Mass-like leakage rate (if Choked)

Using Q_7, Find the upstream leakage L_u at P_u,

$Q_7 = P_u L_u$, (ANSI N14.5, Eq B1) for Choked flow

$L_u = Q_7 / P_u = 1.00 \times 10^{-4}\ (\text{atm-cm}^3/\text{s}) / (1.0)\ (\text{atm})$

$L_u = L_R = 1.00 \times 10^{-4}\ (\text{std-cm}^3/\text{s})$, Upstream Leakage Rate (if Choked)

Given an exit leakage of $L_e = 1.9 \times 10^{-4}$ (cm^3/s) the average leakage was found to be $L_a = 3.76 \times 10^{-6}$ (std-cm^3/s), and the upstream leakage was L_u 1.00×10^{-4} (std-cm^3/s). Applying the flow conductance ratio r_f as shown in Table B1 there is no acceptable leakage solutions as shown on Fig. B3. Although, Fig. B2 will yield a value of r_f or a flow diameter, when that flow diameter is used to calculate a leakage, the wrong equation will calculate the wrong answer.

Using ANSI N14.5-1987 Leakage Equations (Fig. B2) find the proper r_f and flow diameter.

For $L_{R2} = L_a = 3.76 \times 10^{-6}$ (std-cm^3/s),

$r_f = 2.06$ and ANSI N14.5, equation B5 gives us a flow diameter of 3.7×10^{-4} cm

With $D = 3.7 \times 10^{-4}$ cm, $r_f = 2.06$, Back solve for L_R using Fig. B3

$L_{Rl} = L_u = 2.15 \times 10^{-3}$ (std-cm^3/s), Since $r_f \geq 1$

Checking the accuracy of this calculation with $D = 3.7 \times 10^{-4}$ cm,

$Acc = L_{Rl} / L_{R2}$

$L_u / L_a = 2.15 \times 10^{-3}$ (std-cm^3/s) / 3.76×10^{-6} (std-cm^3/s)

Acc = 572.

Using ANSI N14.5-1987 Leakage Equations (Fig. B2) find the proper r_f and flow diameter.

For $L_{Rl} = L_u = 1.00 \times 10^{-4}$ (std-cm^3/s)

$r_f = 0.43$ and ANSI N14.5, equation B5 gives us a flow diameter of 7.72×10^{-5}cm

With $D = 7.72 \times 10^{-5}$cm, $r_f = 0.43$, Back solve for L_R using Fig. B3

$L_{R2} =$ $L_a = 1.575 \times 10^{-8}$ (std-cm^3/s), Since $r_f < 1$

Checking the accuracy of this calculation with D = 7.72 x 10^{-5}cm,

Acc = L_{Rl}/L_{R2}

L_u / L_a = 1.00 × 10^{-4} (std-cm^3/s) / 1.575 × 10^{-8} (std-cm^3/s)

Acc = 6348.

One can see that gross errors can occur if the wrong equations are applied. These errors could be compounded when additional gasses are used. If the conditions of transport have a cover gas that is not air and/or the leak testing is done with a gas like helium. Then a transition zones could be crossed for each gas used in the leakage flow calculations.

Warning, do not use these short cut equations, such as ANSI N14.5 (Eq B8), (Eq B12), and (Eq B13). The use of these short cut equations requires a constant leakage flow regime and does not check to assure that the proper leakage equation is applied. As shown above, frequent errors will occur when the transition zones is crossed. Equation B 13 is shown incorrectly in ANSI N 14.5-1987, the term "(1/P_u)" should be removed.

ANSI N14.5-1987 has a minimum Choked leakage rate at r_f = 1.00, and a maximum UnChoked leakage rate when r_f < 1, lets assume at r_f = 0.999999. These values are shown in Table B2. When the flow diameter is 1.79686 × 10^{-4}cm, and 0.999999 < $r_f \geq$ 1.00 then 2.7781 × 10^{-7} < $L_R \geq$ 5.0739 × 10^{-4}. The leakage flow equations in ANSI N14.5-1987 have a very large change in leakage flow rate for a tiny change in flow diameter.

Equation 2 in ANSI N14.5-1987 has a "CAUTION: Equation B2 may underestimate the leakage rate or overestimate the hole diameter", and (Eq B7) has a "CAUTION: Equation B7 may overestimate the leakage rate or underestimate the hole diameter for long leak paths". Furthermore, in section "**B4.4 Other Flow Equations.** Other flow models may be used if they are justified." These statements from the ANSI N14.5-1987 committee mean that they may have understood the transitional flow zone problem.

How can a solution be obtained when the leakage is in the transition zone? Some analysis just use the smallest flow diameter from either flow equation. Although this solution method does not follow ANSI N14.5-1987 leakage equation flow logic (see Table B1), it yields a extremely conservative answer which can not be back solved. To back solve the leakage equation for a given L_{R1}, calculate D, given D calculate L_{R2}, $L_{Rl} / L_{R2} = 1$ when a stable solution is found.

In order to obtain a back solvable leakage flow equation in the transition zone, lets justify a modification to ANSI N14.5-1987. It seams unreasonable that with a 0.00001% change in the flow diameter results in a 182,600% change in L_R. Lets assume that the transition flow is spread over a 0.1% flow diameter change instead. Therefore, the maximum UnChoked leakage would be at $r_f = 0.9$, $D = 1.61717\times10^{-4}$cm, and $L_a = 1.9233 \times 10^{-7}(cm^3/s)$. Lets assume that the minimum Choked flow is still at $r_f = 1$, $D = 1.79686\times10^{-4}$cm, and $L_u = 5.0739\text{x}10^{-4}(cm^3/s)$. Using a straight line interpolation between these points would yield an answer that was back solvable and more accurate then using the smallest diameter.

Measured test data should be used to justify that r_f=0.9 is were the transition zone begins, and that $r_f = 1$ is were the transition zone ends.

This example problem takes a designer from a known activity of a mixture to be shipped, through the calculations to determine the regulatory requirements for acceptance leakage testing.

Start of Example Problem

A Type-B reusable shipping container will transport a mixture of Uranium Oxide with; a mass of 16,628 grams, total activity of 1.09 Ci, and an A_2 of 0.0866 Ci (see Appendix A) sealed in a laboratory. This container has been analyzed thermally and it will be subjected to a maximum normal temperature of 162°F (100°F with insolation) and a maximum burn test temperature of 530 °F. Determine the leakage test procedure requirements.

Find the maximum pressure in the container

Need to convert temperature,

$T = 273 + T$ °C

$T = 273 + 5 / 9$ (°F-32) °K

for T = 162 °F

$T_N = 273 + 5 / 9$ (162°F-32)°K

$T_N = 345.4$ °K

for T = 530 °F

$T_A = 273 + 5 / 9$ (530 °F-32) °K

$T_A = 549.8$ °K

The Ideal Gas Law rearranged;

$P_1 / T_1 = P_2 / T_2$

$P_2 = P_1(T_2 / T_1)$

Assuming that the laboratory was at 1 atm and 294°K (70 °F) find the increase in container pressure for each condition.

P_N = 1.0(atm) (345.4 °K/294 °K)
P_N = 1.174 atm

P_A = 1.0(atm) (549.8°K /294 °K)
P_A = 1.871 atm

Calculate R_N and R_A; (See Figure 4.1)

The maximum permissible release rate is based on using an A_2 value for a Uranium Oxide Mixture of;

A_2 = 0.0866 (Ci)

The Containment Requirements for Normal Conditions of Transport (NCT);

R_N = $A_2 \times 10^{-6}$ (Ci/hr), From Table 1, ANSI N14.5

R_N = 8.66×10^{-8} (Ci/hr)

The Containment Requirements for Hypothetical Accident Conditions (HAC);

R_A = A_2 (Ci/week), From Table 1, ANSI N14.5

R_A = 0.0866 (Ci/week), or limited to 10,000 Ci/week of Kr85

Following ANSI N14.5-1987 Section 5.3.1, the mixture's activity per unit volume must be calculated to determine the leakage rates. In ANSI N14.5-1987, section B16.31 Example 31, uses Curren's maximum aerosol density, ρ_p, = $9. \times 10^{-6}$, (gm/cm^3). This aerosol density was used to calculate the activity per unit volume of an oxide powered, C (Ci/cm^3) in ANSI N14.5-1987, Section 5.3.1. For this example C_N is equal to C_A, the maximum acitvity per unit volume.

ρ_p, = 9. x 10^{-6} (gm/cm^3), Maximum density of powder aerosols in the fill gas

This density assumes that a maximum amount of radioactive particles are mixed with and carried by the cover gas as it is released. Since the particle mass per cm^3 of gas is set by Curren's maximum aerosol density, the radioactive concentration of the mixture is required. Total Specific Activity (TSA) in Ci/gm of the mixture is the radioactive concentration of the mixture.

m = 16,628 (gm), total nuclide mass in the package available for release

TotA = 1.09 (Ci), total activity in the package available for release

Total Specific Activity (Ci/gm) or radioactive concentration of the floating particles from the mixture, can be calculated by either method. Remember that this is a radioactive concentration based on the specific activity of the mixture and the mass percent, and not the mass total mass.

TSA = Sum of {[Specific activity (C i/gm)] x [Mass %]}, or
TSA = {[Sum of Activity (Ci)] / [Sum of Mass (gm)]}

TSA = TotA / m
TSA = 1.09 (Ci) / 16,628 (gm)
TSA = 6.5552×10^{-5} (Ci/gm)

C_N = activity per unit volume (Ci/cm^3), Normal Conditions of Trasnport

C_N = TSA × ρ_p
C_N = 6.5552×10^{-5} (Ci/gm) × 9. × 10^{-6} (gm/cm^3)
C_N = 5.8997×10^{-10} (Ci/cm^3)

C_A = activity per unit volume (Ci/cm3), Accident Conditions of Transport

C_A = 5.8997×10^{-10} (Ci/cm^3), (for this case $C_A = C_N$)

Section 5.3.2 calculates L_N with (Eq 1), and L_A with (Eq 3) the maximum permissible leakage rate of the fill gas during each condition of transport.

L_N = R_N (Ci/hr) / C_N (Ci/cm^3) / 3600 (s/hr) (ANSI N14.5, Eq 1)
L_N = 8.66×10^{-8} (Ci/hr) / 5.8997×10^{-10} (Ci/cm^3) / 3600 (s/hr)
L_N = 0.04077 (cm^3/sec)

L_A = R_A (Ci/week) / C_A (Ci/cm^3) × 1.65×10^{-6} (week/sec) (ANSI N14.5, Eq 3)
L_A = 0.0866 (Ci/week) / 5.8997×10^{-10}(Ci/cm^3) × 1.65×10^{-6} (week/sec)
L_A = 242.20 (cm^3/sec)

L_N and L_A are both leakage rates that exit the container (L_e) at the exit pressure (P_e). These leakage rates will be used to calculate the standard reference leakage rate (L_R) of air to determine the leak testing criteria.

NORMAL CONDITIONS OF TRANSPORT

The calculation of a maximum permissible leakage rate hole diameter is based on the temperature and pressure of the air fill gas for the Normal Conditions of Transport (NCT). Keeping this calculation conservative the maximum values for temperature and pressure were used as steady state conditions for the NCT. The maximum values were generated by the Insolation calculations.

Input Data for Normal Conditions of Transport

L_N	=	0.04078 (cm^3/sec)	Maximum exit Leakage
P_u	=	1.174(atm),	Upstream Pressure = (17.25 psia)
P_d	=	0.238 (atm),	Downstream pressure = {3.5 psia, per 10 CFR 71.71(3)}
a	=	0.5334 (cm),	Leak path length, [0.210 in. O-ring section diameter]
R_o	=	8.31×10^7 (erg-cm^3 / gmol-°K),	Universal gas Constant

Air Fill Gas

T	=	345.4 (°K),	Fill gas Temperature = (162 °F)
μ	=	0.0209 (cP),	Viscosity at temperature
k	=	1.40,	Ratio of specific heat
r_c	=	0.5283,	Critical pressure ratio for air

The pressure ratio is,

$P_d / P_u =$ 0.238/1.174

$P_d / P_u =$ 0.2027, (NCT) Presure ratio

Flow regime evaluation,

$P_d / P_u \leq r_c$, (NCT) Flow is (UnChoked-Molecular or Choked-Sonic)

The average pressure for UnChoked flow is,

$P_a = (P_u + P_d) / 2 = (1.l74 + 0.238) / 2$

$P_a =$ 0.706 (atm), (NCT) Average Pressure

Since, the flow regime and leakage hole diameter are unknown the mass-like leakage flow rate must be calculated for both UnChoked and Choked flow. Only one of these equation will be valid as specified in the flow matrix.

First the mass-like leakage flow rate must be found,

Q	=	$P_e L_e$	(Eq B1)
L_e	=	L_N	(NCT) exit Leakage

If flow is UnChoked

P_e	=	P_d	UnChoked exit pressure

Q_2 shall be the Mass-like Leakage found for UnChoked flow using the exit leakage L_e at P_e,

Q_2	=	$P_d L_e$	(Eq B1) for UnChoked flow
Q_2	=	(0.238)(atm) (0.04077)(cm³/s)	
Q_2	=	0.0097033 (atm-cm³/s)	(NCT) Mass-like leakage rate (if UnChoked)

Using Q_2, Find the average leakage L_a at P_a, for input into (Eq B2)

Q_2	=	$P_a L_a$,	(Eq B1) for UnChoked flow
L_a	=	Q_2 / P_a = 0.0097033 (atm-cm³/s) / (0.706)(atm)	
L_a	=	0.013744 (cm³/s),	(NCT) Average Leakage Rate (if UnChoked)

L_a seems to be too large for Molecular UnChoked flow, as found in ANSI N14.5-1987, Table B2, but L_a will be checked to show the method.

(If Flow is Molecular) Find the UnChoked Flow Diameter for L_a at (NCT)

Input Data for Normal Conditions of Transport

P_u	=	1.174 (atm),	Upstream Pressure = (17.25 psia)
P_d	=	0.238 (atm),	Downstream Pressure = {3.5 psia, per 10CFR 71.71(3)}
a	=	0.5334 (cm),	Leak path length, [0.210 in. O-ring section diameter]

Air Fill Gas

T	=	345.4 (°K),	Fill gas Temperature = (162 °F)
μ	=	0.0209 (cP),	Viscosity at temperature
r_c	=	0.5283,	Critical pressure ratio for air
P_a	=	0.706 (atm),	(NCT) Average Pressure

Solve equations B2 through B5:

$$L_a = (F_c + F_m) (P_u - P_d) \text{ (cm}^3\text{/s)}, \quad \text{(Eq B2)}$$
$$L_a = (F_c + F_m) (1.174 - 0.238)$$
$$L_a = 0.936 (F_c + F_m) \text{ (cm}^3\text{/s)}$$

$$F_c = (2.49 \times 10^6) D^4 / (a \mu) \text{ (cm}^3\text{/atm-s)} \quad \text{(Eq B3)}$$
$$F_c = (2.49 \times 10^6) D^4 / ((0.5334) (0.0209))$$
$$F_c = (2.2336 \times 10^8) D^4 \text{ (cm}^3\text{/atm-s)}$$

$$F_m = (3.81 \times 10^3) D^3 (T / M)^{.5} / (a P_a) \text{ (cm}^3\text{/atm-s)} \quad \text{(Eq B4)}$$
$$F_m = (3.81 \times 10^3) D^3 (345.4 / 29)^{.5} / ((0.5334) (0.706))$$
$$F_m = (3.4916 \times 10^4) D^3 \text{ (cm}^3\text{/atm-s)}$$

$$r_f = F_c / F_m = (2.2336 \times 10^8) D^4 / (3.4916 \times 10^4) D^3 \quad \text{(Eq B5)}$$
$$r_f = (6.3969 \times 10^3) D$$

From the mass-like leakage calculation,

$$L_a = 0.013744 \text{ (cm}^3\text{/s)}, \quad \text{(NCT) Average Leakage Rate (if UnChoked)}$$

Find the UnChoked leakage hole diameter that sets,

$$L_2 = L_a$$

Using the equations,

$$L_2 = 0.936 (F_c + F_m) \text{ (cm}^3\text{/s)}$$
$$F_c = (2.2336 \times 10^8) D^4 \text{ (cm}^3\text{/atm-s)}$$
$$F_m = (3.4916 \times 10^4) D^3 \text{ (cm}^3\text{/atm-s)}$$

To get a better guess, on a new D use,

$$D = D_2 (L_a / L_2) \wedge .252$$

Now a guess must be made for D_2 to solve Eq B2,

$$D_2 = 0.001$$

Solving for L_a = 0.013744 (cm³/s) (NCT)

Diameter	F_c	F_m	L_2	L_a / L_2
0.001	2.2336×10^{-4}	3.4916×10^{-5}	2.4174×10^{-4}	56.8547
2.7682×10^{-3}	1.3116×10^{-2}	7.4066×10^{-4}	1.2970×10^{-2}	1.05972
2.8090×10^{-3}	1.3906×10^{-2}	7.7390×10^{-4}	1.3741×10^{-2}	1.000253
2.8092×10^{-3}	1.3910×10^{-2}	7.7406×10^{-4}	1.3744×10^{-2}	1

Flow Conductance Ratio

If Flow is UnChoked

$D = 2.8092 \times 10^{-3}$

$r_f = (6.3969 \times 10^{3})\ D$

$r_f = (6.3969 \times 10^{3})\ 2.8092 \times 10^{-3}$

$r_f = 17.97$

Flow regime evaluation,

$P_d / P_u = 0.2027, \quad r_c = 0.5283, \quad r_f = 17.97$

$P_d / P_u \leq r_c$ and $r_f \geq 1$, (NCT) Flow is NOT UnChoked Molecular

(If Flow is Sonic) Find the Choked Flow Diameter for L_u at (NCT)

First the mass-like leakage flow rate must be found,

$Q = P_e L_e$ (Eq B1)

$L_e = L_N$ (NCT) exit Leakage

$P_e = P_u r_c$ Choked exit pressure

Q_7 shall be the Mass-like Leakage found for Choked flow using the exit leakage L_e at P_e,

$Q_7 = P_u r_c L_e$, (Eq B1) for Choked flow

$Q_7 = (1.174)(\text{atm})\ (0.5283)\ (0.04077)(\text{cm}^3/\text{s})$

$Q_7 = 0.025287\ (\text{atm-cm}^3/\text{s})$, (NCT) Mass-like leakage rate (if Choked)

Using Q_7, Find the upstream leakage L_u at P_u, for input into (Eq B7)

$Q_7 = P_u L_u$, For (Eq B7) Choked flow

$L_u = Q_7 / P_u = 0.025287\ (\text{atm-cm}^3/\text{s})\ /\ (1.174)\ (\text{atm})$

$L_u = 0.02154\ (\text{cm}^3/\text{s})$, (NCT) Upstream Leakage Rate (if Choked)

D_7 shall be the hole diameter that satisfies (Eq B7)

$$D_7 = \sqrt{\frac{4\ L_u}{\pi}}\ \left[\frac{2kR_oT_u}{M(k+1)}\right]^{-0.25}\ \left[\frac{2}{k+1}\right]^{-0.5/(k-1)} \quad (cm)$$

Modified (Eq B7)

$$D_7 = \sqrt{\frac{4\ (0.02154)}{\pi}}\ \left[\frac{2\ (1.4)\ (8.31\times10^7)\ (345.4)}{29\ (1.4+1)}\right]^{-0.25}\ \left[\frac{2}{1.4+1}\right]^{-0.5/(1.4-1)}$$

D_7 = 0.0011283 (cm)

Flow Conductance Ratio

$r_f = 654\ D\ P_a\ /(\mu\ \sqrt{(T/M)}\ )$ (Eq B5)

$r_f = 654\ (0.0011283)(0.706)\ /(0.0209\ \sqrt{(345.4/29)}\ )$

r_f = 7.223

Flow regime evaluation,

$P_d\ /\ P_u$ = 0.2027, $r_c = 0.5283$, $r_f = 7.223$

$P_d\ /\ P_u \leq r_c$ and $r_f \geq 1$ (NCT) Flow is Choked Sonic

Therefore,

D = $D_7 = 0.0011283$ (cm)

NCT REFERENCE AIR LEAKAGE RATE

The leakage hole diameter that was found to allow a permissible leak for Normal Conditions of Transport shall be used to determine reference leakage. O-ring seal leakage testing must assure that no leakage is greater than the leakage generated by the hole diameter D = 0.0011283 (cm). Therefore, the normal conditions reference leakage flow rate (L_R) must be calculated to determine the acceptable test leakage rate (L_T).

Input Data for NCT Reference Air Leakage Rate

D	=	0.0011283 (cm),	From the (Choked Flow) Normal Conditions of Transport
P_u	=	1.0 (atm),	Upstream Pressure
P_d	=	0.01 (atm),	Downstream Pressure
T	=	298 (°K),	Fill gas Temperature, (77 °F)
μ	=	0.0185 (cP),	Viscosity at temperature

The pressure ratio is,

P_d / P_u = 0.01 / 1.0

P_d / P_u = 0.01, (NCT$_R$) Pressure ratio

Calculate P_a,

$P_a = (P_u + P_d) / 2 = 0.505$ (atm), (NCT$_R$) Average Pressure

Flow Conductance Ratio,

$$r_f = 654\ D\ P_a / (\mu \sqrt{(T/M)}\ ) \qquad \text{(Eq B5)}$$

$$r_f = 654\ (0.0011283)\ (0.505) / (0.0185 \sqrt{(298/29)}\ )$$

$$r_f = 6.284$$

Flow regime evaluation,

$P_d / P_u = 0.01$, $r_c = 0.5283$, $r_f = 6.284$

$P_d / P_u \leq r_c$ and $r_f \geq 1$, (NCT$_R$) Flow is Choked Sonic

With the diameter and flow regime known, the reference leakage rate can be calculated using Eq B2. The reference leakage rate in (std-cm^3/sec), refers to leak generated by dry air using standard conditions of; T = 298°K, P_u = 1.0 atm, P_d = 0.01 atm.

L_R (std-cm^3/sec) IS ONLY for AIR at; T = 298°K, P_u = 1.0 atm, P_d = 0.01 atm

USE THE REFERENCE CHOKED FLOW LEAKAGE

$$L_R = \frac{\pi D^2}{4} \sqrt{\left[\frac{2kR_oT_R}{M(k+1)}\right] \times \left[\frac{2}{k+1}\right]^{1/(k-1)}} \quad (std \cdot cm^3/s) \qquad \text{(Eq B7)}$$

$$L_R = \frac{\pi(0.0011283)^2}{4} \sqrt{\left[\frac{2\ (1.4)\ (8.31\times 10^7)\ (298)}{29(1.4+1)}\right] \times \left[\frac{2}{1.4+1}\right]^{1/(1.4-1)}}$$

$L_{R,N}$ = 0.020008 (std-cm³/s), (NCT_R) Reference Air Leakage Rate

Hypothetical Accident Conditions of Transport

The calculation of a maximum permissible leakage rate hole diameter is based on the temperature and pressure of the air fill gas for the Hypothetical Accident Conditions (HAC) of transport. Keeping this calculation conservative the maximum values for temperature and pressure were used as steady state conditions for a week. The maximum values were generated during the 30 minute burn test of the HAC.

Input Data for Hypothetical Accident Conditions of Transport

L_A	=	242.20 (cm³/sec),	Maximum exit Leakage
P_u	=	1.871 (atm),	Upstream Pressure = (27.50 psia)
P_d	=	1.0 (atm),	Downstream Pressure
T	=	549.8 (°K),	Fill gas Temperature = (530 °F)
μ	=	0.0285 (cP),	Viscosity at temperature
r_c	=	0.5283,	Air critical pressure ratio

Calculate P_a,

P_a = $(P_u + P_d) / 2 = (1.871 + 1.0) / 2$

P_a = 1.4355 (atm), (HAC) Average Pressure

The pressure ratio is,

P_d / P_u = 1.0 / 1.871

P_d / P_u = 0.5345, (HAC) Presure ratio

Flow regime evaluation,

P_d / P_u = 0.5345, r_c = 0.5283,
$P_d / P_u > r_c$, (HAC) Must be UnChoked (Continuum or Combination)

Q_2 shall be the Mass-like Leakage found for UnChoked flow using the exit leakage L_e at P_e,

$Q_2 = P_d L_e$ (Eq B1) for UnChoked flow
$Q_2 = (1.0)(atm) (242.20)(cm^3/s)$
$Q_2 = 242.20\ (atm\text{-}cm^3/s)$, (HAC) Mass-like leakage rate (UnChoked)

Using Q_2, Find the average leakage L_a at P_a, for input into (Eq B2)

$Q_2 = P_a L_a$ (Eq B1)
$L_a = Q_2 / P_a = 242.20\ (atm\text{-}cm^3/s) / (1.4355)(atm)$
$L_a = 168.72\ (cm^3/s)$, (HAC) Average Leakage Rate (UnChoked)

Find the UnChoked Flow Diameter for L_a at (HAC)

Solve equations B2 through B5:

$L_a = (F_c + F_m) (P_u - P_d) (cm^3/s)$ (Eq B2)
$L_a = (F_c + F_m) (1.871 - 1.0)$
$L_a = 0.871 (F_c + F_m) (cm^3/s)$

$F_c = (2.49 \times 10^6) D^4 / (a \mu) (cm^3/atm\text{-}s)$ (Eq B3)
$F_c = (2.49 \times 10^6) D^4 / ((0.5334) (0.0285))$
$F_c = (1.63795 \times 10^8) D^4 (cm^3/atm\text{-}s)$

$F_m = (3.81 \times 10^3) D^3 (T / M)^{.5} / (a P_a) (cm^3/atm\text{-}s)$ (Eq B4)
$F_m = (3.81 \times 10^3) D^3 (549.8 / 29)^{.5} / ((0.5334) (1.4355))$
$F_m = (2.16657 \times 10^4) D^3 (cm^3/atm\text{-}s)$

$r_f = F_c / F_m = (1.63795 \times 10^8) D^4 / (2.16657 \times 10^4) D^3$ (Eq B5)
$r_f = (7.5601 \times 10^3) D$

From the mass-like leakage calculation,

$L_a = 168.72\ (cm^3/s)$, (HAC) Average Leakage Rate (UnChoked)

We need to find the UnChoked leakage hole diameter that sets

$L_2 = L_a$

Using the equations,

$$L_2 = 0.871\ (F_c + F_m)\ (cm^3/s)$$
$$F_c = (1.63795 \times 10^8)\ D^4\ (cm^3/atm\text{-}s)$$
$$F_m = (2.16657 \times 10^4)\ D^3\ (cm^3/atm\text{-}s)$$

To get a better guess, on a new D use,

$$D = D_2\ (L_a / L_2)\ \hat{}\ .252$$

Now a guess must be made for D_2 to solve Eq B2

$$D_2 = 0.01$$

Solving for L_a = 168.72 (cm^3/s) (HAC)

Diameter	F_c	F_m	L_2	L_a / L_2
0.01	1.63795	0.021666	1.445525	116.719
0.033183	198.5926	0.791625	173.6637	0.97153
0.032942	192.8859	0.774502	168.6782	1.000248
0.032944	192.9328	0.774643	168.7191	1.000005

Flow Conductance Ratio,

If Flow is UnChoked

$$D = 0.032944,$$
$$r_f = (7.5601 \times 10^3)\ D$$
$$r_f = 249.06$$

Flow regime evaluation,

P_d / P_u = 0.5345, $r_c = 0.5283$, $r_f = 249.06$

$P_d / P_u > r_c$ and $r_f \geq 1$, (HAC) Flow is UnChoked Continuum

(HAC) Reference Air Leakage Rate

The leakage hole diameter that was found to allow a permissible leak for the Hypothetical Accident Conditions (HAC) of transport shall be used to determine reference leakage. O-ring seal leakage testing must assure that no leakage is greater than the leakage generated by the hole diameter

D = 0.032944 (cm). Therefore, the Hypothetical Accident conditions reference leakage flow rate (L_R) must be calculated to determine the acceptable test leakage rate (L_T).

Input Data for (HAC) Reference Air Leakage Rate

D	=	0.032944 (cm),	From the Hypothetical Accident Conditions of Transport
P_u	=	1.0 (atm),	Upstream Pressure
P_d	=	0.01 (atm),	Downstream Pressure
T	=	298 (°K),	Fill gas Temperature, (77 °F)
μ	=	0.0185 (cP),	Viscosity at temperature

The pressure ratio is,

P_d / P_u = 0.01 / 1.0

P_d / P_u = 0.01, (HAC$_R$) Presure ratio

Calculate P_a,

P_a = $(P_u + P_d) / 2 = 0.505$ (atm), (HAC$_R$) Average Pressure

Flow Conductance Ratio

$$r_f = 654 \ D \ P_a \ /(\mu \sqrt{(T/M)} \ ) \qquad \text{(Eq B5)}$$

$$r_f = 654 \ (0.032944) \ (0.505) \ /(0.0185 \sqrt{(298/29)} \ )$$

r_f = 183.47

Flow regime evaluation,

P_d / P_u = 0.01, $r_c = 0.5283$, $r_f = 183.47$

$P_d / P_u \leq r_c$ and $r_f \geq 1$, (HAC$_R$) Flow is Choked Sonic

L_R (std-cm^3/sec) IS ONLY for AIR at; T = 298°K, P_u = 1.0 atm, P_d = 0.01 atm

Use the Reference Choked Flow Leakage

$$L_R = \frac{\pi D^2}{4} \sqrt{\left[\frac{2kR_oT_R}{M(k+1)}\right] \times \left[\frac{2}{k+1}\right]^{1/(k-1)}} \quad (std \cdot cm^3/s) \qquad \text{(Eq B7)}$$

$L_{R,A}$ = 17.056 (std-cm^3/s), (HAC$_R$) Reference Air Leakage Rate

$$L_R = \frac{\pi\ (0.032944)^2}{4} \sqrt{\left[\frac{2\ (1.4)\ (8.31 \times 10^7)\ (298)}{29\ (1.4+1)}\right]} \times \left[\frac{2}{1.4+1}\right]^{1/(1.4-1)}$$

Test Procedure Requirements

Maximum permissible release rates and leakage rates were calculated for this example problem following ANSI N14.5-1987. These calculations used the most conservative (worst) known temperatures and pressures for the containment vessel as steady state conditions to calculate the leakage rates.

	Temperature	Pressure
Normal Conditions of Transport	162 °F	17.25 psia
Hypothetical Accident Conditions	530 °F	27.5 psia

The reference air leakage rates are;

Normal Conditions of Transport $L_{R,N} = 0.020008$ (std-cm³/sec)

Hypothetical Accident Conditions $L_{R,A} = 17.056$ (std-cm³/sec)

L_R for ANSI N14.5 Table 5.4 is the smaller value of $L_{R,N}$ or $L_{R,A}$

Reference Air Leakage Rates (std-cm³/sec)	Assembly Testing	Design Testing
$10 \leq L_R$	Not Required	Not Required
$0.1 \leq L_R < 10$	Not Required	Required
$10^{-7} \leq L_R* < 0.1$	Required	Required

L_R (std-cm³/sec) IS ONLY for AIR at; $T = 298°K$, $P_u = 1.0$ atm, $P_d = 0.01$ atm

*When $L_R \leq 10^{-7}$ (std-cm³/sec) the container is considered LEAKTIGHT and $L_R = 10^{-7}$

ASSEMBLY VERIFICATION (6.5) TEST PROCEDURE SESNSITIVITY(R_u or L_u)

Based ONLY on $L_{R,N}$ (std-cm^3/sec)

$R_u \leq 4200\ R_N$ (Ci/hr)
$L_u \leq 4200\ L_{R,N}$ (std-cm^3/sec)
IF $L_u < 10^{-3}$ THEN USE, $L_u = 10^{-3}$ (std-cm^3/sec)
IF $L_u \geq 10^{-1}$ THEN USE, $L_u = 10^{-1}$ (std-cm^3/sec)

NOTE: For this Example, $L_N = 0.04077$ (cm^3/sec) $\neq L_{R,N}$ (std-cm^3/sec)
(see ANSI N14.5, B16.23 example 23)

$L_u \leq 4200\ L_{R,N}$ (std-cm^3/sec)
$L_u = (4200)\ (0.020008)$ (std-cm^3/sec)
$L_u = 84.034$ (std-cm^3/sec)

Since,

$L_u \geq 10^{-1}$ THEN USE, $L_u = 10^{-1}$ (std-cm^3/sec), Assembly Test Procedure Sensitivity (L_u)
$L_u = 10^{-1}$ (std-cm^3/sec)

Allowable Test Leakage Rates and Test Sensitivity (7.1)

Based on $L_{R,N}$ (for Design, Fabrication, and Periodic Verification (NCT))
Based on $L_{R,A}$ (for Post Hypothetical Accident Condition Verification (HAC))

(6.4) Periodic Verification of a reusable Type-B container shall be leak tested within 12-month period before use.

Normal Conditions of Transport $L_{R,N} = 0.020008$ (std-cm^3/sec)
Hypothetical Accident Conditions $L_{R,A} = 17.056$ (std-cm^3/sec)

Leakage Test Sensitivity

$S = L_R / 2$ (ANSI N14.5, Eq B21)

$S_{R,N} = L_{R,N} / 2 = 0.020008 / 2$
$S_{R,N} = 0.01$ (std-cm^3/sec)

$S_{R,A} = L_{R,A} / 2 = 17.056 / 2$
$S_{R,A} = 8.53$ (std-cm^3/sec)

Regulatory Requirements for Acceptance Leakage Testing

Leakage Verification Test (Air)	Allowable Leakage Test Rate L_T (std-cm^3/sec)	Leakage Test Sensitivity S (std-cm^3/sec)
Assembly	0.2	$L_u = 0.1$
Design, Fabrication, and Periodic	$L_T \leq 0.020008$	$S = 0.01$
Post HAC	$L_T \leq 17.056$	$S = 8.53$

Since, the minimum sensitivity of any leakage test is 0.1 the practical application of the leakage rate criteria yields the following.

Leakage Verification Test (Air)	Allowable Leakage Test Rate L_T (std-cm^3/sec)	Leakage Test Sensitivity S (std-cm^3/sec)
Assembly	0.2	$L_u = 0.1$
Design, Fabrication, and Periodic	$L_T \leq 0.02$	$S = 0.01$
Post HAC	$L_T \leq 0.2$	$S = 0.1$

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