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Fabrication Development for High-Level Nuclear Waste Containers for the Tuff Repository

Phase 1 Final Report

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Preface

The container fabrication process development activity (also referred to in text as the Fabrication Project) consists of a multiyear, multiphase project to assess alternatives and to recommend and demonstrate a method for fabrication of disposal containers through production of full-scale prototypes.

This activity is being pursued concurrently with two other process development activities: container closure process development and container closure nondestructive evaluation process development.

This Phase 1 report is a fabrication process assessment; Phase 2 will provide test specimens and sub-scale mockup fabrications with a formal evaluation report and proposed specifications for both a primary and an alternate fabrication process; and Phase 3 will provide a final report and final specification package and several sets of full-scale prototype parts.

The Phase 1 closure process assessment report, "Closure Development for High-Level Nuclear Waste Containers for the Tuff Repository, Phase 1 Final Report," UCRL-15964, is referred to throughout the text as the Closure Development Report; the closure process assessment activity is referred to as the Closure Project.

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List of Acronyms and Abbreviations

AIME	American Institute of Metallurgical Engineers
AISI	American Iron and Steel Institute
AISI 304L	AISI 304L Stainless Steel
AISI 316L	AISI 316L Stainless Steel
Alloy 825	Incoloy 825
ANSI	American National Standards Institute, Inc.
ASM International	American Society for Metals International
ASME	American Society of Mechanical Engineers
ASME BPVC	ASME Boiler & Pressure Vessel Code
ASTM	American Society of Testing and Materials
B&W	Babcock & Wilcox
CDA	Copper Development Association
CDA 102	oxygen-free, high purity copper
CDA 122	phosphorus deoxidized high purity copper
CDA 613	aluminum bronze (7% Al)
CDA 715	70/30 copper-nickel
CDA 801	cast version of oxygen-free copper
CDA 952	cast version of aluminum bronze
CDA 964	cast version of 70/30 copper-nickel
CF3	cast austinic alloy containing ferrite
CF3M	cast austinic alloy containing ferrite
CFR	Code of Federal Regulations
DOE	Department of Energy
HAC	hydrogen-assisted cracking
HAZ	heat-affected zone
HE	hydrogen embrittlement
HIPing	hot isostatic pressing
ID	inside diameter
LH	lower head
LLNL	Lawrence Livermore National Laboratory
LU	lower unit
MT&C	Materials Testing and Characterization
NDE	nondestructive evaluation
NPD	Nuclear Power Division (of B&W)
NRBM	normalized rating for base metal
NRC	Nuclear Regulatory Commission
NRWM	normalized rating for weld metal
OCRWM	Office of Civilian Radioactive Waste Management
OD	outside diameter
OFC	oxygen-free copper
QA	quality assurance
R&D	research and development
RDD	Research and Development Division (of B&W)
SCC	stress corrosion cracking
SGN	Society Generale pour les Techniques Nouvelles (French waste management company)
SKB	Svensk Karnbranslesakerhet AB (Swedish nuclear fuel and waste management company)
TWI	The Welding Institute (in England)
UH	upper head
UT	ultrasonics
YMP	Yucca Mountain Project

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Key Words: High-Level Nuclear Waste Containers, Fabrication Development, Tuff Repository, Austenitic Stainless Steels, Copper, Copper-Base Alloys, Process Selection Criteria, Performance Requirements, Fabrication Requirements

Abstract

This final report completes Phase 1 of an engineering study of potential manufacturing processes for the fabrication of containers for the long-term storage of nuclear waste. Work was conducted under U.S. Department of Energy (DOE) Contract 9172105, administered through the Lawrence Livermore National Laboratory (LLNL), as part of the Yucca Mountain Project (YMP), funded through the DOE Office of Civilian Radioactive Waste Management (OCRWM). An extensive literature and industry review was conducted to identify and characterize various processes. A technical specification was prepared using the American Society of Mechanical Engineers Boiler & Pressure Vessel Code (ASME BPVC) to develop the requirements. A complex weighting and evaluation system was devised as a preliminary method to assess the processes. The system takes into account the likelihood and severity of each possible failure mechanism in service and the effects of various processes on the microstructural features. It is concluded that an integral, seamless lower unit of the container made by back extrusion has potential performance advantages but is also very high in cost. A welded construction offers lower cost and may be adequate for the application. Recommendations are made for the processes to be further evaluated in the next phase when mock-up trials will be conducted to address key concerns with various processes and materials before selecting a primary manufacturing process.

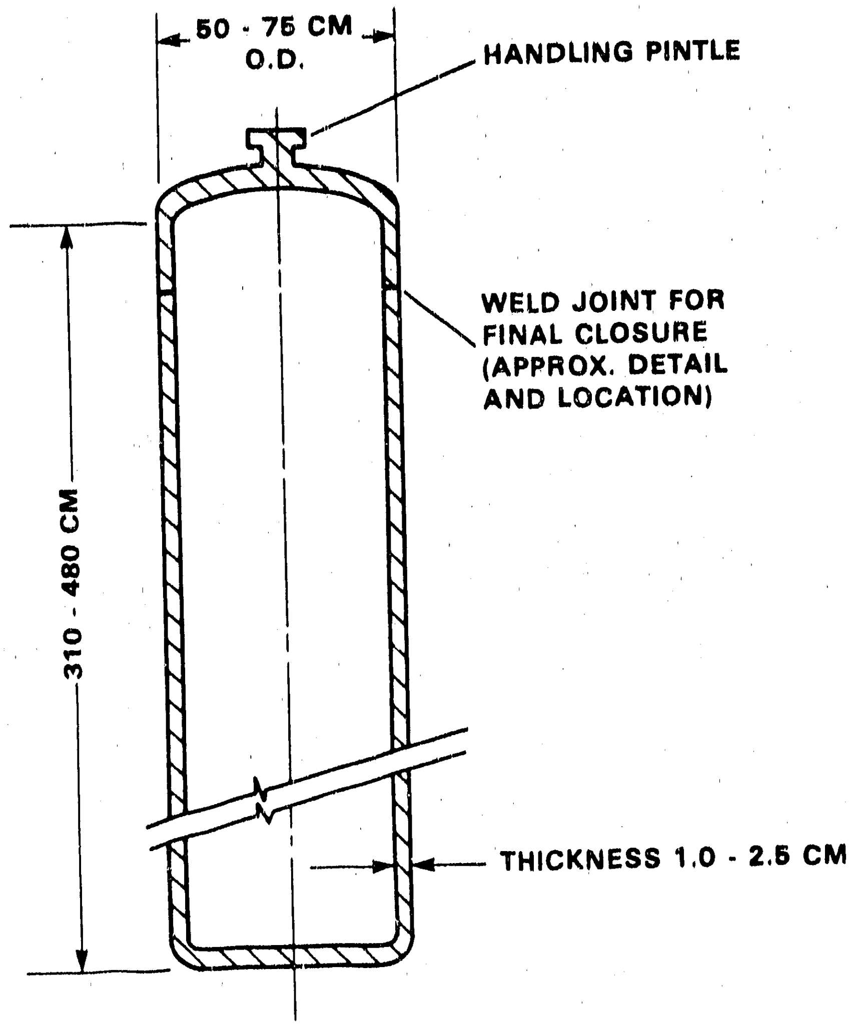
1. Introduction

The U.S. Congress and the President have identified Yucca Mountain, Nevada as the site for consideration for the first U.S. high-level nuclear waste repository. Lawrence Livermore National Laboratory (LLNL), as part of the Yucca Mountain Project (YMP), has the responsibility for designing and developing the waste package for the permanent storage of high-level nuclear waste. To develop a design for the package, LLNL has activities underway in several interrelated areas: the package environment; the selection and testing of the container structural materials; the container design, fabrication, closure after filling, and inspection of the closure area; and the testing and analysis of the package performance under expected repository conditions. All of these projects are currently in the preliminary, conceptual design and development stage. Babcock & Wilcox (B&W) is involved with the YMP as a subcontractor to LLNL. B&W's role is to recommend and demonstrate a method for fabricating the metallic waste container and for performing the final closure of the container after filling it with waste.

At this stage, LLNL contemplates that the container will be a single-wall, corrosion-resistant metal cylinder similar to that shown in Figure 1-1. Candidate materials, currently being evaluated by LLNL's Materials Testing & Characterization (MT&C) technical area are the six shown in Table 1-1. Projected production requirements are shown in Table 1-2. The metallic containment barrier is the primary waste container structural member and is intended to provide substantially complete containment for the nuclear waste for 300 to 1000 years after emplacement in the repository. The waste package is being designed to meet 10 CFR Part 60 (1983) and derivative requirements (O'Neal et al., 1983). The final engineered barrier system design may be composed of a waste form, metallic container, borehole liner, and near-field host rock, or some combination of these components.

The contract is being administered in three phases. Presented herein is the final report for all activities related to recommending fabrication technology in Phase 1. The objective of the Phase 1 activities was to perform an engineering study to assess various alternatives and recommend fabrication processes for the containers. Full-scale production of the containers is not anticipated to begin until 1998.

This report consists of an executive summary (Section 2), an outline of the technical approach to the program (Section 3), a description of the major project activities (Section 4), and a summary of the results and recommendations (Section 5). Quality assurance information (Section 6), a list of references (Section 7), and a bibliography (Section 8) are also provided.



NOTES

1. WALL THICKNESS UNIFORMITY: ± .3 CM
2. CONCENTRICITY OF CONTAINER OD: ± .6 CM AND CONSISTENT WITH CLOSURE JOINT FIT-UP
3. SURFACE FINISH. TYPICAL COLD ROLLED

Figure 1-1. Conceptual layout of nuclear waste container

Table 1-1. Candidate container materials

Common Alloy Name	Common Industry Designation	Unified Numbering System Designation
304L Stainless Steel	AISI 304L	S30403
316L Stainless Steel	AISI 316L	S31603
Incoloy 825	Alloy 825	NO8825
Aluminum Bronze	CDA 613	C61300
70/30 Copper-Nickel	CDA 715	C71500
Oxygen-Free Copper	CDA 122	C12200

Table 1-2. Projected production requirements for containers

Year of Receipt	Containers Annual	Containers Cumulative
1998	150	150
1999	150	300
2000	150	450
2001	350	800
2002	650	1,450
2003	1500	2,950
2004	1500	4,450
2005	1500	5,950
2006	1500	7,450
2007	1500	8,950
2008	1500	10,450
2009	1500	11,950
2010	1500	13,450
2011	1500	14,950
2012	1500	16,450
2013	1500	17,950
2014	1500	19,450
2015	1500	20,950
2016	1500	22,450
2017	1500	23,950
2018	1500	25,450
2019	1500	26,950
2020	1500	28,450
2021	1500	29,950
2022	400	30,350

2. Executive Summary

As part of the U.S. Department of Energy's (DOE) Yucca Mountain Project (YMP), the Lawrence Livermore National Laboratory (LLNL) has the responsibility for designing and developing the package in which to permanently store high-level nuclear waste in the tuff repository site at Yucca Mountain, Nevada. LLNL engaged Babcock & Wilcox (B&W) as a subcontractor to develop the technology for fabricating the waste container and for permanently closing the container after it is filled. Presented herein is the final report for all activities related to fabrication processes in Phase 1 of this contract. Closure activities are addressed in the Closure Development Report.

A three-phase program is being conducted to identify, assess, and demonstrate the optimum manufacturing method for containers, consistent with the performance requirements for Yucca Mountain. The specific purpose of Phase 1 was to conduct an engineering study to assess various alternatives and manufacturing processes, to identify gaps in fabrication technology that need to be examined, and to rank candidate processes with respect to their ability to meet the application requirements. Plans for Phase 2 involve vendor trials to produce mock-ups from the candidate materials by various processes so that both a primary and an alternate manufacturing method can be selected. Prototypes at full scale would then be made in Phase 3 via the primary process for the final material selected by LLNL. Full-scale production of containers is not anticipated to begin until 1998.

Phase 1 was a 6-month study to define the performance requirements and the evaluation criteria, survey the state of the art by a literature and vendor survey, identify candidate manufacturing processes, and then rank those processes according to the criteria.

As B&W began to collect information on the performance requirements from LLNL and DOE, it became evident, because of the preliminary nature of the project, that these requirements were not fully defined. Therefore, it was necessary for B&W to make several assumptions. B&W assumed use of the American Society of Mechanical Engineers Boiler & Pressure Vessel Code (ASME BPVC), Section VIII, "Pressure Vessels," Division 1 (Lethal), to develop a technical specification for fabrication. B&W believes that use of this code, which is well-accepted both legally and by industry, will hasten Nucelar Regulatory Commission (NRC) licensing and public approval. Furthermore, it is believed that, although the code is technically very conservative being that the container is not a pressure vessel, it is more efficient to use an existing standard than to create a new one. B&W also assumed a container geometry, and prepared a drawing that included requirements for surface finish, inspection, and applicable codes.

The state-of-the-art survey included an extensive literature search with over 200 references, which are listed in the bibliography (Section 8). Particular emphasis was placed on the possible effects of various fabrication processes that could possibly influence performance or quality for each of the six candidate alloys (Table 1-1). Forming limitations for each of the alloys were also reviewed. The Copper Development Association (CDA) was used as a consultant to B&W for copper-base materials; they provided access to their data base for the literature search and a report dealing with the possible effects of fabrication processes on the corrosion of copper. The CDA also prepared for B&W several other reports that listed and described potential vendors for the fabrication of copper materials.

B&W visited several European sites to review relevant activities in nuclear-waste container fabrication and closure. A visit was made to The Welding Institute in England (TWI), where research is being conducted on the welding of copper for the Swedish nuclear fuel and waste management company (SKB). SKB has the overall responsibility for Swedish nuclear waste management, and B&W engaged them as a consultant in the project. A visit was also made to three sites in France with personnel from the French waste management program (SGN). These sites included their operating plants for processing and vitrification of nuclear wastes. The French have fabricated over 1000 stainless-steel canisters for the short-term storage of waste.

To identify and characterize the candidate manufacturing processes, B&W conducted seve~al vendor surveys. A general survey was sent out to seek information on vendors' capabilities to make various sizes and geometries of container components using various alloys, and to obtain an expression of interest in the product. A survey of capabilities in spinning and deep drawing was also made since this method of forming seemed like a good way to fabricate the end heads. A heat treating survey was conducted because it was anticipated that the size of the container might be a problem for existing vacuum or atmosphere furnaces. In addition to these surveys, two units of B&W (Nuclear Equipment Division, and McDermott's CCC International Trading Company), who routinely purchase commercial products similar to the container, solicited budgetary quotations for container components. They also contacted various fabrication shops for an expression of interest. Another inquiry package (with B&W's drawing and technical specification) was sent to various vendors requesting quotations for full-size containers in quantities of 1, 5, and 1500 for mock-up, prototype, and production, respectively. Although many vendors did respond to the surveys above, response was generally very slow. To accelerate matters, B&W identified "key vendors" representing various processing technologies, and began a dialogue to obtain more specific quotes and information in a shorter time.

As previously stated, the performance requirements for the container have not yet been fully defined. Therefore, defining an evaluation system to rank the candidate processes was a difficult task. A simple weighting and criteria approach did not seem practical because of the large number of interrelationships between processing effects on each material and the possible failure or degradation mechanisms in service. Because of this, the system that B&W devised is somewhat complex. However, it is intended as a preliminary approach to organizing and quantifying a complicated problem. B&W believes that it will require continuing refinement as the application requirements are better defined.

B&W's evaluation system uses three primary evaluation criteria to judge each process:

1. Performance—how the proposed fabrication method affects performance. The primary concern for long-term storage is nonuniform corrosion.
2. Fabricability—the consistency and reliability of the process in making a good product in terms of dimensions, surface finish, etc.
3. Cost—estimated comparative unit costs at full production quantities. The report presents cost ratings on a relative basis, representing only budgetary estimates.

The performance criteria consist mainly of the effects of each process on microstructural features. The quantity of weld metal has a very large impact on this rating, so a process that makes an integral, seamless container receives very high marks relative to a rolled and welded container. The weighting factors for performance were developed from LLNL's list of 14 possible failure or degradation mechanisms (described in Section 4). Each criterion was related to the failure mechanisms by using the product of the probability of occurrence and the severity of a failure or degradation.

As a result of the activities described previously, many conceivable manufacturing processes were identified by which to fabricate the container. Several processes, such as static sand casting, were excluded from further evaluation in early reviews because of perceived problems with reliability and quality. The processes remaining for the lower unit of the container fell into three general categories: (1) integral, a seamless one-piece forging made by back extrusion or deep drawing, and possibly followed by cold work; (2) welded lower unit with the pipe body made by roll and weld, deep drawing, extrusion, or centrifugal casting, then girth welded to a wrought or cast head; and (3) those processes in (2) that would subsequently involve cold working and annealing to break up the weld microstructure.

Each of these processes was then assessed via the evaluation system described above. Figure 2-1 summarizes the rankings for all three criteria and each process for AISI 304L stainless steel (AISI 304L). In terms of performance, the integral lower unit is the most desirable, and the rolled and welded unit that is not subsequently recrystallized is the least desirable. However, the integral unit is about three times as expensive. Some processes may rate lower in performance, but still meet minimum acceptability standards (to be determined). If the cost of these processes is lower, they may be preferred. The rankings were combined using a vector sum to give a single overall grade.

B&W believes that since the YMP is in the preliminary stages of defining performance requirements, design, material selection, etc., several options should be kept open in Phase 2 for the selection of manufacturing processes. Therefore, B&W is recommending that those processes shown in Table 2-1 be evaluated via mock-up trials in Phase 2. Note that the recommendations do not call for all processes to be used with all six materials. Rather, it is suggested that only key issues be addressed for each process. At the same time, the evaluation system could be further refined to select the optimum process and cost for the application.

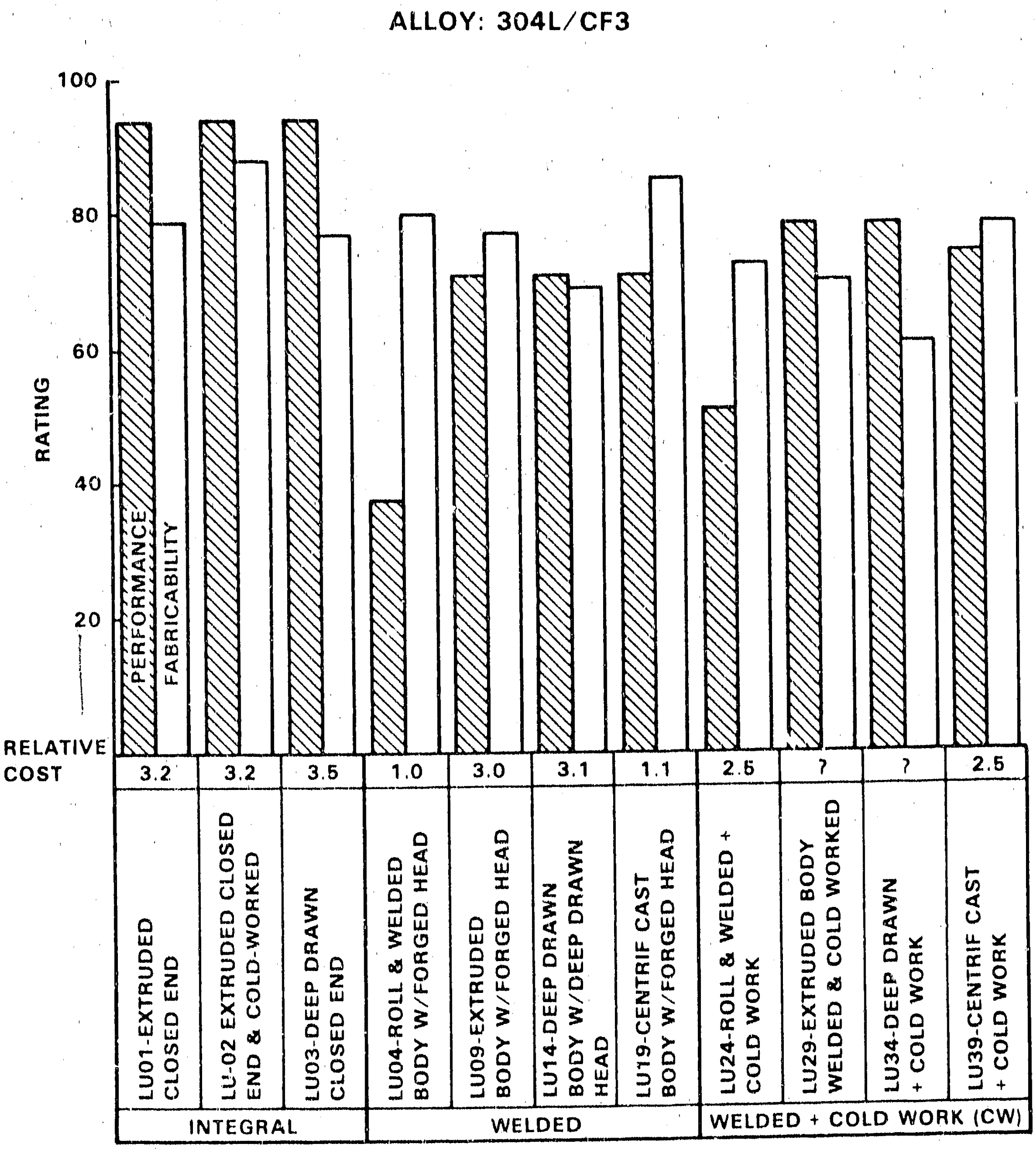


Figure 2-1. Lower unit performance and fabricability ratings and relative costs for AISI 304L/CF3

Table 2-1. Fabrication processes for the lower unit recommended for testing

Process No.	Description	No. of Pieces	Approximate Size, in. OD	Wall	Length	Material 304L	316L	IN 825	CDA 122	CDA 613	CDA 715	Remarks	Key Process Concerns/Issues
	FIRST MOCK-UPS												
1A	Roll and Weld	1 ea.	24	.4	60			x		x	x	No need to evaluate 304L and 316L; technology is proven. No vendor bids for CDA 122.	Consistency o[illegible] microstructure, weld ductility, [illegible] treatment response. Evaluate cold work [illegible] anneal of welds
1B	For Spin Form Trial												
	Preform	1	26	1.25	60						x		
	Finished		24.5	.4	120								
2A	Centrifugal Casting	1 ea.	26	1.25	20					x	x	304L proven with EG&G trials also applies to 316L. No specification for IN 825. No vendor for CDA 122.	Evaluate porosity, pitting, shrinkage, grainsize and UT. Evaluate cold work and anneal of welds and UT.
2B	For Spin Form Trial												
	Preform	1 ea.	26	1.25	40					x	x		
	Finished		24.5	.4	120								
3	Deep Drawing	1 ea.	<12	.4	<12		x	x	x			316L more difficult to draw than 304L. No experience with IN 825. CDA 122 requires thicker stock. Confirm process feasibility	Property, grain size and residual variation at the bottom and corner. Adequacy of hot worked microstructure and properties of closed end. Homogeneity and ovality. Effect on end/wall transition. Homogeneity of properties.
4A	Hot Back Extrusion	1	26	1.25	60			x					
4B	For Spin Form Trial												
	Preform	1	26	1.25	60			x					
	Finished		24.5	.4	120								
	SECOND MOCK-UPS												
5	Roll and Weld											Near prototypical size and configuration. Refine cost study.	Differences between heads. Effect heat treatment on weld, distortion an[illegible] residual stress.
5A	With Spun Head	1	24	.4	144			x					
5B	With Machined Head for Heat Treatment Study.	1	24	.4	144			x					
6A	Back Extrusion & Roll Form.	1	24.5	.4	120			x				Refine cost study.	uniformity of heat treatment, distortion an[illegible] residual stresses.
6B	Back Extrusion & Roll Form for Heat Treatment Study.	1	24.5	.4	120			x					

3. Technical Approach

3.1. Objective

The overall goal of the fabrication project is to identify and demonstrate the optimum manufacturing process for container fabrication consistent with the functional and performance requirements of the application. The solution is complex because the manufacturing method affects the characteristics and properties of the material being produced. These effects must be understood and integrated into the overall program to achieve a material and manufacturing method selection that meets the design requirements and performs satisfactorily for many hundreds of years. Processes and evaluations should be technically conservative to ensure safety and long-term performance.

In this regard, fabrication cost should not impose sacrifices in construction methodology. This statement does not mean to imply that cost is not a concern, only that it is not the top priority.

An ancillary objective of the fabrication project is to provide input to other facets of the waste package development impacted by the fabrication process such as material selection, container design, and closure activities.

3.2. Overview of Technical Plan

As requested by LLNL, the total program has been divided into 3 phases. The specific objective and approach for each phase are shown in Table 3-1. Phase 1 is a paper study to identify candidate processes and rank them relative to the application requirements. In Phase 2, sub-scale mock-ups of the container will be made by several of the leading processes. The mock-ups will help gather information on limitations for some of the candidate materials and aid in narrowing down the candidate processes. For Phase 3, up to 5 full-scale prototypes will be made in one material to demonstrate the preferred procedure.

Figure 3-1 shows the major technical tasks planned for each of the three phases. The plans are described below to highlight key activities. As the work progresses, the plans are expected to be modified as necessary.

3.2.1. Phase 1—Fabrication Process Assessment

Phase 1 was primarily an engineering study to identify and assess candidate fabrication methods. An important initial activity was to establish performance requirements for the application by outlining material, design, functional, and regulatory requirements. B&W expected that most of this information would be available from LLNL to help establish and prioritize the criteria for ranking the various processes. LLNL's initial Invitation for Proposal identified some of the criteria shown in Table 3-2. LLNL instructed that preference be given to established commercial processes that are reasonably well-developed and in common use. It is judged that these will offer the greatest reliability, and will also minimize the need for subsequent development work to establish a production capability.

The evaluation criteria are obviously very important in assuring that the process fits the functional requirements of the design. For example, if a seamless integral body and lower head are deemed important to eliminate a weld joint (and, thus, minimize the chance for localized corrosion), then obviously a welded construction would receive a lower ranking. On the other hand, a welded assembly might offer significant advantages in cost, simplicity, use of standardized components, and be technically well-understood.

Table 3-1. Overview of technical plan

PHASE	TITLE	OBJECTIVE	APPROACH	DELIVERABLES	TERM (MONTHS)
1	Fabrication Process Assessment	Identify and assess candidate processes	- Rank processes based on criteria to meet functional requirements	- Report	6
2	Fabricability Evaluations	Fabricate and test sub-scale sized mock-ups	- Make mock-ups - Test to confirm validity of processing - Narrow candidate processes and produce mock-up of 1 material by 2 processes	- Test specimens - Mock-up remains - Fabrication tooling - Report	24
3	Production of Prototype Containers	Produce full-sized prototypes	- Make prototypes for delivery to LLNL - Make 1 prototype for testing	- Test specimens - Prototype sets - Specification & drawings - Fabrication tooling - Report	13

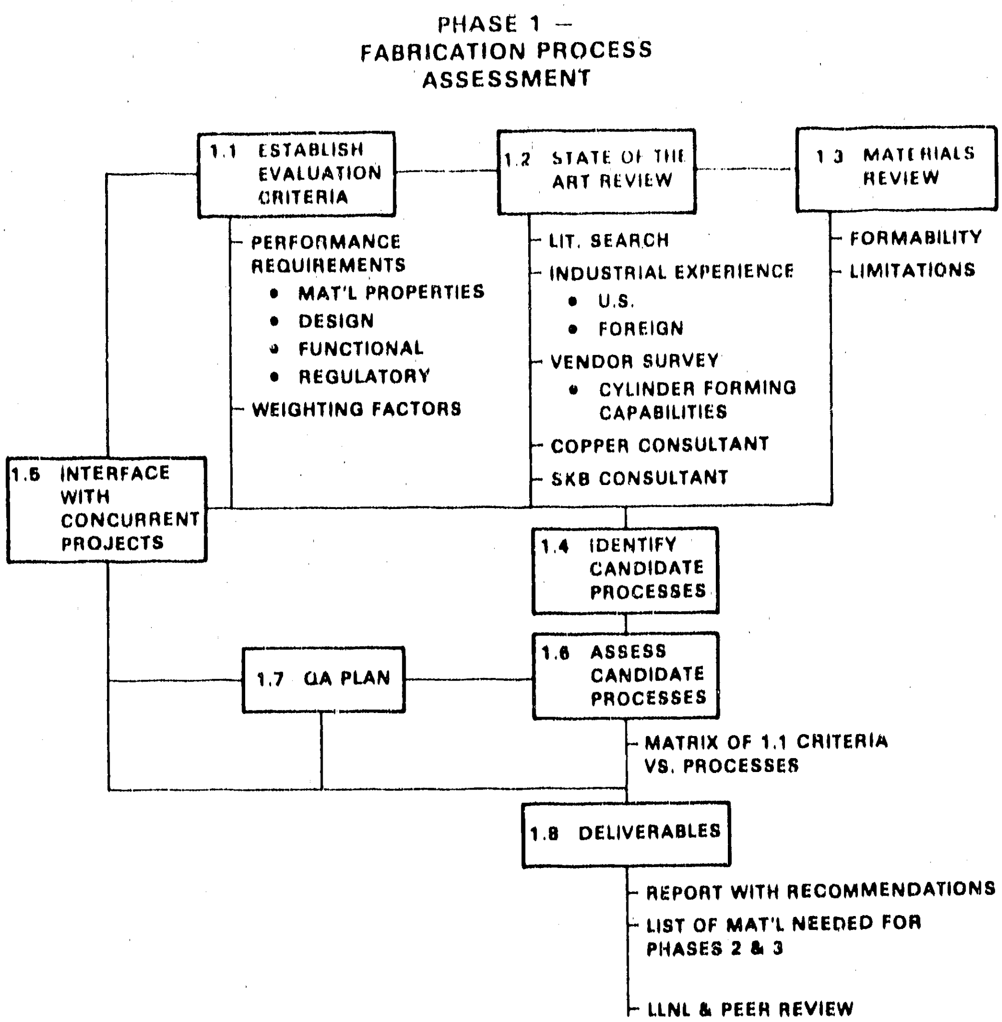


Figure 3-1. Schematic of major technical tasks

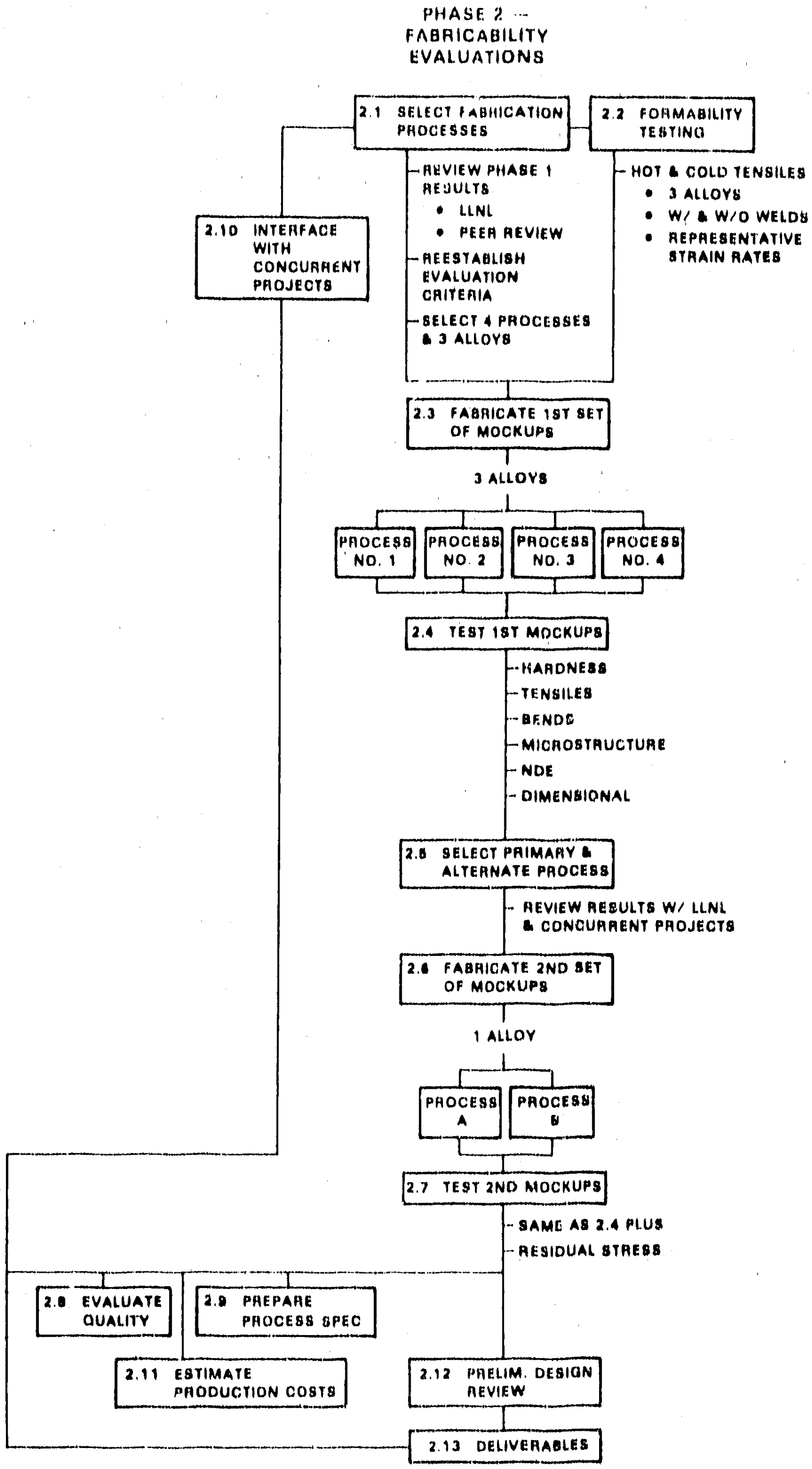


Figure 3-1. Schematic of major technical tasks (cont'd)

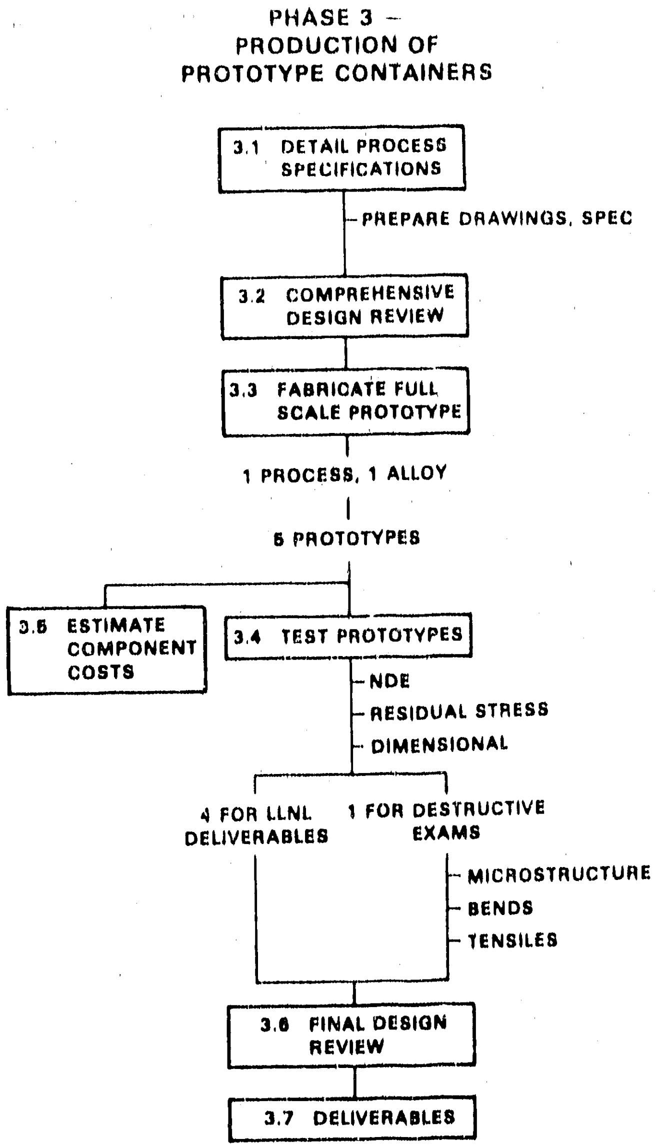


Figure 3-1. Schematic of major technical tasks (cont'd)

Table 3-2. Preliminary listing of evaluation criteria for ranking candidate fabrication processes

1. The process is an established commercial one in common use.
2. The number of joints is minimized.
3. The process is simple.
4. The process is insensitive to the presence of microstructural discontinuities (such as pores, bonding, inclusions, and segregation).
5. The process produces high structural integrity and soundness.
6. There are no requirements for tight control over material composition or thermomechanical parameters.
7. The process is not confined to a single fabrication source, vendor, or facility.
8. Annual production capacity is sufficient to meet projected requirements.
9. The process is cost-effective.
10. The process can be used for all candidate alloys.
11. The process has proven reliability.
12. The process is flexible in producing alternate configurations.
13. The process produces acceptable mechanical properties.
14. The process produces optimal metallurgical structure homogeneously throughout for long-term performance.
15. The process is conducive to state-of-the-art inspection and flaw detection capabilities.
16. Standardized components can be used.

An extensive state-of-the-art review was planned. B&W recognized that many projects involving nuclear-waste storage have been conducted in the last 5 to 10 years. Because there were two other repository projects in competition with the YMP when Phase 1 began, container fabrication was not a new subject. B&W also realized that foreign experience was available, especially in France. The French currently operate waste processing facilities, and have made and used hundreds of smaller-sized canisters. B&W will use the Swedish nuclear fuel and waste management company (SKB) as a consultant on copper alloys and forming because of their experience in the Swedish program. Also, consultants from the Copper Development Association (CDA) will complement the activities related to copper materials.

Although B&W was informed about the capabilities of many vendors, a vendor survey was planned to identify processes and to seek specific capabilities with regard to processes, size limitations, material restrictions, production costs, etc. The intent was to consider all reasonable processes or combinations. The literature was surveyed to investigate workability data for the six candidate alloys, and to elucidate how the alloys might be affected by various types of processing.

From these initial tasks, the proper background information was gathered for a comprehensive list of possible fabrication approaches. The approaches were then evaluated relative to the criteria to obtain a numerical ranking.

3.2.2. Phase 2—Fabricability Evaluations

Fabrication trials will be conducted to produce sub-scale containers for several high-ranked processes from Phase 1. Evaluations will address process feasibility, limitations, and effects of processing on materials. The more difficult or challenging aspects of producing container parts will be emphasized. The size of the sub-scale mock-ups will depend upon readily available materials and tooling, but every effort will be made to assure relevance to the full-size container.

B&W anticipates that there will be a first series of mock-ups with perhaps four processes and three materials. Instead of fabricating using every candidate alloy, B&W will select the materials to represent three classes of alloys shown in Table 1-1: (1) iron nickel alloy (AISI 304L, AISI 316L, Alloy 825), (2) copper-nickel alloy (CDA 715), and (3) copper (CDA 613, CDA 122). B&W would expect to work closely with LLNL's MT&C technical area to select these alloys and to provide input on fabricability limitations.

From the first series of mock-ups, two processes (primary and alternate) will emerge as most promising relative to the evaluation criteria. A second set of mock-ups will be made by these processes. By this time, the final material selection will have been made, so the second set of mock-ups will be made with only one material. Proposed process specifications will be documented and production costs estimated for both the preferred and the alternate processes.

B&W's approach regarding testing will be to perform only limited, routine testing (e.g., hardness, tensile strength, bend strength, dimensional checks, microstructural characterization, and nondestructive evaluation), with emphasis on nonuniform areas (e.g., welds, bends). B&W will not perform corrosion or fracture mechanics testing because this work is being performed by the MT&C technical area.

3.2.3. Phase 3—Production of Prototype Containers

After preview of the Phase 2 results for all the other concurrent activities, such as closure, nondestructive evaluation (NDE), and metal selection, detailed fabrication process specifications and drawings will be prepared. A comprehensive design review involving LLNL and independents will be conducted prior to the fabrication of the prototypes. Up to five full-sized container sets (upper and lower units) will be produced—one for characterization testing by B&W and the remainder for delivery to LLNL.

3.3. Fabrication Approaches

For discussion purposes, one could divide the container into four main components (Figure 3-2). A minimum of two pieces is possible if the upper and lower units are each made integrally, or a maximum of four pieces is possible if each component is made separately.

Figure 3-3 shows some conceivable approaches for fabricating the container components, depending on whether they are made integrally or separately. If an integral lower unit (with no weld joint) is of prime importance in the application, due to potentially higher reliability, then a variety of potential processes exist. As Figure 3-3 shows, these units could be used as-formed, or preforms could be made that could subsequently be hot or cold worked. Some of these processes may have significant cost and size limitations, but they are provided to include complete information. Once the performance specification and process evaluation criteria are established, the number of processes can be narrowed considerably.

One method to produce the lower unit is to fabricate a welded assembly. Several options within this method are also shown in Figure 3-3 in the "separate" approach. The body could be made by using rolled and welded plate, seamless extruded pipe, or centrifugal casting. The body could be welded to the lower head, which could be made from flat plate or a forging (depending on the design configuration). There are many processes available to make these welds. The welded assembly could then be used as is, or it could be further cold worked and annealed to modify the weld metal microstructure. Many process variations are possible, even with a welded fabrication.

This section illustrated the variety of fabrication methods that are available. Specific processes are described in more detail in Section 4.

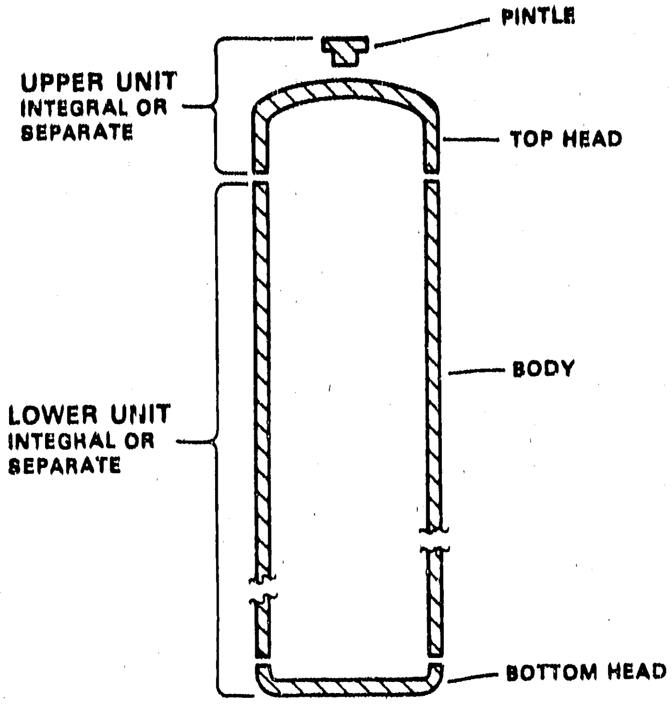


Figure 3-2. Possible container components

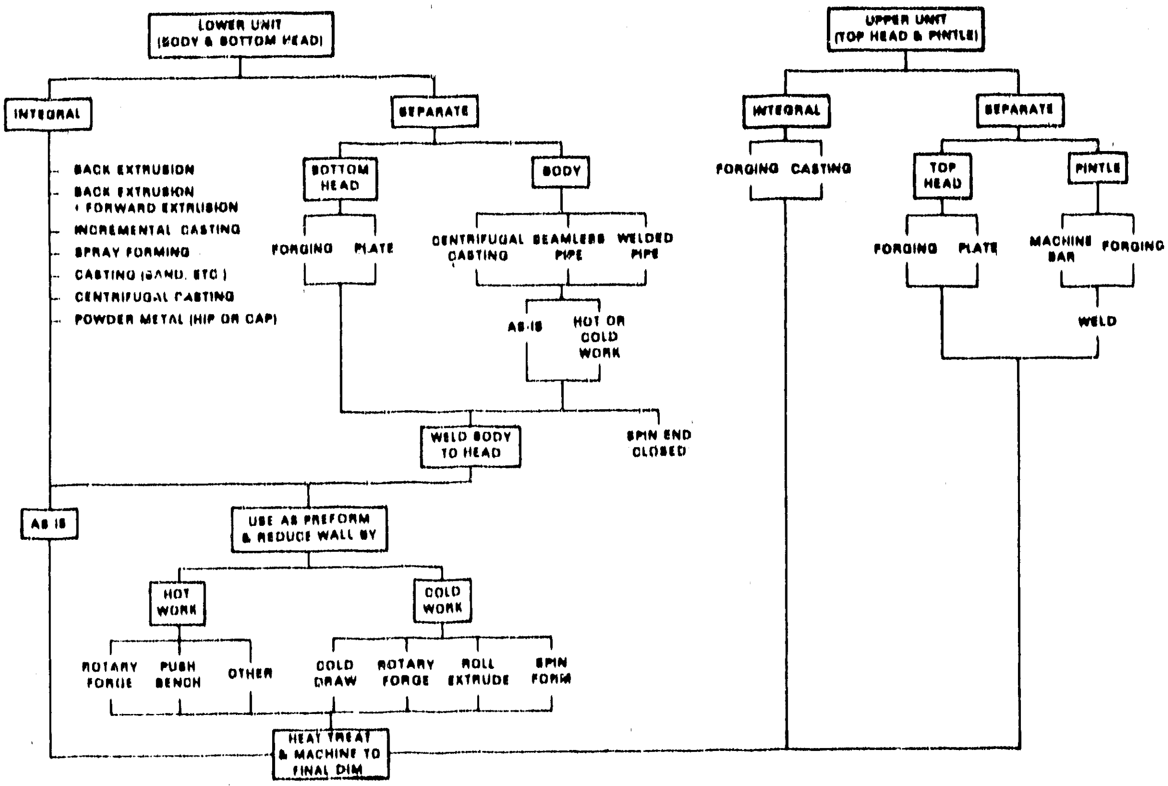


Figure 3-3. Fabrication approaches

4. Major Project Activities

This section describes the activities and the results of the major tasks in the project:

4.1. Performance Requirements

4.1.1. Regulatory Requirements

The 10 CFR Part 60 (1983) requires that the container satisfy the application needs in terms of performance requirements, environmental factors, and closure constraints. Table 4-1 shows design requirements that LLNL has derived from this regulation, other applicable regulations, and waste management system requirements.

Table 4-1. Key LLNL design requirements (O'Neal et al., 1983) derived from 10 CFR Part 60, other applicable regulations, and waste management system requirements

Waste packages shall be designed to:

1. Contain the waste for 300 to 1000 years.[a,b]
2. Maintain a release rate of less than 10^{-5} per year of radionuclide inventory present at the end of the containment period (300 years minimum).[b]
3. Be retrievable for 50 years after the emplacement of the first waste package.[a]
4. Meet nuclear criticality standards, i.e., not exceed an effective multiplication factor (K_{eff}) of 0.95.
5. Not exceed temperature limits of the waste forms, which are 773K (500°C) for defense high-level waste glass, 673K (400°C) for commercial high-level waste glass, and 623K (350°C) for spent fuel cladding.
6. Retain legible, externally labeled identification up to and including the time of retrieval.
7. Meet requirements for cost-effectiveness, including direct package costs and related repository system costs through the operational period.[a]

(a) These requirements determine or affect the selection of containment barrier metal.

(b) Interactions of waste package materials and hole-liner materials must not significantly increase the release rate of the waste forms or the corrosion rate of the containment barriers.

Vagueness in several terms used in the regulations has caused some confusion in defining specific requirements (e.g., the exact meaning of the phrases "substantially complete containment" or "anticipated processes and events"). As a result, specific container requirements are not yet defined, thus making it very difficult to establish evaluation criteria to rank candidate manufacturing processes. B&W's approach to this problem was to assume that the ASME BPVC would be used as the basis for fabrication requirements. Although the use of this code is extremely conservative, B&W felt that it would be more efficient and effective to use an existing code specification that was well understood and accepted. The use of the ASME BPVC for this Phase I effort does not mean that it will be used as a specification for the procurement of production of nuclear-waste containers. It is used here simply because it facilitates comparison of fabrication processes on a common widely understood basis.

The final specification for production of nuclear-waste containers may or may not contain elements of the ASME BPVC.

4.1.2. Codes and Standards for Use in Evaluating Container Fabrication Processes

At the present time, there are no specific codes and standards available for the fabrication of long-term nuclear-waste storage containers. The most frequently used code within the nuclear industry is the ASME BPVC for the design and fabrication of pressure boundary components and appurtenances. The code's Section III, "Nuclear Power Plant Components," or Section VIII, "Pressure Vessels," could be used for these purposes.

Within Section VIII, "Pressure Vessels," Division 1, (1986 Edition) are rules for the fabrication of containers for lethal substances and this appears to be the most appropriate. This was selected as the guide to use in evaluating fabrication processes for these containers because it provides adequate safeguards and proven rules for the fabrication of containers. Although the internal pressure for the containers is expected to be small, the use of a code intended for pressure vessels will provide conservative rules for material specifications and fabrication. B&W gained experience with this code in the fabrication of the Three Mile Island Unit 2 defueling canisters.

Adherence to the ASME BPVC requires that materials used for construction meet the requirements of Section II, "Material Specifications," and be included within the appropriate application section, in this case, Section VIII, Division 1. With these rules it is not possible to use aluminum bronze (CDA 613), one of the candidate alloys, because it is not covered by Section VIII. In other instances, there are no existing specifications for some of the product forms that could be used in fabrication (e.g., Alloy 825 forgings). Table 4-2 shows the material specifications for various product forms that could be used if the ASME BPVC rules are relaxed. These are to be used for interim specifications for making mock-ups. Table 4-3 shows the compositions and specifications for each of the candidate materials.

A draft specification was prepared to solicit budgetary bids for the fabrication of container mock-ups and prototypes.

4.1.3. Assumptions

Assumptions include a container configuration and other interface issues.

4.1.3.1. Container Drawing

Since a detailed drawing of the container had not been provided, B&W prepared the drawing (No. 1167652D-0) shown in Figure 4-1 for discussion with vendors, quotation requests, etc. Various assumptions are provided in this drawing, and it is subject to many revisions. The "reference" top and bottom designs are from the LLNL sketches. The "alternate" designs are suggestions from B&W.

4.1.3.2. Interface Assumptions

The following list contains assumptions that B&W used in the Phase 1 activities:

1. The spent-fuel waste container configuration and size will be as shown in Figure 4-1, using the reference designs for the top and bottom. The fabrication methods should also be applicable to the defense high-level waste container, which has the same diameter and geometry, but is shorter in length.
2. At this point, B&W was not concerned with any structure inside the container that might be required to separate fuel rods, etc.

Table 4-2. Candidate material specifications for mock-ups

	Product Form						
		Centrifugal Casting			Pipe		
Alloy	Bar	Pipe	Other	Forging	Seamless	Welded	Plate
TP304L	SA479			SA336	SA312	SA312 [SA358]	SA240
3PF3,3A		[SA451]	SA351				
TP316L	SA479			SA336	SA312	SA312 [SA358]	SA240
3PF3M		[SA451]	SA351				
IN825	SB425			(SB564/ SB424	SB423*	(SB619/ SB424)*	SB424
CDA122	SB152			(SB283/ SB152)	SB42*	SB543*	SB152
CDA811		(SB271/ SB152)	(SB271/ SB152)				
CDA613 CDA952	QQ-C-450a**	SB271	SB271	(SB283/ QQ-C-450a**)		(SB543/ QQ-C-450a**)	
CDA715				(SB283/ SB402)	SB467*	SB543*	SB402
CDA964		(SB271/ SB402)	(SB271/ SB402)				

[ ] Denotes that the material is acceptable under Section III but not Section VIII.
* The containers are beyond the maximum diameter covered by the specification but could be acceptable according to Paragraph UG-4, Section VIII.
( ) Denotes that the material is made to a process specification not normally covering the alloy but meets the composition and mechanical properties of the alloy plate specification. Currently not acceptable to Section III or VIII but expected to be acceptable to Section VIII for the production containers.
** Not acceptable to either Section III or VIII.

Specification Sources:
SA and SB – ASME BPVC
QQ – Federal Specifications

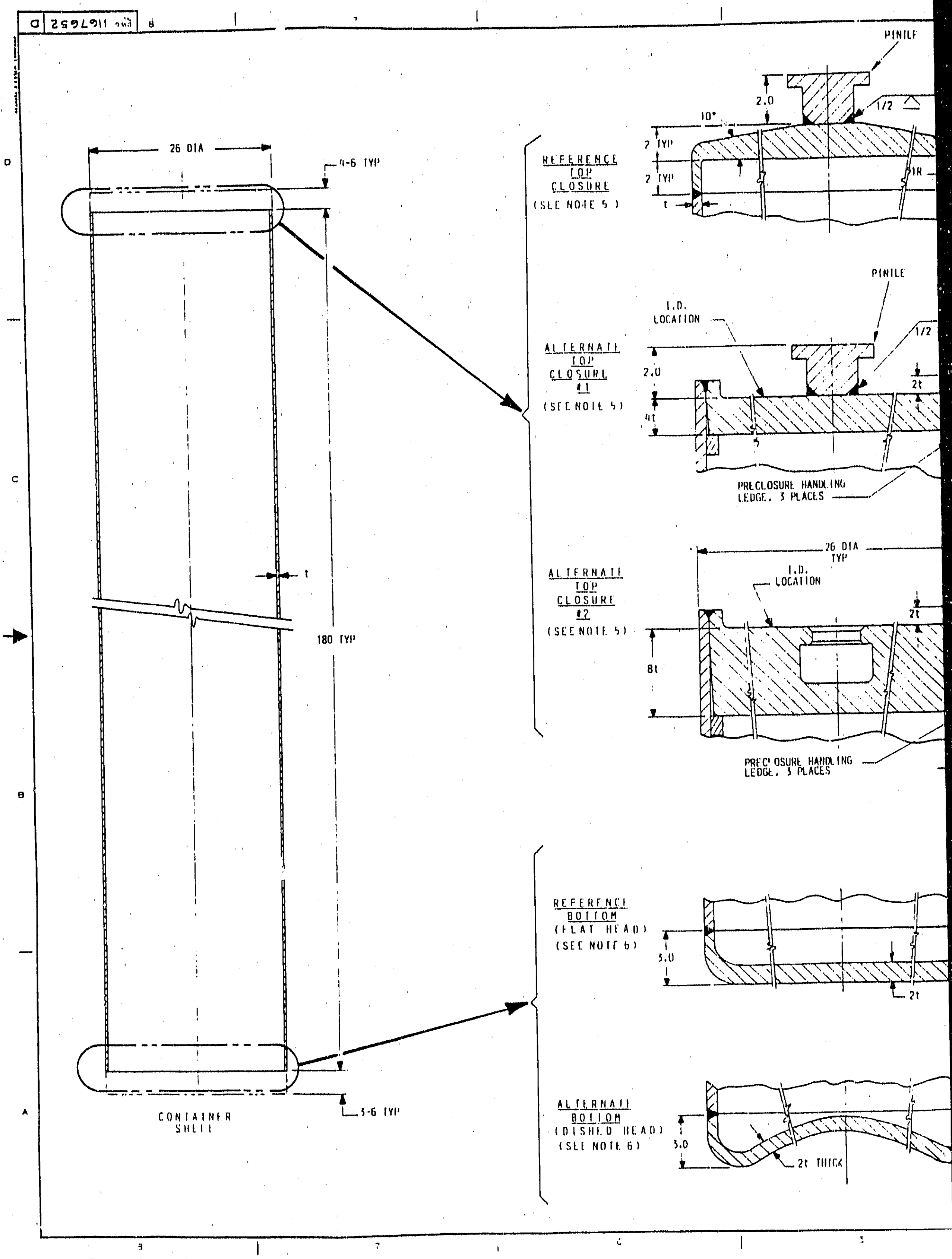
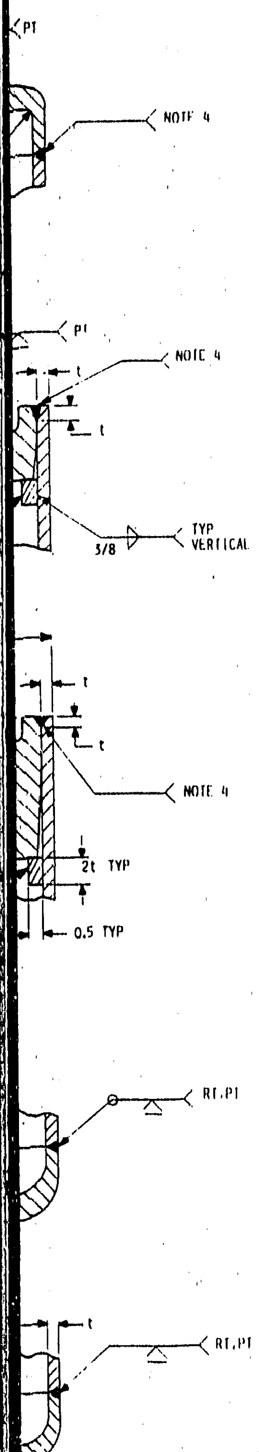


Figure 4-1. Container drawing used for estimating purposes



REVISIONS

LTR.	DESCRIPTION	DATE	APPROVAL

MATERIAL CHART

USE ASME BPVC SECTION VIII, DIVISION 1 (LETHAL)
OR ASME III WHERE AVAILABLE

MATERIAL	ALLOY	BAR	CENTRIFUGAL CASTING * PIPE	CENTRIFUGAL CASTING * OTHER	FORGING	PIPE SEAMLESS	PIPE WELDED	PLATE	WELD WIRE
1	TP304L TP F3,3A	SA479	(SA451)	SA351	SA336	SA312	SA312 (SA358)	SA240	SFA 5.9 ER 308L
2	TP316L TP F3M	SA479	(SA451)	SA351	SA336	SA312	SA312 (SA358)	SA240	SFA 5.9 ER 316L
3	IN825	SB425			(SB564/ SB424)	SB423*	(SB619/ SB424)	SB424	SFA 5.14 UNS N08065 ERNiFeCr-1
4	CDA122 CDA811	SB152	(SB241/ SB152)	(SB241/ SB152)	(SB283/ SB402)	SB42*	SB543*	SB152	SFA 5.7 ER Cu
5	CDA613 CDA952		SB271	SB271					SFA 5.7 ERCuAl-A2 MOD WITH Sn
6	CDA715 CDA964		(SB271/ SB402)	(SB271/ SB402)	(SB283/ SB402)	SB466*	SB 467	SB402	SFA 5.7 ERCuNi

( ) - DENOTES THAT THE MATERIAL IS ACCEPTABLE UNDER SECTION III, BUT NOT SECTION VIII (CURRENTLY).

* - THE CONTAINERS ARE BEYOND THE MAXIMUM DIAMETER COVERED BY THE SPECIFICATION, BUT COULD BE ACCEPTABLE ACCORDING TO PARAGRAPH UG-4, SECTION VIII.

( ) - NOT A CURRENT SPECIFICATION FOR THIS MATERIAL, BUT MEETS COMPOSITION AND MECHANICAL PROPERTIES OF THIS ALLOY FORM, SHOULD BE ACCEPTABLE FOR SECTION VIII INCORPORATION

NOTES:

1. ALL WELDS ARE VISUALLY INSPECTED. ADDITIONAL INSPECTION WHERE NOTED ARE LIQUID PENETRANT TEST (PT), RADIOGRAPHIC TEST (RT) OR ULTRASONIC TEST (UT).
2. t = .375" EXCEPT FOR MATERIAL NO. 4 WHERE t = 1.00"
3. COBALT CONTENT ON MATERIALS 1,2 AND 3 IS 0.1% MAXIMUM.
4. CLOSURE WELD AND WELD PREP BY OTHERS.
5. PINTLE AND TOP CAN BE SUPPLIED AS ONE PIECE.
6. BOTTOM AND CONTAINER SHELL CAN BE SUPPLIED AS ONE PIECE.
7. ASSEMBLIES TO BE ANNEALED
8. WELD REPAIRS ON BASE METAL NOT ASSOCIATED WITH PINTLE ATTACHMENT, LONG SEAM, AND GIRTH WELD ARE PROHIBITED.
9. OUTER SURFACES TO BE 63 RHR OR BETTER.
10. WELD JOINT GEOMETRY AND WELD PROCESS TO BE AT OPTION OF FABRICATOR WITH APPROVAL OF BUYER.
11. PARTS WILL NOT BE CODE STAMPED, BUT WILL USE ASME CODE REQUIREMENTS WHERE APPLICABLE.
12. SEE B&W SPECIFICATION ARC-TP-760 FOR FURTHER REQUIREMENTS.

TOLERANCES UNLESS OTHERWISE SPECIFIED
ALL TOLERANCE DEFINITIONS PER ANSI Y14.5 - 1973
ALL DIMENSIONS ARE FOR PART TEMPERATURE OF 68°F

	UP TO 6 INCL	OVER 6 TO 12 INCL	OVER 12 TO 24 INCL	OVER 24 TO 60 INCL	OVER 60 TO 140 INCL	OVER 140
DECIMAL DIMENSIONS	± .003	± .005	± .005	± .010	± .031	
FRAC DIM MACH	± 1/64	± 1/32	± 1/32	± 1/16	± 1/16	± 1/8
FRAC DIM UNMACH	± 1/16	± 1/16	± 3/32	± 1/8	± 3/16	± 3/16
DIM FOR BURNING	± 1/8	± 1/8	± 1/8	± 1/8	± 3/16	± 3/16

MACHINED SURFACES		
FLATNESS	.001 IN OF SURFACE UP TO .020 MAX	BREAK CORNERS 1/64 R MIN OR CHAMFER
PERPENDICULARITY	.002 IN OF SURFACE UP TO .020 MAX	
CONCENTRICITY	.015 DIA	
ANGULARITY	± 0° 30'	CHAMFER ± 5°
ALL MACHINED SURFACES TO HAVE 250/RHR FINISH UNLESS OTHERWISE NOTED		

M GOWELL
7-20-87

LLNL
SPENT FUEL
CONTAINER
(ESTIMATION ONLY)

Babcock & Wilcox
a McDermott company

SCALE NONE

1167652 D 0

PG 13810 5

Table 4-3. YMP candidate alloys

UNIFIED NUMBER	DESCRIPTION	CHEMICAL COMPOSITION	CROSS REFERENCE SPECIFICATIONS
C10200	Oxygen-Free Copper (OF)	Cu 99 95 min Other Ag included in Cu	AMS 4501, 4602 4701 ASME SB12, SB42, SB75 SB111, SB152, SB359 SB395 ASTM B1, B2, B3, B12 (102), B33, B42 (102), B48 B49, B68 (102), B75 (102), B88 (102), B111 (102), B133 (102), B152 (102), B170 (102), B187 (102), B188 (102), B189 B246, B272, B280 (102), B298, B355, B359 (102), B372 (102), B395 (102) B432 (102), B447 (102), B451, B506 (102), B566, F9 FED QQ-C-502, QQ-C-576, QQ-R-571, QQ-W-343 MIL SPEC MIL-W-85 MIL-T-3235, MIL-W-3318, MIL-R-19631, MIL-W-23068, MIL-W-B-18907 SAE J461 (CA102), J463 (CA102)
C61300	Aluminum Bronze	Al 6 0-7 5 Fe 2 0-3 0 Mn 0 10 max Ni 0 15 max P 0 015 max Pb 0 01 max Si 0 10 max Sn 0 20-0 50 Zn 0 05 max	CDA 613 FED QQ-C-450
C71500	Copper Nickel, 30%	Cu 99 5 min Fe 0 40-1.0 Mn 1 0 max Ni 29 0-33 0 Pb 0 05 max Zn 1.0 max Other Ag included in Cu, Cu 99 5 min including all named elements For welded applications C 0 05 max, P 0 02 max, Pb 0 02 max, S 0.02 max, Zn 0 50 max	ASME SB111, SB171, SB359, SB395, SB402, SB466, SB467, SB543 ASTM B111 (715), B122 (715), B151 (715) B171 (715), B359 (715), B395 (715), B402 (715), B432 (715), B466 (715), B467 (715), B543 (715), B552 (715) MIL SPEC MIL-T-15005, MIL-C-15726, MIL-T-16420, MIL-R-19631, MIL-T-22214 SAE J461 (CA715), J463 (CA715)
C80100	Cast Copper	Cu 99 95 min Other total 0.05 max, Ag included in Cu	
C95200	Cast Aluminum Bronze	Al 8 5-9 5 Cu 86 0 min Fe 2 5-4 0 Other total named elements 99 0 min	ASME SB148, SB271 ASTM B30 (952), B148 (952), B271 (952) B505 FED QQ-B-675, QQ-C-390 MIL SPEC MIL-C-22229 (5) SAE J461 (CA952), J462 (CA952)
C96400	Cast Copper-Nickel	C 0 15 max Cb 0 50-1 5 Cu 65 0-69 0 Fe 0 25-1 5 Mn 1.5 max Ni 28 0-32 0 Pb 0 03 max Si 0 50 max Other For welding grades, Pb 0.01 max	ASTM B30 (964), B369 (964), B433 (964), B505 (964) FED QQ-C-390 MIL SPEC MIL-C-15345 (24), MIL-C-20159 (I)
J92500	Alloy Steel Casting (CF-3)	C 0 03 max Cr 17 0-21 0 Mn 1 50 max Ni 8 0-12 0 P 0 040 max S 0 040 max Si 2 00 max	ACI CF-3 AMS 5370, 5371 ASTM A351 (CF-3), A743 (CF-3), A744 (CF-3)
J92800	Alloy Steel Casting (CF-3M)	C 0 03 max Cr 17 0-21 0 Mn 1 50 max Mo 2 0-3 0 Ni 9 0-13 0 P 0 04 max S 0 04 max Si 1.50 max	ACI CF-3M ASTM A351 (CF3M, CF3MA), A743 (CF-3F), A744 (CF-3M)
N08825	Ni-Fe-Cr Alloy Solid Solution Strengthened (Incoloy 825)	Al 0 2 max C 0 05 max Cr 19 5-23 5 Cu 1 5-3 0 Fe bal Mn 1 0 max Mo 2 5-3 5 Ni 38 0-46 0 S 0 03 max Si 0 5 max Ti 0 6-1.2	ASME SB163, SB423, SB424, SB425 ASTM B163, B423, B424, B425
S30403	Austenitic Cr-Ni Stainless Steel (Low Carbon)	C 0 03 max Cr 18 00-20 00 Mn 2 00 max Ni 8 00-12 00 P 0 045 max S 0 030 max Si 1 00 max	AISI 304 L AMS 5511, 5647 ASME SA182 (304 L), SA213 (304 L), SA240 (304 L), SA249 (304 L), SA312 (304 L), SA403 (304 L), SA479 (304 L), SA688 (304 L) ASTM A167 (304 L), A182 (304 L), A213 (304 L), A240 (304 L), A249 (304 L) A269 (304 L), A276 (304 L), A312 (304 L), A314 (304 L), A403 (304 L), A473 (304 L), A478 (304 L), A479 (304 L), A511 (304 L), A554 (304 L), A580 (304 L), A632 (304 L), A688 (304 L) FED QQ-S-763 (304 L), QQ-S-766 (304 L) MIL SPEC MIL-S-862 (304 L), MIL-S-4043, MIL-S-23195 (304 L), MIL-S-23196 (304 L) SAE J405 (30304 L)
S31603	Austenitic Cr-Ni-Mo Stainless Steel (Low Carbon)	C 0 030 max Cr 16 00-18 00 Mn 2 00 max Mo 2 00-3 00 Ni 10 00-14 00 P 0 045 max S 0.030 max Si 1 00 max	AISI 316 L AMS 5507, 5653 ASME SA182 (316 L), SA213 (316 L), SA240 (316 L), SA249 (316 L), SA312 (316 L), SA403 (316 L), SA479 (316 L) SA688 (316 L) ASTM A167 (316 L), A182 (316 L), A213 (316 L), A240 (316 L), A249 (316 L), A269 (316 L), A276 (316 L), A312 (316 L), A314 (316 L), A403 (316 L), A473 (316 L), A478 (316 L), A479 (316 L), A511 (316 L) A554 (316 L), A580 (316 L), A632 (316 L) A688 (316 L) FED QQ-S-763 (316 L), QQ-S-766 (316 L) MIL SPEC MIL-S-862 (316 L) SAE J405 (30316 L)

3. As previously discussed, where possible the container will be assumed to be made according to requirements in ASME BPVC, Section VIII, Division 1. Helium leak testing will be assumed in lieu of hydrostatic testing, and other exceptions may be made to best fit the application. A material or process will not be eliminated if there is no applicable code.

4. The container components shall be solution annealed to minimize residual stresses and stress corrosion cracking (SCC).

5. Surface finish of the outside surface is more critical than that of the inside (requirements: 63 rms for outside, 250 rms for inside).

6. If the material specifications for mock-ups and prototypes are not available from ASME BPVC, B&W will use B&W-generated specifications (with approval by LLNL) .

7. Casting grades are acceptable as centrifugal castings.

8. Ultrasonic (UT) testing of centrifugal castings will be possible if cold worked and annealed.

9. B&W assumes that the following material combinations are acceptable for weld joints:

Base Metal	Filler Metal
AISI 304L	308L
AISI 316L	316L
Alloy 825	I65 (matching composition or I625)
CDA 122	ER Cu
CDA 613	ER CuAl-A2, ER CuAl-Al
CDA 715	ER CuNi

4.2. Literature Review

The literature review concentrated on factors of the fabrication process that would affect the quality or serviceability of the containers. Of principal concern are:

- Corrosion resistance.
- Chemical homogeneity.
- Uniform microstructure.
- Grain size uniformity.
- Yield strength.
- Decrease in ductility.
- Internal quality, soundness.
- Residual stresses.
- Workability.
- Weldability.
- Heat treatment.
- Inspectability.

The possible effects due to fabrication are:

- Compositional variations
  - Joining of pieces from different heats
  - In weldments, filler versus base metal composition.
- Cold work in forming.
- Grain size variations
  - Joining of pieces with different thermal-mechanical histories
  - Nonuniform working and recrystallization
  - In weldments.

- Residual stresses
  - Due to forming
  - Due to welding.
- Nonuniform microstructure
  - In weldments
  - Nonuniform heat treatments.
- Decrease in ductility.

The cause-and-effect relationships between these variables were searched using computer-based literature retrieval sources, with the American Society of Metals International (ASM) Metadex database as the principal source. The search included the following alloys:

AISI 304L(CF3)	CDA 122 (CDA 811)
AISI 316L (CF3M)	CDA 613 (CDA 952)
Alloy 825	CDA 715 (CDA 964)
Austenitic stainless steel	
Copper	
Copper alloys	

The results of this search are summarized below.

4.2.1. Corrosion Resistance

The primary concerns for corrosion resulting from fabrication are the localized corrosion mechanisms of

- Galvanic corrosion due to chemical composition variations.
- Intergranular corrosion.
- Stress corrosion cracking that is either intergranular or transgranular.
- Pitting and crevice corrosion.
- Hydrogen embrittlement (HE) and hydrogen-assisted cracking (HAC).

4.2.1.1. Galvanic Corrosion

The compositional differences between components of the container and welds due to differences in heats, product form, and wrought versus cast are small (Table 4-4). Whether these differences are large enough to lead to galvanic corrosion is subject to further investigation. A specific search of the literature on this subject failed to produce any information on the galvanic corrosion of components made with different heats of base metal, or the galvanic corrosion of components due to compositional differences between base and weld metal when using matched filler metals. This is taken as evidence that such differences do not produce significant galvanic corrosion effects. For instance, copper-nickel alloys have been used successfully in marine and boat welded construction.

4.2.1.2. Intergranular Corrosion

Intergranular corrosion in these copper and copper-base alloys is apparently insignificant (Hong and Pitt, 1983), but it could be significant for the austenitic stainless steels and Alloy 825. A necessary condition for this mechanism is that the microstructure be sensitized. Procurement of base metal material specified to meet acceptance standards and tests for intergranular corrosion would ensure that the material was initially satisfactory. Because sensitization during welding is a possibility, the re-solution of the chromium carbides that are the cause of intergranular corrosion could be accomplished by solution annealing after welding. Nagawa (1982) investigated the effects of re-solutioning AISI 304, which is more prone to sensitization than AISI 304L, AISI 316L, and Alloy 825, to show that heat variability was reduced and improved corrosion resistance resulted. The exposure of AISI 304L and AISI 316L to temperatures of about 540–815°C (1000–1500°F) (Costello et al., 1969) and Alloy 825 to

Table 4-4. Composition comparisons between cast, wrought, and welding alloys

TP 304L SS

	Wrought	Wrought	Wrought	Cast	Cast	Wrought	Weldmetal
Spec.-->	SA240	SA312	SA336	SA351	SA451	SA479	SFA 5.9
Grade-->	TP 304L	TP 304L	F 304L	CF-3,3A	CPF-3,3A	TP 304L	308L
C	.03	.035	.035	.03	.03	.03	.03
Mn	2.00	2.00	2.00	1.50	1.50	2.00	1.0-2.5
P	.045	.04	.04	.04	.04	.045	.03
S	.03	.03	.03	.04	.04	.03	.03
Si	1.00	.75	1.00	2.00	2.00	1.00	.30-.65
Cr	18.0-20.0	18.0-20.0	18.0-20.0	17.0-21.0	17.0-21.0	18.0-20.0	19.5-22.0
Ni	8.0-12.0	8.0-13.0	8.0-13.0	8.0-12.0	8.0-12.0	8.0-12.0	9.0-11.0
Mo	--	--	--	.50	--	--	.75
N	.10	--	--	--	--	.10	--
Cu	--	--	--	--	--	--	.75

TP 316L SS

Grade-->	TP 316L	TP 316L	F 316L	CF-3M, 3MA	CPF-3M	TP 316L	316L
C	.03	.035	.035	.03	.03	.03	.03
Mn	2.00	2.00	2.00	1.50	1.50	2.00	1.0-2.5
P	.045	.04	.04	.04	.04	.045	.03
S	.03	.03	.03	.04	.04	.03	.03
Si	1.00	.75	1.00	1.50	1.50	1.00	.30-.65
Cr	16.0-18.0	16.0-18.0	16.0-18.0	17.0-21.0	17.0-21.0	16.0-18.0	18.0-20.0
Ni	10.0-14.0	10.0-15.0	10.0-15.0	9.0-13.0	9.0-13.0	10.0-14.0	11.0-14.0
Mo	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0
N	.10	--	--	--	--	.10	--
Cu	--	--	--	--	--	--	.75

IN 825

	Wrought	Wrought	Wrought	Weldmetal
Spec.-->	SB423	SB424	SB425	SFA 5.14
Grade-->	N08825	N08821	N08825	ER Ni Fe Cr-1
C	.05	.05	.05	.05
Mn	1.0	1.0	1.0	1.0
S	.03	.03	.03	.03
Si	.50	.50	.50	.50
Cr	19.5-23.5	19.5-23.5	19.5-23.5	19.5-23.5
Ni	38.0-46.0	38.0-46.0	38.0-46.0	38.0-46.0
Mo	2.5-3.5	2.5-3.5	2.5-3.5	2.5-3.5
Cu	1.5-3.0	1.5-3.0	1.5-3.0	1.5-3.0
Al	.20	.20	.20	.20
Ti	.6-1.2	.6-1.2	.6-1.2	.6-1.2
Fe	22.0 Min.	22.0 Min.	22.0 Min.	22.0 Min.
Others	--	--	--	.50

Table 4-4. Composition comparisons between cast, wrought, and welding alloys (cont'd)

	CDA 122				CDA 613		
	Wrought	Wrought	Wrought	Weldmetal	Wrought	Cast	Weldmetal
Spec.-->	SB 42	SB 152	SB 543	SFA 5.7	QQ-C-450	SB 271, B148	SFA 5.7
Grade-->	C12200	C12200	C12200	ER Cu	613	C 95200	Er Cu Al-A2
Cu+ Ag	99.9	99.9	99.9	98.0	Rem.	88.0 Nom.	Rem.
Fe	--	--	--	--	3.5	3.0 Nom.	1.5
Al	--	--	--	.01	6.0-8.0	9.0 Nom.	9.0-11.0
Zn	--	--	--	--	--	--	.02
Si	--	--	--	.50	--	--	.10
Pb	--	--	--	.02	--	--	.02
Ni+Co	--	--	--	--	.5	--	--
Mn	--	--	--	.5	.5	--	--
S	--	--	--	--	--	--	--
P	.015-.40	.015-.40	.015-.40	.015	--	--	--
C	--	--	--	--	--	--	--
Ti	--	--	--	--	--	--	--
Sn	--	--	--	1.0	.2-.5	--	--
Others	--	--	--	.50	--	--	.50

	CDA 715		
	Wrought	Wrought	Weldmetal
Spec.-->	SB 467	SB 543	SFA 57
Grade-->	C 71500	C 71500	Er Cu Ni
Cu + Ag	65.0 Min.	Rem.	Rem.
Fe	.40-1.0	.40-1.0	.40-.75
Al	--	--	--
Zn	.50	.50	--
Si	--	--	.25
Pb	.02	.02	.02
Ni+Co	29.0-33.0	29.0-33.0	29.0-32.0
Mn	1.0	1.0	1.0
S	.02	.02	.01
P	.02	.02	.02
C	.05	.05	--
Ti	--	--	.20-.50
Sn	--	--	--
Others	--	--	.50

about 650–760°C (1200–1400°F) (Brochure, 1984) required for sensitization will be prohibited after annealing. This practice will produce material that should not be a problem with the austenitic steels (Logan, 1983) and presumably with Alloy 825.

The effect of processing on Alloy 825 is apparently more complex than on the austenitic stainless steels. A stabilizing treatment of 1 hour at about 940°C (1700°F) after a solution anneal of about 1090°C (2000°F) (Brown, 1969) does not restore resistance to intergranular corrosion. Apparently, this alloy is more sensitive to thermal mechanical processing as compared to the austenitic stainless steels.

Work on the development of spent-fuel canisters has shown the beneficial effects of a solution treatment after welding AISI 304, and the increased resistance of AISI 304L to intergranular corrosion even after welding and a furnace sensitization treatment (Philippio, 1980). The use of a re-solution heat treatment for the low carbon grades, AISI 304L and AISI 316L, may not be necessary to prevent intergranular corrosion, but would be added protection against encountering a "fast precipitation" heat of material. The other benefits of a re-solution treatment are discussed below.

For forming operations involving cold work, annealing would provide recovery and recrystallization as well as re-solution of carbides. Using "Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stanless Steels—Practice E," (ASTM, 1986), Solomon (1985) showed that 11% prior work by drawing increased the maximum cooling for sensitization in AISI 304 by a factor of about 7 when compared to annealed material (Figure 4-2).

This figure also illustrates that the minimum cooling rate for annealing to prevent sensitization in a 0.03 Wt %C AISI 304L should be 5°C/s.

The cast alloy and weld metal equivalents to AISI 304L and AISI 316L generally contain some delta ferrite, and sensitization is reduced as compared to their wholly austenitic stainless counterparts. If the ferrite number exceeds $133 \times$ Wt %C, the sensitization of base metal and heat-affected zone (HAZ) is prevented (Matsumoto, 1989).

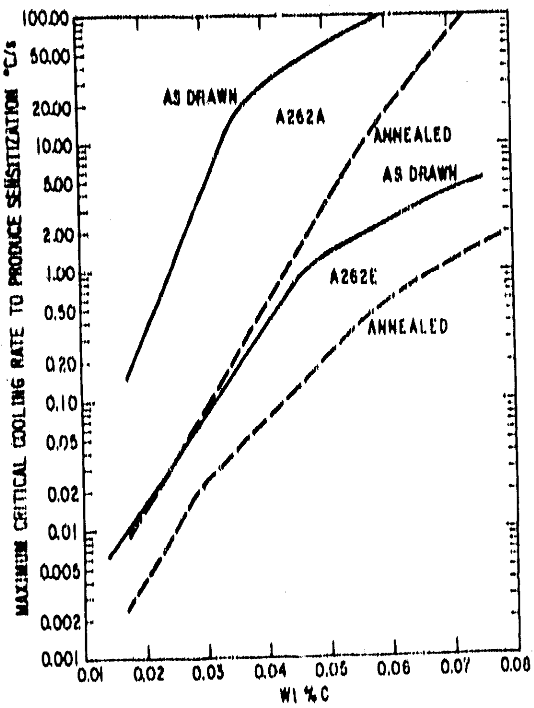
4.2.1.3. Stress Corrosion Cracking (SCC)

The following three essential criteria must be met for either intergranular SCC or transgranular SCC to occur:

- Susceptible microstructure/alloy.
- Hostile environment.
- Tensile stress.

The approach to be used in the fabrication of the containers is to produce the lowest practicable tensile stresses and, thus, avoid failure by these mechanisms. Intergranular SCC and transgranular SCC are not possible in either austenitic (Hanninen, 1979) or copper-base alloys (ASM, 1979), without a sufficiently high tensile stress.

The residual stresses due to either cold working or welding can be reduced to very low levels by stress relief or annealing treatments. Unfortunately, effective stress relief treatments for austenitic stainless steels are also in the range of temperatures in which sensitization occurs. However, solution anneal is effective in reducing residual stresses to an acceptable level while avoiding sensitization, provided that cooling rates from annealing are fast enough and uniform. Short times, less than 1 hour, at 900°C are effective in removing the SCC susceptibility of cold worked AISI 304L and AISI 316L (Cigada et al., 1982). Both of these alloys display threshold amounts of cold work (about 10%) below which SCC does not occur. This would permit the use of minor straightening operations provided that the residual stresses introduced by such operations are also low.



A262A - ASTM A262 Practice A

A262E - ASTM A262 Practice E

Figure 4-2. Comparison of the as-drawn and annealed maximum critical cooling rates for sensitization in AISI 304 (Reprinted from Solomon, 1985)

The stress relaxation that occurs in austenitic stainless steel welds follows a Larsen-Miller relationship (Fidler, 1982) and can be predicted with the following expression:

$$s = 10^{(5.24-0.16\,[T\,(20 + \log t) \times 10^{-3}])} \pm 20\ \mathrm{MNm^{-2}}$$

where
- s = stress, $\mathrm{MNm^{-2}}$;
- T = temperature, K;
- t = time in hours;
- $\pm 20\ \mathrm{MNm^{-2}}$ = predicted accuracy of the stress.

Using 1 hour at 1038°C (1900°F) as an example, the calculated residual stress would be equal to 11.1 $\mathrm{MNmm^{-2}}$ (1.6 ksi), provided that there is no increase in residual stress due to the annealing practice.

The annealing temperatures commonly used for the candidate alloys are given below.

Alloy	Annealing Temperature, °C (°F)	Reference
AISI 304L	1040 (1900) min.	148.1
CF3	1040 (1900) min.	148.6
AISI 316L	1040 (1900) min.	148.1
CF3M	1040 (1900) min.	148.6
Alloy 825	930–980 (1700–1800)	145
CDA 122	370–650 (700–1200)	67
CDA 811	370–650 (700–1200)[a]	--

Alloy	Annealing Temperature, °C (°F)	Reference
CDA 613	610–870 (1125–1600)	67
CDA 952	610–870 (1125–1600)[a]	--
CDA 715	650–820 (1200–1500)	67
CDA 964	650–820 (1200–1500)[a]	--

[a] Annealing is not normally specified for castings but is assumed to be the same as its wrought alloy counterpart.

A principal effect in fabrication with the austenitic stainless steels is the formation of delta ferrite. Delta ferrite is beneficial in castings and weld metals. Large amounts of delta ferrite may produce difficulties in hot working, so it is usually held to very low levels in wrought products. Beeston et al. (1984) compared the mechanical and corrosion-resistance properties of centrifugally cast CF3 and wrought AISI 304L canisters. They concluded that the properties of the cast canisters that contained up to 4.5% ferrite were equivalent to the AISI 304 wrought canisters. In particular, the cast material was found to be slightly less susceptible to SCC as compared to the wrought material. Flowers et al. (1963) have shown that the susceptibility to chloride SCC decreased with increasing ferrite content and that these alloys are more resistant than single-phase alloys.

On the other hand, Baeslack (1979) has shown that increasing the ferrite content up to 10–12% in ferrite-containing stainless-steel welds increases SCC susceptibility. The SCC susceptibility then decreases with further increases in ferrite. The differences in corrosion resistance between the cast and weld-metal cases are attributed to the globular and continuous ferrite morphologies in the cast and weld-metal microstructures, respectively.

No sensitization to intergranular corrosion occurred in stainless steels containing up to 0.054 Wt %C when interpass temperatures did not exceed 300°C (572°F) (Ginn et al., 1983). A common usage of 260°C (500°F) maximum interpass temperature would appear to be satisfactory.

4.2.1.4. Pitting and Crevice Corrosion

There are no data to indicate that fabrication affects the pitting and crevice corrosion resistance of copper and its alloys (CDA, 1987). Qualitative observations and practical experience indicate that the pitting resistance of cold-drawn copper may be greater than that of annealed tubing. Otherwise, the effect of fabrication on these properties appears to be nil.

In comparison, the pitting and crevice corrosion resistance of austenitic stainless steels is of greater concern with respect to the effects of fabrication. These are as follows:

- Crevice corrosion resistance decreases with a decrease in the average grain diameter (critical potential for crevice corrosion, $E_{cc} \propto d^{-1/2}$) (Dayal et al., 1984).
- Crevice corrosion increases with sensitization (Dayal et al., 1984).
- Post-weld annealing reduces pitting in welds (Suutala and Kurkela, 1984)
- Pitting is caused by sulfur segregation during the solidification of autogenous AISI 316 welds (Grekula et al., 1984).
- Pits nucleate preferentially at the austenite/ferrite interface or inside the cores of austenite in AISI 304L welds (Manning et al., 1980).
- Laser glazing reduces pitting corrosion resistance (Lamb et al., 1984) and does not offer a method of improvement.

4.2.1.5. Hydrogen Embrittlement (HE) and Hydrogen-Assisted Cracking (HAC)

Hydrogen embrittlement in copper-base alloys only occurs if oxygen is present in amounts greater than 10 ppm for pure oxygen-free copper (OFC) (CDA, 1987). If the fabrication process includes exposure to an oxidizing atmosphere followed by exposure to hydrogen, then water forms, resulting in voids and cracks. Embrittlement in the other copper alloys is apparently insignificant.

For the austenitic stainless steels, deformation-induced martensite is essential for HAC of low yield strength steels (Briant, 1981; Eliezer, 1981; West, 1981), although there is controversy concerning the role played by the martensite (Lewandowski and Thompson, 1981). Other contributing factors to cracking include chromium depletion of grain boundaries due to sensitization (Briant, 1981; Eliezer, 1981).

The amount of martensite formed in the cold working of metastable austenitic steels is a function of composition and can be predicted using empirical relationships such as those in the table (Table 4-5) summarized by Novak (1979). However, this is not a variable in container fabrication if annealing is performed, since the martensite that formed during cold working would be transformed back to austenite.

Table 4-5. Expressions relating austenite stability and alloy chemistry (reprinted from Novak, 1979)

Reference	Quantity computed	Relationship (elements in weight %)
Post and Eberly[98]	Stability factor Δ	$Ni - \left[\frac{(Cr + 1.5Mo - 20)^2}{12} - 0.5Mn - 35C + 15\right]$
Griffiths and Wright[99]	Stability factor Δ modified to include copper and nitrogen	$Ni - \left[\frac{(Cr + 1.5Mo - 20)^2}{12} - 0.5Mn - 35C - Cu - 27N + 15\right]$
Eichelman and Hull[41]	M_s (°F)	$75(14.6 - Cr) + 110(8.9 - Ni) + 60(1.33 - Mn) + 50(0.47 - Si) + 3000[0.068 - (C + N)]$
Monkman et al.[100]	M_s (°F)	$2160 - 66(Cr) - 102(Ni) - 2620(C + N)$
Angel[94]	M_{d30} (°C)	$413 - 462(C + N) - 9.2Si - 8.1Mn - 13.7Cr - 9.5Ni - 18.5Mo$
Floreen and Mihalisin[101] from Irvine et al.[40] and Eichelman and Hull[41]	Stability factor S	$Ni + 0.68Cr + 0.55Mn + 0.45Si + 27(C + N)$
Floreen and Mayne[102] from Irvine et al.,[40] Eichelman and Hull,[41] and Coutsouradis[103]	Stability factor S	$Ni + 0.68Cr + 0.55Mn + 0.45Si + 27(C + N) + Mo + 0.2Co$

Note: References cited in the table are in Novak (1979)

4.2.2. Forming and Fabrication Limitations

4.2.2.1. Casting

Alloy 825 and CDA 122 are not currently available as cast products. The other four candidate wrought alloys are available as castings with chemical compositions nearly equivalent to their wrought product forms.

B&W and industry's experience with defects in sand castings would preclude their use in these containers. Centrifugal castings are known to have much fewer defects than sand castings and improved mechanical and corrosion-resistant properties. This was demonstrated with the making of prototypical CF3 waste containers and comparing their properties to those for wrought AISI 304L (Beeston et al., 1984; Howell, 1982). One issue that was not addressed in these studies was the UT inspection of centrifugally cast material. The topic is covered in Section 4.2.2.7.

4.2.2.2. Cold Working

All of the six candidate wrought alloys are workable to varying degrees. None of the alloys present a problem in bending and forming into cylinders. Of the four cold forming operations under consideration (bending, spinning, roll extrusion, and deep drawing), deep drawing is the most severe and would reveal the more subtle differences in workability than would the less demanding processes. A commercial producer of deep-drawn tubular components reports the following ratings for the wrought alloys (Holbrook, 1987).

Alloy	Deep Drawability
AISI 304L	Good
AISI 316L	Difficult
Alloy 825	Good
CDA 122	Good
CDA 613	Poor
CDA 715	Good

4.2.2.3. Hot Workability

The effect of alloy composition on hot workability is more apparent than in cold working. The large differences in flow stress as a function of temperature for the iron versus copper-base alloys results in two principal regimes of extrusion temperatures:

Alloy	Extrusion Temperature Range, °C (°F)
AISI 304L	1100–1260 (2000–2300)
AISI 316L	1100–1260 (2000–2300)
Alloy 825	1100–1260 (2000–2300)
CDA 122	760–870 (1400–1600)
CDA 613	790–930 (1450–1700)
CDA 715	930–1040 (1700–1900)

4.2.2.4. Heat Treatments

Recommended heat treatment ranges for the candidate wrought alloys and their casting counterparts are listed below.

Alloy	Post-Weld Heat Treatment Temperatures, °C (°F)	Annealing Temperatures, °C (°F)
AISI 304L	Not recommended	1010–1120 (1850–2050)
AISI 316L	Not recommended	1010–1120 (1850–2050)
Alloy 825	Not recommended	930–980 (1700–1800)
CDA 122	None required	370–650 (700–1200)
CDA 613	600 (1100)	610–870 (1125–1600)
CDA 715	540 (1000)	650–820 (1200–1500)

Heating these alloys in gas-fired or electrical furnaces will produce scaling that is probably not acceptable for nuclear-waste containers. The use of protective atmospheres or vacuums is preferred. To avoid pitting when using protective atmospheres with copper, it is necessary to either prevent or remove the deposition of carbonaceous films on the surface (Mattson, 1980).

4.2.2.5. Grain Size Control

Since all of these alloys are prone to grain growth upon heating, controls that involve cold working and/or heat treatment must be used in fabrication. Large variable grain sizes could produce differences in strength, corrosion resistance, and UT testing sensitivity. Limiting the heat treatments to the lower ends of the temperature ranges should be part of the standard practice for fabrication. Also, avoiding strains and deformations in the range of about 10–30% will preclude the possibility of abnormal grain growth.

For the cast austenitic alloys that contain ferrite, CF3 and CF3M, cold working and recrystallization offer a means of producing fine-grained material (Murakami et al., 1979).

Some of the grain size differences between base and weld metal are due to substructures produced in the weld that are not present in the base metal (Foulds and Moteff, 1982). The only apparent method to reduce these differences is by cold work and recrystallization.

4.2.2.6. Surface Condition

A smooth surface, free of residual stresses, is desirable to avoid pitting and crevice corrosion and to provide a satisfactory surface for UT inspection. The methods used to produce the surface must be scrutinized carefully. For example, the SCC of boiling-water reactor piping was found to be greatly exacerbated by residual stresses left after grinding welds (Chrenko, 1978). Abusive grinding must be avoided after the final annealing treatment.

4.2.2.7. Inspectability

Inspectability is affected not only by the geometrical constraints of container design but also by the following factors:

- Large grain size of base metal, HAZs, and weld metals.
- Anisotropy in weld metals and centrifugal castings. Both of these could be eliminated by cold work and recrystallization.
- Another concern with centrifugal castings is the possibility of porosity affecting radiographic and UT inspectability. This latter effect can apparently be controlled by argon-oxygen decarbonization for the iron-base alloys.

4.2.3. Literature Review Summary

The following issues need to be addressed in the fabrication of YMP containers:

- If welding is used in fabrication, the consequences of the following must be considered:
  - Small compositional differences between the filler and base metal may promote galvanic corrosion.
  - There are practical limits of thermal gradients and cooling rates that can be used in the annealing of the container components (upper head and lower unit) without re-introducing residual stresses in the heat-treated pieces.
  - There is a possibility of avoiding pitting of welds containing delta ferrite by annealing the container. Can the continuous delta ferrite in these welds be eliminated to produce microstructures similar to those in castings?

- The best method must be found to achieve stress-free, smooth surfaces on the containers.

- There is a possibility of using centrifugal castings without subsequent cold work and recrystallization. Is their UT inspectability acceptable?

- The effects of thermal-mechanical processing of Alloy 825 with respect to carbide precipitation and other second-phase reactions must be examined.

4.3. Vendor Surveys and Quotations

The following four principal vendor surveys were conducted by mail and in limited cases by telephone and meetings:

- Capabilities and interest.
- Spin forming.
- Heat treating capabilities.
- B&W Nuclear Equipment Division and Trading Co. purchasing inquiries.

The results of these surveys are summarized below, together with questions received from vendors.

4.3.1. Capabilities and Interest Survey

Companies surveyed	57
Responses (total)	32
Negative responses	9
Expressions of positive interest and descriptions of capabilities	23

The results of this survey indicate a sufficient interest by roll-and-weld fabricators and centrifugal casting companies who wish to participate in the YMP container fabrication project.

A significant limitation appears to be the lack of availability of wrought seamless pipe of sufficient diameter for the container. Special processing such as back extrusion, roll extrusion, and deep drawing appear to be the most attractive options.

4.3.2. Spin Forming Survey

Spinning and deep drawing are two possible methods for fabricating a seamless lower unit (integral cylindrical body and lower head—no welds). The Precision Metal Forming Association (Mr. Karl M. Roth) was contacted and companies in its Metal Spinning Division were surveyed. The survey results were as follows:

Companies surveyed	19
Responses (total)	11
Negative responses	11

The waste-container components exceed the forming capacity of the vendor equipment. From this survey, two other possible vendors and one used-machinery dealer were identified. Additional possible vendors for spin forming and deep drawing were taken from the *Thomas Register of American Manufacturers*.

The same basic letter (with minor revisions) was then sent to 15 more vendors. The results are presented below.

Companies surveyed	15
Returned, no forwarding address	1
Responses (total)	5
Negative responses	2

Positive responses	3
- Interest in total package	1
- Interest in heads only	1
- Sell machinery	1

Vendors interested in fabricating all or part of the container were sent the bid package soliciting quotes. Mr. William J. Molloy of Mohawk Machinery, Inc. has for sale a 75 in. × 100 in. Cincinnati Vertical Hydrospinning Machine used by General Electric to fabricate Minuteman Missiles (60-in. OD × 130-in. long).

The vendor quotes are discussed in Section 4.3.6.

4.3.3. Heat Treating Capabilities Survey

The objective of this survey was to determine if there are any firms interested in, and capable of, annealing the fabricated containers, using either protective bright annealing or vacuum annealing. The results of this survey are summarized in Table 4-6.

Table 4-6. Survey results of heat treating capabilities

Companies surveyed	46
Responses (total)	25
Positive responses	20
Negative responses	5

	Annealing Capabilities			
	Upper Head		Lower Unit	
	Bright	Vacuum	Bright	Vacuum
Number of Companies	10	13	4	2

Virtually all of the respondents could work with all of the alloys. The limiting case was the vacuum annealing of the lower unit; the length of the lower unit limits the number of available vacuum chambers.

4.3.4. B&W Nuclear Equipment Division and Trading Company Purchasing Inquiries

Independent of the surveys described above, purchasing agents from B&W Nuclear Equipment Division and Coutino, Caro & Co. (a trading company within the McDermott Co.), who were familiar with this type of product, solicited budgetary quotations for container components. Additional sources uncovered by these agents included the following:

Tube Sales—welded pipe agents including RaftPipe.
Spincraft—spun heads.
Ladish Co.—forged heads.
Earle M. Jorgensen Co.—forged heads.
Wyman Gordon Co.—forged heads.

The results of these inquiries are included in Section 4.3.6.

4.3.5. Key Vendors

During the course of the study it became apparent that obtaining technical information and quotations from vendors could be better accomplished by identifying certain key vendors for various processes and working more closely with them. The selection of these vendors was based on a number of factors including previous contacts, process capabilities, and responsiveness to our inquiries. These vendors are listed below.

Process	Key Vendor
Roll and weld	B&W Nuclear Equipment Division
Extrusion	Cameron Forge Co.
Roll extrusion	Kaiser Rollmet
Forgings	Ladish Co.
Deep drawing	NI Industries
Centrifugal casting	Wisconsin Centrifugal, Inc.
Welded pipe	Youngstown Welding

This choice of key vendors was made only for the purposes of this report and is not intended to prejudice any subsequent procurements, which are generally subject to free competitive bidding.

4.3.6. Vendor Quotations

To obtain data for use in estimating the cost of various processing options, budgetary quotations were requested from selected vendors. The response varied from highly interested to nonresponsive. This is not surprising in that the potential market for the vendors was too far ahead to motivate much effort, if any, in their responses. In order to obtain a more definite response to meet the near-term needs of Phases 2 (subscale mock-ups) and 3 (prototypes), an inquiry was submitted to 11 potential and interested vendors that could provide complete containers. The inquiry contained Specification ARC-TP-760, Drawing No. 116752-D-0 (Figure 4-1), and other associated specifications. The following points were brought out as a result of these inquiries:

- More specifics and clarifications are required in the bid package to make accurate comparisons between vendors.
- The final heat-treatment requirements need further specification.
- There is a reluctance on the part of the vendors to provide special cleaning of the fabricated containers.
- Only a few vendors may be interested, or capable of, supplying complete containers because of certifications that may be required; vendors are more interested in providing components for assembly.

The vendors listed in Table 4-7 supplied quotations for mock-ups, prototypes, or production units of various components of the containers.

4.3.7. Rationalization of Vendor Quotes

Vendor quotes were sought to identify companies capable of supplying waste-container components and to compare and rank alternate fabrication methods for cost. A reference container was designed (Figure 4-3) and used for quotes. Prior to the design of the reference container, an alternate configuration sketch (Figure 4-4) was used to obtain quotes for an integral pintle and upper head forging. Two vendors quoted modified versions of the alternate configuration sketch as shown in Figures 4-5 and 4-6.

Table 4-7. List of vendors providing quotations

Vendor	Component	Alloys: AISI 304L CF3	AISI 316L CF3M	Alloy 825	CDA 102 CDA 122	CDA 613 CDA 952	CDA 715 CDA 964
Alcoa Forging Division	Pintle and head forgings	X	X	X			X
B&W Nuclear Equipment Div.	Rolled and welded container mock-up, prototype, and production units	X	X	X			
Cameron Forge Co.	Forged open-end closed-end prototype and production cylinders		X	X			X
E. A. Jorgensen Co.	Forgea mock-up heads	X	X				
Kaiser Rollmet	Roll extruded open- and closed-end production cylinders		X	X			X
Ladish Co.	Forged mock-up heads	X	X	X			
NI Industries	Deep drawn seamless and welded head container mock-up and prototype units	X	X	X	X	X	X
Sandusky Foundry Machine	Centrifugally cast mock-up open-end cylinders	X	X	X		X	
Shenango Co.	Centrifugally cast mock-up open-end cylinders	X	X				X
Spincraft	Spun mock-up heads	X	X	X	X	X	X
Trent Tube	Welded pipe	X	X	X			X
Tube Sales	Welded pipe	X	X	X	X		X

Table 4-7. List of vendors providing quotations (cont'd)

		Alloys					
Vendor	Component	AISI 304L CF3	AISI 316L CF3M	Alloy 825	CDA 102 CDA 122	CDA 613 CDA 952	CDA 715 CDA 964
Wisconsin Centrifugal, Inc.	Centrifugally cast welded head, container mock-up, prototype, and production units	X	X			X	X
Wyman Gordon	Pintle and head forgings	X	X	X			X
Zak, Inc.	Rolled and welded container mock-up, prototype, and production units				X		

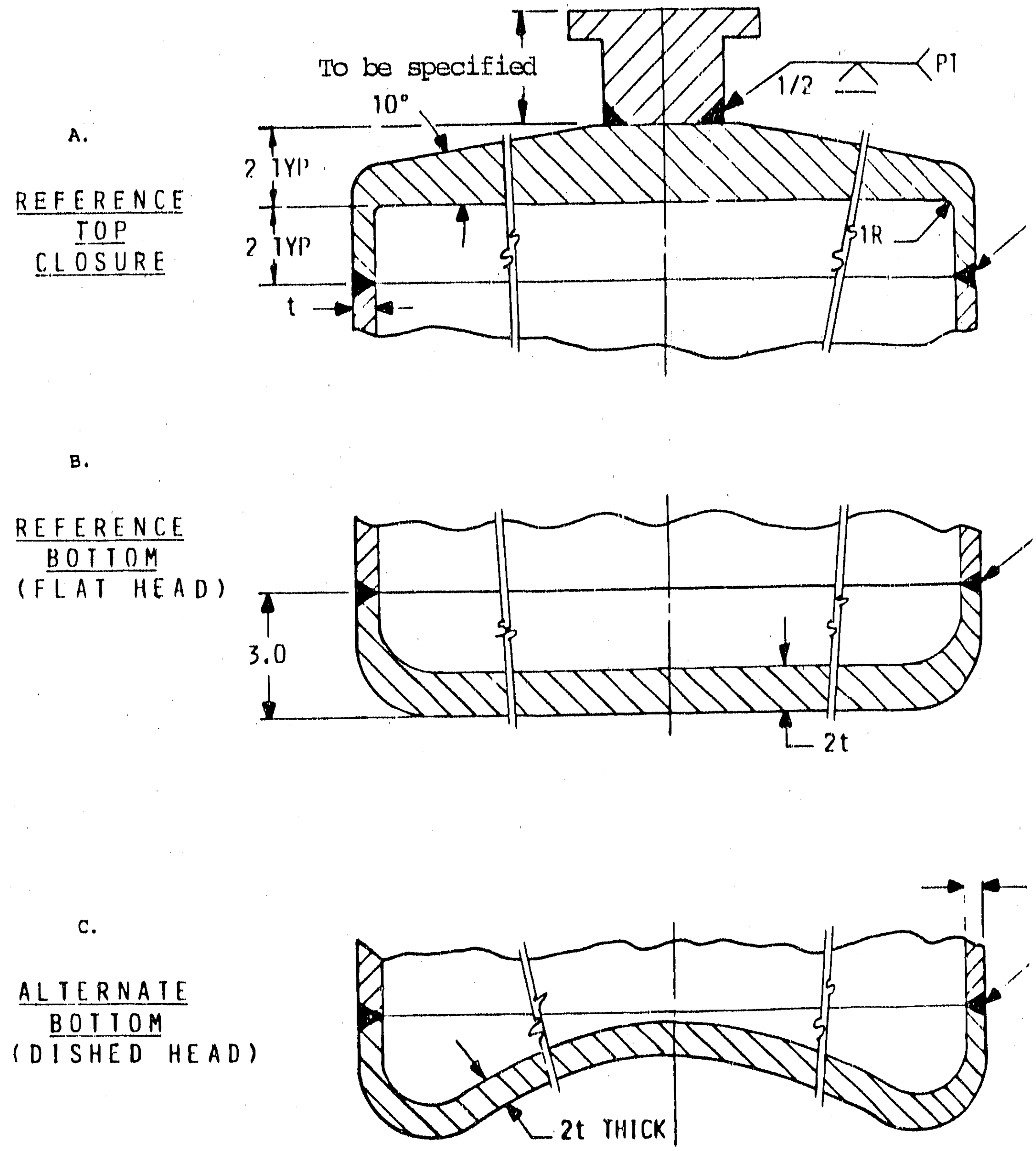


Figure 4-3. Reference container design

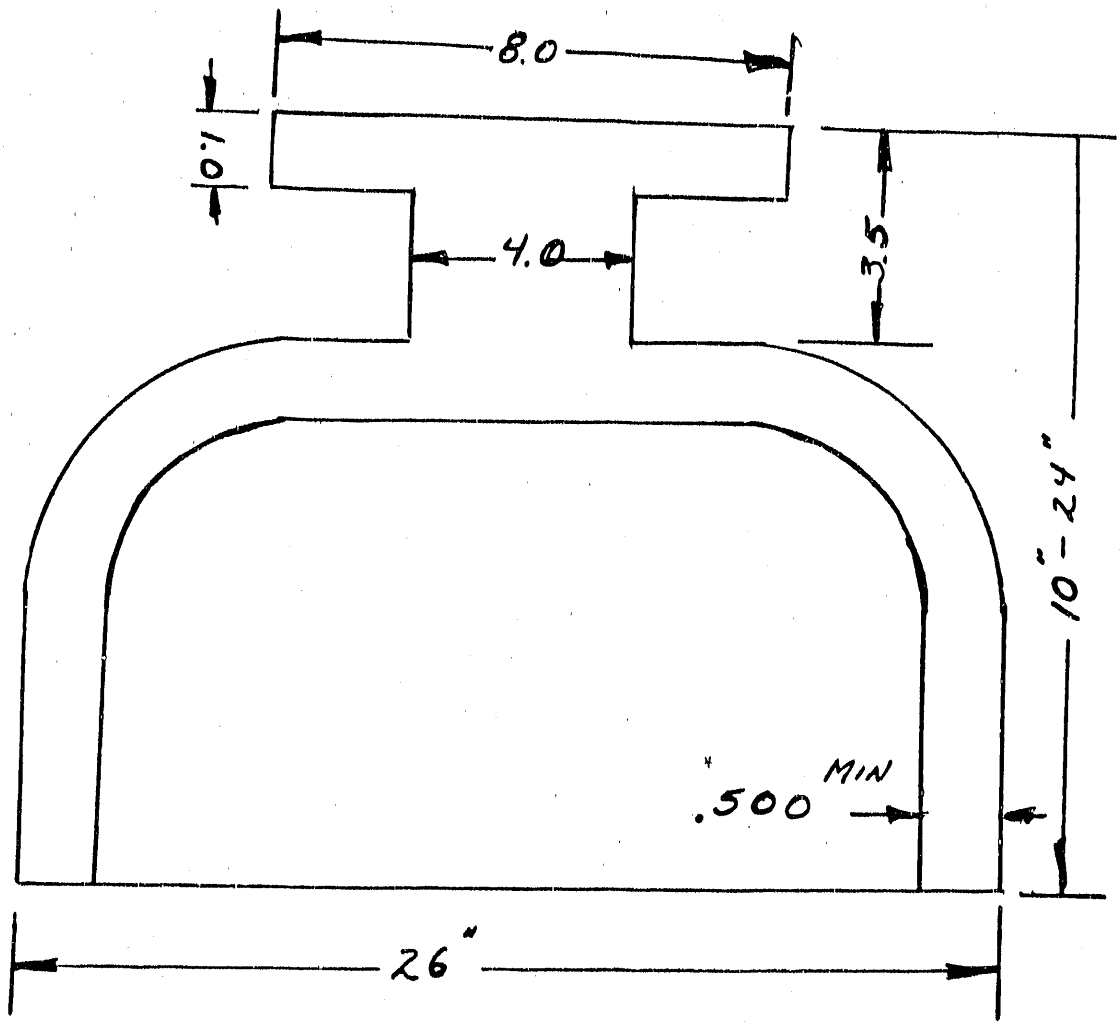
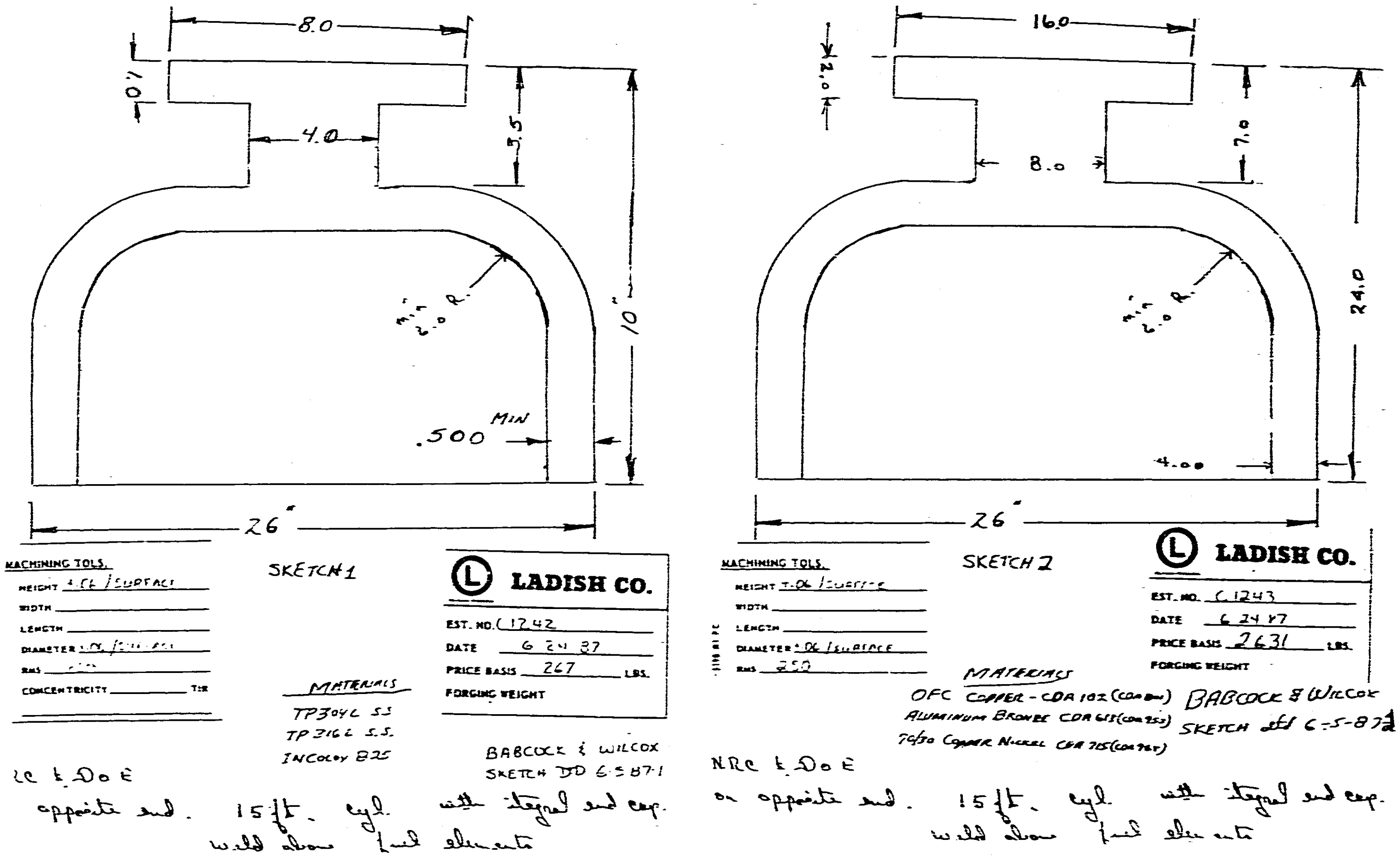
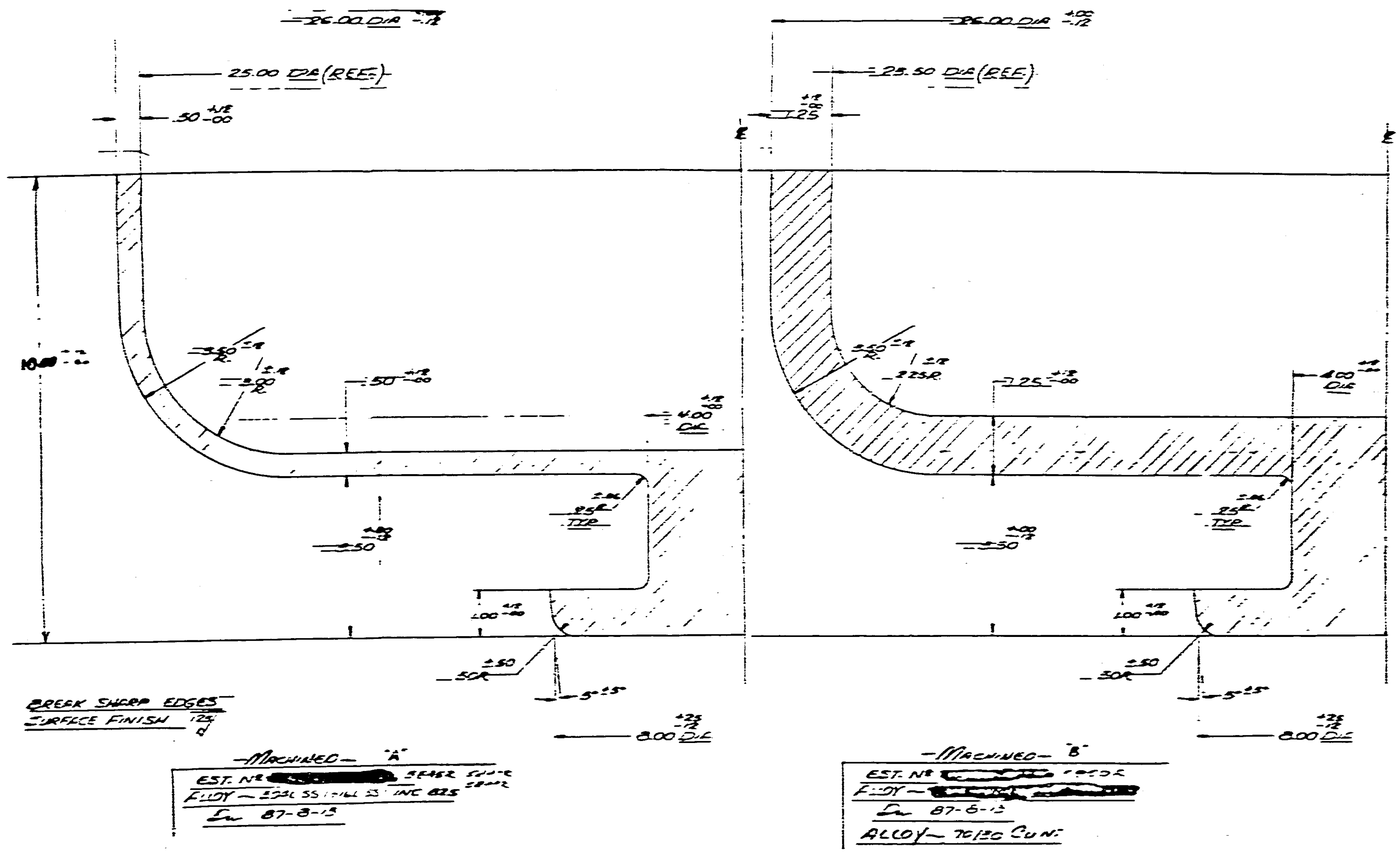


Figure 4-4. Alternate configuration sketch used for integral pintle and head forging quotes



1. For 304L, 316L and IN 825
2. For CDA 102, 613, 715

Figure 4-5. Sketches used for Ladish Co. quotes—integral pintle and head forging



A. For 304L, 316L, and IN 825
B. For 30/30 Cu Ni

Figure 4-6. Alcoa Forging Division drawings for integral pintle and head forging quotes

A bid package was sent out for the reference container design. Four vendors quoted for the whole container (pintle and upper head, and body and lower head). One vendor (Cameron Iron) quoted the whole container to a previous design in separate quotes. Not all material and process combinations were quoted. The five vendors quoting the whole container, the fabrication processes, and alloys are given below.

Babcock & Wilcox Nuclear Equipment Division

- Machined heads, rolled and welded body, and welded pintle and lower head.
- AISI 304L, AISI 316L, Alloy 825.

Cameron Forge

- Forged upper head and pintle, and extruded closed-end body.
- Extruded hollows and preforms.
- AISI 304L, AISI 316L, Alloy 825, and CDA 715 (Cameron was not asked to quote AISI 304L, but can supply it).

NI Industries

- Deep draw as two equal length halves, cut head from one and weld remaining cylinder to other half. Weld pintle to head.
- Deep-draw body full-length, deep-draw shallow head, and weld pintle.
- AISI 304L, AISI 316L, Alloy 825, CDA 122, CDA 613, and CDA 715.

Wisconsin Centrifugal

- Centrifugally cast heads and body, pintle welded to upper head and body welded to lower head.
- CF3, CF3M, CDA 952, and CDA 964.

Zak

- Machined heads, rolled and welded body, pintle welded to upper head, and lower head welded to body
- CDA 122

Various upper head geometries were quoted—Figure 4-3 for centrifugal casting and machining with welded pintle, and Figures 4-4 through 4-6 for forged heads with integral pintle. The lower heads were only quoted machined from plate or centrifugally cast.

For welding of the lower unit (body welded to lower head) three quotes were received covering various materials and processes. These cost estimates varied by an order of magnitude.

Preform bodies for roll extrusion were quoted to a different OD for centrifugal casting and were not quoted for roll and weld.

To estimate projected container costs, assumptions were made to fill in the cost gaps for the lower head, welding the body to the lower head, and body preforms. Because of the uncertainties in design and specifications and disputability of the assumed costs, LLNL requested that the cost estimates not be included in this report. To provide a feel for the costs of various materials and processes, relative costs have been normalized to a welded lower unit (roll-and-weld body welded to a forged head) of AISI 304L. This component is assigned a relative cost of one.

In the following sections, the component geometries and vendor responses are discussed as follows:

- Pintle and Upper Head
  - Pintle welded to head
  - Integral pintle and head
- Body and Lower Head
  - Integral
  - Body welded to head
  - Body welded to head and cold worked

4.3.7.1. Pintle and Upper Head

The pintle and upper head may be fabricated as a machined pintle welded to a head, or an integral pintle and head (no weld). The geometric configuration and vendor responses for each fabrication method are summarized in the following sections.

Pintle Welded to Head—Quotes were requested for the geometry shown in Figure 4-3. Quotes were received for heads machined from wrought material (Babcock & Wilcox) and for centrifugally cast heads (Wisconsin Centrifugal).

For the welded pintle construction, the trade-off between a formed head (forged, spun, or deep drawn) and a machined head will depend on the height of the head. A shallower head favors machining, and a higher or deeper head favors forming. For forging, an integral pintle is preferred, eliminating the pintle weld for an incremental increase in tooling and machining costs.

Integral Pintle and Head—Forging vendors were requested to quote on an integral pintle and head in quantities of 8 and 12 units for the alternate configuration sketch shown in Figure 4-4. Five vendors (Alcoa Forging Division, Cameron Forge, Jorgensen, Ladish, and Wyman Gordon) provided quotes. The vendors consider these quotes as budgetary, approximate, and "ball park," subject to revision based on finished print and specifications. Ladish quoted for the sketches given in Figure 4-5, while the Alcoa Forging Division made the drawings shown in Figure 4-6, and quoted for them. The alternate configuration sketch (Figure 4-4), and the quotes, preceded the reference container design (Figure 4-3).

The designs for the austenitic materials (304L SS, 316L SS, and Alloy 825) are based on nearly identical configurations—same pintle dimensions, height, and shell-wall thickness. Jorgensen did not quote a separate tooling charge; presumably, the tooling charge is included in the unit price.

To estimate costs for production quantities, consider the four vendors who did show tooling charges and

1. Neglect the tooling charge (spread over 1500 units the charge is less than $50 per unit),
2. Average the quotes for 8 units (8 is the only quantity quoted by all vendors), and
3. Take 70% of the average and round to the nearest hundred.

The 70% factor is based on the Ladish quote for 8 and 100 units for the 3 austenitic materials. CDA 122 and CDA 613 were not quoted. CDA 715 was quoted for several configurations. The four vendors, the sketches they quoted from, and the salient differences are given next.

CDA 715—Upper Head and Handling Pintle

Vendor	Figure	Comments
Alcoa Forging Division	4-6	1.25-in. wall × 10-in. high with 4-in. diam pintle.
Cameron Iron	4-4	Assumed 2-in. wall × 10-in. high with 4-in. diam pintle.
Ladish	4-5	4-in. wall × 24-in. high with 8-in. diam pintle.
Wyman Gordon	4-4	Assumed 2-in. wall × 10-in. high with 4-in. diam pintle.

The original inquiry gave a wall range of 2–4 in. for the copper alloys to allow for additional machining when detailed drawings became available. Only CDA 122 would require a wall that heavy. The Alcoa Forging configuration (Figure 4-6) is representative of the current configuration. The Alcoa response for 8 to 11 units is used as the average value. The 70% factor is applied to estimate cost for production quantities.

As noted previously, the purpose of the vendor quotes was to identify vendors and rank fabrication processes for cost. Subsequent to the request based on the alternate configuration sketch in Figure 4-4, the reference container design shown in Figure 4-3 was prepared. The thicker top plate (2-in. thick at the center) may increase the cost, while the shallower overall height (6 in. versus 10 in.) should reduce the cost. The design is subject to further change. The representative values are thought to be reasonable.

Wisconsin Centrifugal suggested a centrifugally cast head with an integral pintle, but did not quote a price for it. No quotes were obtained for a machined integral pintle and head. The forging quotes may contain various amounts of machining based on the nature of the forged shape.

The estimates for production costs derived from the vendor quotes have been normalized relative to the cost of a AISI 304 rolled-and-welded body, welded to a forged head. Table 4-8 presents these normalized estimates.

Table 4-8. Relative cost of upper heads

	Materials					
	AISI 304L CF3	AISI 316L CF3M	Alloy 825	CDA 122	CDA 613 CDA 952	CDA 715 CDA 964
Pintle Welded to Head						
Centrifugally Cast	0.3	0.3			0.1	0.4
Machined	0.9	0.9	1.3	0.3		
Integral Pintle and Head						
Forged	0.3	0.4	0.6			0.7

The pintle-welded-to-head construction is estimated to have costs greater than or equal to the forged integral pintle and head. At equal cost, the integral construction (no pintle weld) would seem advantageous. For forgings, the higher nickel Alloy 825 and CDA 715 are about double the cost of AISI 304L.

4.3.7.2. Body and Lower Head

The body is a cylinder 26-in. OD × 0.375-in. wall × 180-in. long for all alloys except CDA 122, which has a wall thickness of 1.00 in. The reference container design has a flat bottom lower head of thickness two times the body thickness (Figure 4-3, B).

The body and lower head may be made integrally (one piece) by extruding a closed-end hollow or by deep drawing.

The body and lower head may be fabricated separately and joined by welding. A further variation involves cold working the body after welding. (See the following discussion, "Body Welded to Head and Cold Worked.")

The vendor response for each of the fabrication methods (integral, body welded to head, body welded to head and cold worked) is discussed in the following sections.

Integral Body and Lower Head

The following three integral processes are quoted:

- Extruded closed-end cylinder.
- Extruded closed-end and cold-worked cylinder.
- Deep drawn closed-end cylinder.

For the extruded closed-end cylinder, the container wall thickness is 0.600 in. The minimum wall thickness after extrusion is approximately 0.800 in. The unit is bored and turned to 0.600-in.-wall thickness. Machining to lighter wall thickness increases the cost. The most economic size for this process would be the 0.800-in.-wall thickness with minimum machining based on container requirements. The minimum amount of machining is unknown. In process ranking for cost, the response for 1500 units, neglecting tooling charges, is used. For 1500 units, the tooling cost is less than $50 per unit. A quote was not requested for AISI 304L. The quote for AISI 316L will be used for AISI 304L for process evaluation.

The extruded and cold work process involves Cameron Iron for extrusion of a heavy wall preform and Kaiser Rollmet for roll extrusion. This should minimize machining off extrusion and permit finishing to the aim wall thickness of 0.375 in. The estimated total cost is the same or less than the cost of extrusion alone. The reduction in machining (depth of cut and length of cut) helps to offset the cost of roll extrusion. The final length calculation assumes that 55 in. of the preform is cold worked. Again, for process evaluation the tooling cost is neglected ($100 per unit for 1500 units) and the 1500-unit estimates are used. The AISI 316L estimate is used for AISI 304L.

The deep draw quote from NI Industries is for 5 units and assumes starting material for 3 containers to make 1. Production costs "would depend on the equipment available at that time." The extra material cost is about $28K for CDA 122. For other alloys, the extra start material is about $8K. The tooling charge spread over 1500 units is less than $700 per unit. In the estimate for production, the excess material is subtracted from the estimate, and 70% of the balance is taken as the estimate for process evaluation. The uncertainty of the 70% factor is greater here than for the heads. The ratio of costs for 1500 units, versus 2 units for the other integral processes, ranges from 47–70%.

Relative costs for the integral lower unit are given in Table 4-9. For AISI 304L or AISI 316L, the integral body and head is more than 3 times as costly as the roll-and-weld body welded to forged head in AISI 304L. For Alloy 825 and CDA 122, the extruded closed-end is about 6 times as expensive as the AISI 304L reference, and the extrusion/roll extrusion is about 5 times as costly. Because of the manipulation of the deep drawn estimates, the relative costs are less certain.

Body Welded to Head

Costs are for the body, the lower head, and the welding.

Body: The production estimate for the roll-and-weld body used the lowest quote rounded up to the next hundred dollars (except CDA 122 was rounded to the nearest hundred). The tooling cost for Zak, \$2.48M, is the cost to set up a production line for machining and welding the body, heads, and pintle.

The extrusion quote was for 26-in. OD × 0.400-in. wall × 183-in. long (a little heavier wall and longer length). As noted in the discussion of the closed-end extrusion, a heavier wall thickness might be more economical. The 1500-unit quote, neglecting tooling charges, is used for the relative cost. The AISI 316L estimate is used for AISI 304L.

Table 4-9. Relative costs for integral body and head

(Cost relative to AISI 304L roll-and-weld body welded to forged head)

Vendor	Materials: AISI 304L CF3	AISI 316L CF3M	Alloy 825	CDA 122	CDA 952	CDA 715 CDA 964
	Extruded Closed-End					
Cameron Iron[(a)] (26.4-in. OD × 0.600-in. wall × 189-in. long)		3.2	6.1			5.8
	Extruded Closed-End and Cold Worked					
Cameron Iron	Extruded: 27.6-in. OD × 1.200-in. wall × 63-in. long					
Kaiser Rollmet	Roll Extruded: 26.0-in. OD × 0.375-in. wall × 189-in. long					
Extrusion[(a)]		1.8	3.6			3.4
Roll Extrusion[(a)]		1.4	1.3			0.9
Total[(a)] (may differ from sum due to rounding)		3.2	4.9			4.4
	Deep Drawn Closed-End					
NI Industries	3.5	3.5	3.5	4.9	3.5	3.7

(Original quote for 5 units and assumes starting material for 3 containers to make 1. Extra material cost removed. A factor of 70% used to estimate production costs.)

(a)For evaluation assumed same as AISI 316L.

The centrifugal casting quotes are for the reference design body. The minimum quotes for 1500 units, neglecting tooling charges, are used for the production estimate.

Deep drawing can be used to fabricate a container with a single girth weld. The container is deep drawn as two half-length, one-end-closed cylinders. If the closure weld could be made at mid-length, the pintle would be welded to the upper shell. For a closure weld at one end, the closed end is cut from one piece for the upper head. The remaining cylinder is welded to the open end of the other piece.

The NI Industries' quote was for 5 containers. For material they assumed 3 start blanks for 1 finish draw. The tooling cost is 25% less than for deep drawing the lower unit to full length. To estimate production costs, the extra material cost is deducted and a factor of 70% is used. This covers the cost of the lower unit except for welding, and the upper head except for welding the pintle.

Quotes for machined heads and centrifugally cast heads for 1500 units are used for the production estimate. No quotes were received for a forged lower head. The quotes for spun heads are for a thickness lower than desired. The heavier reference design thickness makes the piece more difficult to spin.

A forged lower head should be less expensive than the forged upper head—slightly less weight and simpler to machine. For the lower head, reducing the production estimate for the upper head by $500 seems reasonable.

Welding and finishing the lower head and body includes machining the weld prep, fit-up, welding, x-ray and dye check, annealing, and machining to length. Separate quotes were sought for this work scope. No responses were received.

In responding to the bid package, B&W, Wisconsin Centrifugal, and Zak separated the cost of welding the body and lower head. The B&W quote allowed $2K for heat treatment and x-ray. The assumed processing was not automated. The Wisconsin Centrifugal quote did not include post-weld heat treatment. The Zak quote is between the other quotes. Furthermore, the CDA 122 is thicker (1.00 in.) and harder to weld. The relative production costs for welding and finishing the other materials are reduced slightly from the Zak quote (0.31 versus 0.32).

Estimated relative production costs are given in Table 4-10 for the components: body, lower head, and welding and finishing. By summing the appropriate part and fabrication process combinations, the estimated costs are obtained. These estimates are used in the process evaluation.

Body Welded to Head and Cold Worked

Cold work is performed to deform the weld and obtain a more uniform microstructure in order to improve the container performance for nonuniform corrosion. The part is annealed after the cold working operation. Both long seam and girth welds are to be cold worked via the Kaiser Rollmet external roll extrusion process. Feasibility of roll extruding the girth weld has not been demonstrated.

From a cost perspective, the body preform is hoped to be less expensive than the finished body welded to head to offset the roll extrusion costs. The shorter, heavier wall body preform should be easier to machine (shorter length) and have a higher yield (smaller chip weight as percentage of the total). The relative costs are summarized in Table 4-11.

Quotes for open-ended body preforms were not solicited for roll and weld and extrusion. A closed-end-extrusion preform was quoted. Sizes varied for the centrifugally cast quotes. An estimate was made using the quote for 24-in. OD × 1.200-in. average wall bodies, ratioing the cost on a volume basis.

Table 4-10. Estimated production costs—body welded to head
(Relative to roll and weld AISI 304 lower unit with forged head)

		Materials					
		AISI 304L CF3	AISI 316L CF3M	Alloy 825	CDA 122	CDA 715 CDA 952	CDA 964
Body							
Roll and Weld		0.43	0.49	1.11	2.26	—	1.13
Extruded		2.42	2.42	24.56	—	—	4.39
Deep Drawn		2.78	2.78	2.89	4.12	2.89	3.09
Centrifugally Cast		0.58	0.61	—	—	0.41	1.24
Lower Head							
Forged		0.26	0.30	0.57	—	—	0.65
Machined		0.49	0.44	0.88	0.21	—	—
Centrifugally Cast		0.11	0.11	—	—	0.06	0.16
Welding and Finishing		0.31	0.31	0.31	0.32	0.31	0.31
Body Welded to Head							
Body	Head						
Roll and Weld	Forged	1.00	1.10	1.99	—	—	2.09
	Machined	1.24	1.30	2.30	2.78	—	—
Extruded	Forged	2.99	3.03	5.43	—	—	5.04
	Machined	3.23	3.23	5.74	—	—	—
Deep Drawn	Deep Drawn	3.09	3.09	3.20	4.44	3.20	3.40
Cent. Cast	Forged	1.14	1.22	—	—	—	2.20
	Cent. Cast	1.00	1.03	—	—	0.78	1.71
	Machined	1.38	1.41	—	—	—	—

Table 4-11. Relative costs of body welded to head and cold worked (production quantities)
(Relative to roll and welded AISI 304 lower unit with forged head)

		Materials					
		AISI 304L CF3	AISI 316L CF3M	Alloy 825	CDA 122	CDA 715 CDA 952	CDA 964
Body Preform 1.20 Wall Open Ended Cylinder							
Roll and Weld[a]		0.43	0.49	1.11	2.26		1.13
Extrusion							
Deep Drawn							
Centrifugally Cast		0.48	0.52			0.42	0.98
Lower Head[b]							
Forged		0.31	0.35	0.62			0.70
Machined		0.55	0.55	0.93	0.26		
Cent. Cast		0.16	0.16			0.11	0.22
Weld and Inspect		0.31	0.31	0.31	0.32	0.31	0.31
Roll Extrusion (one end closed)		1.41[c]	1.41	1.29		0.93[d]	0.93
Body Welded to Head and Cold Worked							
Body	Head						
Roll and Weld	Forged	2.46	2.57	3.43			3.07
	Machined	2.70	2.76	3.74			
Extruded	Forged						
	Machined						
Deep Drawn	Deep Drawn						
Cent. Cast	Forged	2.51	2.60				2.92
	Cent. Cast	2.37	2.41			1.77	2.43
	Machined	2.70	2.74				

(a) Assumed same as finished body.
(b) Increased over lower head estimate for extra material.
(c) Assume roll extrusion cost for AISI 304L same as AISI 316L.
(d) Assume roll extrusion cost for CDA 613/952 same as CDA 715/964.

The conversion costs for roll extruding either an open or one-end-closed cylinder were obtained from Kaiser Rollmet. For the one-end-closed cylinder, the conversion cost in the tooling costs is higher. The girth weld should be 8 to 10 in. from the bottom to allow forming across the weld. It is assumed that the conversion cost for AISI 304L/CF3 is the same as for AISI 316L/CF3M, and that the conversion cost for CDA 613 is the same as for CDA 715.

Quotes for roll-extruded open-ended cylinders, including the cost of the preform and roll extrusion, were obtained. In a comparison of the body quotes, the roll-extruded body is more expensive than the roll-and-weld or centrifugally cast bodies, and less expensive than the extruded bodies.

In Table 4-11, the relative costs for a one-end-closed, roll-extruded body are determined as the sum of the following components and operations:

- Body preform.
- Head preform.
- Weld head and inspect.
- Roll extrusion (one end closed).

Only the centrifugally cast body preform has been estimated. The roll and weld cylinder estimates for the finished body are used for the preform body for process ranking. The shorter, thicker preform body may have a slightly lower cost. The preform lower head was not quoted. The head skirt must be thicker to weld to the heavier preform. For the preform lower head estimate, $500 was added to the lower head quotes. For welding and finishing the roll extrusion preform, the costs for welding the finished container were used. The estimate for a welded and roll extruded centrifugally cast preform is below the estimates for the integral lower unit and above the estimates for a roll and weld or centrifugally cast body and welded head.

Summary

Relative Material Costs: Based on quotes for the cylindrical body (26-in. OD × 0.375-in. average wall × 180-in. long) for roll and weld pipe and centrifugally cast hollows, the material costs relative to AISI 304L/CF3 are shown below.

	Material					
	AISI 304L CF3	AISI 316L CF3M	Alloy 825	CDA 122	CDA 613 CDA 952	CDA 715 CDA 964
Welded	1.00	1.15	2.75	—	—	2.66
Centrifugally Cast	1.00	1.06	—	—	0.98	2.91

Relative fabrication costs are summarized next The roll-and-weld body and forged lower head in AISI 304L is the reference or base-line cost.

Relative Fabrication Costs (AISI 304L/CF3)

Pintle and Upper Head	
Pintle Welded to Machined Head	0.9
Integral Pintle and Head Forging	0.3
Body and Lower Head	
Integral	3
Welded	
Seamless Wrought Body	3
Roll and Weld Body	1
Centrifugally Cast Body	1
Welded and Cold Worked	
Seamless Wrought Body	No Data
Roll and Weld Body	2.5
Centrifugally Cast Body	2.5

The relative material cost ratios should not be applied to the fabrication cost ratios because processing costs may not be proportional to material costs, and the costs may be overestimated.

4.4. Copper Development Association Activities

B&W engaged the services of the Copper Development Association (CDA) as a consultant on the Fabrication Project because three copper-base materials are under consideration. CDA's expertise in copper complements B&W's expertise in stainless steels and nickel alloys. CDA has been involved with the LLNL program since 1984. They have provided various data, information, and draft papers directly to LLNL. In particular, Kundig (1986) reviewed fabrication alternatives for copper containers by surveying manufacturing options and representative U.S. facilities.

On May 15, 1987, Mr. W. Stuart Lyman, Vice President of CDA, and Dr. Konrad Kundig, consultant to the CDA, visited B&W to discuss the project. Results of the meeting are described in Domain (1987).

Provided below are the CDA tasks and their resultant activities:

Task 1: Provide specific list of vendors and discussion of capabilities.
Result: The CDA prepared a document that was used for the B&W vendor surveys described in Section 4.3.

Task 2: Review B&W's evaluation criteria and provide documentation on the effects of fabrication on the three copper materials.
Result: CDA responded with two documents. One document was a draft report covering the effect of fabrication on the corrosion performance of the three copper materials. The other document contained CDA's rating of the copper materials with regard to failure mechanisms for welded components.

Task 3: Provide access to CDA's data base and previous copper reports.
Result: CDA provided B&W with a copy of a previous report on fabrication that was prepared for LLNL (Kundig, 1986). They also provided handbooks on standards for cast and wrought products.

CDA provided access to the CDA data base of copper literature that resides at Battelle. They demonstrated usage procedures to a B&W librarian for access by modem. Specific references are provided in Section 4.2.

Task 4: Provide miscellaneous consultation services to B&W.
Result: CDA handled miscellaneous telephone calls addressing questions on copper alloys, vendors, etc.

Task 5: Provide a list of vendors for welding cast copper.
Result: CDA prepared a document.

Task 6: Review draft of B&W final report for Phase 1.
Result: CDA reviewed the report with particular attention to any reference to copper-base materials.

CDA expressed the following opinions about the copper materials on LLNL's list:

1. CDA 102—CDA prefers to use CDA 122 (which is phosphorus deoxidized, high residual copper) because it has better weldability. This information was relayed to LLNL.

2. CDA 613—B&W pointed out that there is no ASME BPVC material specification for CDA 613, whereas CDA 614 is covered by ASME BPVC Specifications SB 150, SB 169, and SB 171 in Section II, "Materials Specifications," Part B—Nonferrous Material (1986 Edition). The compositions of the two alloys are very similar as shown in Table 4-12.

Table 4-12. Chemical composition of CDA 613 and CDA 614

	Cu (incl. Ag)	Pb Max	Fe	Sn	Zn Max	Al	Mn Max	Si Max	Ni+ Co Max	P Max
CDA 613	Bal	0.01	2.0–3.0	0.25–0.50	0.10	6.0–7.5	0.20	0.10	0.15	0.015
CDA 614	Bal	0.01	1.5–3.5	—	0.20	6.0–8.0	0.10	—	—	0.015

CDA reported that the tin (Sn) added to CDA 613 is beneficial in increasing SCC resistance, and for that reason it is preferable to CDA 614. The other properties of CDA 613 are comparable to CDA 614, so if CDA 613 is selected, a code case should be prepared. Until then, B&W should use the properties of CDA 614 to represent CDA 613, when the properties of CDA 613 are unavailable.

4.5. Foreign Technology Review

Recognizing that various European concerns have active programs in waste package fabrication and closure, B&W visited with engineers from the United Kingdom, Sweden, and France. Tours of operating facilities and reviews of research work were conducted at several European sites. Although the European waste management programs differ in scope and approach from that of the U.S., valuable information was gained about their rationale and methodology for container fabrication and closure. Details were presented to LLNL via a trip report in the June 1987 monthly report from B&W. The summary of that report is reproduced below.

SPENT FUEL CONTAINER TRIP REPORT
JUNE 1987

SUMMARY

As part of B&W's work on the waste package fabrication and closure development contract for Lawrence Livermore National Lab (LLNL), a team of engineers was organized to meet with English, Swedish, and French nuclear waste specialists to learn what their respective states-of-the-art are. The English Central Electricity Generating Board (CEGB) was contacted on June 12. The meeting with the Swedish specialist (an SKB engineer) was held on June 15 and 16 in England to simultaneously involve the Welding Institute, which is performing the development work for the SKB. The French firm SGN coordinated our June 17, 18, and 19 meetings in France, which consisted of (1) a tour of LaHague (the French state-of-the-art processing and vitrification plant) and meeting with their canister welding engineers, (2) a meeting with SGN development and design engineers at their Paris office, and (3) a tour of Marcoule (their currently operating processing and vitrification plant) and meeting with their canister fabrication and welding specialists.

The CEGB information was helpful in terms of welding equipment and process development. The primary knowledge gained from the SKB meetings include information on their material selection process, development of a Hot Isostatic Press (HIP) process for encapsulation, research into different welding processes for copper, design of their waste package and expected fuel performance during storage. The information from SGN included a detailed review of their stainless steel canister designs (two different glass canisters and one waste canister) their canister welding technology (including qualifications and operating parameters), their general hot cell philosophy, their fuel handling procedures, and their shipping cask operations.

4.6. Overview of Evaluation Methodology

As previously discussed, the YMP is in the preliminary stages of defining performance requirements, design, material selection, etc. Because of this, and because of the large number of interrelationships between processing effects and the possible failure mechanisms in service, a simple weighing and criteria approach did not seem practical to rank the candidate processes. Therefore, B&W devised a rating system to attempt to account for these interrelationships. The resultant system is somewhat complicated and difficult to understand. This section will provide an overview of the system and preview the final result. Details of the system with specific equations, etc., are provided in Section 4.6.2.

Figure 4-7 shows an overview of the fabrication process evaluation criteria. B&W selected three major criteria to rate various manufacturing routines:

- Performance—how a container made by the process performs in service. The primary concern for long-term storage is localized corrosion.
- Fabricability—the consistency and reliability of the process in making a good product in terms of dimensions, surface finish, etc.
- Cost—estimated unit costs assuming a production quantity of 1500 units per year.

As Figure 4-7 shows, the performance criteria consist of 15 different microstructural features of a product with the importance of each feature determined by how it might impact a potential failure or degradation mode in service. These 14 failure modes were taken from the *LLNL Metal Barrier Draft Plan* (McCright, 1987). To assess the importance of the failure mode, each was rated for its likelihood and then the severity level if failure or degradation occurs. The details are described in Section 4.6.2.

Another important part of the performance criteria is microstructure produced by a process. Four types were taken into account: (1) welded, (2) welded and annealed, (3) welded, cold worked, and annealed, and (4) base metal. Each manufacturing process was rated for microstructural type and amount of each microstructural type. The rating process, then, places a large importance on the amount of weld metal because this area is considered most suspect in localized corrosion mechanisms. Therefore, from a performance standpoint, a rolled and welded container receives a lower mark than a seamless integral container with no welds.

The final output of the evaluation system, after suitable normalizations of data, is a rating grade from 0 to 100 (100 = best) for each primary criterion, material type, and process. For example, a rolled and welded lower unit of AISI 304L was graded 38 for performance, 80 for fabricability, and 87 for cost. An integral extrusion was rated 94, 79, and 60, respectively. Thus, the roll and weld had a relatively poor performance rating but a very good cost rating. Although B&W believes that performance is the most important criterion, we are not sure how much more important it is than fabricability or cost. Therefore, it was difficult to assign weights to each primary criterion. B&W was fully aware that the rolled and welded process may be more than adequate for the application, and that the poorer performance rating may be offset by the better cost rating. To attempt to allow for this, B&W chose to use a vector sum normalized to 100 as a preliminary method of combining the 3 primary criteria. A vector sum is the square root of the sum of the squares of each rating. In other words, a vector sum is really a 3-dimensional plot of each of the 3 criteria as illustrated in Figure 4-7.

This is one method of weighting the 3 criteria. As the program progresses, LLNL may revise or refine this method, or perhaps adopt a go-no go rationale for certain criteria, wherein one would choose the lowest cost option of those that met some minimum acceptance standards.

4.6.1. Description of Candidate Processes

From the activities described above, many container fabrication processes and combinations of processes were identified. In Section 3.3, the container was divided into four components: (1) handling pintle, (2) upper head, (3) body, and (4) lower head. The first two components are called the "upper unit" and the last two components the "lower unit," as shown in Figure 3-2. The schematic in Figure 3-3 shows some general approaches for fabricating the lower and upper units as integral one-piece components or as multiple-piece welded assemblies.

For complete information, many process options are listed in Figure 3-3. However, with the use of engineering judgement and practical experience, many processes can be discarded because of insufficient commercial experience, poor quality, or reliability problems. The following processes are excluded from further consideration for the reasons given below.

Sand Casting: General experience at B&W and in industry is that sand castings require extensive weld repairs, are difficult to obtain in high quality, and would pose a serious quality-control problem. By comparison, centrifugal castings are of higher quality and are viable for container components.

Brazing: Joining sections by brazing produces large compositional variations due to the dissimilar metal required for brazing. These variations could lead to galvanic corrosion.

Adhesive Bonding: Degradation of adhesives by radiation from the container contents and the long-term storage at elevated temperature are judged to be unacceptable.

HIP Encapsulation: This could present problems in the retrievability of the container contents. HIPing is performed at 500°C, which is above the maximum 350°C stipulated for the cladding. This temperature would be expected to degrade or rupture the cladding during HIPing. Inspection methods for the HIPed material have not been developed.

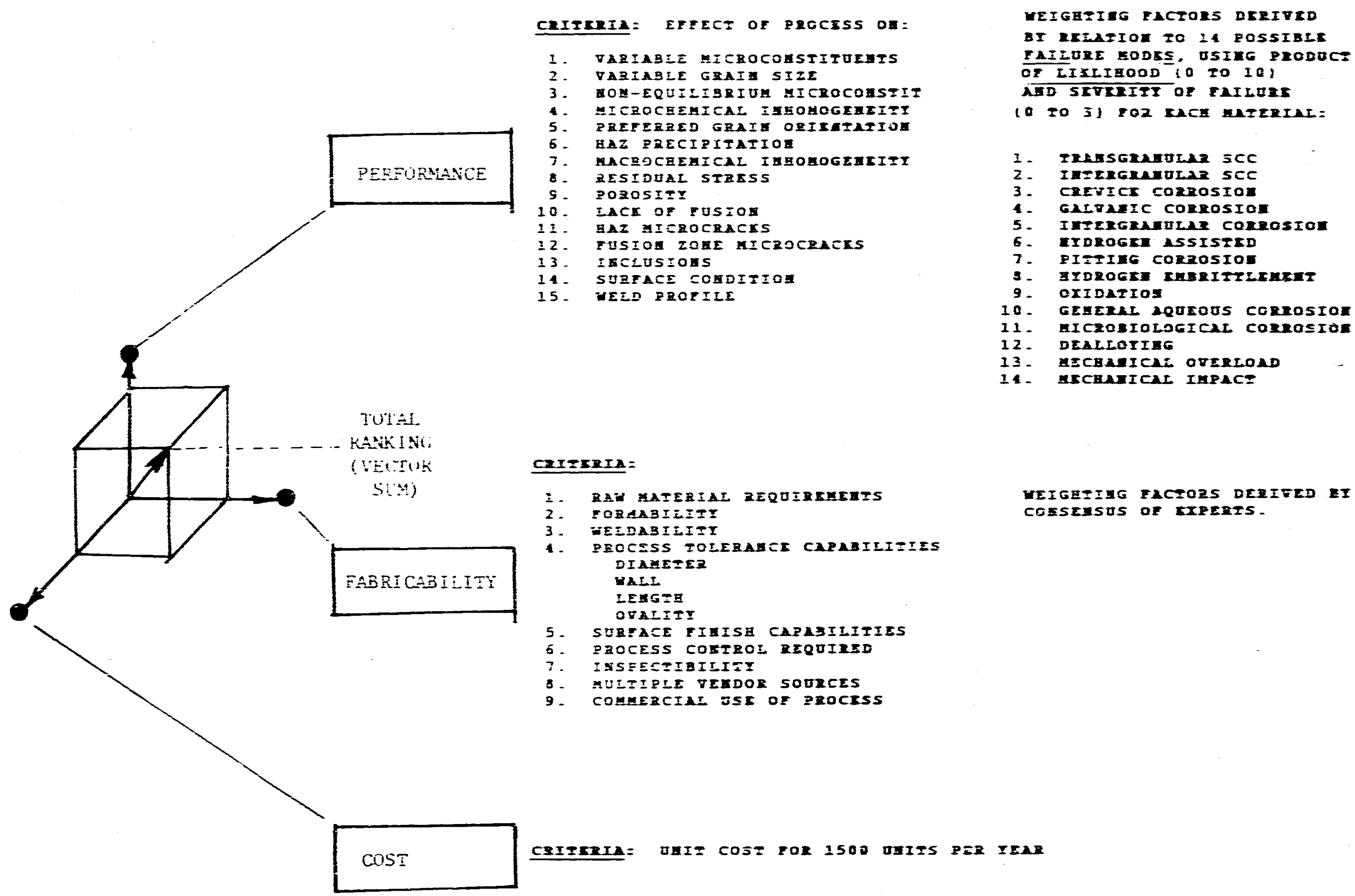


Figure 4-7. Overview of fabrication process evaluation criteria

The processes chosen for evaluation have all been used to make container-like components similar in shape but, in some cases, smaller in size. The processes and related container components are listed below.

- Roll and Weld
  - Welded body.
  - Welded body preform—heavier wall and shorter length.
- Extrusion
  - Integral lower unit—one end closed, hollow.
  - Integral lower unit preform—one end closed, hollow with heavier wall and shorter length.
  - Seamless body.
  - Seamless body preform.
- Deep Drawn
  - Integral lower unit.
  - Integral lower unit preform.
  - Welded lower unit—two half-length one-end-closed hollows; cut end from one for top head and weld remaining cylinder to other piece for lower unit.
  - Heads.
- Centrifugal Casting
  - Seamless body.
  - Seamless body preform.
  - Heads.
- Spinning
  - Integral lower unit preform.
  - Heads.
- Roll Extrusion
  - Convert lower unit preform or body preform to finish size.

These processes are used alone or in combination as described in Section 4.6.2. A brief description of each process follows.

Roll and Weld

The roll and weld process starts with flat rolled plate. The length and thickness of the plate are the same as for the container. The plate width matches the body circumference, allowing for any stretching that may occur in bending.

A three-roll initial pinch bender is shown in Figure 4-8. In this machine, the top roll center is fixed and the roll is undriven or idle. The vertical gap between the pinch and top rolls is set to the plate thickness. The back roll is adjusted to obtain the desired bend radius. The roll bending concerns include obtaining a straight unbent edge at the long seam and good edge match-up over the length of the cylinder for welding. The 15-ft cylinder length may make fit-up more of a problem than with shorter lengths. Depending on the geometric requirements, the plate edges may be pre-bent using a die and pressing beam. The edge fit-up can be handled with fixturing to pull the edges together for the welding (Kundig, 1986). Roll and weld is a common process used for pipe fabrication. Welding and inspection techniques to meet the anticipated container requirements are in place. Many fabricators should be able to meet the requirements.

Extrusion

The Cameron Forge (Houston, Texas) processes for blocking (upsetting and piercing) and tube extrusion are illustrated in Figures 4-9 and 4-10 which are taken from Cameron literature. In the blocking

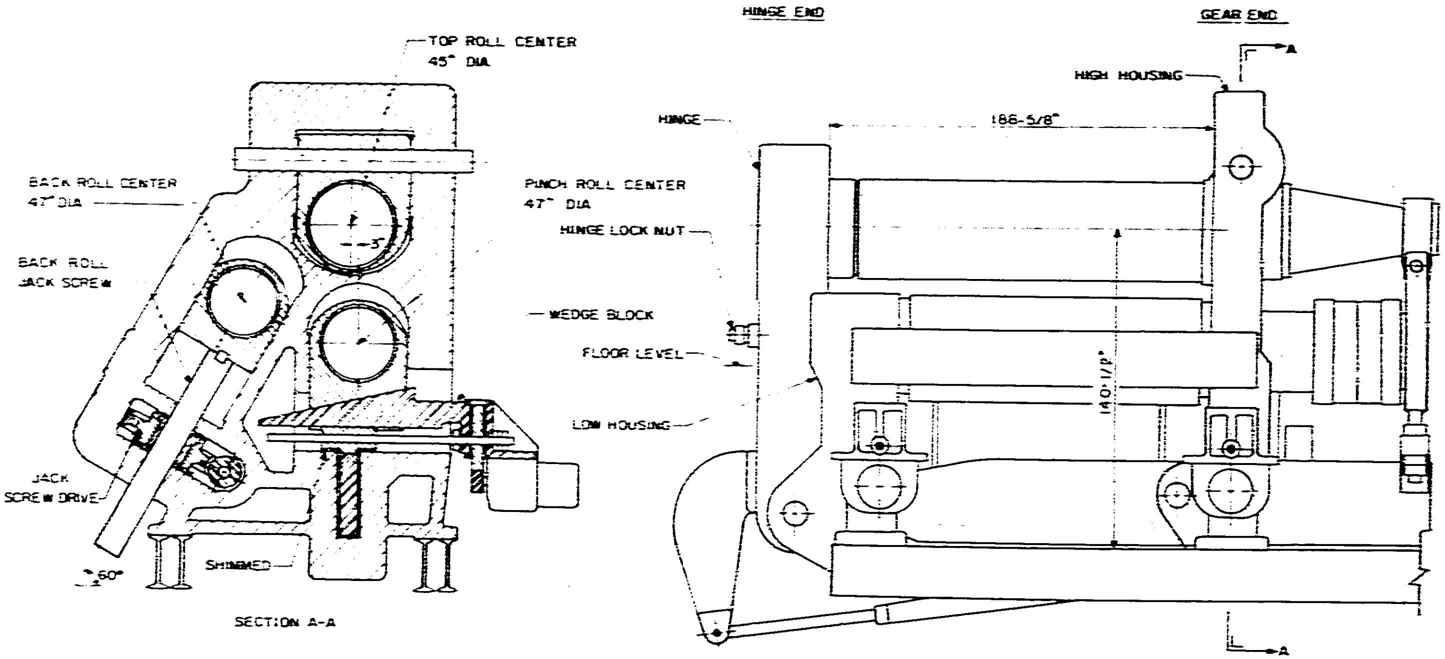


Figure 4-8. Three-roll initial pinch bender

Cameron Seamless Extruded Pipe — Blocking Sequence

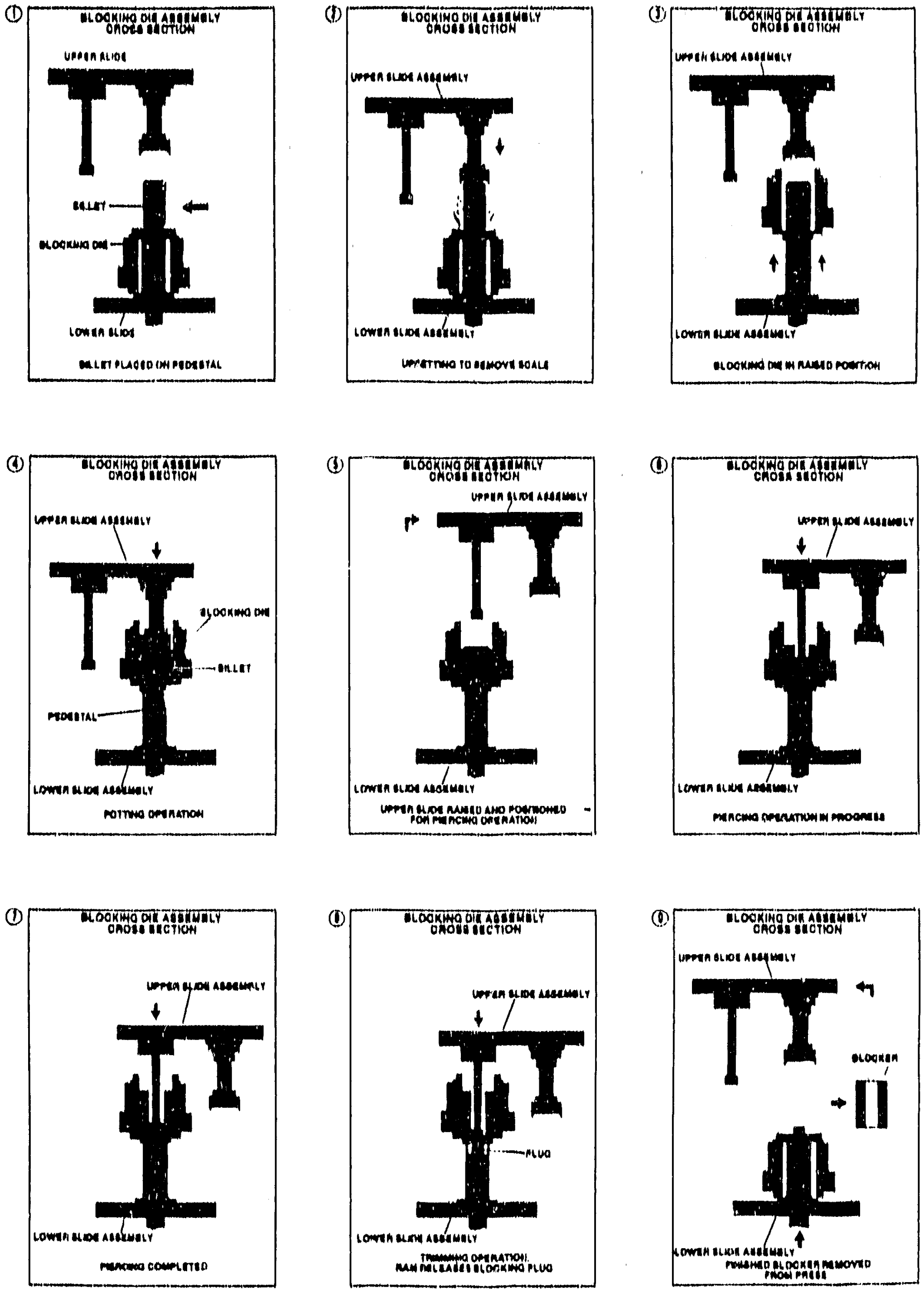


Figure 4-9. Cameron Forge blocking sequence

Cameron Seamless Extruded Pipe **Extrusion Sequence**

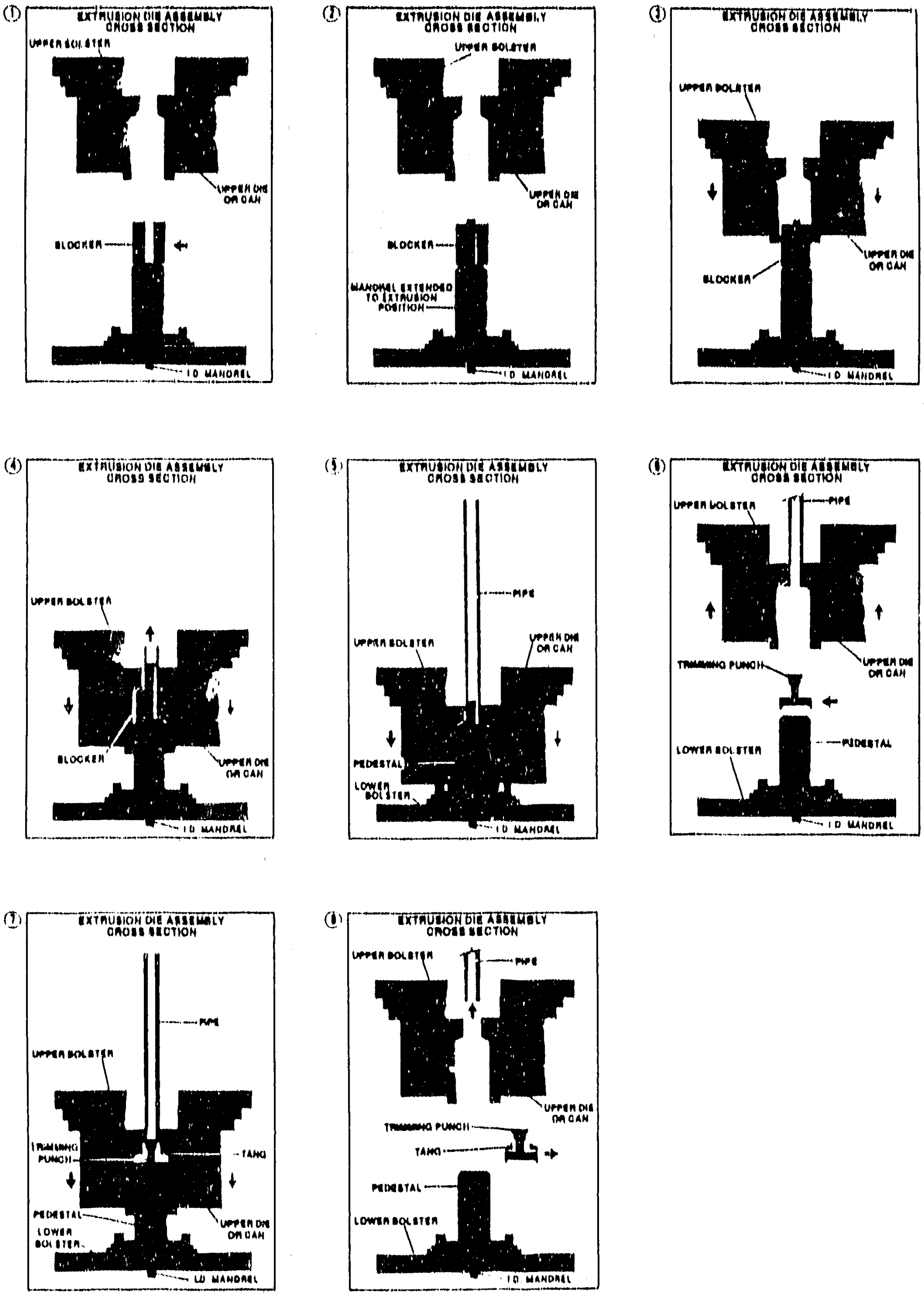


Figure 4-10. Cameron Forge extrusion sequence

sequence, Plates 1 and 2 of Figure 4-9 show upsetting the billet to remove scale, Plates 3 and 4 show the potting operation (upsetting the billet in a closed die to size the diameter), and Plates 5, 6, and 7 show piercing of the center hole or back extrusion. Plate 8 shows the end plug being sheared from the blocker and Plate 9 shows stripping the die from the blocker. For piercing a closed-end billet, the piercing operation (Plate 8) is stopped to leave the desired bottom or end thickness.

The next figure (Figure 4-10) shows the extrusion sequence. Plates 1, 2, and 3 show placing the blocker on the pedestal, raising the mandrel through the blocker, and lowering the extrusion container and die over the blocker. Extrusion is shown in Plates 4 and 5. The upper die is forced down over the pedestal causing the tube to be extruded upward through the annular space between the mandrel and the die. Not all of the blocker can be extruded. The discard is sheared from the tube by the trimming punch as shown in Plates 6 and 7. The pipe is removed, the upper die lifted, and the trimming punch removed as shown in Plate 8.

For extruding pipe with one end closed (blind end), the mandrel (Plate 2) is inserted in the closed-end blocker. At the start of extrusion, the mandrel may be below the die. The extrusion orifice (minimum annular space between mandrel and die) starts large, reduces until the mandrel enters the die, and then remains constant. The closed end is extruded under these non-steady-state conditions. The blocker may be preformed to assist the extrusion start-up.

Deep Drawing

Deep drawing is used to make axisymmetric parts from sheet or plate material (ASM, 1969). Typically, the starting material is a disk of diameter much greater than the thickness. The blank is placed over a circular die hole (Figure 4-11). The holddown ring prevents the blank edges from dashing upward. The punch pushes the blank through the die to form a cup. In the first draw or cupping operation, a 40% reduction in diameter (40-in.-diam blank to 26-in.-diam cup) from blank to cup is typical. The wall thickness generally increases at the edge of the blank due to the radially inward flow. With no wall reduction or ironing from the tooling, and minimal friction, the 40% reduction in diameter (43% logarithmic strain) would cause the edge wall to increase about 21.5%. Also at the edge of the blank, the radial distance between the edge and a circle scribed on the blank near the edge would increase by 21.5% when measured on the cup. With tool friction (die and holddown ring), the wall thickness increase would be less and the edge stretch or elongation more. For deep drawing the container (depth of draw 7 diameters), many draw operations are required depending on the material grade. A part with similar depth-to-diameter ratio is depicted as "Example 265" in Figure 4-12 (ASM, 1969). The 8-in. OD × 0.150-in. wall × 62-in. long piece is one-third the container size. Six drawing operations were required. The material was hot rolled carbon steel, which is easy to work and easy to lubricate.

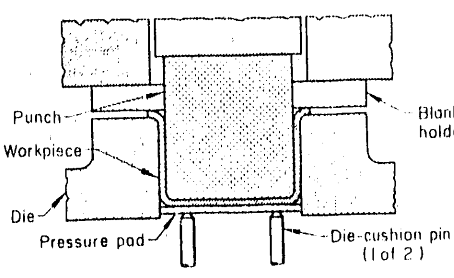
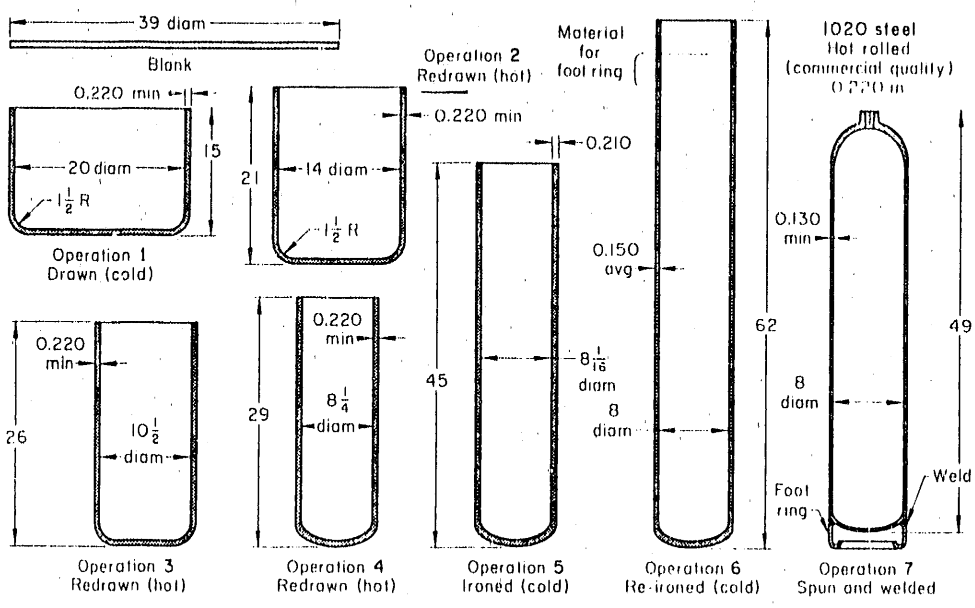


Figure 4-11. Deep drawing of cup (reprinted from ASM, 1969)



Presses:	Die materials:
Draw ....1500-ton double-action hydraulic	Hot operations ....Graphitic tungsten tool steel(b)
First redraw 500-ton double-action hydraulic	Cold operations ....D2 tool steel
Other redraws ....500-ton single-action hydraulic	Die hardness ....Rockwell C 60
Lubricants:	Tool life, pieces per grind(c) 1000
Draw ....Sulfonated oil	Lot size, pieces 1000
Fourth and fifth redraws(a) ....Dry soap	Annual production, pieces 1000

(a) Including ironing operations, which needed additional lubrication. (b) 1.50% C, 0.40% Mn, 0.65% Si, 2.80% W. (c) Tools were reconditioned after annual run.

Fig. 66. Cylinder (for chlorine gas) that was produced from one blank (Example 265)

Figure 4-12. Deep drawing sequences for making gas cylinders (reprinted from ASM, 1969)

Austenitic stainless relative to carbon steel will require about double the force, slower ram speeds, and more between-draw anneals.

Deep drawing requires relatively expensive tooling and is a high volume production technique. The tool cost-per-piece depends on the production volume.

Centrifugal Casting

In the centrifugal casting process, liquid metal is poured into a rotating mold (vertical or horizontal). Most parts are bodies of revolution, however, only axisymmetry is required for balance. The centrifugal force (65 to 100 g—Medley and Quinn, 1987) holds the metal against the mold wall. Solidification is from the mold wall inward as illustrated in Figure 4-13 from Medley and Quinn (1987).

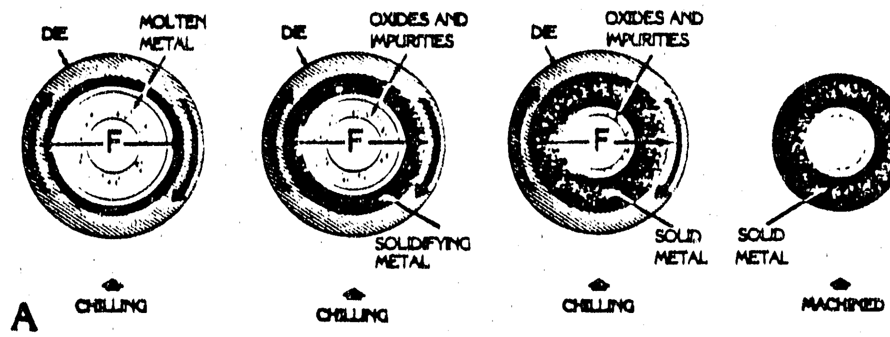


Figure 4-13. Centrifugal casting events (reprinted from Medley and Quinn, 1987)

The lower density oxides and impurities are displaced toward the ID by the higher density liquid metal. As the metal freezes at the mold wall, metal contraction occurs in sequence from cooling liquid, solidification, and cooling solid. The central core of liquid metal forced to the outside provides liquid metal to compensate for the volume change and eliminate void formation. The following summary of advantages for centrifugal casting is from Medley and Quinn (1987).

- High degree of soundness and cleanliness.
- Dense homogeneous structure.
- Uniform strength at all points in all directions.
- Freedom from porosity.
- No directional or center weakness.
- Versatility of shape.

Centrifugal castings of the diameter and length required for the nuclear-waste container are common. The reference 0.375-in. container wall is small relative to typical centrifugal castings, and a double, or slightly heavier, wall might be more economical (less machining). Shorter, heavier wall preforms for subsequent working will not be a problem.

Spinning

Spinning forms bodies of revolution from initially flat disks (Figure 4-14). The start blank (disk) is cut from sheet (plate). The blank is clamped to the form. The spinning roller is positioned and the blank rotated. The spinning roller follows the Figure 4-14 automatic spinning contour set by the tracer. The figure shows several intermediate contours. In this free-spinning process, the blank thickness is not reduced. Blank dimensions were estimated for the container based on part volume (26-in. OD × 0.396-in. wall × 180-in. long, bottom thickness equals blank thickness) as follows:

Blank Size (in.)		Cup Size (in.)		
Thickness	Diameter	OD	Wall	Length
1.188	85	26	1.188	66
1.500	77	26	1.500	55
2.000	68	26	2.000	50

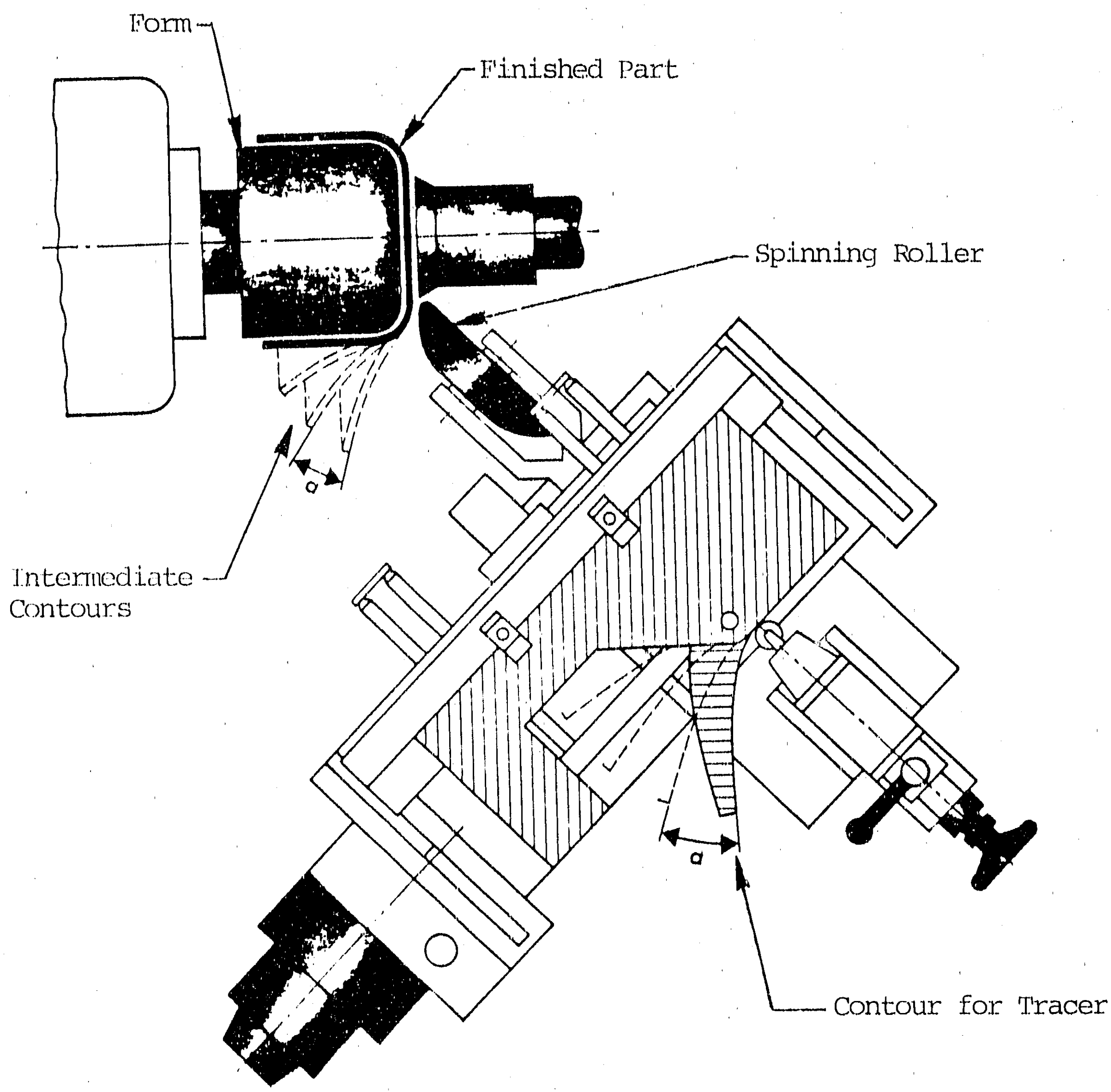


Figure 4-14. Automatic spinning

For cups, the corner radius should be 1 to 1.5 times the blank thickness. The cup made by spinning can then be elongated by roll extrusion (discussed elsewhere) or flow turning. In flow turning, the cup wall thickness is reduced between a mandrel and external roll. In flow turning, the external roll does not encircle the work piece. The roll center is outside of the work piece.

Advantages of spinning include simple start material (sheet or plate) and simplified tooling relative to press forming. The relative tooling expense is sensitive to the part volume—savings are more significant at lower volumes. Typical spun parts are smaller and lighter than the nuclear waste container preform cups.

External Roll Extrusion

The external roll extrusion process was developed by Rollmet (now Kaiser-Rollmet). The process is shown schematically in Figure 4-15. The mandrel is placed inside the tube hollow. The external ring rollers encircle the tube and mandrel. The tube wall is reduced between the roller and mandrel. The tube ID remains nearly constant. The external ring roller centerlines are offset and skewed with respect to the tube axis. The offset causes one ring roller to work the tube on one side of the mandrel and the other roller to work the opposite side. By skewing the axis relative to the tube centerline, the external ring roller contact points are on opposite sides of the tube at the same axial position. This arrangement balances the forces in the horizontal plane. The process is used for precise cylindrical components—high diameter-to-wall ratios (over 15) and precise wall tolerances. The diameter-to-wall ratio for the reference container is 65 to 1. The container geometry is well-suited for the roll extrusion process. Diameter-to-wall ratios greater than 15 are difficult to make with good wall tolerances using primary seamless manufacturing processes such as extrusion. Thus, roll extrusion with a primary seamless process may be a good combination.

Roll extrusion of long seam-welded cylinders requires the highest level of weld integrity to withstand the required deformations. As such, the process is a test of weld integrity.

Roll extrusion of a girth weld apparently has not been attempted. Again, a high level of weld integrity would appear to be necessary. Working of the welds is desired to break up the weld microstructure and reduce susceptibility to nonuniform corrosion.

4.6.2. Evaluation Criteria and Methodology

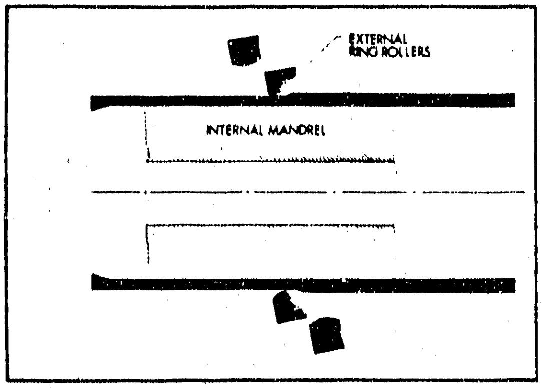
Methodology

To aid in evaluating alternate fabrication methods for the YMP waste containers, three primary criteria were identified:

- Performance—how the proposed fabrication method impacts performance. The primary concern for long-term waste containment is nonuniform corrosion.
- Fabricability—what the fabrication process requires of the starting material (formability, weldability), whether the process meets dimensional requirements (tolerances, surface finish), and whether the process is used commercially.
- Cost—estimated unit costs assuming a production quantity of 1500 units per year.

A process ranking is calculated numerically by considering the product and the process. With respect to each primary criterion (performance, fabrication and cost), a list of product criteria, features, or characteristics is made. A numerical value is assigned to the product criterion based on the relative importance of the feature—the more important the feature, the higher the numerical value.

EXTERNAL ROLL EXTRUSION

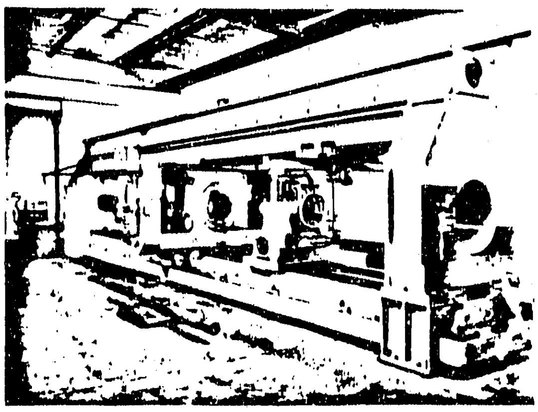


The process starts with a forged cup, ring blank, or right cylinder (pipe, extrusion, etc.). External pressure rollers work the metal from the outside, with or without an internal mandrel, as the blank increases in length.

Dimensional control and special contours can be obtained through tape programming, using one or more passes as required to produce the final form.

APPLICATION

ROLLMET applies wherever the requirement is for high performance, precision cylindrical structural components, especially where welding is undesirable for design or economic reasons. Material and tooling costs are reduced, and subsequent machining is minimized. Typical examples of current applications include components for missiles, chemical process plants, seamless preform sections, gas turbines, aircraft, ordnance, nuclear, commercial, marine and electronic equipment.



MATERIALS

ROLLMET shapes are available in many materials.

MARAGING STEEL	ALUMINUM
TITANIUM	ALLOY STEEL
STAINLESS	NICKEL BASE ALLOYS
COPPER	REFRACTORY METALS
BERYLLIUM	

Additional metals and alloys will be provided as development work progresses. Materials for certain shapes can be either cold or hot rolled.

FEATURES

Completely seamless	Very thin walls available
Eliminates welding	Superior surface finish
Rolled weldments have enhanced properties	Variety of starting blanks can be utilized
Accurate sizing	Maximum material economy

Meets the requirements in such demanding applications as seamless, collapsible expulsion storage containers.

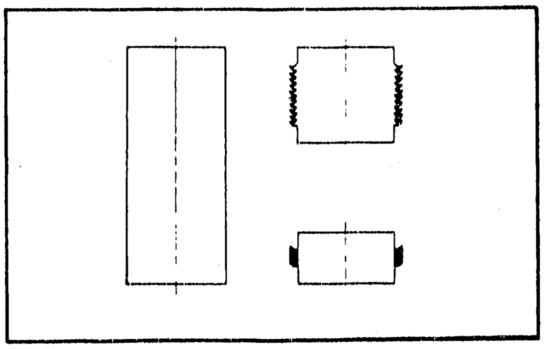


Figure 4-15. Rollmet's external roll extrusion

In the current project, the product features are cast in a negative context (i.e., they represent potential problems). In rating the ability of each process to influence the product features, a process criteria value is assigned between 0 and 5, where 0 indicates that the process eliminates potential problems associated with a particular product feature (e.g., annealing eliminates residual stress as a performance concern) and 5 denotes that the process exacerbates a problem.

A process index value is calculated as the sum of the products of the product criteria values and the process criteria values. In equation form,

$$IV = \sum_{I=1}^{N} PROD(I) \times PROC(I)$$

where IV = index value;
N = number of product criteria;
PROD(I) = product criterion value, relative importance of the product feature;
PROC(I) = process criterion value, influence of the process on the product "0" denotes that the process eliminates problems associated with the product criterion.

After the index values are calculated for each process, they are normalized as follows:

$$NORM = \left(1 - \frac{IV}{IVMAX}\right) \times 100$$

where NORM = normalized value,
IV = index value,
IVMAX = maximum index value (5 times the sum of the product criteria values).

Thus, when IV = 0, NORM = 100, and this is the perfect process.
When IV = IVMAX, NORM = 0, and this is the worst possible process.

Index and normalized values are calculated for performance, fabrication, and cost. Over the course of the project, various methods of weighing the criteria for deriving an overall ranking were considered. Because the rankings of processes for performance and cost may be related—good performance ranking and poor cost ranking or vice versa—an arbitrary weighting system could be used to skew the results in either direction.

Thus, each criterion is evaluated separately and may be combined with emphasis placed on the three primary criteria as desired. Overall rankings for performance and fabrication and for all three criteria are given as vector sums (square root of sum of squares) for the normalized values of the criteria. The combined rankings are normalized to 100 by dividing by the square root of 2 for summing two criteria and by the square root of 3 for summing three criteria.

The ranking procedure for each of the primary criteria—performance, fabrication, and cost—is discussed separately.

<u>Processes</u>

The processes being considered are described next and numbered.

Upper Head (Processes UH-01 to UH-08)

The upper head (UH) includes both the head and the handling pintle. The fabrication processes are:

	Pintle	Upper Head
UH-01	Machined	Forged
UH-02	Machined	Spun
UH-03	Machined	Deep drawn
UH-04	Machined	Centrifugally cast
UH-05	Machined	Machined
UH-06	Integral	Forged
UH-07	Integral	Centrifugally cast
UH-08	Integral	Machined

Processes UH-04 and UH-07 use centrifugally cast components and would use the cast form of the alloys being considered where available. The alloys without cast equivalents are considered to be unavailable as centrifugal castings.

Processes UH-01 to UH-05, machined pintle welded to the head, all require weldability and inspectability. The integral processes, UH-06 to UH-08, do not require welding during fabrication. The closure weld is covered under a separate project.

Lower Unit (Processes LU-01 to LU-43)

The lower unit (LU) consists of the lower head and the cylindrical body section. Processes LU-01 to LU-03 are an integral body and lower head, and have no welds. The remaining 40 processes all have a girth weld joining the body and lower head.

Processes LU-04 to LU-23 represent 4 methods of body manufacture, and 5 methods of head manufacture (20 combinations).

Processes LU-24 to LU-43 represent the same body and head manufacturing methods as LU-04 to LU-23, followed by cold working of the body including the girth weld.

For all processes, the component is final annealed to eliminate residual stresses and sensitization. The processes are enumerated below.

Integral Body and Lower Head

LU-01 Extruded Closed-End Cylinder
LU-02 Extruded Closed-End Cylinder and Cold Worked Body
LU-03 Deep Drawn Closed-End Cylinder

Welded Lower Unit

	Body		Lower Head		Remarks
LU-04	BO1	Roll and Weld	LH-01	Forged	
LU-05			LH-02	Spun	
LU-06			LH-03	Deep Drawn	
LU-07			LH-04	Centrifugally Cast	NA1
LU-08			LH-05	Machined	

Welded Lower Unit (cont'd)

	Body		Lower Head		Remarks
LU-09	BO2	Extruded	LH-01	Forged	
LU-10			LH-02	Spun	
LU-11			LH-03	Deep Drawn	
LU-12			LH-04	Centrifugally Cast	NA1
LU-13			LH-05	Machined	
LU-14	BO3	Deep Drawn	LH-01	Forged	NA2
LU-15			LH-02	Spun	NA2
LU-16			LH-03	Deep Drawn	
LU-17			LH-04	Centrifugally Cast	NA1,2
LU-18			LH-05	Machined	NA2
LU-19	BO4	Centrifugally Cast	LH-01	Forged	
LU-20			LH-02	Spun	
LU-21			LH-03	Deep Drawn	
LU-22			LH-04	Centrifugally Cast	
LU-23			LH-05	Machined	

Welded Lower Unit—Cold Work Body and Girth Weld

	Body		Lower Head		Remarks
LU-24	BO1	Roll and Weld—Cold Work after Welding	LH-01	Forged	
LU-25			LH-02	Spun	
LU-26			LH-03	Deep Drawn	
LU-27			LH-04	Centrifugally Cast	NA1
LU-28			LH-05	Machined	
LU-29	BO2	Extruded—Cold Work after Welding	LH-01	Forged	
LU-30			LH-02	Spun	
LU-31			LH-03	Deep Drawn	
LU-32			LH-04	Centrifugally Cast	NA1
LU-33			LH-05	Machined	
LU-34	BO3	Deep Drawn—Cold Work after Welding	LH-01	Forged	NA2
LU-35			LH-02	Spun	NA2
LU-36			LH-03	Deep Drawn	
LU-37			LH-04	Centrifugally Cast	NA1,2
LU-38			LH-05	Machined	NA2
LU-39	BO4	Centrifugally Cast—Cold Work after Welding	LH-01	Forged	
LU-40			LH-02	Spun	
LU-41			LH-03	Deep Drawn	
LU-42			LH-04	Centrifugally Cast	
LU-43			LH-05	Machined	

NA1 Centrifugally cast head not allowed with forged body.

NA2 Deep drawn body produces the heads as part of the process. Alternate head forming may be used if configuration of the head cannot be met by deep drawing.

Performance Criteria

The performance requirements are based primarily on the expected effects of welds on possible degradation modes given i. the *LLNL Metal Barrier Draft Plan* (McCright, 1987). Experience has shown that, in cases of localized corrosion, welds are more susceptible to failure than base metal because of the inhomogeneities of their composition, microstructure, and stresses. Compared to the welds, the base metal degradation modes are substantially reduced and of lesser importance. For this reason, the number of welds in the container is to be limited to a maximum of a pintle attachment weld, a longitudinal seam weld in the body, and a girth weld attaching the bottom head to the body. Since the base metal corrosion resistance is expected to be so much better than that of the weld metal, a seamless construction is preferred. However, it is not known if a nonwelded fabrication and the concomitant higher costs are necessary.

The performance product criteria values are identical to those developed in the Closure Project. The tables and a brief explanation of the methodology are given. The process is fully described in the Closure Development Report.

The product criteria are the "Summation of the Weighted Material and Process Consideration Factors" for the Closure Development Report. They are developed from the possible degradation or failure modes given in the *LLNL Metal Barrier Draft Plan* (McCright, 1987).

Fourteen potential failure mechanisms are listed in Table 4-13. For each alloy material, the 14 failure mechanisms are assigned numerical values for likelihood of occurrence (L = 0–10) and for severity of occurrence (S = 0–3). For example, the transgranular SCC failure mechanism of the AISI 304L and CF3 alloys is assigned a 5 for likelihood of occurrence and a 3 for severity of occurrence. The cracking is considered to be severe because it is a localized attack and is difficult to allow for in the container design. As another example, the oxidation failure mechanism is likely to occur (L = 10), but the severity is low (S = 0.5) because it is easily allowed for in the container design. Multiplying the likelihood factor (L) by the severity factor (S) gives us the weighting factor (W) for each failure mechanism. The weighting factor indicates the mechanism's relative importance—the higher the number the greater the concern with the failure mechanism. For the AISI 304L and CF3 alloys, the transgranular SCC and oxidation weighting factors are 15 and 5, respectively. The table shows that the weighting factors for those particular alloys fall between the extreme value of 18 for intergranular SCC and 0.9 for galvanic corrosion.

A material index may be calculated as the sum of the weighting factors. A higher numerical value implies a greater concern for failure of a particular material. It was not the intent of the current projects (Fabrication and Closure) to compare materials. The numbers were assigned independently for each material and were not specifically evaluated relative to the other materials. Any subsequent differences in performance ratings among material grades are based on the values in Table 4-13.

Table 4-13. Failure mechanism weighting factors

MATERIAL ORDER	304L, CF3			316L, CF3M			IN825			OFC CDA122			Al-Br CDA613,952			70/30 CuNi CDA715,964		
FAILURE MECHANISM	L	S	W	L	S	W	L	S	W	L	S	W	L	S	W	L	S	W
Transgranular Scc	5.0	3.0	15.0	4.5	3.0	13.5	1.0	3.0	3.0	1.0	3.0	3.0	2.0	3.0	6.0	2.0	3.0	6.0
Intergranular Scc	6.0	3.0	18.0	5.0	3.0	15.0	1.0	3.0	3.0	0.2	3.0	0.6	1.5	3.0	4.5	0.1	3.0	0.3
Crevice corrosion	8.0	2.0	16.0	8.0	2.0	16.0	6.0	1.5	9.0	3.0	1.0	3.0	3.0	1.5	4.5	3.0	1.5	4.5
Galvanic corrosion	0.5	1.8	0.9	0.5	1.8	0.9	0.5	1.0	0.5	0.1	1.0	0.1	0.2	1.0	0.2	0.1	1.0	0.1
Intergranular corrosion	7.0	2.0	14.0	6.0	2.0	12.0	4.0	1.5	6.0	2.0	2.0	4.0	1.0	1.5	1.5	1.0	1.5	1.5
Hydrogen assisted cracking	0.5	3.0	1.5	0.5	3.0	1.5	0.2	2.8	0.6	0.1	3.0	0.3	0.1	2.8	0.3	0.1	2.8	0.3
Pitting corrosion	7.0	2.0	14.0	6.0	2.0	12.0	5.0	1.5	7.5	2.0	1.8	3.6	3.0	1.5	4.5	2.0	1.5	3.0
Hydrogen embrittlement	0.5	3.0	1.5	0.5	3.0	1.5	0.2	2.8	0.6	0.1	3.0	0.3	0.1	2.8	0.3	0.1	2.8	0.3
Oxidation	10.0	0.5	5.0	10.0	0.5	5.0	10.0	0.5	5.0	10.0	0.5	5.0	10.0	0.5	5.0	10.0	0.5	5.0
General aqueous corrosion	10.0	1.0	10.0	10.0	1.0	10.0	10.0	0.8	8.0	10.0	1.0	10.0	10.0	1.0	10.0	10.0	1.0	10.0
Microbiological corrosion	6.0	2.5	15.0	5.8	2.5	14.5	4.0	2.0	8.0	5.0	2.5	12.5	4.0	2.5	10.0	5.0	2.5	12.5
Dealloying	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	2.7	13.5	5.0	2.7	13.5
Mechanical overload	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mechanical impact	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
MATERIAL INDEX			112.9			103.9			53.1			44.4			62.3			59.0

Scc - Stress corrosion cracking
L - Likelihood of occurrence (0-10)
S - Severity of occurrence (0-3)
W - Weighting factor (W=L*S)

Product Criteria

The next step is to identify product criteria or features that relate to the failure mechanisms. The failure mechanisms and product criteria are listed below.

Failure Mechanisms	Product Criteria
Transgranular SCC	Variable Microconstituents
Intergranular SCC	Variable Grain Size
Crevice Corrosion	Nonequilibrium Microconstituents
Galvanic Corrosion	Microchemical Inhomogeneity
Intergranular Corrosion	Preferred Grain Orientation
HAC	HAZ Precipitation
Pitting Corrosion	Macrochemical Inhomogeneity
Hydrogen Embrittlement	Residual Stress
Oxidation	Porosity
General Aqueous Corrosion	Lack of Fusion
Microbiological Corrosion	HAZ Microcracks
Dealloying	Fusion Zone Microcracks
Mechanical Overload	Inclusions
Mechanical Impact	Surface Condition
	Weld Profile

As noted previously, the methodolgy developed in the Closure Development Report is being used. The failure mechanisms are negative in context as are the product criteria. The product criteria are oriented to a welded microstructure.

For each failure mechanism, numerical values or weightings are assigned to each product criterion. These weightings are normalized to 10 in the Closure Development Report. The normalized values for AISI 304L/CF3 for transgranular and intergranular SCC are listed below.

	Transgranular SCC		Intergranular SCC	
Product Criteria	Normalized to 10	Weighting Factor 15	Normalized to 10	Weighting Factor 18
Variable Microconstituents	1.47	22.05	1.36	24.48
Variable Grain Size	0.18	2.70	0.34	6.12
Nonequilibrium Microconstituents	0.74	11.10	0.68	12.24
Microchemical Inhomogeneity	1.65	24.75	1.53	27.54
Preferred Grain Orientation	0.07	1.05	0.68	12.24
HAZ Precipitation	1.47	22.05	1.36	24.48
Macrochemical Inhomogeneity	0.74	11.10	0.68	12.24
Residual Stress	1.84	27.60	1.69	30.42
Porosity	0.18	2.70	0.17	3.06
Lack of Fusion	0.37	5.55	0.34	6.12
HAZ Microcracks	0.37	5.55	0.34	6.12
Fusion Zone Microcracks	0.37	5.55	0.34	6.12
Inclusions	0.18	2.70	0.17	3.06
Surface Condition	0.18	2.70	0.17	3.06
Weld Profile	0.18	2.70	0.17	3.06
	10.00	150.00	10.00	180.00

The normalized values may be thought of as a partition function distributing susceptibility to the failure mechanism among the product criteria. Thus, susceptibility to transgranular SCC is associated primarily with:

	Normalized	As a Percentage
Variable Microconstituents	1.47	14.7
Microchemical Inhomogeneity	1.65	16.5
HAZ Precipitation	1.47	14.7
Residual Stress	1.84	18.4
		64.3

These four product criteria account for more than half the susceptibility of the material to transgranular SCC.

Also shown are the values for intergranular SCC. The same four product criteria are again most important. Multiply the normalized product criteria by the weighting factor for the failure mechanism to obtain a value for each combination of product criterion and failure mechanism. Product criteria values are summed for all failure mechanisms to obtain the product criteria. The product criterion failure mechanism array for AISI 304L/CF3 is given in Table 4-14. (Note: Figures 5-1 through 5-6 in Section 5 contain summary tables for all materials, and detailed tables for AISI 304L/CF3.)

For each failure mechanism, the first row gives the normalized value for each product criterion, which summed across the page has a value of 10. The second row gives the product of the weighting factor from Table 4-13 and the normalized criterion value. By summing vertically, we obtain the unweighted summation and the product criterion values (weighted summation). This establishes the relative importance of each product criterion relative to all failure mechanisms for each material. For AISI 304L/CF3 the product criteria values greater than 100 are:

Product Criterion	Value
Variable Microconstituents	122.70
Nonequilibrium Microconstituents	100.83
Macrochemical Inhomogeneity	158.06
HAZ Precipitation	130.23
	511.82

These four product criteria account for nearly half the susceptibility to failure by the mechanisms listed and would, therefore, be of primary concern in considering how the fabrication process affects them.

The performance product criterion values for all container materials are shown in Table 4-15. Differences in the respective product criteria sums are due solely to differences in the weighting factors given in Table 4-13. The sum of the product criteria is 10 times the material index from Table 4-13.

Process Criteria

The process criterion values represent the ability of the processing to affect the product criteria. As the product criteria are cast in a negative context, the process criteria are assigned values from 0 to 5, with 0 being the best. A "0" indicates that the process eliminates any deleterious effects associated with the product criterion.

Table 4-14. Product criterion failure mechanism array for AISI 304L/CF3

PRODUCT CRITERIA - NORMALIZED AND WEIGHTED VALUES

MATERIAL & PROCESS CONSIDERATION FACTORS (UNWEIGHTED/WEIGHTED)	VARIABLE MICROCONSTITUENTS	VARIABLE GRAIN SIZE	NON-EQUILIBRIUM MICRO-CONSTITUENT	MICROCHEMICAL INHOMOGENEITY	PREFERRED GRAIN ORIENTATION	HAZ PRECIPITATION	MACROCHEMICAL INHOMOGENEITY	RESIDUAL STRESS	POROSITY	LACK OF FUSION	HAZ MICROCRACKS	FUSION ZONE MICROCRACKS	INCLUSIONS	SURFACE CONDITION	WELD PROFILE
Transgranular Scc	1.47	0.18	0.74	1.65	0.07	1.47	0.74	1.84	0.18	0.37	0.37	0.37	0.18	0.18	0.18
weight fctr = 15.00	22.05	2.70	11.10	24.75	1.05	22.05	11.10	27.60	2.70	5.55	5.55	5.55	2.70	2.70	2.70
Intergranular Scc	1.36	0.34	0.68	1.53	0.68	1.36	0.68	1.69	0.17	0.34	0.34	0.34	0.17	0.17	0.17
weight fctr = 18.00	24.48	6.12	12.24	27.54	12.24	24.48	12.24	30.42	3.06	6.12	6.12	6.12	3.06	3.06	3.06
Crevice corrosion	0.72	0.24	0.96	1.08	0.36	0.72	0.36	0.12	1.20	1.20	1.20	1.20	0.48	0.07	0.07
weight fctr = 16.00	11.52	3.84	15.36	17.28	5.76	11.52	5.76	1.92	19.20	19.20	19.20	19.20	7.68	1.12	1.12
Galvanic corrosion	0.90	0.18	0.90	0.90	0.18	1.20	2.99	0.18	0.30	0.30	0.30	0.30	1.20	0.12	0.06
weight fctr = 0.90	0.81	0.16	0.81	0.81	0.16	1.08	2.69	0.16	0.27	0.27	0.27	0.27	1.08	0.11	0.05
Intergranular corrosion	0.92	1.10	0.92	1.28	0.73	1.83	0.73	0.55	0.37	0.37	0.37	0.37	0.37	0.07	0.04
weight fctr = 14.00	12.88	15.40	12.88	17.92	10.22	25.62	10.22	7.70	5.18	5.18	5.18	5.18	5.18	0.98	0.56
Hydrogen assisted cracking	0.75	0.30	0.75	1.05	0.30	0.75	0.60	1.50	0.30	0.75	1.05	1.05	0.69	0.09	0.06
weight fctr = 1.50	1.13	0.45	1.13	1.57	0.45	1.13	0.90	2.25	0.45	1.13	1.57	1.57	1.03	0.14	0.09
Pitting corrosion	0.85	0.49	0.61	1.21	0.36	0.73	0.49	0.24	0.97	0.97	0.97	0.97	0.73	0.36	0.05
weight fctr = 14.00	11.90	6.86	8.54	16.94	5.04	10.22	6.86	3.36	13.58	13.58	13.58	13.58	10.22	5.04	0.70
Hydrogen embrittlement	1.41	0.35	1.06	1.24	0.35	0.88	0.71	1.77	0.35	0.35	0.53	0.53	0.35	0.07	0.04
weight fctr = 1.50	2.12	0.52	1.59	1.86	0.52	1.32	1.06	2.65	0.52	0.52	0.79	0.79	0.52	0.11	0.06
Oxidation	1.11	0.37	0.37	0.74	0.37	1.48	2.22	0.15	0.15	0.15	0.15	0.15	0.15	2.22	0.22
weight fctr = 5.00	5.55	1.85	1.85	3.70	1.85	7.40	11.10	0.75	0.75	0.75	0.75	0.75	0.75	11.10	1.10
General acueous corrosion	1.38	0.34	0.69	1.38	0.34	0.69	2.07	0.14	0.14	0.14	0.14	0.14	0.14	2.07	0.21
weight fctr = 10.00	13.80	3.40	6.90	13.80	3.40	6.90	20.70	1.40	1.40	1.40	1.40	1.40	1.40	20.70	2.10
Microbiological corrosion	0.91	0.23	1.82	2.05	0.23	1.14	0.45	0.09	0.09	0.45	0.45	0.45	1.14	0.45	0.05
weight fctr = 15.00	13.65	3.45	27.30	30.75	3.45	17.10	6.75	1.35	1.35	6.75	6.75	6.75	17.10	6.75	0.75
Dealloying	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
weight fctr = 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mechanical overload	1.53	1.22	0.61	0.61	0.92	0.76	0.76	0.76	0.46	0.76	0.61	0.61	0.31	0.03	0.03
weight fctr = 1.00	1.53	1.22	0.61	0.61	0.92	0.76	0.76	0.76	0.46	0.76	0.61	0.61	0.31	0.03	0.03
Mechanical impact	1.29	1.03	0.52	0.52	0.78	0.65	0.65	0.52	0.39	0.90	1.03	1.03	0.65	0.33	0.03
weight fctr = 1.00	1.29	1.03	0.52	0.52	0.78	0.65	0.65	0.52	0.39	0.90	1.03	1.03	0.65	0.33	0.03
UNWEIGHTED SUMMATION PRODUCT CRITERIA	14.60	6.37	10.63	15.24	5.67	13.66	13.45	9.55	5.07	7.05	7.51	7.51	6.56	5.93	1.21
(WEIGHTED SUMMATION)	122.70	47.01	106.83	158.06	45.85	130.23	90.80	80.85	49.32	62.11	62.81	62.81	51.69	51.86	12.35

Table 4-15. Performance product criteria values for candidate container alloys

Product criteria	304L	CF3	316L	CF3M	IN825	CDA122	CDA613	CDA952	CDA715	CDA964
	MATERIAL GRADES									
Variable microconstituents	122.7	122.7	104.5	104.5	33.3	54.8	72.8	72.8	75.0	75.0
Variable grain size	47.0	47.0	51.7	51.7	32.4	16.8	19.7	19.7	16.0	16.0
Non-equilibrium microconstituents	100.8	100.8	69.3	69.3	21.5	39.4	55.6	55.6	54.7	54.7
Microchemical inhomogeneity	158.1	158.1	144.4	144.4	70.5	57.0	81.0	81.0	76.2	76.2
Preferred grain orientation	45.8	45.8	50.9	50.9	28.4	15.4	19.2	19.2	16.2	[illegible]
HAZ precipitation	130.2	130.2	118.1	118.1	67.1	38.3	62.2	62.2	59.1	59.1
Macrochemical inhomogeneity	90.8	90.8	94.3	94.3	68.3	67.4	99.1	99.1	97.2	97.2
Residual stress	80.8	80.8	71.6	71.6	21.9	15.0	29.8	29.8	21.5	21.5
Porosity	49.3	49.3	47.8	47.8	26.2	14.0	20.3	20.3	18.0	18.0
Lack of fusion	62.1	62.1	59.1	59.1	30.7	19.1	26.0	26.0	23.8	23.8
HAZ microcracks	62.8	62.8	59.5	59.5	31.5	19.7	26.6	26.6	24.5	24.5
Fusion zone microcracks	62.8	62.8	59.5	59.5	31.5	19.7	26.6	26.6	24.5	24.5
Inclusions	51.7	51.7	48.3	48.3	25.2	21.8	27.2	27.2	27.6	27.6
Surface condition	51.9	51.9	49.9	49.9	39.6	43.0	52.5	52.5	51.9	51.9
Weld profile	12.4	12.4	11.4	11.4	3.5	2.7	4.5	4.5	3.7	3.7
Sum of product criteria	1129.2	1129.2	1040.2	1040.2	531.5	444.0	623.2	623.2	590.0	590.0

For each container material, four process conditions are evaluated. These process conditions are later related to fabrication sequences. The four process conditions are:

1. As-welded (cold wire—gas tungsten arc weld).
2. Welded and annealed.
3. Weld, cold worked (including the weld), and annealed.
4. Base metal annealed.

The as-welded process criteria are from the Closure Project for cold wire gas tungsten arc welding. (The criteria are reversed from the Closure Project where 5 was best and 0 was worst.)

For the other processing conditions, multiplicative reduction factors were selected by one of the authors (H. A. Domian) based on his physical metallurgy expertise. The reduction factor may be applied to the as-welded process value and/or to the as-welded performance index for each product criterion. The same reduction factors are used for all the container alloys and are listed below.

	Welded Annealed	Welded Cold Worked Annealed	Base Metal Annealed
Variable Microconstituents	0.50	0.25	0.125
Variable Grain Size	1.00	0.50	0.25
Nonequilibrium Microconstituents	0.00	0.00	0.00
Microchemical Inhomogeneity	0.50	0.25	0.125
Preferred Grain Orientation	1.00	0.00	1.00
HAZ Precipitation	0.00	0.00	0.00
Macrochemical Inhomogeneity	1.00	1.00	0.125
Residual Stress	0.00	0.00	0.00
Porosity	1.00	0.50	0.00
Lack of Fusion	1.00	0.50	0.00
HAZ Microcracks	1.00	1.00	0.00
Fusion Zone Microcracks	1.00	1.00	1.00
Inclusions	1.00	1.00	1.00
Surface Condition	0.00	0.00	0.00
Weld Profile	0.00	0.00	0.00

A reduction factor of 1.00 indicates no effect on the process criterion, while a reduction factor of 0 indicates that deleterious effects of the product criterion are eliminated.

Performance Index and Normalized Rating

The product criteria and calculation of the performance index for AISI 304L are shown in Table 4-16. The product criteria are listed at the left and values are given in the first column. The sum of the product criteria is used later for normalizing the index values. The second column of numbers gives the process criteria for cold wire gas tungsten arc welding. The third column, "index value," is the product of the product criterion and process criterion. The sum of the products is the performance index for the as-welded process. The following three columns are given for each of the other three processes:

- Reduction factor given previously.
- Process criterion—reduction factor times the as-welded process criterion.
- Index value—product of product and process criteria (or reduction factor times the as-welded index value).

Table 4-16. Performance index—product and process criteria values for wrought AISI 304L

PRODUCT CRITERIA	A	AS WELDED GTAW-Cb: PROCESS CRITERIA B	AS WELDED GTAW-Cb: INDEX VALUE C=A*B	WELDED & ANNEALED: REDUCT FACTOR R1	PROC CRIT R1*B	INDEX VALUE R1*C	WELDED COLD WORKED & ANNEALED: REDUCT FACTOR R2	PROC CRIT R2*B	INDEX VALUE R2*C	BASE METAL ANNEALED: REDUCT FACTOR R3	PROC CRIT R3*B	INDEX VALUE R3*C
Variable microconstituents	122.7	3.00	368.1	0.500	1.500	184.1	0.250	0.750	92.0	0.125	0.375	46.0
Variable grain size	47.0	2.00	94.0	1.000	2.000	94.0	0.500	1.000	47.0	0.250	0.500	23.5
Non-equilibrium microconstituents	100.8	2.50	252.1	0.000	0.000	0.0	0.000	0.000	0.0	0.000	0.000	0.0
Microchemical inhomogeneity	158.1	2.00	316.1	0.500	1.000	158.1	0.250	0.500	79.0	0.125	0.250	39.5
Preferred grain orientation	45.8	2.00	91.7	1.000	2.000	91.7	0.000	0.000	0.0	1.000	2.000	91.7
Haz precipitation	130.2	2.00	260.5	0.000	0.000	0.0	0.000	0.000	0.0	0.000	0.000	0.0
Macrochemical inhomogeneity	90.8	2.50	227.0	1.000	2.500	227.0	1.000	2.500	227.0	0.125	0.313	28.4
Residual stress	80.8	3.50	283.0	0.000	0.000	0.0	0.000	0.000	0.0	0.000	0.000	0.0
Porosity	49.3	2.50	123.3	1.000	2.500	123.3	0.500	1.250	61.6	0.000	0.000	0.0
Lack of fusion	62.1	1.50	93.2	1.000	1.500	93.2	0.500	0.750	46.6	0.000	0.000	0.0
Haz microcracks	62.8	2.00	125.6	1.000	2.000	125.6	1.000	2.000	125.6	0.000	0.000	0.0
Fusion zone microcracks	62.8	2.50	157.0	1.000	2.500	157.0	1.000	2.500	157.0	0.000	0.000	0.0
Inclusions	51.7	2.50	129.2	1.000	2.500	129.2	1.000	2.500	129.2	1.000	2.500	129.2
Surface condition	51.9	1.50	77.8	0.000	0.000	0.0	0.000	0.000	0.0	0.000	0.000	0.0
Weld profile	12.4	1.50	18.5	0.000	0.000	0.0	0.000	0.000	0.0	0.000	0.000	0.0
SUM OF PRODUCT CRITERIA	1129.2											
PERFORMANCE INDEX VALUE (INDEX VALUE SUM)			2617.0			1383.1			955.1			358.3

The performance index and normalized ratings for the four process conditions and various container alloys are given in Table 4-17. The index values are normalized relative to 5 times the maximum sum of product criteria, where 5 denotes the worst possible process. The maximum sum of product criteria is 1129.2 for AISI 304L and CF3. The normalized ratings are then:

$$\text{Normalized Rating} = \left[1.0 - \left(\frac{\text{Index Value}}{5 \times 1129.2}\right) \times 100\right]$$

Thus, the perfect process has an index value of 0 and normalized rating of 100. The worst possible process is a normalized rating of 0. The next step is relating the normalized process rating to the various fabrication methods listed previously.

<u>Performance Fabrication Process Rating</u>

For the processes listed previously, the container consists of base metal and various amounts of weld metal. For all processes, it is assumed that the components are annealed after welding or forming. Thus, the worst condition is welded and annealed.

Various methods were considered to allow for the effects of base metal and weld metal in the container. These included:

- Using the lowest normalized rating. This method did not discriminate between a container with a longitudinal seam and girth weld (262 in. of weld) relative to a container with only a girth weld (82 in. of weld). The roll-and-weld construction would seem equivalent to a container with three girth welds, which is less reliable.
- From the normalized rating for the base metal (NRBM), subtracting the product of a normalized weld length "b" and 100 minus the normalized rating of the weld metal (NRWM):

  $$\text{NRBM} - b\,(100 - \text{NRWM})$$

  This makes the final rating depend on the weld length. Depending on the dimensionless weld length "b," the resultant rating could be negative.

The method chosen is based on reliability concepts. If two items must both function for a system to work, and one is 90% reliable, while the other is 70% reliable, the system reliability is the product of the component reliabilities or 63%.

The method selected is as follows:

- Use the normalized ratings as measures of reliability.
- Consider the relative weld length as an exponent of the NRWM.

Thus, the performance rating would be calculated as follows:

$$\begin{matrix}\text{Performance}\\\text{Rating}\end{matrix} = \begin{pmatrix}\text{Normalized}\\\text{Rating}\\\text{Base Metal}\end{pmatrix} \times \begin{pmatrix}\text{Normalized}\\\text{Rating}\\\text{Weld Metal}\end{pmatrix}^{\left(\frac{\text{Weld Length}}{\text{Reference Weld Length}}\right)}$$

$$\text{PR} = \text{NRBM} \times \text{NRWM}^{b}$$

Table 4-17. Performance index and normalized rating for various container alloys

Material		FABRICATED CONDITION							
		WELDED GTAW-CW		WELDED & ANNEALED		WELDED COLD WORKED & ANNEALED		BASE METAL ANNEALED	
		INDEX VALUE	NORMALIZED RATING	INDEX VALUE	NORMALIZED RATING	INDEX VALUE	NORMALIZED RATING	INDEX VALUE	NORMALIZED RATING
304L	Wrought	2617	53.7	1383	75.5	965	82.9	358	93.7
CF3	Centrifugally cast	3058	45.8	1615	71.4	1080	80.9	445	92.1
316L	Wrought	2528	55.2	1368	75.8	898	84.1	372	93.4
CF3M	Centrifugally cast	2939	47.9	1602	71.6	1013	82.1	463	91.8
IN825	Wrought	1223	78.3	728	87.1	489	91.3	195	96.5
CDA122	Wrought	746	86.8	541	90.4	408	92.8	131	97.7
CDA613	Wrought	1135	79.9	710	87.4	553	90.2	176	96.9
CDA952	Centrifugally cast	1345	76.2	835	85.2	636	88.7	209	96.3
CDA715	Wrought	961	83.0	574	89.8	433	92.3	155	97.2
CDA964	Centrifugally cast	1136	79.8	696	87.7	514	90.9	186	96.7

Normalized rating = (1.0 - Index value/MAX Index value) * 100.

MAX Index value = 5.0 * MAX Sum of product criteria

MAX Sum of product criteria = 1129.2 for 304L, CF3

For cases with zero weld length, the base metal rating is obtained. The exponent for the roll-and-weld plus girth-weld case is proportionally larger than the girth-weld case exponent. The girth-weld length of 82 in. was selected as the reference weld length. Thus,

$$PR = NRBM \times NRWM^{\left(\frac{\text{Weld Length}}{82\text{ in.}}\right)}$$

For each material and fabrication process, the appropriate values for NRBM and NRWM are read from Table 4-17.

- Base metal annealed, and welded and annealed weld metal

Processes	Welds	Weld Length (in.)
LH01-05	Welded Pintle	38
LH06-08	Integral Pintle	0
LU01-03	Integral Lower Unit	0
LU04-08	Welded Head and Long Seam	262
LU09-23	Welded Head	82

- Base metal annealed, and welded, cold worked, annealed weld metal

Processes	Welds	Weld Length (in.)
LU24-28	Welded Head and Long Seam	62
LU29-43	Welded Head	82

The calculated performance ratings are shown in Table 4-18 (upper unit) and Table 4-19 (lower unit).

The nonwelded fabrications UH06-08 and LU01-03 are ranked highest for performance, followed by cases involving welding a head to a seamless body. The welded body cases were ranked lowest. Cold working the lower unit (body and girth weld) raised the performance ratings. If the weld length was normalized at 262 in. (Exponent = Weld Length/262 in.), the range of performance ratings would be narrowed.

Fabricability Criteria

Since the candidate alloys are all fabricable with routine commercial processes, there are only some relatively subtle differences depending on the alloy and process being considered. The ratings determined by the fabrication project team (H. A. Domian, E. Martin, R. L. Holbrook, and D. F. LaCount) were based on negative effects of a particular alloy/process combination.

Fabrication product requirements include material property requirements for forming and welding, dimensional and tolerance requirements, inspectability, and commercial considerations. These

Table 4-18. Performance ratings for the upper head and handling pintle

		304L	CF3	316L	CF3M	IN825	CDA122	CDA613	CDA952	CDA715	CDA964
	MACHINED PINTLE WELDED TO UPPER HEAD										
	UPPER HEAD										
UH01	Forged	82		82		91	93	91		93	
UH02	Spun	82		82		91	93	91		93	
UH03	Deep drawn	82		82		91	93	91		93	
UH04	Centrifugally cast		79		79				89		91
UH05	Machined	82		82		91	93	91		93	
	INTEGRAL PINTLE & UPPER HEAD										
UH06	Forged	94		93		97	98	97		97	
UH07	Centrifugally cast		92		92				96		97
JH06	Machined	94		93		97	98	97		97	

Table 4-19. Performance ratings for the lower unit

	Body	Lower head		304L	CF3	316L	CF3M	IN825	CDA122	CDA613	CDA952	CDA715	CDA954
	INTEGRAL LOWER UNIT												
LU01	Extruded closed end			94		93		97	98	97		97	
LU02	Extruded closed end & cold worked			94		93		97	98	97		97	
LU03	Deep drawn closed end			94		93		97	98	97		97	
	WELDED LOWER UNIT												
	BODY	LOWER HEAD											
LU04	Roll & weld	Forged		38		38		62	71	63		69	
LU05		Spun											
LU06		Deep drawn											
LU07		Centrifugally cast	NA1										
LU08		Machined		38		38		62	71	63		69	
LU09	Extruded	Forged		71		71		84	88	85		87	
LU10		Spun											
LU11		Deep drawn											
LU12		Centrifugally cast	NA1										
LU13		Machined		71		71		84	88	85		87	
LU14	Deep drawn	Forged	NA2										
LU15		Spun	NA2										
LU16		Deep drawn		71		71		84	88	85		87	
LU17		Centrifugally cast	NA1,2										
LU18		Machined	NA2										
LU19	Cent. cast	Forged			66		66				82		85
LU20		Spun											
LU21		Deep drawn											
LU22		Centrifugally cast			66		66				82		85
LU23		Machined			66		66				82		85
	COLD WORKED WELDED LOWER UNIT												
	BODY	LOWER HEAD											
LU24	Roll & weld	Forged		51		54		72	77	70		75	
LU25		Spun											
LU26		Deep drawn											
LU27		Centrifugally cast	NA1										
LU28		Machined		51		54		72	77	70		75	
LU29	Extruded	Forged		78		79		88	91	87		90	
LU30		Spun											
LU31		Deep drawn											
LU32		Centrifugally cast	NA1										
LU33		Machined		78		79		88	91	87		90	
LU34	Deep drawn	Forged	NA2										
LU35		Spun	NA2										
LU36		Deep drawn		78		79		88	91	87		90	
LU37		Centrifugally cast	NA1,2										
LU38		Machined	NA2										
LU39	Cent. cast	Forged			74		75				85		88
LU40		Spun											
LU41		Deep drawn											
LU42		Centrifugally cast			74		75				85		88
LU43		Machined			74		75				85		88

NA1 - Centrifugally cast head not allowed with forged body.
NA2 - Deep drawn body produces the heads as part of the process. Alternate head forming is redundant.

fabrication product criteria are the product attributes with respect to fabrication. The thirteen criteria and weighting factors are listed below.

<u>Fabricability—Product Criteria</u>

Product Criterion	Weighting	Description
1. Material Quality	4	Is commercial-quality starting material adequate, or is special quality required?
2. Formability	4	Is normal ductility adequate?
3. Weldability	4	When welding is required, how difficult is the material to weld?
4. Tolerance OD	1	Primary concern is fit-up for closure welding. Better than normal tolerances may be required for ovality.
5. Tolerance Wall	1	
6. Tolerance ID	1	
7. Tolerance Ovality	4	
8. Surface Finish ID	1	The OD surface finish is important for corrosion.
9. Surface Finish OD	2	
10. Process Control	4	Will a high level of process control be required?
11. Inspectability	4	Can the component be inspected by UT, x-ray, and dye penetrant? Will it permit closure weld UT?
12. Vendor Sources	2	Is the material and process available from several sources, or is there only one vendor?
13. Commercial Use	4	Is the process in use for the desired materials and sizes, or is further development required?
TOTAL	36	

The same criteria and values are used for all materials. The weighting was determined by a consensus of the forming project team. The highest weighting, 4, was assigned to required factors:

1. Material Quality—required for QA.
2. Formability—required for manufacture.
3. Weldability—required for manufacture.
7. Ovality Tolerance—required for closure weld fit-up.
10. Process Control—required for QA.
11. Inspectability—required for closure weld NDE.
13. Commercial Use—project requirement to use established commercial processes.

Factors 2, 3, 11, and 13 are material and process dependent. The remaining factors are only process dependent. Welding CDA 122 is considered to be difficult. Centrifugally cast heads have a single source and are not now in commercial use. CDA 122 and Alloy 825 are not available commercially as centrifugal castings.

An index value is calculated for each fabricated component as the sum of the products of the product and process criteria values. Fabricability of the processes and materials is normalized to the "worst case" (e.g., all process criteria equal to 10). The maximum fabricability index is 10 times the sum of the product criteria (36), or 360. All processes are normalized for fabricability as:

$$\text{NORM} = \left(1 - \frac{\text{Index Value}}{360}\right) \times 100 \; .$$

For the upper head and handling pintle, and integral lower unit fabrication processes, the normalized fabricability rating is used. For lower units with the head welded to the body, the normalized fabricability rating is the product of the component ratings:

$$\text{Normalized Rating Welded Lower Unit} = \text{Normalized Rating Body} \times \text{Normalized Rating Head}$$

For the cold worked welded lower unit processes, the normalized rating is the product of three process ratings:

$$\text{Normalized Rating Cold Worked Welded Lower Unit} = \text{Normalized Rating Head} \times \text{Normalized Rating Body} \times \text{Normalized Rating for Cold Work}$$

The normalized fabrication ratings for the upper head and handling pintle are given in Table 4-20 and for the lower unit in Table 4-21. For the upper unit, the forged or machined head and integral pintle are ranked highest (no pintle weld). For the welded pintle, forged, spun, or machined heads are ranked equal to one another. The deep-drawn head is ranked lower because of higher formability and process control requirements. Centrifugally cast heads are ranked low because of poorer inspectability, limited vendor sources, and lack of commercial usage.

For the integral lower unit, the extruded and cold-worked process (LU-02) is ranked highest. The extruded closed-end process (LU-01) is rated lower for tolerances and surface finish. The deep-drawn process is rated lower for high material property requirements and tolerances.

For the welded lower unit (cold worked or not), three body processes rank nearly equal: centrifugally cast (rated good for ovality with concern for inspectability), roll and weld (rated lower for ovality), and extrusion (concerns over surface finish and limited vendor sources). Deep drawn ranks slightly lower (requires higher level of formability and limited vendor sources). The lower head processes ranked as follows: machined head ranks highest (no formability requirement), followed by forged or spun heads, and deep drawn heads (formability and material quality requirements). The centrifugally cast head is considered only with a centrifugally cast body. It is rated lower because of more difficult inspectability, limited vendor sources, and not being in commercial use.

The cold worked processes are ranked lower because of the extra processing required.

For processes involving welding, CDA 122 is ranked lowest. CDA 613 is also ranked lower for weldability than the other alloys. In general, this alloy is readily welded by solid-state processes (e.g., friction welding). Alloy 825 and CDA 122 are not available as centrifugal castings. (An alloy similar to Alloy 825, with niobium substituted for titanium, has been centrifugally cast.)

<u>Cost Criteria</u>

The cost rating is derived from the relative costs presented in Section 4.3.7 and is shown here in Tables 4-22 and 4-23. The reference unit (relative cost equal to 1) is a roll and weld body welded to a forged head in AISI 304L. The relative costs are in multiples of the reference unit.

To obtain a "cost rating," a scale having a range from 0 to 100 is desired, with the higher rating denoting lower cost. The cost ratings are calculated as follows:

Upper Head and Handling Pintle:
Cost Rating = (1 − Relative Cost/2) × 100
(An upper unit with relative cost of 2 would receive a zero rating.)
Lower Unit:
Cost Rating = (1 − Relative Cost/8) × 100
(A lower unit with a relative cost of 8 would receive a zero rating.)

A cost rating of 100 requires zero cost. The relative costs for a zero cost rating (2 for the upper unit and 8 for the lower unit) are chosen based on the relative cost range to give a wide range to the cost ratings.

The cost rating is used in the vector sum process comparisons for performance, fabricability, and cost.

Table 4-20. Fabrication ratings for the upper head and handling pintle

		304L	CF3	316L	CF3M	IN825	CDA122	CDA613	CDA952	CDA715	CDA964
	MACHINED PINTLE WELDED TO UPPER HEAD										
	UPPER HEAD										
UH01	Forged	98		98		98	92	94		98	
UH02	Spun	98		98		98	92	94		98	
UH03	Deep drawn	88		86		86	82	84		88	
UH04	Centrifugally cast		71		71				71		71
UH05	Machined	98		98		98	92	94		98	
	INTEGRAL PINTLE & UPPER HEAD										
UH06	Forged	100		100		100	100	100		100	
UH07	Centrifugally cast		72		72				78		72
UH08	Machined	100		100		100	100	100		100	

Table 4-21. Fabrication ratings for the lower unit

	INTEGRAL LOWER UNIT			304L	CF3	316L	CF3M	IN825	CDA122	CDA613	CDA952	CDA715	CDA954
LU01	Extruded closed end			79		79		79	79	79		79	
LU02	Extruded closed end & cold worked			88		88		82	77	88		88	
LU03	Deep drawn closed end			77		74		74	77	66		77	
	WELDED LOWER UNIT												
	BODY	LOWER HEAD											
LU04	Roll & weld	Forged		80		80		80	60	74		80	
LU05		Spun		80		80		80	60	74		80	
LU06		Deep drawn		74		73		73	56	69		74	
LU07		Centrifugally cast	NA1										
LU08		Machined		83		83		83	52	77		83	
LU09	Extruded	Forged		77		77		77	67	71		77	
LU10		Spun		77		77		77	67	71		77	
LU11		Deep drawn		71		70		70	62	66		71	
LU12		Centrifugally cast	NA1										
LU13		Machined		79		79		79	70	74		79	
LU14	Deep drawn	Forged	NA2										
LU15		Spun	NA2										
LU16		Deep drawn		69		65		65	60	54		69	
LU17		Centrifugally cast	NA1,2										
LU18		Machined	NA2										
LU19	Cent. cast	Forged			79		79				79		79
LU20		Spun			79		79				79		79
LU21		Deep drawn			73		72				74		73
LU22		Centrifugally cast			59		59				63		59
LU23		Machined			82		82				82		82
	COLD WORKED WELDED LOWER UNIT												
	BODY	LOWER HEAD											
LU24	Roll & weld	Forged		61		61		61	43	54		61	
LU25		Spun		61		61		61	43	54		61	
LU26		Deep drawn		57		56		56	40	50		57	
LU27		Centrifugally cast	NA1										
LU28		Machined		63		63		63	44	56		63	
LU29	Extruded	Forged		59		59		59	48	52		59	
LU30		Spun		59		59		59	48	52		59	
LU31		Deep drawn		55		53		53	44	48		55	
LU32		Centrifugally cast	NA1										
LU33		Machined		61		61		61	50	54		61	
LU34	Deep drawn	Forged	NA2										
LU35		Spun	NA2										
LU36		Deep drawn		53		50		50	43	40		53	
LU37		Centrifugally cast	NA1,2										
LU38		Machined	NA2										
LU39	Cent. cast	Forged			61		61				58		61
LU40		Spun			61		61				58		61
LU41		Deep drawn			56		55				54		56
LU42		Centrifugally cast			45		45				46		45
LU43		Machined			63		63				60		63

NA1 - Centrifugally cast head not allowed with forged body.
NA2 - Deep drawn body produces the heads as part of the process. Alternate head forming is redundant.

Table 4-22. Cost ratings for the upper head and handling pintle

		304L	CF3	316L	CF3M	IN825	CDA122	CDA613	CDA952	CDA715	CDA964
	MACHINED PINTLE WELDED TO UPPER HEAD										
	UPPER HEAD										
UH01	Forged										
UH02	Spun										
UH03	Deep drawn										
UH04	Centrifugally cast		86		86				93		80
UH05	Machined	56		56		36	86				
	INTEGRAL PINTLE & UPPER HEAD										
UH06	Forged	85		82		69				65	
UH07	Centrifugally cast										
UH08	Machined										

Table 4-23. Cost ratings for the lower unit

	INTEGRAL LOWER UNIT			304L	CF3	316L	CF3M	IN825	CDA122	CDA613	CDA952	CDA715	CDA964
LU01	Extruded closed end			60		60		24				27	
LU02	Extruded closed end & cold worked			60		60		39				45	
LU03	Deep drawn closed end			56		56		56	38	56		54	
	WELDED LOWER UNIT												
	BODY	LOWER HEAD											
LU04	Roll & weld	Forged		87		86		75				74	
LU05		Spun											
LU06		Deep drawn											
LU07		Centrifugally cast	NA1										
LU08		Machined		85		84		71	65				
LU09	Extruded	Forged		63		62		32				37	
LU10		Spun											
LU11		Deep drawn											
LU12		Centrifugally cast	NA1										
LU13		Machined		60		60		28					
LU14	Deep drawn	Forged	NA2										
LU15		Spun	NA2										
LU16		Deep drawn		61		61		60	44	60		57	
LU17		Centrifugally cast	NA1,2										
LU18		Machined	NA2										73
LU19	Cent. cast	Forged			86		85						
LU20		Spun											
LU21		Deep drawn									90		79
LU22		Centrifugally cast			87		87						
LU23		Machined			83		82						
	COLD WORKED WELDED LOWER UNIT												
	BODY	LOWER HEAD											
LU24	Roll & weld	Forged		69		68		57				62	
LU25		Spun											
LU26		Deep drawn											
LU27		Centrifugally cast	NA1										
LU28		Machined		66		65		53					
LU29	Extruded	Forged											
LU30		Spun											
LU31		Deep drawn											
LU32		Centrifugally cast	NA1										
LU33		Machined											
LU34	Deep drawn	Forged	NA2										
LU35		Spun	NA2										
LU36		Deep drawn											
LU37		Centrifugally cast	NA1,2										
LU38		Machined	NA2										64
LU39	Cent. cast	Forged			69		68						
LU40		Spun											
LU41		Deep drawn									78		70
LU42		Centrifugally cast			70		70						
LU43		Machined			66		66						

NA1 - Centrifugally cast head not allowed with forged body.
NA2 - Deep drawn body produces the heads as part of the process. Alternate head forming is redundant.

Table 4-22. Cost ratings for the upper head and handling pintle

		304L	CF3	316L	CF3M	IN825	CDA122	CDA613	CDA952	CDA715	CDA964
	MACHINED PINTLE WELDED TO UPPER HEAD										
	UPPER HEAD										
UH01	Forged										
UH02	Spun										
UH03	Deep drawn										
UH04	Centrifugally cast		86		86				93		80
UH05	Machined	56		56		36	86				
	INTEGRAL PINTLE & UPPER HEAD										
UH06	Forged	85		82		69				65	
UH07	Centrifugally cast										
UH08	Machined										

5. Summary of Results and Recommendations

An evaluation methodology was used to rank the candidate processes for fabricating a container in which to store high-level nuclear waste. Section 4.6.2 provides an overview of the evaluation methodology used to rank the processes. The fabrication processes were judged on performance, fabricability, and cost and were rated from 0 to 100 based on these three criteria. Figures 5-1 through 5-6 provide an overall summary of the results for each material by showing the performance and fabricability ratings, and the cost relative to rolled and welded AISI 304. In Table 5-1, the three criteria are combined via a vector sum, so that one final value is given for each material and process.

5.1. Selection of Viable Processes

Table 5-2 summarizes the results of applying the fabrication selection criteria to the candidate processes. Not all of the possible combinations of the lower units of the four body and five lower head manufacturing processes are evaluated, for the following reasons:

- There are no substantial differences between forged, spun, and deep-drawn heads, so they are lumped into the category of "forged lower heads."
- All combinations involving a centrifugally cast head with a wrought body were dropped from further consideration because of the poor rating of these heads in comparison to the wrought heads.
- The deep drawing process produces a head, so there is no need to consider any other kind of head when a deep drawn body is available.

Upper Heads

Except for cost, changing alloys has only a small effect on processing the upper heads The ratings for performance and fabrication of the different wrought alloys vary by smaller amounts than do the ratings for a single alloy when different processes are being compared. Eliminating the weld by using an integral process increases both performance and fabrication ratings as illustrated in Table 5-2. The performance and fabrication ratings for forged, spun, and machined heads are essentially equal. The ratings for the heads indicate the following order of preference, high to low, for performance and fabrication:

- Forged, spun, and machined.
- Deep drawn.
- Centrifugally cast.

The lack of cost data in some cases makes it difficult to complete the overall ratings. The available results of Table 5-2 indicate that the relatively poor performance and fabrication of centrifugal castings are offset somewhat by their lower costs. However, the experience in making centrifugal heads was found to be limited to a single vendor, indicating that there may be insufficient experience with this component/process combination.

Lower Units

The performance ratings of integral lower units are viewed as superior to those of the welded lower units. Cold working and annealing welded units improves their performance but decreases their fabrication ratings so that there is little difference in the combined performance and fabrication ratings. When costs are included in these ratings, the spread becomes even smaller. In general, as performance and fabrication ratings increase, the costs also increase, so that the overall rating of the three primary criteria comes closer together. For instance, the values in Table 5-3 are obtained:

Figure 5-1. Lower unit performance and fabricability ratings and relative costs for AISI 304L/CF3

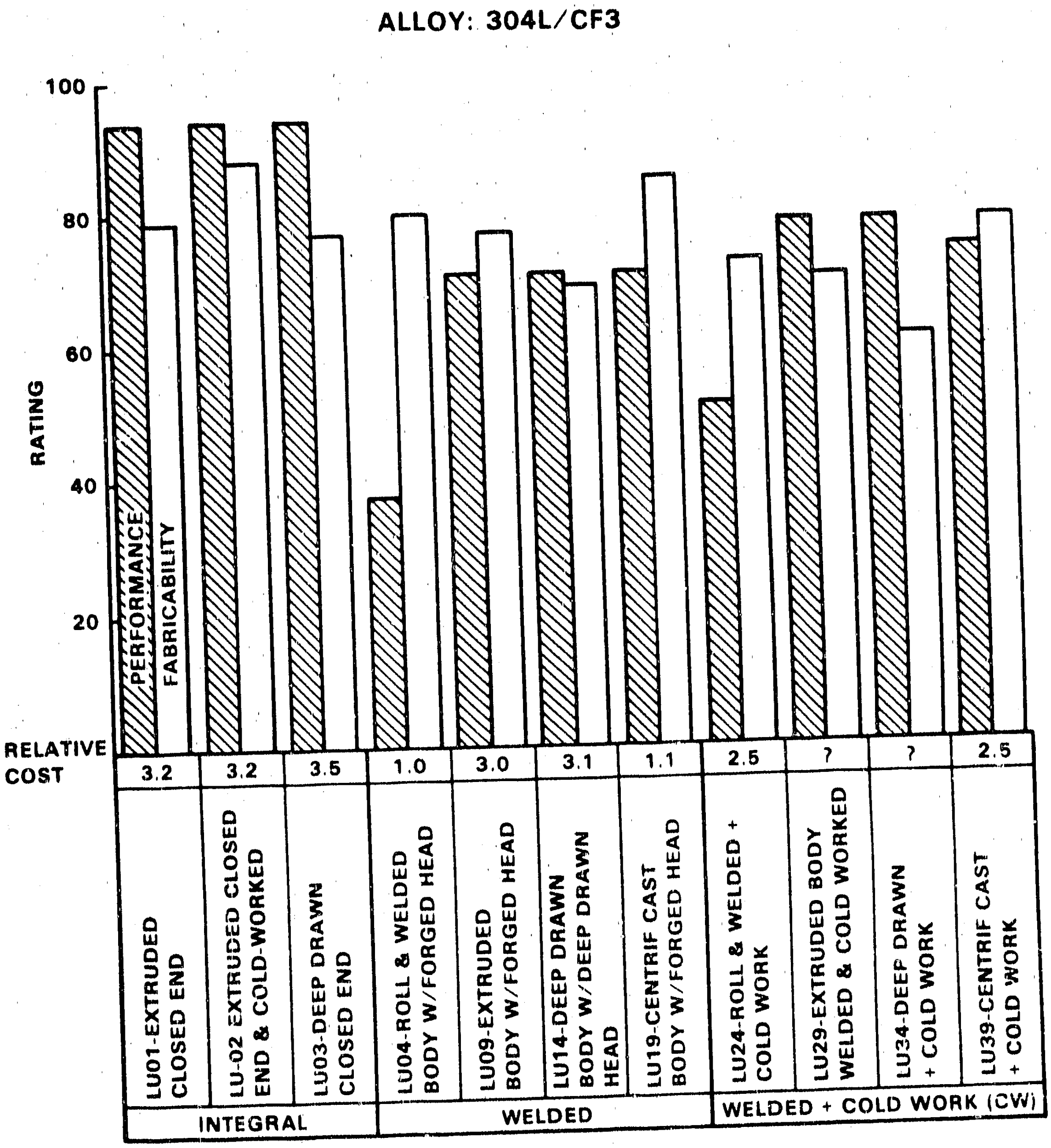


Figure 5-2. Lower unit performance and fabricability ratings and relative costs for AISI 316L/CF3M

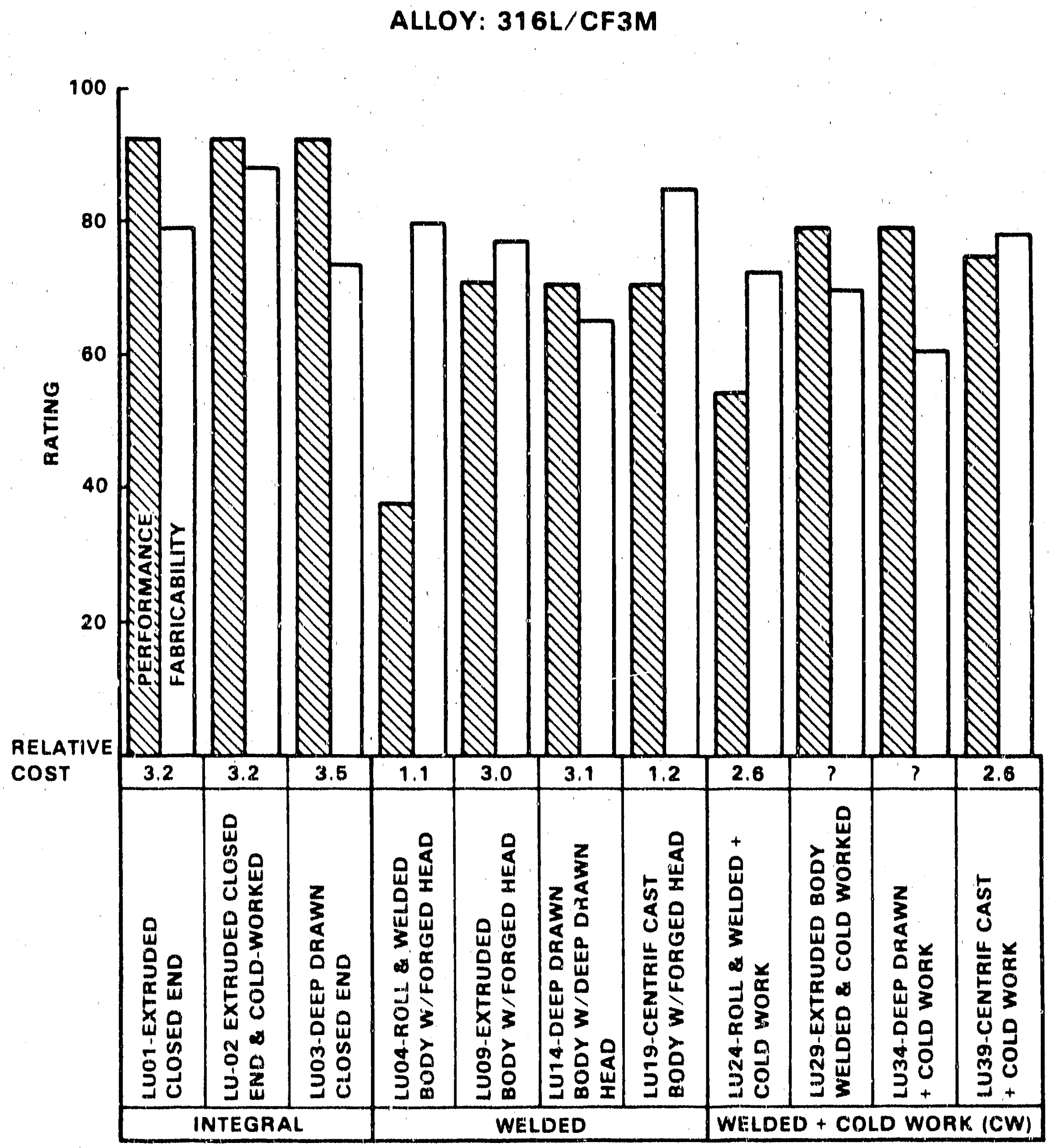


Figure 5-3. Lower unit performance and fabricability ratings and relative costs for Alloy 825

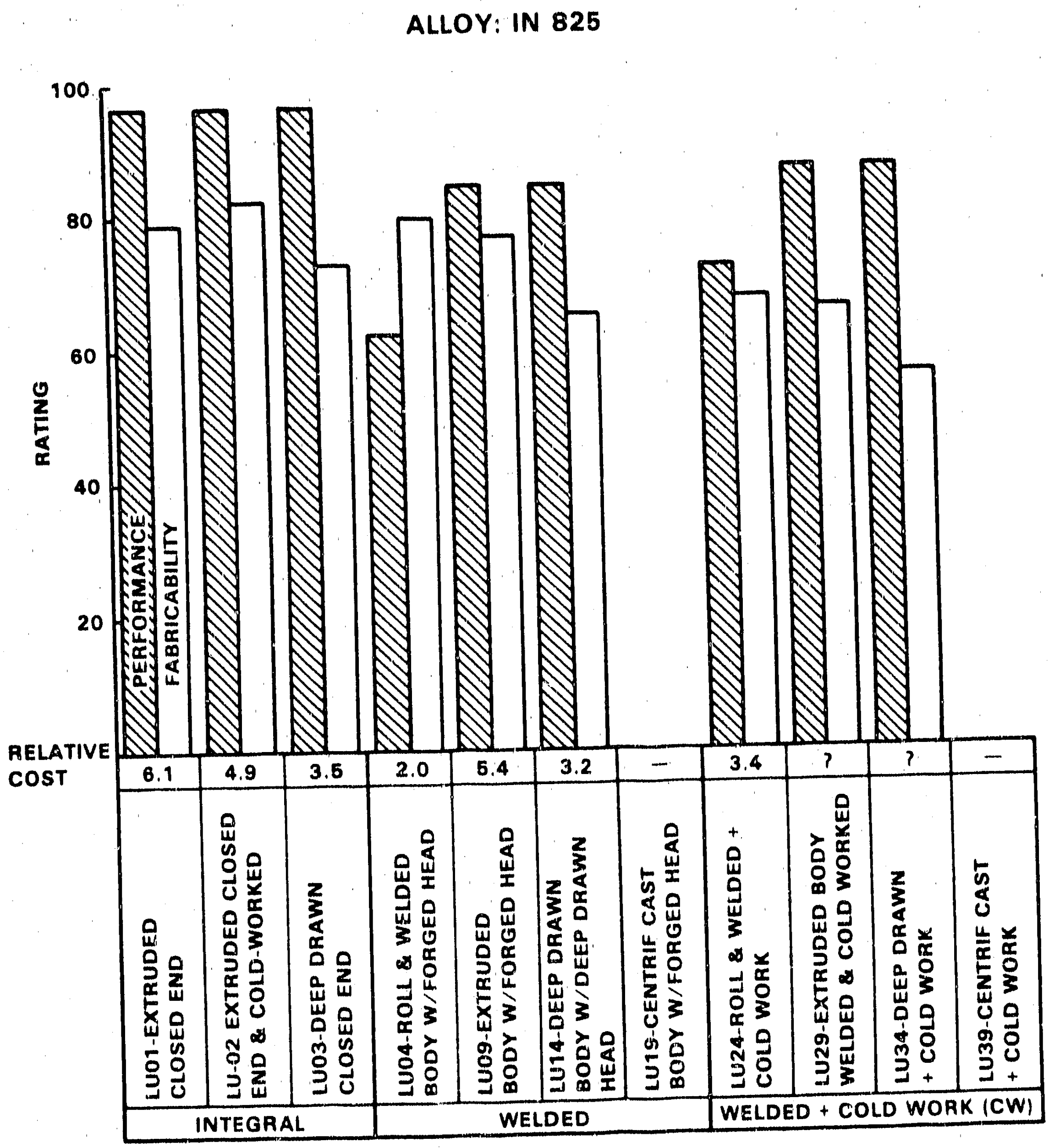


Figure 5-4. Lower unit performance and fabricability ratings and relative costs for CDA 122

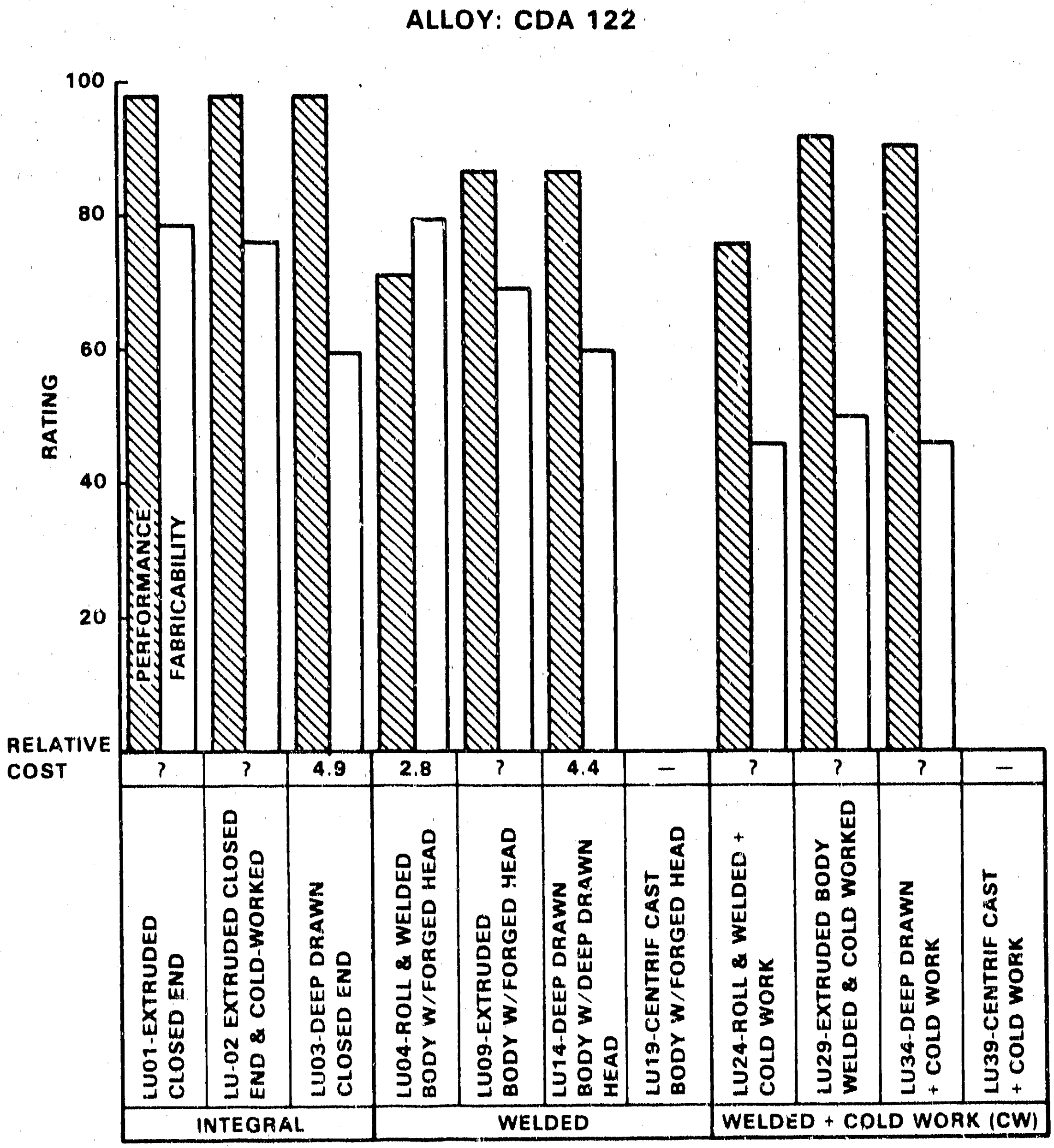


Figure 5-5. Lower unit performance and fabricability ratings and relative costs for CDA 613/952

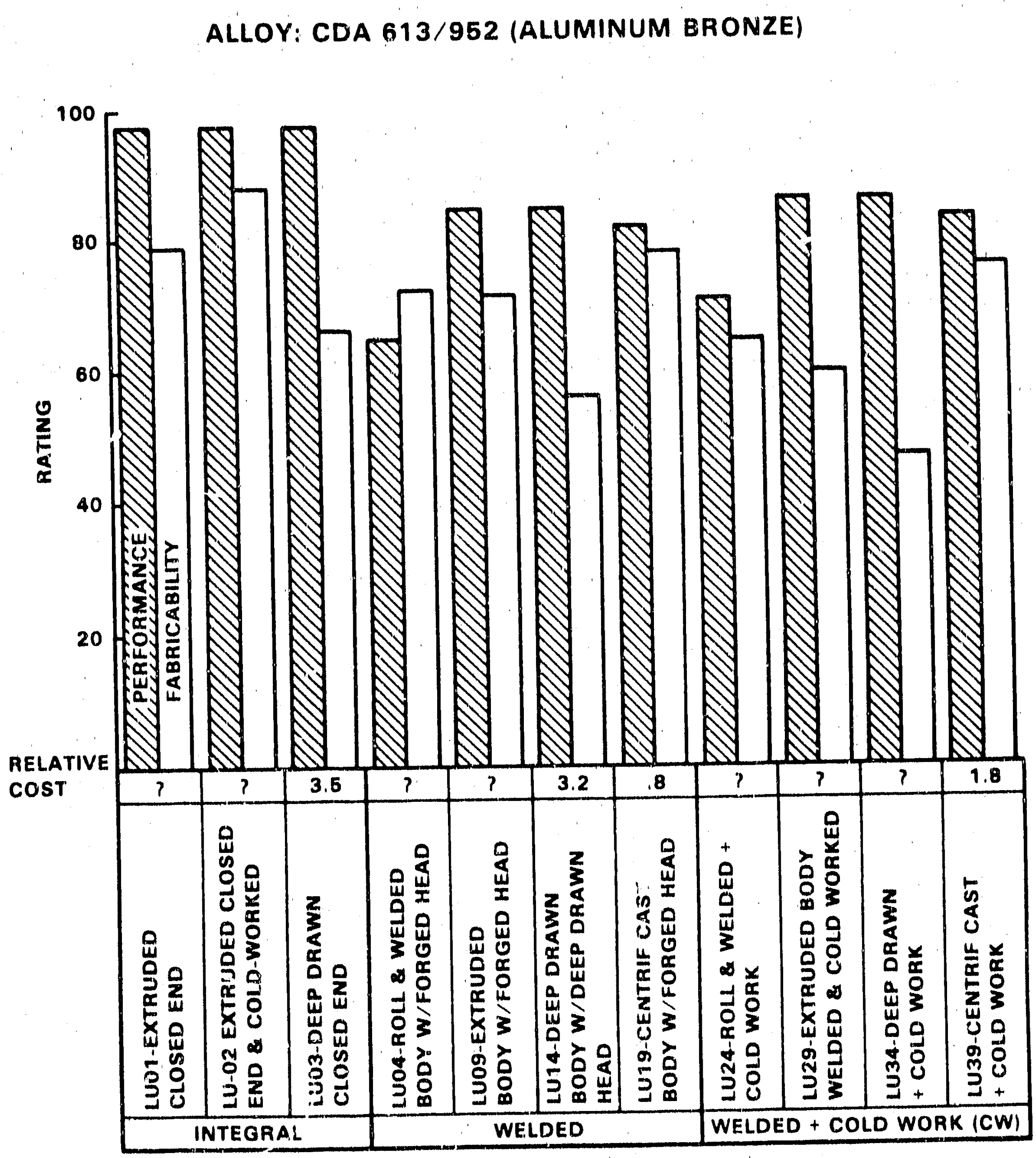


Figure 5-6. Lower unit performance and fabricability ratings and relative costs for CDA 715/964

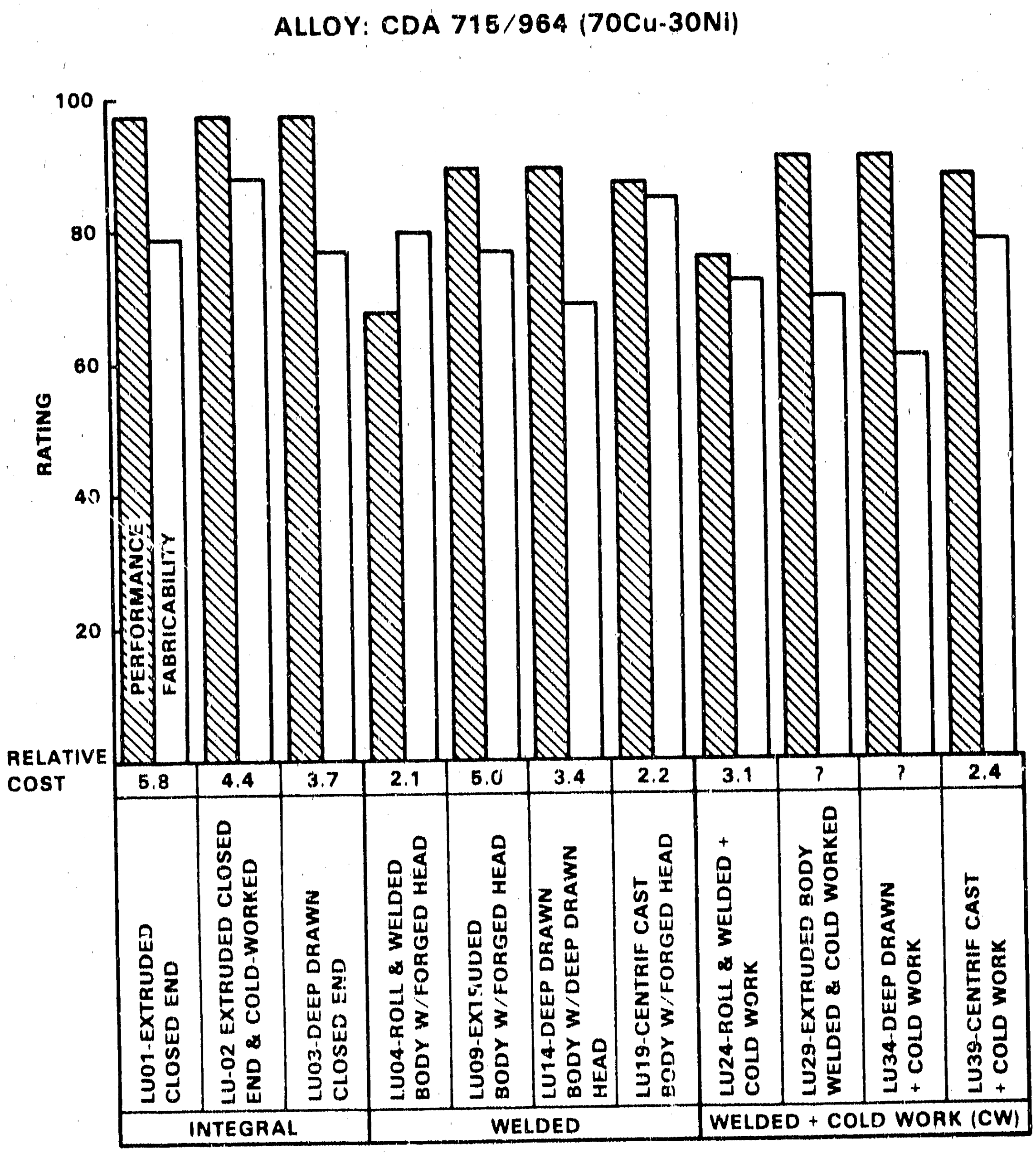


Table 5-1. Combined rating—performance, fabricability, and cost

Fabrication Processes		AISI 304L CF3	AISI 316L CF3M	Alloy 825	CDA 122	CDA 613/ 952	CDA 715/ 964
		Materials					
Pintle and Upper Head							
Pintle Welded to Head							
Forged							
Spun							
Deep drawn							
Centrifugally cast		79	79			85	81
Machined		80	80	80	91		
Integral Pintle and Head							
Forged			93	92	90		89
Centrifugally cast							
Machined							
Body and Lower Head							
Integral							
Extruded closed-end		79	79	74			74
Extruded closed-end cold worked		82	82	77			80
Deep-drawn closed-end		77	76	77	75	75	78
Body Welded to Head							
Body	Lower Head						
Roll and weld	Forged	72	71	73			74
	Machined	72	72	73	66		
Extruded	Forged	70	70	68			70
	Machined	70	70	69			
Deep drawn	Deep drawn	67	66	71	67	68	72
Cent. cast	Forged	77	77				79
	Centrifugally cast	72	72			79	75
	Machined	77	77				
Welded Cold Worked							
Body	Lower Head						
Roll and weld	Forged	61	61	64			66
	Machined	61	61	63			
Extruded	Forged						
	Machined						
Deep drawn	Deep drawn						
Cent. cast	Forged	68	68				72
	Centrifugally cast	65	65			72	70
	Machined	68	68				

Table 5-2. Ratings for performance, fabricability, and cost separately combined

----- FABRICATION PROCESSES -------		A U S T E N I T I C	M A T E R I A L S													
		304L/CF3					316L/CF3M					IN825				
		PERF	FABR	COST	PERF FABR	PERF FABR COST	PERF	FABR	COST	PERF FABR	PERF FABR COST	PERF	FABR	COST	PERF FABR	PERF FABR COST
PINTLF AND UPPER HEAD																
Pintle Welded to Head																
Forged		82	98		90		82	98		90		91	98		94	
Spun		82	98		90		82	98		90		91	98		94	
Deep drawn		82	88		85		82	86		84		91	86		88	
Centrifugally cast		79	71	86	75	79	79	71	86	75	79					
Machined		82	98	56	90	80	82	98	56	90	80	91	98	36	94	80
Integral Pintle & Head																
Forged		94	100	85	97	93	93	100	82	97	92	97	100	69	98	90
Centrifugally cast		92	72		83		92	72		83						
Machined		94	100		97		93	100		97		97	100		98	
BODY AND LOWER HEAD																
Integral																
Extruded closed end		94	79	60	87	79	93	79	60	87	79	97	79	24	88	74
Extruded closed end cold worked		94	88	60	91	82	93	88	60	91	82	97	82	39	90	77
Deep drawn closed end		94	77	56	86	77	93	74	56	84	76	97	74	56	86	77
Body Welded to Head																
Body:	Lower Head:															
Roll & weld	Forged	38	80	87	63	72	38	80	86	63	71	62	80	75	72	73
	Machined	38	83	85	64	72	38	83	84	65	72	62	83	71	73	73
Extruded	Forged	71	77	63	74	70	71	77	62	74	70	84	77	32	81	68
	Machined	71	79	60	75	70	71	79	60	75	70	84	79	28	82	69
Deep drawn	Deep drawn	71	69	61	70	67	71	65	61	68	66	84	65	60	75	71
Cent. cast	Forged	66	79	86	73	77	66	79	85	73	77					
	Centrifugally cast	66	59	87	62	72	66	59	87	62	72					
	Machined	66	82	83	74	77	66	82	82	74	77					
Welded Cold Worked																
Body:	Lower Head:															
Roll & weld	Forged	51	61	69	57	61	54	61	68	58	61	72	61	57	67	64
	Machined	51	63	66	58	61	54	63	65	59	61	72	63	53	68	63
Extruded	Forged	78	59		69		79	59		69		88	59		75	
	Machined	78	61		70		79	61		70		88	61		76	
Deep drawn	Deep drawn	78	53		66		79	50		66		88	50		72	
Cent. cast	Forged	74	61	69	68	68	75	61	68	68	68					
	Centrifugally cast	74	45	70	62	65	75	45	70	62	65					
	Machined	74	63	66	69	68	75	63	66	69	68					

Table 5-2. Ratings for performance, fabricability, and cost separately combined (cont'd)

----- FABRICATION PROCESSES -------		----- C O P P E R	CDA122				B A S E D	CDA613/952				A L L O Y S -----	CDA715/964			
		PERF	FABR	COST	PERF FABR	PERF FABR COST	PERF	FABR	COST	PERF FABR	PERF FABR COST	PERF	FABR	COST	PERF FABR	PERF FABR COST
PINTLE AND UPPER HEAD																
Pintle Welded to Head																
Forged		93	92		93		91	94		93		93	98		95	
Spun		93	92		93		91	94		93		93	98		95	
Deep drawn		93	82		88		91	84		88		93	88		90	
Centrifugally cast							89	71	93	81	85	91	71	80	82	81
Machined		93	92	86	93	91	91	94		93		93	98		95	
Integral Pintle & Head																
Forged		98	100		99		97	100		98		97	100	65	99	89
Centrifugally cast							96	78		88		97	72		85	
Machined		98	100		99		97	100		98		97	100		99	
BODY AND LOWER HEAD																
Integral																
Extruded closed end		98	79		89		97	79		89		97	79	27	89	74
Extruded closed end cold worked		98	77		88		97	88		92		97	88	45	93	80
Deep drawn closed end		98	77	38	88	75	97	66	56	83	75	97	77	54	88	78
Body Welded to Head																
Body:	Lower Head:															
Roll & weld	Forged	71	60		66		63	74		69		69	80	74	75	74
	Machined	71	62	65	67	66	63	77		70		69	83		76	
Extruded	Forged	88	67		79		85	71		78		87	77	37	82	70
	Machined	88	70		80		85	74		79		87	79		83	
Deep drawn	Deep drawn	88	60	44	76	67	85	54	60	71	68	87	69	57	79	72
Cent. cast	Forged						82	79		81		85	79	73	82	79
	Centrifugally cast						82	63	90	73	79	85	59	79	73	75
	Machined						82	82		82		85	82		83	
Welded Cold Worked																
Body:	Lower Head:															
Roll & weld	Forged	77	43		62		70	54		62		75	61	62	69	66
	Machined	77	44		63		70	56		63		75	63		70	
Extruded	Forged	91	48		72		87	52		72		90	59		76	
	Machined	91	50		73		87	54		73		90	61		77	
Deep drawn	Deep drawn	91	43		71		87	40		68		90	53		74	
Cent. cast	Forged						85	58		73		88	61	64	75	72
	Centrifugally cast						85	46	78	69	72	88	45	70	70	70
	Machined						85	60		74		88	63		76	

Table 5-3. Range of rating values for AISI 304L lower units

Rating Criteria	High	Low	Difference
Performance	94	38	56
Fabricability	88	60	28
Performance, Fabricability, and Costs	80	64	16

Results in Table 5-3 indicate the following ranking of process differences, high to low, for the AISI 304L lower units and, in general, are reflected by the ratings for the other alloys as well. Differences of one or two rating points are considered to be insignificant.

Performance and Fabricability
- Integral Units
  - Extruded closed-end and cold worked
  - Extruded closed-end or deep drawn
- Welded Units
  - Extruded body
    - Forged or machined head
  - Centrifugally cast body
    - Forged or machined head
  - Deep-drawn body and head
  - Rolled and welded body
    - Forged or machined head
  - Centrifugally cast body
    - Centrifugally cast head

Performance, Fabricability, and Costs
- Integral Units
  - Extruded closed-end and cold worked
  - Extruded closed-end
  - Deep drawn
- Welded Units
  - Centrifugally cast body
    - Forged or machined head
  - Rolled and welded body
    - Forged or machined head
  - Extruded body
    - Forged or machined head
  - Deep-drawn body and head

5.2. Issues to be Resolved

The issues discussed below need further clarification to make the fabrication selection criteria more accurate. These issues have resulted from discussions with potential vendors, preparation of the fabrication selection criteria, and consideration of methods to reduce container fabrication costs.

5.2.1. Centrifugal Casting

Centrifugal casting for making large diameter seamless pipe is a less expensive method than extrusion or deep drawing. A possible approach is to use centrifugally cast preforms for roll extrusion or deep drawing to reduce costs and produce a wrought product. For some alloys, Kaiser Rollmet has produced seamless pipe by roll extrusion of centrifugal castings. This method should also eliminate the concerns that exist for ultrasonic testing and possible porosity of castings.

Centrifugal casting may not be used for all of the candidate alloys, because there is no casting grade equivalent to Alloy 825 and the centrifugal casting of CDA 122 is not technically feasible.

5.2.2. Uniformity of Closed-End Cylinder Extrusions

The amount of hot work in the closed-end portion of the extrusion will be less than in the wall of the container. If roll extrusion is used, the differential will be exaggerated further because the closed end will not be worked during the thinning of the wall. The property and microstructural differences between the closed end and the wall need to be investigated.

5.2.3. Uniformity of Closed-End Deep Drawn Components

The issue here is similar to that of closed-end cylinder extrusions. The amount of deformation of the closed end is nil compared to the wall, and the same types of evaluations must be performed.

5.2.4. Cold Work and Annealing of Welded Lower Units

Cold working and annealing the longitudinal and girth seam welds, in order to recrystallize them, produces a more uniform microstructure of welded units. This method offers a means to increase performance at acceptable costs. The existence of only limited experience with roll extrusion and deep drawing of welded containers, such as the lower units, requires that the adequacy of this approach be evaluated further with trials.

5.2.5. Annealing of Lower Units

Annealing of the lower units could produce unacceptable distortion, residual stresses, and variations in properties. To avoid descaling after annealing, either a protective atmosphere or a vacuum would have to be employed. For the austenitic stainless steels, a fast cooling rate to avoid sensitization should be employed. The evaluation of the annealing practice with regard to these concerns should be demonstrated with near prototypical containers.

5.2.6. Availability of Starting Materials

The Cameron Forge Company was not able to find a source of supply for CDA 102 or CDA 613. A supplier would have to be found if the back extrusion process and these alloys were selected for the container lower units.

5.2.7. Producibility of Materials

To allow a general comparison of the candidate materials regarding producibility by various processes, Table 5-4 was prepared. This may be of interest to the MT&C technical area. For example, if CDA 122 is chosen, there may be difficulties in obtaining ingots of sufficient size, and in using centrifugal casting.

5.2.8. Advantages and Disadvantages of Candidate Processes

These are summarized in simple terms in Table 5-5.

5.3. Recommendations

B&W recommends that Phase 2 be conducted similar to the original plan discussed in Section 3. However, B&W recognizes the preliminary nature of the total waste-package program and, therefore, believes that more processing options should be kept open until the container design and material selection are better defined. Because of the large potential matrix of processes and materials and limited funding available, B&W is recommending that the Phase 2 mock-up trials be conducted only for selected materials to address key issues for specific processes. Table 5-6 contains specific recommendations for processes, sizes, and materials to be evaluated for the lower unit in Phase 2. Mock-up fabrication will be limited to confirming process feasibility and assessing the more challenging aspects of each process for specific alloys. B&W recommends that mock-up trials for the upper head not be included in Phase 2 since its fabrication can be more routine, and its detailed design configuration has not been established.

The recommendations in Table 5-6 are an attempt to reduce the work scope to fit an anticipated budget. Therefore, not all bases are covered for each process, which could lead to generating insufficient information, depending on which material is finally chosen by the MT&C technical area. For example, the plan calls for only one process to produce mock-ups from AISI 304L or AISI 316L. Although information generated for Alloy 825 should apply, Alloy 825 is somewhat more difficult to work with than the stainless steel, and problems found with Alloy 825 may not be encountered with the stainless steels.

Table 5-4. Producibility of candidate alloys

PROCESS	304L CF-3	316L CF-3M	IN 825	CDA102 CDA122	CDA613 CDA952	CDA715 CDA954
	Materials					
LU01-EXTRUDED CLOSED-END	1	1	1	5	5	1
LU02-EXTRUDED CLOSED END + COLDWORK	1+1	1+1	1+1	5+1	5+1	1+1
LU03-DEEP DRAWN CLOSED-END	1	2	1	1	2	1
LU04-ROLL & WELD BODY W/FORGED HEAD	1	1	1	1	4	1
LU09-EXTRUDED BODY W/FORGED HEAD	1	1	1	5	5	1
LU14-DEEP DRAWN BODY W/DEEP DRAWN HEAD	1	1	1	1	1	1
LU19-CENTR. CAST BODY W/FORGED HEAD	1	1	7	4	1	1
LU24-ROLL & WELD BODY + COLDWORK	1+3	1+3	1+3	1+3	4+3	1+3
LU29-EXTRUDED BODY + COLD WORK	1+3	1+3	1+3	5+3	5+3	1+3
LU34-DEEP DRAWN, WELDED + COLD WORK	1+3	1+3	1+3	1+3	1+3	1+3
LU39-CENTR. CAST, WELDED + COLD WORK	1+3	1+3	7+3	4+3	1+3	1+3

1 - VENDOR(S) CAN READILY PRODUCE
2 - VENDOR(S) POSSIBLY CAN PRODUCE W/SOME DIFFICULTY
3 - VENDOR HAS NOT DETERMINED FEASIBILITY OF COLDWORKING OF GIRTH WELDS
4 - VENDOR(S) CANNOT PRODUCE/OR DID NOT QUOTE
5 - VENDOR(S) COULD PRODUCE IF INGOT SIZE AVAILABLE
6 - VENDOR CAN PRODUCE WITH NEW EQUIPMENT REQUIRED
7 - VENDOR CAN PRODUCE BUT WITH ALTERNATE CAST COMPOSITION

Example of Code

When cold work is used after a primary process, such as cold working after extrusion of a closed-end container, the first digit refers to the first process used and the second to the cold working process. For example, 5+1 for LU02 made with CDA 102 or CDA 122 means that the extrusion vendor could produce it if the proper ingot were available and the second process vendor can easily cold work it.

Table 5-5. General advantages and disadvantages of various processes for lower unit fabrication

PROCESSES	ADVANTAGES	DISADVANTAGES
LU01 - EXTRUDED CLOSED END	SIMPLE, HOMOGENEOUS, HEAVIER WALL EASIER	COST, OVALITY, ECCENTRICITY
LU02 - EXTRUDED CLOSED END + COLD WORKED	REFINED MICROSTRUCTURE, MAYBE CHEAPER TO REDUCE WALL BY COLDWORK RATHER THAN BY MACHINING	IF CAN'T COLD WORK BLIND END, THEN VARIABLE MICROSTRUCTURE?
LU03 - DEEP DRAWN CLOSED END	HOMOGENEOUS AND FINE GRAINED SINCE MADE FROM PLATE	HIGH TOOLING COST, NO MACHINE AVAILABLE YET FOR FULL LENGTH, DIFFICULT FOR SOME ALLOYS
LU04 - ROLL & WELD BODY W/FORGED HEAD	SIMPLE, PROVEN, CHEAP	MORE WELD METAL FOR LOCALIZED CORROSION
LU09 - EXTRUDED BODY W/FORGED HEAD	LESS WELD METAL THAN LU04	MORE EXPENSIVE BODY THAN LU04
LU14 - DEEP DRAWN BODY W/DEEP DRAWN HEAD	ONLY NEED TO MAKE 1 COMPONENT TO FAB ENTIRE CONTAINER	STILL HAVE GIRTH WELD, AT EIGHER LOCATION
LU19 - CENTRIFUGAL CAST BODY W/FORGED HEAD	CHEAP BODY W/NO LONG SEAM WELD	MICROPOROSITY?, LARGE GRAIN?, DIFFICULTIES IN UT. MAY NOT APPLY TO ALL ALLOYS, PUBLIC PERCEPTION
LU24 - ROLL & WELD BODY + COLD WORK	CHEAP PREFORM, COLD WORK TO BREAK-UP WELDS	CAN COLD WORK BREAK-UP WELDS OKAY W/O CAUSING OTHER DAMAGE? + COST
LU29 - EXTRUDED BODY + COLD WORK	MAY BE MORE FEASIBLE THAN LU24 OR LU39	CAN COLD WORK BREAK-UP WELDS OKAY W/O CAUSING OTHER DAMAGE? + COST
LU34 - DEEP DRAWN, WELDED + COLD WORK	MAY NOT REQUIRE AS MUCH COLD WORK, HEAD WOULD ALREADY HAVE COLD WORK. TOOLING COSTS LESS THAN LU14	CAN COLD WORK BREAK-UP WELDS OKAY W/O CAUSING OTHER DAMAGE? + COST
LU39 - CENTRIFUGAL CAST + COLD WORK	SAME AS LU24 BUT NO LONG SEAM	CAN COLD WORK BREAK-UP WELDS OKAY W/O CAUSING OTHER DAMAGE? + COST

Table 5-6. Processes for the lower unit recommended for testing

Process No.	Description	No. of Pieces	Approximate Size, in. OD	Wall	Length	Material 304L	316L	IN 825	CDA 122	CDA 613	CDA 715	Remarks	Key Process Concerns/Issues
					FIRST MOCK-UPS								
1A	Roll and Weld	1 ea.	24	.4	60			x		x	x	No need to evaluate 304L and 316L; technology is proven. No vendor bids for CDA 122.	Consistency of weld, microstructure, weld ductility, heat treatment response. Evaluate cold work & anneal of welds.
1B	For Spin Form Trial												
	Preform	1	26	1.25	60								
	Finished		24.5	.4	120						x		
2A	Centrifugal Casting	1 ea.	26	1.25	20					x	x	304L proven with EG&G trials also applies to 316L. No specification for IN 825. No vendor for CDA 122.	Evaluate porosity, pitting, shrinkage, grainsize and UT. Evaluate cold work and anneal of welds and UT.
2B	For Spin Form Trial												
	Preform	1 ea.	26	1.25	40					x	x		
	Finished		24.5	.4	120								
3	Deep Drawing	1 ea.	<12	.4	<12		x	x	x			316L more difficult to draw than 304L. No experience with IN 825. CDA 122 requires thicker stock. Confirm process feasibility	Property, grain size and residual variation at the bottom and corner. Adequacy of hot worked microstructure and properties of closed end. Homogeneity and ovality. Effect or end/wall transition. Homogeneity of properties.
4A	Hot Back Extrusion	1	26	1.25	60			x					
4B	For Spin Form Trial												
	Preform	1	26	1.25	60			x					
	Finished		24.5	.4	120								
					SECOND MOCK-UPS								
5	Roll and Weld											Near prototypical size and configuration. Refine cost study.	Differences between heads. Effect heat treatment on weld, distortion and residual stress.
5A	With Spun Head	1	24	.4	144			x					
5B	With Machined Head for Heat Treatment Study.	1	24	.4	144			x					
6A	Back Extrusion & Roll Form.	1	24.5	.4	120			x				Refined cost study.	Uniformity of heat treatment, distortion and residual stresses.
6B	Back Extrusion & Roll Form for Heat Treatment Study.	1	24.5	.4	120			x					

6. Quality Assurance

B&W Research and Development Division's Quality Assurance Plan

A copy of the B&W Research and Development Division's QA Plan for Phase 1 (RDD QA Plan No. 87008) is attached. This plan is made in accordance with B&W Nuclear Power Division (NPD) specification 09-1427, dated 10/27/75 and PA 83-776195-00, dated 6/12/87. The NPD QA program is in full compliance with the requirements of the Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants (10 CFR 50, Appendix B), the Quality Assurance Program Requirements for Nuclear Power Plants (ANSI/ASME Standard NQA-1), and the NRC-accepted NPD QA Topical Report (B&W Internal Report BAW-10096A, Lynchberg, VA).

QA Approval

To the best of my knowledge and belief, the work described in this report was completed in accordance with RDD QA Plan No. 87008, Revision 0, dated June 29, 1987.

G. W. Roberts Date
QA Manager
Alliance Research Center
Babcock & Wilcox

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QUALITY ASSURANCE PLAN

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CUSTOMER Nuclear Products Division

QA PROJECT NO. 87008

CUSTOMER CONTRACT NO. 9172105

REVISION 0 DATE 6/29/87

R&DD PROJECT NO. 4380

PROJECT Nuclear Waste Disposal Container Fabrication Development - Phase 1

DATE 3/25/87

IN ACCORDANCE WITH CUSTOMER SPECIFICATION 09-1427 PA83-776195-00 DATED 10/27/75 6/12/87

PREPARED BY:
QA ADMINISTRATOR R. K. Gill

APPROVED BY:
PROJECT LEADER D. F. LaCount

APPROVED BY:
QA MANAGER G. W. Roberts

APPROVED BY:
SUPERVISOR C. M. Weber

THE SECTIONS OF THE R&D QUALITY ASSURANCE MANUAL DESIGNATED BELOW ☒ (AND IMPLEMENTING PROCEDURES REFERENCED IN THE MANUAL) ARE APPLICABLE TO THIS PROJECT.

SECTION			REMARKS
1.0	INTRODUCTION	☒	
2.0	QA PROGRAM	☒	MANUAL REVISION 1/10/85
3.0	DESIGN CONTROL		
	DESIGN REVIEW	☐	
	INDEPENDENT TECHNICAL REVIEW	☒	1704-03 Dated 2/22/85
	CALCULATIONS	☐	
	COMP. PROGRAMS	☐	
4.0	PROCUREMENT DOCUMENT CONTROL (QA REVIEW)	☐	Not Applicable
5.0	INSTRUCTIONS, PROCEDURES & DRAWINGS		
	DRAWINGS	☐	
	ROUTE SHEETS	☐	
	INSPECTION CHECKLISTS	☐	
	ADMIN. PROCEDURES	☒	
	TECHNICAL PROCEDURES	☐	
6.0	DOCUMENT CONTROL		
	ADMIN. PROCEDURES	☒	
	DRAWINGS	☐	
	INSPECTION CHECKLISTS	☐	
	PROPOSAL	☒	
	PROJECT TECHNICAL PLAN	☐	
	QA MANUAL	☒	1702-02 Dated 12/3/86
	QA PLANS	☒	1702-03 Dated 2/12/87
	ROUTE SHEETS	☐	
	FINAL REPORT	☒	
	TECHNICAL PROCEDURES	☐	
	RELEASE OF DATA	☐	

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QA PLAN – PAGE 2 OF 3

QA Project No. 87008 Rev. 0 Date 6/29/87

PROJECT Nuc. Waste Dispos Container Fabrication Dev. - Phase 1 DATE 3/25/87

SECTION		REMARKS
7.0 CONTROL OF PURCHASED MATERIAL, EQUIPMENT & SERVICE		Not Applicable
SOURCE EVALUATION	☐	
APPROVED SUPPLIERS LIST	☐	
SUPPLIER QUALITY HISTORY	☐	
SUPPLIER AUDITS	☐	
SOURCE INSPECTION	☐	
RECEIVING INSPECTION	☐	
8.0 IDENTIFICATION AND CONTROL OF MATERIALS, PARTS & COMPONENTS		Not Applicable
I. D. TAGS	☐	
ROUTE SHEETS	☐	
9.0 CONTROL OF SPECIAL PROCESSES	☐	Not Applicable
10.0 INSPECTION		Not Applicable
INSPECTION CHECKLIST	☐	
11.0 TEST CONTROL		Not Applicable
TEST PROCEDURE	☐	
LOGBOOK/LABORATORY NOTEBOOK	☐	
DATA SHEETS	☐	
CALCULATION	☐	
COMPUTER PROGRAMS	☐	
INDEPENDENT TECHNICAL REVIEW	☐	
12.0 CONTROL OF MEASURING AND TEST EQUIPMENT		Not Applicable
MEAS. EQUIP. CONTROL & CALIB. SYSTEM	☐	
OUT OF CALIB. REPORT	☐	
13.0 HANDLING, STORAGE AND SHIPPING	☐	Not Applicable
14.0 INSPECTION, TEST AND OPERATING STATUS		Not Applicable
ROUTE SHEETS	☐	
LOGBOOK/LABORATORY NOTEBOOK	☐	
INSPECTION CHECKLISTS	☐	
DO NOT OPERATE TAGS	☐	
EQUIP. OPER. NOTICE	☐	
15.0 NONCONFORMING MATERIALS, PARTS OR COMPONENTS		Not Applicable
DISCREPANCY TAG	☐	
CORRECTIVE ACTION REPORT	☐	
16.0 CORRECTIVE ACTION SYSTEM		1717-01 Dated 12/3/86
CORRECTIVE ACTION REPORT	☑	

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QA Project No. 87008 Rev. 0 Date 6/29/87

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SECTION		REMARKS
17.0 QA RECORDS		
RC-194	☒	1718-03 Dated 11/27/85
GO 4028 - 4029	☐	
IWO	☒	
PROPOSAL	☒	
PROJECT TECHNICAL PLAN	☐	
QA PLAN	☒	
INDEPENDENT TECHNICAL REVIEW	☒	
ROUTE SHEETS	☐	
TECHNICAL PROCEDURES	☐	
INSPECTION CHECKLISTS	☐	
AUDIT REPORTS	☐	
CORRECTIVE ACTION REPORTS	☒	(If Applicable)
MATERIAL I. D. TAGS	☐	
DISCREPANCY TAGS	☐	
CORRESPONDENCE	☒	
LOGBOOK/LABORATORY NOTEBOOKS	☐	
3-RING BINDERS	☐	
CALCULATIONS/REVIEWS	☐	
COMPUTER DATA/REVIEWS	☐	
LIST OF DRAWINGS	☐	
SUPPLIER QUALITY HISTORY	☐	
SOURCE INSP. REPORTS	☐	
PURCHASE ORDERS	☐	
INTERIM REPORTS	☐	
DESIGN REVIEW REPORT	☐	
FINAL REPORT – PHASE 1	☒	
OUT OF CALIBRATION REPORTS	☐	
10 CFR 21 REPORTS	☐	
18.0 QA AUDITS		
INTERNAL	☐	
SUPPLIER	☐	
INFORMAL (SURVEILLANCE)	☒	
19.0 CONTROL OF CUSTOMER FURNISHED PROPERTY	☐	Not Applicable

APPENDIX A

DOCUMENTS REQUIRING CUSTOMER APPROVAL

DOCUMENT	APPROX. SUBMITTAL SCHEDULE
QA Plan 87008 Rev. 0 Dated 6/29/87	July 1, 1987

7. References

10 CFR Part 60 (1983), "Disposal of High-Level Radioactive Wastes in Geologic Repositories, Technical Criteria," *Nuclear Regulatory Agency, Federal Register, Rules and Regulations*, Vol. 48, No. 120, pp. 28194–28229. HQ2870302.3019.

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