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FABRICATION AND CLOSURE DEVELOPMENT OF CORROSION RESISTANT CONTAINERS FOR NEVADA'S YUCCA MOUNTAIN HIGH-LEVEL NUCLEAR WASTE REPOSITORY[(1)]

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ABSTRACT

U.S. Congress and the President have determined that the Yucca Mountain site in Nevada is to be characterized to determine its suitability for construction of the first U.S. high-level nuclear waste repository. Work in connection with this site is carried out within the Yucca Mountain Project (YMP). Lawrence Livermore National Laboratory (LLNL) has the responsibility for designing, developing, and projecting the performance of the waste package for the permanent storage of high-level nuclear waste. 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 performing the final closure of the container after it has been filled with waste.

Various fabrication and closure methods are under consideration for the production of containers. This paper presents progress to date in identifying and evaluating the candidate manufacturing processes.

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INTRODUCTION

Researchers at the Lawrence Livermore National Laboratory (LLNL) are participating in the Yucca Mountain Project (YMP) to design containers for the long-term disposal of high-level radioactive waste at the Yucca Mountain, Nevada site. The key waste package design environmental characteristics of the Yucca Mountain site, which consists of strata of welded-tuff rock (volcanic in origin), yields the following major design parameters:

1) The proposed repository horizon is located in an unsaturated zone, several hundred feet above the water table, in a relatively strong rock that does not exhibit significant creep properties; thus, there will be no significant hydrostatic or lithostatic loading on the container.

2) The anticipated flux of water migrating from the surface toward the water table is extremely small (less than 1 mm/year); thus, while aqueous corrosion could occur during transient periods when water may enter the repository environment, aqueous corrosion is not viewed as a likely or continuous occurrence.

3) The water chemistry is expected to be relatively benign: an oxidizing, dilute sodium bicarbonate solution of neutral pH, containing 7 ppm Cl^- and 10 ppm NO_3^-.

4) The temperature of the borehole wall will attain levels of less than 210°C over the first 25 years, then fall to about the local boiling point of water (97°C) during the subsequent 300 years; thus, any fluid will likely be in the form of steam or humid air during this period.

Our plan is to use a corrosion-resistant material for the containers, in the form of a thin-walled, monolithic cylinder (10-30 mm thick), with overall length of about 4.7 m and diameter of roughly 0.7 m. The materials under consideration for containers include three austenitic alloys- AISI 304L stainless steel, AISI 316L stainless steel, and Incoloy 825 (a high nickel, iron-base alloy); and three copper-base alloys- CDA 102, CDA 613, and CDA 715. AISI 304L/316L stainless steels will not be emphasized in Phases 2 or 3 for the following reasons: (a) these metals are already well-understood and characterized, (b) relative to the other candidate alloys, AISI 304L/316L are highly susceptible to certain localized corrosion mechanisms, and thus are not likely to be chosen as the reference container metal. The compositions for the austenitic and copper-base alloys are given in Table 1.

Our goals for the containers are to produce microstructural uniformity throughout each unit: a wrought-like, homogeneous, low-residual stress, microstructure, with controlled composition. Any welds and/or heat affected zones generated during fabrication would be heat treated and/or mechanically worked to dissolve undesirable microstructural features. The final closure, on the other hand, is to be executed remotely in a highly radioactive environment, and must produce the desired features without any post-weld heat treatment or mechanical work.

Babcock and Wilcox (B&W), as a subcontractor to LLNL, is conducting research on the container fabrication and final closure process development. B&W's role is to recommend and demonstrate feasible methods for fabrication and final closure of the containers for each of the candidate metals, consistant with microstructural uniformity as was discussed above. The process development activities are integral to container alloy selection, as well as the container/repository conceptual design development.

FABRICATION

The overall goal of the fabrication effort is to define manufacturing methods to produce containers with optimum performance, reliability, and safety for up to ten-thousand years of service in the repository. The specific objective is to assess various manufacturing alternatives, relative to the performance requirements, and then demonstrate both a primary and a back-up manufacturing method by making prototype containers. In the schematic diagram (see Figure 1), the container is divided into four major components: the lifting pintle, top head, body, and bottom head. A minimum of two components is possible, however, if the upper and lower units are each made integrally.

The activity is broken down into three phases. Phase 1 is an engineering study (on paper) to identify, assess, and rate candidate processes, for each of the six candidate materials based on the application requirements. This involved an assessment of the performance requirements for the container, the methodology devised to evaluate various fabrication processes, the results of several vendor surveys to identify manufacturing methods, and finally, the ratings for each process.[1]

Phase 2 involves trials to produce sub-scale mock-ups of the container body and the top head for the candidate materials by various processes so that both a primary and an alternate manufacturing method can be selected. The plan for Phase 3 is to fabricate full-scale prototypes using the primary process for the final material selected by LLNL. B&W has completed Phase 1, and Phase 2 is currently in progress.

Phase 1 Results

A state-of-the-art survey was conducted, which included an extensive literature search with over 200 references. Particular emphasis was placed on possible effects of various fabrication processes which could influence performance or quality for each of the six candidate alloys. The Copper Development Association (CDA) was used as a consultant to B&W for copper-base materials. CDA provided access to their data base for the literature search, and also prepared several reports for B&W, which listed and described potential copper-base materials fabricators. B&W also reviewed relevant activities in European nuclear waste container fabrication and closure.

To identify and characterize the candidate manufacturing processes, B&W conducted several vendor surveys. A general survey was sent out to seek information on vendor's capabilities to make various container sizes and configurations from the candidate alloys, and to obtain an expression of interest in the product. A survey of heat treatment facilities was conducted because it was anticipated that the size of the container might be a problem for existing vacuum or atmospheric furnaces. In addition to the above surveys, two units of B&W (Nuclear Equipment Division, and McDermott's CCC International Trading Company) who routinely purchase commercial products similar to the container, solicited budgetary quotations for container components. These vendors represented the following processes:

- Roll and Welding
- Extrusion (both forward and backward)
- Roll Extrusion
- Spinning
- Forging
- Deep Drawing
- Centrifugal Casting
- Heat Treating

All processes chosen for evaluation have been used to make container like components - similar in shape but, in some cases, smaller in size. Examples of the processes with related container components are listed below:

- Roll and Welding
  - -- Welded Body - (The "body" is an open-ended cylinder made with a longitudinal weld).
  - -- Welded Body Preform - heavy wall and short length "body" that is subsequently thinned and elongated to full length by roll extrusion.

- Extrusion
  - -- Integral Lower Unit - one end closed cylinder (ie, see schematic diagram above of possible container components).
  - -- Integral Lower Unit Preform - one end, heavy-wall, closed-cylinder that is thinned and elongated by roll extrusion.
  - -- Seamless Body - (open-ended cylinder).
  - -- Seamless Body, heavy-wall Preform - to be thinned and elongated by roll extrusion.

- Spinning
  - -- Integral Lower Unit Preform - heavy-wall, closed-end cylinder for subsequent roll extrusion.
  - -- Heads.

- Deep Drawing
  - -- Integral Lower Unit.
  - -- Integral Lower Unit Preform - heavy wall, closed-end cylinder for subsequent roll extrusion.
  - -- Two-piece Lower Unit - (2 half length, closed-end cylinders deep drawn; lower unit is made by cutting-off one end to make an upper head, and subsequently girth-welding the remaining open cylinder to the other closed-end cylinder.
  - - Heads.

- Centrifugal Casting
  - -- Seamless Body.
  - -- Seamless Body Preform - heavy-wall cylinder for subsequent roll extrusion.
  - -- Heads.

These processes can be used alone or in combination.

Overview of Evaluation Methodology

B&W selected 3 major or primary criteria to rate various manufacturing routines: 1) Performance - how will a container made by the process perform in service? The primary concern for long term storage is localized corrosion; 2) Fabricability - what is the consistency and reliability of the process in making a good product in terms of dimensions, surface finish, etc.; and 3) Cost.

Results of the Phase 1 evaluation methodology are given in Figure 2.

Phase 2

In Phase 2, fabrication trials will be conducted to produce sub-scale containers for several highly ranked processes. Evaluations of the trials will address process feasibility, limitations, and the effects of processing on material properties. The more difficult aspects of producing container parts will be identified. The size of the sub-scale mock-ups will depend on readily available materials and tooling, but every effort is being made to assure relevance to the full sized container. For both the fabrication and closure activities, emphasis will be placed on the three copper-base alloys (CDA 122, CDA 613, CDA 715), and on the high-nickel alloy, Incoloy 825.

Lower unit mock-ups will be produced by several candidate processes according to the matrix in Table 2.

Testing of the mock-ups will evaluate microstructural effects of fabrication processes, particularly in regions of geometric transition and joints, where inhomogeneities or non-uniformities are most probable. Mock-ups of the upper head will be produced by one process, to have a closure joint geometry consistent with the most current container design. Potential problems from and effects of full annealing will be assessed by heat treating trials. Preliminary process specifications will be generated. The evaluation criteria from Phase 1 will be updated and an attempt will be made to make the fabrication-process selection methodology very similar to that used by the LLNL Materials Selection activity. Input from the above tasks will then be used to rank the processes against the evaluation criteria.

Phase 3 Plans

Following a review of the Phase 2 results, detailed fabrication process specifications and drawings will be prepared. A comprehensive design review involving LLNL will be conducted prior to fabrication of the prototypes. Up to five full-sized container sets (upper and lower units) will then be produced - one for characterization testing by B&W, and the remainder for delivery to LLNL.

CLOSURE

The objectives of the Closure effort are to assess the various candidate processes for final closure of the containers, select a process and demonstrate closure for the materials of choice, and to provide detailed design information to aid in the implementation of the selected process. Important ancillary objectives are to provide input to the Fabrication activity and Inspection and Materials Selection activities.

The Closure Project is also divided into three phases. The activities in these phases are as follows:

- In Phase 1, (completed), the various candidate closure processes were assessed (on paper) and ranked with respect to their ability to produce acceptable closures for each of the candidate materials.[2]

- In Phase 2 (in progress), closures will be manufactured using the highest ranked candidate closure processes determined in Phase 1, and tested to demonstrate their properties. This phase will provide samples and data as input to the Material Selection and Inspection activities.

- In Phase 3, the optimum closure process will be demonstrated on mock-up containers of the material of choice (made using the fabrication process of choice). This demonstration will be performed remotely to simulate the conditions anticipated for the actual closures. The quality of these closures will be investigated by testing. Once an acceptable closure process has been demonstrated and approved, detailed process specifications will be generated, to be incorporated in the closure hot cell designs of the repository surface facilities.

Phase 1 Results

A state-of-the-art survey, similar to that described above for the container fabrication activity, was conducted to identify and rank candidate closure processes for each of the candidate materials. It was intended that all reasonable closure processes be considered; thus, a wide field of candidate processes had to be assessed.

To address the need for a decision-making method which is defendable, the operations research technique of defining a "decision tree" was adopted. This technique allows one to consider all of the various issues impacting the decision making process and to provide a "figure of merit" to each issue which reflects its relative importance to candidate process selection.

In making the candidate process selection, we developed a three-level decision tree with two branches: "materials" and "process." We provided figure-of-merit input to the tree based on the results of an industry-wide survey of materials and process experts, an extensive literature review, and our own in-house experience. When the decision tree was completed, we generated the necessary candidate process rankings, and then subjected the rankings (and the decision making process itself) to external technical review.

At the general process-screening level, more than 30 potential closure processes were considered to yield the following potential processes for further consideration: Gas Tungsten Arc Welding, Gas Metal Arc Welding, Flux Cored Arc Welding, Explosion Welding, Electrogas Welding, Electroslag Welding, Submerged Arc Welding, Plasma Arc Welding, Electron Beam Welding, Laser Beam Welding, Brazing, Soldering, Friction/Inertia Welding, Upset Welding, Flash Welding, Diffusion Welding, Adhesive Bonding, Mechanical Seal, Adhesive/Mechanical Seal, Mechanical/Braze Seal, Mechanical/Weld Seal.

Final Process Ranking

The final process ranking for each material was determined by comparing the outputs of the two branches of the decision tree. In most cases the processes which ranked well in terms of materials considerations also ranked well in terms of process implementation considerations. In cases where they differed, the materials considerations were given precedence because they more directly influenced the quality of the closure. In all cases, common engineering sense was also applied at this point to confirm that the decision tree output was valid. Table 3 provides a list of the most highly ranked candidate closure processes along with their relative advantages and disadvantages.

Phase 2

In Phase 2, weld test stations will be set-up to prepare for closure weld manufacturing trials of the most promising processes (as determined in Phase 1) for each of the candidate metals as listed in Table 4.

The qualities of closures produced in sub-scale cylinders will be demonstrated for the matrix shown above. Once reasonable welding parameters have been established, welding procedures will be documented, and tolerance testing will be performed to verify the process limitations. If difficulties in weldability are encountered, investigations will be done to determine if composition limitations are necessary for the particular candidate material. Testing will include metallography, residual stress determination, and mechanical testing. Preliminary system specifications for each closure process (EBW, FRW, PAW) will be written to allow optimum set-up of the process chosen for prototype demonstration.

Phase 3 Plans

Once an acceptable container material is chosen, the optimum closure process for containers of that material will be selected based on information gathered in Phase 2. Then the optimum closure process will be demonstrated by performance of a prototype closure using container lower units and heads developed in the fabrication activity. This phase will culminate with generation of final closure system specifications.

REFERENCES

1. H.A. Domian, et al., Fabrication Development for High-Level Nuclear Waste Containers for the Tuff Repository, Phase I Final Report, UCRL 15965, Lawrence Livermore National Laboratory, Livermore, CA, 1989.

2. E.S. Robitz, et al., Closure Development for High-Level Nuclear Waste Containers for the Tuff Repository, Phase I Final Report, UCRL 15964, Lawrence Livermore National Laboratory, Livermore, CA, 1989.

TABLE 1
AUSTENITIC AND COPPER-BASE ALLOY COMPOSITIONS

Austenitic Alloy Compositions								
Alloy	C (max)	Mn (max)	P (max)	S (max)	Si (max)	Cr (range)	Ni (range)	Other Elements
AISI 304L	0.030	2.00	0.045	0.030	1.00	18.00-20.00	8.00-12.00	N: 0.10 max
AISI 316L	0.030	2.00	0.045	0.030	1.00	16.00-18.00	10.00-14.00	Mo: 2.00-3.00 N: 0.10 max
Incoloy 825	0.05	1.0	Not Spec.	0.03	0.5	19.5-23.5	38.00-46.0	Mo: 2.5-3.5 Ti: 0.6-1.2 Cu: 1.5-3.0 Al: 0.2 max

Copper-base Alloy Compositions								
Alloy	Cu	Fe	Fo	Sn	Al	Mn	Ni	Zn
CDA 102	99.95 (min)	--	--	--	--	--	--	--
CDA 613	92.7 (nom)	3.5 (max)	--	0.2-0.5	6.0-8.0	0.5 (max)	0.5	--
CDA 715	69.5 (nom)	0.4-0.7	0.5 (max)	--	--	1.0 (max)	29.0-33.0	1.0 (max)

TABLE 2
CANDIDATE PROCESSES

Fabrication Process	Materials			
	IN825	CDA102	CDA715	CDA613
A. Roll & Welding	X	X	X	
B. Roll & Welding plus Roll Extrusion	X	X	X	
C. Extrusion plus Roll Extrusion	X			
D. Centrifugal Casting plus Roll Extrusion				X

TABLE 3
Ranking of Closure Processes for HLW Containers for the Tuff Repository

Processes	Advantages	Disadvantages
Friction Welding (FRW)	Small HAZ, (heat affected zone), small .usion zone, minimum risk for second phases, low residual stress, low distortion, good inspectability, ease of in-cell maintenance, low frequency of maintenance, fast weid speed, few welding variables to monitor.	Inside diameter (ID) and outside diameter (OD) scarf (requires OD machining) massive equipment, expensive equipment, repair difficult (full reweld or 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.	Poor crown surface condition and defects in "spike" area, high-vacuum requirements, expensive equipment, 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, possible 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, possible repair welding with same equipment, easier in-cell maintenance, and 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 inspectibility, higher possibility for second phases, in-cell guidance (including seam-tracking) and real-time controls may be needed.

TABLE 4
CANDIDATE METALS

Container Material				
Closure Process	CDA 122	CDA 613	CDA 715	Alloy 825
Electron Beam Welding (EBW)	X			
Friction Welding (FRW)		X	X	X
Plasma Arc Welding (PAW)			X	X

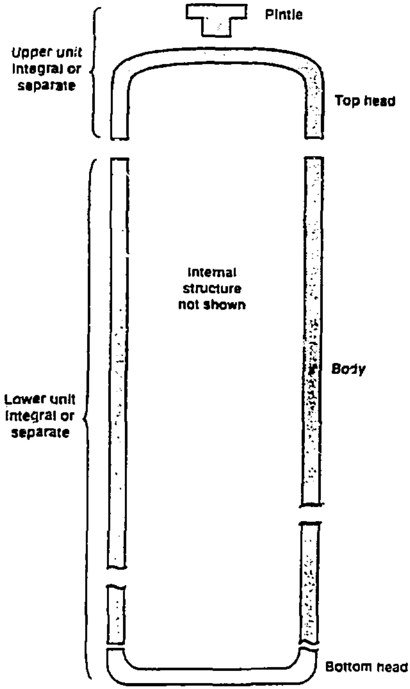

FIGURE 1 - Possible Container Components

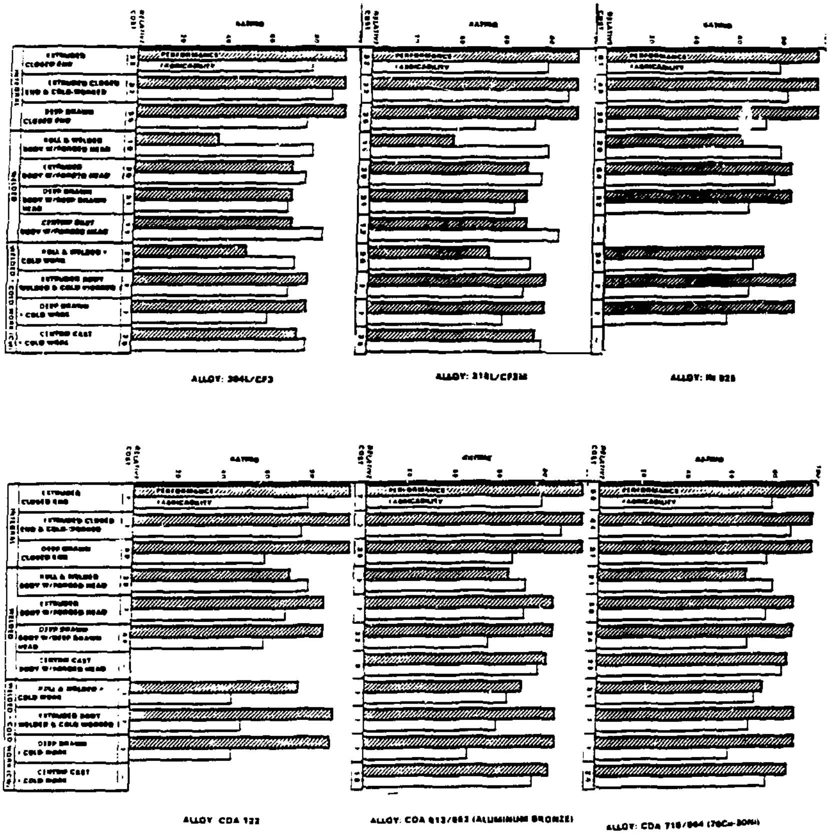

FIGURE 2 - Ranking of Fabrication Processes for HLW containers for the Tuff Repository