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Evaluation of the Molten Salt Reactor Experiment Drain Tanks for Reuse in Salt Disposal, Oak Ridge National Laboratory, Oak Ridge, Tennessee

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**Evaluation of the Molten Salt
Reactor Experiment Drain Tanks
for Reuse in Salt Disposal,
Oak Ridge National Laboratory,
Oak Ridge, Tennessee**

Date Issued—May 1998

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CONTENTS

FIGURES	v
TABLES	v
ABBREVIATIONS	vii
EXECUTIVE SUMMARY	ix
1. INTRODUCTION	1
1.1 REACTOR SERVICE	1
1.2 SHUTDOWN AND ANNEALING	7
1.3 POST-ANNEALING EXPOSURE	8
1.4 EXAMINATION LOADS	8
1.5 NEW SERVICE LOADS	8
2. QUALITY OF NEW AND COLD VESSELS AND PIPING	10
2.1 DESIGN PROPERTIES	10
2.2 FABRICATION	10
2.3 QUALITY CONTROL	11
3. LOAD HISTORY	11
3.1 SEISMIC, VIBRATION, INDUCED OFF-NORMAL LOADS	11
3.2 FIVE YEARS AT UNIFORM TEMPERATURE (1964 TO 1969)	12
3.3 NINETEEN YEARS WITH ANNUAL HEATUPS FOR ABOUT TWO WEEKS (1970 TO 1989)	12
3.4 EIGHT YEARS AT AMBIENT CONDITIONS (1989 TO 1996)	13
3.5 ONE YEAR CONNECTED TO THE RGRS (1997)	13
3.6 CYCLES OF TEMPERATURE AND PRESSURE	13
4. CORROSION HISTORY	14
4.1 EARLY ALLOY DEVELOPMENT	15
4.2 AUTOPSY IN 1970	16
4.3 FLUORINE EVOLUTION	16
4.4 DRY LOW TEMPERATURE EXPOSURE	16
4.5 TOTAL CORROSION	17
5. SALT PROPERTIES	18
5.1 SALT-WETTING PROPERTIES	18
5.2 THERMO-PHYSICAL PROPERTIES OF SALT	18
6. QUALITY REQUIREMENTS FOR INTENDED USE OF DISPOSING OF SALT	19
6.1 DESIGN REQUIREMENTS	19
6.2 ASME CODE SECTION VIII, DIVISION 2, ALTERNATIVE RULES	20

6.3	CREEP AND STRESS TO RUPTURE DEGRADATION	21
6.4	CORROSION ALLOWANCE	21
6.5	COMPARISON OF ASME CODE BETWEEN 1959 AND 1996	21
6.6	IMPORTANCE OF DESIGN TEMPERATURE TO WALL THICKNESS REQUIREMENTS	22
6.7	MODIFICATIONS TO PIPING BY WELDING	22
6.8	RELATED CODES AND STANDARDS	23
6.8.1	ASME B31G Manual for Determining Remaining Strength of Corroded Piping	23
6.8.2	ASME Boiler and Pressure Vessel Code	23
7.	QUALITY VERIFICATION REQUIREMENT RECOMMENDATIONS	24
7.1	PERSONNEL REQUIREMENTS	24
7.2	VISUAL EXAMINATION	24
7.3	ULTRASONIC THICKNESS MEASUREMENT	25
7.3.1	Grid Size	25
7.3.2	Code Basis for Grid Size	26
7.3.3	Statistical Basis for Sample Size	26
7.3.4	Engineering Judgment Basis for Sampling	27
7.4	EDDY CURRENT THICKNESS MEASUREMENT	27
7.5	INTERIOR CONTOUR MEASUREMENT	27
7.6	RFET	28
7.7	LEAK TESTING	28
7.7.1	Inleakage Leak Test	28
7.7.2	Pressure Decay Leak Test	28
8.	VALUE OF NDE	29
8.1	GROSS LOSS OF WALL THICKNESS MEASUREMENT	29
8.2	DIRECT WALL THICKNESS MEASUREMENT	29
8.3	DETECTION OF FLAWS	30
8.4	ALTERNATIVES FOR PREVENTION OF RISK	31
9.	RECOMMENDATIONS SUMMARY	32
9.1	ANALYSIS	32
9.2	VESSEL DESIGN	32
9.3	PROCESS DESIGN	33
9.4	INSPECTION PLAN	33
10.	REFERENCES	33
APPENDIX A	ISSUES RAISED DURING FIT-FOR-SERVICE STUDY	A-1
APPENDIX B	DIMENSIONS, NDE, MATERIAL CERTIFICATIONS FOR TANKS AND PIPING	B-1
APPENDIX C	DRAWINGS	C-1
APPENDIX D	COMPARISON OF ASME CODE FROM ORIGINAL CONSTRUCTION TO TODAY	D-1

FIGURES

1	Existing salt tanks and transfer piping	2
2	Reactor service fuel salt circuit	3
3	Temperature histogram	4
4	Pressure histogram	5
5	Conceptual sketch of molten salt transfer plan	9

TABLES

1	Minimum tank wall thickness (in inches) predicted from corrosion 1964 to 1997	17
2	Thermo-physical properties of salt	18
3	Minimum wall thickness (in inches) before corrosion from new salt transfer operation ...	19
3	Risk-reducing alternatives	31

ABBREVIATIONS

ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
ANSI	American National Standards Institute
BIO	Basis for Interim Operation
CV	check valve
CVS	cell ventilation system
FV	freeze valve
GTAW	gas tungsten arc welding
HCV	hand control valve
INOR 8	nickel alloy developed at ORNL which became Hastelloy N
Hastelloy N	nickel alloy developed for MSRE by ORNL
ksi	kips (1000 lb) per square inch
MSRE	Molten Salt Reactor Experiment
NDE	nondestructive examination
NESA	North Electric Service Area
NPS	nominal pipe size
NRC	National Research Council
RFET	Remote Field Electromagnetic Technique
RGRS	Reactive Gas Removal System
sccs	standard cubic centimeters per second

EXECUTIVE SUMMARY

This report was prepared to identify the source documentation used to evaluate the drain tanks in the Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory (ORNL). The evaluation considered the original quality of the tanks, their service history, and their intended use during the removal of fluoride salts. It also includes recommendations for a quality verification plan.

The estimates of corrosion damage to the salt-containing system at the MSRE are low enough to lend optimism that the system will be fit for its intended use, which is disposal of the salt by transferring it to transport containers. The expected corrosion to date is estimated between 10 and 50 mil, or 2 to 10% of the shell wall. The expected corrosion rate when the tanks are used to remove the salt at 110°F is estimated to be .025 to 0.1 mil per hour of exposure to HF and molten salt. To provide additional assurance that the estimates of corrosion damage are accurate, cost-effective nondestructive examination (NDE) has been recommended.

The NDE procedures are compared with industry standards and give a perspective for the extent of additional measures taken in the recommendation. A methodology for establishing the remaining life has been recommended, and work is progressing towards providing an engineering evaluation based upon thickness and design conditions for the future use of the tanks. These extra measures and the code-based analysis will serve to define the risk of salt or radioactive gases leaking during processing and transfer of the salt as acceptable.

1. INTRODUCTION

The first assumption made in the Decommissioning Plan for the Molten Salt Reactor Experiment (MSRE)¹ is that the drain and flush tanks are empty. Because the procedure for shutdown of the reactor was to drain the fuel salt from the reactor vessel equally into the two drain tanks,² and all decisions since that shutdown have been to leave the salts in place in these tanks, a project had to be conceived to empty the tanks. MSRE was shut down in December 1969. A 1972 document by P. Haubenreich and R. Lindauer³ states: "The parts of the facility that will be needed to melt and transfer the salt into transport containers are preserved." The authors observed that only one fluorination run was needed to recover the uranium (²³³U). The 1972 report includes a checklist (p. 15) to prepare for heat up of the salt inventories that includes leak testing of all piping and equipment.

The time that has passed since 1972 has created a need to evaluate the condition of the tanks to ensure that they are as ready for intended use as they were in 1972 when the operations personnel were armed with data showing that damage to the pressure boundary was minimal. The process by which the salt will be removed has evolved from the 1972 concept. The integrity of the pressure boundary is probably adequate to meet the new process conditions, but it is necessary that this integrity be verified with nondestructive examination (NDE) methods to enable the process to be implemented with an acceptable level of risk.

One significant difference between the heatup of 1964 and the one planned for 2001 is the presence of 24 kg of fissile uranium in the salt. The 1964 startup was done with empty tanks that were charged after being heated with LiF-BeF₂-ZrF₄ salt mixture for prenuclear checkout.² Today's project doesn't have the luxury of being able to perform a prenuclear checkout or heat an empty tank. Heating the tank with frozen salt in it has never been done before. There would be secondary stresses caused by heat sinking effects of the salt.

In addition to the three tanks in the drain tank cell, there is a fuel storage tank in the fuel processing cell. A total of four tanks, as shown in Fig. 1, are the only ones known to contain significant quantities of fuel salt. All of these tanks contain uranium fuel concentrations; however, only the tanks in the drain tank cell are addressed in this document. Figure 2 shows a simplified schematic of the reactor fuel circuit. Figures 3 and 4 are histograms that represent the temperature and pressure envelopes.

1.1 REACTOR SERVICE

During reactor operation the salt circuits were pressurized with inert gas, either helium or argon, to protect the Hastelloy N (a nickel alloy developed for MSRE by ORNL) surfaces from corrosion while the fuel salt circulated from the reactor to the heat exchanger through a pump (see McCoy, p. 2).⁴ When the reactor was returned to standby, the fuel salt was routed to the drain tanks by gravity flow and the salt was essentially static in the drain tanks at nearly constant temperature with the same protective cover gas.

There were 24 drains of the fuel into the drain tanks (see Table 4-2 of TM-3039²) for various reasons. The drain piping was always full and tanks were either full or partially full until fuel salt

Fig. 1. Existing salt tanks and transfer piping.

Fig. 2. Reactor service fuel salt circuit.

Fig. 3. Temperature histogram.

Fig. 4. Pressure histogram.

was transferred to the reactor fuel loop. Depending upon operational needs, the piping was maintained at temperatures between 900 and 1100°F. The duration of drain tank exposures to >900°F fuel salt during the reactor operation accumulated into about 12,650 h from 1964 to 1970 (see Tables 4-11 to 4-14).² During this same period, the drain system, including piping and reactor, was at temperatures >900°F for 31,000 hr.² Afterwards, the salt was frozen with an inert cover gas that has been at ambient temperature except for 20 "annealing cycles," which will be discussed in the next section.

The fuel salts have been a source for tellurium and uranium, which can "attack" the Hastelloy N. The attack can be by intergranular attack due to the formation of molybdenum telluride or chromium depletion corrosion by the reaction $2\text{UF}_4 + \text{Cr} = 2\text{UF}_3 + \text{CrF}_2$ or by carbide precipitation.^{4,5,6} Hastelloy properties are known to degrade from the formation of carbides in the grain boundaries. The fuel salts were nominally composed of 65% LiF, 30% BeF₂, 5% ZrF₄, 0.8% UF₄ when the reactor was operating.⁴ In addition, the salts were a source of some radiation which may have increased the corrosion rate normally assumed for dry corrosion as suggested by the National Research Council (NRC) in its evaluation (p. 43).⁷

During reactor operation, the cells were maintained at a maximum concentration of 5% oxygen in a nitrogen blanket (p. 5).⁸ This precaution was to minimize oxidation of the Hastelloy because it had only 7% chromium and was susceptible to higher oxygen concentration attack as well as to safeguard the fuel salt.

The post-operation study of the heat exchanger, which had 5% oxygen on the outside of the shell, fuel salt in the shell and coolant salt in the tubes, inferred that the air side got as much or more damage than either the coolant or the fuel side: 10 mil air side versus 6 mil fuel side and 5 mil coolant side.⁴ In the same report on p. 160, an analysis of freeze valve 105 made the point that the air side had attack likely involving the removal of chromium and iron that was not observed on the salt side of the fill line.

To complicate the corrosion model further, data from the convection loops (both forced and free convection) showed that the salt can create a mass transfer of chromium from a hot region to a cooler region of the loop so that chromium and iron may be removed at a hot spot and redeposited as a metal in a cooler spot.⁶ The drain system was operated at a uniform temperature as much as possible, and salt was often static in the lines for long periods during operation. It is likely that the experimental convection loops experienced higher mass transfer rates than the MSRE drain piping, since forced flow at constant temperature was the main driving force in the salt circulation system. That is, salt would be either: 1) in the fuel circuit where it was pumped between temperature gradients or 2) in the drain tanks where it was static at nearly constant temperatures. No mention is made in the heat exchanger analysis of differences in chromium from the hot to the cold end. In fact, the chromium depletion attack in the heat exchanger is stated to be minimal (6 mil over 21,000 h).

One breach of the primary containment is known to have occurred when a small crack in the toe of a fillet weld attachment to a freeze valve opened enough to leak fuel salt into the drain tank cell. This occurred on the last day of operation when the reactor fuel was being transferred to the drain tanks. Analysis of the failure concluded that thermal fatigue was the cause of the crack—not corrosion.⁴

Grinding wheels were used to cut the piping around the freeze valves even with salt in the pipes. Some torsion of the pipes and vibration was transmitted through the system as the components were removed for examination at the High Radiation Level Examination Laboratory. These loads were

of short duration, usually a week or less during the campaign that lasted from January to March 1971 (described in the semiannual report for February 1971 by Haubenreich).⁹

Freeze valve (FV) 105 was used to isolate drain tank 2 from drain tank 1 and the reactor drain line 103. The line was filled with salt at temperatures above 500°C for about 21,000 h, and the salt static except when the reactor was being filled. FV105 was removed from the system and was taken to hot cells for examination. Corrosion from both intergranular attack (0.75 mil) and depletion of chromium and oxide film on the cell side (2 mil) was measured by McCoy to be on the order of 3 mil.⁴ The FV105 data may be the most pertinent to evaluating the drain tank system because the other data are about the exposure of parts from the fuel circuit such as the heat exchanger and surveillance specimens that were hanging at the belt line of the reactor.

1.2 SHUTDOWN AND ANNEALING

The last time the drain and flush tanks were heated was in December 1989 to recombine radiolytic fluorine (pp. 1-12).¹⁰ The heating cycles, known as annealing cycles, were intended to recombine the radiolytically liberated fluorine and were performed each year from 1970 to 1989 for about a week (some campaigns took two weeks) at temperatures between 300 and 500°F.^{11,12} The salt containment system has been at ambient temperature (except for these 20 annealing cycles) and nominal pressures well below 50 psig since 1970. During the annealing cycles, the pressures were maintained below atmosphere via the off gas lines.

Since shutdown of the reactor in 1969, the wetted surfaces of the drain system have been exposed to inert blanket gas mixed with radiolytic fluorine, UF₆, MoF₆, small amounts of HF (per analysis taken in 1994) in the freeboard areas, and solid fuel salt with diffused gases that have the potential to corrode.¹⁰

The salt transfer line to the reactor was severed and plugged with a copper-tapered plug that was driven into 1½-in. line 103. FV105 and FV106 were removed and the ends of lines 104, 105, and 106 were fitted with a copper plug and sealed by a clamp-and-screw mechanism.⁹ The seal effected by these clamps was tested at installation to ensure a leak-tight plug.² Infiltrated air was not monitored in many of the lines communicating to the tanks planned to be used for the salt transfer operation until the Reactive Gas Removal System (RGRS) was installed in 1997. But the presence of only trace amounts of HF indicate that infiltration of water has not been gross.¹⁰ Outleakage through the copper plugs has not been detected with sensors in the cell atmosphere even though some estimates of the pressure behind the plugs are as high as 50 psi. Nevertheless, a step in the procedure for assessing the tanks for further service should include a verification of the leak tightness of these plugs as was recommended by Haubenreich.³

Lines 107, 108 and 109 are believed to be still intact for use in transferring the salt from the drain tanks and flush tank to the storage tank in the adjacent fuel processing cell via line 110 (see Fig. 1). The isolation of the tanks through these lines is provided by the valves FV110, FV111, ESV609B, FV107, FV108, FV109, check valve (CV) 609B, and CV609A. The tanks are also connected to the off gas and system and pressure transmitters. Isolation is provided by ten points: V561, V571B, hand control valve (HCV) 533, HV-1B or HCV573, HCV575, HCV577, V572A, V574A, and V576A. The isolation now in the system may be adequate for pressure-testing the system as a whole, but it is doubtful that the integrity of the freeze valves will provide a leak rate low enough to not mask local individual pressure boundary leaks.

1.3 POST-ANNEALING EXPOSURE

After uranium migration to the charcoal bed was detected in 1989, the annealing procedure was terminated, and the tanks were isolated from the auxiliary charcoal bed with a blanket gas of helium at 18-psia pressure. Prior to 1989 (perhaps as early as 1985), migration had been manifested in other parts of the system such as the North Electric Service Area (NESA); however, the annealing cycles persisted until 1989. The radiolytic formation of fluorine and the concomitant generation of volatile gases such as UF_6 and MoF_6 were monitored with available pressure and temperature sensors. Some pressure sensors became inoperative during the annealing years, and reliable recorded pressures are unavailable even up through 1994. As the pressure sensors were restored, the indicated pressures did not exceed 26 psia. There are still some trapped volumes in the system that could be at higher pressures but no evidence will be available until the salt plugs are removed and the RGRS has successfully reduced the entire gas space to subatmospheric levels.

The basic assumption for beginning the molten salt disposal project is that the RGRS will reduce the pressure everywhere to near 0 psia. This is expected by August 1998, and plans are to then begin the in-cell examination of the tanks and associated piping needed for the hydrofluorination and transfer of molten salt from the drain tanks for fluorination of uranium (^{233}U) and subsequent removal of the uranium and salt by 2003.

1.4 EXAMINATION LOADS

The loads that will be imposed during the examination to assess the integrity of the pressure components will come from the attachment reactions of fixtures, the cutting and welding fixtures, the stresses from welding and cutting, and the pressure from cover gases used during the pressure test. All the examination work should be done at ambient temperatures. The test pressure should be adjusted to account for the lower strength of the Hastelloy N at elevated temperatures of 1000 °F or more.

1.5 NEW SERVICE LOADS

The loads that will be imposed during the salt transfer operation include thermal stress during heating, primary stress from internally pressurizing for the transfer, weight of transferred molten salts flowing through the lines to the new receptacles connected to receive the salt for disposition, and static reactions to attached valves or other process equipment. It is recommended that attached equipment loads be delivered to a separate support system to keep them from being delivered to the tank or transfer piping.

As outlined in ER 380,¹⁰ the duration of these loads will be as required to empty the three tanks and connected piping into the receptacles for disposition. Each receptacle has a limiting volume that may necessitate about 60 pressure cycles. This will translate into 15 to 30 cycles per tank if each tank is treated one at a time. A cycle would end when the flow is shut off and a receptacle is replaced by a new, empty one.⁴³ Figure 5 shows a conceptual arrangement for this transfer process.

Plans are for these cycles to occur daily with the heated system being maintained at steady-state temperature at 1000 to 1200°F for 3 years. Contingent plans should require that ten thermal shutdowns and reheats also be planned. These cooldowns and heatups should be controlled at a rate

Fig. 5. Conceptual sketch of molten salt transfer plan.

of 100°F per hour by modulating the heater power to control the imposed thermal gradients and stresses on the tanks and piping as was done during the original reactor operation.²

This report will address the as-built quality of the system components, the in-service history including loads imposed and exposure to corrodants during operation and shutdown, and the quality requirements for the intended use of transferring salt to receptacles. It will also discuss the required verification of quality and structural integrity of the system including suggested NDE methods and will present a comparison with related but nonmandatory national standards that may give a measure of merit to the analyses and examinations used to verify the system is fit for use to transfer molten salt.

2. QUALITY OF NEW AND COLD VESSELS AND PIPING

The quality records available for the vessels and piping when they were new were reviewed. The values in Table 1 were derived from these records, which included drawings (some as built), MSR 62-3 Fabrication Specification, TM-728 Design Description, MSR 61-67 Design Report Calculations.¹³ There is still some Hastelloy N material available at Y-12, Bldg. 9201-3, Rm. 181, filed under IR8405 in the Engineering Technology Division store, according to Jack Wells of Quality Engineering. Certified Material Test Reports are available from Mr. Wells for the heats listed in Appendix B. Several lengths of 1½-in. schedule 40 pipe have been transferred to the MSRE facility under the custody of Fred Peretz.

2.1 DESIGN PROPERTIES

There was a reduction taken in the early calculations for unknown radiation effects on the tensile properties, however, that reduction was not incorporated into the final design of the drain tanks.²³ The material was thought to have negligible corrosion susceptibility based on research at ORNL, so there was no corrosion allowance in the calculations. The allowable stresses used were from code case 1315.³³

McCoy's post operation report⁴ showed measured degradation of 50% for fracture strain at 1200°F. The yield and ultimate strength degradation was not as dramatic as creep degradation, but there was about 10-ksi decrease (20%) in ultimate strength. These data should be used to support a decision to use 80% as a factor for thickness calculations. See the discussion on design requirements and API RP579 standards. Strain to fracture is still not a criterion for tank design because American Society of Mechanical Engineers (ASME) allowable stresses will be used, but it should be addressed in the analysis to show that strains will not approach 20%.

2.2 FABRICATION

Quality control for fabrication was instituted with resident inspectors at Y-12 who reported to Mr. A. Taboada, who implemented the specifications found in MSR 62-3.¹⁴ Each indication of a flaw was dispositioned per his instruction or guidelines from the specification. Welds were dye checked and ultrasonically and radiographically examined when practical. Only trained and qualified welders with demonstrated ability to control the gas tungsten arc welding (GTAW) process with Hastelloy N

were permitted to weld MSRE parts, and their names were checked and recorded on the weld reports for each joint.

2.3 QUALITY CONTROL

The longitudinal and circumferential welds, category A and B, type 1, were all radiographed following a dye check of the root and final passes. The circumferential welds were left in the as-welded condition except for irregularities, which were ground to match the contour of the welds. The heat-affected zone and a small area beyond were examined with a longitudinal ultrasonic beam for possible delaminations. The thickness of all vessel shell and head components was measured at the manufacturer (Haynes Stellite) and again upon receiving inspection at Y-12. All nozzle welds were full penetration groove welds; most were butted to the head as "saddle-on," but the drain and fill lines were through-the-head, full-penetration welds.¹³ The welds in the head that were done to plug holes in the straight flange were full-penetration, type 1 welds that were accepted by radiography and dye-check examination.

The heads were formed in Paducah and were solution-annealed at 2150°F for 1 h. The thimbles were individually leak tested to 10^{-8} sccs. The finished tanks were helium mass-spectrometer leak-tested with a system sensitivity of 10^{-8} sccs. The tanks were hydrostatically tested to 550 psig based upon a design pressure of 65 psig at 1300°F. The as-built dimensions of the height and inside diameter were recorded on the drawing and read "as built."

3. LOAD HISTORY

3.1 SEISMIC, VIBRATION, INDUCED, OFF-NORMAL LOADS

Mechanical loads from gravity have been delivered to the supports or connecting flanges on the tanks as originally designed. Seismic loads have not occurred.¹⁵

Vibratory loads were trivial because the operation of the fuel-circulating system pumps did not produce fluid momentum-induced vibrations according to the comments of R. Engels in a meeting on September 9, 1997. Flow regimes did not impart impact loads to the piping judging from the fact that gravity flow was adequate for normal drainage of the fuel salt from the reactor. Guymon states that 9 to 11 min was all that was needed to drain fuel from reactor by gravity—approximately .14 cfs or 10 fps² (p. 91).

Residual stresses that may have resulted in body force changes to the pressure boundary have not been monitored. Any stress relief that occurred during reactor operations was probably gradual, and any stress relief during the annealing cycles was probably small because the temperatures were not sufficient to provide much metal annealing.

Work done in the drain tank cells in 1970 for the post-operation examination to remove sections of lines 103, 104, 105, and 106 may have permanently deformed lines connected to the tanks, and this condition should be checked during the visual examination. The intent of the 1970 operation was to provide data that would verify that the transfer lines and tanks could be used again to remove the salt, so it is unlikely that there was any careless damage.

The annealing cycles that took place between 1970 and 1989 were done at pressures specified to be subatmospheric, so the pressures of gases that occupied free spaces and unplugged lines were not significantly raised by the heating to 500°F. However, gases in trapped volumes that experienced temperature increases on the order of 500°F could have reached significant pressures, but not overpressures. A 15-psia constant volume heated from 75 to 500°F would only increase to 27 psia, and a 30-psia volume would only increase to 58 psia, well below the allowable pressure for the system at 500°F.

It is unlikely that any yielding took place during the annealing cycles unless there was a pocket of trapped liquid UF_6 involved. But UF_6 could exist as a liquid only in spaces where the pressures and temperatures satisfied the phase diagram. In any region where the pressure is subatmospheric, liquid UF_6 could not form. The condition where liquid UF_6 is trapped in the tanks by condensation upon cooling in voids above 22 psia would require a complicated thermodynamic path beginning with desubliming (unlikely) in a space where there is no communication to lower pressure volumes (where the UF_6 came from in the first place) and the surrounding packing density of the solid is sufficiently tight that there is <30% local void volume in the pocket.

Solid formations of UF_6 in the off-gas lines are not likely to be the site of liquid formation for the same reasons. Were heat transferred to the middle of a plug or volume between plugs, then there could be a trapped volume expansion and subsequent damage to the line, but it is unlikely that such a condition exists for the annealing campaigns. So it is also unlikely that the lines suffered high stresses from expanding liquid phase UF_6 .¹⁶

3.2 FIVE YEARS AT UNIFORM TEMPERATURE (1964 TO 1969)

R. Guymon states that after initial heat up, the system was maintained at 1200°F until shutdown in 1969. There was helium gas conditioning to limit the O_2 and H_2O to less than 1 ppm by passing it through a molecular sieve and a titanium sponge² (p. 161). The steam dome was tested on 2/17/64 by filling drain tank 2 with flush salt and admitting 40 gal of water to the dome (p. 133). The condenser flow was 40 gpm, and the bayonets lowered the salt temperature at 86°F/hr (139 kw). A conductivity probe was used for hi-lo salt level reference (p. 129). Freeboard (or headspace) in the drain tank, when full of salt, may have been 35 in. [half full, the freeboard was perhaps 62 in.].

3.3 NINETEEN YEARS WITH ANNUAL HEATUPS FOR ABOUT TWO WEEKS (1970 TO 1989)

The annealing procedure was executed at subatmospheric pressures. Changes in the thermodynamic state of volatile gases that may have produced local stresses where there were trapped volumes probably did not occur. The thermal conditions before, during, and after annealing would normally serve to remove UF_6 from the salt. Before annealing there is heat from radiation (gamma radiation naturally produced by the salt, or gamma heating) in the salt that should produce a temperature gradient between the salt and metal surfaces away from the salt. Any UF_6 solid in the salt would, if a gas path existed to the ullage, sublime from the salt and desublime on the cooler surfaces away from the fuel salt. Heating would accelerate the temperature difference. During cooling the UF_6 would condense away from the salt at the cooler surfaces.¹⁶ For damage to result, the salt chambers would have to have considerable strength to contain expanding liquid or gas.

Nevertheless, particular attention to assess the possibility of plastic deformation from trapped gas should be given to the drain cup and the thimbles and the ½-in. schedule-40 lines that are known to have been plugged.

3.4 EIGHT YEARS AT AMBIENT CONDITIONS (1989 TO 1996)

Since December 1989,¹⁰ the tanks have been at ambient temperatures established by the drain tank cell. The internal pressures in the tanks were monitored on pressure indicators 572, 574, and 576 in the NESA. These pressures are not thought to have exceeded 50 psia. Plugs in the transmitting lines and malfunctioning gauges rendered the readings unreliable. The pressures were not controlled, and monitoring logs recorded the events and pressures as they were observed. Radiolytic accumulation of fluorine transpired to produce a dry corrodant, but did not significantly increase the pressure. An analysis in 1994 showed a partial pressure of fluorine of 350 mm Hg, 305 mm Hg of inerts, 69 mm Hg UF₆, 5 mm Hg CF₄, 1 mm Hg of HF in a total pressure of 740 mm Hg. A later estimate in 1997 put the pressure of fluorine at 1000 mm Hg in a total pressure of 25 psia.⁴⁵

When the RGRS was valved into line 542 to begin removing reactive gases, the pressures on these gauges were used to measure the effectiveness of the gas removal process in reaching the tank spaces.

3.5 ONE YEAR CONNECTED TO THE RGRS (1997)

Because the RGRS is a passive system that relies upon negative pressure to withdraw the reactive gases, there were no positive pressure increases in the tanks. One exception to this statement is that a few injections of ClF₃-helium mixture were injected at 37 psia to dissolve plugs from the RGR side of the system. There were pressure fluctuations in the tank side of the system from a high of 26 psia to 13 psia in drain tank 1. Drain tank 2 remained at 26 psia during the reactive gas removal processing until a plug was dissolved on January 5, 1998. Since then, the pressures in the two tanks have been equal and have decreased with subsequent gas removal cycles.

3.6 CYCLES OF TEMPERATURE AND PRESSURE

Per ASME Code requirements, the initial hydrostatic tests were performed at room temperature immediately after fabrication¹³. The tanks were heated while empty. The initial salt charge ended on March 4, 1965.²⁸ The transfer pressure for moving flush and fuel salt was on the order of 5 to 7 psig. Salt circulation in the reactor fuel loop was essentially atmospheric, and reactor drain was typically gravity flow. Flush salt was circulated for 1000 h and then stored in the fuel storage tank to await processing to remove oxides. Fill and drain tests as well as helium leak tests at 40 psig were performed during 1964.²⁹ On April 21, 1965, drain tank 2 was charged with 4560 kg from 35 carriers. No uranium was present in the salt. On May 24, 1965, fuel carrier salt was circulated for ten days and then uranium was added from four separate canisters. The first criticality was achieved on June 1, 1965. The fuel system was drained in preparation for full power operation. Uranium was added to drain tank 2 in four charging operations. Each operation included transferring to drain tank 1 and back again to ensure mixing. After zero power experiments were concluded on July 4, 1965, the fuel was drained and the flush salt filled the loop. Maintenance activities went to December 20, 1965, when the reactor again reached criticality.

On January 24, 1966, the reactor was taken to 1 Mw. An attempt on February 15, 1966, to run at 1 Mw did not last more than 47 h before another drain had to be made³⁰ to deal with the plugging problems. The fuel was again drained, and work to clear the several plugs ensued. A sixth run began on April 15, 1966, and ran up to full power until May 16, 1966. Full power run was resumed on June 13, 1966 (run #7) and continued to July 17, 1966. It appears that the tank heaters were modulated to bring the metal temperature down to 900 to 1000°F while the fuel was in the reactor loop.³¹ As of August 31, 1966, there had been 20 fill and drains.

The final reactor run, #20, was completed on December 12, 1969, with a flush cycle completed on December 14, 1969,³² and the heat turned off the drain tanks. Four days later, temperatures in the tanks reached salt liquidus temperature. On January 5, 24 days after the drain, fuel temperatures were near the solidus, and the tank heaters were turned on at low settings to hold the salt in the range 450 to 650°F. (This range was chosen to preclude the evolution of fluorine by radiolysis.)² On p. 24, Guymon reported that

The tanks are filled with helium at 0.5 psig with gas inlet and outlet lines blocked. Equalizer lines between the fuel circulating loop [in the reactor] and the drain tanks are open....The cell aircoolers are shut off, with the cell air at about 140°F.

When the fuel and flush salts began to freeze on December 18, 1969, it was the first time that any salt had frozen in the fuel system (other than freeze valves) since the first loading of molten salt into the drain tanks on November 28, 1964. There had been no difficulty keeping the salt molten throughout the intervening 44,364 hours.

For 21,778 of these hours the fuel was circulating in the fuel loop (i.e., not in the drain tanks) according to Guymon's Table 1.1. Based upon this report, there was only one heating cycle to reach metal temperatures near 1200°F. The heatup rate was held to 100°F per hour and the cooldown was even slower (approximately 100°F per day). Figure 1.2 of the report also shows 13 flush cycles, indicating that the flush salt was almost always in the flush tank.

Each year until 1989, the tanks were heated to 500°F for the purpose of recombining fluorine that could have been generated from the radioactive salt. These heatups were termed "annealing cycles" referring to a restructuring of the salt. After 1989, the tanks have been left at ambient temperature and near atmospheric pressure. However, the pressure did increase during annealing to perhaps twice what it was before heating. Because of trapped volumes, there appear to be conditions where the pressure gradually increased perhaps to 26 psia cold and near 50 psia heated. The plugged volumes made it impossible to directly measure selected pressures, and not until 1997 were the pressures in the tanks directly measured again.

4. CORROSION HISTORY

Hastelloy N suffers from attack by carrier salts, uranium salts, tellurium fission products in the salts and cell atmosphere. Also, carbide precipitation can occur that may lower the ductility properties. The sum total of all attack mechanisms is estimated to result in less than 10 mil of measurable wall loss.⁴² The loss in ductility is thought to be insignificant for the intended use of the drain tanks.

Intergranular cracking will not be detected by thickness measurements. The following discussion will list the estimated damage from mass transfer as well as intergranular attack. The

intergranular attack will in some cases not penetrate any deeper than the oxidation films formed by mass transfer. Voids in the films are usually attributed to dissolving the film in the salt. An analysis of the existing data requires that the conditions in the drain tanks be compared with the components analyzed because they were exposed to different corroding conditions.⁴²

Sampling the salt for concentrations of elements in the Hastelloy that may have transferred to the salt provided a method for determining the soluble elements known to leach chromium and molybdenum. The migration is usually accelerated by temperature increases. The presence of uranium causes chromium depletion.¹⁷ Oxide film forms with nickel and molybdenum and temperature drives the growth of this film.¹⁸

Intergranular attack is associated with the diffusion of tellurium into and carbide precipitation in the grain boundaries. The microstructure becomes cracked when stressed beyond the strength of the affected telluride or carbide, and the cracks may or may not grow deeper with time and/or increased temperature.⁴

4.1 EARLY ALLOY DEVELOPMENT

Mr. Al Taboada's work on early corrosion loops to develop Hastelloy N showed that chromium would dissolve from the Hastelloy into the salt at the high temperatures of the loop and plate out as metallic chromium at the lower temperature regions of the loop. This behavior was demonstrated by micrographs taken at different temperature zones around the loops. According to the author's notes from a conversation with Mr. A. Taboada, molybdenum was added to the alloy for creep strength, chromium was limited to 7% for corrosion resistance, and nickel was known to be compatible with the salts.

Corrosion of metals in salt mixtures occurs by oxidation of the metal components to their fluoride salts, which are readily dissolved by the molten fluorides. This precludes any possibility of protection by passivation of the metal surface by corrosion products, and the extent of corrosion is then controlled by the thermodynamic driving force of the oxidation reaction. Corrosion is manifested by the selective oxidation and removal of the least-noble constituent. In INOR 8 this is chromium. Subsurface voids appear in the depletion zone.

(Note: INOR 8 is a nickel alloy originally developed for MSRE, later called Hastelloy N.)

The oxidation rate of binary nickel-molybdenum alloy passes through a maximum for the alloy containing 15% Mo, and the scale formed by the oxidation is NiMoO_4 and NiO . Upon thermal cycling from 1400 to 660°F, the NiMoO_4 undergoes a phase transformation that causes the protective scale on the oxidized metal to spall. Subsequent temperature cycles then result in an accelerated oxidation rate. Alloys containing more than 6% Cr are insensitive to thermal cycling and to molybdenum content because the oxide film is predominantly stable Cr_2O_3 . For temperatures up to 1200°F, the oxidation rate is not measurable; it is essentially 0 after 1000 h in static air. It is estimated that oxidation of 2 mil would occur in 100,000 h at 1200°F.¹⁹

The depth of this type of attack was reported by McCoy as 5 mil in the report that discusses FV105 (*Postirradiation Examination of Materials from the MSRE*).⁴

4.2 AUTOPSY IN 1970

Postirradiation Examination of Materials from the MSRE is a report on the "autopsy" of eight selected components from the salt system. Included in the report are the FV105, heat exchanger, radiator, sampler cage, and control rod thimble. These parts had little or no neutron damage but there was still oxidation damage from the cell atmosphere and damage from the fuel or cooling salt. From 1965 to 1970, these parts were at 1200°F for 30,000 h while the reactor was in service. The combined corrosion from oxygen and salt and intergranular cracking reported was on the order of 5 mil⁴ as shown in micrographs of Figs. 38 and 39.⁴

Corrosion in the coolant tank was minimal because there was no uranium in the salt circuit. Surveillance samples in the reactor came from both the salt side and the cell side (i.e., <5% oxygen). The outside specimens appeared to have oxidized about 5 mil into the microstructure (p. 14). The salt-side specimens appeared to have microstructural changes about 1 mil deep from cold working and 4 mil from chromium depletion (p. 19). Corrosion of the total wall on the order of 10 mil was reported for the coolant salt components.

4.3 FLUORINE EVOLUTION

The reactor was flushed only nine times during its nuclear operation.²⁰ Each time, the flush salt accumulated only 0.4% of fission products. Thus the potential for fluorine attack from radiolytically evolved fluorine was considerably less in the flush tank than in the drain tanks. The drain tanks, in contrast, have an inventory of perhaps 25,000 curies providing an energy source to liberate fluorine. The fluorine liberation occurs when both an energy source and a low temperature state of the salt mass exist simultaneously.

From 1970 to 1989, the liberation of fluorine was addressed by heating the drain tanks to at least 300°F one or two weeks per year. The rationale for this procedure came from experiments with a ⁶⁰Co source and instrumented capsules of salt in 1964 by H. Savage.²⁰ At shutdown in 1970, the fission products inventory was estimated at 10,000,000 curies. Even at this energy level, the estimates for fluorine liberation were not large (.12 psi/week in the drain tanks). It was thought that reheat would recombine the fluorine, and the pressure would decrease to equilibrium conditions so there was no long-term accumulation of the corrodant fluorine. After 1989, the energy levels were greatly reduced and reheating was terminated so fluorine attack was still minimal. The total attack may have been as much as 10 mil from fluorine and 10 mil from oxide and intergranular attack. A more plausible estimate of attack is zero from oxidation and about 1 mil from F₂ or HF attack.¹⁸

4.4 DRY LOW TEMPERATURE EXPOSURE

For the eight years after annealing cycles were terminated, the corrosive atmosphere was from fluorine liberated from the salt radiolytically in combination with the effects of uranium and tellurium deposits and static air on the cell side. Dry fluorine attack during this period has been estimated at 1 to 10 mil.¹⁸ Intergranular attack during this period would probably have been zero.⁴²

4.5 TOTAL CORROSION

A plausible estimate of total corrosion is 10 mil from 1964 to 1997.⁴²

Period	Probable Wall Loss (includes voids & cracks)	Source
1964 to 1970	5 mil	ORNL/TM-4174, McCoy
1970 to 1989	1 mil	Fluorine Corrosion, Pawel
1990 to 1998	1 mil	Fluorine Corrosion, Pawel
Total	7 mil	—

The components' predicted thickness based on this corrosion estimate and 6 % undertolerance permitted by code is shown in the following table. Comparing this table with the table for thicknesses required in Design Requirements (Table 3) shows that there should be enough wall thickness in the drain cup and thimbles to meet the requirements derived by applying simple Section VIII rules.

**Table 1. Minimum tank wall thickness (in inches)
predicted from corrosion 1964 to 1997**

	Drain Tank 1	Drain Tank 2	Flush
Heads	.695	.695	.695
Shell	.460	.460	.460
Drain cup	.134	.134	None
Thimble	.126	.126	None
Drain line	.092	.092	.092
Vent line	.092	.092	.092
Pressure tap	.092	.092	.092
Level probe	.147	.147	.147
Fill line	.115	.115	.115
Access port	.193	.193	.193

5. SALT PROPERTIES

5.1 SALT-WETTING PROPERTIES

Salt can change from wetting to partially wetting to nonwetting depending upon the oxide state of the molten salt. Metallic zirconium, for example, changed the wetting angle to about 20 degrees (wetting). Nickel fluoride powder changed the wetting angle to 90 degrees (partially wetting) for a short period before it returned to nonwetting (>140 degrees). Thus, Cooke infers that the homogeneous salt mixture does not wet Hastelloy N (see p. 68 of ORNL-4676).

On cooling the salt mixture to 813°F, crystalline LiBeF_4 forms in the salt. At 808°F, Li_2ZrF_6 begins to crystallize. At 781°F, LiUF_5 begins to crystallize. Liquid is present until 662°F is reached, when BeF_2 finally freezes (in a glass form).²¹

5.2 THERMO-PHYSICAL PROPERTIES OF SALT

(65% LiF , 30% BeF_2 , 5% ZrF_4 was fuel, 66/34 LiF/BeF_2 Coolant and Flush Salt).^{2, 21} The information in the following table was taken from ORNL/TM-3039 (Guymon 1973), p. 111.²

Table 2. Thermo-physical properties of salt

		Fuel	Coolant
Thermal conductivity ²	BTU/hr-ft-F	.832	.659
Thermal expansion ²¹	/C	2.1×10^{-4} @ 872F	
Viscosity ²	lb/ft-hr	18.7	23.6
Density ²	lb/ft ³	141.2	123.1
Density ²¹	lb/ft ³	140@1000°F	
Specific heat ²	BTU/lb-F	.4735	.577
Film coefficient ²	BTU/hr-F-ft ²	1497	1989
Surface tension ²²	dyne/cm	250	250
Surface tension ²¹	dyne/cm	260-.12T(C)	
Vapor pressure ²¹	torr	$\log P = 8 - 10,000/t(K)$	
Liquidus temperature ²¹	Fahrenheit	813	
Sonic velocity	m/sec	3420@900F, 3200@1260F	

6. QUALITY REQUIREMENTS FOR INTENDED USE OF DISPOSING OF SALT

Remaining life calculations are needed to determine the minimum permitted wall thickness of the components in the system. Calculations are also needed to determine the maximum allowed flaw size. A corrosion rate and intergranular crack growth rate, as well as a design life, will be needed for these calculations.

While there is no mandatory reason to use the ASME Code, it is simpler to satisfy the code than to reinvent an acceptance criteria. There is some precedent to using the code through DOE command media—the AEC Safety Rules 550, in effect in 1960, required that the pressure vessels be designed to the ASME code. An even later DOE Order in the 5480.4 calls for new pressure vessels to be stamped with the ASME symbol. It is, of course, impossible to stamp the drain tanks, but it is not unreasonable to use the design rules of the ASME code to calculate the remaining life. It is appropriate to choose Division 1 of Section VIII for two reasons: 1) Division 1 permits Hastelloy N to be used to 1300°F and 2) Division 1 was the code of record for the original construction in 1960. Division 2 provides a method for determining the level of fatigue analysis necessary, and these rules should be used as guidelines taking into account the known effects on creep and rupture strength of the last 30 years' exposure.

6.1 DESIGN REQUIREMENTS

The maximum allowable temperature gradient along the tank wall is 4.7°F/in. or 284°F over the entire tank height.²³ This value may be changed if it is demonstrated by upgraded analytical methods that a larger gradient will not exceed the code allowable for secondary stresses. Similarly, through-wall gradients should be qualified by analysis.

Using design conditions of 1100°F and 65 psig, corrosion allowance of 15 mil that includes intergranular crack growth, a 3-year design life, 60 cycles of pressure at 1100°F between -15 psig and +65 psig, joint efficiency of 1.0, and an API "strength factor" of .8, the following table of thicknesses has been calculated from the ASME Code formula UG27(c)1 and UG28 for shells and UG32(e)2 for torispherical heads.^{24,26} Design life is taken from the process plan, and cycles are taken from the conceptual design.⁴³ Corrosion allowance is based upon hydrofluorination in the drain tanks. Temperature based upon recommended design condition.

**Table 3. Minimum wall thickness (in inches)
before corrosion from new salt transfer operation**

	Drain Tank 1	Drain Tank 2	Flush
Heads	.259	.259	.259
Shell	.176	.176	.176
Drain cup	.065	.065	None
Thimbles	.065	.065	None
3-in. access	.083	.083	.083

Comparing the values in Table 3 with those in the Table 1 from the exposure of 33 years indicates that the anticipated actual thickness will be greater than the required calculated thicknesses. It is important that in situ thickness measurements be made. Thickness measurements that are accurate within 30 mil should be taken often enough that there are no regions where there is more than 67% loss of wall. Alternatives to a Section VIII, Division 1 analysis may be justified, depending upon the actual measurements taken of the wall thicknesses.

It should be noted here that selection of higher design temperature will rapidly reduce the ability of these tanks to meet the code, and the accuracy and reliability of the measurements will have to drastically improve at significant cost.

6.2 ASME CODE SECTION VIII, DIVISION 2, ALTERNATIVE RULES²⁶

Division 2 must be used to evaluate the need for fatigue analysis per paragraph AD160 of the code. The bottom cup detail and nozzles may be evaluated per AD160.1(e), which requires that "major thickness change between adjacent members" be evaluated on the basis of experience or detailed stress analysis. Furthermore, a fatigue analysis is not required if the sum of the conditions below are less than 1000 cycles. As can be seen from the discussion below, items a-c are readily satisfied.

- (a) Expected full range pressure cycles, plus

The expected full range cycles from the intended use is 60. The history of the tanks shows about 20 cycles at 50 psig.

- (b) Expected range of pressure cycles that exceed 20% of the Maximum Allowable Working Pressure (MAWP), plus

Transfers within the drain tank cell took place at about 7 psig, far less than the 40 psig needed to count as a cycle.

- (c) Effective number of changes in metal temperature between any two adjacent members is determined by the table.

Adjacent metal temperatures differed by only small amounts—generally less than 4 degrees per inch. The tanks were heated to operating temperatures while empty.

The sum of these cycles is 80 to 100 cycles. No further cyclic analysis is required according to Division 2 Alternate Rules.

It is interesting to observe that the fatigue cycle curve in Figure 5-10.2 of the ASME code will permit 1,000,000 cycles for a membrane stress of 12,400 psi and a temperature of 800°F. The properties of the Hastelloy at 1100°F are still adequate to justify more than enough cycles to perform the transfer of the salts under pressures of 50 psig. One can turn to the original development work by Swindeman for the alloy INOR 8 to support this interpretation.

6.3 CREEP AND STRESS TO RUPTURE DEGRADATION

Referring to Swindeman's early work, it can be seen that the difference between tensile at 800°F and 1100°F is about 14% (110 versus 95 ksi) (Fig. 8).²⁷ Figure 20²⁷ shows that time to rupture at stresses much greater than 12,400 psi is more than 100,000 h at 1100°F with salt exposure. Time to rupture in air is even longer as is shown in Fig. 36.²⁷ Carburization of 10 mil on the surface does affect the tensile by 11% as shown in Fig. 11,²⁷ and time to rupture and some estimate of the extent of carburization should be made to complete the argument that fatigue analysis is not affected by the presence or absence of carburization. According to Mr. Swindeman,

The only area of concern regarding this alloy is that of ductility. Certain heats exhibit low values, especially at temperatures above 1300°F for tensile and around 1100°F in creep tests. This behavior points toward possible problems should carburization or notches occur in the metal. The effect of these two variables on the stress-rupture and tensile properties is a subject that should be studied further.

6.4 CORROSION ALLOWANCE

The work of Youngblood,⁴⁴ DeVan,¹⁷ and Pawel^{18,42} can be used to derive a corrosion allowance. Youngblood found Hastelloy N corrosion from molten salt and hydrofluorination to be 25 mil for 500 h of exposure. DeVan lists less than 2 mil wall loss in a laminar flowing salt after 36,000 h (see Table IV).¹⁷ Furthermore, he suggests that corrosion rate decreases with time in Fig. 10. Pawel suspects that further oxidation on the cell side will be nil and cautions that hydrofluorination may initiate some new corrosion on the salt side of the tanks.

The Conceptual Design Report⁴³ uses 7 or 8 days as the duration of hydrofluorination—say 200 hours. Using Youngblood's 25 mil - $(200/500) \times 25 = 10$ mil with a contingency of 50% produces 15 mil as a corrosion allowance.

6.5 COMPARISON OF ASME CODE BETWEEN 1959 AND 1996

The difference in ASME Code^{33, 34} requirements from 1959 to 1996 is small, and comparison of these differences is useful to ensure that today's service conditions are as close to new construction requirements as is practical. Appendix C lists the differences pertinent to the drain tank design and new service conditions.

The 1959 code³³ allowable stresses for Hastelloy N bolts were lower; however, carbon steel bolts were used, so this will only be an issue if new Hastelloy N bolts are installed on the access port flange. The 1959 code case permitted only GTAW while today's code makes no restriction on the process. The code case also required mandatory radiography for all butt welds. The tanks will not be modified by welding, so these are moot issues.

The 1996 code²⁵ permits plug welds in nonpressure structural applications only. Because the plug welds in the heads are full penetration and were accepted by radiography, they do not have the same design limitations as a non-radiographable fillet style plug weld and should be essentially the same as a repair weld in the heads that would be permitted by the 1996 code. Both codes³⁴ require that the owner define a corrosion allowance. This requirement was not addressed in the original

design and constitutes a significant issue that leads to establishing either an analytical definition or actually confirming the corrosion effects.

Flat spots in the heads and out-of-roundness in the shell not exceeding $\frac{1}{2}$ in. are requirements in both codes.²⁵ Actually measuring these features remotely will be difficult, particularly if the furnace is not disassembled. To confirm that the requirement is satisfied, the only feasible method that can be recommended now is a visual evaluation capable of discerning bulges or deformations of the head and shell. The original design calculations²³ estimated the flattening of the head to be $\frac{1}{8}$ in. at the center from a gradient of 400°F from the support ring to the center of the head, the gradient being due to the radiant and conduction heat from the heaters transferring radially through the head. It is recommended that this calculation be duplicated using a finite element model to predict the deformation and the state of stress that will verify whether the deformation is permanent or elastic. There is no reason to expect that loadings to date have caused the shell or the bottom head to be deformed. The same heat transfer situation is acting on the bottom head, and it will flatten from a radial gradient. The finite element model should be used to check the effects of gradients on the bottom head as well. The original calculations derived a maximum permissible preheat flow through 1-in.-thick Hastelloy N of 1 kw/ft² @ 1300°F, 1.4 kw/ft² @ 1200°F, 3.5 kw/ft² @ 1100°F and 6 kw/ft² @ 1000°F. The same calculation, using the finite element model, should be done to check for allowable gradients during transients such as heatup and draining. Heating in 1999 will be done with the tanks already full (or half full) of salt.

The 1996 code requires inspection access for initial and in-service inspection. This access is provided by the 3-in. port; however, the surface area occluded by thimbles is significant and will inherently limit the extent of visual examination from the inside to 60% with no more than 7 in. of shell circumference in any single view through the thimbles. Because the location of the longitudinal seam is not known, it is not a surety that it will be visible from the access port. But even if it is visible, the portion above the salt is only about half of its total length, and so it, too, will be evaluated on 50% coverage from the inside.

6.6 IMPORTANCE OF DESIGN TEMPERATURE TO WALL THICKNESS REQUIREMENTS

The designers are cautioned to realize that ductility falls off rapidly at temperatures above 1000°F as shown in Swindeman's data and the ASME Section II allowable strength tables. If at all possible, the design temperature should be 1100°F or less.

6.7 MODIFICATIONS TO PIPING BY WELDING

Plans intend that the existing transfer lines be used to the extent possible. However, the temporary copper plugs are not qualified by analysis, experience, or testing for elevated temperature containment of the salt. If remote welding is employed to repair these caps or perhaps run a new transfer line, the welding procedures specifications and welders should be qualified per Section IX of the ASME Code.³⁵

The only methods recommended to qualify the piping are visual examination to the extent practical and pressure testing and integrated in-leakage testing. All other methods require extensive work to access the insulated pipes or require significant development costs. The lines in place are

either 1 or ½ in. nominal pipe size; therefore, examination of the interior is impractical because of access and contamination of the examination equipment.

6.8 RELATED CODES AND STANDARDS

6.8.1 ASME B31G Manual for Determining Remaining Strength of Corroded Pipe

The ASME B31G-1991 applies to carbon steel piping, and although it cannot be used directly to provide acceptance criteria for the NDE, it can give a basis for evaluating defects using a graded approach and so can be used to design the examination procedure. The manual cautions that it "should not be used to evaluate ...girth or longitudinal welds or related heat affected zones, defects caused by mechanical damage, such as gouges and grooves ... introduced during manufacture." The pressure is limited by the formula $P = 2tStF/D$, where t is thickness, S is minimum yield strength, D is diameter, and F and T are strength and temperature derating factors, respectively, from other piping codes.

In Parts 2 and 3, there are guidelines for allowable lengths of corroded areas when the depth of corrosion is between 10 and 80% of the new wall thickness. These lengths are based upon geometric scaling of D/t ratios. For example, in a 52-in. diameter vessel:

- 19/32-in. deep pits in a ¾-in. nominal wall can be 3-in. long; 0.4-in. deep pits in a ½-in. nominal wall, the length can be 2 7/16 in.

For another example, a 2-in. nominal pipe size with .08-in. deep pits in a .109-in. nominal wall can be 5/16-in. long.

6.8.2 ASME Boiler and Pressure Vessel Code

In the ASME Boiler and Pressure Vessel Code for In-service Inspection of Nuclear Power Reactor Components - Section XI, "Division 3 Liquid Metal Cooled Plants," where boundary failure is not accompanied by large releases of energy, the following requirements are listed:

Visual examination

- Personnel shall have passed a Jaeger 1 visual acuity test at 12 in.
- IMA 2211: Internal examination shall ensure that cracks, leakage, and wear are discernible.
- Remote resolution equivalent to direct viewing from a distance of 24 in. @ 30 degree or more: 1/32-in. black line on 18% neutral gray background.
- IMA 2212: External examination shall detect streams, drops, smoke.
- Removing insulation is not necessary.
- IMA 2213: Detect loose parts, debris, loss of integrity of bolted or welded connections.
- May require measurement of clearances, displacements, tightness of bolting.
- Remote dimensional gauges are permitted [for flat spots].
- Confirm settings, functionality of components, such as snubbers, supports.
- IMA 2215: Surface replications must be at least as resolvable as direct viewing.
- IMA 2241: Continuous monitoring of liquid metal leakage and alarms shall be provided.
- IMA 2242: Continuous monitoring of radioactive gas leakage shall be provided.

- IMA 3500: Volumetric flaws shall be reported as area or percent of wall thickness. Surface flaws are defined as any portion of indication within 40% of the width of flaw from the surface edge. A Laminar Planar flaw is parallel to surface within 10 degrees.
- For Class 1 components: First examination is 33% of all welds.
- For Supports: First examination is 100% of all welds.
- For Category C Freeze Valves: First examination shall include 100% functional tests.

7. QUALITY VERIFICATION REQUIREMENT RECOMMENDATIONS

The performance requirements for the visual examination of the system should meet the following requirements that have been taken from the ASME Boiler and Pressure Vessel Code Section XI for In-service Inspection of Nuclear Power Reactor Components:³⁶

7.1 PERSONNEL REQUIREMENTS

Personnel who perform NDEs shall be certified in the method to Level II American Society of Nondestructive Testing (ASNT) per TC-1A, 1992, "Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing." The visual examinations should be performed by a Certified Weld Inspector per the American Weld Society certification requirements.

7.2 VISUAL EXAMINATION

- Personnel shall have passed a Jaeger 1 visual acuity test at 12 in.
- Remote resolution shall be equivalent to direct viewing from a distance of 24 in. @ 30 degree or more: 1/32-in. black line on 18% neutral gray background.
- External examination shall detect evidence of streams, drips, vapor.
- External examination shall detect loose parts, debris, loss of integrity of bolted or welded connections. May require measurement of clearances, displacements, tightness of bolting. Remote dimensional gauges are probably not practical but the laser Structures Light Contour measurements have the potential for measuring flat spots in the cylinder and heads.
- Confirm settings of valve positions, functionality of weigh cells or engagement of screws and or turnbuckles to the supports, clarity to pressure relief devices and pressure indicators.
- Surface replications must be at least as resolvable as with direct viewing.
- Continuous monitoring of liquid salt leakage shall be provided.
- Continuous monitoring of radioactive gas leakage into the drain tank cell shall be provided.

The extent of visual examination of the drain tanks should include:

- the interior surfaces of each of 66 thimbles to detect deformation, discoloration, pitting, deposits, or scaling.
- the exterior of the top head to detect indications of flattening, cracks, deposits, or corrosion of the welds to the nozzles or the support lugs.
- the exterior of the shell to detect indications of deformation, cracks, deposits, or corrosion of the longitudinal and circumferential welds in the vessel.

- the exterior of the bottom head to detect indications of flattening, cracks, deposits, or corrosion of the welds to the drain cup.
- the interior side of the weld joints of the longitudinal seams, the circumferential seams above the salt, the first butt joint to each of nozzles, the weld joint between the head, and each of thimbles in the top head to detect indications of cracks or wastage.
- the outside diameter of the thimbles to the extent possible (approximately 70%) in the vapor space above the salt in the tanks to detect evidence of wastage, pitting, or local corrosion near the welds.
- the surface surrounding the free space above the salt in the interior of the tanks to detect pitting, local areas of wastage, discoloration, or evidence of local yielding at nozzles and support attachments (note that the maximum extent will be less than 30%).
- measuring the dimension from the top of the salt to a reference point, possibly the entrance to the 3-in. nozzle) within $\pm 1/4$ in.

The performance requirements for other NDEs of the system should meet the following requirements:

- Volumetric flaws shall be reported as area or percent of original wall thickness as shown in IMA 3500 of Section XI.
- Indications shall be recorded with position so that the indication can be retrieved and repeated if necessary.

7.3 ULTRASONIC THICKNESS MEASUREMENT

Ultrasonic thickness measurements shall be taken per a written procedure. The procedure shall specify the use of a longitudinal beam. The procedure shall require calibration using a block of known thickness, preferably between $1/2$ in. and 1 in. thick, of Hastelloy N material immediately before and after each set of measurements, for example, a shift. The ultrasonic procedure shall specify that no liquid couplant be used. The procedure shall also specify how many readings to take and where they should be taken—see discussion below on grid size.

The procedure shall require a record of all indications registering more than 50% magnitude of the back reflection from calibration. Each of these losses of back reflection readings shall be recorded and traceable to a scanning map of the location and position of the reading.

7.3.1 Grid Size

Fifteen ultrasonic thickness measurements of the drain tank top head shall be taken in a pattern between the thimbles that includes the knuckle radius region and the access port region in each of the four quadrants.

Fifteen readings of the bottom head shall be scanned on two radial lines at 4-in. intervals.

One hundred and twenty thickness measurements of the shell cylinder shall be taken in an array around the circumference. The portion about 20 in. above the salt shall have 15 readings around the circumference. The portion at the salt level shall have 15 readings taken around the circumference. An additional 2 scans at 4-in. intervals adjacent to the longitudinal weld shall be taken. An additional 15 readings on each side of both shell-to-head welds (total of 60 readings) shall be taken around the circumferential welds.

Each of these 145 readings shall be recorded and traceable to a scanning map that will provide a record of the position and location. The basis of the grid size is discussed below.

7.3.2 Code Basis for Grid Size

There is no standard available that directly relates to these tanks; however, we can use the API code for atmospheric storage tanks, ASME B31G for piping, Section VIII for new construction, to establish some reference. The API 653 Code³⁷ offers some empirical formulas for deriving the minimum allowable thickness and the extent to which an ultrasonic examination grid should be used when discovering a thin spot. The allowable thickness is based on the weight of the fluid being contained and the geometry of the vessel and the material of the vessel.

The ASME B31G Code (Paragraph 2.3.3.1) gives 0.118 in. as the minimum acceptable thickness for the drain tank. The length of acceptable corrosion area, assuming a .118-in. deep spot were found, would be $8\frac{1}{4}$ in. The grid to apply would be $8.25/5 = 1.6$ in. per 2.3.2.1. Per Part 2 of the ASME B31G Code³⁸ the allowable length of a corrosion area where 80% of the wall is gone in the tank is 2.3 in. Because these codes are for carbon steel in chemical service where the risk of bursting is either explosive or toxic release to the environment or both, they may be considered more conservative than what is needed for the drain tanks. If 2 in. is selected as the reasonable size of a corrosion site that must be detected by ultrasonic examination, then a grid size of 2 in. will ensure that there are three chances to detect a 2-in.-long area with a $\frac{3}{4}$ -in.-diameter search unit.

The ASME Code²⁵ for new construction specifies a 3-in. grid with a minimum search unit diameter of $\frac{3}{4}$ in.

The ASME Code for In-service Inspection of Power Reactors, App. III, requires 100% coverage of the examination area with 50% overlap of the search unit (III-2410) at a maximum rate of 6 in./s. It should be noted that this scan is for weld defects, not planar defects typical of corrosion.

The search of the top head will be more random because there is an array of thimbles and other nozzles that leaves no orthogonal grid so the shape and number of readings will necessarily be a best effort of perhaps 10 readings. The bottom head will require a manipulator tool with a joint that can bend up to approximately 110° .

7.3.3 Statistical Basis for Sample Size

A model based upon experimental design was constructed by J. Draper.³⁹ In his model, he evaluated the standard deviation of existing thickness measurements on the new plate and addressed areas of the tanks that would have different responses to the corrodant. He then chose values of standard deviation of the mean from ultrasonic measurements to be taken that would give good "statistical power" to the measurements as they are compared with estimated corrosion and required accuracy for making decisions regarding the wall thickness. He also determined the fraction of readings taken related to the total available readings that can be taken with a $\frac{1}{2}$ -in. transducer to suggest a minimum number of readings. This number of readings passes his test for power and reliability of the data and serves as guide to limiting the number of readings but still getting statistically reliable results. The sample plan in the grid size discussion above is based on Draper's derivations.

7.3.4 Engineering Judgment Basis for Sampling

It can be argued that a sampling plan on the cylinder that includes only a few longitudinal meridians might well represent the entire circumference. The only obvious feature of the cylinders that would react differently to the corrodants in the tank around the circumference is the longitudinal weld. One circumferential scan should give evidence of how the corrosion is changing around the circumference. It would be prudent to take readings along each side of the circumferential and longitudinal weld and then one or two other longitudinal meridians that are easy enough to reach. If the readings agree within 10% of each other, then there are probably no local areas that would be detected that differ from these readings by more than 10%.

7.4 EDDY CURRENT THICKNESS MEASUREMENT

Eddy current wall loss measurements shall be taken per a written procedure. The procedure shall require calibration using a standard with wall loss bands of 5, 10, 20 and 50% of thickness in a 1½-in., schedule 40 Hastelloy N pipe immediately before and after each set of measurements, for example a shift.

The location of each indication from a screening coil that integrates the volume of a circumferential band that shows loss of wall greater than 6% of nominal should be recorded. For each of these indications, the thickness shall be measured to find the distribution of wall loss and characterize the presence of deeper pits. This second measurement may be done with a second pancake coil that measures thickness in a small region. The thickness measurement shall be done per a written procedure and is needed for checking areas where the wall loss coil indicates more than 6% loss of wall.

Eddy current measurements of the thimbles should correlate with the ultrasonic readings of corrosion on the tank walls to the extent that the same loss of metal is measured by each method.

7.5 INTERIOR CONTOUR MEASURING

Methods that may be used to confirm the thickness measurements are being studied. One method involves using a laser to reflect off the surface into a charge-coupled device camera; another uses a receiving photo sensor synchronized to measure time of flight of the laser beam that will correlate to a change in contour. These ideas were born from experience at ORNL and other laboratories where structured light surface mapping was used to detect and characterize pits in concrete Gunit tank walls at a radius of 25+ ft. The pits in the walls of the MSRE drain tanks are expected to be on the order of 10 to 20 mil deep by 50 mil in diameter, barely within the detectible limits of eddy current or ultrasonic or remote field electromagnetic technique (RFET), but probably within the limits of detection for structured light or laser triangulation techniques. In spite of the promise, there are time and budget constraints that must be overcome before a viable contour measuring technique is employed.

The greatest challenge for this machine is that it must perform inside the tanks without the benefit of a stiff positioning mechanisms that would normally be used to keep the laser beam from wandering. Placing a precision mechanism inside the tank will take at least a 75-in. stroke packaged inside a can mounted on the access port sealing valve. The linear actuation may be through a dynamic seal or it may be contained within the can. The wobble on the end of a 75-in. mast as it

rotates to provide a circumferential raster scan will necessarily be small and repeatable so that the calibration required will not be influenced by light paths not normal to the tank surface.

7.6 RFET

A recently evaluated method uses the flux leakage principle to detect defects in the volume of interest. This method has the advantage of not being sensitive to lift off or thickness of the base metal under 1/2-in. thick. It offers a C-Scan type presentation that detects and sizes all indications of interest to this project. It can be used to quickly screen for defects much like the eddy current coil can, but it can also size defects, which the eddy current coil cannot. It will not measure the wall thickness directly, but it can be easily complemented with a few ultrasonic spot measurements to show that there is no change in thickness over a given defect-free area. The method lends itself to examining both the shell and the thimbles, although with separate probes. The technique requires highly skilled persons to perform the examination but the presentation is straightforward and easier to interpret than either ultrasonic or eddy current presentations.

7.7 LEAK TESTING

7.7.1 Inleakage Leak Test

An inleakage test to discover gross breaches in the system pressure boundary should complement the visual and NDE. It should be done before a positive pressure decay leak test. A two-part test is proposed.

The first part involves filling each thimble with nitrogen dioxide (N_2O) and eliminating each thimble one by one. In the second part, the drain tank cell and reactor cell are flooded with nitrogen dioxide. Both cells are interconnected to the cell ventilation system (CVS) via a 30-in. hole in the south wall to the reactor cell, which means that there is a large cell volume to manage. In each part a system response to a standard leak would be made to determine the time and magnitude of the signal from the standard. A standard leak of perhaps 10^{-4} sccs of N_2O could be readily manufactured.

N_2O is preferable because it is readily detectable by the RGRS, and there is no background of N_2O in the salt containment system. Virtual leaks from the salt and other crevices in the piping system will be minimized. The considerable volume of the drain tank cell with its adjoining reactor cell will not require extreme quantities of N_2O to provide a concentration that can detect reasonably sensitive leak rates through the salt system. An estimate of the cell volume is 26,720 ft³. A 10% concentration of N_2O would be about 267 standard ft³ or less than one 3000-psi gas cylinder per volume change. N_2O is neither toxic nor hazardous at these concentrations; nevertheless, appropriate safeguards will be taken to protect workers from asphyxiation or levels mandated by OSHA regulations.⁴⁰

7.7.2 Pressure Decay Leak Test

After a thorough visual examination of the tanks and the connecting piping, a general measurement of component wall thickness with special attention to pitting and wastage, and an integrated inleakage test, the system could be subjected to a pressure holding test at ambient temperature derived from the same requirements as a newly constructed tank per Section VIII, Division 1.

By following the code, the pressure holding test would be at $1.25 \times (\text{Design Pressure}) \times (\text{Temperature Factor})$ for 1 h. The temperature factor is the ratio of the allowable strength at test temperature divided by the allowable strength at design temperature. For a design temperature of 1100°F, the factor is $25/12.4 = 2.02$ and the test pressure will be 125 psig. Pressure relief devices set below test pressure must be temporarily gagged.

The system should be further inspected to ensure that the overpressure, overtemperature, and undertemperature controls are reliable and set at the proper set point for operations.

8. VALUE OF NDE

8.1 GROSS LOSS OF WALL THICKNESS MEASUREMENT

An eddy current coil that can be rapidly inserted in the thimbles and will produce a lisajou pattern that can be compared with a pattern from a standard where bands of thinner wall have been machined is useful to screen and "pass" the thimbles quickly. This technique will indicate the total integrated volume of the pipe that has been lost—for example, a ring around the thimble. The indication will give only a correlation between 100% wall and degrees of total wastage of the wall. If the thimble shows no wastage above a preselected acceptance criteria, the examination is complete and very rapid.

Distinctive lisajou patterns have been demonstrated with an absolute coil for 10, 20, and 40% wall loss. It is quite feasible to examine all 32 thimbles in the drain tank quickly with this integrating coil. Distinctive lisajou patterns have been demonstrated with an absolute coil for 10, 20 and 40 % wall loss. It is expected that such a scanning plan would show any thinning from salt level in each of 32 scans. Since the existing level has been the same since 1970, there may be thinning at the existing level; however, during operation, the level was not constant. The expected corrosion from the dry period is so low that there is only a small chance there will be an observable salt level correlation.

8.2 DIRECT WALL THICKNESS MEASUREMENT

Direct wall thickness measurements used to detect wastage and general corrosion thinning by the ultrasonic or eddy current method have been demonstrated to be accurate and repeatable within 4 mil on a work bench. On the end of a long handle tool, the accuracy may be 10 mil. The chances of higher accuracy in the thimbles are good because there are fewer variables changing during the measurement. There is also a smaller new metal thickness in the thimbles so the percentage of wall removed is higher and therefore easier to detect. The measured thickness will be the same within a few standard deviations unless there are notch effects in the Hastelloy N. These thimble measurements should correlate with ultrasonic thickness measurements of the tank wall at least in height location if not absolute wall loss measurement.

A study by J. Draper³⁹ indicated that 145 tank wall measurements would provide enough data to realize that the thicknesses measured were comparable to the actual thickness of the tank wall plate using bench top methods. It appears that enough data points can be collected to know the wall thickness to within 10% with a high degree of confidence.

No other confirming method is known for the tank wall thickness measurement except low frequency scanning, which is being evaluated. Its advantage is that it will provide 100% coverage and characterize size and shape of defects where ultrasonic searching will be limited to a few well-selected spots where just thickness (one dimensional) is determined. Where corrosion thinning is suspected, such as in the welds, the low frequency remote field technique will better define actual conditions. Its disadvantage is that it is expensive for a one-time use.

There is a promising concept being pursued where confirming data on the interior surface contour can be measured with a laser reflector or structured light mapping technique. The technique would combine visual examination of the interior with a contour measurement that would describe the flat spots, pits, and salt buildup on the interior tank wall above the salt. The contour measurements should confirm the ultrasonic thickness and/or remote field flaw detection. Similar contour measurements have been done at ORNL that were approximately 50-ft-diameter concrete underground tanks. The advantage of such a system is direct measurement of contour while viewing the tank interior surface. The disadvantage is that there is considerable development of the algorithms, laser, and receiving camera components and the mechanism that must necessarily work within a sealed can. The can would house a translating mechanism that moves the laser through an open valve on the 3-in. access port of the tank.

The value of this set of measurements rests in the claim that an established national standard, the National Boiler Inspectors Code, which is based upon thickness measurements for remaining life calculations, was met. This standard, while not based on scientific measurements of flaws, is based upon consensus experience by the pressure vessel industry that is adequate for private sector liability determinations. Only the nuclear power industry pushes the requirements for more rigorous NDE methods where the revenues for such examination pay for the risk-saving NDE methods. The nuclear utility methods, in contrast to what is herein proposed, are estimated to cost several million dollars. This cost is largely attributed to the tooling necessary to provide precision transducer positioning that is auditable (i.e., documented). The tooling herein proposed will have documentation of transducer position by testament of the operator rather than by expensive encoders and readouts.

There is motive for the position to be accurately although not precisely known because indications that may be challenged or require verification will have to be reproduced. To this end, some ideas on marking indications are being evaluated. The long handle tool itself can be fitted with depth and rotational markings. Inclinoimeters are also being evaluated that will digitally record the scanning paths. The footprint of the transducer may be marked with a benign media. All these ideas will necessarily need a map to help interpret the readings.

8.3 FLAW DETECTION

The probability of detecting flaws on the order of 100 mil on a side using eddy current scanning on the thimbles is likely less than 50%. This raises the question as to the value of performing the proposed eddy current scanning and how the probability of detection could be increased. The only demonstrated technique for increasing this detection probability is RFET.

RFET is not based on eddy current production in the workpiece. It provides a spatial map of the field discontinuities that are sensitive to defects. This technique has detected and characterized a through-wall hole of 67 mil diameter in a 1½-in., schedule 40 (145 mil) Hastelloy N pipe. The resolution of the characterization of a defect is a function of the array of pickup coils that can be

placed in the search unit. The probability of detection with RFET is nearly 100% for the area covered; therefore, the total probability of detection would be the percentage of area covered.

8.4 ALTERNATIVES FOR RISK PREVENTION

The analytical model used to establish critical flaw size is intended to be deterministic, not probabilistic. The basis for the formulas has some margin so that failure may not necessarily occur if there is a critical flaw; however, there is no alternative for the analysis and the occurrence of failure needs to be presumed.

If there is a leak before failure, such as a small crack propagating through the pressure boundary, the consequences would be much like that of FV105 leakage on December 12, 1969. The cell radioactivity would go up, and the leaking salt would freeze by air cooling. The heaters would be de-energized, and the cooled metal would possibly stop the leak. If a tank were to be breached by a larger opening, there would likely be more leakage flow and a larger deposit of salt would deposit in the furnace or cell before freezing temperatures were reached. In either case, the salt would eventually freeze because of the action of removing heat energy and would not constitute a threat to people outside the cell. The cell ventilation would transfer airborne particles to the filter bed and there would not be a particulate release. Some radioactive gas release may occur. The Facility Authorization Basis and associated safety analyses will address this in more detail.

None of the NDE methods are guaranteed to detect such a crack. The method most likely to detect a through-wall crack is pressure decay leak testing; however, the method does not locate the leak, it just detects it. There are even conditions where the leak test may not detect a leak. For example, the crack may be filled with salt that holds the pressure or the crack does not open until the metal has reached an elevated temperature.

As mentioned previously, the value of the proposed NDE methods is to reduce the risk of operating with a known defect that would prevent use. What are the conditions where a leak will stop the process and what are the alternatives to the proposed NDE? The volume of the salt already leaked into the cell is estimated to be 3 cubic in. The Basis for Interim Operation (BIO)⁴¹ has identified this amount as Category IV risk, and the release paths have been judged as adequate to handle this amount of solid salt. A leak of liquid salt will be of a higher activity but will eventually give the same hazard level as the existing salt deposits. It seems that using this volume as an allowable leak will only permit hazards that were already safely contained in the past and should not increase the risk of hot operation.

Table 4 lists failure events with a suggested criteria for acceptable risk and some action that could further reduce or prevent risk.

Table 4. Risk-reducing alternatives

Event	Limiting Condition	Alternative Prevention
Through-wall crack in tank below salt level detected visually and by radiation monitors	Leak up to 3 in. ³ or a value from a revised BIO.	1) Leak test at temperature before each transfer 2) 100% scan of tank surfaces. Note that this will still not ensure detection of crack

Table 4 (continued)

Event	Limiting Condition	Alternative Prevention
Through-wall crack in thimble below the salt level detected by radiation monitors	Leak will seek liquid level until ullage pressure overflows thimble. More volume should be tolerable in the thimble than the 3 in. ³ above; perhaps 90 in. ³ could drain into a thimble before shutting down the transfer	1) Leak test at temperature before each transfer 2) 100% scan for flaws
Through-wall crack in tank above salt level detected by radiation monitors	Leak up to capacity of cell vent system to remove hazardous gases without exceeding release limits	1) Leak test at temperature before each transfer. 2) 100% scan for flaws
Through-wall crack in thimble above the salt level detected by radiation monitors	Leak up to capacity of cell vent system to remove hazardous gases without exceeding release limits	1) Leak test at temperature before each transfer 2) 100% scan for flaws

9. RECOMMENDATIONS SUMMARY

9.1 ANALYSIS

- Use API RP 579 for allowable defects.
- Use S. J. Pawel's estimation of corrosion damage from past history.
- Use zero as the probable seismic, vibratory, and plastic deformation loads.
- Use R. W. Swindeman's properties for loss of ductility.

9.2 VESSEL DESIGN

- The maximum allowable working pressure should be 65 psig at 1100°F.
- The maximum allowable working temperature should be 1100°F.
- The corrosion allowance should be 50 mil.
- The component thicknesses should be based on ASME Section VIII, Division 1, 1998 edition.
- The design should also be based upon a finite element analysis that details the state of stress in the drain cup connection, the thimble connections, the access port connection, and the support ring connection. Use 80% of allowable stresses from Section VIII, Division 1 as appropriate for steady static loads and transient secondary stresses.
- Life of the vessel should be 5 years.
- Use 200 cycles at coincident temperature of 1100°F for future pressure cycles.
- Use 60 pressure cycles at coincident temperature of 1100°F for past cycles.
- Use Swindeman properties for creep strain.

9.3 PROCESS DESIGN

- Control the process to limit tank wall temperature gradients to 100°F in any direction.
- Provide overpressure protection via the off gas lines now connected to the vessels.
- Provide over temperature protection to limit Hastelloy temperatures to 1300°F.
- Provide corrosion protection to be commensurate with 50 mil of total corrosion over the life of the vessel.
- Perform in-service inspection if the life of the vessel is to be extended past five years.
- Replace the plugs in lines 103, 104, 105, and 106 with fittings qualified to 65 psig at 1100°F.
- Remove FV104.
- Monitor cell radiation.
- Monitor cell air radiation.
- Limit the furnace heating rate to 100 F/hour.
- Monitor loss of heating as it relates to gradients in the tank wall.

9.4 INSPECTION PLAN

- Perform leak testing for the system with a method that can detect 10E-4 sccs air.
- Inspect the nozzles, drain cup, head, and shell for evidence of plastic deformation such as flat spots, bulges, and bent connections.
- Inspect the nozzles, drain cup, and tank surroundings for evidence of seepage.
- Measure shell, head, and thimbles.
- Search for defects in shell, thimble base metal, and weld joints.
- Report all indications of wall loss greater than 15 mil.
- Use personnel qualified per the ASME Code requirements in Section XI.

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APPENDIX A
ISSUES RAISED DURING THIS FIT-FOR-SERVICE STUDY

DOCUMENTATION ISSUES

1. *What is the risk if a critical flaw is undetected by NDE?*

The analytic models used to establish critical flaws are intended to be determinant, not probabilistic. The basis for them has some margin so that failure may not necessarily occur if there is a critical flaw; however, there is no alternative for the analysis and the risk of failure needs to be presumed. If there is a failure such as a crack propagating through the pressure boundary, the consequences would be much like that of FV105 leakage on December 12, 1969. The cell radioactivity would go up, the leaking salt would freeze and possibly stop the leak, flush salt would be pumped through the leak if it were in a pipe and probably not aggravate the leak. If a tank were to be breached by a through wall crack, there would likely be more leakage flow and a larger deposit of salt would deposit in the cell. In either case, the salt would freeze and not constitute a threat to people outside the cell. The cell ventilation would transfer airborne particles to the filter bed and there would not be a particulate release. Some radioactive gas release may occur. The BIO and associated safety analyses will address this in more detail.

2. *What is thermal history of each tank and pipeline?*

The system was brought to operating temperature (between 900 and 1300°F) in 1964 and remained at this temperature until December 1969 when the reactor was drained and the heaters were deenergized. After this shutdown, the tanks in the drain cell were heated to (300 to 500°F) recombine radiolytically generated fluorine gas. This recombination heating took place annually for a period of a week or two until 1989. After 1989, it was decided to cease the recombination process, and the tanks have been at ambient temperature ever since.

METALLURGICAL ISSUES

1. *How critical to the Fit For Service question is post-weld heat treat (PWHT) as specified in a memo to Hise from Taboada on 5/22/62?*

In a conversation with Al Taboada on 8/5/97 he could not recall the exact context for the memo but he did know that the entire tank was not PWHT. The records show some piping subassemblies having PWHT but it is doubtful that the tank welds had PWHT. The code states that PWHT is neither required nor prohibited and that heat treat for extremely corrosive conditions can be beneficial. Presumably, the 2150°F heat treatment would dissolve carbides. In a meeting on 7/17/97 with M&C engineers the opinion was offered that PWHT was not necessary and would not be specified today if Hastelloy N were used as a repair or modification. If Hastelloy N is not available for modification and a new alloy such as Haynes 242 is selected, the PWHT issue will likely be the same—that is, it helps but is not critical to providing a longer corrosion life.

CORROSION ISSUES

1. *What is the predicted thickness using derived corrosion rates?*

A review of the documents addressing corrosion presents a wide range of possible predictions. Swindeman knew of carburization during the alloy development work in the late fifties. The

work done on the corrosion loops in the sixties seems to have been focused on chromium depletion. After the autopsy in 1970, there was some measure of the intergranular affects of tellurium. The surveillance specimens that were periodically evaluated by McCoy during the late sixties seemed to show some radiation affects and perhaps some tellurium effects but the data did not appear to be consistent. Youngblood's writings concerning Hastelloy N in the fluorinator provide markedly higher corrosion rates than dry corrosion or even salt and oxide corrosion. A high number to use would be 50 mil; a more probable number is 30 mil. The corrosion may even be as low as 10 mil, which is what the autopsy in 1970 disclosed. The intergranular cracking, while it does degrade the mechanical properties to some extent, is not detectable except with micrographs; no NDE method is known that will detect the few mil of micro cracking. Eddy current, ultrasound and RFETs require extremely skilled operators and well controlled conditions to differentiate the noise from the signal given by the cracks. The most obvious decision is to assign a value for intergranular degradation based upon micrographs. There is no evidence to suggest that more than 5 mil needs to be assigned to intergranular degradation. Furthermore the micrographs indicate that the cracking is within the layer of corrosion by leaching.

2. *What wastage is expected?*

Wastage is a term that can be assigned to the gross loss of wall from mass transfer. That is, it can be used to differentiate corrosion from intergranular attack. It is possible to measure wastage with RFET and eddy current testing. RFET is capable of describing the size and shape of the wastage. Less than 20 mil is expected.

3. *TM-4174 suggests that cell side oxidation is worse than salt side corrosion. How can TM-4174 data be used to predict remaining life of fuel storage tank?*

The corrosion found on the heat exchanger that is due to oxidation is probably the best estimate to use for the loss of wall of the fuel storage tank due to cell atmospheric attack.

4. *What are the consequences of oil leaks into the salt system (corrosion, plugging)?*

The vent lines sometimes plugged during reactor operation. It was thought that the plugging was caused by oil leakage from the circulating pump that mixed with the salt and contributed to precipitation and plugging in the vapor spaces such as the vent lines. See p. 130 of TM-3039, Systems Performance, by Guymon (1973).

5. *Do all tanks have the same rate of corrosion attack?*

Drain tanks 1 and 2: Drain tank 2 appears to have been used slightly more than drain tank 1 in the early prenuclear operations. After reactor operations began with uranium, it was logical to use them approximately equally to reduce corrosive effects of the fuel salt. When the reactor was shut down, the tanks were equally filled with salt that froze and the corrosion rate should be the same from December 1969 until now. The corrosion measured during operation was very small, on the order of 1 mil or less, so the difference between the tanks would be trivial.

Fuel flush tank: Should be less than the drain tank or the fuel storage tank because there was not as much uranium in the flush salt.

Fuel storage tank: Should be the worst of the tanks for corrosion damage because the fluorination process took place in these tanks. However, the uranium recovery and fission product removal cycles did not occur often. Once in 1969 and perhaps once or twice before that.

Coolant drain tank: Should be less than the fuel flush tank because there was no uranium in the cooling salt.

6. *What effect does uranium have on the corrosion of Hastelloy N?*

The corrosion equations $\text{Cr} + 2\text{UF}_4 = \text{CrF}_2 + 2\text{UF}_3$, and $\text{Fe} + 2\text{UF}_4 = \text{FeF}_2 + 2\text{UF}_3$ reached equilibrium rapidly in Hastelloy N as was evidenced by the extremely low amount of corrosion measured during operations and after in autopsy studies. The effect of uranium is to provide a different valence state that will allow chromium and iron to form fluorides while reducing the uranium fluoride.

7. *If corrosion attack is separate from intergranular attack, what are the magnitudes of each?*

From the autopsy report one might generalize that the magnitudes are equal (about 1 or 2 mil each). From the archive samples taken during operation the data also supports this; however, each group did not yield the same magnitudes.

8. *Will the NDE methods be blind to the intergranular attack?*

Yes. No technique proposed will provide the kind of search accuracy that a typical intergranular stress corrosion cracking examination requires.

9. *Will the NDE methods be blind to the chromium depletion depth (sponginess in the microstructure)?*

Yes. It remains to be seen whether the sponginess will even show up as a loss of wall. It is entirely possible that the NDE will not detect any loss of wall if all the corrosion is of the magnitude reported by McCoy, DeVan, and others.

10. *Gamma levels in the salt are probably greater than 640 R/hr. Most of this energy is from ^{137}Cs at 660 Kev. (NRC p. 27). Does there appear to be any radiation induced chemical effects on the alloy such as accelerated combination of fluorine with Cr, Ni, Mo, or Te diffusion or uranium catalysis—see NRC p. 43?*

During irradiation trials using the HFIR cooling pool tests it appears that radiation induced corrosion is not an issue because the passive metal fluoride acts to protect the alloy. The formation of Li_2NiF_6 mentioned in the NRC report has not been seen in any of the work by Chem. Tech. people such as D. Williams who addressed this question in an E-mail on 2/13/98.

11. *Is there an annular space around the salt inside the tanks where crevice corrosion or radiation enhanced corrosion could take place—see NRC p. 44?*

In discussion with R. Engel on 9/9/97, he characterized the salt as not being able to wick into capillaries like oil or water would but would span cracks like mercury does; thus, he expects that there are gaps between the Hastelloy surface and the solid salt surface. On the other hand there may also be mounds of salt that lie up against the metal and form fillets even though the surface energy of the liquid salt is high. The notion that there could be large voids in the salt at the Hastelloy interface, combined with the possibility of UF_6 condensing at the triple point

during an annealing process, begs the question of pressure cells within the salt and isolated from pressure venting becoming a source of yielding of the tanks.

PROCESS ISSUES

1. *If POOLMELT is used, will the temperature gradients be different than for the heat transferring from the tank walls?*

POOLMELT is the baseline process being developed as of December 1997. The currently accepted thermal model for POOLMELT is that the tank walls will be heated first until a uniform salt mass temperature within 125°F of the liquidus temperature is reached. The temperature gradients necessary to reach this preheat of the salt will be controlled per rules derived from the thermal stress analysis. As the salt is withdrawn, the salt level will slowly go down and the solid salt to tank wall interface will change position creating a moving gradient that will have to be controlled within the limits of the thermal analysis. The flush tank is visualized to be emptied within 4 months, and each of the drain tanks should be emptied within 2 months. The furnaces surrounding the tanks will then be turned off and the tanks will cool to ambient equilibrium. See memo from C. Anderson, 12/18/97.

2. *What T/C locations are needed to POOLMELT?*

Plans are to use the existing thermocouples used to monitor the tank wall. Other instruments, such as an infrared or visible light camera and/or acoustic sensors, will also be used to monitor the pool. The thimbles can also be used to provide more thermocouples samples.

3. *Will there be any post transfer flushing water at room temperature (See pp. 1-19 of ER-480 and p. 99 of ORNL/CF-77-391 Decommissioning Plan.)? Will cleaning the residue salt from the freeboard surfaces require a process with elevated temperature and pressure using corrosive gases that may accelerate the corrosion rate during the salt disposition campaign (see NRC pp. 47-3)?*

There are better liquids to use than water to accomplish a flush—see D. Williams E-mail and NRC "Evaluation of Alternatives for Disposition of MSRE Fluoride Salts" discussion about plutonium residue. The scope of the salt removal portion of the job will not include removing residues in or out of the tanks. The tanks may need to be reevaluated later when the final cleanup and decommissioning phase is implemented. It is not visualized that the design requirements for the tanks will significantly change for the post salt removal campaign.

Dave Williams suggests that water washing is not the preferred method of cleaning residual salts after the transfers are complete because salt solubility on the order of 0.2 mole/liter is not high enough to consider water an efficient solvent. ORNL-3262, Chemical Aspects of MSRE Safety, and ORNL/RAP 17, Decommissioning of MSRE, a Technical Evaluation, provide data to show the solubility of salts in water and other solvents. Regardless of the solvent chosen, the residual salt remaining should be in the form of thin films or small isolated pockets in spaces such as the drain cup. It is not likely that there are crevices at weld joints in the tanks although wastage in the heat affected zone might capture significant deposits. Crevices will occur at temporary plugs and any socket weld joints that may be used in upgrading the piping for transferring. Solvent cleaning will have to reach such crevices and will be required to remove Pu and ^{232, 233, 235}U.

4. *Will hydrofluorination precede melting (NRC pp. 47-6)?*

The present concept is that hydrofluorination be done concurrent with the POOLMELT by bubbling fluorine or HF into the pool. See 12/18/97 memo from C. Anderson.

5. *Which tank will be heated and drained first? (See NRC p. 49—The flush tank is recommended by the NRC as the first to be done simply because the fuel inventory is least and the melting dynamics are pretty close to the more enriched fuel salts.)*

The decision on this question has not been finalized; however, it is now thought that the sequence will be the flush tank, drain tank 2, and drain tank 1. This decision eliminates the advantage of having flush salt available to do a final cleanup of the emptied drain tanks. All three tanks may be near liquidus temperature to reduce gradients. And if the existing lines (107, 108, and 109) are used, the freeze valves can be used to isolate the molten flow. If new transfer piping is used, then the tanks can function even more independently and may be heated individually.

6. *If sparging in the POOLMELT is done in the drain tank, what flow will be used and how will this balance with the capacity of the RGRS when considering a viable throughput?*

These rates are not finalized yet but the plan is for both head space purging and sparging gas to be used. Head space purge is planned to 50 LPM and sparging may be of similar magnitude. There is a conceptual design report being prepared which will address this question in more detail.

7. *Will the fuel storage tank and caustic scrubber and adsorbers communicate to the RGRS and is there a compatible flow regime with the RGRS to support fluorination?*

The flow capacity of the RGRS will be used to design the gas removal rate. Present plans do not include flowing to the fuel storage tank, caustic scrubber and associated filters.

8. *If heating is replaced by CO₂ blasting, will the tanks still need to be qualified and for what operating conditions of temperature and pressure?*

There are no plans to use CO₂ blasting.

9. *How long will the system have to be at temperature to complete the total inventory transfer?*

The tanks will be heated at a controlled rate until the salt within them is within 125°F of the liquidus temperature. Once this has been accomplished, the transfer cycles, planned to last about 9 months, will begin. Once it is confirmed that 99% of the salt is removed, the tank heaters will be turned off and the system will return to ambient conditions.

10. *Will there be a need for a post-removal purge of minute salt deposits to manage the plutonium residues? (see NRC p. 41).*

In a conversation with F. Peretz on 10/9/97 the perspective offered was that the total inventory of plutonium is small (see ER-380: only 21 Cu per Table 1.7 and 740 g per Table 1.4) and should not require any special process to reduce this amount. Whatever is plated out in the

system is already low enough that further treatment won't be required. In ORNL-72-1-1, Haubenreich writes that there is 743 g of plutonium total inventory (about 743/4,500,000 wt. fraction, or 16 ppm). Perhaps 2% of the flush salt has plutonium. The total uranium inventory is 37 kg. The small amount of plutonium is not removed from the salt by fluorination as the uranium is; so it will stay in the flush salt even if the uranium is removed unless other means are devised for plutonium removal. Since the amount is so small, his recommendation is to leave it in the flush tank.

11. *What configuration is required after the salt is transferred?*

The goal for the salt removal project is to remove 99% of the total salt inventory in the three tanks in the drain tank cell.

CHEMISTRY ISSUES

1. *What is the density of the salts?*

135 lb/ft³ @1200°F per TM-3039, p. 3.

2. *Does the salt wet the Hastelloy?*

See p. 3, memo Briggs to Wigner, 12/10/63, see also TM- 4174, p. 15—salt may wet as a function of temperature. In discussion with R. Engel in 8/97, he characterized the salt as not wicking into capillaries like oil or water but spanning cracks like mercury; thus, he expects that there are gaps between the Hastelloy surface and the solid salt surface. On the other hand, there may also be mounds of salt that lie up against the metal and form fillets even though the surface energy of the liquid salt is high. In a discussion on 8/5/97 with Al Taboada he felt that there would be some salt sticking to the Hastelloy surface, albeit not tenaciously. The salt did adhere when it spilled out on the internals and formed mounds so there will probably be mounds of salt lying against the thimbles and tank walls. One implication is that ultrasonic testing could not detect the salt interface from a scan down the thimbles or the tank side walls. Eddy current testing may detect the salt surface but it depends on how large the gap between the metal to the salt—a gap of 15 mil is probably enough to render the probe blind to the interface. Electrical conductivity of the salt is also a factor here.

3. *What is the probability and consequence of hydraulic pressure from pockets of locally melted salt?*

The probability of this happening is high unless careful procedural control is exercised during heat up. The literature contains several accounts of this happening in the salt loops at Y-12 and various corrosion loops. The freeze valves are especially vulnerable to this situation if they are not heated in sequence. There are three heaters in a valve that are designed to melt from the outside to inside of the valve. If there are other solid plugs in lines, the space between them can be a source for pipe-bursting pressures. Within the tanks, the bottom drain cup should remain solid until the salt above it is liquid. There is the possibility of liquid salt forming in the space between the tank wall and the salt mass if the heat transfer from the heaters reaches the salt before the center of the salt is melted. If POOLMELT is used, this problem should be under control. The original heatup of the tanks in 1964 did not have this problem because the tanks

were hot before they received salt. The 1998 heatup must be controlled using different thermal profiles.

4. *Did anneal cycles from 1969 to 1989 produce local yielding?*

Probably not. The salt is visualized to be swarming with cracks so that gas containment is not likely. The tanks were heated to only 500°F so there was no melting. The bottom cup could have been stressed by the expansion of solid salt if there was a significant difference between the cup temperature and the salt, but this is not probable since the heatup was conducted with some monitoring of thermocouples on the tanks. Temperature gradients along the lines 107, 108, and 109 certainly didn't exceed 400°F total and were well within tolerance if the lengths for these gradients were 7 or more ft. If not the gradient would still have to be severe (say 1 ft or so) to cause yielding.

5. *Is there a possibility of liquid UF₆ residing in the tanks in pockets that can build extreme local pressures that will not communicate with overpressure protection?*

No. A complicated sequence would be required in which UF₆ formed or desublimed into a pocket that had a high packing density sufficiently strong to hold the trapped material against the Hastelloy boundary. Thermal conditions conspire to remove UF₆ rather than to confine it in pockets. Any region that experienced subatmospheric pressure would not form liquid UF₆ (per comments by Lee Trowbridge, 11/10/97).

6. *Which tanks were annealed?*

The three tanks in the drain tank cell: drain tanks 1 and 2 and the fuel flush tank.

7. *Did cooldown in 1969 or initial heatup in 1964 produce local yielding?*

Initial heat up in 1964 was controlled with a slow temperature rise rate of 100°F per hour. This rate was based on calculations that would prevent yield stresses from occurring. The cooldown in 1969 was slower than the heat up. After 3 days, the temperature had only dropped about 300°F.

8. *Has the change in concentration of U, Be, Zr, and Li caused a change in the operating temperature of the tanks?*

Neither Li, Be, nor Zr are considered volatile when combined with fluoride, so their concentrations have not changed significantly from annealing or ambient temperature outgassing. The volatile constituent of the salt is uranium, and it was less than 1% of the salt mixture when it was new. Migration of all the uranium as a gas should not significantly change the liquidus temperature of the salt.

9. *Will temperatures to melt the new phases of salt be significantly different than the original operating conditions?*

The reduction of Zr, U, Be, and Li to the metallic state has changed the concentration of the salts. Tests are to be conducted to predict the properties of the salt. At this time, it is not expected that the melting temperatures will differ significantly from those of the original salts.

10. *The gas analysis from the RGRS indicates 1.7% MoF₆ gas. The molybdenum could be from Hastelloy N or it may be a fission product or both. If it is from the Hastelloy, is this expected and is it a significant magnitude to indicate additional attack or is it under the same attack that was measured during operation using CrF₆ quantities?*

Lee Trowbridge has analyzed the condition and written an E-Mail (8/8/97) discussing the MoF₆. It "presumably originated from F₂ attack during the annealing cycles" and the long-term ambient attack since the cycles ended. The 1.7% MoF₆ is coming from the flush tank space. He estimates that 360 g of molybdenum have been depleted and if one postulates surfaces above the salt on the flush and drain tanks to have lost this Mo, then .34 mil of Hastelloy N have been depleted of Mo. These numbers should be used with caution and not taken as expected values at a given location. Thoma (ORNL-4658) reported .43 mil of Hastelloy being depleted of chromium by similar arguments. Apparently there is some fission product ⁹⁹Mo that may also be part of the volatile MoF₆.

OPERATIONS ISSUES

1. *Is the maintenance shield necessary for drain tank cell work?*

Yes, per work plan guidelines. The shielding is excessive and the portholes are not matched to the tools as well as we might wish; however, a shield is needed and it is considered cost prohibitive at this time to modify or redesign the existing shield since it can be made to work. In CF/77-391, Decommissioning Plan, p. 92, the maintenance shield was not needed for work in 1970 in the drain tank cell. Mention is also made of considerable dust that was washed away to prepare for the work. Preliminary exploration of the cell with a remote camera did not indicate evidence of the washing or accumulated dust.

2. *For the heatup cycle, what temperature gradients will occur during heat up and cooldown?*

The signals coming from the weigh cells change due to thermal effects on the piping and the tanks during heatup. The existing thermocouples had a drift or apparent deviation from actual temperature of 40°F. The reactor operators used average temperature to control heaters and alarms so their gradients were probably on the order of 40 to 100°F. Effects of gradients of this magnitude were observed on the weigh cell output per p. 409 of TM-3039.

On some corrosion loops such as the Forced Convection Loop described by J. Koger in ORNL-4676, p. 202, uneven thickness of insulation of 1 in. was enough to cause overheating and rupture from trapped melted salt (144°F gradient).

3. *What temperature gradients will occur at 32 thimbles, along shell, at 3-in. nozzle, other nozzles (transfer, fill, etc.) including low point drain cup in bottom head of drain tanks?*

A new finite element analysis model will be made to answer these questions.

4. *What will the thermal cycles be?*

The original operating procedure (TM-908, p. 5c, Guymon, 9/7/65) requires a maximum of 100°F per hour heating rate. The allowable temperature gradient between thermocouples should

also be specified and may be assumed to be 100°F but this should be documented if possible. The heating did not occur until the entire system was purged of oxygen to <100 ppm. Tanks were specified to be heated first, followed by connected lines to be heated out to the first freeze valve. The system was not to cool below 400°F to avoid evolution of fluorine. Empty lines were permitted to cool to ambient.

5. *Is there a possibility of melting some salt before the ends of a given volume are melted and thereby build up enough hydraulic pressure from the expansion of the liquid to rupture the tank or transfer lines?*

Such occurrences have been recorded already—see for example ORNL 4676, p. 202. It will be necessary to survey the entire salt transfer system specifically to identify potential causes of differential melting as for example from:

- Gaps in the insulation
- Lack of emergency power at regions where freezing can take place rapidly.
- Large masses of salt surrounding heat sinks (the drain cup could be in this situation if it did not receive adequate radiant heating from the heaters and conduction from the tank head).
- The bottom of the thimbles, reducing cross sections in the piping.
- Malfunctioning FV heaters.
- Plugs in the transfer lines 107, 108, and 109 (or new lines if used.)

6. *Is there overpressure protection?*

Lines 572, 574, and 576 can be fitted with pressure relief valves that will discharge into the filtered outgas system. The original reactor design used off gas piping routed through the charcoal filters to provide overpressure protection.

7. *Will emergency power be required to ensure clarity to PRV and avoid trapped volumes?*

This issue has not been addressed yet.

8. *How is clarity to PRV maintained to prevent plugging?*

This issue has not been addressed yet. It is known that there were several instances of plugging in lines 572, 574, and 576, so it is likely that cold spots will have to be prevented for this protection as well as for other process uses of these lines.

9. *Is there over temperature protection?*

All the heaters have over current protection and thermocouples are available to use for active control of the heaters.

10. *What breach occurred in the leakage during shutdown?*

FV105 had a weld crack at toe of the fillet weld through the process pipe wall. The crack caused a small leak in the drain tank cell. See TM-4174, H. McCoy, for autopsy discussion.

11. *What precautions are needed because of the cutout tubes in the heat exchanger?*

The patch over an oval piece that was removed (see TM-4174, p. 70) is sealed with RTV polymer sealant, as are some of the drain line plugs (according to R. Guymon in ORNL/RAP/LTR-87/18, p. 2). The patch is on the fuel side of the heat exchanger and is completely isolated from the salt transfer process in the drain tank cell.

12. *What are the beryllium issues associated with the radiator?*

The airborne particles of BeF(salt) are a health hazard to workers because of respiratory damage from particles in the salt. Beryllium can come from leakage in lines 201, 202, 204 and 206 from the heat exchanger or breaches in the radiator itself.

13. *Are the steam domes needed?*

No, cooling the salt quickly is not required. The Steam Dome bayonets are occupying space in the thimbles which appear to be critical in the Fitness-For-Service of the tank. The thimbles were only 145 mil when new and cold and they have suffered the same corrosion and intergranular attack as the tank walls. Estimates of corrosion damage vary from 10 to 50 mil. Local damage to a thimble could manifest as a leak that constitutes an unacceptable risk. The way to reduce this risk is to perform some nonintrusive and NDE to confirm that there is no apparent severe damage to either side of the thimble wall.

14. *Are the plugs in lines 104, 105, and 106 worthy of holding pressure and heat?*

It is doubtful that these plugs can hold during either a pressure test or during the transfer process. They will likely require special modifications or replacement since they are attached by a screw clamp to cut off piping.

INSPECTION ISSUES

1. *What extent of examination is mandatory?*

Visual testing to evaluate the presence of flaws. As discussed elsewhere, "mandatory" is a management decision based upon related codes and standards that may have "mandatory" requirements. Section XI of the ASME Code for In-Service Inspection and the National Board of Oiler Inspectors both require mandatory visual examination and some method of determining the remaining wall thickness of a pressure vessel.

2. *What will be tolerated for insulation damage?*

P. Haubenreich wrote in ORNL 72-1-1 that before recovery of the uranium could start the work listed below would be required: "checkout of all in-cell heaters and thermocouples; (this is one of the most critical items since operability of certain critical heaters or thermocouples could require difficult and expensive replacement in a highly radioactive cell or require devising alternate methods for heating or temperature measurement.)" As mentioned earlier, salt lines have burst when there was 1 in. of missing insulation.

3. *Where are the copper and Hastelloy N capped lines?*

Nozzles on the tanks are capped with Hastelloy N caps according to the drawings. The drain lines 103, 104, 105 and 106 are apparently capped with tapered copper plugs. Some of these plugs have been seen in video surveys of the drain cell by Dave Dunning in December 1997.

4. *What NDE methods are applicable?*

Ultrasound, eddy current, electromagnetic acoustic transmission, low frequency electromagnetic flux leakage, mass spectrometer leak testing, self gamma exposure radiography, visual. Of these only the self gamma can be ruled out early as too dependent on elaborate shutter mechanisms. However, only eddy current and low frequency electromagnetic technique and visual appear to be practical without a very challenging manipulator with "tweaking" degrees of freedom to adjust touch and lift-off.

5. *What is the minimum detectable flaw size from the NDE methods?*

To date, the eddy current probes have been able to measure circumferential steps in thickness of 10% of the wall; however, they have not been able to detect small volumes such as notches, through wall holes, flat bottom holes on the OD. It is felt that a selection of frequency and coil design can be made that will detect small volume flaws, but this remains to be demonstrated. What has been demonstrated is the ability for the eddy current testing to measure gross loss of wall thickness. The ultrasonic testing technique will detect wall thinning of a smaller volume; however, the technique is slow and will require a lot of time to collect a grid of measurements. Continuous scanning for defects with an ultrasonic technique does not appear feasible yet. William Simpson has recommended the EMAT method for quickly scanning to collect thickness data rapidly. A probe capable of detecting weld cracks has been demonstrated by Royal Cline; however, the interest in this device is centered around the weld of the drain cup and it is now judged excessively expensive to fabricate a long handle tool that will place the probe on the weld with surgical precision. A standard boiler tube technique by TesTex has been shown to be useful in detecting small volume flaws and Zetec is also known to be a source for special case coil design solutions. The TesTex method (RFET) has detected through wall holes .032 in. in dia. in the thimble and .032-in.-dia. holes in a 1/2-in. Hastelloy N plate. It is expected that a modification to the standard system so that differential rather than absolute signals are processed will produce detectable flaws on notches on the order of 40 × 40 × 250 mil. Ultrasonic techniques have demonstrated the ability to detect wall thinning but not cracks.

6. *Which NDEs are to be used: visual, dimensional, penetrant, hardness, ultrasonic, radiographic, eddy current, material sample, surface replication, or acoustic emission (AE) testing?*

The methods selected to date are: visual testing with video cameras, ultrasonic testing of tank wall thickness at spots, eddy current testing of the loss of wall in the thimbles, RFETs for flaw detection of the thimbles and the tank walls, pressure decay leak testing, and N²O inleakage testing.

Surface replication has been ruled out as unnecessary for microstructure information; however, for gross wastage, a technique has been developed in case it becomes necessary to augment the visual or ultrasonic testing methods.

7. *What is the value of AE and could it be employed in the drain tank cell?*

The state of the art of AE is such that there is inadequate baseline information and no time to acquire it. It is possible to get a baseline during the tank leak testing but it will not be interpretable until there are other AE signatures to use.

8. *What has been the propagation of flaws from new to now?*

The surfaces are known to be cracked per the autopsy work of H. McCoy in TM-4174. The depth of the intergranular cracking is to be estimated by S. Pawel. McCoy's paper reported a depth of .0015 in. at the FV105 failure site (p. 40) after 6 years' exposure to salt, which was judged then to be insignificant degradation of the tensile properties. Wastage is thought to be very low because the flow velocity in the pipes was on the order of 2 fps (See "Implication of Tellurium in FV105", by Haubenreich.).

9. *What are the likely sites of damage?*

At fillets, thickness imbalances, heat transfer imbalances such as the drain cup weld joint and other saddle-on joints and attachment fillets such as the support ring and drip tube supports.

10. *What is the probability that NDE will miss a flaw of critical size?*

A study based on experimental design has been done by J. Draper to address the required number of spots to be taken using the ultrasonic testing method so that the probability of knowing the entire wall thickness is 95%. Similar logic can be applied to RFET searching of the tank walls where less than 100% coverage is planned. The examination of the thimbles will be 100% by both the RFET and eddy current testing methods and so the probability of detection should be above 95%.

11. *Any local deposits, discolorations, pits from steam, wear from rubbing cooling tubes?*

Steam was admitted to the bayonets in place in the drain tanks only once for trial measurement of the cooling capacity. Cooldown was accomplished without steam and the only time steam was generated was in tests prior to power operation of the reactor. See p. 133 of TM-3039. The thimbles were not wetted by steam, only the inside of the bayonets so steam pitting is not relevant to the thimble surfaces. The top and bottom of the bayonets were fitted with centering pads that served to keep a clearance between the thimble and the bayonet. It is not likely that there was any contact between them and hence no rubbing from thermal growth or insertion at assembly. The only probable source of contamination is from the cell where there was reportedly a lot of dust, perhaps from construction. When the thimbles were 1200°F they could have discolored by producing some oxide film or other compound from the contamination.

12. *Are there qualified WPS and performance records for welders for Hastelloy N pipe?*

WPS is still in existence but no welders are qualified to it. The WPS should be reviewed against Section IX requirements. New qualifications should be imposed if repair or modification welds are made.

13. *Why is the ultrasonic technique nontraditional?*

The reason for the special requirement that no liquid couplant be used is that management of coupling fluids is judged to constitute a risk and/or elaborate system of tooling to mediate criticality concerns. Water or other hydrogen bearing fluids have been determined to create a small risk of criticality if the fluid forms a reflector or moderator around a collected mass of U_{233} .

One proposal to fill the thimbles sequentially with couplant fluid and empty the thimble after a set of measurements was thought to be too complicated and produce the risk that fluid may leak into the salt if there was a thimble leak path. Another proposal to use a rubber tire search unit as is done in the steel mills met with the complication that off the shelf wheels were too big to enter the heater openings. Furthermore, the long handle tool to engage the wheel against the shell would be elaborate and expensive.

The only option that was attractive was to use a transducer fitted with a delay shoe that has an elastomer coating that will couple the sound waves without liquid couplant. The disadvantage of this dry couplant transducer is that it can't be rubbed or drug along the surface. Thus its deployment is a series of discrete engagements on a grid rather than a sweep of continuous readings and the time for collecting the readings is very slow. Such a transducer has been procured and tried for use on the shell. The dry couplant was satisfactory and another transducer for thimbles has been ordered.

DESIGN ISSUES

1. *Can the original weld efficiency be used to calculate remaining life or should 70% be used because there is no chance for RT now and aging could have produced weld cracks?*

No. In the API RP 579-2.4.2.2 Standard, a "Remaining Strength Factor" of .9 (or a Plastic Load Limit Ratio) is recommended to go along with the original calculations. The original calculations used a joint efficiency 1.0. Using 70% would be too conservative and penalize the wall thickness out of context with the intent of the code which is written for new construction. Using 90% of the original efficiency as stated in API 579 is more appropriate for in service remaining life applications.

2. *What heaters will require emergency power to protect against trapped volumes?*

This has not been addressed yet.

3. *Will the caustic scrubber be included in the tank qualification exercise?*

No.

4. *How many thermal cycles should be planned?*

One is planned with a contingency for 10 off-normal cooldowns and reheats.

5. *Are all loads in UG 20 addressed in analysis?*

The analysis is not complete yet but the requirements of the analysis include loads in UG20.

6. *What startup stresses are expected on the thimbles in the drain tank?*

Stresses well below 2000 psi are expected based upon a preliminary finite element analysis performed by S. Chae, LMES Engineering, in October 1997.

7. *What lines exist to provide pressure driving force for salt transfer?*

Per ORNL-72-1-1, Haubenreich, p. 2, "The line connecting the tanks to the salt-processing tank in the adjacent cell is intact, blocked with a plug of frozen salt. Cover-gas supply lines to the tanks are capped outside the cell; vent lines are valved off outside the cell. Pressure and temperature instrumentation continue in operation." The drain tanks have a 1/2-in., schedule 40 and 1-in., schedule 40 pipe lines that descend into the tank bottom. Lines 107, 108, and 109 go from the bottom of the drain cup (or low point in flush tank) and merge to form line 110 into the fuel processing cell. Lines 104, 105, and 106 go from near the bottom of the tanks to copper plugs. These internal pipes can be reused if new transfer piping is installed.

8. *Is there a possibility of locking salt in a syphon or losing it in a syphon break?*

There is a difference in elevation between the drain tanks and all other equipment in the facility; therefore, the drain tanks will be able to syphon drain anything connected to them. Further, there are only two tubes available to the bottom of the drain tanks, so backflow to the salt will be limited to these two lines or the other three nozzles, which are capable of backflow to the top of the salt. Of the four nozzles in the top, one is capped (1/2 in.), one is connected to the helium supply (1/2 in.), one is connected to the level probe (2 1/4 in. i.d.), one is the center access port (3 in.), which will be used for all internal operations (such as video inspection, leak testing, pool melt heaters) and may be connected to the maintenance shield bulkhead. The 3-in. port could also backflow cell atmosphere if there was a leak in equipment connected to its 150-lb-rated flange.

Potential sources of backflow to the drain tanks with the present concept are:

- salt container
- salt container loading station
- caustic scrubber
- fluorinator or fuel storage tank
- helium pressurization line
- pressure transmitter line
- cell atmosphere
- fluids in deployment mechanisms
- level probe
- lines 573 or 575 balance line to the fuel pump
- line 572 to the RGRS
- lines 574 or 576 to the NESA pressure transducers
- line 542 to the RGRS

9. *What seismic loads have occurred?*

On November 30, 1973, a strong motion recording at Y-12 indicated .024g on the 2nd floor and less than .01g on the ground floor. This motion was from a seismic event centered at Maryville. This magnitude of motion is "very insignificant and would not affect structures on the reservation." See E-Mail from Joe Hunt, 7/22/97 for more discussion.

10. *What vibratory loads have occurred?*

The vibrations from rotating equipment and turbulent salt flow were minimal and were never considered to be a load that would produce significant stresses. This testimony from Dick Engel on 9/9/97.

11. *Is B31G-1991 the latest version of the Residual Life Code for Piping?*

Yes. This is the version listed on the VHS at the Y-12 Library.

12. *What is the allowable uniformity of heat from the heaters?*

100°F gradient or 4 degree per inch on the tank surfaces according to the Design Report by E. Bettis, MSR-61-67, and the selected heating rate of 100°F/hour. In combination with the internal heater for POOLMELT, the temperatures monitored during reactor operation may be different than for the transfer process. The startup for the reactor began with empty tanks that were heated prior to admitting salt to them so there was a different thermal inertia and gradients will be more difficult to control. The most critical item in the tanks for POOLMELT are probably the thimbles that will act like heat sinks to the cell. It is likely that the thimble fitted with thermocouples will be the controller for the POOLMELT heater.

13. *What properties can be used for calculating remaining life of the tanks?*

ASME Section IID 1995, addenda 1996 can be used. The code of record is the ASME VIII Division 1 1959, addenda 1960. The properties and allowable stresses have not changed but there are more requirements for load consideration now than in the original code. See MSR 61-67 Design Report for original code calculations.

14. *What is the pressure to be used to transfer the salts?*

The July 14, 1997, conceptual design called for transfer to the fuel storage tank, which is about 20 ft above the bottom of the drain cell tanks. Using a salt density of 2.31 gm/cc (p. 2, ORNL-72-1-1), the hydrostatic head will be 46 ft water or 20 psid. Previous operations recirculated the salt at 30 psig to the top of the tanks (p. 225, TM-728) with flow restrictors being used to limit flow to the reactor. The new transfer process will likely not require this flow limit, but using 50 psig is reasonable at this time and is probably higher than actual hydraulic conditions for transfer will be. If another conceptual design is adopted, say the one offered in ORNL-72-1-1 by Haubenreich, the head may be a few feet more (30 ft of salt = 30 psid) but the line losses can be lowered so that 50 psig for a design pressure for the tank should still be adequate to transfer the salt. A more recent conceptual design calls for loading molten salt in shipping canisters in the highbay a full 40 ft above the bottom of the drain tanks. A hydraulic head of 40 ft may require a vacuum boost to make up for line losses and could still result in a 50-psid design pressure for the tank.

15. *What is the pressure capacity at temperature of the plugs (copper, Hastelloy, etc.)?*

The sst plugs are thought to be sealed with RTV as described in a meeting with L. Pugh on June 10, 1997; therefore they have no pressure or temperature rating. A video survey of the drain tank cell on August 7, 1997 showed copper plug restrained in the line 105 with a screw actuator. Dick Engel thought (on 9/9/97) that the plugs in the drain tank cell were copper and metal-to-metal sealed by a screw actuator. This actuator pressure rating is unknown and is assumed to be zero since the clamping friction is indeterminate.

16. *What were the minimum wall thicknesses of each component?*

The new and cold specifications for the tanks show: 3/4 in. for the heads and 1/2 in. for the shell in the drain tanks and flush tank and fuel storage tank. All nozzles except the level probe are schedule 40. The sizes range from 1/2 to 1 to 1 1/2 in. The level probes were machined from bar stock and were .160 in. thick. The coolant tank was thinner: 5/8-in. heads and 3/8-in. shell with schedule 40 nozzles. See drawings DFFA 40430 and 40457-40462.

17. *Do code cases 1331-5, 1272N-5, 1315 and 1345 still apply to reheat operation?*

Code case 1331-5 says "Under what rules shall Class 1 Nuclear components be constructed when metal temperatures exceed those for which allowable stress values are given by Section III? The stress limits for Section III are applicable only where creep effects are negligible. ... attachment welds shall have surfaces free from weld irregularities and abrupt changes in contour." Reheat is not a Class 1 Nuclear application so the case does not literally apply. Code case 1272N says "Under what variations from code case 1270N and the rules of Section VIII may containment vessels be built and be acceptable as meeting the requirements of the Code?" All welds shall be radiographed if the joint is radiographable. Otherwise, the weld shall be PT or ultrasonic testing examined. The NDE requirements of Section III were met when the tanks were constructed.

Code Case 1315 says "Is it permissible, in welded construction conforming to the requirements of Section VIII of the Code, to use Ni-Mo-Cr-Fe wrought material and forgings which meet the chemical and mechanical property requirements given in Table 1 below, and further meet all the applicable requirements of the specifications listed in Table 2? [Table 1 is for Hastelloy N] The maximum allowable stresses permitted shall be per Table 3 (6,000 psi at 1200°F). When maximum corrosion resistance is required, it may be advisable to heat treat in such a manner as to place all carbides in solution. For such service it is recommended that the vessel be heated to 2150°F and held for not less than 1 h/in., subsequently all parts should be quenched uniformly and as rapidly as possible in water or air." These stress values should be superseded by the latest edition of the Code. Code Case 1345 says "May Ni-Mo-Cr-Fe alloys be used in the construction of nuclear vessels in accordance with Section III? Materials conforming to SB 167 for pipe, SB 334 for plate, SB 336 for rod and SB 182 for forgings may be used if they also conform to Table 2 for chemistry and Table 3 for mechanical properties (100 ksi ultimate and 40 ksi yield and 35% elongation) and welding is done only by the GTAW process using filler metal that complies to the properties of the base metal." These materials are still permitted in the Code, so the case is not needed today.

18. *Do Drain Tank 3" Sampler Nozzle Ports have extruded nozzles as recommended in calculations?*

No, see drawing 40458 detail. The stress analysis did not show this to be required but it may have been recommended in the design calculations to address cyclic loadings. Today's criteria for fatigue analysis in Section VIII Division 2 of the ASME Code does not require detailed analysis for less than 1000 cycles and the joint shown on the drawing is permitted with Section VIII Division 1 rules.

APPENDIX B
DIMENSIONS, NDE, MATERIAL CERTIFICATIONS
FOR TANKS AND PIPING

Dimensions, NDE, material certifications for tanks and piping¹³

Identification	Dimensions	Heat	Weld Filler Ht.
Drain tank 1	49.945 in. dia × 86 1/8 in. high,	na	5090 and 5101
	3/4-in. top hd.,	5058	"
	3/4-in. bottom hd.,	5058	"
	1/2-in. shell,	5085	"
	1 1/2 in. × sch 40 (.145 in.) thimbles (32 a),	5094	"
	1 1/2 in. × sch 40 T/C thimble	5094	"
	1 in. × sch 40 (.104 in.) fill lines (2 a),	5094	"
	2 1/4 in. × .152-in. level nozzle,	2477	"
	1/2 in. × sch 40 (.088 in.) vent & 2 each	N25100	"
	pressure tap nozzles,	2477	"
	3-in. sch 40 access port	Y8487	"
Drain tank 2	49.940 in. dia × 86 1/8 in. high,	na	na
	3/4-in. top hd.,	5058	5090 and 5101
	3/4-in. bottom hd.,	5058	"
	1/2-in. shell,	5082-1	"
	1 1/2 in. × sch 40 (.145-in.) thimbles (32 a),	5094	"
	1 1/2 in. × sch 40 T/C thimble	5094	"
	1 in. × sch 40 (.104-in.) fill lines (2 a),	5094	"
	2 1/4 in. × .152-in. level nozzle,	2477	"
	1/2 in. × sch 40 (.088-in.) vent & 2 each	N25100	"
	pressure tap nozzles, one cap	5071	"
	3-in. sch 40 access port	Y8487	"
Flush tank	50 in. dia × 84 in. high,	na	na
	3/4-in. top hd.,	5058	5090 and 5101
	3/4-in. bottom hd.,	5058	"
	1/2-in. shell,	5082	"
	3-in. sch 40 access port	Y8487	"
	1 in. × sch 30 (.104-in.) fill lines (2 a),	5094	"
	2 1/4 in. × sch 40 (.152-in.) level nozzle,	2477	"
	1/2 in. × sch 40 (.088-in.) 2 each, vent &	N25100	"
	pressure tap nozzles (2),	2477	"
	2-in. Drain Cup	NI5069	"
Fuel storage tank	50 in. dia × 116 in. high,	na	na
	.75-in. top hd.,	5058	5090 and 5101
	.75-in. bottom hd.,	5058	"
	.50-in. shell,	5082	"
	3-in. sch 40 access port	Y8487	"
	1-in. × .104-in. fill lines (2 a),	5094	"
	2 1/4-in. × .152-in. level nozzle,	2477	"
	1/2-in. × .088 in. vent & pressure tap nozzles	N25100	"
	(2), 2-in. drain cup	NI 5069	

B-4
Table B. (continued)

Identification	Dimensions	Heat	Weld Filler Ht.
Coolant drain tank	40 in. dia × 78 in. high,	na	na
	.625-in. top hd.,	5070	5090
	.75-in. bottom hd.,		"
	.375-in. shell,	5068	"
			"
	1-in. × .104-in. fill lines (2 a),	5094	"
	2 1/4-in. × .152-in. level nozzle,		"
	1/2-in. × .088 vent & pressure tap nozzles (2),	N25100	"
	3-in. access port	Y8487	"

APPENDIX C
DRAWINGS

LIST OF DRAWINGS REFERENCED

DFFA 40455 - Drain Tank #1 Assembly
DFFA 40456 - Bayonet Assembly Details
DFFA 40457 - Drain Tank #1 Assembly
DFFA 40458 - Drain Tank #1 Upper Head Assembly
DFFA 40460 - Drain Tank #1 Shell and Lower Head
DFFA 40459 - Drain Tank Details
DFFA 40460 - Drain Tank Details
DFFA 40461 - Coolant Tank Assembly
DFFA 40462 - Flush Tank Assembly
DFFA 40430 - Fuel Storage Tank Assembly
EFFB 40731 - Drain Tank #2 Assembly
DFFA 40733 - Drain Tank #2 Upper Head Assembly
DFFA 40745 - Formed Heads for MSRE
DFFA 40752 - Drain Tank #2 Assembly
DAAA 40882 - Fuel Drain Tank System Flow Sheet
EGGD 41512 - Piping Plan for drain tank cell, Sheet 1
EGGD 41512 - Piping Plan for drain tank cell, Sheet 2
EGGD 41513 - Piping Section for drain tank cell
ENNB 55449 - Piping Plan for FPC
ENNB 55450 - Piping Sections for FPC
ENNB 55453 - Piping Sections for FPC in High Bay
ENNB 55455 - Piping Sections for FPC

APPENDIX D
COMPARISON OF ASME CODE
FROM ORIGINAL CONSTRUCTION TO TODAY

Table D. Comparison of ASME VIII Code Requirements between 1959 and 1995 for Hastelloy N

Requirement	1959	1995	Notes
Material	Hastelloy N - Code case 1315	USN10003, SB 434 Plate	
Allowable Temperature	1300°F	1300°F Max	
Allowable Stress	3.5 ksi @ 1300°F	3.5 ksi @ 1300°F	Strongly temperature dependent
PWHT	Not Required	Not Required	
Heat Treat	Not Required	Not Require	
Thickness	UG16c - Same as UG17c - 1995 for plate. UG16d - Use next heavier wall schedule for pipe wall to provide for undertolerance	UG17c - Plate shall be ordered not thinner than the design thickness. Plate that is furnished .01 in. or 6% undertolerance is acceptable.	
General Design		UG17e - All dimensions used in the design represent the corroded condition.	
Design Temperature	UG20 Temp. based upon: a) actual metal temperature or b) highest probable operating temperature for cyclic changes	UG20a - Max. design temperature shall not be greater than the mean metal temperature	
Allowable Temperature		Sect. II Table 1B 1300°F is max. design temp. permitted. Table 2B allows only 800°F	1300 is out of the question if we honor the code thickness
Simultaneous Loads	UG21 - Same as UG21 1995	UG21 - Max. design pressure shall be based on the most severe coincident pressures & temperatures in normal operation.	
All loads to be considered	UG22 - Same as UG22 1995	UG22 - Consider the loadings from a) internal pressure external pressure b) weight of contents including static head from liquids c) attached equipment reactions d) attachment of internals, rings e) cyclic and dynamic reactions from mechanical loadings or fluctuating pressures f) seismic reactions g) temperature gradients & differential thermal expansion	
Corrosion Allowance	UG25a - Vessels subject to corrosion shall have provision made for desired life by increased thickness over design formulas.	UG25a- The owner shall specify corrosion allowances	Corrosion experts should accept this value. Now I am taking 10 mil per year for hydro-fluorination in the drain tanks.
Design life Specified	UG25c - No additional thickness needed when experience shows only superficial corrosion.	UG25b- Vessels subject to thinning shall have provision for the desired life by an increase in the calculated thickness	Disposition process should be consistent with this design life.

D-4
Table D. (continued)

Requirement	1959	1995	Notes
Means of Monitoring Corrosion	UG25d- Same as UG25b 1995 except 3/16" dia hole	UG25e- Teltale shall be 1/16 in. dia & 80% of the thickness required for a shell & placed where least deterioration is expected.	This shows the flaw size permitted. Do not recommend meeting this requirement because of containment miseries.
Hoop Stress Calculation for Cylinder & Thimble	UG27c1 - Same as 1995	UG27c1-Cylindrical Shell thickness= $PR/(SE-.6P)$, where E is weld efficiency	API 520 further suggest a strength factor be applied to "S."
Vacuum Service Instability	UG31 - Tubes sized per Figure UG31	UG31 - Tubes shall be sized per UG28 for external pressure	Should be routine calculation
Hoop Stress Calculation for Heads	UG32e2 - Same as 1995	UG32e2- Torispherical Head thickness= $.885PL/(SE-.1P)$, where L is inside crown radius, knuckle radius $\geq 6\%L$ or $3t$, $L \leq OD$, skirt shall accommodate 3:1 taper in UW31-1	Should be routine but design temperature may push this beyond code allowables
Openings and Ligament Calculations	UG32p - Same as 1995	UG32p- Openings per UG36 thru 46 & ligaments for tubes per UG53	Should be a routine calculation
Nozzle Wall Thickness	UG45 - Same as 1995	UG45a- thickness per loads of UG22 and $>1/16$ in. or UG45b3- $=std\ wall + CA$	Corrosion on nozzles will have to be addressed as a Fit For Service Issue.
Design Requirement	UG46 - Same as 1995. Opening is an alternate to tell tale hole.	UG46- Inspection openings required.	3-in. Access Port occluded by thimbles for 40% of vessel wall and 30% of the thimbles.
Out-of-Round	UG80a - 1% of nominal diameter is max. difference between ID measurements		
NDE Requirement for New Construction	UW50 -Same as 1995.	UW50- PT all welds around openings and attachment welds that are subject to pneumatic test	PT exam of openings not relevant except for possible cracks. Oil bad for internal welds
Weld Reinforcement	UW51 - 1/16" max. crown		Most permitted in 3" access port weld joints. Probably was ground flush.
X ray Penetrameters	UW51e4 - 2% of thickness is detectable defect size or .005", whichever is greater. Penetrameters have 2T, 3T and 4T holes		
In-service inspection, nonmandatory Appendix X	UA805a5) - When corrosion rate is $<4\%$ per year, inspect every 5 years; 6) when no corrosion expected, inspect at least every 5 years.	No such appendix	
In-service Inspection	UA806c) - Isolated pits can be ignored if their depth is $<50\%$ of wall and total area is $<7\ in.^2$ in in an 8-in. dia circle	No such appendix	Useful to guide us in criteria for acceptance of pits

D-5
Table D. (continued)

Requirement	1959	1995	Notes
In-service Inspection	UA808b) - Examine all surfaces of shell; c) - Inner surface of of knuckle radius; d) - Inner and outer surfaces of joints for cracks; e) - nozzles for cracks in attachment welds.	No such appendix	Useful to guide us in criteria for inspection plan

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