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INTERIM REPORT
SEALED STORAGE CASK CONCEPT
CASK CLOSURE CONCEPT EVALUATION

E. L. Moore and W. H. O'Brien

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INTERIM REPORT
SEALED STORAGE CASK CONCEPT
CASK CLOSURE CONCEPT EVALUATION

1.0 INTRODUCTION

One concept of interim storage (described in previous report) under evaluation by ERDA for storage of commercial high level waste

~~The Retrievable Surface Storage Facility (RSSF)~~ would utilize the Sealed Storage Cask Concept (SSCC) to safely store commercially generated high-level radioactive waste for up to 100 years. The stainless steel canister containing the solidified high-level waste would be inspected upon receipt at the RSSF and substandard canisters would be overpacked in thin-wall stainless steel containers, or decontaminated, as the situation dictates. The waste would then be sealed in a heavy-wall (2-inch-thick reference design), low carbon steel storage cask. The storage cask in turn would be placed in a concrete shield and transported to a storage area where the storage unit, consisting of the waste, canister, storage cask, and concrete shield would be cooled by natural convection. The air would enter through ports at the bottom of the shield, flow up through the annulus between the storage cask and the concrete shield, and exit through ports at the top.

It is necessary that the storage cask be structurally sound and provide an adequate barrier between the waste material and the environment should the inside waste canister fail. The storage cask closure configuration and the ability to nondestructively examine the weld area to ensure structural soundness are of the utmost importance.

The objective of this report is to summarize the studies performed for the purpose of evaluating several candidate storage cask closure configurations (concepts). Where needed, portions of the program were subcontracted to obtain specific expertise.

These studies were documented and are included in the Appendix of this report.

2.0 SUMMARY

A program was conducted to evaluate four candidate storage cask closure configurations. Four major areas were evaluated to provide a basis for selection of an acceptable closure(s). These were: (1) weldability, (2) suitability of available nondestructive examination methods for determining weld soundness, (3) closure configuration structural soundness, and (4) economics.

A relative ranking of each closure configuration was made using the study results. The corner weld configuration was ranked as the most desirable, followed by the threaded plug and seal weld, the circumferential butt-weld and the multiplate in order of decreasing desirability. This report recommends that the structural analysis be continued on the first and second ranked closures to provide a quantitative evaluation capability of their structural integrity and that ultrasonic examination of the corner weld closure configuration be demonstrated. A remote demonstration of welding and nondestructive examination capability of the corner weld is also recommended.

3.0 PROGRAM

3.1 Design Basis

The design of the storage cask and closure is not firm due to possible changes in waste form or storage philosophy; therefore, the storage cask closures proposed and evaluated in this report are also subject to change as the design matures.

The storage cask is, however, to be designed using ASME Boiler and Pressure Vessel Code, Section III, as a guide (i.e., the storage cask closure configuration need not meet the code).⁽¹⁾

With this as part of the design basis, the storage cask closure evaluation study was conducted in which four candidate storage cask closure configurations were evaluated. Should code needs change at a later date, one closure configuration was chosen out of the four for evaluation that would meet the requirements of Section III or Section VIII of the ASME Boiler and Pressure Vessel Code: the full penetration circumferential butt-weld. This configuration was known to be the most expensive so alternatives (the multiplate, the threaded plug and seal weld and the corner weld) were evaluated in an attempt to find suitable and more economical configurations.

Additional design bases assumed in selecting the four candidate storage cask closure configurations for evaluation were a 100-year design life and an average corrosion allowance of 0.003 inches per year. A 2-inch wall for the storage cask was also assumed in accordance with the original reference design which allowed for external loading. No temperature or internal pressure was assumed.

3.2 Welding Evaluation

Three candidate storage cask closure configurations were evaluated: the full penetration circumferential butt-weld, the multiplate, and the threaded plug and seal weld, depicted in Figures 1 through 3. Welding of the alternate full penetration weld, the corner weld (Figure 4), was not demonstrated since the techniques for

(1) ARH-LD-140 (unclassified), June 1976, "Retrievable Surface Storage Facility, Conceptual System Design Description," Section 4.6.2.b.

performing this weld do not differ significantly from the full penetration circumferential butt-weld.

The welding evaluation was performed using ring sections cut from a length of heavy-wall carbon steel pipe and machined to form the appropriate closure configuration. The welding procedures and evaluation results are contained in References 1 and 2.

The full penetration circumferential butt-weld configuration (Figure 1) selected for evaluation incorporated a backup ring which would remain in place after closure of the storage cask. Full weld penetration was demonstrated on the test assembly by maintaining a root gap between the mating machined surfaces. This was accomplished by means of the backing ring acting as a locating spacer in addition to providing control of inner bead contour.

The overall weld time and the potential for downtime, weld rework, etc., are greatest for this closure concept in view of the more complex operation required under remote operating conditions.

The multiplate closure configuration (Figure 2) is essentially four one-half-inch plates, individually fillet welded one on top of the other. Although this closure configuration does not conform to the ASME Boiler and Pressure Vessel requirements, it does possess some desirable features. The ability to visually inspect 100 percent of each individual fillet weld as the weld is made is desirable. In addition, the feature of individual welds being independent of one another provides separable barriers to the environment with a very low probability

of the occurrence of a leak path from the inside to the outside of the storage cask. Welding of a prototype test assembly was successfully demonstrated.

The weldability of the threaded plug and seal weld closure configuration (Figure 3) was demonstrated. This closure configuration has the lowest potential for weld repair, etc., since the major portion of the joint (threaded interface) is prepared outside the hot cell by conventional machining operation. Completion of the seal weld operation requires the shortest welding time of the four cask closure configurations and hence is least likely to require downtime for weld repair.

Welding of a test prototype of the alternate corner weld configuration (Figure 4) was not conducted because the welding variables would be essentially the same as for the full penetration circumferential butt-weld although slightly less time would be required.

Evaluating the four candidate closure configurations solely on the basis of required welding time and potential for downtime and rework would rank them in the following order of decreasing desirability: the threaded plug and seal weld, the multiplate, the corner weld, and the full penetration circumferential butt-weld.

3.3 NONDESTRUCTIVE EXAMINATION

Although compliance with the ASME Boiler and Pressure Vessel Code, with regard to the quality of the storage cask,

was not mandatory for this evaluation, the feasibility of radiographic examination of the full penetration circumferential butt-weld was investigated. The results of this investigation are reported in detail in Appendix A. The Battelle-Northwest Laboratory (BNW) study, as reported, established essentially that the use of the radiographic method of non-destructive testing the full penetration circumferential butt-weld with the backing ring in place is not adequately effective and so it is not recommended. Also, the radiation background and elevated temperature of the storage cask would make radiographic examination ineffective.

Should compliance with the ASME Boiler and Pressure Vessel Code become mandatory for fabrication of the storage cask, the results of the above evaluation permit the use of Code Case 1444 to allow use of ultrasonic examination in lieu of radiographic examination. The feasibility of using ultrasonic examination to verify the quality of the full penetration circumferential butt-weld, the threaded plug and seal weld and the multiplate closures were studied by BNW. The results of this study are reported in detail in Appendix A.

In conducting the ultrasonic test studies, BNW imposed the following considerations to establish the general test requirements and capabilities.

1. Ultrasonic tests must be capable of detecting and locating cracks to a predetermined dimension, location, and orientation.
2. All tests by design are to be redundant where possible to enhance test confidence level.

3. Thermal surface temperatures up to 500° F are anticipated for worst case coupling.
4. Gamma radiation intensities of up to 10^5 R/hr are anticipated.
5. The test developed must have the provisions for remote handling and test manipulation.
6. If possible, the weld examination should be performed to an acceptable level consistent with the ASME Boiler and Pressure Vessel Code.

The general conclusion of this work conducted by BNW was that these requirements and capabilities could be met by the ultrasonic test method of examination. Based on the relative difficulties of examining each closure to ensure a sound joint, it is possible to rank the closures. Since only the top plate of the multiplate closure can be ultrasonically examined, it would be ranked as least desirable. Because of the position of the weld in the threaded plug and seal weld closure relative to the outside edge of the closure, the weld bead would probably have to be ground flat to accomplish an adequate ultrasonic examination, which would rank this closure next to the multiplate. The backing ring in the full penetration circumferential butt-weld would contribute additional reflective surfaces which could slightly complicate interpretation of the ultrasonic examination. This would rank this joint next to the corner weld, which would be the "cleanest" or most readily examined; however, verification of this remains to be done.

Provisions for loading the cask with a tracer gas, for subsequent leak testing as a primary nondestructive test function were investigated by Atlantic Richfield Hanford Company. As noted in Figure 1, a porous metal disc containing helium was considered for placement inside the storage cask prior to welding. By performing a post closure leak detection procedure, the absence of helium detection would ensure leak tightness of the closure. In later consideration of the potential cost to manufacture the disc for use in a storage container of this size and the additional handling operations required in its placement in the container, an alternate method was considered in lieu of using the porous disc. The trace gas would be placed in the cask before welding the initial root weld bead by inserting a long flexible steel tube into the pressure relief vent holes provided, as shown in Figures 5 through 8. A complete description of the method and details of the loading operation are discussed in reference 2 of this report.

3.4 STRUCTURAL INTEGRITY

The relative integrity of the four candidate closure concepts for the storage cask was evaluated by the Structures and Mechanics Section of BNW. The work is reported in Appendix B of this report. Conditions chosen to evaluate relative threats to integrity were: residual welding stresses, handling by a top bail, accidental dropping on the closure head, and initiation and propagation of a crack at a weld defect due to thermal stress fluctuations during long-term field storage. A rating system was devised to judge relative threats to loss of integrity under these four conditions.

The potential influence of residual welding stresses on cask integrity was of interest. Only the top of the cask was modeled using finite element analysis. As would be expected, the amount of distortion due to residual welding stresses increased as the amount of weld metal deposited increased. However, this result was not useful in assessing differences in threats to structural integrity between the closure concepts.

Lifting of the storage cask by a bail attached at the center of the top was evaluated for its effect on structural integrity. The magnitude of the stresses at various points in the top of the cask was determined by computer analysis by imposing a lifting force at the center of each closure configuration. The magnitude and location of the stresses were used to rate the closure concepts. The full penetration circumferential butt-weld closure was rated best and the multiplate closure was rated as the worst.

The end drop analysis on an unyielding surface, conducted by finite element modeling, defined regions of the closure configurations which experience large stress values. The results showed that the multiplate closure is much more susceptible to tension or shear failure and was rated as least acceptable. The remaining closure configurations were rated equal.

The relative resistance to crack propagation of each closure configuration under thermal transient conditions was evaluated. For this evaluation, the case of a sustained blocked air flow leading to a temperature excursion, followed by a sudden unblocked state, was considered. The sudden cooling would result in a thermal transient, which would cause stressing of the closure weld, and would act as the driving force for the activation and propagation of an assumed defect in the weld region.

The analysis showed that the circumferential full-penetration, butt-weld would resist crack propagation through the wall and thus it was rated as the best. In decreasing order of resistance to crack propagation would be the corner weld, the threaded plug and seal weld, and the multiplate closure configurations.

3.5 ECONOMICS AND HOT CELL OPERATION

For the economic evaluation, the operating and capital cost were compared for 3100 storage casks for the first ten years of storage. The results appear in Appendix C. Also, a commentary on the impact of the closure concepts on hot cell operation is included in Appendix D. The multiplate closure rated as the most economical to perform and the full-penetration circumferential butt-weld the most expensive. Considering the difficulties of working in a hot cell, the most desirable closure would be one performed in the vertical position with the least amount of welding time which would be the threaded plug and seal weld. The least desirable would be the full penetration circumferential butt-weld which would require welding in the horizontal position and require the most weld deposit.

The ease of decasking, should it become necessary, was also considered. Assuming that this would be simply related to the amount of weld metal to be removed, the full-penetration circumferential butt-weld would be the most difficult and the threaded plug and seal weld the least difficult.

3.6 CLOSURE CONCEPT SELECTION METHOD

A relative ranking of the four closure configurations was made at the end of sections 3.2 through 3.5 and appears in tabular form in Table I. Each closure configuration is given a numerical value or rating of 1 through 4, and appears in parenthesis in the table. The highest number demotes the least desirable closure. The relative importance of each closure selection criteria (sections 3.2 through 3.5) is denoted by a weighting factor the overall ranking of each cask closure configuration was obtained by multiplying these two numbers.

3.7 CONCLUSIONS AND RECOMMENDATIONS

The corner weld closure configuration was not as fully evaluated in this study as were the remaining closure configurations since it was selected as an alternate later in the program. However, based on studies performed, it is currently rated the best choice for use in the RSSF but the rating will need to be verified by further analyses. The threaded plug and seal weld, the full penetration circumferential butt-weld, and the multiplate closure are recommended in decreasing order of desirability.

It is recommended that a helium tracer gas be used for post closure leak detection. The introduction of the gas would be through a flexible tube inserted into the pressure relief vent holes in the weld joint and withdrawn prior to welding the root pass. The following recommendations are made to further the work:

- Continue the structural analysis on the corner weld and on the threaded plug and seal weld, as an alternate closure configuration.

to provide a quantitative evaluation of their structural integrity.

- Demonstrate in the laboratory the adequacy of ultrasonic examination for verification of the integrity of the corner weld.
- Conduct a demonstration of the remote welding and ultrasonic examination of the corner weld closure configuration.
- Carefully analyzed and possibly repeat this study after the design criteria for the storage cask have been finalized. Changes in code needs, definitive waste characterization, or relative changes in weight between safety criteria and economic criteria might make significant changes in the relative standing of the weld closures.

4.0 REFERENCES

- (1) ARH-CD-363 (unclassified), June 24, 1975, W. H. O'Brien, "Interim Report No.1, Retrievable Surface Storage Facility Welding and Nondestructive Test Development"
 - (2) ARH-CD-363 2 (unclassified), June 24, 1975, W. H. O'Brien, "Interim Report No. 2, Retrievable Surface Storage Facility Welding and Nondestructive Test Development"
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TABLE I
SUMMARY OF RELATIVE RANKING

	Circumferential Butt-Joint	Corner Weld Joint	Multi- Plate	Threaded Plug/Seal Weld
Handling	(4)	(1)	(3)	(2)
Factor = 1*	[4]	[1]	[3]	[2]
Welding	(4)	(3)	(2)	(1)
Factor = 3*	[12]	[9]	[6]	[3]
Nondestructive Testing	(2)	(1)	(4)	(3)
Factor = 3*	[6]	[3]	[12]	[9]
Structural Integrity	(1)	(2)	(4)	(3)
Factor = 2*	[2]	[4]	[8]	[6]
Economics	(4)	(1)	(2)	(3)
Factor = 1*	[4]	[3]	[2]	[3]
Decasking	(4)	(3)	(2)	(1)
Factor = 1*	[4]	[3]	[2]	[1]
Overall Rating	[32]	[21]	[33]	[24]

* Weighting factor

() Relative rating of four closure configurations

[] Absolute rating = Weighting factor times relative rating

FIGURE 1

FULL PENETRATION CIRCUMFERENTIAL BUTT-WELD
CLOSURE WITH HELIUM STORAGE DISC

FIGURE 2

MULTIPLATE CLOSURE WITH HELIUM STORAGE DISC

FIGURE 3

THREADED PLUG AND SEAL WELD CLOSURE WITH HELIUM STORAGE DISC

FIGURE 4

CORNER WELD CLOSURE WITH HELIUM STORAGE DISC

FIGURE 5

FULL PENETRATION CIRCUMFERENTIAL BUTT-WELD
CLOSURE WITH HELIUM FILL VENT

FIGURE 6

MULTIPLATE CLOSURE WITH HELIUM FILL VENT

FIGURE 7

THREADED PLUG AND SEAL WELD CLOSURE WITH HELIUM FILL VENT

FIGURE 8

CORNER WELD CLOSURE WITH HELIUM FILL VENT

APPENDIX A

STUDY OF NONDESTRUCTIVE EVALUATION TECHNIQUES
FOR INSPECTING THREE WELD CLOSURES PROPOSED
FOR RSSF WASTE STORAGE CASK

by

Nondestructive Testing Section
Physics and Instrumentation Department

Battelle-Northwest
Richland, Washington 99352

for

Atlantic Richfield Hanford Company
Richland, Washington

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STUDY OF NONDESTRUCTIVE EVALUATION TECHNIQUES
FOR INSPECTING THREE WELD CLOSURES PROPOSED
FOR RSSF WASTE STORAGE CASK

INTRODUCTION

For the past eighteen months Battelle-Northwest has worked with the Atlantic Richfield Hanford Company staff to develop nondestructive testing techniques that could be used for inspecting the weld closure of the three weld configurations being studied by ARHCO for sealing the high level waste storage casks designed for the RSSF program. This effort has included a review of the weld configurations to study practical means for applying meaningful nondestructive tests that could be used as part of a quality control program for verifying the weld integrity. We have also reviewed suggestions for changes in weld design to accommodate the nondestructive testing program and enhance the inspectability of the specific weld configurations. The study program has included a review of appropriate ASME Code requirements to assess the potential for complying with a standard code. Under ASME Codes radiographic examination would be required for all welds proposed. Although compliance with ASME is not mandatory for the cask weld closures, Battelle's study, in compliance with ARHCO's request, has included application of radiographic, ultrasonic, magnetic particle and penetrant test methods.

The three weld closures studied included:

1. The full penetration butt joint closure weld
2. The multi-plate fillet weld closure
3. The threaded plug and seal closure weld configuration.

In the final application any test method developed must meet environmental conditions which include remote examination of a welded structure which has an ambient surface temperature of 400 - 500⁰ F and which has gamma radiation levels estimated at 5×10^5 R/hr. A paper review of the weld configuration by the Battelle staff indicated the ultrasonic method would

have the highest probability of providing a valid weld test. While special techniques would have to be developed for each weld style, the potential for developing a successful test was high. Since the radiographic test method has some potential for examination of the full penetration butt weld, a study was introduced to determine the effectiveness of radiography for this weld. Both penetrant and magnetic particle test methods, while potentially applicable, are difficult to apply and interpret under the remote and environmental conditions and cleaning procedures are extremely difficult. Neither magnetic particle or penetrant testing was considered beyond the paper study review.

Following the initial studies Battelle performed a series of research studies and laboratory tests to verify the capability and limits of inspection for the ultrasonic and radiographic test methods. Battelle's study has established that ultrasonic test techniques can be used to verify the quality of weld for any of the welds proposed for closure of the waste storage casks. The study has also shown that radiographic techniques are not effective and are not recommended for any of the presently proposed welds. This report describes the details of ultrasonic and radiographic programs. In developing the test criteria and techniques, the nondestructive testing staff of Battelle has worked closely with Mr. W.E. Anderson, also of the Battelle staff, who has developed the fracture mechanics analysis for the three weld configurations.

Note: ARHCO has already established that a helium leak test method will be applied for the closure weld as one primary test of weld integrity.

ULTRASONIC PROGRAM REVIEW

Ultrasonic laboratory test development and evaluation work^(1,2,3,4,5) was initiated in June of 1975 to evaluate three types of closure weld assemblies proposed for the Retrievable Surface Storage Facility (RSSF). This section covers the ultrasonic test development work conducted on weld assembly No. 1 (Full Penetration Butt Joint Closure Weld, weld assembly No. 2 (Multi-Plate Fillet Closure Weld), and weld assembly No. 3 (Threaded Plug and Seal Closure Weld).

The study was initiated to establish the value of using ultrasonic technology as a means for testing seal weld integrity on RSSF vessel weld assemblies 1, 2 and 3. The ultrasonic tests have established the sensitivity of the method for detecting simulated cracks made by Electrospark Discharge Machining (EDM). The specific size, location and orientation of the simulated cracks or notches used as ultrasonic references were established from fracture analysis^(6,7) for each weld configuration. In the tests described in the report, the ultrasonic signal from the reference notches provided a minimum of 2 to 1 signal to background or artifact noise response for predicted "worst case" crack orientation and location.

EDM was used to fabricate notches of specific dimension and orientation in the weld penetration section of the weld assembly. The fracture mechanics study made by W.E. Anderson, Battelle-Northwest, was used to establish the criteria for the detection limits required for the ultrasonic tests. A report⁽⁶⁾ on this subject is being issued simultaneously with this report. The ultrasonic tests were performed at room temperature and at temperatures as high as 500⁰ F. Our results indicate that all tests recommended can be designed for remote evaluation of the three types of weld assemblies in the anticipated temperature and radiation environment of the storage area in the RSSF.

TEST REQUIREMENTS

The following considerations are made to establish the general ultrasonic weld test requirements and capabilities:

1. Ultrasonic tests must be capable of detecting and locating cracks to a predetermined dimension, location and orientation.
2. All tests by design are to be redundant where possible to enhance test confidence level.
3. Thermal surface temperatures up to 500⁰ F are anticipated for worst case coupling.
4. Gamma radiation intensities of up to 5×10^5 R/hr are anticipated.

5. The test developed must have the capability for remote handling and test manipulation.
6. When and if appropriate, the weld examination should be performed to an acceptance level consistent with the ASME Boiler and Pressure Vessel Code.

WELD SAMPLES

WELD ASSEMBLY NO. 1

Figure 1 shows sections of the OD surface notch sample (top) and the ID surface notch sample (bottom) for the Full Penetration Butt Joint Closure Weld subsequently designated weld assembly No. 1. A 45° shear coupling wedge and test transducer is shown mounted on the OD surface notch sample.

Notch Criteria, Weld Assembly No. 1

EDM notches were fabricated in weld assembly No. 1 to specific dimensions and orientation in the ID and OD weld penetration zone. Dimensions and "worst case" orientation were referenced to fracture mechanics analysis recommendations.

The fracture analysis established that a zero degree crack 0.5 in. (12.7 mm) deep by 1.0 in. (25.4 mm) represented a "critical crack" dimension for the full penetration butt weld closure. The cask material in the weld is near 2.0 in. thick. The ultrasonic tests were based on the "critical crack dimensions" and notches both larger and smaller were EDM machined into the weld zone to provide a representative reflector. The notch length for this case is a minimum of two times greater than the depth or 1.0 in. (25.4 mm). Notch orientation of up to (+) 30° off weld center line is included per fracture mechanics model crack orientation predictions. A total of 11 notches were fabricated in weld assembly no. 1. The notch locations and orientations are shown in Figure 2. The notch identification numbers, depth dimension and orientation are given in Figure 4. The notches range in depth from 0.25 in. (6.3 mm) by 0.5 in. (12.7 mm) long to 0.75 in. (19 mm) deep by 1.5 in. (38.1 mm) long. The total weld thickness is near

FIGURE 1. Sectioned Samples from Full Penetration Butt Closure Weld, Assembly No. 1, Top, OD Notch Standards and Bottom, ID Notch Standards

FIGURE 2. Notch Orientations for Weld Assembly No. 1, (a) I.D. Surface Notches and (b) O.D. Surface Notches (n_2 and n_3 Show Worst Case Notch Orientation)

$$\theta_1 = \theta_2 = \text{TEST WEDGE COMPLEMENTARY ANGLE} = 53^\circ$$

$$\theta_3 = \text{I.D. SURFACE TEST} = \text{O.D. SURFACE TEST} = 45^\circ \text{ SHEAR}$$

FIGURE 3. Weld Assembly No. 1 Showing Optimum UT Propagation Paths for I.D. and O.D. Surface Test

I. D. SURFACE			
NOTCH NUMBER	DEPTH, in.	LENGTH, in.	ORIENTATION
1	0.50	0.5	0°
2	0.50	0.5	+30°
2	0.50	0.5	-30°
*3	0.50	1.0	0°
4	0.75	1.0	0°
5	0.25	0.5	0°

NOTE #1:

BACKUP PLATE 1/8" RELIEF
STEP SIGNAL AT PEAK
AMPLITUDE

O. D. SURFACE			
NOTCH NUMBER	DEPTH, in.	LENGTH, in.	ORIENTATION
1	0.50	0.5	0°
2	0.50	0.5	+30°
3	0.50	0.5	-30°
*4	0.50	1.0	0°
5	0.75	1.5	0°
6	0.25	0.5	0°

*INDICATES CRITICAL CRACK DIMENSION
AND ORIENTATION

FIGURE 4. UT Area-Amplitude Response to EDM Notches, Weld Assembly No. 1, Showing Proportionality to Anticipated Worst Case Notch Orientation, (a) I.D. Notch Response and (b) O.D. Notch Response

2.0 in. (50 mm) with a 60° included weld penetration angle on the ID surface and a 30° included weld penetration angle on the OD surface. Weld assembly No. 1 dimensions are shown in Figure 3.

Test Criteria - Weld Assembly No. 1

The ultrasonic tests evaluated for notch area-amplitude response employed angle beam shear wave propagation at 45° to OD normal surface along the axis of the weld assembly shown in Figure 3. A total of six shear wave beams were evaluated, including:

1. Propagation angle 45° , 0.5 in. beam dia., 5 MHz
2. Propagation angle 60° , 0.5 in. beam dia., 5 MHz
3. Propagation angle 45° , 0.5 in. beam dia., 2.25 MHz
4. Propagation angle 60° , 0.5 in. beam dia., 2.25 MHz
5. Propagation angle 45° , 0.75 in. x 1.0 in. 2.25 MHz
6. Propagation angle 45° , 1.0 x 0.75 in., 2.25 MHz

Test Results, Weld Assembly No. 1

Two separate tests are required for UT on weld assembly No. 1. Test No. 1 is used to test the weld penetration volume extending from the ID surface backup plate weld penetration to approximately 1.0 in. into the weld. Test No. 1 is redundant to test No. 2 in that fracture mechanics studies indicate that failure should occur at the OD surface of the structure. The propagation path and point of incidence are shown in Figure 3. Test No. 2 is used to test the OD surface weld penetration to approximately 1.0 in. deep (1/2 wall thickness).

The test demonstrating the best proportionality to transducer notch dimensions for the ID surface notch test was the shear 45° angle beam, with a 0.75 in. by 1.0 in. beam operated at a frequency of 2.25 MHz. The area-amplitude response is shown in Figure 4. A continuous signal is obtained from the backup plate relief step which is ahead in time of the received signal wave train of any notch or weld crack generated signal. This plate relief signal can be used to continuously monitor the presence of the ID crack test and a loss of signal would indicate a laminar crack in the plate region outside the weld penetration volume, or loss of couplant.

Background noise for the ID surface test does not exceed 10% on the notch area-amplitude curve. The distance of the beam entry point can be established by moving toward the weld bead until the backup plate relief signal peaks in amplitude at about 20% scale and continue moving toward the weld bead until this signal drops to near 5% scale. The test can then be translated circumferentially around the vessel and only one rotation completes the ID surface crack test for laminar cracks, ID surface cracks, and couplant verification.

The test demonstrating the best proportionality for the OD surface notches was the 45° angle beam transducer with a 1.0 in. by 0.75 in. beam operated at 2.25 MHz. Test area-amplitude is shown in Figure 4. In application, it is anticipated that the test transducer coupling wedge assembly for the OD test can be mechanically coupled and positioned by the transducer used for the ID test. The operator would position the assemblies relative to the signal from the backup plate relief counterbore. The test, when applied in this manner, would require two test heads and a single rotation translation of the weld assembly. Best results are achieved by inspection from both sides of the weld.

Signal noise or artifact signals were noted in weld areas where a welding electrode had frozen in the crater at the termination of weld and been subsequently cut off. One location was noted to contain signal amplitudes to 10% of the amplitude shown in the OD surface notch response of Figure 4.

In summary, a two transducer test head (two transducers in tandem assembly) using high temperature coupling wedge material and a silicon base couplant gives adequate test capability for evaluating weld assembly No. 1 for cracks extending from 25 to 100% of the weld penetration thickness.

WELD ASSEMBLY NO. 2

Figure 5 (top) shows a section of the exposed surface of weld assembly No. 2, MultiPlate Fillet Closure Weld, with a guiding fixture and test transducer in place. Figure 5 (bottom) shows the cut-away plates and the location of EDM notches. The test was approached from fracture analysis in

the same fashion described for weld assembly No. 1. The stress analysis study indicated that stress cracks were likely to initiate near the root of the back surface weld bead and propagate along or parallel to the included angle boundaries of the weld penetration. Figure 6 shows the weld penetration boundary, weld sample geometry and the two preferential crack orientations for weld assembly No. 2. The included angle of the weld penetration is 75° split about normal incidence to the exposed weld bead. The n_1 and n_2 lines represent anticipated crack propagation paths.

Notch Criteria - Weld Assembly No. 2

Notches were fabricated in the cut-away weld sample, Figure 5, in the orientation shown in Figure 6. The notches were fabricated to the dimension and orientation tabulated in the legend shown in Figure 8. The choice of notch dimensions was established by the fracture analysis study.

The critical crack dimension established by the fracture analysis study is 0.062 in. (1.55 mm) deep by 0.250 in. (6.25 mm) long. The orientation used for this work is the crack oriented $(-)$ 75° off normal to the plate surfaces. This corresponds to notch orientation n_1 of Figure 6.

Five notches were fabricated by EDM and range in depth from 0.03 in. (.075 mm) to 0.15 in. (3 mm) and are all 0.25 in. (6.35 mm) long or longer.

Test Criteria - Weld Assembly No. 2

The ultrasonic tests used on weld assembly No. 2 consist of angle beam shear wave tests. A total of nine shear wave beams were evaluated including:

1. Propagation angle 64° , 0.5 in., beam diameter, 5 MHz
2. Propagation angle 64° , 0.25 in., beam diameter, 5 MHz
3. Propagation angle 64° , 0.5 in., beam diameter, 2.25 MHz
4. Propagation angle 60° , 0.25 in., beam diameter, 5 MHz
5. Propagation angle 60° , 0.5 in., beam diameter 5 MHz
6. Propagation angle 60° , 0.5 in., beam diameter 2.25 MHz
7. Propagation angle 45° , 0.25 in., beam diameter, 5 MHz
8. Propagation angle 45° , 0.5 in., beam diameter, 5 MHz
9. Propagation angle 45° , 0.5 in., beam diameter, 2.25 MHz

Each test gave unique response.

FIGURE 6. Notch Orientation, Location and Finished Sample Geometry for Weld Assembly No. 2 (n_1 and n_2 Show Worst Case Notch Orientation)

FIGURE 7. Weld Assembly No. 2 Showing Optimum UT Propagation Path

<u>NOTCH NUMBER</u>	<u>DEPTH</u>	<u>ORIENTATION</u>
1	0.030"	(-) 75°
2	0.030"	0°
*3	0.056"	(-) 75°
4	0.115"	(-) 75°
5	0.110"	0°

* INDICATES CRITICAL CRACK DIMENSION AND ORIENTATION

FIGURE 8. UT Area-Amplitude Response to EDM Notches, Weld Assembly No. 2, Showing Proportionality to Anticipated Worst Case Notch Orientation and Back Corner Surface Signal Amplitude

Test Results - Weld Assembly No. 2

The test which gave the best response proportionality to notch dimensions regardless of orientation was the 64° shear angle using a 0.5 in., 5 MHz transducer beam. Figure 7 shows the sample geometry, angle beam path and wedge coupling angle. Figure 8 shows the notch amplitude-area response, signal amplitude band from the top outside corner of the sample propagating through the weld area and the notch identification depth and orientation. The signal from the top outside corner of the weld sample constitutes a redundant test in that the signal provides both couplant verification and assurance that no crack has penetrated the fillet weld. This amplitude-area curve represents an acceptable test for closure weld integrity. The signal-to-noise for this test was better than 3 to 1 as compared to the signal amplitude received from notch No. 2 scale.

In summary, a single transducer test head using high temperature coupling wedge material and a silicon base coupling mounted in a holding and guiding fixture such as that shown in Figure 5 provides adequate test capability for evaluating weld assembly No. 2 for cracks extending from 10 to 100% of the weld penetration thickness. Continuous signals reflected from the outside corner of the structure shell are required to enhance the level of testing confidence.

WELD ASSEMBLY NO. 3

Figure 9 (top) shows the exposed surfaces of sectioned sample weld assembly No. 3, Threaded Plug and Seal Closure Weld, with a guiding fixture and test transducer in place. Figure 9 (bottom) shows the cut-away view of the threaded plug, weld area and notch location. Note that the weld bead was removed in this sample. Note: This particular weld sample was experimental and is dimensionally non-typical of the final weld design. No machining would be required to accommodate the inspection for the present weld closure design proposed for this closure.

FIGURE 9. Sectioned Samples from Threaded Plug and Seal Closure Weld, Assembly No. 3, Top, View with Translation Fixture and Transducer in Place, Bottom, Cutaway View Showing Notch Locations

Notch Criteria - Weld Assembly No. 3

The fracture mechanics analysis for weld assembly No. 3 indicated that cracks were likely to propagate in any orientation within the included angle of the weld penetration. Figure 10 shows the prepared sample geometry, weld penetration angle and the potential crack orientation angles represented by n_1 , n_2 , and n_3 .

The critical crack dimension established by the fracture analysis study is 0.062 in. (1.55 mm) deep by 0.250 in. (6.25 mm) long. The orientation of the crack used for this work is parallel to the weld center line (i.e., 0° , normal to the end cap surface) or the n_2 orientation shown in Figure 10.

Notches were fabricated in weld sample No. 3 in the orientation shown in Figure 10. The same criteria applied to weld sample No. 3 that was described in weld sample No. 1 and 2. Six notches were fabricated by EDM to the dimensions and orientation tabulated in the notch legend of Figure 12. The notches range in depth from 0.02 in. (0.5 mm) to 0.135 in. (3.5 mm) and are all 0.25 in. (6.35 mm) long or longer.

Test Criteria - Weld Assembly No. 3

The ultrasonic tests were chosen on the same basis as for weld assembly No. 1 and No. 2. Only six tests were evaluated for weld assembly No. 3, however. These tests include the following:

1. Propagation angle 60° , 0.5 in., beam diameter, 5 MHz
2. Propagation angle 60° , 0.25 in., beam diameter, 5 MHz
3. Propagation angle 60° , 0.5 in., beam diameter, 2.25 MHz
4. Propagation angle 45° , 0.25 in., beam diameter, 5 MHz
5. Propagation angle 45° , 0.5 in., beam diameter, 5 MHz
6. Propagation angle 45° , 0.5 in., beam diameter, 2.25 MHz

As in welds No. 1 and 2, each test gave unique response.

Test Results - Weld Assembly No. 3

The test which gave the best proportionality response to notch dimensions regardless of orientation was the 60° shear angle using a 0.5 in. diameter 2.25 MHz transducer. Figure 11 shows the sample geometry, angle beam path and wedge coupling angle. Figure 12 shows the notch

FIGURE 10. Notch Orientation, Location and Finished Sample Geometry for Weld Assembly No. 3 (n_1 and n_3 Worst Case Orientation for Testing)

- $\theta_1 = 60^\circ$ OFF NORMAL = METAL PATH TO PLATE SURFACE
- $\theta_2 = 48^\circ$ OFF NORMAL = LUCITE WEDGE COMPLEMENTARY COUPLING ANGLE
- $\theta_3 = 60^\circ$ = INCLUDED ANGLE OF WELD PENETRATION ABOUT NORMAL

FIGURE 11. Weld Assembly No. 3 Showing Optimum UT Propagation Path

NOTCH NUMBER	DEPTH	ORIENTATION
1	0.020"	(-) 30°
2	0.032"	(+) 30°
3	0.038"	0°
4	0.135"	0°
5	0.125"	(+) 30°
*6	0.063"	0°

*INDICATES CRITICAL CRACK DIMENSION AND ORIENTATION

FIGURE 12. UT Area-Amplitude Response to EDM Notches, Weld Assembly No. 3, to Anticipated Worst Case Notch Orientation

amplitude-area response, identification, depth and orientation. These notch data show adequate amplitude proportionality to notch area to provide an acceptable test for seal weld integrity. Signal-to-noise was better than 6 to 1 respectively for notch 1 as compared to the signal response from notch No. 1.

The weld dimension and bead were excessive in the experimental weld specimen evaluated which required removal of the weld bead to accommodate the test. In the final weld design the weld bead is narrower (e.g., 1/4 - 3/8 in.) allowing the fixture to position the transducer so the sound beam will pass through the weld zone and no post weld machining should be required.

A second test was evaluated as a backup for the shear angle beam test. This test uses a 1/2 in. diameter beam at a frequency of 5 MHz to detect the lack of penetration at the root of the weld. The transducer is located as shown in Figure 11 on the OD surface of the weld assembly and propagates a longitudinal beam at normal incidence to the weld assembly surface. Linear proportionality was obtained from the notches oriented in the vertical or center line axis of the weld penetration zone, however, orientations of $\pm 30^\circ$ were not proportionally detected. This test would be limited to lack of penetration only in the specially prepared weld root area which is a normal incident surface to the beam propagation direction. The normal incidence test constitutes a redundant test to the angle beam test in that both tests should detect root cracks or lack of penetration in the weld.

In summary, a two transducer test head (one for the shear test, one for longitudinal test) is required to provide the high confidence test level required by the fracture mechanics analysis for weld assembly No. 3. A test of this type readily detects simulated lack of penetration and all anticipated notch orientation from 5 to 100% of the bottom one-half of the weld penetration depth. The tests outlined are limited in that no couplant verification has been incorporated in either the weld crack or weld penetration tests. Level of confidence of the tests would be enhanced by the addition of auxiliary transducers designed for this purpose.

TEST CONFIDENCE LEVEL

Establishment of test confidence level is difficult as our test results are based on EDM notches instead of real cracks and our estimates are based on ultrasonic experience rather than statistical sampling. The following review outlines a best efforts estimate of NDE confidence levels for the three types of closures involved. The following considerations were included for establishing test confidence level:

- Test reproducibility
- Signal-to-noise ratios
- Crack orientation, both planes, relative to test propagation path
- Fracture mechanics predicted crack orientation deviation
- Fracture mechanics predicted notch "worst case" location, dimension, and orientation
- Use of redundant test to verify test integrity and/or to verify ultrasonic couplant between transducer and material surface
- Test instrumentation capability, dependability
- Search test sensitivity level
- Weighted test reject level
- Capability for flaw or crack evaluation after location
- Test end requirement (i.e., sealed closure welds, 100% crack penetration)
- Acceptable flaw types and dimensions

Based on the above criteria, we have established the following test confidence levels in descending order. Confidence factors include a remote test at high temperatures and include a further refinement of the weld inspection techniques described.

1. Weld Assembly No. 2, Multi-Plate Closure Weld

Note: Only the last weld (cover plate #4) of the multi-plate closure is considered in this discussion.

- A. Confidence level for detecting through plate crack with length equal to weldment - 90-95%.
- B. Confidence level for detecting crack in weldment - half through weldment and 0.25 in. length in any position between n_1 and n_2 - 85-90%.

- C. Confidence level for detecting crack size 0.062 in. (1.55 mm) deep with a length of 0.25 in. - 80-85%.

These estimates are based on the redundancy of signal information particularly on the angle beam test for the top plate surface. Under this consideration the reflection from the actual crack plus the couplant verification from the signal reflected from the corner of the shell plus the amplitude of the corner echo provide a higher confidence factor. Any dimensional change in the weld or availability of the signal from the corner reflector would substantially change the test confidence level.

2. Weld Assembly No. 1, Full Penetration Butt Closure Weld

- A. Confidence level for detecting a crack in the weld zone that exceeds 1/2 wall thickness from either ID or OD surface is estimated between 80-90%.
- B. Confidence level for detecting a critical crack size of 0.50 in. (12.5 mm) is 70-80% from either the ID or OD surface.

These estimates are again based on test redundancy and a verification signal that can be used to assure test integrity. The continuous signal reflection from the backup plate notch provides a signal that can be used to verify test integrity for the ID test. The non-specular reflection normally associated with the weld bead provides a measure of assurance for OD test integrity (not as positive as ID test). The dual beam configuration provides the coverage of both the ID and OD surfaces. In addition, the critical crack dimension (0.50 in. - 12.5 mm) is substantially larger than those for either weld configuration No. 2 or No. 3.

The lack of a secondary reflection surface (e.g., back cover of weld No. 2) reduces the confidence level of the test.

3. Weld Assembly No. 3, Threaded Plug and Seal Closure Weld

- A. Confidence level for detecting a through weld crack with a length equal to thickness of weldment - 75-80%.
- B. Confidence level for detecting a critical crack (e.g., 0.062 in. - 1.55 mm deep by 0.25 in. - 6.25 mm long) is 60-70%.

The lack of a redundant test reduces the confidence level for this weld design. We envision weld conditions and crack orientation which reduces the relationship between weld crack size and signal amplitude. The secondary test for lack of penetration by the second test at the OD provides an additional measure of test confidence. The fact that no secondary reflecting surface exists in the present design that might be used to verify couplant and test integrity influence the level of testing confidence. The addition of a second transducer on the shell side of the closure weld to record a through transmission test for providing the verification and measurement signal would substantially improve the confidence level of the ultrasonic test on the weld design. This test configuration was conceived after the evaluation phase of the program and has not been as yet evaluated.

We must emphasize that our tests have been limited to near perfect notch type ultrasonic reflectors. Real cracks present a significantly different response, however, we have factored these considerations into our estimates.

ADDITIONAL TEST EVALUATION

High temperature application of the test for the ID surface backup plate relief UT response was made on weld assembly No. 1. Figure 13 shows the weld sample supported by hot plates and the test equipment in the background. Figure 14 shows the amplitude-temperature response curve from ambient up to 500° F. A recently commercially available wedge material named Aerotharm sold by Aerotech, Inc. was evaluated for this work. This material has the lowest attenuation and least change in velocity (i.e., variation of refraction angle) of any material tested to date by the author. (This includes the commonly used Vespel material good to about 600 - 700° F.

FIGURE 13. ID Surface Notch Sample, Weld Assembly No. 1, and Test Equipment Used for Taking High Temperature and Other Data

FIGURE 14. UT Response for Weld Assembly No. 1, Backup Plate Relief Step Signal, Aerothrm Coupling Wedge, Dow-Corning Temperature Stable Silicon Grease Couplant, Surface Temperature to 500°F

Several types of high temperature couplant were used for this evaluation including glycerine, Apiezon H grease, Krautkramer Type ZG coupling paste, mylar and polyethylene sheet film, Dow-Corning 111 compound (viscous silicone lubricant) and Dow-Corning Stopcock grease (heat stable silicon lubricant). The heat stable stopcock grease provided superior coupling capabilities. It is also anticipated that low viscosity fluids such as silicon base vacuum pump lubricant or high purity peanut oil will provide coupling to 500⁰ F. Alternatives to direct high temperature wedge silicon coupling are available such as high temperature, resilient wheels which also require a wet surface to effect coupling. Figure 15 shows a simplified UT evaluation of storage cask closure welds.

RADIOGRAPHIC PROGRAM REVIEW

Three weld designs are being considered as candidate closures for the waste storage casks. While compliance with ASME Codes is not mandatory for any of the weld designs, a study program was initiated to determine if radiographic procedures as described under ASME Section V could be an effective means for establishing the integrity of the welds. Of the three welds only Weld No. 1, the full penetration butt weld, had any potential for utilization of the radiographic test method. This report describes the results of the radiographic examination performed on a sample butt weld supplied by ARHCO.

Considering the environmental and remote inspection aspects of the proposed test the initial concern was whether any film techniques could be applied. Contact with Kodak's x-ray film specialists established that a forced air cooled cassette could be developed to provide a film container and that if the exposure could be made in a short enough time period the film fog due to inherent radiation could be overcome. Calculations showed that conventional radiographic sources (e.g., 3-500 kv) would require excessive exposure times but a linear accelerator with a 5-10 MEV capacity would provide a source adequate to perform radiographic examination.

FIGURE 15. Simplified Fixturing for Implementing Remote UT on RSSF Vessels

To explore this potential Battelle shipped the specimen full penetration butt weld to Concord Naval Weapons Station in Concord, California for evaluation on their 10 MEV linear accelerator facility. A series of radiographs was made of both single and double wall exposures and the film records were returned to Battelle for analysis. Concord Naval Weapons staff set up and ran all tests on the weld specimen utilizing the best potential techniques. Procedures followed were typical for compliance with ASME Section V Code.

While the single wall tests are of academic interest in describing the sensitivity of the linear accelerator source, the final examination of any waste storage cask must be made using a double wall exposure. In double wall examinations a minimum of twice the cask wall thickness must be radiographed and the sensitivity of the test is based on this material thickness.

Appendix I shows sketches of the various radiographic setups used during the study. The weld specimen initially contained a void metal spacer designed as a permanent helium source for leak detection. Radiographs were made with and without the void metal spacer, however, as it is now determined the void metal spacer will not be utilized in this weld design. Figure 16 shows the inspection approach which might be applied to the currently proposed full penetration butt weld. The sketch shows that the source was placed at a 12° angle from the plane of the weld. This attitude provided a clear separation of both weld surfaces (top and bottom). The exposure time was timed for 650 R (several minutes) at 7.5 MEV. The test sensitivity is judged at 2-2.5% of the double wall thickness of 5 in. or .1 to .125 in.

As in all radiographic tests orientation of the defect plays a significant role. To achieve maximum sensitivity the defect must be in the plane of the x-ray beam. Fracture mechanics has established that one of the more significant critical cracks for the butt weld is a 0° crack that is 0.5 in. (12.7 mm) by 1.0 in. (25.4 mm) long. Potential crack orientation falls within a $\pm 30^{\circ}$ of the normal plane with 0° the worst case condition.

FIGURE 16. Simplified Fixturing for Implementing Radiographic Test

The quality of the radiographs received from the Concord Naval Weapons Station was excellent and clearly defined the capability of the linear accelerator systems. The 2% sensitivity indications from the 4.5 penetrameter were readily detectable. However, because of the nature of the weld the interpretation of the radiographs was quite difficult. The position of the fitup counterbore and the position of the fixed weld backup ring are overlayed on the film in several critical interpretation regions. This resulted in substantial density variations which potentially could mask actual cracks that existed in these regions. The roughness and nature of the weld crown also reduced the film interpretability. Further, the angle of examination (e.g., 12°) is not favorable for detecting cracks which do not lie along the radiographic source to film axis. While taking additional radiographs at different angles would overcome this inherent limitation and increase the probability of detecting cracks in the welds, the environmental conditions and the costs associated with the equipment, fixturing and additional radiography would be excessively high. While radiography is a technically practical method, other factors of cost, environment and test complexity establish the method as being unacceptable for this butt weld configuration.

Radiographs obtained from Concord Naval Weapons Station are available for further study by interested parties.

REPORT CONCLUSIONS

The conclusions reached by the Battelle staff are that the ultrasonic test method can be effectively used for all three weld configurations proposed. Special techniques, procedures, references, and fixtures would have to be developed but commercially available flaw detectors can be used for the test. The work in the laboratory at both room temperature and at temperatures as high as 500° F indicate that weld defects which approach a "critical crack" dimension can be reliably detected. Detection probability and testing confidence levels are highest for all inspections which incorporate a dual or validation test. The threaded plug closure weld carries the lowest test confidence and if chosen for the final closure design added research is required to develop a dual or validation test.

Present testing confidence levels are based on laboratory results from notch (near perfect) reflectors; real weld defects will have some degrading influence. The biggest single problem of ultrasonic testing relates to the selection and application of the ultrasonic couplant between the transducer head and the test surface. Further work is desired to develop techniques for demonstrating the reliability of achieving and maintaining surface wetting throughout the test cycle. The next step in the development process for implementing the ultrasonic test is to build a breadboard demonstration model which incorporates the weld configuration of the design selected for the RSSF program.

No meaningful radiographic test technique can be developed for the multi-plate fillet weld or the threaded plug and seal closures studied. The full penetration butt weld closure could be radiographed but the problems of cost and implementation of the radiographic test method in the environment makes the approach both impractical and unacceptable.

RECOMMENDATIONS

Ultrasonic test methods can provide an adequate test for each of the weld closures studied. Our recommendation is that further development of the ultrasonic test technique be initiated on the weld joint chosen for the final design of the RSSF waste cask and that a demonstration model of a test installation be fabricated and tested. The principal areas of development should be the ultrasonic couplant, ultrasonic search unit, and the test head/fixture for performing the test. Commercially available flaw detectors are adequate for the ultrasonic test instrument.

APPENDIX I

Copy of data supplied by Concord
Naval Weapons Station

SKETCH MADE BY	SKETCH NO.	N/V NO.	PAGE	DATE
SET-UP MADE BY	DATE	FILM REVIEWED BY	OF	DATE
MATERIAL	PART NAME	DWG NO.	TC	
STEEL	RADIOACTIVE MATERIAL CONTAINER			
SKETCH ORIGINALLY PREPARED FOR REVISION				

APPROVED	1.	2.
	3.	4.

VIEWS	A10°	A10°	A10°	B10°	B20°	C0°	D12°
SOURCE	X-RAY	-	-	-	-	-	-
SOURCE CURIES ORKV	2500	7500	-	-	-	-	-
MA	250MA	N/A	-	-	-	-	-
DISTANCE SOURCE TO FILM	10'	-	-	-	-	-	-
TIME	1 MIN	80R	80R	520R	-	100R	650R
MATERIAL THICKNESS RADIOGRAPHED	2 3/8	-	-	4 3/4"	-	2 1/2	5"
PENETRATOR	STL (2) 2.2	-	-	(2) 4.5	-	(2) 2.2	(2) 4.5
PEN BLOCK	IVONE	-	-	-	-	-	-
FILM SIZE	8X10	-	-	14X17	-	-	-
FILM TYPE	T/M (2) M	-	-	T/M	-	(2) M	-
SCREEN Pb BACK	030	-	-	-	-	-	-
SCREEN Pb FRONT	030	-	-	-	-	-	-
SENSITIVITY	2%	-	-	-	-	-	-

NOTE: SKETCH SHOWS FINISHED DIMENSIONS

SHOOTING SKETCH NO.

PAGE

OF

"A" 10" SINGLE WALL WITH VOID MATERIAL
"A" 20" SINGLE WALL WITH VOID MATERIAL
"A" 20" SINGLE WALL WITH VOID MATERIAL

8x10 FILM

SCALE 10

20.3435

PART SCALE 40

19x17 FLM
20.3438

1250 (REV. 1955) (7-54)

C 7.5 MEV.
SINGLE WALL
NO VOID MATERIAL.

14X17 FILM

D 12° 7.5 kV
DOUBLE WALL
w/o VOID MATERIAL

20.2428 "14x17 FILM

FORM NO. 20.2428 (7-66)

PART SCALE 4:0

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APPENDIX B

RELATIVE EVALUATION OF STRUCTURAL INTEGRITY
IN CANDIDATE CASK CLOSURES FOR THE REFERENCE
SEALED STORAGE CASK DESIGN

W. E. Anderson
R. L. England
J. R. Friley
M. Vagins

October 1975

for

ATLANTIC RICHFIELD HANFORD COMPANY

Richland, Washington

by

BATTELLE

Pacific Northwest Laboratories

Richland, Washington 99352

RELATIVE EVALUATION OF STRUCTURAL INTEGRITY
IN CANDIDATE CASK CLOSURES FOR THE REFERENCE
SEALED STORAGE CASK DESIGN

Structural integrity is one aspect of the overall evaluation of the Retrievable Surface Storage Facility (RSSF), an above-ground storage method for high-level radioactive wastes. Coupled with other estimates relating to processing, local retention and transportation, integrity valuations will assist in strategically rating this form of storage.

One scheme for above-ground storage of waste is the Sealed Storage Cask Concept (SSCC), pictured schematically in Figure 1. The waste is sealed in a canister which in turn is sealed in a cask, all of which is placed in a concrete shield and positioned in the field.

This report is concerned with the cask. It describes integrity evaluations of a reference Sealed Storage Cask (SSC). In particular, this report describes a relative evaluation of four candidate cask closure concepts: a solid head butt joint, a multi-plate, a threaded plug/seal weld and a solid head/corner weld.

Relative integrity was determined for elementary considerations of four conditions: residual welding stresses; handling by a top bale; accidental drop on the closure head; and, resistance to cracking from thermal fluctuations.

CONCLUSIONS

The multi-plate concept was most susceptible to loss of structural integrity on a relative basis and thus least desirable of the closure concepts. The threaded plug/seal weld was about half as susceptible as the multi-plate. The solid head corner weld closure was somewhat better than the threaded plug/seal weld. The solid head butt weld closure was almost four times better than the multi-plate concept, all on a relative comparison basis.

RELATIVE INTEGRITY EVALUATIONS

In the reference configuration of the RSSF, Figure 1, the Sealed Storage Cask (SSC) is shown. It is of mild steel, having two-inch thick walls; it would be closed after canister insertion with one of the candidate concepts pictures in figures 2, 3, 4, or 5.

RETRIEVABLE SURFACE STORAGE FACILITY STORAGE UNIT

Figure 1

Reference Configuration for RSSF in
BNWL-B-442

Figure 2
Solid Head/Butt Weld
Closure Concept

Figure 3
Multi-Plate
Closure Concept

BNML-B-442

Relative structural integrity was evaluated under four conditions: residual welding stresses; handling by a top bale; accidental end drop on the closure head; and, cracking from a defect due to thermal stress fluctuations caused by field storage experiences. The evaluation consisted of assigning a factor of importance to each of these conditions. Each closure was then analyzed for behavioral response to each condition. The response of each closure was rated from one to five; one being the best and five the worst.

Problems which might arise from residual welding stresses were considered important at a minimum level since stress relief could be applied if possible difficulties during storage were identified; hence the factor of unity was assigned to this condition. A unity factor was also assigned to the end drop condition. Although this seems an important problem, it is clear that if a cask dropped during handling, it would surely be cut open so that the canister could be examined. The top bale handling condition was assigned an importance of two, because the cask is not only handled during loading in the shield but during retrieval operations also.

During field storage the SCC is subjected to thermal fluctuations over its entire usage period. These fluctuations could activate crack progression from an undetected flaw at an undesirable location. A crack enlarged in this way could be considered a threat to structural integrity. Hence, resistance to cracking under field conditions is an important factor in evaluating the relative merits of the enclosure concepts. In order to judge the impact of picking an importance factor too big or too small, the actual ratings were carried out with a factor of four and also with a factor of twelve.

From each analysis, behavioral response of the closure was assigned an appropriate value. Then, for each condition, the response rating was multiplied by the importance rating of the condition. This product became the evaluation factor for the closure at that condition. A smaller product sum means a better relative rating. Results are shown

in the Summary Table, page 37.

FINITE ELEMENT MODELING

Modern computers permit modeling of structures by performing an immense number of calculations about bits of material (elements) of small, but finite size, which are shaped and joined in the form of the structure. Equations are programmed for each type of element and these are solved in a special way to determine the deformations and stresses in the material(s) comprising the structural model under the imposed constraints and loadings selected by the analyst. Properly carried out, finite element methods provide excellent forecasts of real structural behavior under these situations. The method is particularly useful for comparative evaluation of various structural designs which are intended to perform the same ultimate function.

Figure 6 shows a sketch of how the cask closure models are oriented to the entire cask and a typical finite element model. Stresses are determined for each element and may be pictorially represented by vectors drawn to scale. (A computer program, AXISØL, which is BNW's version of Wilson's method⁽¹⁾ was used for all finite element computations.)

RESIDUAL WELDING STRESSES

All closures are completed by welding. One question of interest relates to the potential influence of residual welding stresses on cask integrity. Stress relief of the weld areas might be considered if the residual stresses appeared to be any significant threat. Such action is unattractive because of complexities in remote, hot-cell operations on the one hand, and, the possibilities for unnecessarily raising the canister temperatures on the other.

Simulation of the likely residual stress patterns in each closure was conducted by assigning temperatures to selected nodal points in a finite-element model. By equilibrating to the assigned temperature net, the model exhibited stresses and distortions estimated to approximate actual behavior.

Only the top portion of the cask was modeled, see Figure 6. From the several solutions obtained by this simulation, it was apparent that

Example computer model
of top portion of cask.

Cut away view of cask top
showing general orientation
of computer models .

Dotted lines indicate
section for full length model.

Figure 6

Demonstration Sketch Showing
Computer Model Orientations

distortions were greater when the volume of weld deposit was greater.* This agreement with known behavior gave some confidence to the simulation, but wasn't clearly useful in assessing difference in structural integrity between the concepts due to the residual stresses alone.

Since the cask temperature would be several hundred degrees and since any fluctuations would tend to "work" the residually stressed region, these residual stresses would be expected to decay or be relieved over some period of time. Consequently, it would be unlikely that intentional heating of the welds to cause stress relief would prove worth the trouble. The types and sizes of defects that would be undesirable to permit in and around the weld regions are defined in the section on crack extension.

Based on the total volume of weld deposits and the distortions and stresses shown in Appendix One, the concepts were rated: solid head/butt weld as five; solid heat corner weld as five; multi-plate as four; and threaded plug/seal weld as unity.

HANDLING WITH CENTER BALE

Handling the filled cask with a center bale was the suggested method for analysis. Although a specific configuration of the bale (or bales) was not provided, relative comparisons can be made by imposing a lifting force at the center of each closure top and observing the magnitude of the resulting stresses at various points in the cask.

On an elementary basis it can be readily observed that the multi-plate design and the threaded plug/seal weld design have the least weld area to support lifting loads. However, the threaded plug has multiple thread engagements to assist in load reactions, hence it's much more resistant to actual failure than the multi-plate closure being lifted by the top plate only.

The solid head/corner weld was not modeled, but lifting loads tend to cause tension stresses on the inside of the cask where any undetected weld defects are most likely to be. This design is therefore less secure than the solid head butt weld which is the most lightly stressed of all.

*See Appendix Section One

To obtain an appreciation of the lifting load stresses (at one g) as they would be superimposed on residual welding stresses, the multi-plate and the threaded plug/seal weld computer solutions are shown in Appendix Two. Comparison with the same models shown in Appendix One (for residual welding stresses only) indicates how small the lifting load stresses would be under dead weight of the filled cask.

In the event that field exposure and thermal fluctuations were to cause cracking in the weld region of each design, it is clear that the multi-plate would again be most likely to fail during retrieval; it is therefore rated worst, at five. The solid head butt weld is best, rated at unity; and the other two designs are rated at two.

END DROP ANALYSIS

Finite element analyses for an end drop of the SSC on an unyielding surface were conducted with the computer program, AXISOL*. The solid head butt weld model employed 57 elements and 103 nodal points while the multi-plate model employed 120 elements and 221 nodal points (refer to figures 7 & 8). Effect of the canister impacting the closure was incorporated in the multi-plate model by imposing inertia forces (in terms of surface pressure) on the inner closure plate. This simulation was not imposed on the solid head because canister impact forces would be directly transmitted to ground, thus not influencing the closure/shell joint behavior to any appreciable degree.

It can be shown (see Appendix Three) that the deceleration is proportional to a constant times the square root of the drop height for a linear elastic prismatic bar. However, behavior of a cask during impact may not be linearly elastic. Actual deceleration may be modified by plastic deformation somewhere in the cask during the impact period. Therefore, a mathematical model describing impact of the cask may be nonlinear. This difficulty can be circumvented by obtaining suitable experimental data. Measurement of cask deceleration due to falling from a given height can be obtained from test.

A relevant experiment has been reported⁽²⁾. Deceleration of a GE 15/140 cask (without canister) after a 30-foot drop was measured at 275 g's. The proportionality constant is then found to be 14.5.

* See Appendix Three for explanation of the elastic-plastic treatment in AXISOL.

Figure 7
Solid Head/
Butt Weld
End-drop
Model

Figure 8
Multi-Plate
End-drop
Model

Unyielding Surface

Unyielding Surface

The modeling calculations for both closure designs were obtained for decelerations of 150 g's and 300 g's. By employing the constant of 14.5, the corresponding drop heights are 8.9 feet and 35.7 feet, respectively.

From the results of computer modeling, selected elements were found which experienced large values of maximum principal stress and maximum shear stress. These elements are shown in bold, underlined numerals on figures 9 and 10. The computed results, which include plastic deformation when appropriate, are shown in Table One.

Maximum principal stresses listed in Table One result from a calculation which involves both the hoop stresses and the bending stresses. It is only the bending action which can be visualized in study Figures 9 and 10; but since the hoop stresses also enter into the principal stress calculation, some of the listed stresses in Table One may appear out of place. However, these stresses reflect conditions at the center of the element (not on the surface) and a casual view of combined effects should be resisted.

It is apparent from the tabulation that the multi-plate design is much more susceptible to tension or shear failure than the solid head butt weld design. Although the other designs were not subjected to this modeling, they are likely to be more akin to the solid head butt weld behavior than the multi-plate.

In view of these considerations, the multi-plate was rated as five; while the other three designs were rated as unity.

FIGURE 9

SOLID HEAD MODEL SHOWING ELEMENT NUMBERS
USED IN TABLE 1

FIGURE 10

MULTI-PLATE MODEL SHOWING ELEMENT NUMBERS
USED IN TABLE 1

Clo- sure	Element Number	Deceleration					
		150 g's (Equivalent to drop height of 8.9 feet).			300 g's (Equivalent to drop height of 35.7 feet)		
		Maximum Principal Stress (psi)	Minimum Principal Stress (psi)	Maximum Shearing Stress (psi)	Maximum Principal Stress (psi)	Minimum Principal Stress (psi)	Maximum Shearing Stress (psi)
Solid Head Butt Weld	38	- 1,018	-12,570	5,778	- 2,440	-24,414	14,090
	42	713	-14,720	7,717	- 534	-28,700	14,080
	49	- 1,406	-20,440	9,518	- 3,143	-37,077	** 16,970
Multi- Plate	46	28 320	3,862	12,230	**56,130	9,827	**23,150
	51	5,196	-12,750	8,972	21,455	13,210	**17,330
	45	21,590	5,079	8,257	**60,640	14,750	** 22,940

* Deceleration consequences are shown as the maximum and minimum principal stresses and the maximum shear stress in the designated cask element; negative values indicate compression. Results are based on a yield stress of 24,500 psi; values larger than yield stress reflect plastic deformation of sufficient extent to cause the indicated stresses from bi-linear stress-strain relations where the plastic slope is 1/25 the elastic modulus.

** Shear stress above 16,000 psi or tension stresses above 50,000 psi indicate likelihood of local fracture.

TABLE ONE

STRESSES IN SELECTED ELEMENTS DUE TO END DROP

Resistance to Mechanical Crack Extensions from Thermal Stress FluctuationsAxisymmetric, Uniform-Length Model

A simple reference point for thermal stress calculations is the uniform-length/temperature gradient problem. The model is axisymmetric without any axial heat flow; that is, the so-called one-dimensional situation applies. Figure 11 shows an end-on view and its symbolic representation. Solutions for problems with no air flow are directly solved by hand iteration in a few minutes for each case, and the equations which were used for this report are given in Appendix Four. Ranges of properties needed for hand calculations are given in Table 2. In work of this type it is only necessary to use one temperature for the cask wall because its conductivity is so large compared with its thickness that little gradient occurs across it.

The strong influence of shield conductivity and emissivity coefficients on the canister temperature and the cask temperature and the shield itself are evident in the solutions, Table Two. Such results indicate that modest differences in processing or fabricating the storage system can have considerable impact on the storage environment consequences. Although not readily helpful in closure selection, this finding merits closer examination at a later time.

These preliminary hand calculations did not include heat removal by the pumped air since this more involved procedure was not judged significantly useful in making a closure selection. In Figure 12 comparisons among several temperature profiles including some from the hand calculations are presented.

In considering degrading effects from thermal stresses, one possibility is that of very slow "cycling" from one temperature to another, caused by changes of emissivity factor with age. This process could be complicated by flaking or spalling of the surface which again changes to a "new" state which could then "age". Should this turn out to be a credible situation, some effort would be desirable on evaluating the thermal consequences if the changes were local, not general. This topic isn't pursued further in this report.

FIGURE 11

SYMBOLIC REPRESENTATION OF HEAT FLOW

(For Steady-State, Blocked-Flow, Hand Calculations)

TABLE TWO

FACTORS FOR STEADY-STATE, BLOCKED-FLOW, HAND CALCULATIONS

(See Appendix Four)

**Cases shown in Figure 12

Case No.		Factor Notation														
		h_{air}	ϵ_{so}	T_{amb}	T_{so}	T_{si}	h_{cs}	ϵ_{si}	ϵ_{csko}	T_{csk}	h_{cc}	ϵ_{cski}	ϵ_{can}	T_{can}	K_s	ϵ_{sky}
***	1	.61	.6	70°F	155°F	1316°F	.29	.90	.85	1339°F	.29	.85	.18	1472°F	.54	1.0
	2	.61	.7	70°F	150°F	568°F	.29	.70	.60	715°F	.29	.60	.45	922°F	1.5	1.0
	3	10.	.85	-20°F	-9°F	409°F	.29	.85	.85	559°F	.29	.85	.45	798°F	1.5	1.0
***	4	.61	.6	120°F	195°F	1449°F	.29	.60	.30	1503°F	.29	.30	.18	1646°F	.5	1.0
	5	.61	.8	70°F	144°F	1040°F	.29	.72	.80	1086°F	.29	.72	.55	1172°F	.7	1.0
***	ARHCO	.25	.7	70°F	-	-	-	.7	.6	-	-	.6	.45	-	.5	-

FIGURE 12

TEMPERATURE PROFILES - COMPARISON OF SELECTED CASES

The present value of the blocked-flow calculations is that they can provide a starting point from which sudden cooling can occur when the blockage is removed. Sudden cooling results in a thermal transient which can cause stressing of the closure weld, consequently, the transient consideration provides one means of comparing the resistance to cracking developed by each of the closure concepts. The next step in closure evaluation is, therefore, to determine the relative magnitude of this kind of thermal stressing.

Axisymmetric Thermal Transients

Generally, diurnal and annual environmental fluctuations would be tempered by the massive shield before interacting directly with the cask. These sources of temperature changes are nominally slow-cycling; about 10^5 sec/cycle to about 3×10^7 sec/cycle. A spectrum of thermal loads resulting from these fluctuations could be developed from historical records; event probabilities could also be developed from such data.

For purposes of preliminary evaluation, only one event has been considered; a sustained air blockage followed by a sudden unblocked state which is simulated in the extreme by letting the hot cask lose heat to a cold, black, night sky (i.e., with no shield)*. Thermal transients resulting from the sudden removal of the blockage have been taken as the driving forces threatening cask integrity through activation of assumed defects in the worst location in each closure concept.

Blocked-flow, steady-state temperatures of (either) solid head, the threaded-plug/seal weld, and, the multi-layer closure configurations were determined using a computer program, TRUMP, utilizing simplified models of the upper SSC system, shown (as a solid head model) in Figure 13. Starting from some initial condition, the transient occurs and cools the cask; an example result for the multi-plate is shown in Figure 14.

* See Appendix Five.

FIGURE 13

MODEL REGION FOR THERMAL TRANSIENT CALCULATIONS

FIGURE 14

EXAMPLE TRANSIENT IN MULTI-PLATE CLOSURE

Upon completion of a coherent series of computer calculations, utilizing acceptable factors for emissivity, conductivity, etc., the temperature conditions at some worst-case time during the transient can be imposed on the appropriate finite element model and the thermal stresses determined. This effort has been initiated, but not completed.

In the absence of actual computer results, an estimate can be made of the likely form of thermal stress distributions for the various closure concepts. In general, the interior of the cask would be expected to be hotter than the exterior during a transient. The cask shell therefore tends to experience compression stresses on the inside and tension stresses on the outside. Furthermore, the head might be expected to be somewhat cooler than the shell, thus tending to pull away from the shell, and tending to cause the head/shell section A-A to experience a degree of tension, see Figure 15.

Three of the four closures are welded in region A-A. However, the solid head/butt weld configuration is joined at section B-B. It would experience somewhat larger compression stresses on the interior at B-B than from the temperature gradient alone, due to the inward pull exerted by the cooler head. Consequently, the solid head/butt weld closure tends to be highly resistant to crack propagation through the shell, because of the compressive stresses along the inner wall.

Since the other closures have welding regions in the top portion of the cask and are thus more susceptible to cracking from tension stresses caused by the cooler head, the solid head/butt weld closure can be rated as unity (best), while the other designs will have some poorer rating.

To find a numerical comparison for the designs, it is necessary to make approximate calculations of the likely relative cracking rates in each of the designs, due to repeated thermal stressing. As noted earlier, only one consideration of thermal stressing will be used to define the nature of the problem, recognizing fully that numerical solutions are only expected to be relative, not absolute.

A method for quantitative treatment of cracking from cycling loads is described in the next section, followed by comparative calculations for all four closures.

Section A-A tends to experience radial tension for the simplified case shown.

FIGURE 15

SCHEMATIC OF RELATIVE TEMPERATURES NEAR CASK HEAD REGION DURING TRANSIENT

Description of Analysis Method

The analysis method is based on the concept that a stress field parameter, K , describes the intensity of the elastic stress field surrounding a crack or defect border ⁽³⁾⁽⁴⁾⁽⁵⁾. Although derived from linear elastic theory, the method has been found useful for a wide range of cracking analysis problems, even when some localized yielding occurs in the neighborhood of the crack border ⁽⁶⁾⁽⁷⁾⁽⁸⁾. Current research includes study of methods for treating cracking problems which involve significant regions of plasticity ⁽⁹⁾⁽¹⁰⁾ and experiments at wide ranges of temperatures and environments ⁽¹¹⁾⁽¹²⁾⁽¹³⁾. Unfortunately, little information of either theoretical or experimental nature can be found for the long-time behavioral regime inherent with the present problem.

As a first approximation, then, structural integrity analysis of the cask closure concepts has been conducted with elementary procedures for calculating crack extension due to cyclic loads ⁽¹⁴⁾⁽¹⁵⁾. We rationalize that future, definitive experiments may show that deteriorating influences from temperature/environment processes could be approximately offset by stress-relieving effects resulting from the elevated temperatures and long times.

Elementary procedures for estimating progressive extension of a crack or crack-like defect undergoing loading cycles depends on the observation that the average extension associated with each fluctuation, in a given material, is primarily dependent on the magnitude of the stress field parameter, K , and its range of excursion, even though temperature and environment and loading frequency may have important effects on the cracking behavior. In some circumstances it has been observed that the crack border will extend even under static loading only. Such behavior likely involves a complexity of chemical and metallurgical reactions to the actual stress state at the crack border and nearby regions. Nevertheless, these eventual findings are unlikely to alter significantly the relative cracking responses of the several closure concepts since the same materials and environments would be experienced by each.

Consider a simply-cracked plate so large that the crack is very small compared to the body dimensions. If the plate is remotely stressed and the stress is cycled through some range, the crack will extend an increment each cycle, but with an increasing incremental rate as the crack gets larger; refer to the lower curve in Figure 16. If the cracked plate is loaded along the crack-line in a cyclic fashion, the crack extension rate becomes slower with increasing crack size; see the upper curve in Figure 16.

At any point along the curves, the slope is da/dN , the instantaneous crack extension rate. Wherever the slopes are the same the crack extension rate is the same. Hence, in Figure 16, cracking rate da/dN_1 is the same value at a short crack length in the remotely stressed plate as it is at a long crack length in the crack-line loaded plate; and vice versa for da/dN_2 .

The stress-field parameter, K , is determined from crack-length, imposed stress or force, and, the particular geometry of the cracked-body problem. K is independent of material properties (for the linear elastic situation) and is a rather unusual function of loading, configuration and crack dimension, having the units of stress times length to the half-power (e.g., ksi $\sqrt{\text{in}}$). In general, K is proportional to load times the square root of the crack dimension characteristic; configuration effects can be considered as some numerical constant and a factor depending on relative crack size. Hence, for a specific case,

$$K = A (\text{Load}) \sqrt{(\text{Crack dimension})} f(\text{crack dimension})$$

Details may be found elsewhere (5)(16)(17). For the center-cracked plate of width, W , under remote, uniform stress, Figure 16, lower curve,

$$K = B\sigma\sqrt{\pi a} f(a/W), \text{ or, } \frac{K}{\sigma} = B \sqrt{\pi a} f(a/W)$$

For the other, similarly-cracked plate shown in Figure 16, but under point loads, $P = F/t$, where t is plate thickness,

$$K = C \frac{P}{\sqrt{\pi a}} g(a/W), \text{ or, } \frac{K}{P} = \frac{C}{\sqrt{\pi a}} g(a/W)$$

The change of K/σ and K/P with relative crack dimension, a/W , is shown schematically in Figure 17. It is often useful to prepare the stress field parameter results for a particular problem in these terms.

BOTH TESTS AT SAME LOAD OR
STRESS CYCLING RATIO MINIMUM
TO MAXIMUM, AND OTHER TEST
CONDITIONS.

OBSERVED CRACK LENGTH a

FIGURE 16

EXAMPLE MATERIAL CRACKING UNDER REMOTE AND CRACK-LINE LOADING CONDITIONS

FIGURE 17

SCHEMATIC OF STRESS FIELD PARAMETER CHANGE AT DIFFERENT RELATIVE CRACK LENGTHS

Fluctuating load $\Delta\sigma$ or ΔP causes fluctuation ΔK . For a given situation, the mechanics factors are, therefore, $K_{\max}$ and ΔK . Since K is a function of crack dimension, there is a certain value of $K_{\max}$ and ΔK associated with each crack dimension, for a given load fluctuation range. Consequently, both $K_{\max}$ and ΔK can be related to a certain cracking rate, da/dn , observed from experiment, Figure 16, through the associated value of crack size, a .

The particular material cracking behavior represented by the experimental results can be replotted, Figure 18, on the basis of $K_{\max}$, ΔK and da/dn . It is seen that the cracking behavior is correlated by this procedure, even though the individual specimen responses were oppositely changing rates; Figure 17.

Observed correlation of the cracking behavior in a particular material for these two extreme loading situations suggests that cracking rates under similar temperature/environment and cycling rates could be predicted for any form of loading on a cracked plate of the same material by working the problem backwards. All that would be needed is a solution for the change of K with crack dimension and an appropriate description of the experimentally determined cracking response for the material of interest. The $K_{\max}/\Delta K$ cracking rate data may be considered as a basic characteristic of the material response to the imposed conditions.

Evaluation of the cask closure has been carried out by this procedure.

Susceptible regions in the cask were identified, where defects might be enlarged through thermal stress cycling; see Figures 19-22.

Variation of stress-field parameter, K , and the assumed fluctuation, ΔK , were determined for each closure; see Figure 23.

Literature data was interpreted so to obtain cracking resistance behavior for the cask material under field storage conditions; Figure 24.

Calculations were then performed to determine how many thermal fluctuations would likely cause the crack to penetrate one structural element of the closure. See Table 3, and, Figure 25.

Closures were then rated quantitatively; this rating isn't solely conclusive nor necessarily descriptive of total integrity loss, but is taken as a preliminary rating factor, only.

FIGURE 18
CORRELATION OF DIVERGENT MATERIAL CRACKING RATES UNDER REMOTE AND
CRACK-LINE LOADING ON BASIS OF STRESS FIELD PARAMETER

Estimates of Relative Cracking Resistance to Thermal Excursions

A likely driving force for cyclic extension of defects in the cask wall or closure-weld region arises from thermal excursions imposed on the cask system. One thermal excursion would be expected to cause a change in stress state from a prior condition to a new condition. The change in stresses will activate the defect border into a tearing or extensional experience during one form of change and then squeeze the defect border shut during another form of change. This dual action can be considered a "cycle" in an elementary situation.

One type of "cycle" might be that developing from sudden unblocking of the air flow paths. It would be expected that a thermal excursion of this sort would be drastic, and, infrequently experienced during the course of storage. However, a drastic cycle of this kind, repeatedly applied, should provide means for quantitative, though relative, comparison of the cracking resistance afforded by each closure concept. Such calculations are described here. The results permit assessing or rating the closures on this cracking resistance basis.

It is assumed that the "weak path" for each concept lies in the weld region, along or near the heat-affected zone. From NDE considerations it is further assumed that crack-like flaws of 1/2 inch depth might be missed in the solid head/butt weld closure and 1/4 inch deep flaws missed in the other closures. These are "starting crack sizes" used in the analysis. They are pictured in Figures 19, 20, 21 and 22.

Thermal transient stresses resulting from the assumed cooling of the cask have not been determined explicitly, but for these preliminary purposes it may be seen that temperature differences across the multi-plate closure will surely be larger than for other head closures; the colder outer plate will try to contract, thus stressing the ligament near the cask wall in tension. Other closures will experience somewhat similar but considerably reduced level of thermal transient stressing through the thickness.

FIGURE 19
ASSUMED CRACK LOCATION
AND INITIAL SIZE IN
SOLID HEAD/BUTT-WELD
CLOSURE CONCEPT

FIGURE 20
ASSUMED CRACK LOCATION
AND INITIAL SIZE IN
MULTI-PLATE CLOSURE

FIGURE 21
ASSUMED CRACK LOCATION
AND INITIAL SIZE IN
THREADED PLUG/SEAL-WELD
CLOSURE CONCEPT

FIGURE 22
ASSUMED CRACK LOCATION
AND INITIAL SIZE IN
SOLID HEAD/CORNER-WELD
CLOSURE CONCEPT

The form of the variation in the stress-field parameter for each defect closure assumption may be understood in the following general way. When a crack is very small compared with the unbroken ligament, the influence of the crack on the total body is very small; in return, the crack is not influenced by the far-away boundary. As the ligament is broken more by the expanding crack their mutual interactions become more obvious; by the time the crack has broken through a large fraction of the ligament, the boundary effect is very strong. (It may be recalled that this behavior could be observed in the upturned ends of the curves shown in Figure 17.)

In the multi-plate situation, the outer plate is cooler than the inner plates and so it exerts inward loads on the ligament joining it to the cask body. Even under thermal cycling the ligament would doubtless experience nominal tension cycling. For the geometry pictured in Figure 20, it may also be readily appreciated that the bending action would aggravate cracking and that the boundary influence would be increasingly pronounced on the crack which is a substantial fraction of the ligament to begin with. The stress-field parameter change with increasing crack depth would be expected to be much more severe than for the same cycling tensile stresses activating the same absolute sized crack imbedded in the edge of a semi-infinite body. For purposes of this comparative evaluation, the thermal cycling stresses in the outer plate are taken to be 5000 psi; the contrast in response between these two cases is shown in Figure 23. (Indeed, the crack-driving fluctuations of ΔK in the outer plate are the most severe of any of closures under this assumed, sudden-unblocked-air, repeated thermal excursion.)

A similar argument holds for the ligament of the threaded-plug/seal-weld closure. However, the thermal stress range would not be expected to be as severe as for the multi-plate, since the threaded head is solid. Consequently, the fluctuating stress-field parameter change with crack size should be less drastic, and this is apparent in Figure 23.

In the solid-head/corner-weld closure, Figure 22, the same size defect is initially a smaller fraction of the ligament than either of the two closures just discussed. The boundary effect is thus "delayed" on an absolute scale and so the lower-lying of the three upper curves in Figure 23 appears a reasonable estimate for this case. (Cross-over of the two curves at short

crack lengths is only included to emphasize that comprehensive, thermal stress solutions are not available and the closure behaviors should be expected to be different in detail, though not form, from the individual responses pictured in Figure 23. The potentially strong effects on calculated thermal stresses caused by different "choices" of heat flow factors were pointed out in an earlier section.)

The solid-head/butt-weld closure is basically different from the other three closures because the assumed defect is in the cask wall where the stresses in the ligament of the concern change from tensile in the outer region to compressive in the inner region, even during an excursion. Consequently, although the outer region contained a defect as large as one-half inch, Figure 19, the crack driving force would decrease as the crack enlarged toward the mid-thickness. The stress-field parameter reflects this, and so the response curve for this condition turns down, as indicated in Figure 23.

In order to perform a numerical integration of the crack extension due to repeated thermal fluctuations, the material behavior under the assumed conditions must also be described. This behavior is taken to be that shown in Figure 24. (In a more complete analysis, appropriate experimental data would be obtained. One basic difficulty stems from lack of information about cracking rates for materials under long-term exposures and slowly cycling stresses relevant to the present problem. Nevertheless, for immediate purposes, a material response has been estimated, as shown.)

Now, with both stress field parameter variations and material response properties specified, the calculations of crack extension can proceed, since an initial crack size has been defined.

The procedure consists of selecting a small increment of crack extension beyond the prior crack size and then finding an average value of ΔK corresponding to the average crack dimension. From the material response curve, a value of cracking rate is found which would result from imposition of a loading cycle at the average ΔK . The increment of crack extension is then divided by the rate to provide an approximate number of cycles of load excursions which would cause the crack to extend from the prior value to the enlarged dimension. The process is then repeated and the cycles cumulatively summed. Finally, a plot can be constructed of crack size and accumulated cycles.

FIGURE 23

ESTIMATED CRACK DRIVING FORCES FOR EACH CLOSURE DUE TO
ASSUMED THERMAL TRANSIENTS

FIGURE 24
ASSUMED MATERIAL RESPONSE TO THERMAL TRANSIENT CYCLES

For more detailed demonstration purposes, consider the threaded plug. An initial crack size of 1/4 inch has been assumed. A reasonably small increment of crack extension is 0.02 inches, resulting in a "new" crack size of 0.27, with an average crack of 0.26. Referring to Figure 23, and the appropriate curve, K for a crack of 0.26 is found to be about 5.9 ksi $\sqrt{\text{in.}}$, whence, for this K , the value of da/dN is found from Figure 24 to be about 2.0×10^{-4} in./cycle. Dividing the selected value of incremental crack extension (0.02) by the rate (2.1×10^{-4}), a value of 95 cycles is obtained. Consequently, approximately 95 cycles of thermal excursions of the magnitude producing the relation shown in Figure 23 in a material responding as indicated by Figure 24 will extend a crack in the designated region of the threaded plug from 0.25 to 0.27 inches.

Tabulation of several repetitions for this case are shown in Table 3.

TABLE 3. SAMPLE CALCULATION FOR THREADED PLUG

<u>Crack Size</u>	<u>Average Crack</u>	<u>Average ΔK (Fig.23)</u>	<u>Average da/dN (Fig.24)</u>	<u>Crack Incr.</u>	<u>Cycle Incr.</u>	<u>Cycle Cum.</u>
0.25	0.26	5.9 ksi $\sqrt{\text{in.}}$	2.1×10^{-4} in./cycle	0.02	95	
0.27	0.28	6.4 ksi $\sqrt{\text{in.}}$	2.8×10^{-4} in./cycle	0.02	72	95
0.29	0.30	6.9 ksi $\sqrt{\text{in.}}$	3.6×10^{-4} in./cycle	0.02	56	167
0.31	0.32	7.4 ksi $\sqrt{\text{in.}}$	4.5×10^{-4} in./cycle	0.02	45	223
0.33						268

Proceeding in a similar fashion, each of the closures can be evaluated; the results are plotted as accumulated cycles and developed crack depths in Figure 25.

From these relative calculations for each concept it is apparent that the solid head/butt weld resists cracking through the wall and thus rates best at unity. The solid head/corner weld is next best; rated at two. The threaded-plug/seal weld is not as resistant and thus rated at three, while the multi-plate is clearly poorest and rates worst, at five.

FIGURE 25

RELATIVE COMPARISONS OF CLOSURE CONCEPTS' RESISTANCE TO CRACKING FAILURE
FROM THERMAL TRANSIENT CYCLES

SUMMARY

Ratings of each closure have been described at the end of the various sections; the relative importance of each analyzed condition was described earlier. Multiplying the rating of each closure by the relative importance for each condition permits a simple, numerical comparison and this result is shown in Table Four.

TABLE FOUR. SUMMARY OF RELATIVE EVALUATIONS

	Solid Head Butt Weld	Multi- Layer	Threaded Plug Seal Weld	Solid Head Corner Weld
(Closure Ratings) Residual Welding (Factor = 1)	(5) 5	(4) 4	(1) 1	(5) 5
Handling Stresses w/Top-Center Bale (Factor = 2)	(1) 2	(5) 10	(2) 4	(2) 4
Relative Damage, End Drop (Factor = 1)	(1) 1	(5) 5	(1) 1	(1) 1
Cracking from Thermal Stress Fluctuations (Factor = 12)	(1) 12	(5) 60	(3) 36	(2) 24
Overall Rating with Cracking Factor at 12. (Small Number Best)	20	79	42	34
SUMMATION WITH CRACKING FACTOR REDUCED FROM 12 TO 4				
Cracking from Thermal Stress Fluctuations Factor = 4	(1) 4	(5) 20	(3) 12	(2) 8
Overall Rating (Small Number Best)	12	39	18	18

CONCLUSIONS

It is concluded, on the basis of calculations described herein, that the multi-plate closure is most susceptible to compromise of structural integrity and the solid head/butt-weld closure the most resistant to loss of structural integrity. The threaded-plug/seal weld and the solid-head/corner weld are intermediate but considerably better than the multi-plate closure.

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APPENDIX ONE

RESIDUAL WELDING STRESSES

in

SOLID HEAD, BUTT/WELD
MULTI-PLATE
THREADED PLUG/SEAL WELD

WI

Residual Welding Stress Model of Solid-Head Vee Weld Closure Concept

Stresses were approximated by causing the elements indicated to contract differentially by the amount associated with the temperatures shown in the elements.

A large grid of graph paper with a 10x10 grid of squares. The top-left corner is folded over, and the bottom-right corner is folded over, creating a smaller grid of 6x6 squares in the center. The grid is used for a mathematical exercise involving numbers and operations.

WI

Nodal temperatures from 12 Mar.

ELASTIC CALCULATIONS ONLY ----
NO RELAXATION

Twice Size: Maximum & Minimum
Principal

Stress Vectors in this plane
are shown at 20 ksi/in.

This particular solution
is for the situation of initial
conditions used by the computer
program to make the next iter-
ation, based on how many of the
elements have exceeded the
yield strength.

For demonstration purposes only

— Tension

— Compression

ARCSKWD

Residual Welding Stress Model of Four-Plate Closure Concept

Stresses were approximated by causing the elements indicated to contract differentially by the amount associated with the temperatures shown in the elements.

ONE-3

BNWL-B-442

K Ø

Nod. Temps from 14 Mar
alpha hoop = 0

Twice Size: Maximum &
Minimum
Principal ..

Stress Vectors in this
plane are shown at 20
ksi/in.

Compare next two plots;
showing negligible effect
of hoop strain influence
on R-Z stresses.

Tension Compression

Residual Welding Stress Model of Threaded-Plug Closure Concept

Stresses were approximated by causing the elements indicated to contract differentially by the amount associated with the temperature shown in the elements

Temperatures shown in the lower thread region simulate jamming the plug onto the body.

APPENDIX SECTION TWO

Lift with Center Bale
in

Four-Layer
Threaded Plug

RESIDUAL WELDING STRESSES INCLUDED

IQ

Nod. temps from 14 Mar. alpha
hoop = 0

Cask and canister total wt. = 4^k

Lift with center bale, 3.2" dia.

Maximum & Minimum Principal
Stress vectors in this plane are
shown at 20 ksi/in.
Compare with KØ. Note definite
but small changes in stress vectors
near upper plate/body joint.

* KØ is in Appendix One

TWO

APPENDIX THREE

END DROP ANALYSIS

- . Description of End Drop Height Calculations
- . Elastic Plastic Treatment by the Computer
Program AXISOL

DESCRIPTION OF END DROP HEIGHT CALCULATIONS

For a linear elastic prismatic member, the relationship between the accelerative force and the drop height can be derived in the following manner:

Impact velocity (for a free drop) is given by

$$V_0 = \sqrt{2gH} \quad (1)$$

After impact the cask begins to decelerate and eventually comes to a complete stop.

$$V_f = 0 = V_0^2 - 2a\Delta\ell \quad (2)$$

$$2gH - 2a\Delta\ell = 0 \quad (3)$$

From equation (3), the deceleration, a , can be expressed as

$$a = \frac{H}{\Delta\ell} g \quad (4)$$

g = gravitational acceleration

H = Drop Height

$\Delta\ell$ = Total deformation of a cask after impact

For an idealized case, the kinetic energy can be taken equal to the potential energy, resulting from the drop through height H ,

$$K.E. = W \cdot H \quad (5)$$

The total strain energy, U , expended on impact is

$$U = \frac{1}{2} P \cdot \Delta\ell \quad (6)$$

W = Weight of cask

P = Impact of force

When the system comes to simple equilibrium,

$$W \cdot H = \frac{1}{2} P \cdot \Delta\ell \quad (7)$$

For a prismatic bar striking on end, the total shortening is

$$\Delta\ell = \frac{P\ell}{AE}$$

ℓ = original length of cask

or,

$$P = \frac{AE}{\ell} \cdot \Delta \ell \quad (8)$$

substitute (8) into (7), yields

$$H = \frac{1}{2} \frac{AE}{W \cdot \ell} \cdot \Delta \ell^2 \quad (9)$$

Combining equations (4) and (9),

$$a = C \cdot H^{1/2} \cdot g \quad (10)$$

where

$$C = \sqrt{\left(\frac{1}{2}\right) \left(\frac{AE}{W \cdot \ell}\right)}$$

From equation (10) it is concluded that for a linearly elastic system the deceleration is directly proportional to the square root of the drop height.

The measurement of the deceleration of the cask after a given drop can be obtained from an actual test, from which the value C in equation (10) can be determined.

For instance, the deceleration of a GE 15/140 spent fuel cask (without canister) at a 30' drop height (360 inches) was measured at 275 g⁽²⁾. The C value is thus,

$$C = \frac{a}{(H)^{1/2}} = \frac{275}{(360)^{1/2}} = 14.5$$

Equation (10) then becomes

$$a = 14.5 H^{1/2} \cdot (g) \quad (11)$$

or

$$H = (a/14.5 \text{ g})^2 \quad (12)$$

If equation (12) is used in this study, the corresponding drop heights for decelerations of 150g and 300g would be 8.9' and 35.7' respectively.

$$H = \left(\frac{150g}{14.5g}\right)^2 = 107 \text{ inches} = 8.9 \text{ feet}$$

$$H = \left(\frac{300g}{14.5g}\right)^2 = 428 \text{ inches} = 35.7 \text{ feet}$$

ELASTIC PLASTIC TREATMENT BY THE COMPUTER PROGRAM AXISOL

The elastic-plastic analysis capability in AXISOL is based on the use of a bilinear stress-strain curve. In keeping with this, the yield stress used in the analysis has been adjusted upward to a proper value (see Figure 3-1 and downward to that expected at cask temperatures.

Some important parameters used in AXISOL and Figure 3-1.

F_{TU} = Ultimate Tensile Strength

F_{PL} = Proportional Limit

F'_{TY} = Adjusted Yield Stress in Tension (Computer Input Value)

E_p = Plastic Modulus = $\frac{DH}{CH}$

E_e = Elastic Modulus = $\frac{BE}{AE}$

$\gamma = \frac{E_p}{E_e} = \text{Modulus Ratio} = 0.04$

g = Deceleration

FIGURE 3-1 Typical Stress-Strain Curve

The decelerations of 150g and 300g were used in the analysis for both cases. This is accomplished in the program by increasing the mass of each element 150 times or 300 times, respectively.

APPENDIX FOUR

BASIC EQUATIONS FOR
HAND CALCULATIONS OF
BLOCKED-FLOW, STEADY STATE

HP 9100B PROGRAM
RESULTING TEMPERATURE PROFILES

HEAT TRANSFER HAND CALCULATIONS

Equations:

Radiation

$$Q = \frac{\sigma A (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} \quad (1)$$

$$Q = \sigma F_\epsilon A (T_1^4 - T_2^4) \quad (2)$$

$$F_\epsilon = \frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} \quad (3)$$

Convection

$$Q = h A (T_w - T_\infty) \quad (4)$$

Conduction

$$Q = \frac{-KA}{\Delta X} (T_2 - T_1) \quad (5)$$

$$Q = 2\pi \frac{(T_2 - T_1) K}{\ln \frac{r_2}{r_1}} \quad (6)$$

Q = heat

A = area

T = temperature

 ϵ = emissivity σ = Stefan-Boltzman Constant $= 0.1714 \times 10^{-8} \text{ BTU/hr-ft}^2 \cdot \text{°R}^4$

h = convection coefficient

K = conduction coefficient

r = radius

If the system is under blocked flow conditions we know that the "Q" is constant across the system. Assuming an outside temperature and knowing that "Q" is constant enables us to calculate all of the internal temperatures by using an iterative process. The following equations are used for the iteration:

$$\sigma A_1 (T_{so}^4 - T_{amb}^4) F_{\epsilon 1} + h_{sa} A_1 (T_{so} - T_{amb}) = Q \quad (7)$$

$$\frac{2\pi (T_{si} - T_{so})}{\ln \frac{r_{so}}{r_{si}}} = Q \quad (8)$$

$$\sigma A_2 (T_{csk}^4 - T_{si}^4) F_{\epsilon 2} + h A_2 (T_{csk} - T_{si}) = Q \quad (9)$$

$$\sigma A_3 (T_{cain}^4 - T_{csk}^4) F_{\epsilon 3} + h A_3 (T_{cain} - T_{csk}) = Q \quad (10)$$

In equation 7, Q and T_{amb} are known therefore, T_{so} can be found. T_{so} and Q are then substituted into equation 8 and T_{si} is found. This same procedure is repeated until all the temperatures are found.

HP 9100B PROGRAM FOR
ONE-DIMENSIONAL BLOCKED-FLOW HEAT TRANSFER FOR RSSF

Temperatures are calculated from the outside of the shield inward, where:

- Storage "e" is the outside air temperature (°R).
- Storage "f" is the temperature guess (°R).
- Storage "d" is the Stefan Boltzman Constant (1.714×10^{-9}) and is never changed.
- Storage "c" is the outside area of the shield.
- Storage "b" is one over the emissivity of the outside of the shield.
- Storage "a" is one over the emissivity of the sky.
- Storage "9" is used internally and is the Q due only to radiation for all cases.
- Storage "8" is the convection coefficient for the outside air.
- Storage "7" is

$$(Q) \frac{\ln \frac{r_o}{r_i}}{2\pi K}$$

This gives the temperature differential across the concrete.

When the proper numbers have been put in storage, press GO TO -00 and then CONTINUE. If the proper Q doesn't appear in the Y register, guess a new temperature (°R) and store in "f". Press GO TO -00 and CONTINUE. Repeat until proper Q is obtained. Press CONTINUE and see 101 displayed in X. Temperature of outside of shield is in Y (°F). Press CONTINUE and see 102 in X. Temperature on the inside of the shield is displayed in Y (°F). Press CONTINUE and see 103 in X. Now input the values for heat transfer between shield and cask. Outside area of the cask goes in "c"; one over the emissivity of the inside of the shield goes in "b"; one over the emissivity of the outside of the cask goes in "a"; and h for shield to cask goes in "8". Place guess temperature for cask in "f" (°R). Press CONTINUE and see 104 in X. If value for Q, displayed in Y, is not correct, place new guess temperature (°R) in "f" and press GO TO -22 and then CONTINUE. See 3 in X. Press CONTINUE. Repeat until correct Q is obtained. When Q is correct, press CONTINUE and see 105 displayed in X.

Y display is the temperature of the cask ($^{\circ}\text{F}$). Now input the values for heat transfer between the cask and canister. Outside area of the canister goes in "c"; one over the emissivity of the inside of the cask goes in "b"; one over the emissivity of the canister goes in "a"; and h between cask and canister goes in "8". Input guess temperature for canister in "f" ($^{\circ}\text{R}$). Press CONTINUE and see 106 displayed. If value for Q, displayed in Y is not correct, place new guess temperature ($^{\circ}\text{R}$) in "f" and press GO TO -39 and then CONTINUE. See 5 in X. Press CONTINUE. Q value is displayed in Y. Repeat until correct Q is obtained. When correct Q is obtained, press CONTINUE and see 107 in X. Y is canister temperature ($^{\circ}\text{F}$). END OF PROGRAM.

Title ONE Dimensions Blockade has transfer RSF

HEWLETT · PACKARD

HEWLETT · PACKARD

HEWLETT · PACKARD

HEWLETT · PACKARD

Step	Key	Code	X	Y	Step	Key	Code	X	Y	Step	Key	Code	X	Y
0	Go to	44			30	f	15			0				
1	sub	77			1	X →	23			1				
2	+	35			2	e	12			2				
3	3	01			3	↑	24			3				
4	0	06			4	4	04			4				
5	Slop	41			5	6	06			5				
6	f	15			6	0	00			6				
7	↑	27			7	-	34			7				
8	4	04			8	1	01			8				
9	6	06			9	0	00			9				
10	0	00			10	5	05			10				
11	-	34			11	Slop	41			11				
12	1	01			12	Go to	44			12				
13	0	00			13	S/R	47			13				
14	1	01			14	+	35			14				
15	1	01			15	3	03			15				
16	0	00			16	0	00			16				
17	7	07			17	1	01			17				
18	+	33			18	6	06			18				
19	0	00			19	0	00			19				
20	0	00			20	Slop	41			20				
21	2	02			21	f	15			21				
22	X ←	67			22	↑	27			22				
23	7	07			23	0	00			23				
24	+	33			24	1	01			24				
25	1	01			25	6	06			25				
26	0	00			26	0	00			26				
27	2	02			27	Slop	41			27				
28	0	00			28	f	15			28				
29	4	04			29	↑	27			29				
30	Slop	41			30	0	00			30				
31	0	00			31	1	01			31				
32	1	01			32	6	06			32				
33	0	00			33	0	00			33				
34	+	33			34	1	01			34				
35	0	00			35	6	06			35				
36	1	01			36	Slop	41			36				
37	0	00			37	f	15			37				
38	4	04			38	↑	27			38				
39	6	06			39	0	00			39				
40	0	00			40	1	01			40				
41	+	33			41	6	06			41				
42	0	00			42	0	00			42				
43	1	01			43	Slop	41			43				
44	0	00			44	f	15			44				
45	4	04			45	↑	27			45				
46	6	06			46	0	00			46				
47	0	00			47	1	01			47				
48	+	33			48	6	06			48				
49	0	00			49	0	00			49				
50	1	01			50	Slop	41			50				
51	0	00			51	f	15			51				
52	4	04			52	↑	27			52				
53	6	06			53	0	00			53				
54	0	00			54	1	01			54				
55	+	33			55	6	06			55				
56	0	00			56	0	00			56				
57	1	01			57	Slop	41			57				
58	0	00			58	f	15			58				
59	4	04			59	↑	27			59				
60	6	06			60	0	00			60				
61	0	00			61	1	01			61				
62	+	33			62	6	06			62				
63	0	00			63	0	00			63				
64	1	01			64	Slop	41			64				
65	0	00			65	f	15			65				
66	4	04			66	↑	27			66				
67	6	06			67	0	00			67				
68	0	00			68	1	01			68				
69	+	33			69	6	06			69				
70	0	00			70	0	00			70				
71	1	01			71	Slop	41			71				
72	0	00			72	f	15			72				
73	4	04			73	↑	27			73				
74	6	06			74	0	00			74				
75	0	00			75	1	01			75				
76	+	33			76	6	06			76				
77	0	00			77	0	00			77				
78	1	01			78	Slop	41			78				
79	0	00			79	f	15			79				
80	4	04			80	↑	27			80				
81	6	06			81	0	00			81				
82	0	00			82	1	01			82				
83	+	33			83	6	06			83				
84	0	00			84	0	00			84				
85	1	01			85	Slop	41			85				
86	0	00			86	f	15			86				
87	4	04			87	↑	27			87				
88	6	06			88	0	00			88				
89	0	00			89	1	01			89				
90	+	33			90	6	06			90				
91	0	00			91	0	00			91				
92	1	01			92	Slop	41			92				
93	0	00			93	f	15			93				
94	4	04			94	↑	27			94				
95	6	06			95	0	00			95				
96	0	00			96	1	01			96				
97	+	33			97	6	06			97				
98	0	00			98	0	00			98				
99	1	01			99	Slop	41			99				
100	0	00			100	f	15			100				
101	4	04			101	↑	27			101				
102	6	06			102	0	00			102				
103	0	00			103	1	01			103				
104	+	33			104	6	06			104				
105	0	00			105	0	00			105				
106	1	01			106	Slop	41			106				
107	0	00			107	f	15			107				
108	4	04			108	↑	27			108				
109	6	06			109	0	00			109				
110	0	00			110	1	01			110				
111	+	33			111	6	06			111				
112	0	00			112	0	00			112				
113	1	01			113	Slop	41			113				
114	0	00			114	f	15			114				
115	4	04			115	↑	27			115				
116	6	06			116	0	00			116				
117	0	0												

Title *radiation conversion Subroutine*

HEWLETT · PACKARD					HEWLETT · PACKARD					HEWLETT · PACKARD					HEWLETT · PACKARD				
Step	Key	Code	Display		Step	Key	Code	Display		Step	Key	Code	Display						
30	f	15			60	+ s/r	33 79			0									
11	1/4 x	65			1					1									
2	↓	27			2					2									
3	4	04			3					3									
4	x	3c			4					4									
5	↓	25			5					5									
6	e x	74			6					6									
7	↓	27			7					7									
8	e	12			8					8									
9	1/4 x	65			9					9									
a	↓	27			a					a									
b	4	04			b					b									
c	x	3c			c					c									
d	↓	25			d					d									
40	e x	74			0					0									
1	-	34			1					1									
2	d	17			2					2									
3	x	3c			3					3									
4	c	16			4					4									
5	x	3c			5					5									
6	b	14			6					6									
7	↓	27			7					7									
8	0	13			8					8									
9	+	33			9					9									
a	1	01			a					a									
b	-	34			b					b									
c	↓	25			c					c									
d	1/.	35			d					d									
50	1/4 x	40			0					Storage									
11	9	11			1														
2	f	15			2														
3	↓	27			3														
4	e	12			4														
5	-	34			5														
6	x	67			6														
7	8	10			7														
8	x	3c			8														
9	x	67			9														
a	c	16			a														
b	x	3c			b														
c	x	67			c														
d	9	11			d														

APPENDIX FIVE

HEAT TRANSFER COEFFICIENTS
FOR
THERMAL TRANSIENTS

HEAT TRANSFER COEFFICIENTS

Transfer coefficients will be calculated for the various regions shown in Figure Five-1. The coefficients will be applicable to a range of temperatures and will be based upon the properties given in Table Five-1. The identified regions are air spaces and will be assumed to possess radiation and convection modes of transfer. The intervening regions are structural and will be assumed to possess only a conduction capability.

REGION A

A1 Radiation:

For concentric cylinders the emissivity factor is given by (Hsu - Engineering Heat Transfer p. 146)

$$F_{\epsilon} = \left[\frac{1}{\epsilon_1} + \frac{R_1}{R_2} \left(\frac{1}{\epsilon_2} - 1 \right) \right]^{-1}$$

Where R_1 = Container radius = 6.0 inches

R_2 = Cask inner radius = 7.5 inches

Four sets of emissivity factors are calculated to bracket the range of the factor

ϵ_1	0.15	0.85	0.15	0.85
ϵ_2	0.85	0.15	0.15	0.85
F_{ϵ}	0.147	0.175	0.0893	0.76

Area factor for this configuration is 1.

A2 Radiation:

For two parallel discs with concentric centers the emissivity factor is given (Hsu - page 147) by

$$F_{\epsilon} = \left[\frac{1}{\epsilon_1} + \left(\frac{1}{\epsilon_2} - 1 \right) \right]^{-1}$$

CASK THERMAL ANALYSIS
HEAT TRANSFER REGIONS

FIGURE FIVE-1

Note: This sketch is
not to scale.

TABLE FIVE-1
EXAMPLE HEAT FLOW FACTORS

Temp °F	Emissivities			Conductivity BTU/hvFt°F			Specific Heat BTU/lb°F			Density lb/ft ³			Pr
	Clean Steel	Oxidized Steel	Conc.	Steel	Conc.	Air	Steel	Conc.	Air	Steel	Conc.	Air	
-20						0.0125			0.24				0.72
32						0.014	0.11		0.24			0.081	0.72
70	0.15 ⁽¹⁾	0.85 ⁽¹⁾	0.9 ⁽²⁾	36	0.54 ⁽³⁾	0.015	0.11	0.2 ⁽⁴⁾	0.24	488	150 ⁽⁴⁾	0.071	0.72
200				35		0.017	0.12		0.241			0.060	0.72
400				31.6		0.0212	0.12		0.245			0.046	0.689
600	0.18	0.85		28.3		0.025	0.13		0.25			0.0373	0.685
800				25.4		0.029	0.14		0.256			0.0314	0.697
1200	0.22	0.85		20.1		0.035	0.18		0.268				0.726
1600			0.9	16.0		0.0415	0.23		0.278			0.0202	0.742
2000			0.8			0.0471			0.286			0.0161	0.753

- (1) 301 Stainless Steel can be 0.54 to 0.63 at temperatures of 400 - 1600°F. Polished iron can be 0.14 to 0.38 near 1200°F. Cast iron can be 0.6 - 0.7 at about 1600°F.
- (2) Range from 0.7 at R.T to 0.6 at 1200°F may be more likely.
- (3) Can be as much as 1.5 with certain sand/aggregate mixes.
- (4) Could be quite different with unusual mixtures.

FIVE-3

Again calculating four sets for the range

ϵ_1	0.15	0.85	0.15	0.85
ϵ_2	0.85	0.15	0.15	0.85
F_ϵ	0.17	0.15	0.08	0.74
Area factor (for $\frac{b}{k} = \frac{6.}{6.}$), $F_a = 0.17$ hence				
$F_a \cdot F_\epsilon$	0.029	0.026	0.014	0.126

AI Convection:

Using data related to enclosed vertical spaces, Table Five-2 expresses convection coefficients versus reference temperatures. The coefficient is based upon a gap width, Δ , of 1.5 inches and embodies two surface natural convection coefficients and conduction through air.

Grashar number
$$Gr = b^3 \cdot \frac{g\beta\Delta^2}{\mu} \cdot \Delta T$$

Nusselt No.
$$Nu = \frac{U \cdot b}{k}$$

Where U = Required gap coefficient $\frac{\text{BTU}}{\text{HrFt}^2\text{°F}}$

k = Air conductivity $\frac{\text{BTU}}{\text{HrFt}^2\text{°F}}$

A plot of Nu versus Gr is given in reference Kreith, F., "Principles of Heat Transfer"

TABLE FIVE-2

Temp °F	-20	32	70	200	400	600	800	1200	1600	2000
$U_{50}(\Delta T = 50\text{°F})$	0.4	0.37	0.29	0.31	0.24	0.24	0.23	0.28	0.33	0.37
$U_{100}(\Delta T = 100\text{°F})$	0.5	0.47	0.4	0.34	0.36	0.28	0.28	0.28	0.33	0.38
$U_{200}(\Delta T = 200\text{°F})$	0.62	0.66	0.52	0.45	0.39	0.4	0.32	0.31	0.33	0.38

A2 Convection:

For convection between two horizontally enclosed discs use will be made of the equations from McAdams "Heat Transmission" p. 182.

$$\text{Nu} = 0.21 [\text{Gr} \cdot \text{Pr}]^{\frac{1}{4}} \quad 10^4 < \text{Gr} < 3.2 \times 10^5$$

$$\text{Nu} = 0.075 [\text{Gr} \cdot \text{Pr}]^{\frac{1}{3}} \quad 3.2 \times 10^5 < \text{Gr} < 10^7$$

Where Pr = Prandtl Number

Nu = Nusselt Number

$$= U \cdot \frac{b}{k}$$

b = Air Gap - 0.5 Feet

k = Air Thermal Conductivity

TABLE FIVE-3

Temp °F	-20	32	70	200	400	600	800	1200	1600	2000
U ₅₀ (ΔT = 50°F)	0.54	0.50	0.45	0.41	0.33	0.29	0.27	0.25	0.23	0.22
U ₁₀₀ (ΔT = 100°F)	0.68	0.63	0.56	0.51	0.41	0.36	0.33	0.29	0.27	0.25
U ₅₀₀ (ΔT = 500°F)	1.16	1.08	0.97	0.87	0.70	0.62	0.57	0.49	0.42	0.38

REGION B**B1 Radiation:**

Using the formula from Hsu (Engineering Heat Transfer p. 146) and establishing a range of radiation factors

$$F_{\epsilon} = \left[\frac{1}{\epsilon_1} + \frac{R_1}{R_2} \left(\frac{1}{\epsilon_2} - 1 \right) \right]^{-1}$$

Where R₁ = Radius of Cask = 9.5 inches

Where R₂ = Inside Radius of Shield = 15.5 inches

ε ₁	0.15	0.85
ε ₂	0.9	0.9
F _ε	0.0149	0.804

Area factor this configuration is 1.

B2 Radiation:

From Hsu p. 147 for two parallel discs

$$F_{\epsilon} = \left[\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1 \right]^{-1}$$

ϵ_1	0.15	0.85
ϵ_2	0.9	0.9
F_{ϵ}	0.148	0.777

Separation distance $k = 6.0$ inches

$$\therefore \frac{b}{k} = \frac{7.5}{6.0} = 1.25$$

$\therefore$ from Hsu figures 5-18, F_a (Area factor) = 0.25

Hence $F_a \cdot F_{\epsilon}$ 0.037 0.194

B1 Convection:

A; Passages blocked.

Using the theory for enclosed vertical spaces and computing Grashof numbers based upon the space between cask and shield. (Kreith, F., "Principles of Heat Transfer, p. 347)

$$\text{Grashof } Gr = b^3 \left(\frac{g \beta \rho^2}{\mu} \right) \Delta T$$

$$\text{Nusselt } Nu = \frac{U b}{r}$$

$$b = (15.5 - 9.5) = 6.0 \text{ inches}$$

TABLE FIVE-4

Temp °F	-20	32	70	200	400	600	800	1200	1600	2000
U_{50} ($\Delta T = 50^\circ\text{F}$)	0.47	0.43	0.38	0.33	0.25	0.22	0.19	0.17	0.160	0.14
U_{100} ($\Delta T = 100^\circ\text{F}$)	0.62	0.56	0.48	0.43	0.34	0.28	0.26	0.21	0.20	0.17
U_{200} ($\Delta T = 200^\circ\text{F}$)	0.81	0.73	0.63	0.54	0.45	0.36	0.32	0.27	0.22	0.22

B: Passages free.

It will be assumed that the air flows in through the lower ports, up the vertical annulus and out through the upper ports. Two sets of free convection coefficients will be computed; one for the cask face and one for the inner face of the shield.

Calculations for the free convection coefficient will be based upon equation (7-9c), p. 181 of McAdams, "Heat Transmission."

A length $L = 10.5$ feet will be used

$$\text{Nusselt } Nu \left(\frac{h \cdot L}{k} \right) = 0.13 \left[\text{Gr} \cdot \text{Pr} \right]^{\frac{1}{3}}$$

Where Grashof Gr is based upon L and $\Delta T = (T_{\text{surface}} - T_{\text{air}})$

TABLE FIVE - 5

Temp °F	<u>-20</u>	<u>32</u>	<u>70</u>	<u>200</u>	<u>400</u>	<u>600</u>	<u>800</u>	<u>1200</u>	<u>1600</u>	<u>2000</u>
$U_{25} (\Delta T = 25^\circ\text{F})$	0.8	0.7	0.61	0.55	0.45	0.40	0.36	0.32	0.27	0.23
$U_{50} (\Delta T = 50^\circ\text{F})$	1.0	0.88	0.77	0.69	0.57	0.50	0.45	0.40	0.34	0.29
$U_{100} (\Delta T = 100^\circ\text{F})$	1.25	1.11	0.98	0.87	0.72	0.63	0.57	0.50	0.42	0.36

B2 Convection:**A: Blocked Condition**

For the blocked passage condition the transfer coefficients will be calculated on the basis of an enclosed horizontal space. Using the relations from Kreith, F., "Principles of Heat Transfer", Fig. 7-12, p. 347

$$\text{Grashof } Gr = b^3 \left(\frac{\rho^2 g \beta}{\mu} \right) \Delta T$$

$$\text{Nusselt } Nu = \frac{U b}{k}$$

$b = \text{Cask to shield distance} = 6.0 \text{ inches}$

TABLE FIVE-6

Temp °F	<u>-20</u>	<u>32</u>	<u>70</u>	<u>200</u>	<u>400</u>	<u>600</u>	<u>800</u>	<u>1200</u>	<u>1600</u>	<u>2000</u>
U_{25}	0.6	0.5	0.42	0.37	0.29	0.28	0.22	0.25	0.21	0.18
U_{50}	0.7	0.64	0.57	0.48	0.38	0.31	0.27	0.26	0.26	0.23
U_{100}	0.96	0.84	0.72	0.65	0.5	0.4	0.36	0.29	0.29	0.28
U_{200}	1.27	1.12	0.96	0.82	0.63	0.55	0.46	0.39	0.32	0.33
U_{400}	1.61	1.46	1.26	1.12	0.84	0.70	0.58	0.49	0.40	0.35

B: Open Passages

It will be assumed that the horizontal surfaces are both convecting to a free airstream. The coefficients will be calculated from relations given by Hsu, "Engineering Heat Transfer", p. 385

Laminar Flow	$Nu = 0.71 (Gr.Pr)^{\frac{1}{4}}$	Facing Upward
$10^3 < Gr \ Pr < 10^9$	$Nu = 0.35 (Gr.Pr)^{\frac{1}{4}}$	Facing downward

Under these conditions all flow is laminar.

TABLE FIVE-7

Convection from upwards facing surface

Temp °F	<u>-20</u>	<u>32</u>	<u>70</u>	<u>200</u>	<u>400</u>	<u>600</u>	<u>800</u>	<u>1200</u>	<u>1600</u>	<u>2000</u>
U_{25}	1.09	1.04	0.96	0.92	0.82	0.78	0.75	0.72	0.66	0.61
U_{50}	1.30	1.22	1.13	1.08	0.98	0.92	0.90	0.85	0.79	0.72
U_{100}	1.56	1.46	1.36	1.28	1.16	1.09	1.06	1.01	0.93	0.85

TABLE FIVE-8

Convection from downwards facing surface

Temp °F	<u>-20</u>	<u>32</u>	<u>70</u>	<u>200</u>	<u>400</u>	<u>600</u>	<u>800</u>	<u>1200</u>	<u>1600</u>	<u>2000</u>
U_{25}	0.55	0.52	0.48	0.46	0.41	0.39	0.38	0.36	0.33	0.30
U_{50}	0.65	0.61	0.57	0.54	0.49	0.46	0.45	0.43	0.40	0.36
U_{100}	0.78	0.73	0.68	0.64	0.58	0.55	0.53	0.50	0.47	0.43

C1, C2 Radiation:

Both surfaces will have an emissivity

$$\epsilon = 0.9$$

And an area factor

$$Fa = 1$$

C1 Convection:

Table 5 coefficients will be used for free convection conditions. This is based upon a length of 10 feet, which is the approximate location of the cask head.

C2 Convection:

The equations used for free convection on an upwards facing surface will be from Hsu, "Engineering Heat Transfer" p. 385. They will be based upon the diameter of the top surface which is

$$D = 111 \text{ inches} = 9.25 \text{ feet}$$

$$\text{Laminar } Nu = 0.71 (Gr.Pr)^{\frac{1}{4}} \quad (Gr.Pr < 10^9)$$

$$\text{Turbulent } Nu = 0.17 (Gr.Pr)^{\frac{1}{3}} \quad (Gr.Pr > 10^9)$$

TABLE FIVE-9

Temp °F	<u>-20</u>	<u>32</u>	<u>70</u>	<u>200</u>	<u>400</u>	<u>600</u>	<u>800</u>	<u>1200</u>	<u>1600</u>	<u>2000</u>
U_{10}	0.75	0.68	0.59	0.53	0.44	0.30	0.29	0.27	0.27	0.23
U_{20}	0.93	0.85	0.75	0.66	0.55	0.48	0.34	0.32	0.32	0.27
U_{40}	1.18	1.07	0.95	0.83	0.69	0.61	0.55	0.38	0.38	0.33

C. Forced Convection

Forced convection to the exterior surfaces will be through the equation [Hsu, (10-17)]

$$Nu = \frac{hD}{k} = 0.00128 (Re)^{0.5} = 0.46 (Re)^{0.5}$$

Where the Reynolds number Re is based upon the diameter of the shield
= 9.25 feet

TABLE FIVE-10

Temp °F	<u>-20</u>	<u>32</u>	<u>70</u>	<u>200</u>	<u>400</u>	<u>600</u>	<u>800</u>	<u>1200</u>	<u>1600</u>	<u>2000</u>
$h_{10}(v = 10 \text{ F/s})$	1.83	1.82	1.78	1.47	1.25	1.08	1.10	0.95	0.80	0.71
$h_{20}(v = 20 \text{ F/s})$	3.16	3.33	3.24	2.57	2.27	1.92	1.76	1.51	1.36	1.17
$h_{40}(v = 40 \text{ F/s})$	7.03	5.75	5.84	4.60	3.86	3.38	3.29	2.69	2.41	2.03

END OF APPENDIX FIVE

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S. N. Liu
M. Vagins (4)
Technical Information (3)

APPENDIX C

Date: October 29, 1975
To: E. L. Moore
From: J. R. LaRiviere *JR LaRiviere*
Subject: CLOSURE CONCEPT EVALUATION - RETRIEVABLE
SURFACE STORAGE FACILITY DEMONSTRATION
PROGRAM

The four welding closures under consideration in the Retrievable Surface Storage Facility Demonstration Program would have various effects upon the operation and design of the RSSF. I have tried to evaluate these differences and compare the effects in terms of capital and operating costs.

Capital Cost

Equipment requirements have been studied by Kaiser Engineers for performing the remote welding operations in the weld and test cell for storage cask closure. Equipment can be furnished which will rotate the storage cask in a vertical position for circumferential welding, tilt the storage cask at a 45 degree angle and also rotate it for circumferential welding, and rotate the storage cask 90 degrees to a horizontal position for performing a circumferential butt weld in the down-hand position.

The difference in equipment cost is negligible but the difference in hot cell space is significant. In the conceptual design of the weld and test cell, two welding stations are furnished in the cell. The cell is 10' wide and has a throughput capacity adequate for the first ten years of operation. The two welding closures which are performed with the storage cask in the vertical position require two cell spaces each at 10' x 7'. The multi-plate closure is performed with the storage cask at a 45 degree angle, and this requires two cell spaces each at 10' x 11-1/2'. The butt-weld joint closure is performed with the storage cask in the horizontal position, and this requires two cell spaces, each at 10' x 16'.

E. L. Moore
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October 29, 1975

Norm Dresser has estimated the total project cost of the cell per foot at \$7000, based on October 1975 costs. The results are shown in Table I.

Operating Cost

Table II shows the operating cost comparison. The machining work is performed in the shops at a rate of \$20/hour. The hot cell is rated at \$80/hour to take into consideration the operations and maintenance of a complex facility.

Summary

In comparing the operating costs for the first ten years, it is assumed that 3100 storage casks will be processed. The total operating and capital costs are compared in Table III. The multi-plate closure costs are \$1.17 MM, and the threaded plug closure costs are \$3.34 MM. The others are in between these costs.

JRL:ml

Att. (3)

cc: w/att.
JM Davis
JR LaRiviere (2)
DC Nelson

TABLE I

CAPITAL (PROJECT) COST

Closure No.	1	2	3	4
Description	Butt-Weld	Multi-Plate	Threaded Plug	Alternate Butt Joint
Welding Position	Horizontal	45°	Vertical	Vertical
Cell Floor Space Two Spaces @	10' x 16'	10' x 11-1/2'	10' x 7'	10' x 7'
Project Cost @ \$7000/ Lineal Foot	\$224,000	\$161,000	\$98,000	\$98,000

TABLE II
OPERATING COST
PER STORAGE CASK

Closure No.	1	2	3	4
Description	Butt-Weld	Multi-Plate	Threaded Plug	Alternate Butt Joint
Machining Time, hr	16	12	48	16
Cost @ \$20/hr, \$	320	240	960	320
Welding Time, hr	6	1	1	4
Cost @ \$80/hr, \$	480	80	80	320
Weld Wire, \$	33	6	6	30
TOTAL \$	833	326	1046	670

Note: The electricity costs to operate the welder are negligible.

TABLE III

OPERATING AND CAPITAL COSTS FOR
FIRST TEN YEARS (3100 STORAGE CASKS)

Closure No.	1	2	3	4
Description	Butt-Weld	Multi-Plate	Threaded Plug	Alternate Butt Joint
Operating Cost per Storage Cask, \$	833	326	1046	670
Operating Cost for 3100 Storage Casks, MM \$	2.58	1.01	3.24	2.08
Capital Cost, MM \$	.22	.16	.10	.10
TOTAL COMPARATIVE COST, MM \$	2.80	1.17	3.34	2.18

APPENDIX D

Date: January 22, 1976
To: E. L. Moore
From: J. M. Davis, 2-6682
Subject: COMMENTARY ON IMPACT OF RSSF CASK CLOSURE
CONCEPTS ON HOT CELL DESIGN AND OPERATIONS

Per your request, I have considered the impact on hot cell design and operation of the four concepts of closing the RSSF cask:

1. Butt weld in horizontal position
2. Multiple welded plates in 45° position
3. Corner weld in vertical position
4. Screw plug with seal weld in vertical position

Hot Cell Design

Many factors will influence the design of the RSSF welding cell, but the major ones which dictate dimensions and required viewing are:

1. Size of objects which must be handled.
2. In-cell equipment which must be provided to perform the required tasks.
3. Maneuvering room for required operations, such as loading and unloading containers, positioning objects relative to equipment, etc.
4. Observing, controlling and monitoring operations performed with equipment.
5. Nondestructive examinations of completed operations.
6. Repair, replacement, and maintenance of in-cell equipment.
7. Required production rate.

Cell height is dictated by the vertical handling of the cask and canister, plus viewing and manipulating the closure system and examination of the closure.

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Cell length and width is dictated by the equipment required for receiving, nondestructive examination, assembly, welding, nondestructive testing, decontamination, shipping, maneuvering room and redundancy to achieve production rates.

The cask closure system chosen will obviously affect the cell length, and may possibly affect width. Vertical handling and positioning in equipment systems requires the least maneuvering and positioning space, horizontal positioning and handling requires the most, and a 45° position would require something in between. If there are redundant welding stations, then this effect is multiplied by the number of stations.

It is difficult to discuss the effect of slanted or horizontal positioning for welding upon viewing stations, until various equipment layouts could be drawn. Accessibility of equipment for control, repair, and maintenance is so important that layouts might show the necessity for additional operating stations.

Hot Cell Operations

It is more difficult to evaluate the impact of the four closure systems on cell operations than on cell design, because so many more factors influence operations - and many of these operations factors are dependent upon design. However, one can generalize on a few points:

1. Handling heavy weights in a hot cell is always awkward and fraught with risk of damage to equipment or objects, especially when maneuvering in crowded spaces. Loads tend to swing and turn, and the heavier they are the more difficult control becomes. If, in addition, one must tilt the load or lay it down, additional in-cell guiding and alignment fixtures become necessary to prevent accidental damage. If horizontal positioning is required, then a temporary lid or other restraint is needed to prevent the canister from slipping out of the cask and changing the center of gravity to the point where the load will tilt and allow the canister to fall out.

E. L. Moore

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2. There is considerable difference in the quantity of welding wire required for the four concepts, and thus in the time required to complete the welds. The weld area must be cleaned after each pass, and the torch cleaned of spattered flux after every few minutes of welding. Thus, the butt weld will require the longest operating time, the corner weld next, the multiple plate next, and the screw plug least. This factor will certainly affect the decision on redundancy of weld stations, and will affect the maintenance and repair frequency on the equipment. In addition, cell operators who perform the welding must be very skillful, highly trained, and most responsible. The longer the welding time for each cask, the more such operators will be needed. It is hard to assess this sort of impact, but it might be quite important.

Conclusions

Without indulging in sophisticated analysis and tradeoff studies, my experience in hot cell design and operation would lead me to prefer a closure concept which is performed in the vertical position, and which requires the least welding time. I believe this would result in the least cell space needed, the least risky handling, the simplest equipment, the least redundancy to achieve production, the minimum equipment repair and maintenance requirement, and the least need for highly trained operators.

JMD: dad

cc: JR LaRiviere
DC Nelson
WH O'Brian
DD Wodrich
File