UCRL--15964
DE91 009760

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

Phase 1 Final Report

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Manuscript date: September 1988

Prepared for
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Acknowledgments

The work reported herein is the product of the efforts of many individuals at Babcock & Wilcox Company and Lawrence Livermore National Laboratory. The authors gratefully recognize their help and efforts. In particular, the efforts of E. W. Russell of the Lawrence Livermore National Laboratory and technical liaison to this activity, W. S. Lyman of the Copper Development Association, and J. Bachelay of the Societe Generale pour les Techniques Nouvelles are acknowledged.

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Preface

The container final closure development activity (also referred to in text as the Closure Project) consists of a multiyear, multiphase project to assess alternatives, to recommend and demonstrate a joining method, and to design a full-scale functioning system for the final closure of disposal containers at the repository.

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

This Phase 1 report is a joining process assessment; Phase 2 will provide sub-scale and full-scale test closure joints with a formal evaluation report and proposed specifications for both primary and alternate joining processes; and Phase 3 will provide a final report and final drawings and specifications and full-scale closure joints.

The Phase 1 fabrication process development report, "Fabrication Development for High-Level Nuclear Waste Containers for the Tuff Repository, Phase 1 Final Report," UCRL-15965, is referred to throughout the text as the Fabrication Development Report; the fabrication process assessment activity is referred to throughout the text as the Fabrication Project.

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List of Acronyms and Abbreviations

AGR	advanced gas reactor
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.
ARC	Alliance Research Center (of B&W)
ASME	American Society of Mechanical Engineers
ASME BPVC	ASME Boiler and Pressure Vessel Code
ASM International	American Society for Metals International
ASTM	American Society for Testing and Materials
AVC	automatic voltage control
AWS	American Welding Society
B&W	Babcock & Wilcox
BWR	boiling water reactor
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
CEA	French Atomic Energy Commission
CEGB	Central Electricity Generating Board (in England)
CFR	Code of Federal Regulations
CW	cold wire
DOE	Department of Energy
EBS	engineered barrier system
EBW	electron beam welding
EEC	European Economic Community
EMAD	engine maintenance, assembly, and disassembly
EPA	Environmental Protection Agency
EWI	Edison Welding Institute
FRW	friction welding
GMAW	gas metal arc welding
GTAW	gas tungsten arc welding
HAZ	heat-affected zone
HIPing	hot isostatic pressing
HLW	high-level nuclear waste
HW	hot wire
IGSCC	intergranular stress corrosion cracking
INCRA	International Copper Research Association Inc.
LBW	laser beam welding
LLNL	Lawrence Livermore National Laboratory
MEL	Marchwood Engineering Laboratories (of CEGB)
MT&C	Materials Testing and Characterization
NDE	nondestructive evaluation
NPD	Nuclear Power Division (of B&W)

List of Acronyms and Abbreviations (Cont'd)

NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
NWPA	Nuclear Waste Policy Act of 1982
OCRWM	Office of Civilian Radioactive Waste Management
PAW	plasma arc welding
PWHT	postweld heat treatment
PWR	pressurized water reactor
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)
SMAW	shielded metal arc welding
SNAP	Systems for Nuclear Auxiliary Power
TVA	Tennessee Valley Authority
TWI	The Welding Institute (in England)
UT	ultrasonics
YMP	Yucca Mountain Project

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Key Words: Nuclear, Nuclear Waste, Welding, Radioactive, Remote Welding, Automated Systems

Abstract

This report summarizes Phase 1 activities for closure development of the high-level nuclear waste package task for the tuff repository. 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). The goal of this phase was to select five closure processes for further evaluation in later phases of the program. A decision tree methodology was utilized to perform an objective evaluation of 15 potential closure processes. Information was gathered via a literature survey, industrial contacts, and discussions with project team members, other experts in the field, and the LLNL waste package task staff. The five processes selected were friction welding, electron beam welding, laser beam welding, gas tungsten arc welding, and plasma arc welding. These are felt to represent the best combination of weldment material properties and process performance in a remote, radioactive environment. Conceptual designs have been generated for these processes to illustrate how they would be implemented in practice. Homopolar resistance welding was included in the Phase 1 analysis, and developments in this process will be monitored via literature in Phases 2 and 3. Work was conducted in accordance with the YMP Quality Assurance Program.

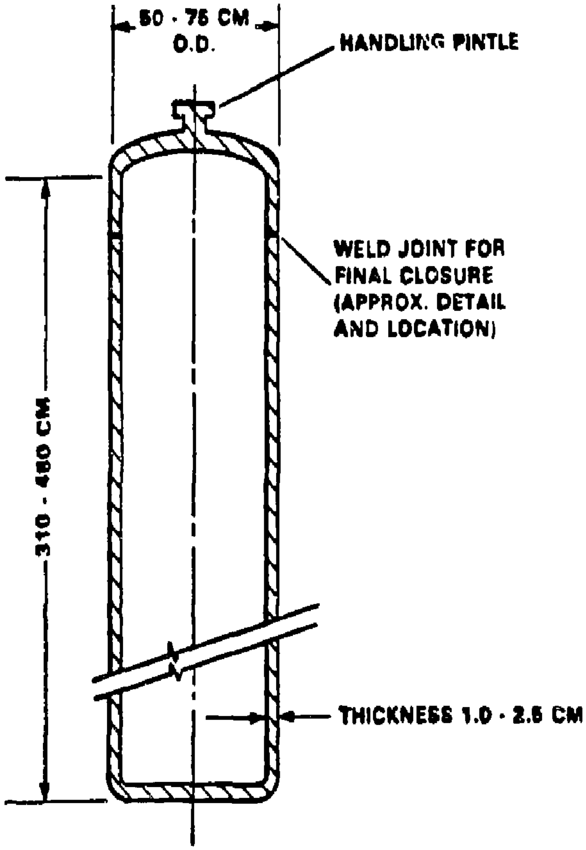
1. Introduction

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 a method for 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 and Characterization (MT&C) technical area are those 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 material and is intended to provide storage 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., 1984). The final engineered barrier system (EBS) design may be composed of a waste form, metallic container, overpack, borehole liner, and near-field host rock, or some combination of these components.

The B&W contract is being administered in three phases. Presented herein is the final report for all Phase 1 activities related to recommending methods for fabricating the waste container. 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.

Section 2 contains an executive summary, and Section 3 outlines the technical approach to the program. Section 4 contains the major project activities, and Section 5 presents a summary of the results and recommendations. Section 6 has information on quality assurance (QA), and Sections 7 and 8 list the references and bibliography, respectively.



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.

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.

	Containers	
Year of Receipt	Annual	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's) YMP, LLNL has the responsibility for designing and developing the package in which to permanently store high-level nuclear waste in the proposed tuff repository site at Yucca Mountain, Nevada. LLNL has engaged 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 closure technology in Phase 1 of this contract. Fabrication activities are addressed in a separate report (UCRL-15965).

A three-phase program is being conducted to assess alternatives, recommend and demonstrate a joining method, and design a full-scale functioning system for closure welding nuclear waste containment vessels.

The objective of Phase 1 has been to perform an engineering study to assess various alternatives and recommend closure processes for the containers. Phase 1 consisted of a study involving literature review, industry impact, and B&W experience to identify and rank candidate processes based on criteria to meet the functional requirements of the application. Phase 1A involved further evaluations to reduce the number of candidate processes to three. Phase 2 of the program will involve welding/testing the test weldment using processes identified in Phase 1, final process selection, and mock-up welding with the preferred process. In Phase 3, the preferred method will be used to produce closure welds in full-sized prototypes, and a detailed system design will be prepared. Full-scale production of containers is not anticipated to begin until 1998.

A decision tree methodology has been used to perform an evaluation of the potential closure processes. Information has been gathered via a literature survey, industrial contacts, and discussions with project team members, other experts in the field, and the LLNL project staff. B&W's team members include the French waste management company (SGN), the Swedish nuclear fuel and waste management company (SKB), and the U.S. Copper Development Association (CDA) for general copper manufacturing technology. The process selection methodology was reviewed by the various team members, The Edison Welding Institute (USA), The Welding Institute (England), and Dr. Carl Lundin (University of Tennessee). The project was conducted in accordance with the YMP QA Program.

Five closure processes for the waste containers have been selected for further evaluation in Phase 1A of the program: friction welding (FRW), electron beam welding (EBW), laser beam welding (LBW), plasma arc welding (PAW), and gas tungsten arc welding (GTAW). These processes are felt to provide an optimum combination of weldment material condition and process performance in a remote, hot cell environment. They also represent three different families of welding processes: solid-state welding, high-energy density beam welding, and arc welding. This range will provide a comprehensive data base for the testing planned for Phase 2 of the program.

Conceptual designs have been generated for the selected processes to illustrate how they would be implemented in practice. Phase 2 should complete the selection of a repair welding methodology so that modifications may be incorporated into the hot cell design. Methods for gripping the container heads during FRW should be evaluated in terms of container cost and materials performance. Requirements for the proposed modified joint design and in-cell machining should be completed.

3. Technical Approach

3.1. Objective

The objective of the three-phase activity is to assess alternatives, recommend and demonstrate a joining method, and design a full-scale functioning system for closure welding nuclear waste containment vessels. This activity is administered through LLNL to develop high-level nuclear waste (HLW) container designs for use at the propsed tuff repository in the unsaturated zone. This activity is one of four major nuclear waste container activities for the YMP: (1) materials selection and testing, (2) container fabrication development, (3) container closure development, and (4) inspection development.

The proposed containers are single-wall, metal cylinders fabricated from one of the six materials listed in Table 1-1. The final design is intended to store high-level nuclear waste for 300 to 1000 years in the stable geological repository. Long-term containment concerns for the containers include general corrosion, localized corrosion [stress corrosion cracking (SCC), crevice corrosion, pitting, and radiolysis and galvanic effects], and the presence and propagation of material defects during handling and storage.

The closure weldment is a very critical part of the container since several of the concerns above are emphasized in the vicinity of the closure. For example, postweld stress relief of the closure weld probably will not be feasible, so high residual stresses may exist in the weldment or the region adjacent to it. [However, this subject is under study and the implementation of some form of postweld heat treatment (PWHT) has not been completely rejected.] This stress, combined with the possibility of sensitization in the HAZs of some materials, could produce a higher susceptibility to SCC near the closure weld than for the rest of the container. Some of the possible welding processes may also produce spatter or flash on the inside of a container, which could lead to pitting or crevice corrosion. To improve weldability, weld metals often have a slightly different chemical composition than their associated base metals, so that galvanic effects may be present. Finally, the potential for crack propagation in the closure weldment is higher because of the possible presence of high residual stresses.

A goal of this activity is to design a closure weldment that addresses the concerns above. The aim is to minimize residual stresses, minimize flash or spatter left on the vessel surfaces, match compositions as much as possible, and minimize welding defects. Input from the other activities in the task was used for the design of the final weldment. For example, the nondestructive examination (NDE) of weldments in the austenitic materials using ultrasonic (UT) techniques is usually difficult because of the presence of large columnar grain structures. Therefore, processes or techniques that produce finer, more uniform microstructures are preferred. Methods for producing finer structures within a given process (current pulsing, magnetic stirring, etc.) will be evaluated.

The final closure welding system must not only produce weldments that are consistent with the long-term storage needs, but must also be amenable to remote operation in a radioactive environment. Therefore, the requirements are that this system must be fully compatible with the containment material, amenable to repetition, and capable of remote operation in a radioactive environment, and must produce a high level of joint integrity and reliability with minimum maintenance requirements. The design will emphasize fabrication simplicity and conservative technology using standardized equipment, proven materials, adequate safety factors, and reliable fabrication techniques. The system must be compatible with the handling, emplacement, and retrieval operations. Cost effectiveness, without compromising design requirements, will be a factor in designing the system. The design will be completed using thorough and adequate engineering analyses and will be verified through prototype testing.

Finally, the success of this program is dependent upon close interactions with the parallel efforts addressing materials selection and testing, fabrication development, and inspection. For example, the selection of the final closure process cannot be made until the reference material is chosen. On the other hand, the weldability of any of the candidate materials will have an impact on the selection of the reference material, so the closure and material selection tasks are mutually interrelated. Similar interactions between all of the parallel efforts are required for each of the major decision points of the activities. Therefore, close coordination of schedules and continuous cognizance of results from the other efforts are necessary. In addition to these interactions, close interactions will continue with three subcontracted outside organizations as team members to take advantage of previous materials and waste storage closure welding development. Those three organizations are SGN, SKB, and CDA. SGN is a French architect-engineering firm that has extensive experience with the design and engineering of complex nuclear facilities in Europe. They are the licensee of the French Atomic Energy Commission (CEA) for a number of advanced nuclear waste canisters. Techniques for producing autogenous (without filler metal) plasma-arc welding were selected, developed, and demonstrated for the French storage canisters, primarily made from austenitic stainless steels. SKB is developing methods to store radioactive wastes in thick copper canisters. Closure is performed by electron beam welding (EBW) or hot isostatic pressing (solid-state welding). CDA and their consultants have several years of experience with the fabrication and welding of copper and copper alloys. They have direct experience with the application of copper to nuclear waste disposal containers through a subcontract with LLNL. Close interactions with these organizations, including the stationing of engineers from SGN and SKB at the Alliance Research Center (ARC) of B&W for periods of time, will minimize the development work required and maximize the reliability of the final closure welding system.

3.2. Overview of the Phase 1 Technical Plan

The objective of this effort is to identify and evaluate candidate closure joining processes that meet the system requirements outlined in Section 3.1. This work has been divided into four subtasks:

1. Review of literature and assessment of application.
2. Identification of possible closure processes with conceptual design.
3. Identification of criteria for closure process evaluation.
4. Evaluation and selection of processes for further testing.

This assessment (when combined with the Phase 1A efforts) will result in the selection of three candidate joining processes to be subjected to further testing. The evaluation criteria used for process selection resulted from literature/industry review and from interactions with LLNL, the parallel development activities, and team members. Conceptual designs were formulated for potential closure processes in this phase to ensure that adequate emphasis was placed on the system implementation issues (remote control, maintenance, cost, etc.).

Special emphasis was placed on the compatibility of the selected closure processes with the candidate containment materials. Welding processes that produce high joint integrity; minimize residual stresses; produce adequate mechanical, corrosion, and inspectability properties; and are amenable to most of the candidate materials were selected. Candidate processes that are unique to one or two of the materials were eliminated unless there were substantial overriding factors.

Another emphasis of this phase was to choose welding systems that are technically conservative. Processes using reliable, well-proven equipment and techniques were selected. Since maintenance inside a hot cell is a significant concern, it was a major evaluation criterion. Simple, reliable equipment capable of adequate production rates and requiring minimal adjustments and service within the remote environment was preferred.

Interactions with the other team members (SGN, CDA, and SKB) were very important in this phase of the program, since important process selections and program planning for subsequent phases were performed. Interactions with LLNL and the other parallel programs were also very important for accurately defining the functional requirements of the containment canisters and for formulating the correct criteria for process evaluation. The evaluation methodology was reviewed by other technical experts in the field.

4. Major Project Activities

This section describes the major project activities involved in choosing three closure processes for evaluation in later phases of the development program. These activities include conducting literature and industrial surveys, defining performance requirements, defining an evaluation methodology (decision tree), selecting the five processes, and generating conceptual designs for the selected processes. Process selection was based on a decision tree approach because of the large number of performance requirements and the complex nature of their interactions. The decision tree allowed a large number of evaluation criteria to be weighted as a function of their importance. Details of each major activity are presented below. Before initiating laboratory testing, we plan to further reduce the number of candidate welding processes from five to three. This reduction will be based on the process rankings and on discussions with LLNL personnel.

4.1. Literature and Industry Survey

4.1.1. Literature Gathered

Four major literature searches were performed for Phase 1 of the Closure Development Project. The following databases were searched:

1. Edison Welding Institute (EWI) Dialog search of the Weldasearch Data Base File 99.
2. ARC Dialog search of the DOE Energy Data Base Files 103 and 104.
3. ARC Dialog search of the ASM International Metadex File 32.
4. CDA Data Base.

In addition to these Closure Development Project searches, six other searches performed by the concurrent Fabrication Development Project were reviewed. As the result of all of these searches, more than 1000 documents were identified for further evaluation. Of the numerous documents identified, more than 200 were gathered, reviewed, and used for the process selection. These documents are listed in Section 8.

4.1.2. Industry Contacts

In addition to the extensive literature that was collected and reviewed, a number of industrial and research organization contacts were made. This section presents a summary of some of the more pertinent discussions conducted during the course of the Phase 1 activities.

4.1.2.1. Weldability and Service Aspects. Industrial contacts were made to address issues regarding the weldability and service aspects of copper and copper alloys. Contacts were also made to address similar issues with respect to Alloy 825. Recorded below are summaries of conversations with the indicated representative of each company listed. At the end of this section, a summary of the issues is offered for each material.

Inco Alloys International, Inc.
(Sam Kiser)
The weldability and service aspects of Alloy 825 and 70/30 copper-nickel were discussed. Mr. Kiser pointed out that Inco provides Alloy 825 in the mill-annealed condition. The mill anneal involves heating at 940°C for 1 hour. Mr. Kiser stated that, during the mill anneal, titanium carbides precipitate in preference to chromium carbide. The mill-annealed condition also allows the replenishment of chromium by diffusion into the denuded zones formed around any chromium carbides that form. In the welding process, the already-precipitated carbides do not return to solution, so they cannot reprecipitate and sensitize. Mr. Kiser pointed out that Alloy 825 was designed for relatively low-temperature acid-resistant/aqueous corrosion-resistant

applications. Mr. Kiser stated that most of the precipitation in this alloy occurs in the range of 1100 to 1300°F. Inco recommends welding products I-112 and I-625 for Alloy 825. These both have an Alloy 625 composition. Inco also makes welding wires that more closely match the Alloy 825 composition. These are the bare wire I-65 and the electrode
I-135. The wires are known to yield deposits that are more susceptible to hot cracking than are the higher nickel materials.

No base metal fissuring problems have ever been reported.

With regard to 70/30 copper-nickel, Mr. Kiser pointed out that the wrought product produced by Inco has good weldability, because the residuals are kept low. Inco is aware of weldability concerns for cast products containing lead, tin, zinc, cadmium, silver, and antimony.

(Tom Limke)
Mr. Limke discussed service aspects of Alloy 825. Mr. Limke recommended that we talk to Peter Cheng at HPD Company regarding their service experience with this alloy. HPD uses Alloy 825 in the manufacture of conventional radioactive waste evaporators. In these units, Alloy 825 is exposed to sulfuric acid at a pH of about 4. It is also possible that it might get exposed to chloride ion, phosphates, boric acid, and metal ions at temperatures up to about 104°C. Mr. Limke said that if we are concerned about weld metal corrosion, we should use Alloy 625 filler, since it is more noble than the rest of the container. He could provide no comment about the possibility of knife-line corrosion in the HAZ adjacent to I-625 filler metal. Mr. Limke stated that Inco does not sell Alloy 825 in the solution-annealed condition (1010°C/1 hour), because of the possibility of subsequent sensitization. He stated that the mill anneal is intended to precipitate chromium carbides and then replenish the chromium. Mr. Limke knew of no application in which Alloy 825 might be exposed to conditions favorable to long-term sensitization at low temperatures.

<u>HPD Company (Alloy 825)</u>
(Peter Cheng)
Mr. Cheng discussed HPD radioactive-waste evaporator application experience with Alloy 825. Mr. Cheng stated that they used Alloy 825 extensively, and that during the last 11 years they have had no problems related to welds. They buy their material in the mill-annealed condition and weld with an Alloy 625 filler metal. In HPD's application, Alloy 825 is exposed to a concentrated radioactive-waste liquid with a vapor interface.

<u>Nickel Development Institute (Alloy 825)</u>
(Barbara Maxwell)
The Nickel Development Institute was established by 14 nickel alloy producers to disseminate information regarding nickel. Ms. Maxwell discussed the availability of resources regarding Alloy 825. Relevant articles were provided by mail.

<u>Youngstown Welding & Engineering (Copper and Alloys)</u>
(Russ Cleghorn)
Mr. Cleghorn discussed weldability issues concerning copper and copper alloys. He stated that the only way to weld CDA 102 is to use gas metal arc welding (GMAW). They use a matching filler, a 50% argon and 50% helium cover gas, and a preheat of 538°C for thicknesses in excess of 0.375 in. These welds are for electrical connection purposes only; they are <u>not</u> structural welds. Mr. Cleghorn reports an oxidation problem in welding this alloy. The weld must be cleaned with a wire brush before every pass. He also reported fusion zone hot cracking problems when the width-to-depth ratio of the weld nugget becomes too large. Too low a preheat results in crater cracks. Youngstown Welding has welded this alloy using GTAW in sections up to 0.375 in. thick. They have some limited experience in the application of EBW to CDA 102. They used EBW to perform a butt joint between 0.500-in. thick tubes. They required a back-up to prevent

the beam from striking the opposite wall of the tube. To make the weld, they required a machined joint with a maximum 0.005-in. gap. X-rays detected a great deal of porosity. Mr. Cleghorn stated that all of the copper alloys in question are electron beam weldable.

Mr. Cleghorn reported that CDA 613 can be welded using GTAW, GMAW, or shielded metal arc welding (SMAW). Youngstown Welding uses a room temperature preheat. (Typical welding nomenclature defines "preheat" as the temperature of the workpiece immediately prior to welding.) Mr. Cleghorn speculated that distortion problems might be encountered using higher preheats. A matching filler composition is used in performing these welds. The company has made structural welds using this material for American Standard and the U.S. Navy. For American Standard, Youngstown Welding attached a domed head to a pipe, and for the Navy, they butt welded tube-to-tube sections. Mr. Cleghorn commented that this material welds "very nicely." They have had no problems with hot cracking. They do require that this material be cleaned with a wire brush between passes. They have welded a 0.25-in. thick section in a single pass.

Youngstown Welding has had no problems welding CDA 715. They have had success using GTAW, GMAW, or SMAW. They use a room temperature preheat and a matching filler metal.

In general, Mr. Cleghorn stressed the need for beginning with a clean joint. They clean the weld joint at least an inch on each side using acetone to remove grease and a wire brush to remove oxides.

Alaskan Copper (Copper and Alloys)
(Don Rosen)
Mr. Rosen reported that Alaskan Copper had experienced "big problems" in welding CDA 102. The company uses CDA 102 to make heavy wall crucibles for titanium and zirconium manufacture. They perform a longitudinal weld in these crucibles. Mr. Rosen stated that for the thickness we intend to weld, we will need a preheat of 1000°F in the manufacture of these seams using the GMAW process. He also recommended the use of a large backing bar when trying to achieve 100% penetration. Once the weld breaks through to the back side of the joint, the material is so fluid that it will flow out of the joint unless the bar is there. In order to make their long seam weld, Alaskan Copper wraps the entire crucible with a 2-in. to 3-in. thick insulating blanket, exposing only the seam.

Mr. Rosen stated that they make CDA 715 as 2-ft diameter pipe. They gas metal arc weld it with room temperature preheat and clean with a wire brush between passes. The interpass temperature does not exceed 350°F. They have successfully welded up to 2-in. thick sections of this material. Alaskan Copper finds that CDA 715 can be UT inspected, but most of their problems with this alloy involve porosity, not cracking. Much attention is focused on cleanliness. Alaskan Copper has some experience in PAW of this material, but they feel much more comfortable with GMAW.

Alaskan Copper has welded CDA 613 using GMAW, GTAW, and PAW. They find CDA 613 to be more sensitive to cracking than CDA 715. For this reason, they are more cautious about preheat and keep it low for high-restraint applications.

Swepco Tube (Copper and Alloys)
(Victor Battistuz)
Mr. Battistuz stated that Swepco Tube developed welding procedures for 145 different materials. Although their experience is not extensive with CDA 102 and CDA 715, he did comment that they need a high preheat to weld CDA 102. He also commented that CDA 715 is welded with an autogenous GTAW root, followed by welding with a matching filler.

Zak Inc. (Copper and Alloys)

(Gene Zak)

Mr. Zak stated that the company does not have much experience with CDA 102, but does have extensive experience in welding CDA 122 (phosphorous deoxidized copper). They have been welding it since 1954 for use in water-cooled copper crucibles for holding molten metal in the electric arc process. They have had no failures. The wall thickness in question is between 0.625 and 1.25 in. Mr. Zak stated that their process of choice for welding CDA 122 is GTAW. They use this process with a relatively low preheat (288°C) and thereby produce less porosity. They found that the welding speed is greater with GMAW, but there is more porosity due to the higher preheat needed. Mr. Zak would not estimate the preheat needed for GMAW. They fill the joint with multiple passes. They use stringer beads without weaving and magnetic field control to achieve good tie-in. Mr. Zak commented that interpass cleaning is very important. He stated that cleaning with a wire brush is necessary between beads.

Zak likes CDA 613 but they have little experience with it. They use it as a buttering layer in welding copper to stainless steel. Zak uses the GMAW process in welding CDA 613. They accept some porosity. The porosity takes the form of 0.0625- to 0.125-in. diameter pores. They use a room temperature preheat.

Zak has some experience in using CDA 715 to weld copper-nickel piping for GE's Knolls Atomic Power Laboratory. They use the GMAW process with consumable inserts. Mr. Zak guessed the preheat to be 93 to 149°C.

AMPCO Metal (Copper and Alloys)

(Carl Dralle)

Mr. Dralle expressed the opinion that a preheat of 500°F would present no problem in the welding of either CDA 613 or CDA 715. He stated that the ductility dip for CDA 613 occurs at 1000°F. From this, he inferred that the 500°F preheat should not be a problem for this alloy. Mr. Dralle stated that the filler metals for the two copper alloys were

CDA 613 — ECuAl-A2
CDA 715 — ECuNi.

The copper-nickel filler is single phase. For CDA 613, ECuAl-A2 has about 15% beta phase, so AMPCO uses an ECuAl-A1 capping pass for de-alloying resistance. The two-phase filler is initially needed to provide hot cracking resistance. Mr. Dralle commented that cast 70/30 copper-nickel may hot crack due to its large solidification range. ASTM lists weldability criteria for cast CDA 715 in "Standard Specification for Copper-Nickel Alloy Castings," ASTM B 369 (ASTM, 1987). The cast aluminum bronze probably would not crack, because of its 4°C solidification range. Mr. Dralle stated that there would be no problem in EBW either of the copper alloys in question. For a high quality weld, AMPCO uses GTAW, but GMAW is also acceptable. It is necessary to clean with a wire brush between passes for both alloys. CDA 613 develops a black, sooty deposit which must be removed. AMPCO has had good results with FRW CDA 613.

Edison Welding Institute (EWI)

(Harvey Castner)

Harvey Castner believes that a preheat temperature of approximately 538°C will be required for conventional arc welding processes on oxygen-free copper (CDA 102 or 122). He also stated that the tighter chemistry control on alloy CDA 613 may improve weldability over alloy CDA 614. Mr. Castner believes that the natural preheat of the containers (150–250°C) may not totally eliminate the arc welding processes for the aluminum bronze and copper-nickel materials, but may require some special considerations since the materials do experience a ductility dip.

The Welding Institute (Copper and Alloys)
(Mike Scott)
Mr. Scott stated that we would have no problem in EBW either CDA 613 or CDA 715. He felt that the 250°C preheat should not be a problem in the welding of CDA 715, but that it might be a problem for CDA 613. Mr. Scott was not sure about CDA 613, but by analogy with CDA 614, he expected that there might be a problem with ductility dip cracking. Mr. Scott stated that CDA 613 was developed for SCC resistance in high-pressure steam. He said that iron is used as a grain refiner in this alloy. Tin precipitates at grain boundaries, giving rise to SCC resistance in this alloy. Mr. Scott stated that CDA 715 is welded with a matching filler with titanium added. He stated that the Cu-10%Al filler used for CDA 613 forms a beta phase that is corrosion sensitive. The beta phase can further decompose to gamma-2, which is brittle.

International Copper Research Association Inc. (INCRA) (Copper and Alloys)
(Dr. Dale Peters)
Dr. Peters recognizes that hot cracking is an issue with CDA 613 and CDA 715, but he feels that this problem can be avoided by specifying alloys with low residuals (antimony, arsenic, bismuth, etc.). Dr. Peters supplied a number of INCRA reports which addressed the weldability of these alloys.

Dr. Martin Prager (formerly with CDA) (Copper and Alloys)
Dr. Prager addressed copper and copper alloy welding concerns. In this capacity, he (and others) provided a review of our process selection methodology. Dr. Prager commented that he would not rule out arc welding for pure copper. He felt that it might reasonably be welded with a preheat as low as 250°C, using perhaps the GTAW process. He also commented that he felt that the hot cracking tendencies of CDA 613 and CDA 715 can be overcome by controlling composition. Dr. Prager felt that creep might be a problem for pure copper in the waste container application.

Summary of Weldability and Service Aspects

The following comments summarize an interpretation of the information gathered via the conversations outlined above. The comments are offered on an alloy-by-alloy basis. These comments served as input in conjunction with the literature review results and in-house experience considerations at the final process selection of this project (Section 4.3.6).

Based on the discussions above, the following observations are made on CDA 102 and CDA 122:

1. There seems to be a difference of opinion regarding the preheat necessary for arc welding pure copper. Across the industry, the reported necessary preheats are 250-538°C. Although it may be possible to weld pure copper at the lower preheats, the use of such low preheats on a production basis for container closure would seem questionable. It is believed that the lower preheats would present problems in terms of potential joint quality and production concerns.

2. A general problem in the arc welding of copper and copper alloys is the tendency of these materials to oxidize. This tendency to oxidize presents a particular problem for multipass welds in that failure to clean with a wire brush between passes gives rise to porosity in the fusion zone of the weld. This problem would be particularly true for pure copper, because of the large number of arc welding passes necessary to fill the relatively thick joint.

3. For the purposes of this Phase 1 study our assumption has been that the closure weld will be made in the 2G (horizontal) position. When arc welding in this position using a reasonable preheat, it will be difficult, if not impossible, to keep the molten copper within the joint due to its fluidity.

4. Some success in EBW of pure copper was reported by Youngstown Welding & Engineering. Problems with EBW-generated porosity with pure copper need further resolution.

Comments concerning the use of CDA 613 are listed below:

1. Industry experience exists for welding CDA 613 using the GMAW, GTAW, SMAW, EBW, PAW, and FRW processes. For high-quality welds, GTAW is most commonly favored, but GMAW is also used regularly. Differences in quality are judged mainly based on the level of porosity in the weld.

2. In high-restraint applications, CDA 613 is arc-welded using a two-phase filler material (ECuAl-A2) to accommodate fusion zone hot cracking tendencies. The beta phase of this alpha-beta alloy is susceptible to corrosion and degradation to a brittle gamma-2 phase. In environments in which corrosion resistance is important, the use of a capping pass of a single (alpha) phase filler is advisable. This combination of fillers would likely be necessary for the waste container application.

3. CDA 613 exhibits a ductility dip in the vicinity of 538°C, which may be exacerbated by the relatively high preheat (250°C) that the container may experience. Potential for such problems may exist in the vicinity of the closure weld. High preheat may also give rise to additional distortion potential in closure welds.

Comments concerning the use of CDA 715 are listed below.

1. Industry experience exists for welding this alloy using the GTAW, GMAW, SMAW, and EBW processes. Like CDA 613, GTAW is commonly preferred to manufacture high quality (low porosity) welds, but GMAW is also regularly used.

2. CDA 715 is arc welded using a matching composition filler metal (ECuNi). The alloy itself has a wide freezing range that can cause problems when welding its cast equivalent. Care must be taken to control trace element levels to avoid hot cracking in this alloy. These elements would include lead, tin, zinc, cadmium, antimony, bismuth, silver, and arsenic.

3. Common industry practice is to use a room temperature preheat with this alloy, and to ensure that the interpass temperature does not exceed 177°C. It is not clear what effect a preheat of 250°C will have on the use of this alloy.

Based on the discussions above, the following observations are made regarding the use of Alloy 825:

1. Industry experience has been favorable for use of Alloy 825 at temperatures up to about 104°C in severe environments.

2. There is no indication of sensitization problems with Alloy 825 in the as-welded mill-annealed condition. However, the possibility of long-term low-temperature sensitization in the HAZ of the alloy may not be discounted now.

3. Some difficulty is reported in welding Alloy 825 with a matching filler metal. If possible, the alloy should be welded with an Alloy 625 filler.

4.1.2.2. Process Implementation Considerations. A wide variety of process implementation issues were discussed with industry and laboratory contacts. Typical issues discussed included:

1. The use of adhesives in closure.

2. Laser implementation issues such as how to transport the beam from outside the hot cell to the workpiece.
3. Friction and homopolar resistance welding capabilities.
4. The effect of closure process selection on inspectability.

An overview of these discussions is provided below.

Edison Welding Institute (EWI)
(Robert Rivet, Larry Reitter)
Discussions addressed the use of adhesives for the permanent closure of the high-level waste (HLW) containers. The use of adhesives for metal-to-metal bonding began around 1968. The majority of the work has been performed with carbon steel and stainless steel materials. Information on bonding copper-base materials is very limited. In general, the turn-around time for the modification of a given adhesive formula is approximately 18 months; therefore, no long-term performance data for adhesives exist. Elevated temperature exposure is one of the major causes of adhesive bond failure. Elevated temperatures cause the adhesive to become "inert," thereby forming a liquid at the bond interface. At the present time, adhesives capable of withstanding temperatures of 250°C can only do so for a matter of minutes.

The reference joint design would be extremely difficult to ultrasonically inspect for voids. No nondestructive inspection method exists that can determine bond strength or adhesion. Concerns regarding environmental degradation were raised. Moisture is one of the most hostile environments for an adhesive. Limited information regarding the performance of adhesives when exposed to irradiated environments is available at this time. The EWI does not view the use of adhesives as a viable closure method.

(Bruce Madigan)
Discussions with Mr. Madigan focused on current methods being used to slope-out deep penetration circumferential laser welds. Mr. Madigan contacted The Welding Institute (TWI), Cambridge, England, where the actual laser welding work would be performed. From discussions with TWI, it was Mr. Madigan's understanding that it is possible to slope-out laser welds by controlling the beam power level and/or focus point in real time. Methods do exist, with limitations, for real time control of the weld penetration.

Babcock & Wilcox, Lynchburg Research Facility (Hot Cells)
(Robert Womack)
Discussions with Mr. Womack addressed hot cell equipment issues as they are affected by the environment. Optical components (i.e., lenses and fiber optics) are subject to a phenomenon called "browning." This effect can be evident in a period of hours depending upon the radiation field level. The "browning" effect is especially true for fiber optic bundles, and they are therefore not recommended for use in the hot cell. Commercial cameras "hardened" for radioactive environments are available. Special shielding considerations may be required for any electrical components desired to be used in the cell (i.e., tracking devices).

Aerodynamic windows (pressure differential holes) are commonly used in hot cells to allow access to such instruments as microscopes. Mr. Womack foresees no design problems using an aerodynamic window to bring in a laser beam from outside the cell, thus eliminating any required transmitive lenses. If the use of transmitive optics is desired, he again foresees no design problems. The hot cell can be designed to allow glove box access in a restricted area. This design would permit the maintenance and repair of the closure system equipment without removing it from the cell.

Sciaky Brothers (LBW and PAW)
(David Gustiferri, Roland Kenning, Robert Lloyd)

Discussions with Sciaky addressed their current capabilities in the areas of LBW and PAW. At the present time, the largest laser that Sciaky has available for research and development (R&D) work is a 5-kW carbon dioxide machine (Spectra Physics). However, the use of higher-powered machines can be arranged. The company feels that the size of the laser required for the closure operation will be largely dependent upon the physical characteristics of the laser (i.e., beam mode) and the beam delivery system. These characteristics are manufacturer-dependent; therefore, the laser power output required to achieve the given depth of penetration will vary depending upon the system's manufacturer.

No major weldability problems are foreseen for the candidate materials. Sciaky has limited experience with the aluminum bronze (up to 0.100-in. thick), and no direct experience with the copper-nickel. In Sciaky's opinion, laser systems in the 10- to 15-kW range should be capable of making full penetration welds in all of the materials except the oxygen-free copper. The major problem foreseen for laser welding a circumferential seam is the potential for defects in the slope-out region of the welds. Sciaky has developed slope-out techniques by regulating beam power, surface velocity, and focus position.

The Plasma Keyhole mode (one pass) is not recommended for performing the closure weld. The upper limit on material thicknesses for horizontal keyhole welds is believed to be 0.25 in. The company recommends that a multipass technique be evaluated.

<u>Manufacturing Technology, Inc. (FRW)</u>
(Dan Kuruzar)
Mr. Kuruzar discussed the use of friction or inertia welding for the closure weld on the waste containers. Machines exist today that are capable of welding cross sectional areas (interface) up to 75 in.^{2} These machines are horizontal type designs. No vertical machine exists that is large enough to demonstrate welds of the desired diameters and cross sections.

Manufacturing Technology, Inc. has previously evaluated the use of friction or inertia welding for the closures on HLW canisters for Pacific Northwest and Savannah River Laboratories. During these evaluations, two types of closures were considered. The first closure was a full diameter weld (27-in. o.d.) and the second was a "plug type" (8-in. o.d.) in the top of the canister. Actual weld samples for both closure types were made using AISI 304L with a wall thickness of 0.375 in. For the "plug type" closure, conceptual equipment designs and predicted life calculations were generated.

Investigations aimed at determining the effect of inclusion content (base metal) on the weld properties of both friction and inertia welds were performed using carbon steel materials. For both processes, weld properties improved significantly as the base inclusion content was lowered. In all cases, the inertia welds exhibited better mechanical properties than did the friction welds. For the materials under consideration, the copper and copper-base alloys present the most challenge. This is due to the potential for twisting and galling the container caused by the seizing of the weld interface while the flywheel of the machine still contains an appreciable amount of energy.

Mr. Kuruzar provided copies of reports addressing the previous investigations. Photographs of the equipment, welded specimens, and weld cross sections were also provided.

Lawrence Livermore National Laboratory (General)

(Robert Day)

Mr. Day addressed the UT inspection concerns for the various closure processes being considered. He believes that UT inspection of brazed joints can be performed quite readily and with a high degree of confidence. By properly choosing the braze material, based on the acoustical properties, the reflection caused by the dissimilar metal interface can be reduced to a "ghost" image. The lack of bond regions will be distinctly detectable. What cannot be determined, however, is the strength of the brazed joint. Both the brazed butt joint and mechanical/braze seal being considered for container closure are believed to be inspectable by UT methods. The thread region of the mechanical seal is complicated from a transducer placement aspect.

The inertia and friction welds are believed to be the most desirable profile of the methods being considered. Mr. Day referenced work being conducted at The Ohio State University by Dr. Lazlo Adler. The fusion welding processes are considered to be the least desirable profiles to inspect. The larger the fusion zone, heat-affected zone (HAZ), and grain size become, the more complicated the inspection and the lower the confidence level. Therefore, electron beam and laser beam welds would be easier to inspect than would be gas tungsten arc welds.

Mr. Day also noted that eddy current inspection is being considered for the closure weld evaluation.

(Charles Witherell)

Mr. Witherell addressed the use of high-powered carbon dioxide lasers in a hot cell environment. Mr. Witherell confirmed the possibility of transmitting the laser beam through a lens in the hot cell wall, even for very high-powered laser systems (15-25 kW). Mr. Witherell also confirmed the use of an aerodynamic window as an alternate approach for bringing the laser beam into the hot cell. Mr. Witherell referenced a high-powered laser system being used in a hot cell environment at the Oak Ridge National Laboratory. This system transmits the beam into the cell using a large-diameter lens embedded in the wall of the chamber. Mr. Witherell expressed concerns on the tolerances (joint alignment, focus, beam power, etc.) required for the laser welding process. At this time, LBW is not clearly a viable process for the closure welding application.

Oak Ridge National Laboratory (LBW)

(Gene Goodwin)

Mr. Goodwin addressed the use of a high-power laser system in a hot cell environment. The facility does have a 12-15 kW carbon dioxide laser for cutting the ends off of radioactively hot fuel rods. The laser system is housed above the hot cell, with the beam transmitted through the wall using optics. The design layout of the work area also allows the laser beam to be reflected to other hot cells or work stations. Only limited welding has been performed with this system. Beam power fluctuations of ±10% have been observed. The major problem encountered during welding is the control of the plasma plume.

Welding Consultants, Inc. (UT Inspection)

(Bill Svekric)

Mr. Svekric addressed the UT inspection of the closure welds made by candidate processes. In the UT inspection of brazed joints, the difference in acoustic properties between the base material and braze material determines the flaw size that can be detected. This acoustical property difference is related to a reflection factor. The smaller the reflection factor, the smaller the flaw size that can be detected. In general, brazed joints can be classified as readily inspectable with UT. The mechanical/braze seal complicates the issue, but has been performed before using a special square thread design. The major problem posed by the mechanical seal is the location of the transducer (remotely). Grain size is the major concern when inspecting austenitic weldments. Large grain size results in grain boundary reflections that lower the confidence of flaw detection. The use of a low frequency transducer minimizes this problem, but reduces the detectable flaw size. Welds made by the electron beam and laser beam processes are believed to be easier to inspect than welds made with conventional arc welding processes. The internal flash on the inertia weld is believed to cause an inspection problem. Because of reflections from this internal flash, a full volumetric inspection may not be possible. This may result in an inspection procedure in which the internal flash region is not inspected (partial penetration inspection).

Ohio State University (UT Inspection)
(Lazlo Adler)
Dr. Adler addressed the UT inspection of inertia welds. The inspection of inertia welds in austenitic materials is difficult, but has been demonstrated with good results. He believes that a flaw indication can be distinguished from a false signal with a high degree of confidence. His work is part of a continuing project that has been underway for the past three years. The current focus of the project is in developing a computer simulation model that detects the joint geometry, material type, and desired flaw entered by the user. The program responds with the optimum transducer frequency, angle, and positions.

The University of Texas, Austin, Center for Electromechanics
(Dr. William F. Weldon)
Dr. Weldon addressed the current state of technology for the use of Homopolar Generators for resistance welding. This process was developed in the 1800s, but has never found wide acceptance in industry. At the present time, the Center for Electromechanics and Parker Kinetic Designs, Inc. (Austin, Texas) are the only ones performing development and commercialization of this process in the United States.

To date, the largest cross-sectional weld (stainless steel) made using these stored energy generators was 12.5 in.^{2} However, the University of Texas currently has a new 60-MW generator believed to be capable of welding up to 100 in.^{2} in cross section.

Homopolar generators were considered by E.I. DuPont de Nemours and Company for high-current resistance welding of defense waste canisters (Savannah River). These generators were removed from further consideration because they were not commercially available at that time.

Limited development work has been performed with stainless steel and Inconel. Dr. Weldon has no recollection of work performed using aluminum-bronze, copper-nickel, or oxygen-free high conductivity copper.

Although these generators are now commercially available, all work to date has been developmental. In Dr. Weldon's opinion, homopolar resistance welding is a viable closure process for all candidate materials, with the possible exception of the oxygen-free copper. This process offers a solid-state weld with no flash generation and smooth root and face profiles. This process is believed to be readily adaptable to remote operation, with weld quality determined by process parameter monitoring.

Summary of Process Implementation Considerations

As can be seen from a review of the information above, numerous industry and research laboratory contacts were initiated to clarify process implementation issues. These discussions helped to gage the feasibility of some processes and gave some insight as to how others might be implemented. These discussions provided input to allow the ranking of the relative merits of the various processes. They also provided valuable input at the conceptual design stage.

4.1.3. Materials-Related Results

An extensive literature review was initiated in order to provide background information to direct thinking on closure process recommendations and to aid in assigning weighting factors in Level 3 of the decision tree (discussed later). This review addressed general issues such as world-wide waste disposal efforts, container weld design and regulatory requirements, emplacement environment, inspection, and a number of other issues that are not material-specific. In addition to the general review, a review was undertaken to address the closure-related concerns for each specific material. The issues identified in these reviews and corresponding bibliographic entries are provided in the Bibliography section. The results of these material-specific efforts are provided in the following sections.

4.1.3.1. AISI 304L and AISI 316L. A literature review was performed to identify welding-related issues that might impact the manufacture and service life of closure welds in AISI 304L and AISI 316L containers. The Bibliography provides a list of the identified issues and the corresponding bibliographic entries. The following primary welding-related concerns are identified with respect to the manufacture and service life of the final closures.

> Manufacture: Because of the popularity of these materials, there is extensive experience in their practical application. Although these materials have been found to be prone to some manufacturing difficulties, for the most part those encountered to date have been solved, or rather, controlled. The literature is replete with the documentation of these efforts.
>
> One manufacturing problem worthy of mention is the possibility of hot cracking during the fusion welding of these materials. For the most part, these problems have been solved by the judicious selection of base and filler metal composition. For optimum results, the base and filler metals should have low residuals, and the filler metal should have an overall composition that ensures that it will solidify as ferrite and result in a minimum of about 3% delta ferrite in the room temperature microstructure. Common industry diagrams that predict the percentage of ferrite at room temperature should be adequate guides for the purposes of materials selection.
>
> A second potential manufacturing problem with these materials is the potential for distortion. Because of their low thermal conductivity and their relatively high coefficient of thermal expansion, these materials are sometimes subject to excessive distortion and the development of large regions of objectionable residual stresses on cooling. As a rule of thumb, to minimize distortion and residual stress due to shrinkage, one can select welding procedures that minimize the weld nugget size for single-pass welds or the number of passes for multipass welds.
>
> Please note that the most effective remedy for excessive residual stresses is to perform a general postweld, stress-relief heat treatment, in which the part is uniformly heated to a temperature adequate to allow material flow and stress reduction. Such a general heat treatment may not be performed for the waste containers because the fuel rods are not allowed to exceed 350°C at any point in the processing. If no means of stress reduction can be identified and implemented, there will be regions of yield point, tensile residual stresses in the vicinity of arc welds. An examination of the literature indicates that high tensile residual stresses may well exist at the external surface of the container. The literature reviewed to date indicates no other effective means of alleviating this stress with any degree of assurance; however, this subject is currently under study, and the possibility of implementing some form of stress reduction has not been completely rejected.
>
> The last manufacturing-related potential problem is concerned with the requirements of NDE. For the most part, UT inspection clearly will be necessary for the volumetric inspection of the closure welds. The large columnar-oriented grain structure possible for most arc welding processes is normally difficult to inspect using UT techniques. The best way to minimize this problem is to reduce the volume of the fused weld zone.

Service: As mentioned above, for fusion welding processes, these materials are prone to the build-up of high residual stress regions in the vicinity of the weld. Such a region will likely extend to the external surface of the container. This possibility, combined with the possibility of either welding or service-induced sensitization in the HAZ of closure welds, suggests that closure welds *may* (over their life) be susceptible to SCC. To minimize this possibility, closure processes that minimize the residual stresses in the vicinity of the weld and that minimize the extent of the HAZ should be selected.

A second, less tractable, problem with service for these materials is the possibility of enhanced localized corrosion due to the use of a two-phase filler material. A filler with 3 to 10% residual ferrite appears to be optimum to alleviate hot cracking problems for many stainless steel welding applications. If such a filler is required, the residual ferrite in some cases can enhance localized corrosion. Also, even at the relatively low temperatures of service, the delta ferrite might possibly degenerate over long periods of time toward a sigma phase, which might deteriorate corrosion and mechanical properties. AISI 316L would be expected to be more susceptible to this kind of damage than would AISI 304L. If this potential problem were judged to have a high probability of occurrence for either material, then preference would be given to those processes that require a minimum of ferrite to ensure sound welds.

4.1.3.2. Alloy 825. A literature review was performed to identify issues that might impact the manufacture and service life of closure welds in nickel Alloy 825 containers. The Bibliography provides a list of the identified issues and corresponding bibliographic entries. The following discussion presents the primary welding-related concerns identified with respect to the manufacture and service life of the final closures.

Manufacture: As noted in the Welding Handbook (Kearns, 1984), "the presence of very small quantities of some elements can have a profound effect on the weldability of nickel alloys.' Thus, the potential for hot cracking problems in the fusion welding of this alloy needs to be addressed. To control this potential, the levels of trace elements such as phosphorous, sulfur, and others that form low melting point constituents in the Ni-Cr-Fe system should be minimized. The use of an Alloy 625 filler metal is also recommended to minimize hot cracking.

Another potential area of concern for fusion welding with Alloy 825 is the possibility of "fluidity" problems. Molten nickel alloy weld metal is not as "fluid" as that of other materials. "Fluidity" is a measure of the molten metal's ability to flow to fill the seams, laps, or any other geometrical discontinuity in the vicinity of a weld. Thus, a lack of fluidity might indicate a higher probability of weld metal defects. This area needs to be further investigated.

The final area of manufacturing concern involves the fact that nickel alloys have been shown to exhibit variable weld penetration based on the amount and type of trace elements in the fusion zone. For example, deeper penetrating weld nuggets are associated with increased amounts of sulfur in nickel alloy weld pools, and deeper penetration is generally desirable to ensure full penetration of the weld. Note that this tendency would indicate that higher sulfur levels are desirable, while the hot cracking problem would indicate that low sulfur levels are necessary. These opposed interests need to be optimized. As a minimum, the potential for variable penetration is a problem that needs attention in the further evaluation of this material.

Service: Like the stainless steels, Alloy 825 has some tendency toward sensitization. To minimize this potential problem, the material is normally delivered from the vendor in the "stabilized" condition. "Stabilization" involves a "mill anneal" heat treatment at a temperature at which the sensitizing chromium carbides are intentionally precipitated. Once the carbides are precipitated, the mill anneal is continued to allow for chromium diffusion to "heal" the *sensitized microstructure. This procedure is effective in producing a stable* microstructure for controlling service-induced sensitization in the wrought condition of the alloy.

Closure processes that involve large heat input have some potential to destabilize Alloy 825 in the HAZs in which sensitization or incipient sensitization may be developed. Incipient sensitization would perhaps lead to true sensitization with extended times at service temperatures. In either case, there is some possibility that the closure process could lead to sensitization in this material (although perhaps this is less of a problem for Alloy 825 than for the stainless steels previously mentioned). This would suggest the potential for SCC in this alloy. To minimize the potential for SCC, processes in which heat input and residual stresses are minimized might be selected. However, for most conventional applications, this alloy is used in the as-welded condition.

The literature suggests that sigma formation is not a problem with this alloy (Sedriks, 1982). In general, the weld regions of this material are expected to respond better to the service environment than those of the stainless steels.

4.1.3.3. CDA 613 and **CDA 715**. A literature review was performed to identify issues that might impact the manufacture and service life of closure welds in CDA 613 and CDA 715 containers. The Bibliography provides a list of the identified issues and corresponding bibliographic entries. The following primary welding-related concerns are identified with respect to the manufacture and service life of the final closures.

Manufacture: In-process oxidation is a concern for the fusion welding of either of these copper alloys. The ready formation of oxides at elevated temperatures leads to the formation of an oxide scale during each welding pass. If this scale is not removed, subsequent passes can be subjected to objectionable porosity or inclusion content in the fusion zone of a weld. An industry-wide common practice is to clean with a wire brush prior to welding and between fusion weld passes.

Solidification hot cracking is a possibility in the performance of the closure weld in CDA 715. CDA 715 is more sensitive to this phenomenon than is CDA 613 because of its much wider freezing range. Susceptibility to hot cracking is, in general, a strong function of the levels of trace elements present. Prager (1986) provides a long list of objectionable elements; however, if the levels of these elements are controlled, the occurrence of hot cracking in these alloys can be controlled to a great extent.

In conjunction with the compositional effects discussed above, the microstructural condition also has a strong bearing on weld cracking susceptibility in these alloys. As an example, significant coring is experienced in the solidification of CDA 715 due to its wide freezing range. This causes the cast CDA 715 to be somewhat more sensitive to hot cracking than is the wrought product. Care must also be taken with CDA 613 to avoid the use of adversely segregated base material.

For CDA 613, ductility dip sub-solidus cracking is more likely when a single-phase filler metal is used in a multipass weld. Ductility dip cracking occurs in this alloy between 400 and 600°C. For this reason, a higher aluminum (alpha + beta) filler is often selected for the early passes of a multipass weld in CDA 613. Final passes are often made with a single-phase filler with a matching composition to the base metal because of corrosion concerns. Ductility dip cracking is also possible for CDA 613. Ductility is regulated by controlling heat input, restraint, and the level of residual elements.

In the welding of both of these copper alloys, the potential ambient temperature of a container (250°C) is above the recommended preheat temperature maximum. As an example, the British

CDA recommends that the preheat and interpass temperatures not exceed 150°C for CDA 613 castings due to concerns about hot cracking (ASM International, 1983; British CDA, 1980). The preheat and interpass temperature recommended by the AWS for copper-nickel is 66°C maximum. However, it has been reported that a high preheat and interpass temperature can be advantageous in avoiding hot cracking in copper-nickel alloys (Witherell, 1960). In spite of the concerns, the successful arc welding of either of these materials at the ambient temperature of the container is believed to be possible by carefully controlling both the material composition and the welding parameters.

Service: Two service problems that relate to the composition of the filler used for CDA 613 are worthy of mention. First, the filler wire for CDA 613 must have between 0.2 and 0.5% tin. If it does not, this material is potentially subject to SCC. Second, the beta phase in high aluminum deposits is subject to decomposition to gamma-2 which, in turn, is subject to rapid local corrosion. For the most part, controlling the aluminum content of the deposit will help to solve this problem. As was mentioned earlier, final passes with a matching composition to the base metal (i.e., all alpha phase) are often used to control this potential problem.

SCC is also possible for copper-nickel alloys; however, Medley and Quinn (1987) report that this problem can be diminished by the addition of soluble iron to the matrix. The iron must remain in solution to be effective. This suggests that low heat input processes should be favored.

4.1.3.4. CDA 102 and CDA 122. A literature review was performed to identify issues that might impact the manufacture and service life of closure welds in pure copper containers. The Bibliography provides a list of the identified issues and corresponding bibliographic entries. The following primary welding-related concerns are identified with respect to the manufacture and service life of the final closures.

Manufacture: The most salient property that affects the weldability of this class of material is its thermal conductivity. The high thermal conductivity of this material leads to rapid heat dissipation away from the weld region. This property requires that the power density be maximized in the performance of these welds. The degree to which this is necessary is a function of preheat. Typically, a preheat of 538°C would be required for the arc welding manufacture of such welds in thicknesses greater than 1/2 in. This would seem to rule out most arc welding processes for closure applications in pure copper containers, since the maximum allowable temperature of the containers (roughly 250°C) is dictated by the design requirements.

At high preheat temperatures, the copper weld pool becomes extremely fluid. For this reason, such welds would normally be made with the weld in the flat position to keep the molten copper from running out of the joint. The high weld pool fluidity would also likely require the use of a large backing bar to preclude the copper from running out of the back of the joint or sagging. The considerations above cast further doubt on the ability of arc welding processes to manufacture horizontally oriented closure welds in copper containers.

The situation above is further aggravated by the tendency of this material to form porosity in the fusion zone. This tendency is affected by the weld cleanliness and the effectiveness of any shielding. In spite of the use of filler materials containing deoxidants, pure copper closures generated using an arc welding process seem to have tendencies toward porosity formation. Such discontinuities might also exist in high-energy density welds, but perhaps to a lesser extent. The information above indicates that the arc welding processes would be a poor choice for performing a closure in a pure copper container.

Service: Service-related weld problems are expected to be minimal with this alloy selection. They are far and away overridden by the closure weld manufacturing concerns.

4.1.4. *Process-Related Results*

A major emphasis of the literature and industrial surveys for closure processes was previous closure experience for waste containers and canisters. The majority of this section is devoted to describing this experience. In addition to previously utilized processes, other joining processes that appear to be applicable have been considered. A more detailed discussion of processes considered is presented in Section 4.3.5.1.

4.1.4.1. General Results. Processes reviewed for closure application have included welding processes, brazing processes, adhesives, mechanical joints, and combinations of these processes. The American Welding Society (AWS) currently recognizes almost 50 welding and allied processes. A number of these are felt to be applicable to this closure. The processes of interest here are described in Section 4.3.5.1. The remainder of this section describes prior closure welding experience in this country and abroad.

4.1.4.2. Prior Closure Welding Experience. The following discussion summarizes the work conducted in the United States and abroad to develop methods of HLW and spent fuel assembly encapsulation.

<u>United States</u>

<u>Oak Ridge National Laboratory</u>
In 1969, Oak Ridge National Laboratory (Gunkel et al., 1969) evaluated the use of the EBW process for the seal welding of fuel capsules for the Systems for Nuclear Auxiliary Power (SNAP) power generation systems. These fuel capsules contained a relatively inexpensive radioisotope fuel (strontium-90 titanate) that was being considered as a heat source to power thermal electric generators. These systems would be used to provide power to areas of limited access.

In the past, fuel capsules of this type were routinely seal welded using the gas tungsten arc process in a hot cell environment. Because of potential accident conditions that might result in a deep sea burial, the EBW process was evaluated to provide deeper weld penetration.

The fuel capsules were made of Hastelloy C, with a wall thickness of 0.400 in. The seal weld was made between the main body and end-cap sections (stepped groove joint configuration), using a modular, low-voltage electron beam system. Because of capsule design considerations, equipment modifications inside the vacuum chamber included provisions for helium backfilling and a gas tungsten arc torch for tack welding the components prior to welding and for seal welding the vent hole.

Full-scale mock-ups were welded in an actual remote condition. Welding parameters were developed to accommodate the natural preheat of the capsules (300-420°C) and to obtain at least a 0.110-in. weld penetration. Weld quality was found to be excellent. Quality was determined by remote UT inspection and helium leak check methods on the actual capsules.

<u>Atlantic Richfield Hanford Company</u>
The Atlantic Richfield Hanford Company conducted a preliminary evaluation of the inertia welding process (Wormeli, 1969) for potential use as a closure method for HLW containers. These containers would be used for the long-term storage of radioactive fission isotopes such as strontium-90 and cesium-137. The waste form was expected to be a solid, with a doubly encapsulated container design.

Preliminary weld trials were made to evaluate the capability of the process using 3.0-in. schedule 80 stainless steel (AISI 304L) pipe material to represent the container body. An end-cap was welded to the pipe section using a cylinder-to-plate joint configuration.

Results from this evaluation showed inertial welding to be readily adaptable to remote operation, with only three parameters to control. This process was found to be tolerant of joint alignment, surface finish, and cleanliness. All weld samples exhibited excellent mechanical properties with repeatable upset. Weld quality was determined by UT inspection, micrographs, and mechanical property tests.

A second evaluation of storage concepts for the long-lived, high heat producing radioisotopes strontium-90 and cesium-137 was conducted in 1971 (Wormeli, 1971; Wormeli, 1972; O'Brien, 1974). The approach considered was to process the stored nitrates into strontium fluoride and cesium chloride and doubly encapsulate these solid compounds for interim storage in deionized water basins. Once a final storage facility was completed, these capsules would be relocated.

Battelle Pacific Northwest conducted a material compatibility study in which Haynes 25 and Hastelloy C-276 alloys were chosen for applications involving the strontium fluoride compound. AISI 316L was found to be a suitable material for the encapsulation of the cesium chloride.

The storage containers consisted of an inner and outer capsule. Each of these capsules was composed of three components, namely a main body and two end caps. The end caps were machined with a step configuration so that, upon assembly, this step provided alignment and shielding for the back side of the weld. Two of these end caps (one per capsule) were welded and inspected prior to emplacement in the hot cell. The wall thickness of the capsules was approximately 0.120 in.

Closure process requirements were that the process must be able to operate remotely, provide high quality and consistent results, be inspectable by remote UT and helium leak check methods, be tolerant of the natural preheat of the capsules (93–482°C), and provide a depth of penetration at least equal to the wall thickness of the capsule. The EBW, GTAW, and inertia welding processes were all found to be capable of meeting the closure requirements. The GTAW process was chosen for further development because of equipment implementation costs.

Weld trials were conducted to evaluate weld parameters, penetration, elevated temperature, and shielding gas effects. Because of capsule design considerations, a vent hole was used to minimize weld pool blow-out resulting from an internal pressure build-up. This vent hole was seal welded after completing the closure. Weld quality was determined by a helium leak check and remote UT inspection (Steffens et al., 1971). Mock-up capsules were fabricated using AISI 304L and were filled with high density salts to simulate the waste form. These capsules were subjected to various tests including thermal cycling, thermal shock, external and internal pressure, shear resistance, and impact resistance. All test results were acceptable.

E.I. DuPont de Nemours and Company

In 1982, the E.I. DuPont de Nemours and Company evaluated remote closure methods for the encapsulation of high-level, borosilicate glass waste for eventual permanent storage (Eberhard et al., 1983; Yutani and Reynolds, 1976; Eberhard and Keller, 1982). This work was performed for the Savannah River Laboratory.

A number of welding processes was considered for the final closure, which would be performed remotely in a radioactively hot environment. The conventional arc welding processes were rejected because of process control problems, slag generation, and insufficient penetration capability. EBW and LBW were deemed impractical because of maintenance, joint preparation, and fit-up requirements. The upset and inertia welding processes were chosen as possible closure methods, with the upset welding process being the primary method based on required equipment development costs.

The upset welding process was evaluated at the Savannah River Laboratory. The closure method evaluated involved the seal welding of a 5.0-in. diameter plug in the bottleneck region of the AISI 304L canister. Mock-up weld samples were made to evaluate weld quality and parameter tolerances and to qualify a weld procedure. Visual examination, metallography, UT, and mechanical property testing were all performed on the test welds.

Results from the weld evaluation showed that the upset welding process was capable of producing repeatable, high-quality welds. The process was also found to offer other advantages in that the system has very few moving parts, requires no consumables, and the majority of the equipment could be located outside the hot cell.

UT inspection was found to be of limited value due to the poor resolution of the weld depth and defect size. Weld quality was therefore controlled by monitoring the weld parameter variables and maintaining them within defined limits.

Battelle Pacific Northwest Laboratory

Battelle Pacific Northwest Laboratory evaluated the use of the inertia welding process (1986) for closure welding of defense, vitrified glass waste canisters for interim storage (Klein and Siemens, 1986; Kuruzar, 1983a; Kuruzar, 1983b). Requirements of the closure process were that it must provide repeatable high-quality welds that are not greatly influenced by external conditions. External conditions include base metal chemistry, part tolerance, joint alignment, surface contamination, and electrical input variations.

The closure weld was to be made in the bottleneck region of the AISI 304L canisters. A vertically emplaced inertia welding machine would be used to weld an 8.0-in. diameter cap to the top of the canister. Provisions were also addressed to provide a secondary closure in case the primary closure was found to be defective.

Several mock-up welds simulating the actual closure joint were made using a horizontal machine. These welds were evaluated by UT, metallographic, and mechanical property tests. All results indicate that the inertia welding process can make both the primary and secondary closure joint of acceptable quality.

Gilbert/Commonwealth, Inc.

Gilbert/Commonwealth, Inc. evaluated closure methods for HLW containers that were to be emplaced in the basalt rock formation at the Hanford repository (Jayaraman, 1986).

Advanced conceptual designs of the containers for the repository were developed by Gilbert/Commonwealth. These designs have focused on three HLW forms: pressurized water reactor (PWR) fuel assemblies, consolidated PWR fuel rods, and West Valley HLW. The materials being evaluated for these containers were A-27 carbon steel, copper, and 90/10 cupronickel ("Standard Specification for Steel Castings, Carbon, for General Application," ASTM, 1987).

Three welding processes were considered as candidate closure methods: EBW, brazing, and narrow-gap GTAW/GMAW. Based on a literature review, the EBW process was selected as the most promising candidate. Induction brazing was also selected as a possible joining method, but would require further feasibility studies. The narrow gap processes were believed to be inherently plagued with weld defects requiring repair.

Westinghouse Electric Corporation

Westinghouse Electric Corporation conducted a program for Rockwell Hanford Operations (1980–1985) to design and qualify canisters for the encapsulation of spent light water reactor fuel assemblies and high-level vitrified waste (Sprecace and Blankenship, 1982; Kurasch et al., 1980; Kurasch, 1980; Wright, 1985). The final system was implemented and demonstrated at the engine maintenance, assembly, and disassembly (EMAD) facility, NTS. This program was in support of the Nuclear Waste Terminal Storage Program.

The design of the storage canister was in accordance with the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME BPVC), Section III, Division 1, Class 3 where applicable. The canister was fabricated from carbon steel with a wall thickness of 0.25 in. The closure weld was made on the full diameter of the canister (12.75 in.) in the horizontal position. Based on the constraints imposed by the existing equipment at the EMAD facility, three welding processes were evaluated for the closure: pulsed GTAW, pulsed GMAW, and PAW. After a short testing program, all three processes were found to be viable closure methods, but the plasma arc welding process was found to be the most desirable based on the given constraints.

A plasma arc system was purchased and evaluated at the Westinghouse facility prior to installation at the NTS. Modifications to the equipment and weld head were required before repeatable weld quality was obtained. The intended method for closure was to use the keyhole mode and complete the weld in one pass. During the weld trials, special techniques were found to be required to initiate and slope-out the keyhole. Filler wire additions were required (second pass) in the slope-out region. Weld procedure qualification was in accordance to ASME BPVC, Section IX.

During the procedure qualification, weld quality was determined by visual, dye penetrant, radiographic, UT, and mechanical test methods. During the welding of radioactive canisters, weld quality would be determined by process parameter monitoring and control. Conceptual designs for remote UT inspection were completed, but not implemented.

Once the equipment modifications were completed and a suitable weld procedure was developed, the plasma arc system was relocated at the EMAD facility for demonstration in a completely remote environment. The closure equipment previously used at the EMAD facility was a gas tungsten arc system that had been used for seal welding stainless steel, spent fuel canisters. Processes were found to be able to perform adequate closures.

England

The Central Electricity Generating Board (CEGB) is currently developing closure welding technology for the nuclear waste management program at their Marchwood Engineering Laboratories (MEL). MEL is currently developing closure welding techniques (Brown et al., 1987) for containers to store high-level wastes from their advanced gas reactor (AGR) systems. Their current plans are to store spent AGR fuel elements in a temporary, dry storage facility at a site that has not yet been selected. The facility will be cooled by natural convection to maintain the container temperature below 280°C. Retrieval/repackaging is envisioned after 100 years, with the cells monitored and corrective actions taken if problems occur during that period.

The current funding for the total waste management system development is estimated at 600M (pounds sterling) over 5 years, supplied by the CEGB. The CEGB is presently a public utility [similar to Tennessee Valley Authority (TVA)] and produces all of the electricity for England and Wales. However, as a result of the re-election of Prime Minister Thatcher, the board is to be privatized to fulfill a campaign promise to lower taxes. The future of this project is therefore unknown, since the various regions will be split into private utilities. Funding mechanisms for large projects such as this have not been defined at this time. Also, a good chance exists that the project will be put on hold in the near future until preliminary public hearings can be completed for the overall waste management concept.

The container [illegible]-mm thick and of low carbon steel (seamless drawn tubing, grade BS 3602; forged heads, BS 16[illegible], and a lifting pintle on the top head). Three circumferential welds are incorporated: shell-to-bottom head, top head-to-pintle, and top head-to-shell (final closure). Most of the development has involved the closure weld. The quality requirements for the closure weld are that the process parameters be monitored to ensure welding within an allowable "tolerance box," be leak-tight to 6 bars pressure, and have no visual defects. Undercut on the root of the closure weld is considered undesirable. Also, the goal is to weld eight containers/day, with the ability to complete at least eight welds without changing the torch. Considering all of the operations involved in loading and encapsulating the waste, this schedule allows about 15 minutes for each closure weld. For the bottom head-to-shell weld, MEL has recommended inspection to BS-2633 requirements. However, the CEGB committee responsible for the overall design has rejected this, since they feel that more stringent requirements are needed.

For the closure weld, several processes were considered, including laser welding, electron beam welding, FRW, PAW, and GTAW. Development was performed for the PAW and GTAW processes. The cold-wire GTAW process was found to be too slow, requiring about 40 minutes to complete a weld (35.5-cm OD x 6-mm thick). The hot-wire GTAW was more promising from the weld speed aspect, but was rejected due to start-up problems, particularly in the root pass. Single-pass PAW in the keyhole mode was desirable for its high speed (about 12 minutes), but was rejected due to large quantities of porosity (some pores 4-mm in diameter) and problems with closing the keyhole. The process finally chosen was a multipass PAW, with a root pass performed in the keyhole mode and two fill passes using cold wire (CW) additions. The joint design is a single U, with a 3-mm root thickness and a 10-degree bevel on the sidewalls. A large factorial program was completed to determine the acceptable range of operating conditions, i.e., tolerance box, and to provide statistics on expected porosity levels. The process can tolerate preheat variations between ambient and 150°C, with a slight negative pressure (2-in. water) during welding. Fit-up tolerances are 0.5 mm mismatch for the seam and 0.25 mm for the root. Even though this concept does not meet the 15-minute goal (requires about 22 minutes per weld), it is felt to be the best compromise at this time.

If closure welding were to commence immediately, the MEL personnel would recommend the following concept: a Hobart PAW system, a laser seam tracking device, automatic voltage control (AVC) to maintain arc gap, television cameras for general viewing, the three-pass procedure listed above, and the quality requirements listed above. Redundancy in some of the equipment above should be considered due to environmental effects. With more time for development, they would reconsider hot-wire GTAW and try to overcome the starting problems. They would also consider the use of a feedback system for maintaining full penetration on the root pass.

France

France has been reprocessing and storing high-level nuclear wastes since the early 1970s. The Societe Generale pour les Techniques Nouvelles (SGN) is the designer and builder of the HLW facilities and their accompanying waste packages. The first facility for these activities was at Marcoule, where spent fuel assemblies are disassembled, fuel rods are chopped and dissolved in an acid bath, reusable fuels are separated, wastes are vitrified in molten glass and poured into containers, lids are placed on the containers, and closure welding is completed. Waste containers are stored in an adjacent, temporary storage facility where they are cooled by natural convection and monitored for leakage. The facility being constructed at LaHague performs the same functions, but has a slightly different layout. Most of the operations above are carried out in one hot cell at Marcoule, whereas the various operations are separated into a number of interconnected cells at LaHague. Although the current storage is only temporary, Marcoule has stored wastes since about 1970 with no major incidents. Plans for underground permanent storage, using an overpack container, are now being formulated.

Since long-term storage, with potential for aggressive environments was not a criterion when container materials were initially selected, many of our material selection concerns are not relevant. Knowing that the storage environment was dry and relatively inert, corrosion considerations were not considered to be important. Therefore, stainless steels were selected due to their high-temperature strength and ease of decontamination. High-temperature strength is required to withstand static pressures during the pouring of the vitrified waste (900°C). Also, materials that rust or need to be painted are difficult to decontaminate. Stainless steels were the least expensive materials that met these criteria. Three alloys were initially considered: AISI 304, 309, and 310. AISI 304 was eliminated because its 900°C strength was too low, and AISI 310 was eliminated due to weldability problems. AISI 309 was selected as the best material, although special control of the carbon content was imposed (carbon is limited to be about 0.08%). Lower carbon will degrade high-temperature strength and higher carbon will reduce ferrite in the weldment, which could lead to hot cracking problems. There are some AISI 304L containers for plutonium storage, but details of these were not provided.

Closure welding of vitrified waste containers at both locations is performed with PAW. The only exceptions are 164 containers that were completed with mechanical locking devices and have been stored at Marcoule (with no problems) since about 1970. The PAW systems at both locations are essentially the same, with the container held stationary and the torch rotated around the axis of the container. The containers resemble large milk cans with a flat surface on top of the lifting pintle. A lid is placed on top of the pintle and held in place with an alignment device at LaHague and tack welded in eight locations around the lid at Marcoule. The LaHague alignment device holds the lid down with a 400-kg force, while a small tack weld is made (no rotation, 2-3 seconds arc time). The torch is then rotated 180 degrees, and the closure weld is initiated. The LaHague lid has an internal aligning rim that fits inside the bottle, while the Marcoule lid is aligned without the aid of a rim. The pintle lip and lid are 5- and 3-mm thick, respectively. The lid was reduced from an initial 5-mm thickness, due to cracking problems with the thicker material. An autogenous (no filler metal) PAW fillet weld is then made between the bottle lip and the lid. Containers are then cleaned (200 bars water spray pressure), swabbed, and surface contamination is checked with a robot arm. All operations are performed remotely with fully automated devices.

There is a slight modification of the container for storing other wastes and scrap, such as failed in-cell equipment. The closure weld on these scrap containers is made just above the shell-to-upper head transition. A short lip is turned in at that point, and the upper head is designed to overlap this lip slightly to allow a closure fillet weld to be made. With this concept, the bottle lid has already been welded into place before loading the top head into the hot cell. The closure weld is made with PAW systems that are similar to those used for closing the vitrified glass containers. Since this is a larger diameter weld joint, about 8 minutes (weld-on time) are required to complete the weld. Only 3 minutes are required for the lid welds. Additionally, the scrap container welds cannot be completed in one operation. When about 95% of the weld is completed, the process must be stopped to allow the container to cool. This procedure minimizes defects in the last inch of the closure, which might result from pressure differential due to the hotter internal gases. When cooled, the last portion of the weld is completed.

Quality control is maintained by recording process parameters and visually inspecting the welds. One mock-up weld per year is made inside the hot cells, and a destructive analysis is performed to ensure that the process is under control. Torch assemblies are qualified on mock-ups outside the hot cells. Process parameters recorded are voltage, current, plasma and shield gas flows, coolant flow rate, and welding speed. Another quality control measure is to perform a bead-on-plate qualification weld for each heat of container material for LaHague. The material is rejected if an unacceptable bead shape and size are found. No grinding of the final weld surfaces is performed since surface defects might be masked. At LaHague, when welding parameters fall outside the allowable tolerance box, the process is automatically shut down and corrective actions taken (torch replaced, if necessary). Once the problem is resolved, the torch is backed up 16 degrees and the weld is completed. The parameter recordings are maintained as part of the QA file. The torch is usually replaced if problems are encountered with it, and the used torch is scrapped. There are provisions for making torch position changes to resolve specific welding problems, but based on Marcoule experience, this is only expected in about 1 of 2000 welds.

The hot cells are constructed almost totally from AISI 304L, primarily for decontamination purposes. The SGN-designed welding fixtures are also built from AISI 304L, except for a few carbon steel bolts. The welding fixture has a spiral mechanism above the torch to allow space to wrap the cable. The containers are grounded for welding by direct contact with flat, braided copper cables located on the bottom plate of the fixture. A constant arc length (fixed torch) of 3 mm is used, with no AVC. The welding arc is very soft (not keyhole) and travels relatively slowly (16-20 cm/min) with an overlap of 12 to 15 seconds. The plasma gas is pure argon, while the shielding gas is an argon plus 5% helium mixture. Between 125 and 200 vitrified glass container closure welds can be made per torch. Torches (including cables) are then discarded and no attempt is made to repair them. A torch is replaced in about a 1-hour operation. SGN has a great deal of experience with their welding system and feels that it is very reliable. Of the approximately 1500 closure welds made at Marcoule, none have been rejected and only about 20 have required any specialized welding (semi-mechanized rewelding of a portion of the initial weld).

Due to the nature of the current French storage scheme, no minimum leak path is specified for the closure welds. The weld bead cross section has a width-to-thickness ratio of about 3, with a thickness less than the container thickness. This joint design is not expected to be used in the permanent (overpack) closure welds.

The canisters are fabricated from welded pipe and stamped or spun bottom head, upper head, and funnel mouth components. The LaHague cans have polished welds, while those at Marcoule do not. The cans cost about $1500 each and are only source inspected, not receipt inspected. They are identified by a series of 0.5-mm indentations in the closure lid.

Finally, the French are evaluating technology for the permanent storage of waste. An overpack container is being considered. The current containers would be slipped inside an overpack (one container per overpack), and a filling material such as bentonite or alumina would be used to fill the gap between the two vessels. A closure weld would then be made on the overpack. Criteria for selecting the overpack material are as follows (not necessarily in order of importance): thermal conductivity, mechanical behavior, corrosion, radiolysis effects (very important), and weldability. A tentative materials choice has been carbon steel, 15-cm thick, welded with the EBW process. Other materials that were considered were titanium and Inconel 625. Only limited development with minimal funding has been performed to date. No development in this area has been performed in over a year, and none is planned for the near future. However, the European Economic Community (EEC) does have an on-going program to evaluate various materials for these applications. Corrosion testing is being performed for two Hastelloy alloys, Alloy 825, titanium, stainless steels, and carbon steels (cast iron was eliminated due to weldability problems).

Sweden

In Sweden, there are currently 12 nuclear facilities that produce approximately 45% of the electric power. The government has determined that all nuclear power production will be terminated by approximately 1995 and that long-term disposal of the nuclear waste must be accomplished. The responsibility for the design, specifications, etc. has been given to SKB. SKB is a utility-owned company in Sweden. A final site for burial has not yet been selected; however, several preliminary sites on existing utility property have been selected. Test holes have been drilled and the storage environment has been analyzed. The Swedish spent fuel will be stored at a depth of about 500 m with a hydrostatic pressure of about 50 bars. Oxygen-free water is present flowing at a rate of about 1 liter/m^2/yr, with approximately 50–60 ppm chloride. No final specifications, designs, or selections have yet been made by SKB. However, the program is aimed at making a final design selection by 1992, with implementation in 1995.

Initially, many materials were considered for storage containers, but a systematic methodology was not used. The Swedish approach (Benjamin et al., 1983; National Research Council, 1984) has attempted to avoid difficult corrosion issues such as localized corrosion (e.g., SCC). Titanium and stainless steel have been rejected for localized corrosion reasons. Nickel-base alloys were not considered, primarily because they are not being considered elsewhere. Concern for the localized corrosion issue and the difficulty for repassivation in oxygen-free water for stainless steels has led to the selection of copper as the material for container construction. Also, owing to the hyperbaric pressure that can give rise to stress corrosion, a decision has been made to use a solid storage unit. SKB has not specified or is not totally sure of the limit to place on the fuel cladding temperature but considers 400°C to be adequate.

The containers are being designed to accommodate nine bundles of boiling water reactor (BWR) fuel, which will require an outer diameter of 800 mm with a length of about 4400 mm, giving a wall thickness of about 100 mm for the copper container. The 100-mm wall thickness is derived by general corrosion allowance for a storage period of 10,000 to 100,000 years in the specified environment. In future tests, SKB may consider reducing the wall thickness of the container by as much as 50%. However, no container designs will be considered with wall thicknesses less than 50 mm, because of current design criteria. Below this value is believed to require an analysis of the effects of radiolysis on the OD surface of the container.

SKB has two approaches for container fabrication and storage. The primary method being considered is a forged bottle (perhaps with integral lower head or perhaps with welded head) with an upper lid. This stopper-in-a-bottle approach will be sealed by EBW. The second alternative is for hot isostatic pressing (HIPing) copper powder to form a solid container. Details of each of these approaches are given in subsequent paragraphs.

Electron Beam Welding

TWI has provided assistance to SKB for welding process selection and preliminary mock-up evaluations (Sanderson et al., 1972; Sanderson et al., 1983). The effect of alloy composition on electron beam weldability has been studied. At the present time, only forged copper specimens are being utilized. Earlier work with cast and extruded samples found that the UT inspection method being used was unable to successfully inspect the 100-mm thick material. The thermal/mechanical treatment of the forged copper is not known. A maximum grain size specification of 0.1 mm has been established based on UT inspectability. Defects as small as 1 to 2 mm can be detected. Only subsize mock-up material has been produced to date by a firm in Finland that has made both plate and pipe. Scale-up to full production size is not considered a technical risk, only a matter of larger machine capacity (but obviously this has not been confirmed). Weld trials using a square butt weld preparation had been made without total success. The EBW process applied to full penetration joints removes material from the weld underbead and leaves a very large crevice. The joint design has been changed. A tight-fitting solid stopper is inserted into the cylinder so that a partial penetration of the electron beam into the solid stopper results, leaving a very small crevice between the stopper and the ID cylinder surface. EBW has been chosen primarily because at thicknesses of 100 mm, it is the only welding process deemed feasible for this joint. FRW was considered, but the equipment to produce such a weld is too massive. Other arc welding processes have been considered, but were rejected because of the potential for excessive heat build-up on the inside of the container. This build-up results from the need for preheats up to 538°C to achieve successful welds. Such heat build-up could damage the fuel cladding and the lead filling used around the fuel rods. Weld trials have demonstrated that low phosphorus copper may be prone to weld defects. Also, the presence of oxygen and hydrogen have caused weld defects. The current material quality requirements for good EBW requires less than 5 ppm oxygen, less than 1 ppm hydrogen, and no phosphorus. This information is summarized in SKB report 83-25.

Examinations of electron beam welds have shown the presence of root defects (porosity). These are not considered harmful in the present configuration, because the defects are located in the solid stopper material and are not part of the joint. However, attempts to terminate the weld by sloping out the welding sequence have resulted in a continuation of these root defects through the joint thickness to the surface. Serious concern exists that this string of root defects may be a connecting path that might cause leaks to the outer environment. TWI is currently addressing slope-out techniques to mitigate this problem.

The fabrication sequence will consist of producing the forged cylinder, perhaps with an integral forged head or with an electron-beam-welded head (the final decision has not been made). The fuel assemblies will be inserted into the cylinder, and the assembly will be filled with molten lead that is then allowed to solidify. The filling height of the lead has not been finalized, but the current intent is to provide a 2% void at the top of the unit. The lead must be removed from the EBW location because it will cause contamination and welding problems. The unit is filled with lead because of the hydrostatic pressure experienced in the storage environment, such that a solid container unit is desired. The 2% void at the top, however, gives rise to a possible creep problem. Therefore, a continuing R&D program to assess the creep of copper and electron beam-welded copper joints is currently being conducted. Residual stress measurements have been performed on electron beam-welded copper mock-ups, with the results indicating a -32 to +36 K N/m^2 residual stress and with tensile values determined in the electron beam weld.

The information above describes the primary approach for providing solid, sealed containers for the Swedish program. A summary of the key technical points is as follows.

Forged material is required for UT inspectability, where a grain size of 0.1 mm or less is required. However, for the 100-mm wall thickness, defect-free electron beam welds have not yet been made, with root defects being the predominant problem. Very high quality copper is needed for successful EBW (low oxygen, hydrogen, and phosphorous required), and the lead void near the electron beam weld will require creep analysis owing to the hydrostatic storage pressure. No full size prototypes have been made or are close to being made (no fabrication drawings or specifications exist).

The Welding Institute

The Welding Institute (TWI), under contract to SKB, has been developing suitable EBW procedures for the copper containers. When initially approached, TWI was asked to recommend potential welding processes. Arc welding was ruled out owing to the high preheat and high heat input needed to complete the joint. This could result in the melting of the lead filling or the fuel element cladding. Diffusion bonding was considered, but the high temperature (700°C) needed to complete the joint was considered excessive, and the bond could not be inspected. Inertia welding was evaluated, but was considered impracticable, owing to the very large size of a machine needed to provide the total energy for welding these thicknesses. Lastly, EBW was selected, because it was feasible to produce the joint and it could be performed relatively quickly. Initially, full penetration welds were made on plate material, resulting in unacceptable weld quality. The weld bead maintained a dagger-shaped profile and produced severe undercut on the underbead portion of the welds. A partial penetration weld technique using a stopper-in-a-bottle joint design was evaluated next; trials were made, with weld penetrations from 5 to 8 in. being obtained on 2-ft diameter mock-up pieces. Heat build-up from this welding can cause the penetration to change from 5 to 8 in., with the interpass temperature reaching 525°C near the overlapping region of the weld. The material freezes very rapidly during EBW, so that any significant gas content in the base metal results in porous welds. Initially, low phosphorus (70 ppm) copper was evaluated, but poor performance (excessive microporosity) was obtained. Now, oxygen-free copper is considered to be optimum. The weld fusion zone is approximately 5-mm wide. Tight control is recommended for base material grain size (low variability) and impurities.

The Welding Institute's current work uses a new electron gun with an indirectly heated cathode type of diode electron beam gun. The emitter is about 2-3 mm long and approximately 4 mm in diameter. Filament emitter life has been shown to be very long with this indirectly heated material (perhaps 1 year). Therefore, with this type of assembly, replacement of the emitter would be required approximately on an annual basis. Additionally, the rest of the gun could become contaminated, but this could be reduced by welding through small metal foil. Two locations in England have experience with EBW in a hot cell environment. A reasonable approach may be simply to use the electron gun for approximately 1 year and then replace it.

TWI offers the following comments concerning our welding application. A 5-kW carbon dioxide laser welding system is commercially available. A 10-kW system is available for experimental use, but the equipment reliability has not yet been proven. A 10-kW laser would be needed to weld 1-cm thickness in all the materials of interest with the exception of copper. By comparison to EBW, a higher welding heat input is needed, primarily due to the reflectance of the plasma at the weld surface. This also results in slightly wider laser welds as compared to electron beam welds. For circle seam welding, weld slope-out may be a significant issue in that there have been no techniques developed to date for defect-free slope-out with laser equipment. A discussion was held regarding locating the laser system outside the hot cell environment. Zinc selenide windows could be considered for transmission of the laser beam. It was indicated that these are not foolproof, and there may be a high risk of failure because to date this material is not capable of passing 10 kW of beam power. An aerodynamic window with approximately a 1-mm diameter hole with suitable optics may be considered. However, this approach may cause concern regarding radiation containment in the hot cell.

Future activities at TWI will concentrate on EBW procedure developments to produce an acceptable slope-out region. This work has been scheduled, but is not currently in progress owing to other high priority activities utilizing the EBW equipment. Also, a large development program for out-of-vacuum EBW is planned, commencing in about one year. The SKB plans to utilize new TWI facilities to evaluate out-of-vacuum welding for their applications.

In general, TWI personnel feel that EBW could be used for all six materials and laser welding for all but the pure copper. They have experience with all the copper alloys and rank them in order of best to worst weldability: 70/30 copper-nickel, aluminum bronze, and pure copper. They also recommend the use of FRW for these containers, since the sizes and thicknesses are less than those for the SKB containers. A modification of the process, radial FRW, should also be considered.

Hot Isostatic Pressed Containers

The second approach to container fabrication and sealing consists of HIPed containers. Much difficulty has been encountered with this approach, but it is still considered a feasible alternative. The hypothesized fabrication sequence essentially consists of the following.

A stainless steel can is loaded with waste fuel elements, and copper powder of two particle sizes is poured into the container and vibrated to achieve approximately 70% density. The closure lid is welded on. There is no inspection on the weld of the closure lid. The unit is heated and purged with hydrogen to remove surface oxygen on the copper particles. The unit is then evacuated to 10^{-2} torr with mechanical roughing pumps and the can is crimped and GTA welded shut. The unit is hot isostatic pressed (HIPed) by first applying pressure to consolidate the copper powder around the fuel pins to prevent ballooning of the cladding. The heat to complete the HIPing operation is then applied (600°C is the temperature currently being projected, but a range 500–600°C is apparently adequate). The resulting container is a dense monolith from which the steel can is removed by machining. There have been no material handling design features specified yet, but they intend to use a recessed socket.

Much has been learned with this HIPing approach, but serious issues still remain. The most serious is that the HIPed unit cannot be adequately inspected by current methods. A non-bond cannot be detected without the existence of fortuitously located "leakers." This issue may require SKB to place another container around the HIPed unit. Another issue is that the HIPing temperature exceeds the fuel cladding temperature allowance. To date this issue has only been reconciled by their technique of fully supporting the cladding material by pressurizing prior to heating in the HIPing operation. The Swedish tests have not simulated the effects of high-strength spacer grids and extremely low ductility Zircaloy fuel rod cladding—their densification gains and smooth deformations may not be repeatable in more realistic environments. The acquisition of adequate powder for HIPing and sufficiently low surface oxygen content appears to be difficult. Finally, the need for extended drying (several hours) of the powders with warm hydrogen after initial compacting is undesirable, especially in an irradiated environment. Hydrogen embrittlement of the copper, as well as the fuel rod cladding, may also occur.

Two particle sizes are used in the HIPing operation. Large particles of 700 to 800 microns in diameter are used in combination with particles of 100 to 200 microns to achieve a high volume fill density. Powders used to date have been obtained from Alcan (a German company). Trials have shown that common commercial powder cannot be adequately HIPed; it becomes brittle because of the high surface oxygen content. From 1000 to 2000 ppm oxygen is too high. A final oxygen content has not yet been specified, but perhaps a limit of 200 ppm oxygen is needed. A problem exists, though, in that some surface oxygen content is needed because the powders cannot be properly poured with very clean powder surfaces. Surface oxygen is removed prior to HIPing by blowing hydrogen. The hydrogen blowing operation can result in hydrogen embrittlement in the canning material and, hence, stainless steel cans have been selected. Current trials with HIPing involve 1% zirconium additions to the powder for use as a getter.

No surface finish specifications exist to date; however, SKB currently accepts no surface scratches or crevices exceeding 3 mm.

The current projections call for 5,000 to 6,000 total containers to be produced at the rate of about 1 container per day. There will be about 1.4 tons of fuel per container, for a total disposal of about 9,000 tons of fuel. The completed assembly ready for storage will weigh about 18–20 tons. No retrievability plans are currently under consideration.

SKB Future Activity

Four main programs for future activities are currently in existence. The Swedish Corrosion Institute will identify potential alternative materials to copper from ongoing corrosion tests. Materials under current consideration are titanium, carbon steel, and a copper alloy. EBW trials (both in and out of vacuum) at TWI will continue, in an effort to develop defect-free welding conditions, focusing primarily on the slope-out region. UT examinations of wrought copper and HIPed copper material continue. And lastly, creep testing of copper and electron beam-welded copper is ongoing, with the first report for 10,000 hours of testing due by the end of 1987.

Canada

Whiteshell Nuclear Research Establishment

Whiteshell Nuclear Research Establishment managed a program to develop the technology necessary to remotely close and inspect containers for the storage of nonreprocessed spent nuclear fuel (called "used fuel" in Canada)(Lawson and Dolbey, 1983; Crosthwaite et al., 1982; Nuttall et al., 1983; Crosthwaite, 1981). Burial of these containers was foreseen to take place in a deep (1000 m) geological repository. This work was in support of the Canadian Nuclear Waste Management Program

Two storage concepts were being considered, with the first addressing the isolation of the radioactive waste for periods of at least 300 years. The second concept focused on more long-term storage methods. The work presented in this report was carried out in support of the short-term storage concepts.

Several container designs were developed, with titanium, copper, Inconel 625, and AISI 316L recommended as possible container materials. Weld trials performed later in this evaluation used AISI 316L because of availability and cost issues.

Closure process requirements were that the process must provide a leak-tight weld with a depth of penetration equal to the base material thickness and a high confidence factor on weld quality. The closure process must not degrade the mechanical and corrosion properties of the storage container. The use of ASME, Section III was recommended for determining weld quality.

Several welding processes and container closure joint designs were considered for the various candidate materials. These three issues are interrelated; therefore, a given material type and joint design will dictate the most suitable closure process. The welding processes considered included electron beam, laser beam, plasma arc, brazing, resistance, diffusion, gas metal arc, and gas tungsten arc welding.

EBW was found to be the preferred process when the components can be placed in a vacuum for welding. LBW was seen as a substitute process for EBW when the welding had to be performed at atmospheric pressure. The electrical resistance and diffusion bonding methods were found to be among the most readily applicable processes for automation. The open arc processes (GMAW and GTAW) were judged to be the least suitable for closure applications, with plasma arc being somewhat better. The process ranking above was based on a literature review, with no weld trials made.

As part of the materials property and performance portion of this project, full-scale mock-up containers were fabricated. These containers were fabricated using AISI 316L, with the gas tungsten arc process used for the closure weld. This material and closure process was selected because of cost and availability issues. The closure weld was made in the 1G, flat, welding position, on the full diameter of the container (26 in.), with a wall thickness of 1.125 in. No backing ring was used to support the root pass for the groove joint prep. The closure weld required 36 passes to completely fill the joint. The welding procedure was conducted in accordance with ASME BPVC, Section IX. Elevated temperature effects, which may result from the thermal radiation from the fuel, were not addressed.

Weld quality on the mock-up components was determined by visual, dye penetrant, and radiographic methods. All welds were found to be acceptable using ASME BPVC, Section III criteria. Weld quality for the actual containers will include process parameter monitoring and control along with other requirements that will be defined later.

4.2. Closure Process Selection Guidelines

A number of sources has been used to aid in defining the guidelines for the design and service requirements of waste container closure welds. These guidelines were the basis of functional assumptions necessary for making closure process selections.

The sources for the guidelines took a number of forms, ranging from papers in the open literature, to government regulations, to conversations with LLNL personnel. In this section, the various written guidelines consulted are quoted and commented upon. In the next section, the resultant assumptions are provided.

4.2.1. Design Objectives and Philosophy

The first issue for consideration is the overall design objectives and philosophy of the YMP with respect to the container and container closure. These subjects are discussed in O'Neal et al. (1984) and Acton and McCright (1986).

O'Neal et al.: Objective
"To support license application by demonstrating conformance with requirements for safe handling, emplacement, retrieval, containment, and release rate per 10 CFR Part 60 (1983)."

O'Neal et al.: Philosophy
"To meet the Nuclear Regulatory Commission (NRC) design criteria with flexibility in technical performance and cost."

Acton and McCright
"The paramount consideration in selecting a container material is whether it can withstand the environment and provide substantially complete containment for a 300- to 1000-year period."

"The YMP emphasis is on using the metal container itself in conjunction with the anticipated repository conditions as the barrier for at least the first 300 years. The YMP interprets substantially complete containment to mean demonstration that a very large fraction of the containers remain unbreached during this time. The metal thickness needed to meet this requirement will depend on corrosion rates and mechanism in the expected environment. These in turn will depend on parameters such as the type of metal and its metallurgical condition and microstructure, the number and nature of any defects in the metal, the type of stress that the container must withstand, radiolysis effects, and galvanic effects."

Based on the information above, the following comments are offered:

1. Since the "objective" is to support license application, precedence should be given to conservative technical soundness, thoroughness of documentation, and modelability.
2. Flexibility in technical performance implies providing a margin of safety with respect to the manufacture and service of a closure weld.
3. Achieving the design life of 300 to 1000 years is a "paramount consideration." This statement implies that factors influencing the service life of a closure are also of paramount concern because the life of the container is severely degraded when a closure fails.
4. The required metal thickness is based primarily on anticipated corrosion rates and mechanisms. This "required thickness" should also be valid for the closure region.

This last comment is also consistent with the weld quality requirements defined by the Canadians, which are summarized below.

<u>Canadian Closure Weld Quality Requirements</u> (Lawson and Dolbey, 1983)

1. The weld must not leak after closure.
2. There must be a small probability of defects that might cause perforation by fracture during handling, emplacement, or due to flooding.
3. Neither the corrosion resistance nor the mechanical properties of the shell material must be impaired, e.g., by contamination or microstructural change, by welding operations.
4. The depth of the weld must not be less than that portion of the container wall thickness for which credit is given as a corrosion barrier.

4.2.2. Nuclear Regulatory Commission Requirements

With the YMP design objectives and philosophy in mind, it is next appropriate to give consideration to the imposed regulatory requirements. The following sections from 10 CFR Part 60 (1983) are provided to identify general requirements and to provide definitions for pertinent words and catch phrases.

<u>10 CFR Part 60 (1983)</u>
"The engineered barrier system shall be designed so that assuming anticipated processes and events: (A) Containment of HLW will be substantially complete during the period when radiation and thermal conditions in the engineered barrier system are dominated by fission product decay; and (B) any release of radionuclides from the engineered barrier system shall be a gradual process which results in small fractional releases to the geologic setting over long times."

- It is our understanding that the following interpretations are valid:

1. "Anticipated processes and events" refers to post-closure performance requirements. It refers to processes or events whose probability of occurrence over the period of concern are greater than 0.1 (cumulative, not annual).
2. With respect to the requirement of "substantially complete containment," absolutes are not reasonable. There will be 20,000 to 40,000 waste packages in the repository. There is a chance for gradual release from a small fraction of these.

"Containment of HLW within the waste packages will be substantially complete for a period... not less than 300 years nor more than 1000 years after permanent closure."

- This seems to indicate that although there are no absolutes with respect to closure, the integrity of the containers is an important issue.

"The release rate of any radionuclide from the engineered barrier system following the containment period shall not exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1000 years following permanent closure."

- This describes the allowable release rate after the 1000-year containment period.

"Additional requirements may be found to be necessary to satisfy the overall system performance objective as it relates to unanticipated processes and events."

- Additional requirements may be imposed in the future.

The following are some pertinent definitions (quotes) from this regulation:

- "Barrier means any material or structure that prevents or substantially delays movement of water or radionuclides."

- "Containment means the confinement of radioactive waste within a designated boundary."

- "Engineered barrier system means the waste packages and the underground facility."

- "Waste package means the waste form and any containers, shielding, packaging, and other absorbent materials immediately surrounding an individual waste container."

- "Retrievability of waste: The... area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced... any or all of the emplaced waste could be retrieved on a reasonable schedule at any time up to 50 years after waste emplacement operations are initiated."

The following are factors (quotes) which must be considered in container and closure design:

- "The design shall include but not be limited to consideration of the following factors: solubility, oxidation/reduction reactions, corrosion, hydriding, gas generation, thermal effects, mechanical strength, mechanical stress, radiolysis, radiation damage, radionuclide retardation, leaching, fire and explosion hazards, thermal loads, and synergistic interactions."

- "Waste packages shall not contain... chemically active materials."

The 10 CFR Part 60 (1983) requirements above have been summarized in references published by YMP personnel as follows:

- Some Closure-Relevant LLNL Design Requirements Derived from 10 CFR Part 60 (1983) (Russell et al., 1983; O'Neal et al., 1984)

  Waste packages shall be designed to:

  1. Contain the waste for 300 to 1000 years.
  2. Be retrievable for 50 years after the emplacement of the first waste package.
  3. Not exceed the temperature limits of the waste forms... 350°C for spent fuel cladding.
  4. Meet requirements with considerations for cost effectiveness, including direct package costs and related repository system costs through the operational period.

4.2.3. Licensing Considerations

With some understanding of the imposed regulatory requirements, further consideration of licensing issues is worthwhile. An overview of many of these issues is provided in Johnson et al. (1986):

- "The NRC is charged by the Atomic Energy Act of 1954, as amended; the Energy Reorganization Act of 1974; and the Nuclear Waste Policy Act of 1982 (NWPA) to develop regulations and to license the *operation of high-level radioactive waste repositories.*"

- "The NWPA assigns the responsibility for development, construction, and operation of the repository to the DOE."

- "Environmental standards for the disposal of radioactive wastes have been promulgated by the Environmental Protection Agency (EPA), as specified by NWPA."

- "Regulations are based on the philosophy that a geologic repository controls the rate of radionuclide release to the accessible environment by means of two major subsystems: (1) the geologic setting and (2) the engineered system.

- "It is recognized that the geologic sciences are far from being precisely predictive and, as a result, the models and most of the geological data upon which they rely are subject to sizeable uncertainties."

- "In order to compensate for uncertainties in predicting the behavior of the geologic system, the NWPA relies on the engineered system... One of the functions of this system is to contain the wastes for periods sufficient to allow most of the fission products to decay to very low levels... During the containment period, the geologic system provides a back-up to the engineered system to account for those scenarios which may result in loss of containment."

- "Because there will be no opportunity to observe actual repository performance prior to licensing, the (NRC) recognizes that physically based models must figure prominently into the predictive process... The bounding process should accommodate possible rather than best estimate conditions."

This section emphasizes the point that assurance of the integrity of the weld closure (as part of the "engineered system") should be given a high priority, and that this integrity should be guaranteed in the face of any reasonably possible adverse condition. This position gives rise to much of the conservatism implied in the functional assumptions which follow. For instance, if it were "possible" that a failure mechanism might be active, the approach taken was to design against that possibility.

4.2.4. Material Considerations

LLNL personnel have identified a number of issues that affect the selection of an acceptable candidate container material. These same issues are expected to impact the selection of an acceptable closure process. Desirable container material/closure qualities are provided as follows:

Definition of Required Properties to Address Important "Anticipated Processes and Events"
from the LLNL Metal Barrier Plan (Halsey and McCright, 1988)

1. Resistance to oxidation.
2. Resistance to general aqueous corrosion.
3. Resistance to environmentally assisted cracking.
4. *Resistance to pitting, crevice, or other localized attack.*
5. Demonstration of adequate mechanical properties.
6. Resistance to mechanical embrittlement.

Metallurgical features that affect the ability of a selected material to provide the desirable qualities listed on the preceding page are provided below:

Definition of Important Microstructural Features
from the Metal Barrier Plan (Halsey and McCright, 1988)

1. Primary phases present and their distribution.
2. Secondary phases and evidence of precipitation reactions.
3. Segregation effects.
4. Grain size and distribution of grain size.
5. Evidence of preferred orientation.
6. Identification and distribution of non-metallic inclusions.

The two lists above provided by the "Metal Barrier Draft Plan" formed the nucleus of the issues later addressed in the decision tree for closure process selection. These lists were expanded upon for our purposes, and the decision tree was simply used to provide a structure whereby the concerns above were interrelated.

Assumed Emplacement Environment

One extremely important consideration with respect to the successful design of a waste container closure is a good definition of the assumed emplacement environment. The four sources quoted below address this subject (Russell et al., 1983; Gause and Abraham, 1986; McCright et al., 1984; Acton and McCright, 1986):

- "The YMP has selected the Topopah Spring Member of the Paintbrush Tuff as the repository target horizon for a repository sited at Yucca Mountain. The repository will be located in a welded portion of the tuff unit." (Russell et al., 1983)

- "Tuff is an igneous rock of volcanic origin and is composed of volcanic rock fragments (shards) and ash. During an eruption, the shards and ash are propelled by gases and are deposited downslope from the crater. In the Basin and Range area of the United States... the age of these deposits is estimated at between 8 and 27 million years old. Deposits of tuff exceed 3,000 m in thickness and lateral ranges of tens of kilometers occur in certain locations... these deposits have been extensively characterized." (McCright et al., 1984)

- "The static water level in Yucca Mountain lies about 530 m below the surface. A nuclear waste repository could be located in a horizon above this depth in the welded devitrified zone. This horizon will be the Topopah Spring member. Among the advantages of locating a repository in this so-called unsaturated zone are the expected reduction in the severity of the corrosive environment due to minimum water and the elimination of a hydrostatic stress component on the waste package. Further advantages to locating the repository in the welded zone are the higher thermal conductivity and higher compressive strength of the tuff in this zone. The chemical composition of the welded tuff in this zone is given in the table on the next page."

According to Russell et al. (1983), "The static water level is over 100 meters below the repository level." The depths given here are based on information obtained from geologic and hydrologic boreholes around the edge of the repository block and from the principal borehole (USW G-4) at the location of the planned exploratory shaft. The exact depth of the repository horizon will be established during the exploratory shaft phase of the program.

Major Element Bulk Composition for Reference Welded Tuff (Gause and Abraham, 1986)

	Typical Range, wt %
SiO_2	68–75
TiO_2	0.0–0.4
Al_2O_3	10–17
Fe_2O_3	0.1-2.0
FeO	0.1-2.0
MnO	0.0–0.2
MgO	0.1-1.5
CaO	0.5-2.5
Na_2O	1.0–6.0
K_2O	2.0–7.0
P_2O_5	0.0–0.2
S	0.0–2.0
H_2O	1.0–5.0

The choice of the unsaturated zone marks a departure from the conventional environment for which repository siting has been proposed. There are many characteristics of the unsaturated zone that make it particularly attractive for a HLW repository site. Several advantages of the unsaturated zone over the saturated zone are described below.

- The waste containers will not be submerged in a continuum of water. Rather, they will be subjected to constant contact with water vapor and to intermittent contact with limited amounts of liquid water.

- The environmental pressure exerted on the containers will be approximately 1 atm. There is no hydrostatic pressure, because there is not a continuum of water above or around the canisters.

- The environment to which the container is exposed will be of air plus water vapor, if the temperature is more than about 100°C. This is a consequence of the absence of hydrostatic pressure.

- Aqueous corrosion of the container or overpack can only begin after the temperature has dropped to less than about 100°C. This is because liquid water cannot exist in the unsaturated zone at temperatures higher than 100°C, the 1-atm boiling point of water.

- The vadose water and atmosphere of the repository will be mildly oxidizing. This may promote the growth of a protective coating of oxidation products on the skin of the metal components of the waste package. Such oxidized coatings can form protective layers against further corrosion, as in the cases of stainless steel, zirconium, and titanium.

- Water available for corrosion and waste from dissolution are limited to the small amount supplied by downward infiltration from the overlying unsaturated media, a flux currently estimated to be less than 0.5 mm/year.

- The low pressure in the repository means that containers and overpacks do not need to be designed to withstand high hydrostatic pressures. The only strength requirements for canisters and overpacks will be that they must withstand any stress conditions that might arise during normal and accident handling and emplacement operations, or during retrieval operations and expected seismic events.

Gause and Abraham (1986) also address the subject of the potential flux of vadose water at the emplacement site. According to the authors, The porous nature of the rock implies that air will be present and that the limited amount of vadose water will be air-saturated." (The projected water flux at the repository horizon is less than 0.5 mm/year downward. Rainfall at Yucca Mountain is less than

150 mm/year, and most of the water evaporates rather than penetrating deep into the ground.) Heat and radiolysis (i.e., the interaction of radiation, air, and water) will change the composition of the post-closure environment.

"Initial heat transfer calculations for the tuff repository indicated that surface temperatures on most spent fuel waste packages and in the immediately surrounding rock would remain above 96ºC, the non-confined boiling point of water at this elevation, in excess of 300 years, so that 'the majority of containers will be exposed to a water vapor and air environment during a significant fraction of the containment period. Immersion is an unanticipated event in the proposed repository period. Immersion is an unanticipated event in the proposed repository location during the post closure period' (Gause and Abraham, 1986). This is what was assumed in this Phase 1 study. Subsequent heat transfer analysis has shown this conclusion to be very sensitive to the heat output and spacing of the containers assumed in the calculations, and since these parameters are not firmly established at present, estimates of the fraction of containers remaining above the boiling point during the containment period are subject to change in the future as design parameters become more firm."

"The ambient temperature in the repository horizon is expected to be 29ºC . . . nearby Well J-13 produces water which has the chemical composition given in the table below:"

Reference Groundwater Composition for Tuff Repositories
(Based on Composition of Jackass Flats Well J-13 at the NTS)

Element	Concentration, mg/liter
Lithium	0.05
Sodium	51.0
Potassium	4.9
Magnesium	2.1
Calcium	14.0
Strontium	0.05
Barium	0.003
Iron	0.04
Aluminum	0.03
Silica	61.0
Fluoride	2.2
Chloride	7.5
Carbonate	0.0
Bicarbonate	120.0
Sulfate	22.0
Nitrate	5.6
Phosphate	0.12
pH - slightly basic (7.1)	

Figure 4-1 shows the thermal history of a spent fuel package as a function of time. This thermal history is based on the indicated thermal power and areal power densities.

"While the rock temperature exceeds 95ºC and the dehydration zone extends more than approximately one meter into the rock surrounding the waste package . . . radiolysis products will be restricted to those resulting from interaction of gamma radiation with moist air. These radiolysis products are not well

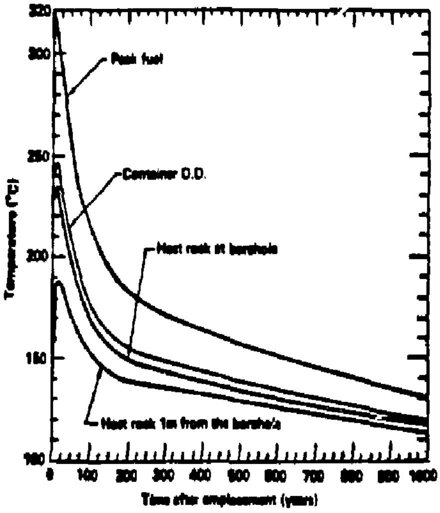


Figure 4-1. Temperature histories of a spent fuel waste package in tuff. The 70-cm diameter package contains 10-year aged PWR fuel with thermal power of 3.3 kW, vertically emplaced in an array with areal power density of 57 kW/acre (O'Neal et al., 1984).

established although theoretical and experimental evidence suggests that, at temperatures below approximately 120°C, the most abundant products are HNO_3, N_2O, and a small amount of O_3. Between approximately 120°C and 133°C, NO_2, N_2O_4, N_2O, and O_3 dominate; above approximately 133°C, NO, N_2O and O_3 are prevalent. The fate of these species is not known in detail, although with the exception of N_2O all of the species will react with rock to form a variety of reaction products."

"After the rock temperature has dropped below 95°C and liquid water intrudes within one meter of the waste container, the radiolysis products will depend on the concentration of solutes and on the radiation dose. When J-13 water has equilibrated with tuff, solute concentrations are only on the order of 10^{-3} to 10^{-2} M. A negligible amount of nitrite and nitrate ions will be produced in solution due to irradiation. In addition, hydrogen ion production will not be sufficient to overwhelm the buffering capacity of the bicarbonate present; therefore, the solution pH will remain near neutral."

4.2.5. Manufacturing Considerations

All considerations discussed before this section relate to the service environment and requirements for materials in the closure joint. However, a number of other considerations result from the need to perform the closure remotely in a hot cell environment. These considerations relate to the ability to reliably produce sound welds and to maintain equipment remotely. Therefore, the additional requirements for the process selection include candidates that are fully compatible with the containment material, are amenable to repetition, are capable of remote operation in a radioactive environment, produce a high level of joint integrity, and are reliable with minimum maintenance requirements. The process selection will emphasize fabrication simplicity and conservative technology using standardized equipment, proven materials, adequate safety factors, and reliable fabrication techniques. The processes will be compatible with planned handling, emplacement, and retrieval operations. Cost effectiveness without design requirement compromise will be a factor in choosing the three closure processes for further evaluation.

4.2.6. Summary of Guidelines

This section contains a body of information that guided efforts on closure process selection. The "Design Objectives," "Design Philosophy," Nuclear Regulation Requirements, and Licensing Considerations provided general goals with wide implications. The more specific information in the "Metal Barrier Draft Plan" and in papers addressing site environmental issues aided in identifying the optimum closure processes.

In the following section, the functional assumptions are offered. These are assumptions necessary to define the closure process requirements and restrictions. These assumptions are based on the information discussed in the previous paragraph and on verbal input from LLNL.

4.2.6.1. Environment-Related Assumptions. The following assumptions were used to provide the environment-related boundary conditions for the selection of the candidate processes.

1. Temperature

The container wall temperature can range from 150 to 250°C at the time of welding.

- Temperature will be sensed and the procedure may have to be adjusted to accommodate variation in preheat.
- Procedure qualifications should include variable preheat.
- A maximum spent fuel temperature of 350°C is the limiting case.

The temperature of the container will be uniform about the circumference immediately prior to welding.

- Controls will be provided to ensure this.

The temperature of both sides of the joint will be equilibrated before welding.

The temperature of the fuel rods shall not exceed 350°C.

After emplacement, the rock in the vicinity of the containers will be at a temperature above the boiling point of water (96°C) for 300 years—implying only dry steam in contact with the container wall for the first 300 years, then water contact is possible. As noted above, this assumption is sensitive to the parameters used in the heat transfer calculation, and is subject to change as these become more firmly established.

- Corrosion failure in the dry steam is a low probability event.

2. Atmosphere

It will be possible to "inert" the inside of the container during and after welding.

- May require design modifications to container or cell.

- May be inert gas or vacuum. Further study is needed of possible heat transfer problems of fuel rods in vacuum.

3. External Environment Factors

Water may be in contact with the container for up to 700 years or more.

- This water will be concentrated to some degree in sulfates and chloride ions, making SCC of the stainless steels and nickel alloys possible and making the corrosion attack of copper alloys *possible.*
- Radiolysis of the water will give rise to oxidizing species, nitrogen-bearing acids, nitrates, and nitrites that can attack copper.

Closure procedures are being designed in a conservative manner with respect to the occurrence of these possibilities. In spite of the low probability of the events above, welding is to be performed as if the events can and will occur.

4. Overload/Impact

Overload might occur during handling. Although there is interest in maintaining strength in the vicinity of the weld, it is assumed that the strength issue is of secondary importance. Section load carrying capabilities can always be achieved by increasing the cross section at the weld.

Impact might occur during handling. It is unlikely to occur during service.

Service-related overload or impact is a low probability event.

5. Internal Environment

Approximately 0.01% of the fuel rods are believed to be failed and to contain water. At the present time, a decision has not been made as to whether this water will be removed before sealing the rods in the waste containers. For purposes of this Phase 1 study, it has been assumed that this is not a problem, although the matter is receiving further study.

This assumption has a large impact on the weld process and procedure selection in that the back side of the weld (i.e., at the ID of the container) is not a big issue if this assumption is made.

Residual brazing flux remaining on the inside of a container is assumed to present service problems.

4.2.6.2. Design-Related Assumptions. The following assumptions were used to provide the design-related boundary conditions for selection of the candidate processes.

1. Joint Design

Wall thickness for copper CDA 122 is 3 cm (it is 1 cm for all other materials).

Crevices at the internal surface were assumed to be acceptable as long as they do not act as stress raisers.

- That is, internal crevice corrosion is assumed not to be a concern. This assumption will be re-examined in future work.
- Backing rings and similar devices are acceptable. Some spatter on the inside of the joint is acceptable. A spatter shield may be incorporated into the container design if necessary.

Weld profile at the external surface is important in terms of stress and inspectability.

Some radial shrinkage at the weld is anticipated to occur. The weld is being designed to control distortion and residual stress.

- It is assumed that there are yield point tensile residual stresses at the external surface for any weld involving fusion (from thermal contraction).

2. Inspectability

Little can be done to favorably influence the inspectability of any of the six materials. However, the inspectability of any of the materials can be increased by minimizing the size of the fusion zone.

- The proposed joint design might help inspectability, i.e., the design that incorporates a lip onto the head.
- Items inspected for cracks, inclusions, laps, seams, porosity, and lack of penetration will be controlled to the extent possible by process and procedure selection.

3. Other Design-Related Issues

Some means of joint alignment, such as the internal lip or other guiding design features, can be incorporated into the joint.

Process selection is assumed to be unaffected by internal brackets or spacers. These items are assumed to be unattached to the container wall and have no influence on:

- Welding thermal stresses.
- Welding distortion.
- Welding temperature distribution.

B&W assumes that an internal ceramic liner, if used, would be designed and positioned in such a way that it would not be adversely affected by welding process selection.

- It is assumed, at this point, that the closure joint does not include a ceramic member.

The thickness of the joint is assumed to be equivalent to the necessary wall thickness designed to account for corrosion and strength considerations.

Mating portions of the shell to be joined are assumed to be concentric, with acceptable ovality.

It is also assumed that the closure will be performed with the container in the vertical position, and with the closure joint in the horizontal position.

4.2.6.3. Materials-Related Assumptions. The following assumptions were used to provide the materials-related boundary conditions for selection of the candidate processes.

1. Sensitization*

Assuming that AISI 304L, AISI 316L, and Alloy 825 might be subject to sensitization during the service life of a container, the weld process is selected to minimize this effect.

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*Austenitic stainless steels might be subject to sensitization due to a combination of (1) original condition, (2) weld temperature history, (3) long time, low-temperature in-service conditions. LLNL has an ongoing effort to demonstrate the avoidance of sensitization.

- It is recognized that the anticipated preheat will probably adversely affect sensitization in these alloys.

2. Galvanic Effects—Microstructure-Related

It is recognized that two-phase regions can present a problem in this regard. To the extent possible, efforts will be made to diminish this effect; e.g.,

- Working to a delta-ferrite maximum for the stainless steels.
- Providing a capping pass for *aluminum bronze*—in that the typical filler is two-phase to prevent hot shortness tendencies of the single-phase alloy.

However, in some instances, because of *weldability* concerns, *the use of a filler of a composition* different from the base is advisable. To some extent, this is true for all of the alloys of consideration, but it is particularly true of

- Alloy 825, where Alloy 625 filler is recommended.
- *Aluminum bronze, where a high aluminum filler is recommended.* Recall, however, that a capping pass may be used.

When weldability is at issue, it is assumed that a *reasonable filler metal that is more noble than the* base metal can be used.

It is assumed that the following base metal/filler metal combinations are acceptable:

Base Metal	Filler Metal
AISI 304L	AISI 308L
AISI 316L	AISI 316L
Alloy 825	I825 (Matching composition) or I625 (Alloy 625 composition)
CDA 102, 122	ERCu
CDA 613	ER CuAl-A2 ER CuAl-A1 (Capping pass)
CDA 715	ER CuNi

3. Cleanliness

If multiple passes are required, it is assumed that it will be possible to clean with a wire brush or grind between passes.

- This will be particularly important for the copper alloys, but it may also affect all of the alloys.

4. Base Metal Condition

The closure process used is chosen with the assumption that the base metal is in a uniform and good condition (per the dictates of the MT&C technical area) on both a micro- and macro-scale at the outset of the closure procedure.

5. Weldability

Processes that yield a significant probability of hot cracks, microfissures, and other UT rejectables are assumed to be unacceptable.

6. Phase Transformation

For austenitic stainless steel, it is assumed that delta ferrite will partially transform to other objectionable phases.

7. Microbiological Effects

Microbiological effects that give rise to an increased potential for pitting and crevice corrosion are assumed to be possible.

4.3. Process Evaluation and Selection

This section describes the methodology used to evaluate potential closure processes and the selection of five processes for further evaluation. Evaluation criteria are based on the guidelines defined in Section 4.2.

4.3.1. Decision Tree Overview

4.3.1.1. The Need for a Decision Tree for Closure Process Selection. The reader will recall that the goal of Phase 1 of the Closure Development Project was to select (in combination with Phase 1A) three closure processes worthy of further laboratory testing in Phase 2. To achieve this goal, a methodology had to be developed to screen all of the potential closure processes and select only those truly worthy of further evaluation. The selected methodology should indicate (if possible on a semi-quantitative basis) those processes that could meet demanding and complex interrelated materials and process performance requirements.

One way of making these selections might have been to convene a *conference of experts* and to solicit their opinions regarding the best closure processes. This approach was not used, because it was also deemed necessary that the selection rationale be documented on a step-by-step basis. Because of the complex relationships that need to be considered, it would have been extremely difficult to provide the step-by-step rationale that guided the decision-making process of a "conference of experts."

Because of the need to perform a more detailed screening and to develop a screening process in which it would be possible to demonstrate the rationale behind the screening decisions, a decision tree approach was adopted. The primary purpose of a decision tree is to provide a tool by which complex decisions can be made. A decision tree can be used to consider the significance of numerous interrelated factors based on the subjective opinion of the user to decide on an optimum output.

A secondary purpose of the decision tree is to provide a means by which the assumptions and logic of the user can be verified by an "interested expert." The descriptive "interested" is used because decision trees can by their nature be fairly complicated, involving a multiplicity of levels and tables, and total inspection of the tree can be quite involved and tedious. However, it is possible to evaluate, in detail, the workings of the tree and to decide on the validity of the rationale that underlies the tree.

4.3.1.2. The Structure of the Decision Tree Approach. In deciding on the optimum closure processes, it is necessary to balance the demands of two concurrent perspectives: (1) the "Materials Perspective" and (2) the "Process Perspective."

The selected processes would be those that deliver a closure with a high probability of survival in the repository service environment for the intended period of time. Because of this, the service performance closures of any material/process combination needs to be considered in process selection. Thus, closure process selection would involve considerations from a "Materials Perspective."

The closure process selected should be reliable and should perform well under the strenuous conditions of a hot cell environment. Thus, the manufacturing performance of each process needs to be considered in process selection. Thus, closure process selection would also involve considerations from a "Process Perspective."

Early in the evaluation, it was apparent that factors that influence the decisions for the "Materials Perspective" might be entirely different from those that influence decisions for the "Process Perspective". For this reason, two separate decision tree branches were generated: one to take into account the "Materials Perspective," and one to take into account the "Process Perspective." The outputs of these two branches were later compared to make process selections for this level of the evaluation.

An overview of the entire decision tree structure that incorporates both the "Materials" and "Process" branches is depicted in Figure 4-2. In the decision-making process, the various influential factors on each level are "weighted" with respect to their importance. Then, with all the factors weighted, the tree can be traversed across both branches, and "scores" can be accumulated for the processes under consideration. The best scores from both branches are selected and the results are compared to make process selections as the output of this level. These selections are later verified against practical experience to make the final process recommendations.

4.3.2. "Process Perspective" Decision Tree Overview

This section provides an overview of the "Process Perspective" decision tree. In Section 4.3.3, the "Materials Perspective" decision tree is discussed.

This section describes the decision tree structure used to evaluate and rank closure processes with respect to both the individual process characteristics and the manufacturing requirements of the hot cell environment. Several assumptions (documented later in this text) were made in order to perform this evaluation. Changes in these assumptions will impact the process rankings.

The decision tree structure for the "Process" characteristics concerns is a three-level hierarchical network structure. The three levels for the tree structure are:

1. General screening to eliminate from consideration welding processes that are obviously unacceptable.
2. Evaluation of the remaining potential welding processes with respect to closure weld criteria.
3. Ranking of the welding process(es) in terms of the process characteristics, environmental constraints, weld integrity, and inspectability.

As with the "Materials Perspective" evaluation, this decision tree program is flexible and "user friendly." Evaluation criteria may be added or deleted as desired by the user. The initial criteria listed have been provided by B&W from prior experience, literature review, and discussion with experts in the field of welding.

Details of the Process-Related Decision Tree

The following discussions provide a summary of the various components of the decision-making structure as it relates to the welding process characteristics and the weld environment.

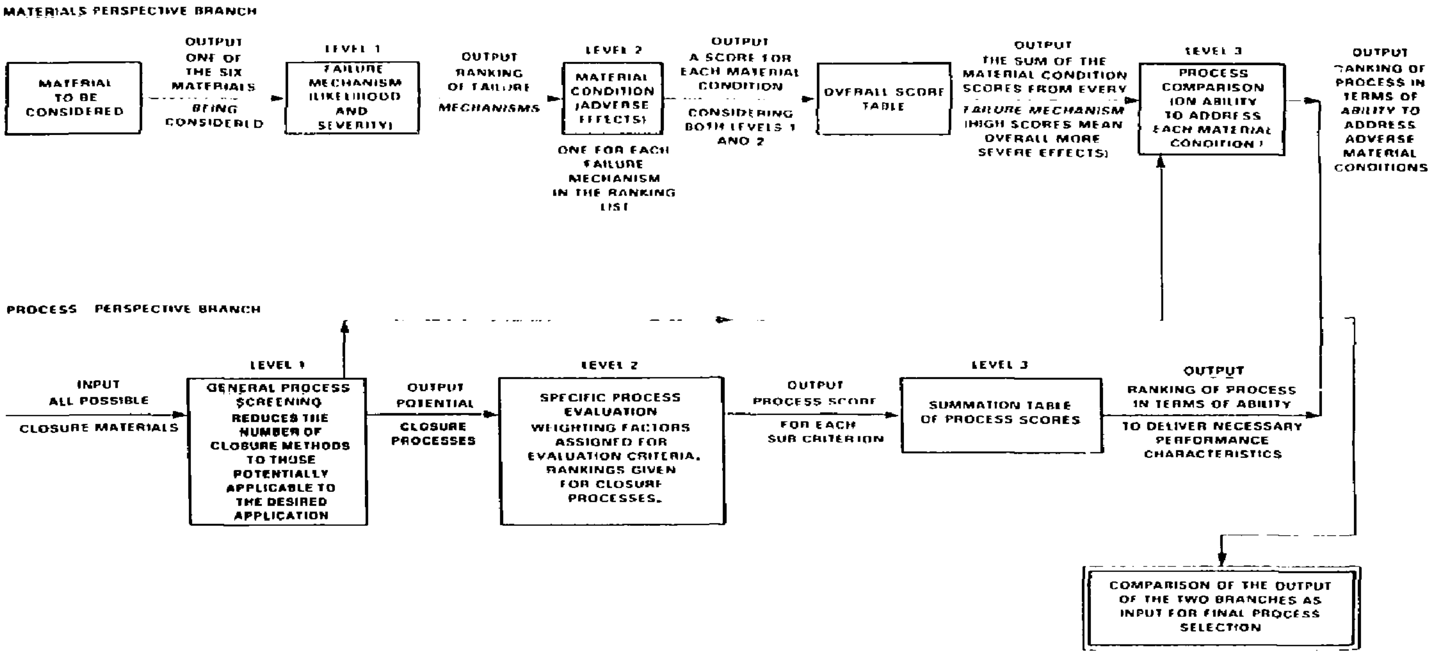


Figure 4-2. Closure Development Project decision tree structure.

Level 1: General Process Screening

The purpose of this level is to evaluate the current state of technology for candidate closure processes and to screen out those processes that are clearly not applicable to the container closure. This screening level is separated into two parts, with the first being the elimination of all closure processes that are obviously not suitable for the desired application. Then, all of the remaining "potential" closure processes are evaluated with regard to six basic criteria pertaining to the closure application. Those processes that meet all of the criteria will be further evaluated in Level 2. The following list contains the six criteria to be used for evaluation:

1. The closure process is amenable to at least one of the six candidate materials.
2. The closure process is applicable to remote operation and maintenance.
3. With the current state of process technology, the closure process is applicable to the material thickness and joint location in the reference design. This is excluding limited development that may be required for implementation of a given process.
4. The requirements of the closure process (preheat and/or heat input) maintain the fuel rod cladding temperature below the specified 350°C limit for at least one of the candidate materials.
5. With the reference design, the closure process produces a corrosion barrier of a thickness at least equal to the container wall.
6. The closure process is tolerant of the elevated container temperature (250°C) prior to and during the closure.

This Level 1 screening reduced the field of closure processes under consideration to those shown in Table 4-1, while the total matrix of closure processes evaluated would include those processes given in Tables 4-5 and 4-6.

Table 4-1. Closure processes under consideration after Level 1 screening.

Gas Tungsten Arc Welding—Cold Wire
Gas Tungsten Arc Welding—Hot Wire
Gas Metal Arc Welding
Flux Cored Arc Welding
Plasma Arc Welding—With Filler Metal
Plasma Arc Welding—Without Filler Metal
Electron Beam Welding—With Filler Metal
Electron Beam Welding—Without Filler Metal
Laser Beam Welding—With Filler Metal
Laser Beam Welding—Without Filler Metal
Brazing
Friction Welding—Standard
Friction Welding—Radial
Flash Butt Welding
Mechanical Joint with Braze Seal

Level 2: Specific Process Evaluation

For Level 2 of the "Process Perspective" branch, those welding processes found to be potentially applicable in Level 1 will be evaluated against criteria specific to the container closure. These criteria address both closure process characteristics and environment. These criteria have been divided into eight main categories. Each of these main categories has been assigned a weighting factor (1 to 5) that determines its "importance of concern" as it relates to the overall project goals. This "importance of concern" increases as the weighting factor increases.

Within each main category are several subcriteria for consideration. These subcriteria have also been assigned weighting factors from 1 to 5. The weighting factor for a subcriterion determines the importance of the individual criterion as it relates to the overall main category. Again, the higher the numerical value of the weighting factor, the more important the criterion is considered with respect to the main category. The categories, subcriteria, and weighting factors given need not be considered all-inclusive. The program user may add or subtract information as the situation dictates.

Each closure process that was evaluated was assigned a ranking from 1 to 5 for each of the subcriteria. Again, the higher the score value, the more suitable the process is considered to be for the closure weld. The weld process scores given for each of the criteria were based on a literature review, prior engineering experience, and discussions with experts in the field of closure. Section 4.2.4.2 will present additional information on the ranking of each of the subcriteria.

Level 3: Weld Process Ranking

In Level 3 of the "Process Perspective" branch, a total score is calculated for each process by summing the values for the product of the main category weighting factor times the subcriterion factor (effective) times the weld process score. The weld processes are ranked based on this total score.

In order to calculate a total process score that relates to the importance of the main categories, both an effective subcriterion weighting factor and an effective process score must be calculated. These effective values are calculated by summing the actual weighting factors and process scores for a given category. These summation values are then divided into a constant of proportionality, for instance 10. This resulting number is then multiplied times each individual value for the subcriterion and process score to yield the effective values.

Table 4-2. Final closure process ranking, Level 3 "Process Perspective" decision tree.

Material Type	GTAW, CW	GTAW, HW	GMAW	FCAW	PAW, CW	PAW, HW	PAW, Autogenous
Alloy 825	1010.40	875.93	737.05	636.94	977.90	846.06	933.89
AISI 304L and AISI 316L	1010.40	875.93	737.05	—	977.90	846.06	933.89
Aluminum bronze 70/30 copper-nickel	955.99	860.93	737.05	—	923.49	831.06	912.29
Oxygen-free high conductivity copper	—	—	—	—	868.70	794.07	—

Material Type	EBW	LBW	Brazing Induction	Friction Standard	Flash Butt	Braze Seal
Alloy 825	958.01	979.19	847.47	1178.83	830.75	784.91
AISI 304L and AISI 316L	958.01	979.19	847.47	1178.83	830.75	784.91
Aluminum bronze 70/30 copper-nickel	987.63	072.22	847.47	1153.42	797.99	784.91
Oxygen-free high conductivity copper	1006.86	—	—	1142.97	—	—

The purpose of these "effective" values is to ensure that those main categories with a large number of relevant subcriteria do not unfairly affect the overall welding process(es) rankings merely by virtue of having large numbers of criteria that must be considered.

Based on the total score, the processes are ranked from "most desirable" to "least desirable" (high score to low score) based on the evaluation criteria and assigned weighting factors (see Table 4-2). These results are depicted in bar chart form in Figures 4-3 through 4-6. These results will be married (in Section 4.3.6) with the materials consideration evaluation to yield the three "best" processes recommended for further evaluation in Phase 2 of the project. Section 4.3.4.2 provides a more detailed description of the workings of the "Process Perspective" branch of the decision tree for the interested reader.

4.3.3. "Materials Perspective" Decision Tree—Overview

In the Level 1 of the "Process Perspective" branch of the decision tree, a rationale was developed whereby the field of closure processes was narrowed from all possible processes down to about a dozen. In this preliminary screening, those processes that were clearly unacceptable were eliminated. For this initial screening, acceptability was judged based only on major materials and/or closure process performance concerns. This initial screening reduced the field of closure processes under consideration to those shown in Table 4-1.

The previous section of this report developed a ranking of these closure processes based on a "Process Perspective." In this section, a ranking of these same closure processes is developed based on a "Materials Perspective."

This section describes the "Materials Perspective" branch of the decision tree (recall Figure 4-2). The output of this section will be a ranking of the various closure processes based solely on materials considerations. This output will later be considered in conjunction with the output of the "Performance Perspective" branch (Table 4-2) to make the final closure process recommendations. The complete description of the "Materials Perspective" decision tree that follows in the next section is lengthy and involved. The current section is intended to provide the reader with sufficient information to either set the stage for a better understanding of the next section, or to allow the reader to read past the next, more detailed section and still have a working knowledge of the tree and its output. The more detailed section is provided for those with specific interest in evaluating the workings of the tree.

In order to provide the "Materials Perspective" decision tree, a decision tree program was written and implemented on a personal computer using the Lotus 1-2-3 program. The decision tree branch for the "Materials Perspective" evaluation involves a three-level hierarchical network structure. The three levels are:

Level 1: The failure mechanisms of concern for the material being considered.
Level 2: The adverse materials and weldment conditions that give rise to, or enhance, the failure mechanisms above.
Level 3: The welding process characteristics that ameliorate the materials and weldment conditions above.

Each of the components of every level is weighted with respect to its relative influences. For each of the six materials being considered, a Level 1 table is generated. In each Level 1 table, the failure mechanisms are ranked in terms of their "likelihood" (0 to 10) and "severity" (1 to 3). The rationale for the rankings is derived from the literature review described in Section 4.1.3. The output of Level 1 involves multiplying a likelihood value times the corresponding severity to establish a ranking of the various failure mechanisms with respect to their relative importance to the material being evaluated. Important mechanisms have high Level 1 weights. This ranking process is illustrated in the example decision tree for carbon steel shown in Figure 4-7. At point "A," the example Level 1 ranking is shown.

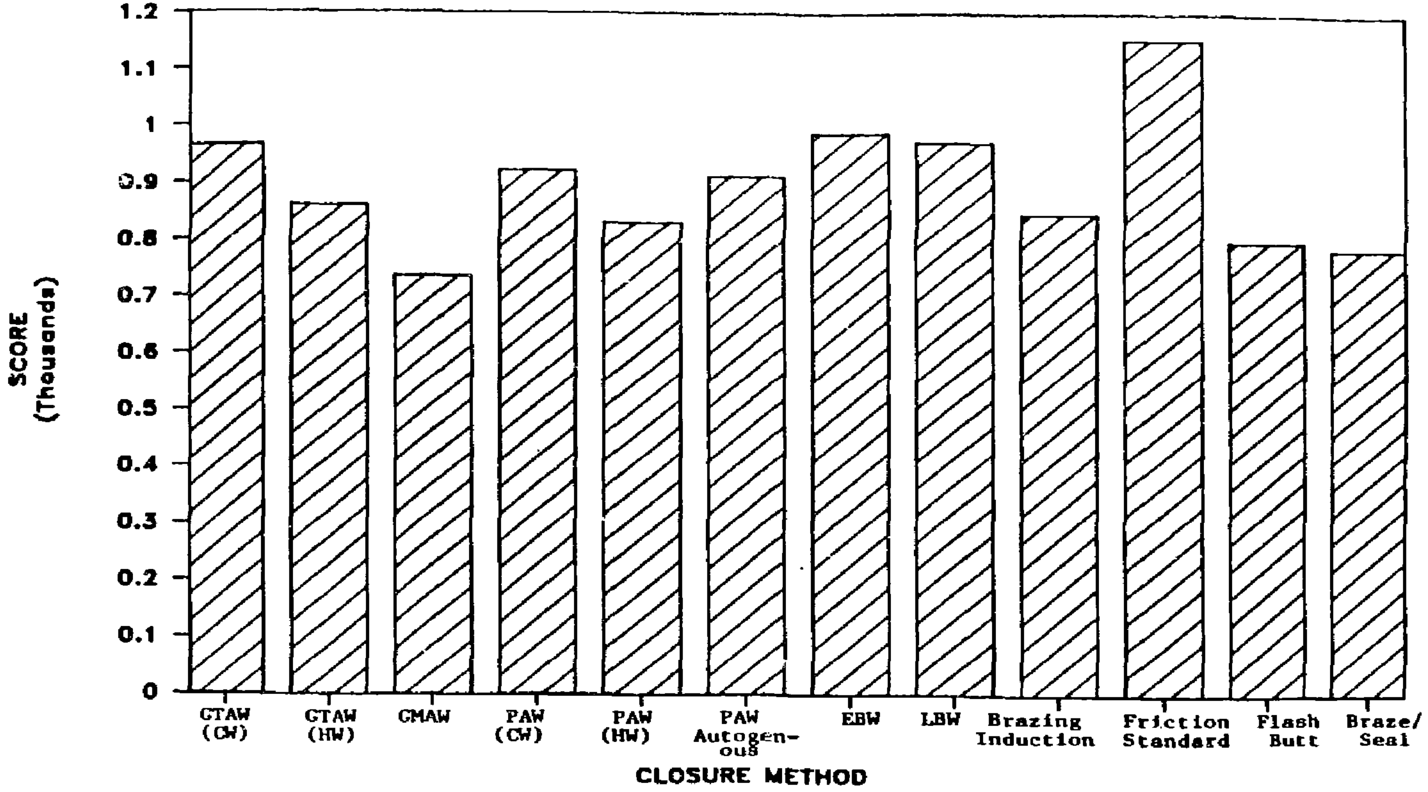


Figure 4-3. Closure process final scores for aluminum bronze and 70/30 copper-nickel; "Process Perspective" decision tree.

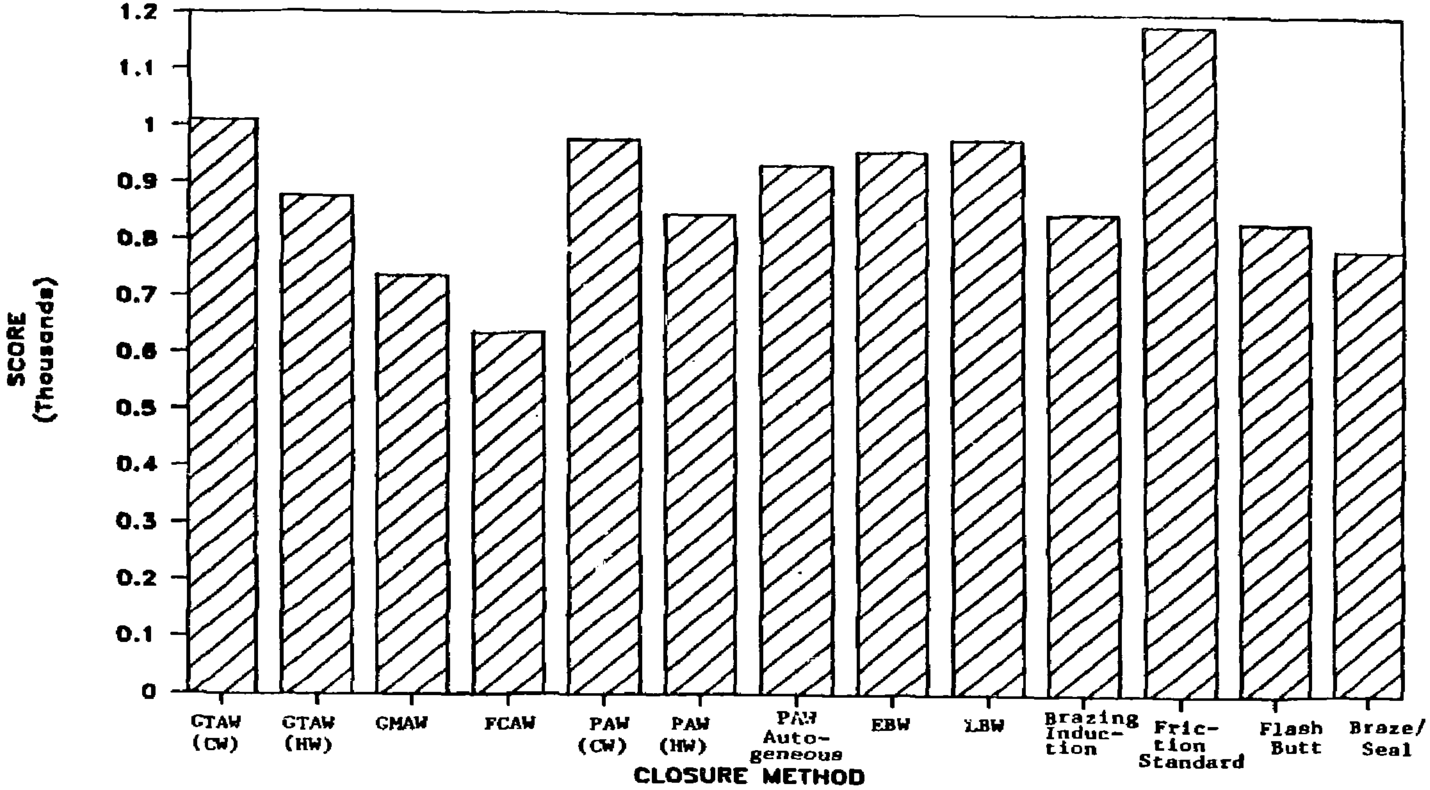


Figure 4-4. Closure process final scores for AISI 304L and AISI 316L; "Process Perspective" decision tree.

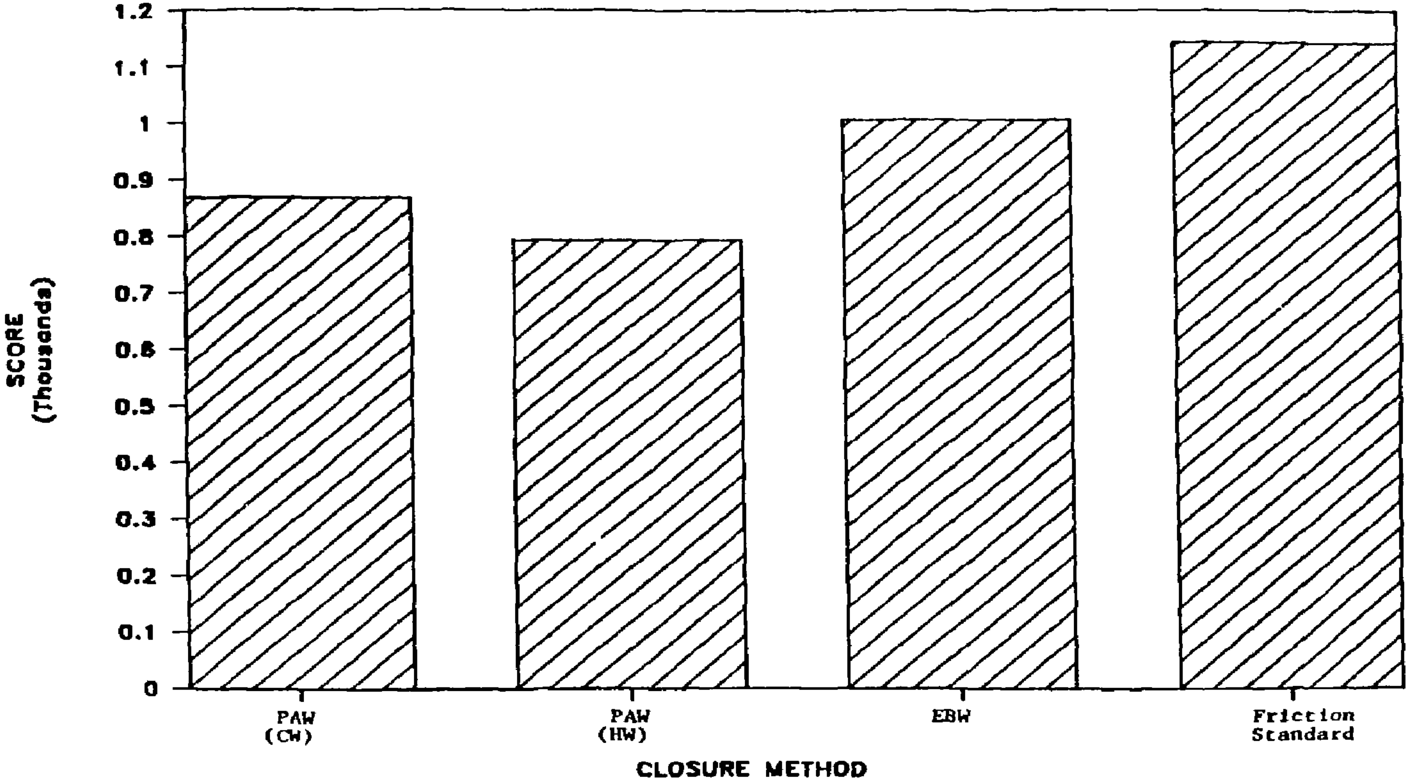


Figure 4-5. Closure process final scores for oxygen-free, high conductivity copper; "Process Perspective" decision tree.

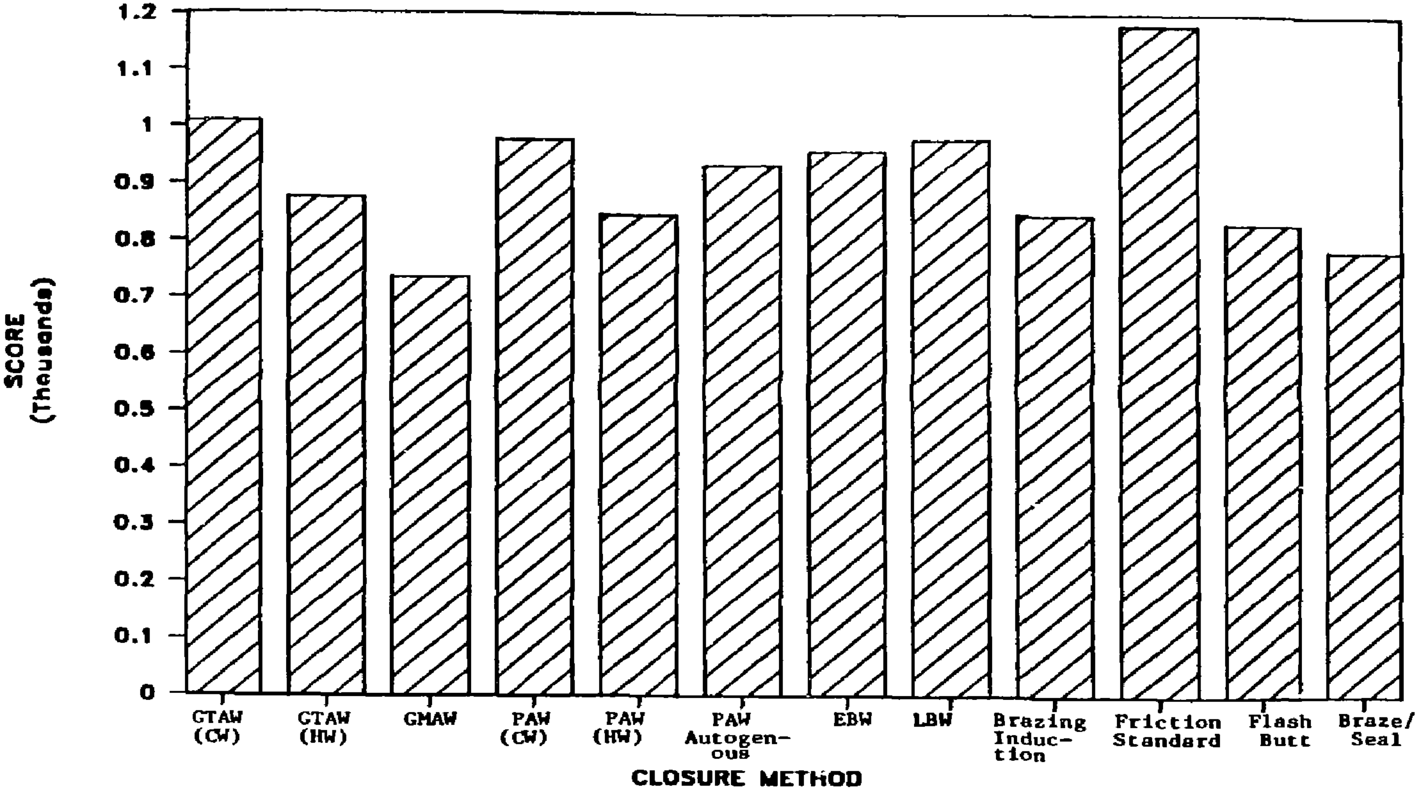


Figure 4-6. Closure process final scores for Alloy 825; "Process Perspective" decision tree.

A Level 2 table is generated for each of the failure mechanisms listed in Level 1. Level 2 identifies objectionable "material conditions" that influence the occurrence or severity of the failure mechanism being investigated. Material conditions that are highly influential are given high rating values (5, with 0 being the lowest possible). The rationale for the "weighting value" selected is derived primarily from the literature review. Point "B" in Figure 4-7 illustrates the weighting values assigned to each of the "material conditions" that influences (in this case) the IGSCC mechanism in carbon steel. (Note: Carbon steel is not a material being considered for this application, but is used here as a simplified example.) With the Level 2 weights established, the Level 2 entries must be normalized to sum to a constant (i.e., 10). This normalization generates an "effective weight" for each of the material conditions; see point "B*" in Figure 4-7.

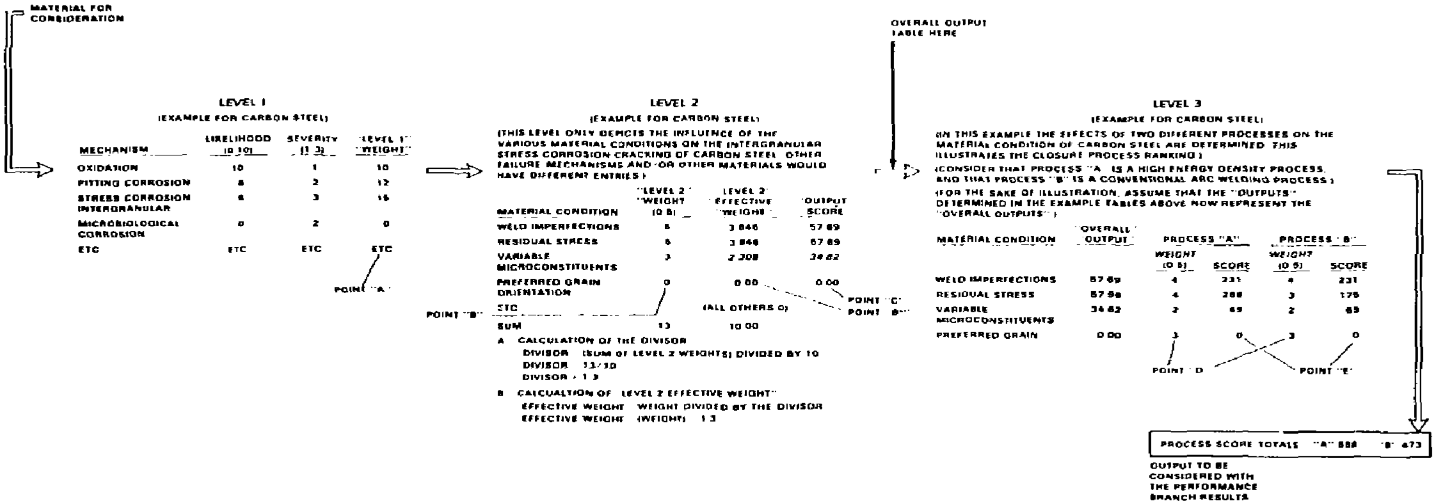
By combining the output of Levels 1 and 2 (by multiplying the Level 1 "weight" times each of the Level 2 "effective weights"), a "score" may be calculated for each of the "material conditions" on Level 2. This "output score" is illustrated by Point "C" in Figure 4-7.

Once Level 2 score tables are developed for all of the mechanisms relevant to a material, the scores for a material condition can be summed into an overall score table. Such an overall table would have the form of the table at Point "C" of Figure 4-7, but the values in this table would be the sums of all the Level 1 times Level 2 products. This overall score table would represent the relative importance of all the material conditions, taking all of the failure mechanisms into account. "Material conditions" with higher scores are more important.

On Level 3, each of the processes under consideration is ranked in terms of its influence on the objectionable "material conditions" listed in the "overall score" tables. Processes with the ability to completely ameliorate an objectionable condition were given a high ranking. Rankings range from weights of 0 to 5. These entries are represented by point "D" in the decision tree example in Figure 4-7.

Once the processes on Level 3 have been ranked, the value in the "overall score" table can be multiplied times its corresponding weight in Level 3 to determine a "score" for each process. These entries are illustrated at Point "E" of the decision tree example. By summing the Level 3 scores, a total score can be determined for each process under consideration. High total scores would indicate that a process under consideration had good potential at ameliorating detrimental material conditions. Thus, in our example in Figure 4-7, Process "A" would be more favorable than Process "B."

Figures 4-8 through 4-14 depict the actual process rankings in bar chart form. Table 4-3 provides the process abbreviation key for Figures 4-8 through 4-14. Note after inspection of Figures 4-8 through 4-14 that, from a "Materials Perspective," processes are generally preferred that minimize heat input and do not utilize a filler metal. (These process characteristics generally lead to the favorable weldment conditions described in more detail later.) It is the output of Figures 4-8 through 4-14 which is later compared with the output from the "Process Perspective" branch. Table 4-4 shows the four best closure processes for each material.



LEVEL 1

(EXAMPLE FOR CARBON STEEL)

MECHANISM	LIKELIHOOD (0-10)	SEVERITY (1-3)	"LEVEL 1" "WEIGHT"
OXIDATION	10	1	10
PITTING CORROSION	6	2	12
STRESS CORROSION INTERGRANULAR	6	3	18
MICROBIOLOGICAL CORROSION	0	2	0
ETC	ETC	ETC	ETC

LEVEL 2

(EXAMPLE FOR CARBON STEEL)

(THIS LEVEL ONLY DEPICTS THE INFLUENCE OF THE VARIOUS MATERIAL CONDITIONS ON THE INTERGRANULAR STRESS CORROSION CRACKING OF CARBON STEEL. OTHER FAILURE MECHANISMS AND/OR OTHER MATERIALS WOULD HAVE DIFFERENT ENTRIES.)

MATERIAL CONDITION	"LEVEL 2" "WEIGHT" (0-8)	"LEVEL 2" "EFFECTIVE WEIGHT"	"OUTPUT SCORE"
WELD IMPERFECTIONS	5	3.846	57.69
RESIDUAL STRESS	5	3.846	57.69
VARIABLE MICROCONSTITUENTS	3	2.308	34.62
PREFERRED GRAIN ORIENTATION	0	0.00	0.00
ETC		(ALL OTHERS 0)	
SUM	13	10.00	

A. CALCULATION OF THE DIVISOR
DIVISOR = (SUM OF LEVEL 2 WEIGHTS) DIVIDED BY 10
DIVISOR = 13/10
DIVISOR = 1.3

B. CALCUALTION OF "LEVEL 2 EFFECTIVE WEIGHT"
EFFECTIVE WEIGHT = WEIGHT DIVIDED BY THE DIVISOR
EFFECTIVE WEIGHT = (WEIGHT)/1.3

LEVEL 3

(EXAMPLE FOR CARBON STEEL)

(IN THIS EXAMPLE THE EFFECTS OF TWO DIFFERENT PROCESSES ON THE MATERIAL CONDITION OF CARBON STEEL ARE DETERMINED. THIS ILLUSTRATES THE CLOSURE PROCESS RANKING.)

(CONSIDER THAT PROCESS "A" IS A HIGH ENERGY DENSITY PROCESS, AND THAT PROCESS "B" IS A CONVENTIONAL ARC WELDING PROCESS.)

(FOR THE SAKE OF ILLUSTRATION, ASSUME THAT THE "OUTPUTS" DETERMINED IN THE EXAMPLE TABLES ABOVE NOW REPRESENT THE "OVERALL OUTPUTS".)

MATERIAL CONDITION	"OVERALL" "OUTPUT"	PROCESS "A"		PROCESS "B"	
		WEIGHT (0-5)	SCORE	WEIGHT (0-5)	SCORE
WELD IMPERFECTIONS	57.69	4	231	4	231
RESIDUAL STRESS	57.69	4	231	3	173
VARIABLE MICROCONSTITUENTS	34.62	2	69	2	69
PREFERRED GRAIN	0.00	3	0	3	0

PROCESS SCORE TOTALS "A" 531 "B" 473

Figure 4-7. Illustration of "Materials Perspective" branch of the decision tree using a hypothetical carbon steel example.

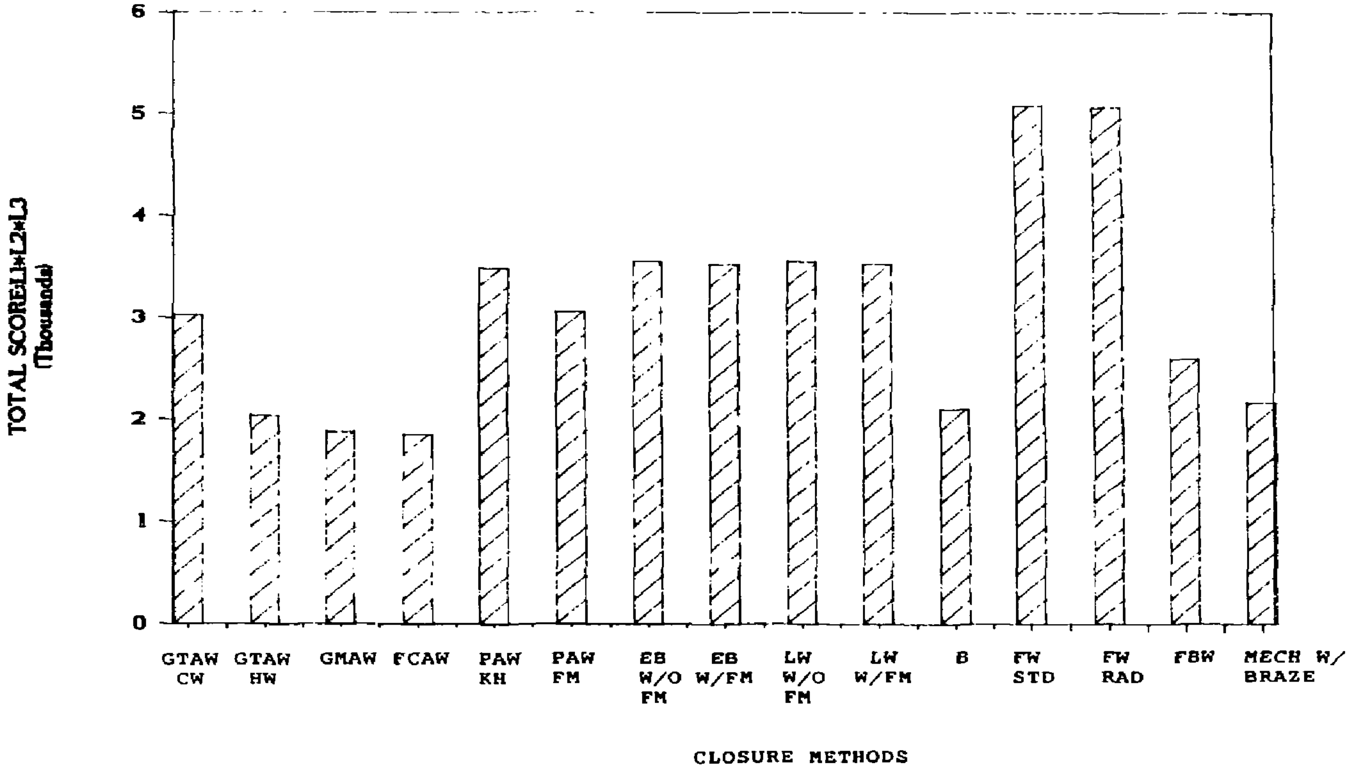


Figure 4-8. Total score: Closure methods—AISI 304L with AISI 308L filler metal.

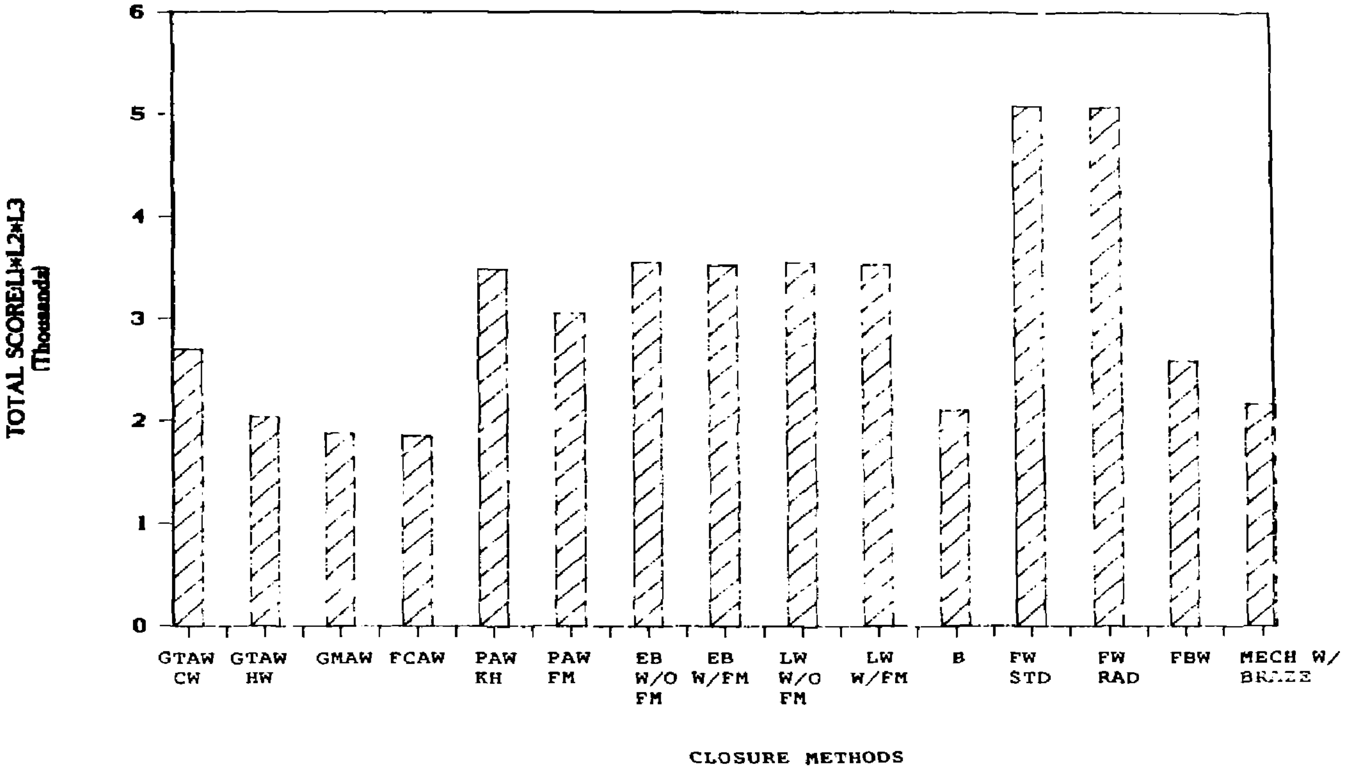


Figure 4-9. Total score: Closure methods—AISI 316L with AISI 316L filler metal.

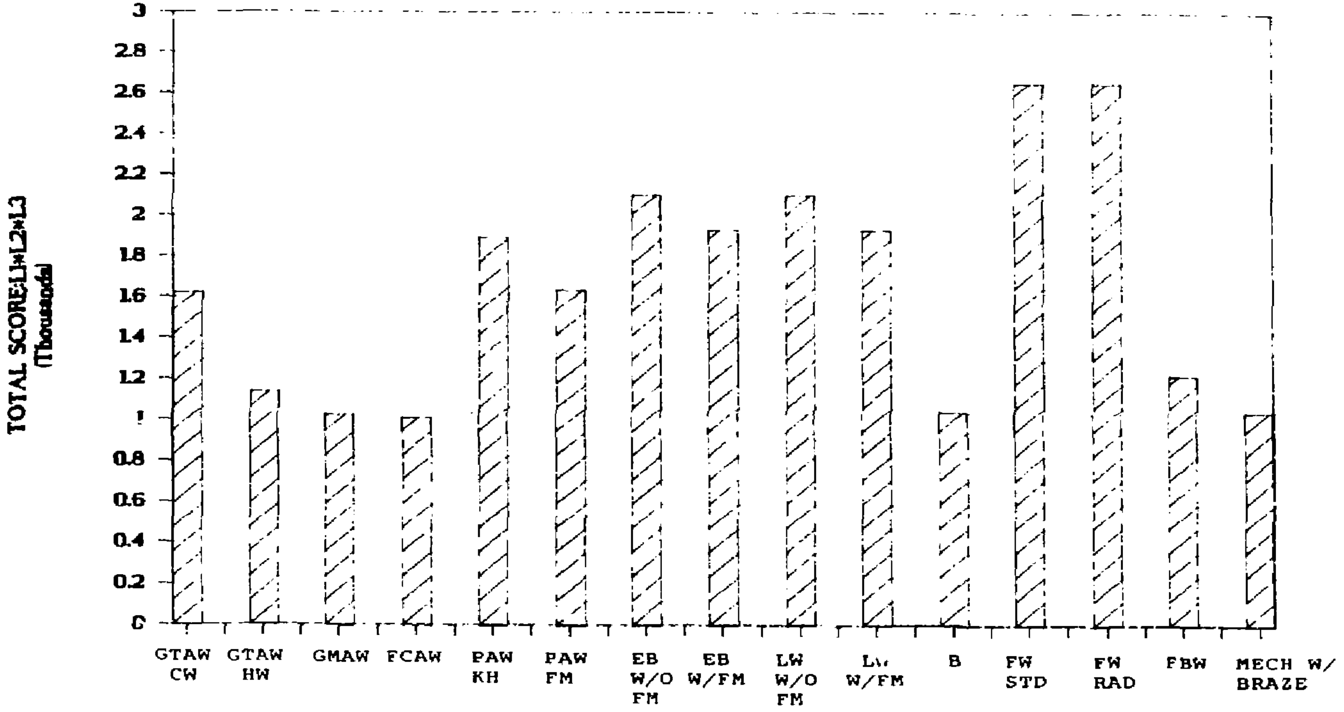


Figure 4-10. Total score: Closure methods—Alloy 825 with Alloy 825 filler metal.

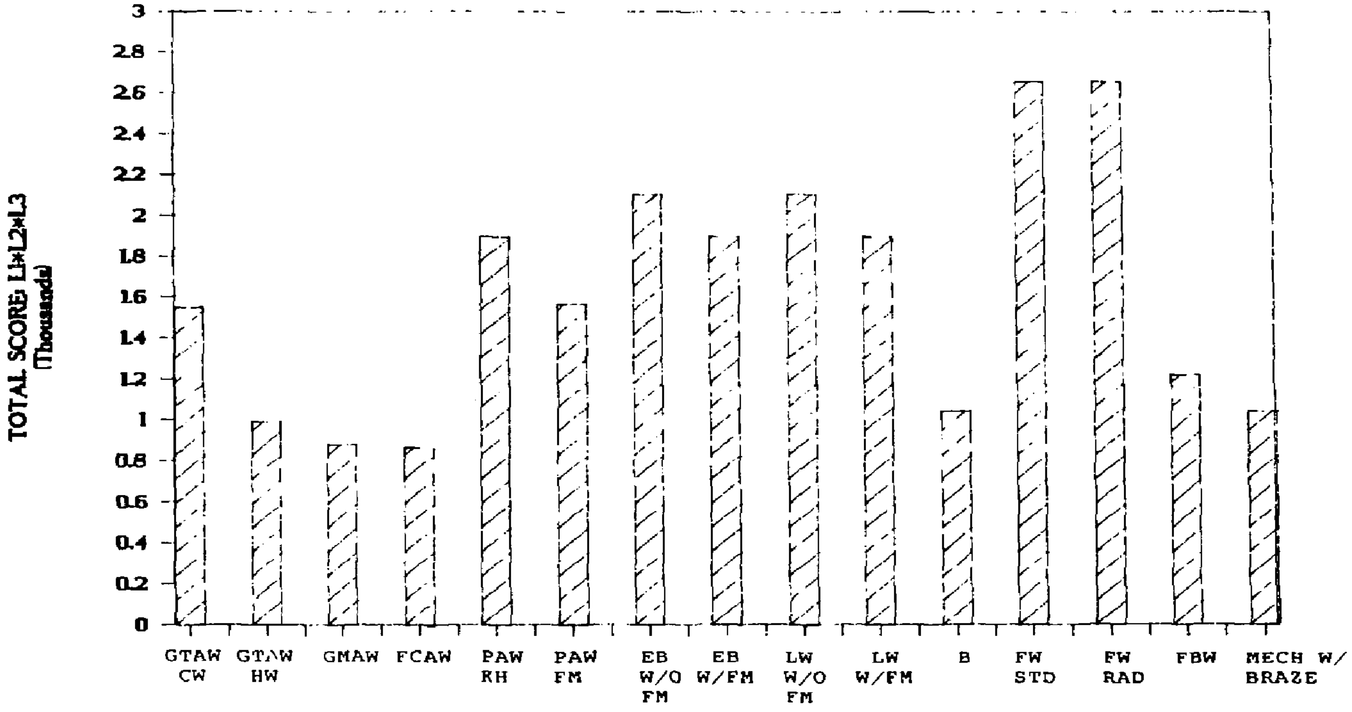


Figure 4-11. Total score: Closure methods—Alloy 825 with Alloy 625 filler metal.

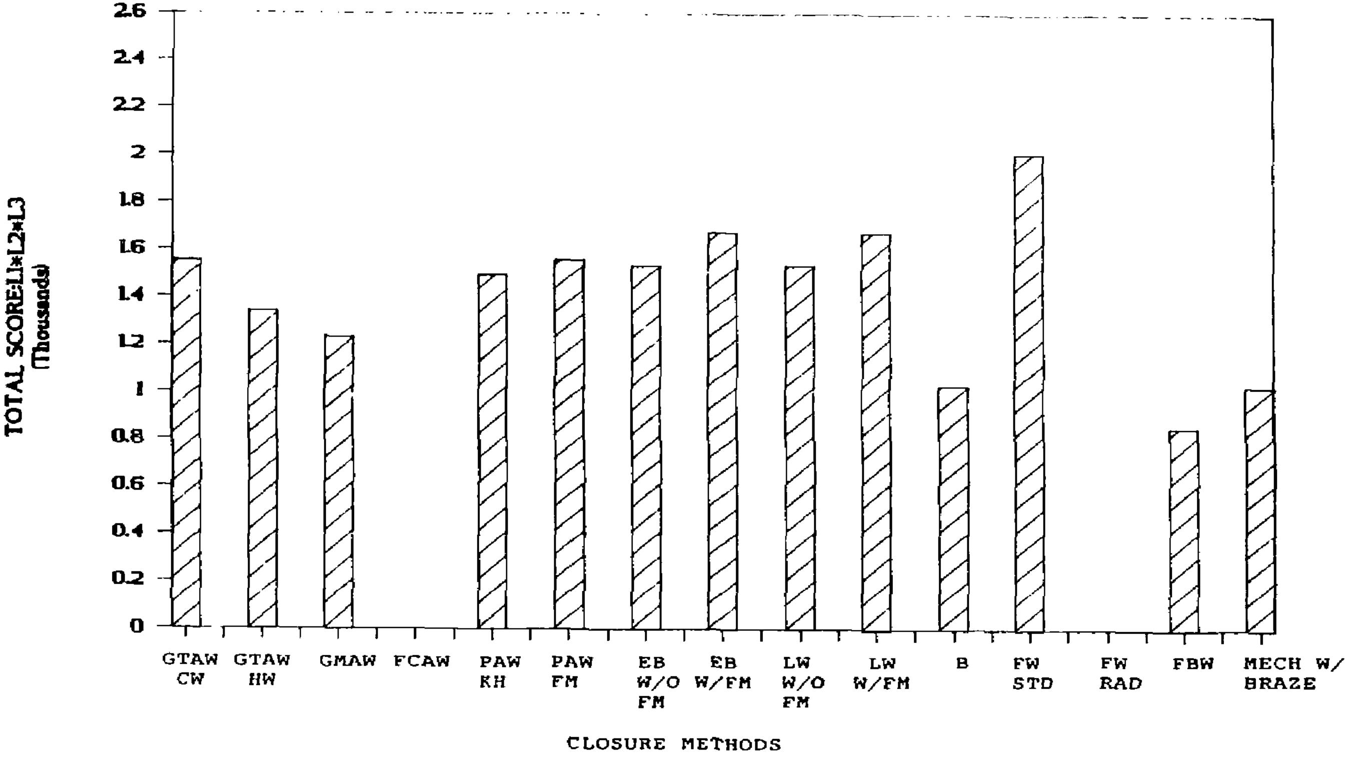


Figure 4-12. Total score: Closure methods—CDA 715.

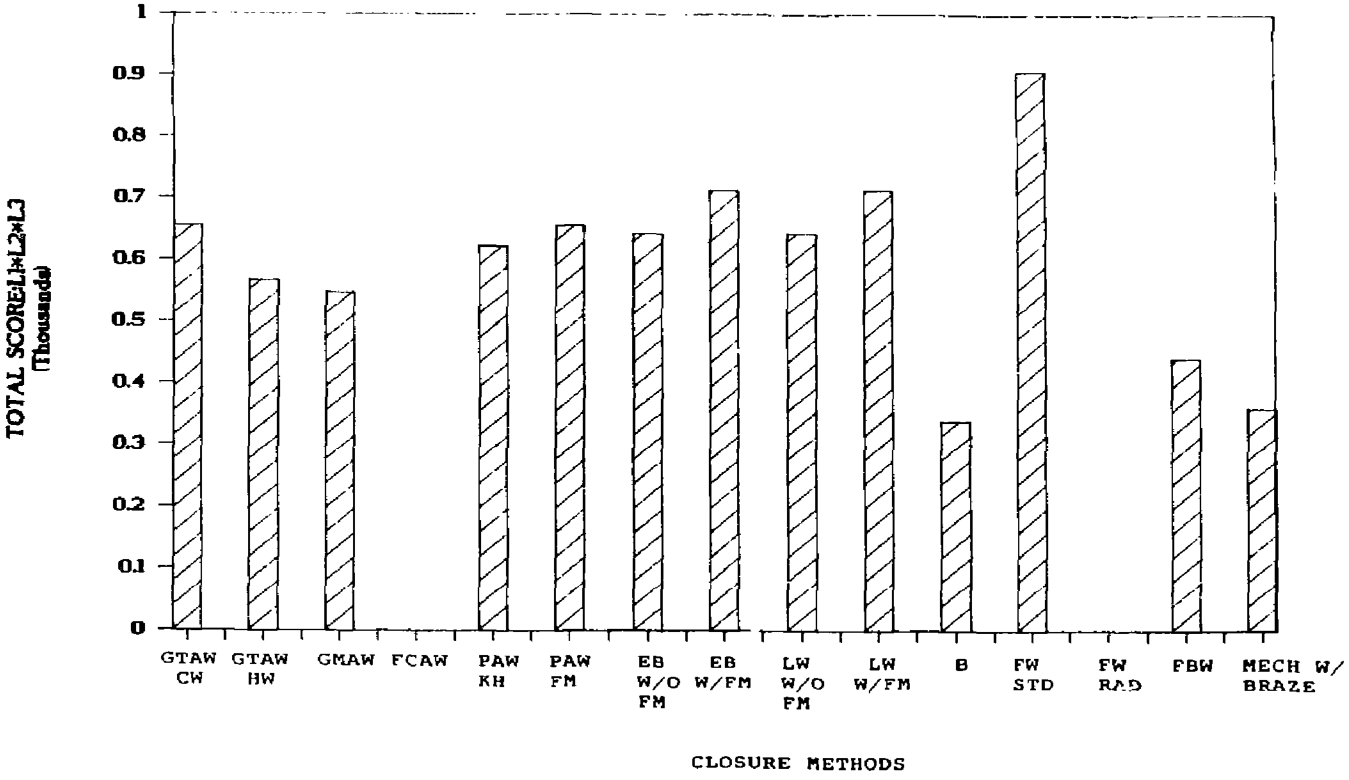


Figure 4-13. Total score: Closure methods—CDA 613.

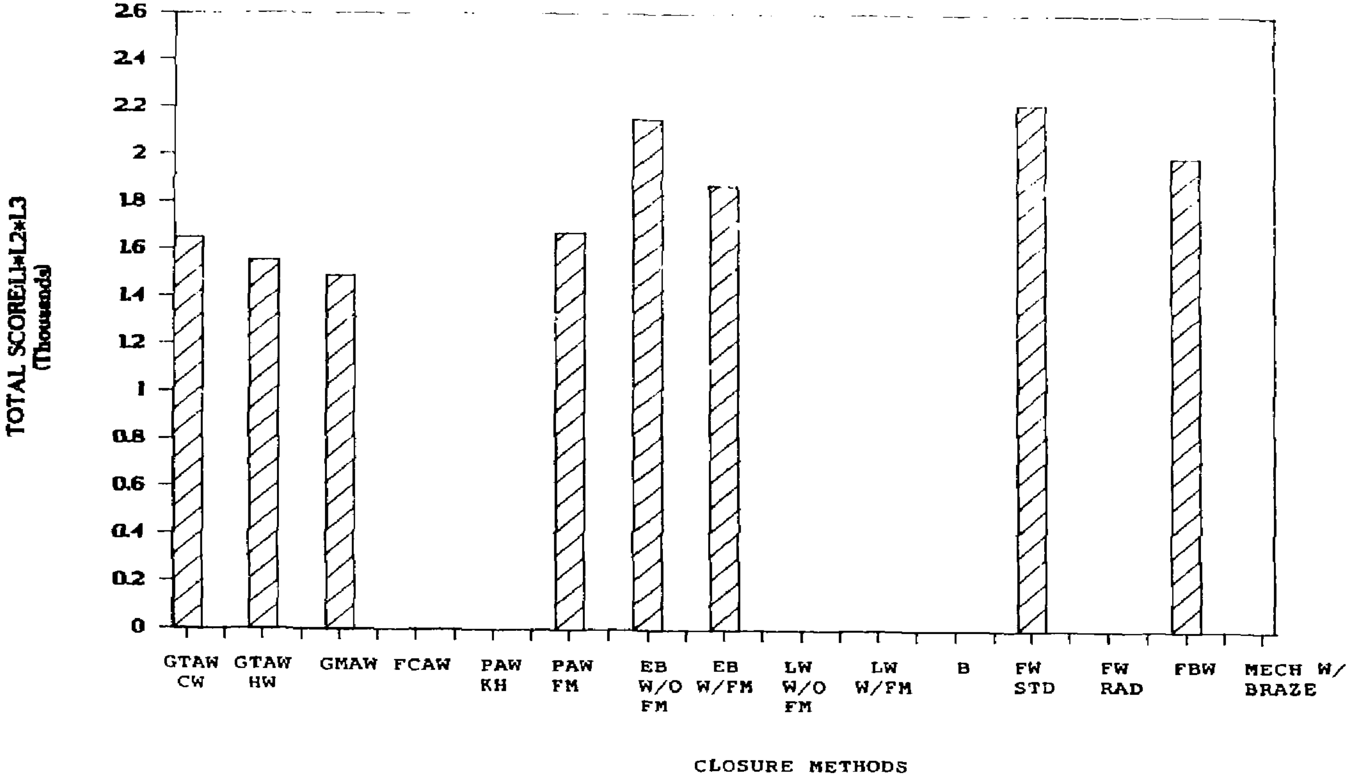


Figure 4-14. Total score: Closure methods—CDA 122.

Table 4-3. Process abbreviation key.

GTAW:CW—Gas Tungsten Arc Weld: Cold Wire
GTAW:HW—Gas Tungsten Arc Weld: Hot Wire
GMAW—Gas Metal Arc Weld
FCAW—Flux Cored Arc Weld
PAW:KH—Plasma Arc Weld: Keyhole Design
PAW:FM—Plasma Arc Weld: With Filler Metal
EB:W/O FM—Electron Beam Weld: Without Filler Metal
EB:W/FM—Electron Beam Weld: With Filler Metal
LW:W/O/FM—Laser Weld: Without Filler Metal
LW:W/FM—Laser Weld: With Filler Metal
B—Braze
FRW:STD—Friction Weld: Standard
FRW:RAD—Friction Weld: Radial
FBW—Flash Butt Weld
MECH:W/BRAZE—Mechanical Joint: With Braze

Table 4-4. Decision tree results, "Materials Perspective" branch of the decision tree.

AISI 304L	*AISI 316L*	Alloy *825*	CDA *122*	CDA *613*	CDA *715*
Friction Welding	Friction Welding	Friction Welding	Friction Welding	Friction Welding	Friction Welding
Electron Beam Welding	Electron Beam Welding	Electron Beam Welding	Electron Beam Welding	Electron Beam Welding	Electron Beam Welding
Laser Beam Welding	Laser Beam Welding	Laser Beam Welding	Flash Butt Welding	Laser Beam Welding	Laser Beam Welding
Plasma Arc Welding	Plasma Arc Welding	Plasma Arc Welding	Plasma Arc Welding	Plasma Arc Welding	Gas Tungsten Arc Welding

Overview Summary

As can be determined from the previous discussion, a flow of logic is provided between the three levels that permits process selections to be made in the third level based on input in the first and intervening level. Thus, a technique is provided to allow closure process selection with consideration of all the important material-related implications of all the reasonable failure mechanisms for a material of concern. As can be seen from this example, the decision tree program provides a powerful tool for ranking the various processes.

4.3.4. Details of the Decision Tree

This section provides a more detailed explanation of both branches of the decision tree along with an example of how it works and of how the materials branch works.

4.3.4.1. Decision Tree Features. The decision tree is implemented with the use of the computer program Lotus 1-2-3. This program allows for ease of data entry and updating. For most levels of the tree, data entry will take the form of "weighting factors" that indicate the significance of the item of consideration relative to other items in the level. These weighting factors have been provided by B&W as output of literature reviews and discussions with experts in government and industry. The weighting factors are, of course, subject to approval and change by LLNL or others as increasingly accurate information is obtained. In other words, the decision-making system is flexible.

In line with the desire for flexibility, the number of items for consideration on a given level may be increased. B&W has provided a list of reasonable failure mechanisms from research and experience, but the program may expand the list of failure mechanisms under consideration.

Output from the program would involve generating tables of the input on any given level. Also generated will be the scores and characteristics of the various processes. As mentioned earlier, the "Materials Perspective" scores so generated by the decision tree are later used in conjunction with similarly generated "Process Perspective" scores to help to decide which processes are worth further evaluation. Please note that in making the decisions regarding recommendations for further evaluation, the output of the decision tree program has been verified first against common industry experience for the process and material combination of concern.

4.3.4.2. Decision Tree—"Process Perspective" Results. This section presents the details for the "Process Perspective" branch of the decision tree evaluation of closure processes for YMP containers. In this evaluation, a three-level hierarchical network structure was used to systematically evaluate and rank the closure methods based on the individual requirements of the process, environmental constraints, weld quality, and inspectability. In this evaluation, a very broad range of metal-to-metal joining methods was considered. This included various welding, adhesive bonding, and mechanical seal methods. The results from this evaluation were later combined with the materials evaluation results to provide a ranking of closure processes as they address the requirements of the overall YMP container project. Based on these requirements, conceptual designs illustrating the "best" five processes were drawn and can be found in Section 4.4.

An extensive literature and industry review was conducted (Section 4.1.4) to obtain information on previously performed work that may be applicable to the selection and evaluation of the closure processes. This information was implemented in the process selection program. Emphasis was placed on prior experience for which the joining process was used, or intended to be used, in a remote environment (i.e., hot cell). A review of prior work conducted in both the United States and abroad that addresses remote welding of radioactive components is given in Section 4.1.2. Section 4.1.2 contains a review of all industry contacts pertaining to the process evaluation and selection.

The following text addresses the evaluation and ranking of the closure methods using the "Process Perspective" decision tree. The three levels of the process-related decision tree are as follows:

Level 1: General screening to reduce the number of closure methods to those which may be applicable.
Level 2: Evaluation of the potential processes with respect to the decision tree criteria.
Level 3: Ranking of the closure processes defined in terms of the process characteristics, environmental constraints, weld integrity, and inspectability.

Level 1: General Process Screening

The objective of the general process screening was to provide a very broad review of metal-to-metal joining methods and to determine those processes that may be applicable to closure welding YMP containers. This evaluation was divided into two sections, the first addressing closure process limitations and the second focusing on specific criteria for the application. Because more than 30 joining methods were considered, no process descriptions are offered.

In the first section, a review of the current state of technology was made for the various metal-to-metal joining processes (including welding, adhesive bonding, and mechanical seals) to identify and screen out those processes obviously not applicable to the container closure application. Table 4-5 provides a list of those processes removed from further consideration in this program.

Table 4-5. Joining processes not considered in the Level 1, "Process Perspective" decision tree.

Oxyfuel Gas Welding	Process inappropriate due to excessive heat input and cleanliness problems.
Thermit Welding	Process inappropriate due to: implementation difficulties, not conducive for alloys selected, and high potential for defects.
Stud Welding	Not applicable for geometry of weldment.
Cold Welding	Excessive deformation associated with this process in unacceptable.
Pressure Gas Welding	Process inappropriate due to excessive heat input and cleanliness problems.
Forge Welding	Container deformation would likely be excessive, also process not appropriate for geometry of container.
Carbon Arc Welding	Antiquated process. Implementation problems make this process impractical.
Bare Metal Arc Welding	Antiquated process not amenable to process or quality control. Excessive porosity would be anticipated.
Atomic Hydrogen Welding	Antiquated process which results in welds having questionable properties.
Resistance Welding	Process difficult to control and no equipment available for intended weld geometry.
High Frequency Welding	Process difficult to control and no equipment available for intended weld geometry.

A second, more detailed screening of the remaining processes was made using criteria specific to closure application to further reduce the number of closure processes to a more manageable number. As a requirement of this screening level, only those closure methods that meet all of the following six criteria were retained for further evaluation in Level 2 and Level 3 of the process and materials decision trees, respectively. These criteria represent basic requirements of the closure process(es) as we understand them today. Changes in these criteria or assumptions may alter the results of this evaluation. The results of this evaluation along with the six criteria are provided in Table 4-6.

List of Criteria

1. The closure process is amenable to at least one of the six candidate materials.
2. The closure process is applicable to remote operation and maintenance.

3. With the current state of process technology, the closure process is applicable to the material thicknesses and joint location. This is excluding limited development that may be required for a given process.
4. The requirements of the closure process (preheat and/or heat input) maintain the fuel rod cladding temperature below the specified 350°C limit for at least one of the candidate materials.
5. With the reference designs, the closure process produces a corrosion barrier of a thickness at least equal to the container wall.
6. The closure process is tolerant of the elevated temperature of the container (up to 250°C) prior to *and during the closure.*

Table 4-6. Detailed screening of potential closure processes (Level 1, "Process Perspective" decision tree).

	Criteria[(a)]					
Process	1	2	3	4	5	6
Shielded Metal Arc Welding	Y	N	Y	Y	Y	Y
Gas Tungsten Arc Welding	Y	Y	Y	Y	Y	Y
Gas Metal Arc Welding	Y	Y	Y	Y	Y	Y
Flux Cored Arc Welding	Y	Y	Y	Y	Y	Y
Explosion Welding	Y	Y	Y	Y	N	Y
Electrogas Welding	Y	N	N	N	N	Y
Electroslag Welding	Y	N	N	N	N	Y
Submerged Arc Welding	Y	N	N	Y	N	Y
Plasma Arc Welding	Y	Y	Y	Y	Y	Y
Electron Beam Welding	Y	Y	Y	Y	Y	Y
Laser Beam Welding	Y	Y	Y	Y	Y	Y
Brazing	Y	Y	Y	Y	Y	Y
Soldering	Y	Y	N	Y	Y	Y
Friction/Inertia Welding	Y	Y	Y	Y	Y	Y
Upset Welding	Y	Y	N	Y	Y	Y
Flash Welding	Y	Y	Y	Y	Y	Y
Diffusion Welding	Y	Y	Y	N	Y	Y
Adhesive Bonding	Y	Y	Y	Y	Y	N
Mechanical Seal	Y	Y	Y	Y	N	Y
Adhesive/Mechanical Seal	Y	Y	Y	Y	Y	N
Mechanical/Braze Seal	Y	Y	Y	Y	Y	Y
Mechanical/Weld Seal	Y	Y	Y	Y	N	Y

(a) Y = Yes and N = No.

Level 2: Specific Process Evaluation

In Level 2, a detailed list of evaluation criteria addressing the current requirements of the YMP container project was compiled and used to evaluate the closure methods remaining from Level 1. These criteria were subdivided into major categories for interrelated topics.

The major categories include:

1. Economics.
2. Remote Operation.
3. General Process Considerations.
4. *Repair Process.*
5. External Process Influences.
6. Maintenance.
7. Joint Integrity.
8. *Inspectability.*

Note that a number of subcriteria is embodied in the major category descriptions above. For instance, for the major category "Economics," examples of subcriteria would be initial equipment costs, joint preparation costs, consumables costs, closure production rate, frequency of repair, etc. (A more detailed description of the major categories and subcriteria is provided below.)

Each of the main categories and subcriteria was assigned a weighting factor (1 to 5) identifying its foreseen level importance. The major categories addressed the objectives of the overall YMP container program, while the subcriteria importance factor related only to its main category. The higher the numerical value of the weighting factor, the more important the issue.

A preliminary list of the Level 2 criteria and corresponding weighting factors was submitted to LLNL and outside consultants for review. These reviews were to address the overall methodology of the selection process, the completeness of the criteria, and the soundness of the assigned weighting factors. The corresponding responses were factored into the program on a case-by-case basis along with several internal iterations as additional information was obtained.

Once weighting factors are assigned, an effective factor is calculated by forcing the total summation of the assigned subcriteria weighting factors for each major category to a value of 10. The purpose of normalizing the subcriteria was to eliminate the possibility of any one category with a large number of subcriteria to solely determine the final process selection. This factor will be used in Level 3 of the decision tree to determine the final ranking of the closure processes.

The following discussion provides a brief review of the main categories and subcriteria used for the Level 2 evaluation. Note also that our evaluation assumed the joint designs shown in Figure 4-15 for each indicated process.

1. Economics

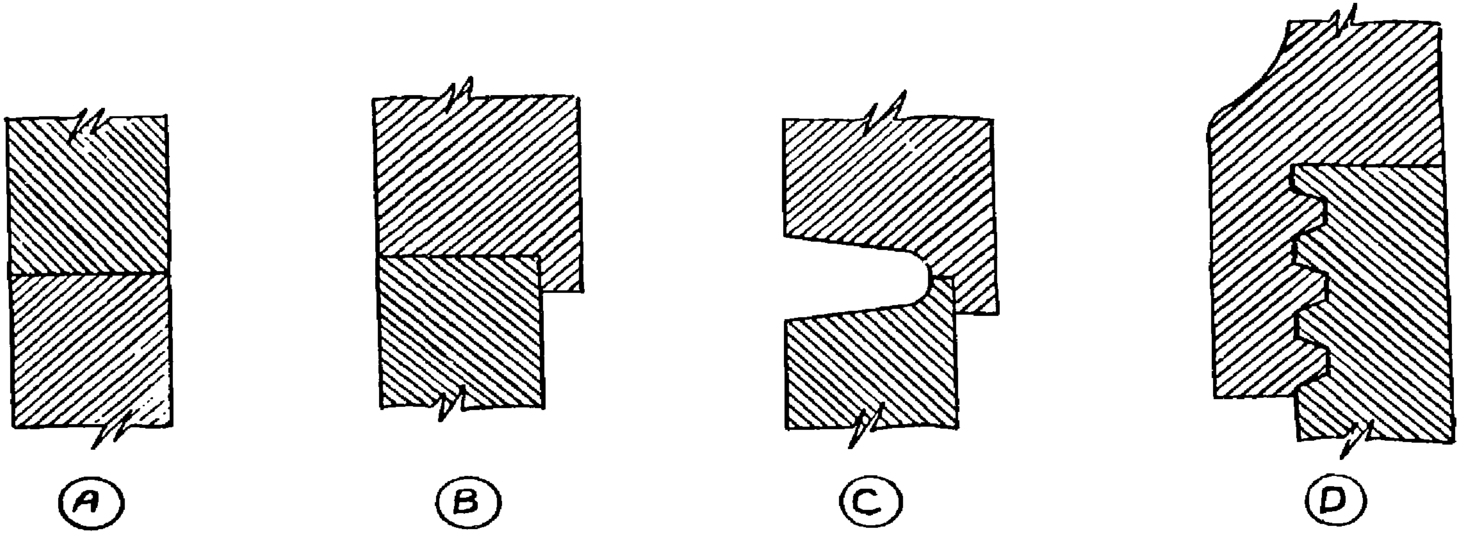
The subcriteria in this category address process-related economic issues. Capital cost considerations have been given for the equipment and fixturing associated with the closure system. Additional equipment costs have also been included to address special requirements for several of the processes. This equipment may include seam tracking devices, remote viewing systems, and even an additional closure system for performing a partial repair. Operational costs associated with closure production rate, closure repair rate, and equipment downtime have also been addressed. Costs related to joint preparation and consumables are included, but these are expected to be minimal.

Closure processes that require minimal capital investment, produce high quality closures with minimal repair, and have low maintenance equipment are judged to be advantageous.

2. Remote Operation

The criteria in this category address any additional requirements for the closure system or facility associated with operating a given process in a totally remote environment (i.e., hot cell). Consideration has been given to additional sensors or devices that may be required to aid the operator to perform the closure. Prior process experience in a remote and/or hot cell environment is judged to be very important and has therefore been weighted heavily.

Also addressed are possible impacts that the process might have on the overall design requirements of the hot cell. This may include additional feed-throughs, special shielding requirements, reinforced structural supports, and any special positioning or manipulation equipment required for specific processes.



A
Plasma Arc - Autogenous
Friction Standard
Brazing Induction
Flash Butt

B
Electron Beam
Laser Beam

C
Gas Tungsten Arc - CW
Gas Tungsten Arc - HW
Gas Metal Arc
Flux Cored Arc
Plasma Arc - CW
Plasma Arc - HW

D
Braze/Seal

Figure 4-15. *Reference joint designs for Level 2, "Process Perspective" decision tree, closure processes.*

Those processes that have been previously used in remote conditions, require minimal operator intervention, and do not require special modifications to the hot cell have been ranked favorably.

Safety aspects of performing the various weld procedures in a hot cell have not been considered explicitly in Phase 1. These issues will receive more specific attention in post-Phase 1 work.

3. General Process Considerations

Subcriteria in this category focus on process-specific characteristics that may influence hot cell operation or the integrity of the container closure. These criteria address spatter and waste material generation, process flexibility, and developmental requirements for implementation.

A desirable process would be amenable to a majority of the candidate materials, require only one pass with no filler wire, generate no spatter or waste materials, and require minimal process developments for implementation.

4. Repair Process

In this category, it has been assumed that provisions for performing both a partial and full closure repair will be provided in the hot cell. The partial repair procedure (for most closure methods) is foreseen to require machining a groove to a depth below the defect around the entire circumference of the container. The profile and depth of the repair groove will be determined by prequalified repair procedures. A suitable welding process, which may or may not be the same process used for the initial closure, would be used to fill the groove with the appropriate filler material.

Those processes capable of making a high integrity closure repair without additional equipment or extensive machining have been weighted favorably.

5. External Process Influences

Criteria in this category address the impact of external influences on weld quality. This includes joint cleanliness, joint alignment requirements, sensitivity to preheat variations, primary power variations, and process variable fluctuations. Processes that are tolerant of external influences are considered more desirable and are so weighted.

6. Maintenance

In this category, the issues address the foreseen maintenance requirements for the various processes. Consideration has been given to the impact that the hot cell environment may have on the fixturing and closure process equipment. This includes possible degradation of components or devices by the radiation field. Also considered in the category was the percentage of the equipment located in the hot cell. Maintenance of this equipment is believed to be more costly and time consuming.

Those processes that require a low percentage of the equipment to be inside the hot cell and utilize components or devices not adversely affected by the environment have been weighted favorably.

7. Joint Integrity

Subcriteria in this category address issues that may affect weld quality. This includes the possible presence of porosity, cracks, nonfusion, inclusions, and undercut in the closure joint. A higher ranking has been given to those processes judged to have a lower probability of generating such discontinuities.

8. Inspectability

Subcriteria in this category focus on issues that are judged to affect the nondestructive evaluation of the final closure joint. The assigned process weightings are based on information obtained in the literature and industry reviews.

Once the evaluation criteria and weighting factors were finalized, the remaining closure processes from Level 1 were assigned a score from 0 to 5, relative to each other, for each of the subcriteria. The higher the score given, the more favorable the process was considered to be with respect to the specific subcriteria and overall goals of the YMP container program.

For example, if we consider the economics category of the process-related decision tree, those closure processes that provide a lower capital investment and closure production costs have been assigned higher scores, as opposed to more costly processes for the respective subcriteria. This scoring methodology has been used for the remaining criteria.

These assigned "process scores" reflect input from the literature search, industry contacts, prior process experience, and independent consultants. This process ranking procedure was completed four separate times to address all of the candidate material groups, since weld quality, inspectability, and applicable closure process(es) are material-dependent issues.

Level 3: Final Closure Process Score

In this level of the decision tree, a final ranking of the closure processes for each of the four material groups is given. This ranking is based on the tabulation of the assigned weighting factors and process scores. The following discussion explains the tabulation procedure.

For a given process and subcriterion, a number was calculated and stored for summation. This number represents the product of the major category weighting factor times the subcriterion "effective" weighting factor times the assigned process score. This procedure was repeated for each of the subcriteria. These final numerical products were summed to yield a numerical ranking of the closure processes. The higher the final numerical ranking, the "more desirable" the process was considered to be.

The final process ranking for the four material groups is given in Table 4-2. These results are also shown in the bar charts of Figures 4-3 through 4-6. As shown, the top five closure processes spanning all four material groups are FRW, EBW, GTAW, PAW:CW, and LBW.

4.3.4.3. "Performance Perspective" Candidate Process Description. Described below are some of the features offered by the five candidate closure processes identified in the "Performance Perspective" decision tree analysis. FRW was ranked significantly higher than all the other closure processes for all four material groups. This process offers a solid-state bond that eliminates solidification defects such as undercut, porosity, and fusion zone cracking. This process is believed to be readily adaptable to a remote environment, with only three parameters to control and little operator intervention required. The majority of the equipment can be housed outside of the hot cell and is expected to require minimum maintenance. The time to perform the actual closure is expected to be less than 2 minutes, with very little radial distortion observed. Friction-welded joints have been ranked as the "most desired" joint profile for UT inspection (see industry contacts in Section 4.1.2).

The electron beam process was found to be applicable to all of the material groups. The process offers the advantage of a single-pass weld with a small fusion zone and minimal radial distortion.

The electron beam process does require a vacuum for welding, resulting in high capital costs. Since the majority of this equipment is located inside the hot cell, it is foreseen to require extensive maintenance.

Laser beam processes offer essentially the same advantages over conventional arc welding processes as electron beam welding, with the added advantage that the weldment could be performed in air. Also, the laser beam power supply would be housed outside the hot cell, minimizing maintenance issues and allowing the beam to be directed to other work stations. However, this process does require developmental work in the areas of the beam delivery system, parameter control, plume generation control, and weld slope-out procedures.

The gas tungsten arc and plasma arc processes offer essentially the same advantages. They represent a very conservative approach and have been demonstrated in remote or hot cell environments. Both processes would require a machined weld groove that would be filled with the appropriate filler materials. These processes offer the possibility of fusion-related defects and substantial radial distortion of the container. Capital costs for these processes are believed to be minimal, as compared to the other processes, and would not impose special requirements on the hot cell design.

4.3.4.4. Evaluation of Homopolar Resistance Welding. Late in the process evaluation program, B&W was requested to re-evaluate high current resistance welding with a homopolar generator as a power source. Presently, development or commercialization of these generators in the United States is being pursued by The Center for Electromechanics at The University of Texas in Austin.

To date, all work with this process has been developmental, with the majority of the work addressing carbon steel, stainless steel, and Inconel. The largest cross-sectional area welded (stainless steel) with this process is 12.5 in.^{2}, although a new 60-megawatt generator has been installed and is believed to be capable of welding up to 100 in.^{2} of material cross section.

Homopolar generators were considered by DuPont for closure welding defense waste canisters (Savannah River), but were later dropped from consideration because these systems were not commercially available. These generators have now been developed for commercial use (up to 60 megawatts) by Parker, Design Kinetics, Inc.

Since this process is still in the developmental stages and has not been demonstrated on material cross-sectional areas equal to those in the intended application, it was not included in this evaluation. However, this process does offer many of the same advantages as the FRW process, with the added advantage that rotating the head would no longer be required. Should sufficient funding be available, further investigation into the capabilities of this process may be appropriate.

4.3.4.5. "Materials Perspective" Decision Tree Details. The following details are offered to provide an understanding of the various components of the decision-making structure. For each material of consideration, input will be required for the following three levels.

Level 1: Failure Mechanisms

Components of this level are an exhaustive listing of the known failure mechanisms of concern for the material under consideration. Examples of these components are:

1. General Aqueous Corrosion
2. Oxidation
3. Crevice Corrosion
4. Pitting Corrosion
5. Galvanic Corrosion
6. Intergranular Corrosion
7. Transgranular SCC
8. IGSCC
9. Hydrogen-Assisted Cracking
10. Hydrogen Embrittlement
11. Mechanical Overload
12. Mechanical Impact
13. Microbiological Corrosion
14. De-alloying

Also included in Level 1 is a means of ranking these mechanisms with respect to one another. The intent here is that while none of the mechanisms above should be permitted to cause failure in the specified lifetime of a container, some failure mechanisms are more likely to occur, or are more severe when they occur; therefore, the closure process selection is more heavily weighted toward avoiding the occurrence of these mechanisms. To provide for this event, the user of the decision tree is asked to rank the processes with respect to one another in terms of likelihood of occurrence (on a scale of 0 to 10, with 10 being the most likely) and severity (on a scale of 1 to 3, with 3 being the most severe). B&W provided initial ranking values.

To the extent possible, these rankings are supported by evidence in literature. However, in cases where this evidence is lacking, rankings are offered based on the engineering judgment of industry and government experts. If the results of investigations indicate that more substantial evidence is required and that engineering judgment is not sufficient, then this would point toward the need for additional laboratory efforts.

4.3.4.6 Simplified Example of Decision Tree Application.

To clarify the workings of the decision tree, a simplified running example follows to indicate how the tree might be applied to carbon steel. A material not currently under consideration for container application was chosen for this example to emphasize the fact that this is only a simplified example. This example is offered only to represent how the decision tree works.

As an example, consider a representative set of Level 1 entries for carbon steel (shown below).

LEVEL 1
(Example for Carbon Steel)

Mechanism	Likelihood (0-10)	Severity (1-3)	Level 1 Weight
Oxidation	10	1	—
Pitting Corrosion	6	2	—
Stress Corrosion—Intergranular	5	3	—
Microbiological Corrosion	0	2	—

As can be seen from the entries, oxidation is rated as having a high likelihood of occurrence (10), but a low severity (1). Thus, oxidation will probably occur but must occur over a long period for its impact to be felt. On the other hand, IGSCC is much less likely to occur (thus, the likelihood of 5), but if it does occur it will have a short-term impact (so the severity is rated high, i.e., 3). Microbiological corrosion has no likelihood of occurrence, thus it has a likelihood of 0. With this in mind, move on to consider the output of Level 1.

The output of Level 1 is obtained by multiplying the likelihood times the severity for each of the mechanisms under consideration. The output thus obtained is a numerical ranking of all the failure mechanisms in terms of likelihood and severity for the material of concern. The numerical value for a given mechanism is termed a "Level 1 weight." Higher Level 1 weights indicate that a mechanism was of particular concern. A Level 1 weight of zero indicates that a mechanism was not active for the material being considered.

(EXAMPLE CONTINUED)

To reach the desired Level 1 weights, multiply the likelihood value times the severity value for each mechanism. These results are shown below. Inspection of these results indicates that IGSCC is of particular concern, having a Level 1 weight of 15. Oxidation now is of moderate importance, with a Level 1 weight of 10. *Microbiological corrosion* is deemed to be irrelevant to carbon steel with a Level 1 weight of 0.

LEVEL 1
(Example for Carbon Steel)

Mechanism	Likelihood (0-10)	Severity (1-3)	Level 1 Weight
Oxidation	10	1	10
Pitting Corrosion	6	2	12
Stress Corrosion—*Intergranular*	5	3	15
Microbiological Corrosion	0	2	0

Note: For the purposes of this investigation, those mechanisms that were deemed "irrelevant" are not included in the evaluation tables.

Level 2: Influential Material and Weldment Conditions

Components of Level 2 are an exhaustive listing of the welding-generated material and weldment conditions that influence the occurrence of the failure mechanisms listed in Level 1. Examples of and an explanation of these components are:

Level 2—Influential Conditions

1. Variable Microconstituents—This condition entails the occurrence of different phases or different phase proportions in the vicinity of the weldment.
2. Variable Grain Size—This condition entails the occurrence of grain size variations across a weldment.
3. Non-Equilibrium Microconstituents—This condition entails the occurrence of perhaps innocuous but thermodynamically unstable or metastable microconstituents that might degrade to objectionable constituents during the intended life of the container.
4. Microchemical Inhomogeneity—This condition entails the occurrence of extremely local chemical inhomogeneity in the vicinity of a weldment.
5. Preferred Grain Orientation—This condition entails the occurrence of preferred grain orientations in the weld fusion zone.
6. Precipitation in the HAZ—This condition entails objectionable precipitation of, or coarsening of, second-phase particles in the HAZ of the closure weldment.
7. Macroscopic Composition Variation—This condition comes about due to alloy losses in the arc or due to the use of a filler with a composition different from that of the base metal.
8. Residual Stresses—By their nature, many welding processes can give rise to objectionable yield point stresses in the vicinity of the weld. The condition of particular concern here is the occurrence of high tensile residual stresses at the outside surface of the closure weldment.
9. Weld Imperfections—These criteria take into account the fact that for any weldment, a variety of imperfections might be anticipated, and that the occurrence of any given imperfection will be more or less likely based on the closure process selected.

Imperfections of concern are:
1. Porosity.
2. Lack of fusion.
3. HAZ microcracks.
4. Fusion zone microcracks.
5. Inclusions.

10. *General Weld Condition*—*This criterion* takes into account that, depending on the process selected, different weldment conditions may evolve. The conditions are not necessarily defined as imperfections, but may result in the reduced performance of a weldment.

1. Surface Condition—Poor surface condition may give rise to difficulties in inspection and may also serve as a contributing factor in decreasing corrosion resistance.
2. Weld Profile—Objectionable weld profiles can lead to regions of stress concentration and may also reduce inspectability.

With the components of Level 2 defined above, it is helpful to define how weighting factors will be applied on this level. Recall that the intent of the decision tree is to allow the selection of welding processes based on their individual abilities to avoid the occurrence of the failure mechanisms of concern. Therefore, Level 1, the failure mechanisms, is to be directly correlated with Level 3, the welding process selection. For this direct correlation to occur, the weighting factors for the various components on Level 2 must sum to a constant total. For this to be true, a "Level 2 Weight" would need to have variable significance.

However, for comparison between mechanisms, it would be convenient to apply a consistent weighting factor to a component on Level 2, i.e., for ease of comparison, a weighting factor should have a constant significance (e.g., a Level 2 weight of 5 should indicate a serious condition regardless of the mechanism of consideration).

To address both of the concerns above, the following weighting technique is employed for Level 2. First, each of the components of Level 2 is rated on a scale of 0 to 5 in terms of the magnitude of its influence (with 5 being the most influential). This 0 to 5 rating system allows for a consistent means of comparison between mechanisms.

(EXAMPLE CONTINUED)

A "Level 2 Table of Material Conditions" is generated for each of the failure mechanisms listed in Level 1. So, for the carbon steel example, separate "Level 2 Tables of Materials Conditions" would be generated for the oxidation, pitting corrosion, and intergranular stress corrosion mechanisms. There would be no need for such a table corresponding to microbiological corrosion since it was deemed irrelevant in the Level 1 analysis (i.e., it had a Level 1 weight value of 0).

For the purposes of continuing the example, consider the "Level 2 Table of Material Conditions" for the IGSCC mechanism listed in Level 1. The following is an abbreviated example of such a table:

LEVEL 2
(Example for Carbon Steel)

(This level only depicts the influence of the various material conditions on the IGSCC of carbon steel. Other failure mechanisms and/or other materials would have different entries.)

Material Condition	Level 2 Weight (0-5)	Level 2 Effective Weight	Output
Weld Imperfections	5	—	—
Residual Stress	5	—	—
Variable Microconstituents	3	—	—
Preferred Grain Orientation	0	—	—
etc.	(all others 0)		
SUM	13	—	—

Several features of this table are worth noting. First, the 0 to 5 entries in the "Level 2 weight" column provide a consistent way of comparing the various material conditions. The individual who compiled the table entries judged that high residual stress and the presence of weld imperfections are both very important contributors to the occurrence of IGSCC of carbon steel. Further, they are both equally important, so an entry of 5 was made for each of these material conditions.

The presence of martensite in the HAZ of a weld in this carbon steel was deemed of moderate importance so "variable microconstituents" was given an entry of 3.

Preferred grain orientations (and all other material condition possibilities) were deemed irrelevant, and thus had entries of 0.

So the weighting scheme above allows one to inspect the Level 2 table and learn how the individual who made the entries judged the relevance of the various conditions with respect to the occurrence of a given failure mechanism.

Logically, the next step to occur would be the combining of the Level 1 and Level 2 influences. The "Output Table" is used for this purpose. In the table, a value might be calculated for each of the material conditions by multiplying the Level 1 weight (for the failure mechanism under consideration) times the Level 2 weight for a given material condition. The values in such an output table might then be inspected to aid in the selection of the best welding process. However, one step remains before such an "output table" is generated.

The intention (and goal) of the decision tree is to directly relate the failure mechanisms (the components of Level 1) to the weld process selection (the components of Level 3). For this correlation to occur, the numbers in the Level 2 output table must still reflect the relative importance of the various failure mechanisms in Level 1. Notice, however, that the number of components that affect any given *failure mechanism can vary. This freedom permits the sum of the Level 2 weighting* factors also to vary. By allowing this variation, the significance of any failure mechanism may be magnified or decreased by simply changing the number of different material conditions that affect it. Clearly, this should not be the intent of the decision tree. To eliminate this potential aberration, it was decided that the Level 2 weights should sum to a constant. This was accomplished using the concept of an "effective weight."

Next, in order to have the total of the material condition Level 2 weights to sum to a constant, "Level 2 effective weights" are calculated for each component so that the sum of the effective weights yields a constant (i.e., 10). To calculate the effective weights, first sum the Level 2 weights, then divide that sum by 10 to yield a "divisor." Then, divide all the original Level 2 weights by the "divisor" to achieve an effective weight for each component. Calculated in this manner, the sum of the effective weights would be a constant (10) as desired.

(EXAMPLE CONTINUED)

As an example of the methodology above, consider its application to Level 2 for carbon steel. In the example below, a divisor is first calculated. The Level 2 effective weights are calculated for each material condition by dividing the Level 2 weight by the divisor. As is shown, the sum of the effective weights is now equal to the constant (10).

<u>CALCULATION OF THE DIVISOR</u>
DIVISOR = (SUM OF LEVEL 2 WEIGHTS) divided by (10)
DIVISOR = 13 / 10 = 1.3

CALCULATION OF A "LEVEL 2 EFFECTIVE WEIGHT"
EFFECTIVE WEIGHT = WEIGHT divided by the DIVISOR
EFFECTIVE WEIGHT = (WEIGHT) / 1.3

LEVEL 2
(Example for Carbon Steel)

(This level only depicts the influence of the various material conditions on the IGSCC of carbon steel. Other failure mechanisms and/or other materials would have different entries).

Material Condition	Level 2 Weight (0-5)	Level 2 Effective Weight	Output
Weld Imperfections	5	3.846	—
Residual Stress	5	3.846	—
Variable Microconstituents	3	2.308	—
Preferred Grain Orientation	0	0.000	—
etc.	(all others 0)		
SUM	13	10.00	—

Rating of the Relative Importance of the Various Material Conditions

With weighting factors assigned to each material condition in Level 2 and effective weighting factors calculated, it is then possible to calculate the combined output of Levels 1 and 2. Multiply the Level 1 weighting factor for a given mechanism times the effective weighting factor of each material condition that contributes to the mechanism.

The result is a table that rates the effect of each material condition on a particular failure mechanism. The magnitudes of the numbers in the table will be higher or lower depending on the importance of the failure mechanism being considered. A similar table is generated for each failure mechanism of concern for a given material.

(EXAMPLE CONTINUED)

For the example, look at the Level 2 table for IGSCC of carbon steel, and multiply the Level 1 weight (for the failure mechanism of concern) times the Level 2 effective weight (for each individual material condition) to obtain the Level 2 output.

Recall that the Level 1 weights were given as shown in the table below. The material condition is intergranular stress corrosion, so the Level 1 weight needed for the current purposes is 15.

LEVEL 1
(Example for Carbon Steel)

Mechanism	Likelihood (0-10)	Severity (1-3)	Level 1 Weight
Oxidation	10	1	10
Pitting Corrosion	6	2	12
Stress Corrosion—Intergranular	5	3	15
Microbiological Corrosion	0	2	0

The output may be obtained by multiplying the Level 1 weight times the effective weight for each material condition.

LEVEL 2

(Example for Carbon Steel)

(This level only depicts the influence of the various material conditions on the IGSCC of carbon steel. Other failure mechanisms and/or other materials would have different entries.)

Material Condition	Level 2 Weight (0-5)	Level 2 Effective Weight	Output
Weld Imperfections	5	3.846	57.69
Residual Stress	5	3.846	57.69
Variable Microconstituents	3	2.309	34.62
Preferred Grain Orientation	0	0.000	0.000
etc.	(all others 0)		
SUM	13	10.00	—

In this way, an output table is generated for each failure mechanism relevant to a material of concern. This means that this same procedure would be repeated for the pitting corrosion and oxidation mechanisms for our carbon steel example. These tables may contain the same or different material conditions. The output values in the tables for the less important failure mechanisms will generally be smaller individually. The sum of the output values for the other mechanisms will also be smaller individually [i.e., because we are multiplying a smaller Level 1 weight times a constant (10)]. The technique employed has thus allowed the significance of the Level 1 failure mechanisms to carry through to the output tables.

With all of the output tables assembled for a given material, the next step is to sum all of the values for a particular material condition (across all of the tables for the material). These sums are used to generate an overall output table for the combined Levels 1 and 2. By inspection of the output table, it is possible to determine the overall relative importance of each of the material conditions considered in Level 2.

Level 3: Process Characterization

On this level, the processes are compared. Process comparison involves characterizing the various closure processes and ranking them with respect to their relative abilities to favorably address the material conditions listed in the output table. Process comparison involves the following steps:

1. Rank all of the processes with respect to their ability to ameliorate a material condition. This ranking is on a scale of 0 to 5, with a 5 ranking indicating that the process of concern completely ameliorates the condition.
2. Determine a score for each of the processes with respect to each of the material conditions by multiplying the ranking determined above times the material condition value in the output table.
3. Sum all of the scores for a process to develop a process total.
4. Rank all of the processes relative to one another by comparing their totals. Higher process totals indicate a more favorable process.

(EXAMPLE CONTINUED)

The process comparison routine is illustrated below. Each of the processes being compared is rated on a scale of 0 to 5 based on its ability to ameliorate the indicated material condition. A rating of 5 indicates that a process can completely relieve a bad material condition.

LEVEL 3
(Example for Carbon Steel)
Intergranular SCC

(In this example, the effects of two different processes on the material condition of carbon steel are determined. This illustrates the closure process ranking. Consider that Process "A" is a high-energy density process, and that Process "B" is a conventional arc welding process. For the sake of illustration, assume that the outputs determined in the example tables above now represent the overall outputs.)

		Process "A"		Process "B"	
Material Condition	Output	Weight (0-5)	Score	Weight (0-5)	Score
Weld Imperfections	57.69	4	—	4	—
Residual Stress	57.69	5	—	3	—
Variable Microconstituents	34.62	2	—	2	—
Preferred Grain Orientation	0.00	3	—	3	—
PROCESS SCORE TOTALS:		"A"		"B"	

Once the processes under consideration are rated (using the 0 to 5 weights), the next step is to develop scores for each process under consideration by multiplying the overall output value for each material condition times the weight assigned to the process for ameliorating the material condition being scored. Once all of the scores have been determined, process scores are determined for each process by summing all of the scores for a process. This concept is illustrated below.

Note at this point that the overall output is higher for those bad material conditions that are most severe. Note also, that by assigning high values (i.e., 5) for processes that totally ameliorate a bad material condition, those processes that are best at addressing the more severe material conditions achieve high scores. Thus, the process with the highest process score total is rated the best. So in the rankings below, Process "A" is better than Process "B."

LEVEL 3
(Example for Carbon Steel)
Intergranular SCC

(In this example, the effects of two different processes on the material condition of carbon steel are determined. This illustrates the closure process ranking. Consider that Process "A" is a high energy density process, and that Process "B" is a conventional arc welding process. For the sake of illustration, assume that the outputs determined in the example tables above now represent the overall outputs.)

		Process "A"		Process "B"	
Material Condition	Overall Output	Weight (0-5)	Score	Weight (0-5)	Score
Weld Imperfections	57.69	4	231	4	231
Residual Stress	57.69	5	288	3	173
Variable Microconstituents	34.62	2	69	2	69
Preferred Grain Orientation	0.00	3	0	3	0
PROCESS SCORE TOTALS:		"A"	588	"B"	473

This completes the running example of how the decision tree would be applied to carbon steel to select Process "A" for making a closure weld in this material when considering intergranular SCC. Figures 4-8 through 4-14 show the actual closure process ranking developed as above in bar chart form. Table 4-4 shows the four best closure processes for each material.

Note that a total of 15 processes/process variations was evaluated in Level 3 for all of the materials except CDA 122. The number of processes considered for pure copper was reduced, because fewer processes were applicable. The screening process for the closure processes evaluated by the decision tree are described in Section 4.3.2.1.

This exercise has demonstrated that if the components on each level of a decision tree are clearly defined and the weighting factors are sensible, then the decision tree technique provides a powerful tool for making (and illustrating) the necessary closure process comparisons and rankings. This opinion will be developed in a later section of this report in which the results of this decision tree selection process are gaged against practical experience. In the next major section of this report, the results of the "Materials Perspective" decision tree are compared with the results of the "Process Perspective" decision tree in order to make the first cut at final closure process selection.

4.3.5. Decision Tree Results

This section individually summarizes the results of the process and materials branches of the decision tree.

4.3.5.1. Decision Tree Results—"Process Perspective." The results of the "Process Perspective" of the decision tree are illustrated graphically in Figures 4-3 through 4-6.

Table 4-2 demonstrates from a process perspective that FRW, GTAW, PAW, LBW, and EBW are most amenable to performing closure in the intended environment.

4.3.5.2. Decision Tree Results—"Materials Perspective." The results from the decision tree for the "Materials Perspective" are illustrated graphically in Figures 4-8 through 4-14. The processes input into the decision tree were those that passed the initial screening criteria, as described in Section 4.3.2.1. For the figures above, the EBW and LW processes have two categories each, with and without filler metal. These reflect the possible need for a second weld process to be utilized for producing a smooth cover pass for these weldments. However, it is felt that there is a good chance for making these welds without the second process. Also, the standard and radial FRW processes were evaluated separately here. Subsequently, it was decided to consider these processes as one process for the purposes of this phase of the evaluation.

Table 4-4 demonstrates from a materials perspective that FRW, EBW, LW, and PAW (keyhole mode) provide the optimum closure joints. These processes provide the lowest effective heat inputs, thus minimizing adverse effects of heating the surrounding base metals (HAZs). They typically would not use filler metals, thus minimizing galvanic effects of fillers with slightly different compositions. Residual stresses and distortions could be relatively low in these weldments, particularly for FRW. The potential for producing sound weldments is reasonably high, and the surface condition of the container exterior appears to be adequate (equipment for removing OD flash is required for FRW). It appears that all of these processes can be implemented in a remote, hot cell environment. Implementation of the processes is discussed in Section 4.4.

4.3.6. Final Process Selection

To this point in the program, optimum processes have been selected separately based on materials and process considerations. From the material perspective, the best four processes were: FRW, EBW, LBW, and PAW. From the process perspective, the five best processes had similar scores: FRW, GTAW, PAW, LBW, and EBW. The FRW process ranked highest from both sides of the evaluation. All of these processes are applicable to the remote, hot cell environment; all have been used for similar material diameters and thicknesses; and all can be adapted to the welding environment. The processes are applicable to all of the materials, except for pure copper, for which B&W feels that only EBW, FRW, and possibly PAW can be used. At this time, processes are being selected for further evaluation, not as the final closure process. The final ranking of closure processes is shown in Table 4-7, along with the primary advantages and disadvantages of each.

The following discussion summarizes the ranking procedure for the processes. FRW ranked notably higher than the other processes due to its speed and ease of welding, ease of in-cell equipment maintenance, and desirable weldment material conditions. The major foreseen disadvantages for the FRW process, and particularly inertia welding are:

- Process generates a flash on the ID and OD surface. OD scarf must be removed.
- Equipment is massive and expensive.
- Repair welding is difficult (full reweld or second process repair).
- Process influences the container design.

In the "Process Perspective" decision tree structure, the disadvantages above were addressed. FRW received lower scores, relative to conventional arc welding processes, for the decision tree criteria addressing the concerns above. However, the scores FRW received for the advantages it offers as a closure process outweighted these low scores, resulting in a high overall ranking of the process.

Overall, EBW and LBW ranked next, primarily influenced by a more desirable weldment material condition compared with the arc welding processes. However, at this point, LBW was moved down in ranking due to concerns with the developmental nature of equipment large enough to penetrate these thicknesses and due to its inability to make welds in pure copper. Of the arc welding processes, PAW and GTAW ranked highest, with PAW producing a slightly better weldment material condition when operating in the keyhole mode. B&W does not feel comfortable with either of these processes for pure copper, due to high preheats probably required to successfully produce quality welds. However, PAW may have the best chance (of the arc-welding processes) for welding pure copper. The ranking of the PAW process was increased to above LBW at this point, due to its versatility (keyhole or filler metal addition modes) and the larger amount of prior closure welding experience with the process.

In summary, five closure processes worthy of further evaluation have been selected. The selection was based on a decision tree analysis followed by a somewhat subjective analysis of the results. These processes provide an optimum combination of weldment material condition and equipment considerations in a remote, hot cell environment. They also represent three types of welds for evaluation in the program: solid-state welds (FRW), high-energy density beam welds (EBW, LBW), and arc welds (PAW, GTAW).

In addition to the above processes the progress of Homopolar Resistance Welding will be followed as a possible back-up process for FRW. Homopolar welding was evaluated late in the Phase 1 program. This process was not included in the "Process Perspective" decision tree evaluation because it had not yet been demonstrated on joint cross-sectional areas comparable with the currently proposed container design. However, a new equipment design being offered is believed to be capable of welding cross-sectional areas in stainless steels up to 100 in.^{2}

Table 4-7. Ranking of closure processes for HLW containers for the tuff facility.

Process	Advantages	Disadvantages
Friction Welding (FRW)	Small HAZ, small fusion zone, minimum risk for second phases, low residual stress, low distortion, good inspectability, ease of in-cell maintenance, low frequency of maintenance, fast weld speed, few welding variables to monitor.	ID and OD scarf (requires OD machining) massive equipment, expensive equipment, repair difficult (full reweld of second process repair), may impact container design, additional safety considerations.
Electron Beam Welding (EBW)	Low heat input, relatively small fusion zone and HAZ, relatively low residual stresses and distortion, good inspectability, fast weld speeds, chance for repair welding without machining, no filler metal.	Could experience poor crown surface condition and defects in "spike" area, expensive equipment, in-cell vacuum chamber required, in-cell maintenance expensive, safety considerations.
Plasma Arc Welding (PAW)	Low to medium heat input, no filler metal with keyhole, relatively low cost equipment, much previous closure experience, versatile equipment, repair welding with same process, arc length more forgiving than GTAW.	Many weld variables to monitor, in-cell monitors (guidance and real-time controls) could be required. Fairly complex torch, possibility for porosity in keyhole mode, medium inspectability, higher possibility for second phases if filler metal is used, machining for repair welding possibly required.
Laser Beam Welding (LBW)	Same as EBW.	Pushing current technology with material thicknesses, expensive equipment, beam must penetrate cell wall at some point, maintenance could be expensive, not applicable for pure copper.
Gas Tungsten Arc Welding (GTAW)	Medium heat input, low cost equipment, fewer variables than PAW, much previous in-cell experience, repair welding with same equipment, easier in-cell maintenance, less expensive than the processes above.	A greater volume of material affected by high residual stresses and greater distortions than the processes above, filler metals required, repairs require re-machining, larger fusion zone and HAZ, lower inspectability, higher possibility for second phases, in-cell guidance and real-time controls may be needed.

4.4. Conceptual Process Designs

Preliminary conceptual designs, Figures 4-16 through 4-19, have been drawn for the five "best" closure processes from the "Process Perspective" decision tree results. These illustrations depict the LBW, PAW, GTAW, EBW, and FRW processes as they might be implemented in a hot cell for closure welding YMP containers. No effort has been made to detail manipulation and transportation equipment required in the cell. These conceptual designs only illustrate the basic requirements for each process. Details of the weld joint configuration have not been developed yet, but will be developed in Phase 2.

For the FRW process (Figure 4-19), almost all of the equipment is foreseen to be placed in a separate machine room above the hot cell. Only the rotating shaft of the machine penetrates the hot cell ceiling. Air flow would be restricted from entering the machine room to allow entry for maintenance purposes. The majority of this equipment is mechanical devices believed to require very low maintenance.

A fixturing device to securely hold and rotate the container lid would be attached to the rotating shaft of the machine. A device for centering the container is located just below the weld joint. This device would also grip the container to resist the torque generated during welding. The upset force required to complete the weld is foreseen to be provided by a thrust cylinder located below the container in the hot cell floor. A machining device would be used to remove the weld upset on the outside diameter of the container.

Closure welding using the electron beam process (Figure 4-18) is foreseen to occur inside a separate chamber in the hot cell. This chamber is slightly larger than the container assembly to minimize the time required to establish the partial vacuum (10^{-3} to 1 torr) needed for welding. The mechanical pumping system and high voltage power supply could be housed in a separate room outside the welding area. Safety provisions inside this room would allow personnel entry for maintenance requirements. Only the electron beam gun and viewing system would be located inside the welding chamber.

In this design, the electron beam gun remains stationary, while the container rotates to complete the weld. A centering device, located just below the weld joint, will be used to maintain a consistent gun-to-work distance. A remote video camera and an electron scanning device could be used for weld joint alignment.

For the plasma arc or gas tungsten arc process (Figure 4-17), the welding torch and wire feed system (if required) would be located inside the hot cell and maintained in a stationary position. Closure welding would be completed by rotating the container. The power supplies, control console, cooling system, and shielding gas would all be located outside the hot cell environment. Alignment of the weld torch could be visually performed through a portal or by using a remote video system. An AVC system may also be used to maintain the desired stand-off distance. This design is representative of other conventional arc welding processes, should they be considered in the future.

Figure 4-16 illustrates one possible method for implementing the laser beam process for closure welding YMP containers. The laser beam power supply and cooling system could be located outside the hot cell, with only the beam delivery and focusing mechanism penetrating the wall. As shown, the beam would be maintained in a stationary position, with the weld being completed by rotating the container.

In this illustration, a lens is used to transmit the laser beam into the hot cell. This lens would require periodic replacement since it will be subject to "browning" from the radiation field. An alternate method for bringing the laser beam into the hot cell would be to use an aerodynamic window. This window is essentially a "hole," having a bent optical axis, with a pressure differential being constantly maintained across it.

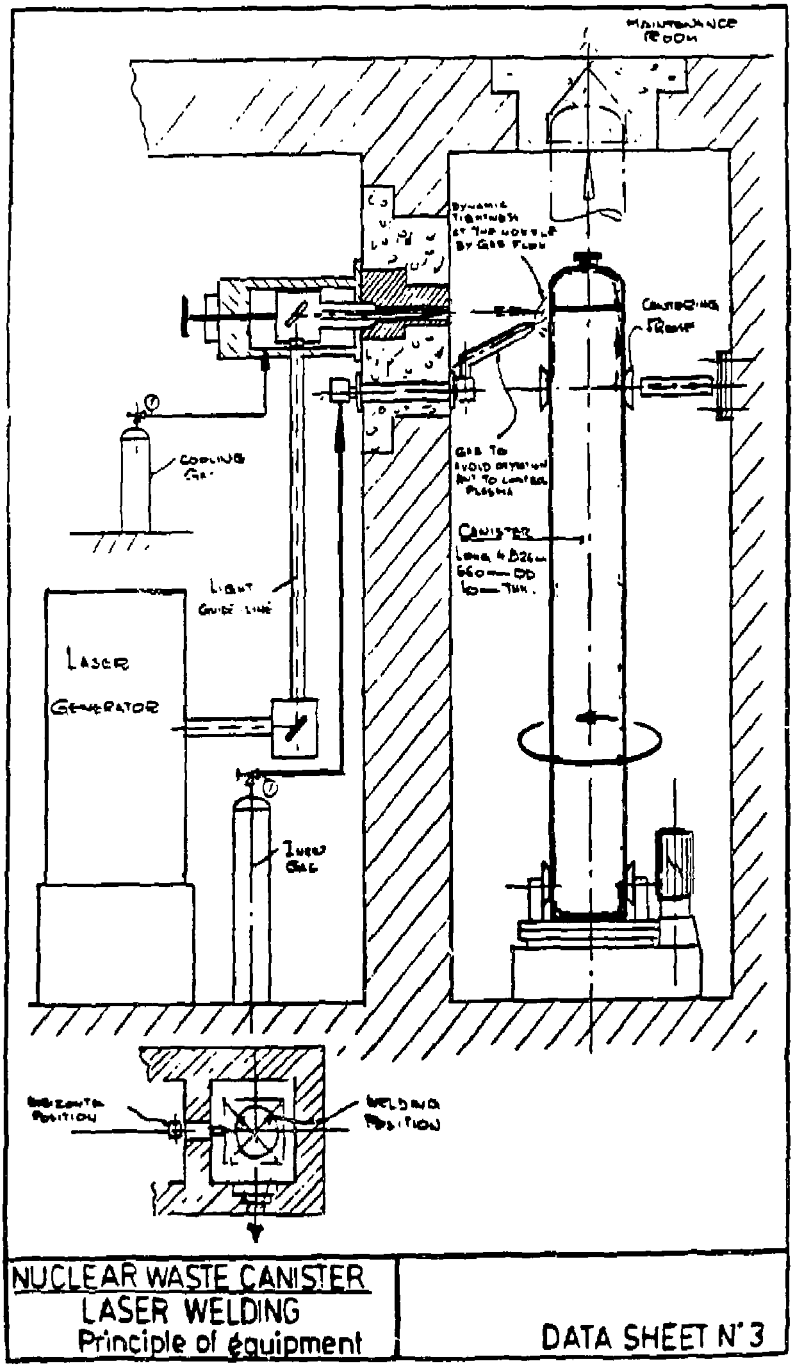


Figure 4-16. Conceptual design of the LBW system.

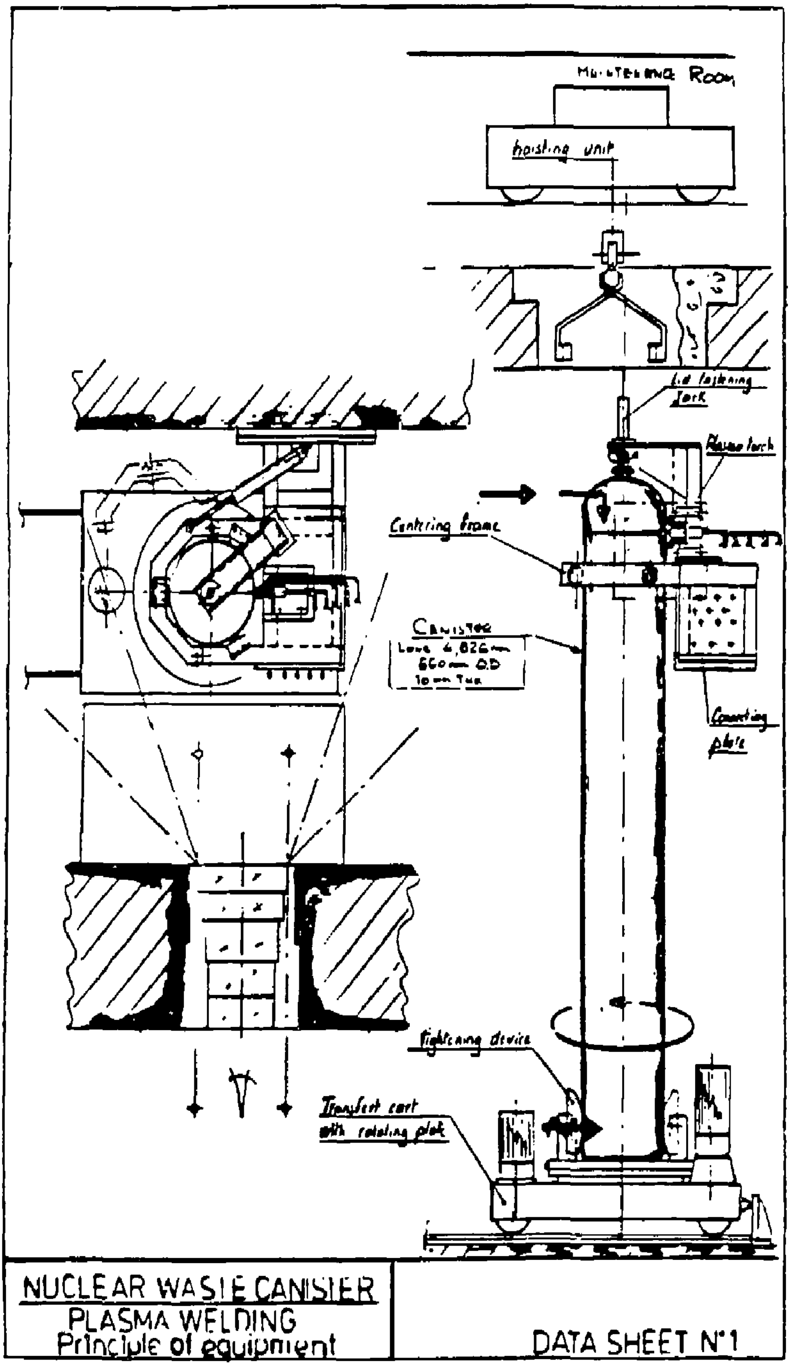


Figure 4-17. Conceptual design of the PAW or GTAW system.

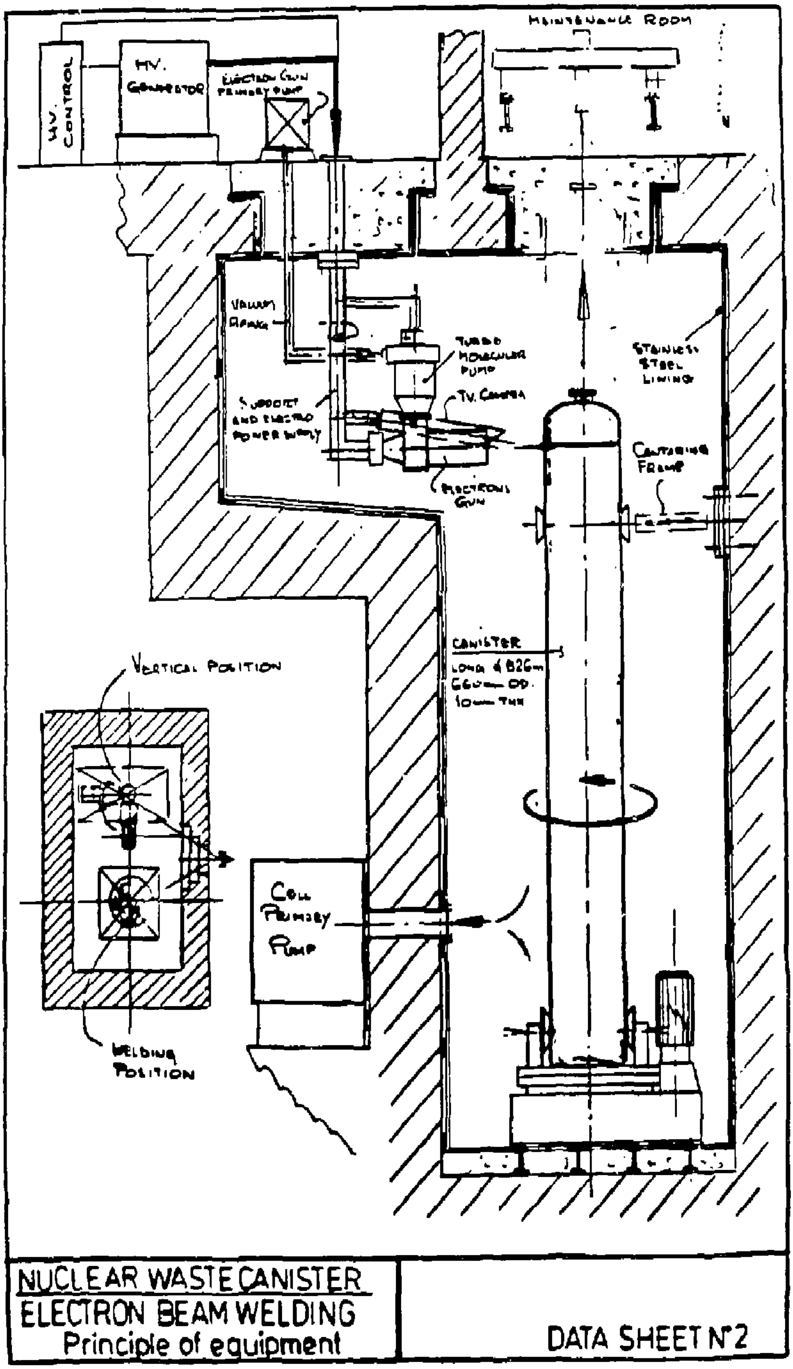


Figure 4-18. Conceptual design of the EBW system.

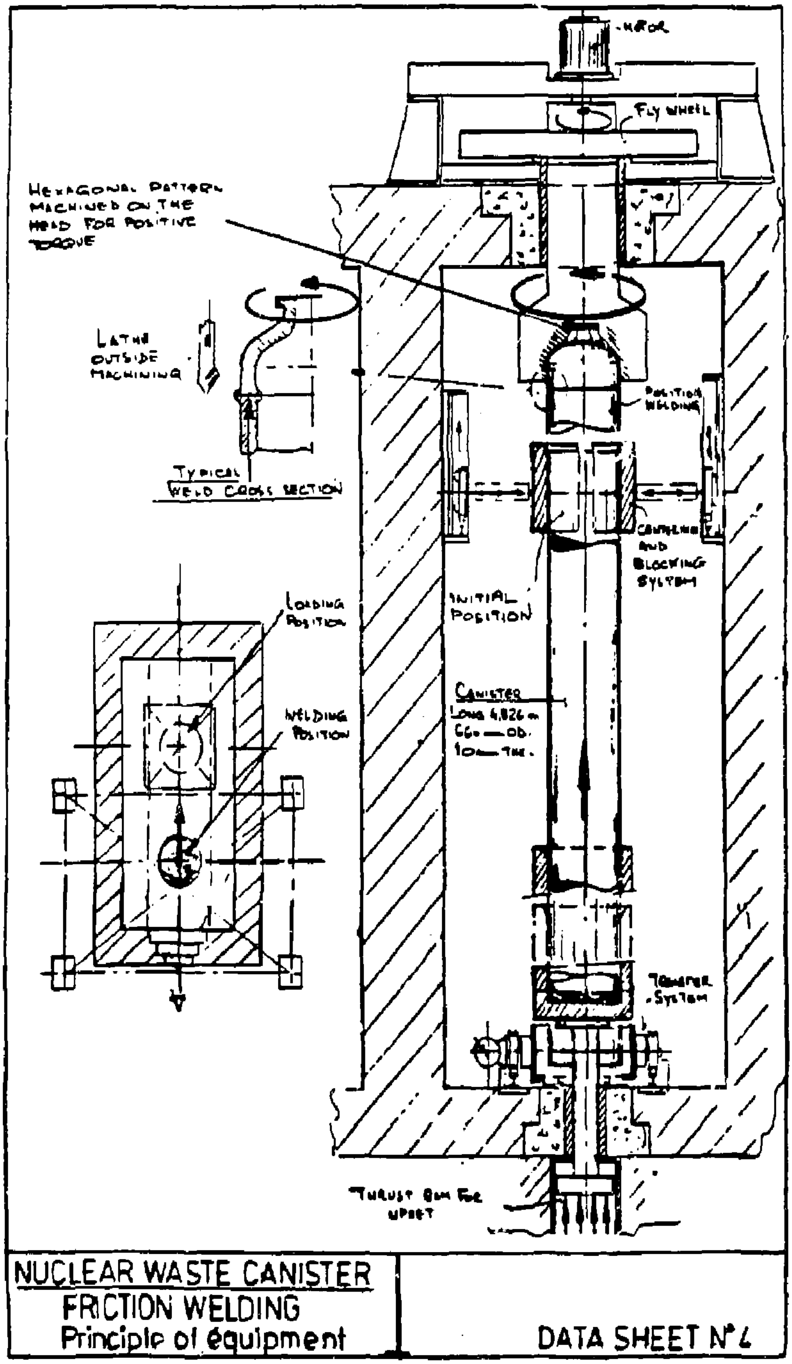


Figure 4-19. Conceptual design of the friction/inertia welding system.

The welding operation would be performed at atmospheric pressure. Joint alignment may utilize remote cameras and/or visible wavelength lasers. One advantage to using this process is the possibility of having an alternate work station, if desired.

Detailed aspects of interfacing these welding processes with the hot cell will be considered in future work.

5. Summary of Results and Recommendations

The decision tree methodology was used to identify the optimum processes for closure welding a container in which to store high-level nuclear waste. The five recommended processes were ranked in the following order: FRW, EBW, PAW, LBW, and GTAW. Currently, the recommendation is to perform further Phase 2 evaluation and testing utilizing the six materials and three of these processes identified at the end of Phase 1A. If the scope of Phase 2 were to be expanded in the future, the other two processes should be added to the test program. All these processes rank very closely and each possesses some desirable attributes.

The issue of closure joint repair is very important, particularly since volumetric (UT) inspection is currently planned. A certain number of containers will require either partial or total repair welding. The optimum condition would be if the closure process could be used to re-fuse the weldment and eliminate the NDE indication, without the need for machining the joint. This procedure may be effective in some instances for EBW, LBW, and keyhole PAW, but is not expected to work every time. The worst case is when the total weldment must be separated, machined again, and welded again. This would always be the case for defective FRW welds, unless a second process were utilized for repair. An intermediate option is to perform a partial thickness repair of the weldment, where predetermined weld configurations would be machined around the full circumference of the joint. The repair groove configuration chosen would be a function of the depth of the rejectable indication. For the PAW and GTAW processes, the primary closure welding system could be utilized for this repair. For the EBW, LBW, and FRW processes, a second process would be required for partial thickness repairs. Another option would be to perform no partial thickness repairs, and design for totally remachining and rewelding the joints. In any case, some in-cell machining capabilities will be required. The issue of a repair welding methodology needs to be resolved in Phase 2 and incorporated into the hot cell design.

Finally, certain negative aspects of the selected processes should be emphasized and addressed in detail in Phase 2 of the program. These relate to materials performance, container fabrication costs, and overall hot cell design. First, for the FRW process, some convenient mechanism for gripping the container heads is needed. A gripping device could be devised for holding the cylindrical head section, but some marring of the outside surfaces may result from slipping during final stages of the weld. This might particularly be true for the softer copper materials. A hex configuration could be machined on the cylinder head, but this would add to the cost of fabrication. Another issue that must be addressed with respect to FRW is the impact of this process on the hot cell design to accommodate safety issues. For the EBW, LBW, and possibly PAW, a modified joint design has been proposed and accepted by the LLNL staff. This joint utilizes an inside lip extending from the container head to help align the joint and to absorb excess energy from the weld process. Exact requirements for this joint design need to be better defined. Finally, in-cell machining capabilities are necessary for removing the OD scarf for the FRW process and for preparing for weld repairs for all processes. The question of whether this capability should be built into the welding station or provided at a separate station needs to be addressed quickly and incorporated into the hot cell design.

The following recommendations pertain to Phase 2 development activities, materials performance, and hot cell design.

1. Phase 1A evaluations should continue with the intent of reducing the number of candidate processes from five to three.
2. The issue of closure joint repair should be resolved in the near term and incorporated into the hot cell design.
3. Methods for gripping the container heads for FRW should be evaluated in terms of container cost and materials performance in Phase 2.
4. The proposed modified joint design should be completed in Phase 2.
5. In-cell machining requirements should be completed and incorporated into the hot cell design.

6. Quality Assurance

QA Plan

The B&W Research and Development Division's QA plan for Phase 1 (RDD QA Plan No. 87007) was conducted 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 was 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. 87007, Revision 0, dated June 29, 1987.

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QA Manager
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8. Bibliography

General issues addressed by the literature review are as follows.

Issue	Citations
Requirements	3,5,7,8,10,11,12,13,16,18,19,20,164,180
Worldwide efforts	2,10,17,161,162,164,167,168,171,177,178
Environment	5,6,7,11,12,22,113,176,180
UT inspection	7,45,46,47,48,53,63,170,171
Repair	10
Life estimation	16
Residual stresses	7,23,2[illegible],25,27,28,29,31,52,58,92,93,94,97,98,100,102
Distortion	29,94,95,97,98,100
Thermal modeling	15
Radiolysis	17,180
Hot cracking theory	83,84,89,91,101
Penetration control	99
Cost	5,9,11,19

Issues and citations addressed by the literature review for stainless steels and alloy 825 are as follows.

Issue	AISI 304L	AISI 316L	Alloy 825
Welding processes	64,66,67,77,70,95,104	64,65,66,67,114	--
Welding parameters	1,32,36,38,57,75,78,108, 119,123,124,129	1,38,57,107,108,110, 124,129	131,151
Filler metal selection	72,73,104,111,125,129,132,141	125,129,133	125,132,133,151,174
Alloying/trace elements	44,62,75,76,80,81,82,122, 125,145	61,80,81,102,110,140,145	134,135,141,143,145, 149,174
Fluidity	--	--	131,144
Porosity	--	--	151
Hot cracking	62,66,72,73,75,77,80,82,87, 88,118,129	61,66,74,129	132,135,151
Solidification mode	72,75,79,80,81,87,111,112	71,80,81,87,110	--
Delta ferrite	6,77,78,85,87,105,111	56,68,71,74,85,105,109, 110	--
Residual stress	26,31,32,34,36,39,52,95, 104,122	30,35,61,104,122	--
Distortion	95,125	61	--
Mechanical properties	--	54	135
Toughness	78	56	149
General corrosion	78,87,105,113,119,141	105,109,113,119,133,141	143
IGSCC/IGA	32,44,104,112,118,123,125,136	107,118,122,124,127,128 136,140	128,136,138,141
Pitting corrosion	104,107,125,141,145	104,106,107,109,110,125, 141,145	125,126,133,141
Crevice corrosion	125,145	106,109,125,137,145	126,137
Sensitization	6,26,37,38,42,43,44,49,50,57, 104,108,117,123,124	26,38,50,55,57,107,108, 109,118,124,125,140	128,134,138,143
Long-term low temperature sensitization	22,33,37,40,42	--	41
Stabilization	--	--	128,134,138
Sigma phase	70,86	50,56,57,90,102,109, 128,140,145	125,128,134

Issues and citations addressed by the literature review for copper and copper alloys are as follows.

Issue	CDA 122	CDA 613	CDA 715
Welding processes	4,161,162,163,164,170,175	115,162,175	162,175
Welding parameters	130,160	116,130,132,152,169	121,130,132,152
Filler metal selection	130,132,139,174	130,132,139,154,155, 157,169,174	130,132,139,155,159
Alloying/trace elements	130,132,165,174	115,130,132,152,154,174	120,121,130,132,142, 146,152,153,159
Prior processing	--	174	--
Hot cracking/ weldability	130,132,152	130,150,152,154,169	120,130,132,142,146, 147,148,153
Hot ductility	--	115,139,154,157,169	153
Residual stress	102	--	--
Distortion	175	--	--
Oxide inclusions	160	--	--
Porosity	130,139,163,171	115,130	130
Mechanical properties	--	116,150	159
General corrosion	102,166,176,180	115,150,152,154,157, 172,176,180	72,158,176,180
SCC	166,168	157	--
Pitting corrosion	160,165,166,168,176	150	126
Crevice corrosion	--	150	126
Dealuminification	--	150	--
Beta phase	--	150,152,156,157	--
Gamma-2 phase	--	150,152,156,157	--
Oxidation	--	169,172	--

The following list of citations was consulted in identifying evaluation criteria, assigning weighting factors, selecting the closure processes, and preparing background information for this document. These citations primarily address previous closure experience, materials concerns both during closure and service, and general closure process technology.

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Appendix A

This report does not use any information from the Reference Information Base nor contain any candidate information for the Reference Information Base or the Site and Engineering Properties Data Base (SEPDB).