APPENDICES
FOR THE
FINAL SAFETY ANALYSIS REPORT
FOR THE
VSC-24 VENTILATED STORAGE CASK SYSTEM

APPENDIX A

FUEL ASSEMBLY REGION EFFECTIVE THERMAL CONDUCTIVITY

A APPENDIX A - FUEL ASSEMBLY REGION EFFECTIVE THERMAL CONDUCTIVITY

A.1 INTRODUCTION

This appendix describes the calculation of an effective thermal conductivity for the fuel assembly region (i.e., the region within a storage sleeve). Two different approaches are utilized and a resulting conservative value was used in the subsequent ANSYS analyses of the MSB interior.

A.2 DESIGN INPUT AND ASSUMPTIONS

A.2.1 ASSUMPTIONS

The main assumption is that heat transfer within the fuel assembly and from the outer row of fuel rods to the guide sleeve wall can be handled by an effective thermal conductivity. The actual heat transfer is by a combination of conduction, convection and radiation. However, if one tried to model all the processes and the actual geometry (204 rods) the model would become extremely complex and probably undoable with the ANSYS code. Therefore, the effective thermal conductivity method is utilized.

A.2.2 INPUT

The main input to this problem is test data from several cask tests (References 4.3 - 4.7) and the standard solutions to the heat transfer equations and the Wooten-Epstein correlation (4.8).

A.3 CALCULATIONS

A.3.1 APPLICATION OF THE WOOTEN-EPSTEIN CORRELATION

The Wooten-Epstein Correlation (WEC) was specifically developed to model the heat flow out of fuel assemblies in shipping cask storage sleeves. It has been used several times in the past for both shipping cask and storage systems.

The WEC is shown below.

$$Q = \sigma C_1 F_1 A (T_E^4 - T_W^4) + C_2 A (T_E - T_W)^{4/3}$$

where,

$$C_1 = [(4N)/(N+1)^2] = [(4)(15)/(15+1)^2] = 60/256 = 0.234$$

$$A = \text{Bundle surface area} = 4\,H\,L$$

H	=	144" = 12'
L	=	8.5" = 0.708'
A	=	$4(12)(0.708) = 33.99\ ft^2$
T_E	=	Hottest rod temperature (°R)
T_w	=	Cavity wall temperature (°R)
C_2	=	Conduction constant = 0.118 for air (which if used for He will be conservative)
F_1	=	Exchange Factor
	=	$[(1/\epsilon_e)+(1/\epsilon_w)]^{-1} = [(1/.8)+(1/.8) - 1]^{-1} = 0.67$
ϵ_e	=	$\epsilon_{zircaloy} = 0.8$
ϵ_w	=	0.8 (coated A-516 carbon steel)
σ	=	1.714×10^{-9} BTU/hr-ft^2 °R^4
Q	=	$(1.714 \times 10^{-9})(.234)(.67)(34.00)(T_E^4 - T_w^4)+(0.12)(34.0)(T_E-T_w)^{4/3}$
Q/A	=	$2.68 \times 10^{-10} (T_E^4 - T_w^4) + 0.12 (T_E - T_w)^{4/3} = q''$

Using the above equation we can calculate Q for various selections of T_E and T_w. By then comparing this to the solution of the heat conduction equation for a square (see next section) we can calculate an effective thermal conductivity by the following equations.

$$Q/A = \frac{k_{eff}\,\Delta T}{1\,(.590)} = 2.68 \times 10^{-10} (T_E^4 - T_w^4) + 0.12 (T_E - T_w)^{4/3}$$

Using this relationship, k_{eff} was calculated for a number of selected values of T_E and T_w.

The results are summarized below.

T_w (°F)	ΔT (wall to hottest rod)	Q Radiation (BTU/hr)	Q Convection (BTU/hr)	k_{eff} (BTU/hr ft °F)
100	127	1136	2289	0.17
200	111	1494	1922	0.20
300	95	1834	1569	0.23

T_w(°F)	ΔT (wall to hottest rod)	Q Radiation (BTU/hr)	Q Convention (BTU/hr)	k_{eff} (BTU/hr ft °F)
400	81	2165	1275	0.27
500	67	2403	946	0.32
582	58	2605	826	0.38
690	47	2776	628	0.46

A.3.2 EXAMINATION OF CASK TEST DATA AND PRE AND POST TEST ANALYSIS USING HYDRA AND COBRA

The cask test data previously used for the surface heat transfer coefficient was also examined to determine the effective heat transfer coefficient for each test.

The central assembly of each cask test was examined in the center (axially) region so that one can safely assume that all the heat transfer is radially out of the assembly.

The equation used to calculate the effective thermal conductivity is that for two dimensional square heat sources. This is conservative because in reality the heat is not flowing equally out all four sides of the square tubes but is instead tending to flow radially out from the center of the MSB to the outside. Hence, more heat will be flowing out of the face of the storage sleeve closer to the out of the MSB. In this case, modeling the heat flow as through an infinite slab would be more correct. The difference between the two models is shown below for a square heat producing region.*

$$\Delta T = \frac{k_{eff}}{q''' L^2} [1/2 [1 - (x/L)^2] - 2 \Sigma \frac{(-1)^n}{(mL)^3} \frac{(\cosh my)}{(\cosh mL)}$$

evaluated for,

$$x = 0, y = 0$$

where,

$$m = \frac{(2n + 1)\pi}{2L}, n = 1, 2, 3, 4, \ldots$$

Which for our case of L = 4.5 in reduces to:

$$\Delta T = \frac{0.295 q''' L^2}{k_{eff}}$$

for the infinite slab

$$\Delta T = \frac{q''' L^2}{2 k_{eff}} = \frac{0.50 q''' L^2}{k_{eff}}$$

For conservatism the equation for the square heat source was used.

However, to be applicable, the differences in material properties (particularly emissivity) between the test cask and the MSB had to be considered. This was done by using the WEC to estimate the relative split between the radiative heat transfer and the convection/conduction and then raising the radiative portion by the difference in the exchange factor $[(1/\epsilon_c) + (1/\epsilon_w) - 1]^{-1}$.

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* V. S. Arpaci, Conduction Heat Transfer, pp 219, 220.

Using this methodology, the following table was developed.

Test	T_w (°F)	ΔT (°F)	k_{eff} (BTU/hr ft °F)	Corrected k_{eff} (using MSB mat. emis.)
Reference 4.5	635°F	36	0.71	1.16
Reference 4.6	184°F	46	0.25	0.50
Reference 4.7	392°F	63	0.33	0.76

A.3.3 MODEL TN-24 TEST

As a third check on the effective heat conductivity of the fuel region, the cask test reported in Reference 4.3 was modeled with the ANSYS model used to calculate the MSB temperatures. A fuel region effective thermal conductivity of 0.4 was used based upon calculations similar to those discussed in Sections A.3.1 and A.3.2. This value gave excellent agreement with the TN-24 test results. A summary is shown below.

Location	Test Value (°F)	ANSYS Model (°F)
T1	380	373
T29	429	429
T31	373	353
T33	402	395
T37	361	343
T39	297	245
MSB Surface T171	193	195

For this TN-24 cask, no correction for emissivities is necessary as a value of 0.8 for both fuel and the basket was assumed.

However, calculations with 0.4 as the k_{eff} for the MSB led to higher temperatures (~700°F) so that the value of 0.4 @ 429°F was modified by the estimated increase in the radiative portion of the heat transfer (as determined by the WEC) if the fuel temperatures increase to approximately 700°F (the calculated values for the MSB). The factor from the WEC calculation

$$\frac{0.46}{0.27} = 1.7$$

which would yield an effective k_{eff} of 0.68 for the MSB central assembly if its wall temperature were around 700°F. Calculations using a value of 0.6 were then performed for the MSB. These resulted in approximately a 30°F reduction in the MSB fuel temperatures. This calculation also shows the sensitivity of the ANSYS model to the effective thermal conductives – as k_{eff} goes from 0.4 to 0.6, fuel temperatures increase by approximately 30°F.

A.4 CONCLUSIONS

Using the three methods described above, the following k_{eff}s for the MSB were determined as a function of storage sleeve temperature.

	METHOD		
T_{wall} (°F)	WEC	Test Results	ANSYS Modeling of TN-24 Test
100	0.17		
184		0.50	
200	0.20		
300	0.23		
392		0.76	
400	0.27		
429			0.40
500	0.32		
582	0.38		
635		1.16	
690	0.46		
700			0.68

Based on this table the following conclusions were drawn.

1. The WEC appears to be overly conservative when compared to the cask test data.
2. k_{eff}s from the test data appear to run from 0.4 to 1.2 (corrected for MSB emissivities). Therefore, one might expect the outer [cooler (300 - 500°F)] fuel assemblies to have k_{eff}s in the range of 0.4 - 0.6 and the inner [hotter (500 - 700°F)] assemblies to have k_{eff}s in the range of 0.6 to 1.0.
3. To be conservative a value of 0.6 was used throughout the VSC thermal analyses. This will overestimate the clad temperatures in the central regions and may or may not underestimate the temperatures in the outer fuel regions.

In any regard, a sensitivity study was made and the peak cladding temperature was:

k_{eff} = 0.4 T_{clad} (max) = 750°F (398°C)

k_{eff} = 0.6 T_{clad} (max) = 719°F (382°C)

Hence, the overall difference is not significant.

APPENDIX B

OPTIONAL CASK TRANSPORTER AND VSC LIFTING LUGS

B APPENDIX B - OPTIONAL CASK TRANSPORTER AND VSC LIFTING LUGS

B.1 INTRODUCTION

As an alternative to the trailer and skid movement of the VSC, some users may choose an optional cask transporter to move the loaded VSC to the storage pad. The transporter is designed to lift the VSC 6 to 18 inches off the ground so that the transporter and cask can be moved to the storage location. The transporter may be self-propelled or towed by a truck or other suitable vehicle. Because the VSC is analyzed for drops of up to 60 inches, or a tip-over, the VSC is lifted less than 60 inches, and the transporter is not important to safety, the cask may be lifted by a lift fixture embedded in the concrete or positioned in the skid channels under the cask. Because the lift height of the cask is limited, the attachments are not important to safety. However, their design and analysis are described in the sections below to demonstrate that commercially available equipment can be used.

B.2 TRANSPORTER

The transporter is a vehicle capable of lifting and transporting the loaded VSC. The cask transporter assembly is comprised of a lower deck and an upper frame. The lower deck is mounted on the suspension and houses the steering mechanism/towing bar assembly, hydraulic power supply, and propulsion system. The lower deck is U-shaped to allow the cask transporter to straddle various sizes of casks during lifting, transporting, and lowering operations. A cask restraint system is mounted on the lower deck to attach to the cask and prevent unwanted movement of the cask during transport. The lift beam support structure is mounted on the lower deck and contains hydraulic cylinders or other means (hoists, etc.) to lift the cask.

B.3 *VSC LIFTING LUGS*

The VSC lifting lugs are not important to safety, due to the eighteen-inch maximum lift height. However, the design of the lifting lugs is described below.

The lifting of the VSC is accomplished via transporter lifting arms, two lifting lug assemblies embedded on top of the VSC body, and two pins inserted through the lifting arms and lifting lugs. The embedded devices are capable of safely handling the fully loaded VSC. A weight of 302,000 lbs. is conservatively assumed. The analysis of the embedded assemblies is discussed below.

The lifting devices for the VSC were analyzed in accordance with ANSI N14.6 and ACI 349. The allowable stress for the load-bearing members is the lesser of $S_y/3$ or $S_u/5$. The lowest service temperature for the VSC lifting components is 0°F. The VSC lifting lugs arrangement is shown in Figure B.3-1.

Pin

The lifting pin is a steel bar, 9 inches long and 4 inches diameter, made of 4340 steel (Sy = 80 ksi, Su = 120 ksi). The maximum shear stress on this pin is 8.0 ksi; the bearing stress is 15.1 ksi; and the maximum principal stress is 18.6 ksi. This provides a design factor of 4.3 on yield strength and 6.4 on tensile strength. These factors exceed the ANSI N14.6 design factors of 3 on yield and 5 on ultimate.

Lifting Arm

Lifting arms are steel plates 12 inches wide and 2-1/2 inches thick, with a 4.125-inch hole (see Figure B.3-2). They are constructed of A537 steel (S_y = 50 ksi, S_u = 70 ksi). The design load is 151 kips. The tension membrane stress is 7.7 ksi. The design factor is 6.5 on yield and 9.1 on tensile strength. These factors are significantly larger than the ANSI N14.6 requirements of 3 on yield and 5 on tensile strength.

The shear stress in the lifting arm is 7.7 ksi, which provides a design factor of 6.5 on yield and 9.1 on tensile strength (principal stress is equal to the shear stress). In accordance with ANSI N14.6, the design stress factors shall not be applied to the high local stresses that can be relieved by slight yielding of the material. From Reference 5.4, the stress concentration factor is 5.55, and the highest stress is 42.7 ksi. This is less than the material yield strength of 50 ksi.

Lifting Lugs

The lifting lug assemblies consist of two, 14-inch-square by 2-inch-thick plates, each with a 4.125-inch hole for the pin. The lifting lug assemblies are constructed of A537 steel. The design load per lifting lug assembly vertical plate is 75.5 kips. The lifting lug vertical plate tensile membrane stress is 3.8 ksi. The lifting lug assembly vertical plate shear stress is 4.8 ksi. The design shear stresses are well within the allowable stress limits. The stress concentration factor is 5.55, and the maximum stress is 21.1 ksi, which is less than the 50 ksi yield strength for A537 steel.

Rebar

The rebars are #11 A706 steel (S_y = 60 ksi, S_u = 80 ksi) weldable rebar. The attachment plate is A537 (S_y = 50 ksi, S_u = 70 ksi). The design stress in the rebar is 12.1 ksi. Thus, the rebar design factor is 4.96 times yield and 6.6 times the tensile strength of A706 steel, which meets the ANSI N14.6 requirements of 3 on yield and 5 on tensile strength. The development length required by ACI 349, Section 12.2 is the greater of 34 inches and 59 inches. The requirement of ACI 349 is satisfied by the 70-inch embedment.

Weld

The weld joints between the rebar and the lifting lugs are complete penetration and can be evaluated based on the allowable stress for the weaker material. Because A706 (rebar material) is stronger than A537 (lug material), the evaluation of the weld is based on the strength of A537.

The design stress in the weld is 12.1 ksi, which meets the ANSI N14.6 requirements of 3 on yield and 5 on tensile strength.

Testing

The cask lifting lugs are load tested to 1.25 times their rated capacity.

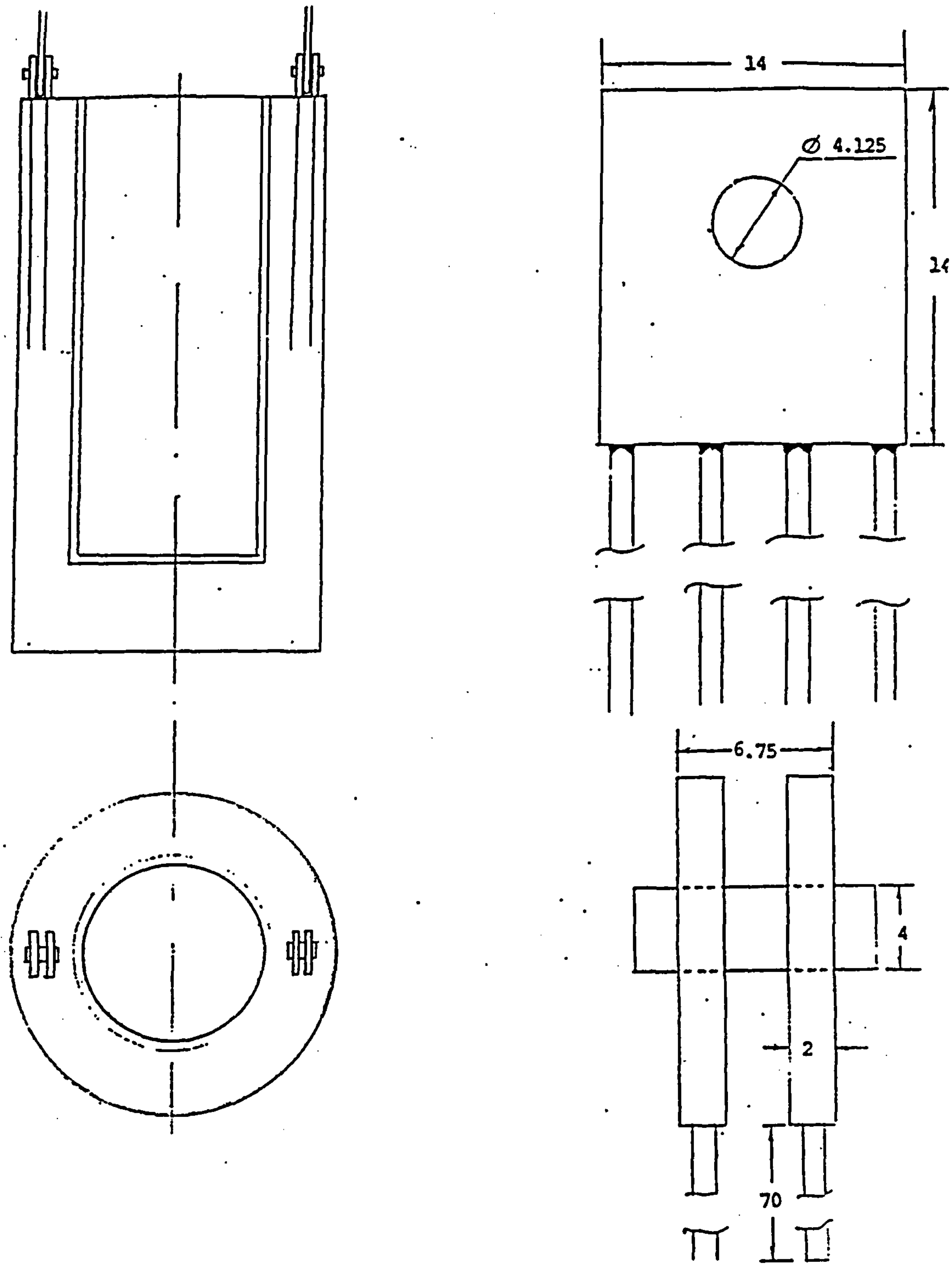

Figure B.3-1 - VSC Lifting Arrangement

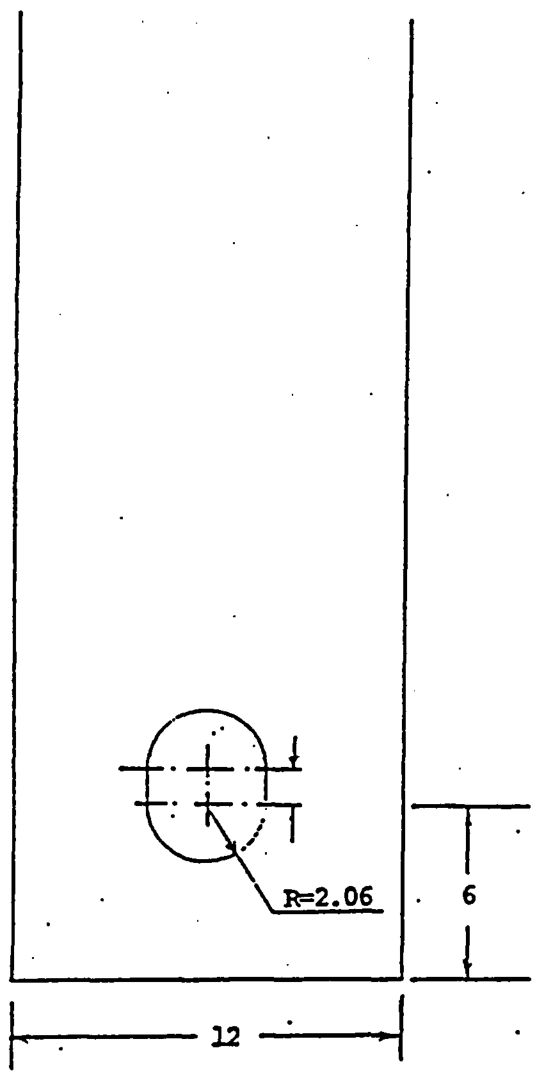

Figure B.3-2 - VSC Lifting Arm

APPENDIX C

FUEL INERT DRY STORAGE TEMPERATURE LIMITS

C APPENDIX C - FUEL INERT DRY STORAGE TEMPERATURE LIMITS

C.1 INTRODUCTION

The principal potential breach mechanisms for zircaloy clad irradiated fuel during inert gas dry storage have been identified as creep rupture, stress corrosion cracking, and delayed hydride cracking (Reference 4.1). However, cladding breach due to stress corrosion and delayed hydride cracking is not expected because the threshold stress intensity levels for these mechanisms are greater than those expected for spent fuel. Thus, prevention of creep rupture (by limiting the maximum initial dry storage temperature) is the primary means of preventing cladding breach during dry storage.

The maximum allowable initial dry storage temperature is a complex function of fuel design, burnup level, fuel age and the geometry and makeup of the dry storage cask. In order to account for these variations, the graphical use of generic temperature limit curves described and developed in Reference 4.1 has been adopted. This methodology defines a specific temperature limit, below which the probability of cladding breach due to creep rupture is less than 0.5% per spent fuel rod for a 40 year storage period.

C.2 ANALYSIS

The assemblies considered are as follows:

- B&W Mark C (17 x 17)
- B&W Mark B-4 (15 x 15)
- CE 15 x 15 (Palisades)
- Westinghouse PWR (17 x 17)
- Westinghouse PWR (15 x15)
- Westinghouse PWR (14 x 14)

From Reference 4.1,

$$\sigma_{mhoop} = [(p)(D_{mid})]/2t$$

where,

σ_{mhoop} = cladding hoop stress

p = internal gas pressure of rod (fission gas and fill)

D_{mid} = clad midwall diameter

t = clad thickness

This relationship between stress and temperature (actually gas pressure which is related via the perfect gas law) is plotted for the various fuel assemblies in Figure C.2-1. Also, the generic temperature limit curves for 5, 6, 7, 10 and 15 year cooling period from Reference 4.1 are plotted on the same axis. The intersection of the stress temperature relationship line for a given fuel assembly with the 5, 6, 7, 10 and 15 year limit curves then defines the maximum allowable initial dry storage temperature for fuel of this type.

C.3 RESULTS AND CONCLUSIONS

The results of this study are illustrated in Figure C.2-1. As seen from Figure 2.1.1 applied to Figure C.2-1, the 5 year cooling limit is the most restrictive, as clad temperatures after 6, 7, 10 and 15 years are well below their respective limit curves. Hence, a temperature limit of 712°F after 5 years cooling is adequate to ensure a less than 0.5% per rod probability of stress induced clad failure over a storage period of 40 years. However, as noted by the fairly wide range of limits obtained from Figure C.2-1, this limit may be quite restrictive for certain fuel types.

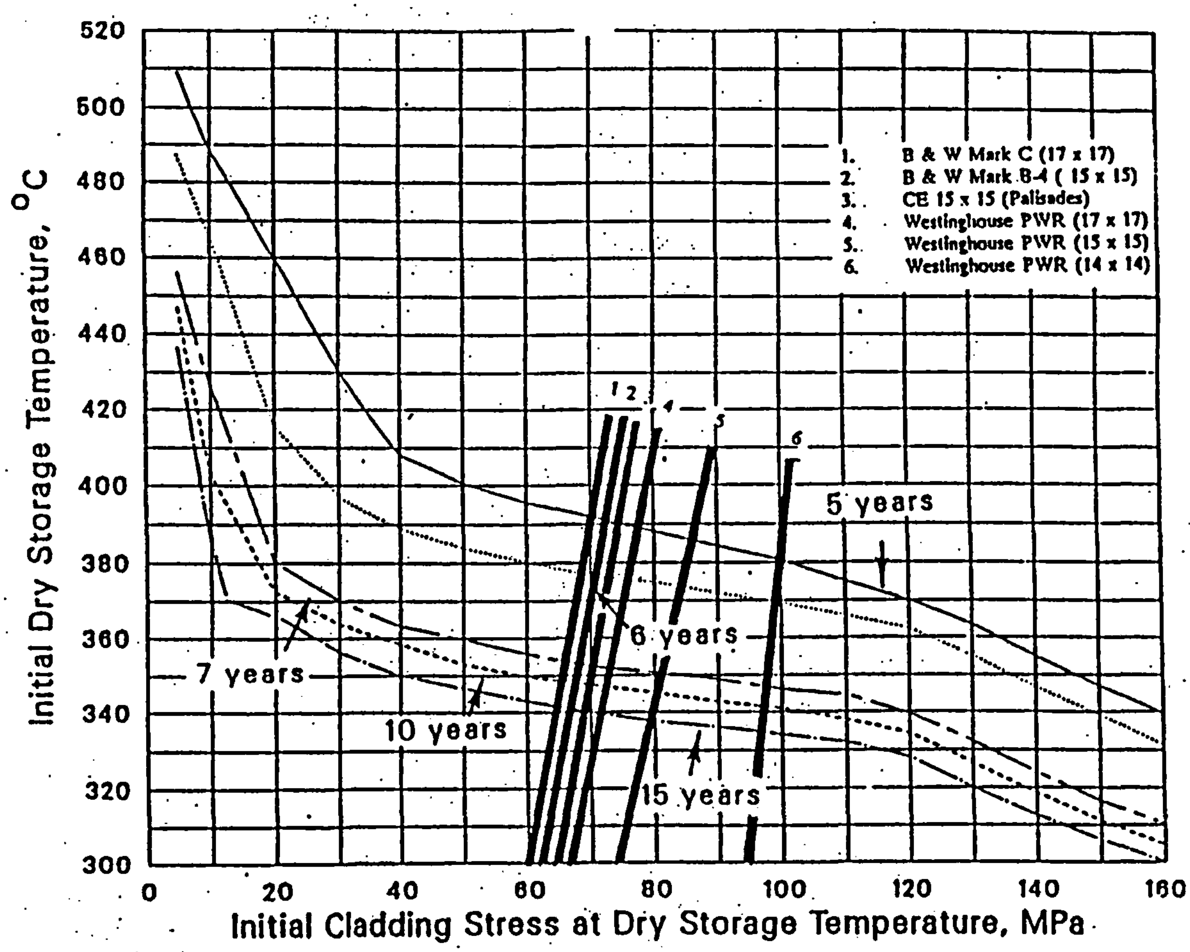

Figure C.2-1 - Comparison of IDS Cladding Temperature Limit Curves For Spent Fuel Of Varying Ages

APPENDIX D

EFFECTIVE THERMAL CONDUCTIVITIES
FOR WIDE AND NARROW AREAS WITHIN THE MSB

D APPENDIX D - EFFECTIVE THERMAL CONDUCTIVITIES FOR WIDE AND NARROW AREAS WITHIN THE MSB

D.1 INTRODUCTION

Heat transfer through the wide and narrow areas formed by the MSB inner wall and the sleeve assemblies occurs by a complex interplay of radiation, convection and conduction through the helium backfill gas. In the radial sector ANSYS model used to analyze the MSB internals, radiation heat transfer from the sleeves to the MSB is directly addressed through the use of radiation link elements extending from nodes on the basket face to nodes on the MSB wall. These elements require readily available input (i.e., emissivities, areas, view factors). Conduction through the gas is modelled using solid elements which require as input material properties.

The direct treatment of convection heat transfer in the areas is not possible in the radial sector model, however, due to the complex axial flow patterns of the gas and the corresponding variation in heat transfer coefficients. Therefore, an alternative method of treating convection heat transfer in these areas as a conduction through the gas with an effective thermal conductivity (k_e) was developed. This value of k_e was determined by examination of data obtained from various tests performed with similar casks.

D.2 ANALYSIS

The form of the equation sought for k_e is as follows:

$$q_r = k_e \cdot A \cdot dT/dr = h \cdot A_s \cdot (T_s - T_b)$$

where,

A	=	conduction area
dT/dr	=	temperature gradient across gap
h	=	convection coefficient
A_s	=	convection surface area
T_s	=	convection surface temperature
T_b	=	gas bulk temperature
q_r	=	radial heat flow through gap

By examining thermocouple data presented in references the required temperatures to solve the above equation for k_e in terms of the remaining known quantities may be obtained. However, in order for the above equation to apply, the heat flow through the gap must first be divided into that arising from conduction and convection and that arising from radiation. The required adjustment is as follows:

$$q_r'' = k_e \cdot dT/dr + e\sigma (T_s^4 - T_w^4)$$

where,

q_r''	=	radial heat flux at basket surface
e	=	basket surface emissivity
σ	=	Stefan-Boltzman Constant
T_w	=	MSB wall temperature

from which the expression for k_e can be derived as:

$$k_e = [q_r'' - e\sigma (T_s^4 - T_w^4)] \times \delta r/(T_s - T_w)$$

where,

δr = average radial gap between basket and wall (which is essentially the hydraulic diameter for the geometrics question).

D.3 RESULTS AND CONCLUSIONS

Results from two casks which have very similar geometries to the VSC-24 were used (4.3, 4.6). The data used is shown below:

Reference	q_r (BTU/hr-ft^2)	e		T_s(°F)	T_w(°F)	δr(ft)	k_e (BTU/hr-ft-°F)
4.3	332.7	0.8	wide	242	198	0.16	2.8
			narrow	301	199	0.16	0.24
4.6	192	0.2	wide	210	167	0.87	3.6
			narrow	230	167	0.17	0.46

Results from the cask test reported in Reference 4.3 yielded the most conservative k_e = 2.8 BTU/hr-ft-°F for the wide areas and k_e = 0.24 BTU/hr-ft-°F for the narrow areas. The data for k_e was used in the ANSYS MSB radial model. The wide area dT (dT=Ts-Tw) was found to be accurately and conservatively calculated. However, the narrow area dT was not conservatively calculated, using the determined k_e = 0.24 BTU/hr-ft-°F. Therefore, for narrow areas, the lowest possible value of k_e (k of helium gas = 0.11 BTU/hr-ft-°F) was used. With this value the narrow area dT was calculated to within 10% of the test data. This was considered accurate enough since the wide area k_e gave a Δk 10% higher than the test data. Therefore, the following values were used to model the wide and narrow areas in the VSC-24 MSB ANSYS model:

Wide areas: k_e = 2.8 BTU/hr-ft-°F

Narrow areas: k_e = k helium = 0.11 BTU/hr-ft-°F

These values conservatively predict observed temperature gradients in the test performed with similar casks and the results of their use are summarized in Table D.1-1. Table D.1-1 also shows some of the results of the parametric variation analysis that were performed. In this analysis the wide area k_e was varied from 4.6 to 0.58 with the narrow area held constant at 0.11. As this table shows the ΔT across the wide area only increased by 32°F as the k_e falls from 2.8 to 0.58. Likewise, the narrow area ΔT only increases by 14°F. The overall impact on the fuel temperature was a 22°F rise which is insignificant compared to the roughly 400°F ΔT from the MSB shell to the hottest fuel rod. Hence, it was concluded that the fuel temperature depends much more on conduction through the steel basket and radiation than on the conduction or convection through the helium.

Table D.1-1 - Summary of Wide and Narrow Area Thermal Analysis

	k_e BTU/hr-ft-°F		ΔT°F	
	Wide	Narrow	Wide	Narrow
Test Results	--	--	43	102
ANSYS Run 1	2.8	0.24	46	81
ANSYS Run 2	2.8	0.11	48	90
ANSYS Run 3	0.58	0.11	80	104

APPENDIX E

NOT USED

APPENDIX F

SPECIFICATION VMSB-98-001

APPENDIX F

SPECIFICATION VMSB-98-001

SIERRA NUCLEAR CORP.

1 Victor Square
Scotts Valley, CA 95066
Phone (408) 438-6444
Fax (408) 438-5206

620 Colonial Park Drive
Roswell, GA 30075
Phone (770) 518-7785
Fax (770) 518-7883

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PREPARED BY: A. Q. Tran

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SAFETY CLASSIFICATION: IMPORTANT TO SAFETY

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Reviewed and Approved By: K. E. Moeckel, Engineering Manager Date 8/13/98

RECORD OF REVISIONS

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TITLE: GUIDELINE REQUIREMENTS FOR THE TIME-OF-FLIGHT DIFFRACTION ULTRASONIC EXAMINATION OF THE VSC-24 STRUCTURAL LID TO SHELL WELD

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1.0 Purpose/Scope

1.1 The purpose of this document is to provide technical guidelines for conducting the Time-of-Flight Diffraction (TOFD) ultrasonic testing (UT) examination of the VSC-24 Multi-assembly Sealed Basket (MSB) structural lid to shell weld either in the transfer cask (MTC) or concrete cask (VCC).

1.2 The scope of this guideline includes the establishment of flaw acceptance criteria, examination parameters, examination process and technique development, and qualification of examination procedures and examination personnel.

1.3 The guideline provides the technical basis for specific operating procedures that would be used to address any required actions resulting from the ultrasonic testing examination of the VSC-24.

2.0 References

2.1 ASME Section XI, 1989 Edition, IWB-3600

2.2 ASME Section XI, 1989 Edition, IWA-3300

2.3 Certificate of Compliance, Title 10 Code of Federal Regulations Part 72, Number: 1007

2.4 Safety Analysis Report for the Ventilated Storage Cask System

2.5 ASNT Recommended Practice No. SNT-TC-1A, "Personnel Qualification and Certification in Nondestructive Testing", 1984 Edition

2.6 Structural Integrity Associates Analysis, "Allowable Flaw Size Definition for VSC-24 Dry Storage Cask Structural Lid to Shell Weld: File No. CPC-06Q-301"

2.7 Flaw Tech drawing 7C037R5, "Flawed Specimen-Palisades DFS Mock-Up"

2.8 Flaw Tech drawing 7C037AR4, "Flawed Specimen-Flaw Locations"

2.9 SNC WEP-109.002.2, MSB-24 Load Combination Evaluation

3.0 Definitions

3.1 Time-of-Flight Diffraction (TOFD) - A method of performing an ultrasonic examination on components which floods the examination volume with sound used for detection and sizing of indications in the examined component. The technique uses changes due to diffraction of the input sound energy across the indication for both detection and sizing.

3.2 Flaw Depth - The flaw dimension normal to the surface (inside or outside) of the component.

3.3 Flaw Length - The flaw dimension parallel to the surface (inside or outside) of the componenent.

4.0 Quality Assurance Requirements

All work performed in compliance with this guideline document shall be performed in accordance with Quality Assurance Programs that meet the applicable quality assurance requirements of 10CFR50, Appendix B.

5.0 Responsibilities

The responsibilities of the VSC-24 Certificate Holder and VSC-24 Owner or Owners Group are as follows:

- VSC-24 Certificate Holder

  The VSC-24 Certificate Holder is responsible for establishing acceptance criteria including dispositioning of flaws and developing, distributing and revising this guideline document and examination procedure(s).

- VSC-24 Owner or Owners Group

  The VSC-24 Owner or Owners Group is responsible for developing site specific evaluations and procedures and qualifying examination processes, techniques, procedures and personnel.

6.0 Screening Criteria

Screening criteria for flaw indications shall be established based on analysis and used to disposition flaw indications. The "Screening Criteria for Use During Ultrasonic Examination of VSC-24 Structural Lid to Shell Welds" is contained in Attachment 4.

6.1 Basis for Screening Criteria

Screening criteria and supporting analysis for Arkansas Nuclear One, Palisades and Point Beach Nuclear Plants are contained in Structural Integrity analysis "Allowable Flaw Size Definition for VSC-24 Dry Storage Cask Structural Lid to Shell Weld: File No. CPC-06Q-301", Reference 2.6.

The screening criteria provide the basis for initial evaluation and disposition of flaw indications detected during volumetric examination. These criteria are based on the criteria of ASME Section XI, 1989 Edition, with a conservative set of assumptions as follows:

- All factors of safety on applied stress required by ASME Section XI were included.
- The analyses are all based on linear elastic fracture mechanics (LEFM), assuming that the failure mode is brittle fracture. Actual material toughness tests results show that all materials are highly resistant to such failures.
- Weld residual stresses were treated as constant tensile stresses normal to the limiting (circumferential) flaw direction. The magnitude of these tensile stresses was taken to be at the minimum specified yield stress of the base material.
- The Screening criteria were derived using the lower bound of material toughness determined by test for representative materials.
- Welding processes used by each plant to fabricate specimens for Charpy V-notch and toughness testing were intentionally performed near the high end of the heat input reported during original welding procedure qualification, in order to determine the lower limit on material toughness.
- The fracture mechanics analyses performed to determine acceptance criteria used analytical models of flaws in flat plates. The actual weld configuration provides considerably more restraint to hypothetical flaw locations. The increased restraint would produce larger allowable flaw sizes.

If further evaluation of flaws is required, it may include either LEFM or Elastic Plastic Fracture Mechanics (EPFM) analyses. This latter method is applicable for high toughness materials such as are indicated by the actual material test results. The key parameter is the fracture toughness represented by the critical J integral, J_{IC}. The assumed mechanism is ductile crack extension.

6.1.1 Code Requirements

The methods of ASME Section XI, IWB-3600, Reference 2.1, are used to determine screening criteria and to further evaluate flaw indications.

6.1.2 Load Limits

The limiting loading conditions on the MSB are identified in the VSC-24 SAR, Reference 2.4, as supplemented in Sierra Nuclear Corporation calculation WEP-109.002.2, MSB Load Combination Evaluation (Reference 2.9).

6.1.3 Operational Limits

The MSB operational temperature limits, which determine the appropriate material properties, are identified in the VSC-24 C of C, Reference 2.3.

6.1.4 Material Properties

a. Requirement

Material specimens representative of the structural lid and shell materials and actual weld processes used during loading shall be used to develop screening criteria. Charpy V-notch impact tests and material toughness tests shall be performed on these specimens.

Charpy V-notch impact and toughness tests shall be performed at 0°F.

The material toughness properties shall be established by supplemental tests performed in accordance with ASTM E-1737-96.

b. Testing Performed

Charpy V-notch impact tests at 0°F and material toughness tests in accordance with ASTM E-1737-96 were performed. The results of these tests are summarized in Structural Integrity Analysis, Reference 2.6.

c. Future Procurement

Specifications for future procurement of pressure retaining materials including weld metal, shall specify a minimum Charpy V-notch impact absorbed energy value of 45 ft-lbs at 0°F in addition to the current requirement of 15 ft-lbs minimum at -50°F. Future materials which satisfy these minimum values will not invalidate the acceptance criteria in the Structural Integrity Analysis, Reference 2.6.

In addition, low-sulfur, calcium-treated, vacuum-degassed steel, such as produced by the Lukens Fineline® process, shall be specified in future orders for the VSC-24 MSB pressure boundary material. Welding consumables with low hydrogen levels (less than 10ml/H_2/STP/100g) shall be utilized for all lid welds.

6.2 Flaw Disposition

Flaw indications identified during examination are required to be dispositioned as outlined in the Flaw Disposition Flow Chart, Attachment 1, and as described below:

6.2.1 Characterization

Flaws detected by examination shall be described in terms of location, length, depth, orientation (e.g., circumferential, transverse, laminar etc.), and type, to the extent possible (e.g., planer and/or volumetric).

6.2.2 Flaw Proximity

Adjacent flaws shall be evaluated using the flaw proximity criteria of ASME Section XI, IWA-3300.

6.2.3 Screening Criteria

Each flaw shall be compared with the screening criteria in Attachment 4 and the flaw proximity requirements of 6.2.2. Flaws which satisfy this criteria are acceptable and require no further action. Flaws which do not satisfy the screening criteria may be determined to be acceptable by further evaluation or alternatively, may be repaired.

6.2.4 Flaw Evaluation Methods

Flaws which do not meet 6.2.3 may be shown to be acceptable for continued operation using fracture mechanics techniques (Linear Elastic Fracture Mechanics or Elastic-Plastic Fracture Mechanics) as appropriate, as described in 6.1 and Structural Integrity Analysis, Reference 2.6.

6.2.5 Repairs

Flaws which are not acceptable based on the requirements described in 6.2.3 or 6.2.4 above shall be repaired. Repair shall be accomplished by removing the flaw or reducing the flaw to an acceptable level as described in 6.2.3 and 6.2.4 above.

7.0 Examination Parameters

Examination parameters are bounded by the requirements and specifications of the VSC-24 SAR and C of C, including source terms and heat load in the MSB, location of the MSB in the MTC or VCC and plant specific operational constraints.

Examination of the MSB structural lid to shell weld occurs following loading of the MSB with spent fuel assemblies and therefore the concerns of ALARA shall be addressed in the qualification of examination procedures and operational planning.

Changes to the licensed configuration or operation of the VSC-24 system to accommodate the examination require the appropriate evaluations such as, but not limited to, 72.48 and plant ALARA. Consideration shall be given as a minimum to the areas described in 7.1 and 7.2.

7.1 MSB in MTC

Examination of the structural lid to shell weld with the MSB in the MTC shall consider the following:

7.1.1 Configuration Limitations

Access to the structural lid to shell weld on the MSB top is not constrained. Access to the shell side of the weld is limited to a nominal 0.5 inch gap. However, during loading activities, shims are installed in this gap to limit radiation streaming. Operations without the shims in place require further site specific evaluation.

7.1.2 Radiation/Shielding

The MTC, in addition to lifting the MSB, provides shielding of the loaded spent fuel assemblies.

The design basis calculated radiation at the structural lid, the gap between the MSB shell and MTC and at the side MTC is provided in the VSC-24 SAR, Reference 2.4. Actual dose measurements during previous loading operations generally support the design basis calculations. However, variations in the source terms, such as "old" fuel assembly end fittings, can have a significant effect on measured radiation.

A dose evaluation shall be performed to assure that the examination procedure is in compliance with the Owner's plant ALARA requirements.

7.1.3 Component Temperature

The MSB structural lid and shell temperature will increase with time due to spent fuel decay heat. The maximum calculated design basis equilibrium fuel temperature of the MSB (with He) in the MTC is provided in the VSC-24 SAR, Reference 2.4.

A thermal evaluation will be required to assure that the examination procedure can accommodate the planned MSB heat loads. In any case, the UT examination shall be performed with a metal temperature of 200°F or less.

If the thermal analysis indicates that the planned heat loads will exceed the examination process limitations, then provisions to cool the MSB components will need to be implemented.

7.1.4 Operational Limitations

The operational limits of the system, such as the "minimum temperature for moving the MSB or lifting the MTC" and the "handling height" are defined in the VSC-24 C of C, Reference 2.3.

7.2 MSB in VCC

Examination of the structural lid to shell weld with the MSB in the VCC shall consider the following:

7.2.1 Configurational Limitations

Access to the structural lid to shell weld on the MSB top requires lifting the VCC shield ring. Operations conducted with the shield ring elevated or removed will require evaluation. Although the annular gap between the MSB and VCC liner is nominally 4.0 inches, access to the MSB shell side is restricted by the VCC shield lid support ring welded to the liner.

7.2.2 Radiation/Shielding

The VCC, in addition to providing cooling of the MSB, provides shielding of the loaded spent fuel assemblies.

The design basis calculated radiation at the structural lid and at the side of the VCC is provided in the VSC-24 SAR, Reference 2.4. Actual dose measurements during previous loading operations generally support the design basis calculation. However, variations in the source terms, such as "old" fuel assembly end fittings, can have a significant effect on measured radiation.

A dose evaluation shall be performed to assure that the examination procedure is in compliance with the Owner's plant ALARA requirements.

7.2.3 Temperature

The maximum calculated design basis equilibrium temperature of the MSB in the VCC is provided in the VSC-24 C of C, Reference 2.3. The SAR indicates that the lid temperatures are limited to less than 160°F for the design basis heat load and therefore will not impact the examination procedure.

7.2.4 Operational Limitations

The operational limits of the system, such as the "minimum temperature for moving the MSB" and the "handling height" of the VCC are defined in the VSC-24 C of C, Reference 2.3. The rigging used to facilitate examination shall have the same safety factors as applied to the rigging used for handling of components such as the VCC weather cover and shield ring during loading.

7.2.5 Weather Cover Removal

The weather cover will only be removed for a short period of time to facilitate the UT examination in the VCC and on the condition of no impending threat of severe weather.

Potential accident conditions during removal of cover while performing UT examination in the VCC shall be addressed on a site-specific basis.

8.0 Development of Examination Processes and Techniques

Examination processes and techniques capable of conducting a volumetric ultrasonic testing (UT) examination of the structural lid to shell weld shall be developed.

8.1 Examination Process and Technique Requirements

The processes and techniques developed for the examination of the MSB structural lid to shell weld shall meet the following requirements:

8.1.1 Circumferentially Oriented Flaws

1. Detection

The examination shall detect flaws with depth greater than 0.100".

2. Length Sizing Acceptance Criteria

The examination shall length size the detected flaws as follows:

Flaw lengths shall be within 0.75 RMS.

3. Depth Sizing Acceptance Criteria

The examination shall depth size the detected flaws as follows:

The mean error in the flaw depth will be calculated and documented. If the mean error is less than or equal to a positive 0.072 inches, the RMS error must be less than or equal to 0.125 inches. If the mean error is greater than a positive 0.072 inches, this contribution to the RMS error will be removed and recorded. The remaining error must be less than or equal to 0.102 inches (reference Attachment 3: White paper on Depth Sizing Acceptance Criteria for Time-of-Flight Diffraction Ultrasonic Examination of the VSC-24 Structural Lid to Shell Weld).

8.1.2 Transverse (Axially) Oriented Flaws

1. Detection

The examination shall detect flaws with depth greater than 0.100".

2. Length and Depth Sizing Acceptance Criteria

Transverse flaws do not affect the structural adequacy of the structural lid to shell weld. The minimum examination requirement is to demonstrate that an inside surface connected transverse flaw does not extend into the upper 25% of the weld ligament, so that the pressure integrity and leak tightness of the weld is not impaired. For this screening examination, detailed length sizing for transverse flaws is not required, and such flaws may be assumed to extend completely across the weld in the transverse direction.

3. Any undersizing depth error identified during the personnel qualification activities will be added to the reported flaw depth for transverse flaws.

8.1.3 Permanent Records

The examination shall produce a permanent record.

8.1.4 Operational Requirements

The examination shall meet the requirements described above under the conditions outlined in Section 7.0 - Examination Parameters.

8.2 Examination Equipment

The equipment to be used for examination of the MSB structural lid to shell weld shall meet the following requirements:

8.2.1 Automated and/or Semi-Automated Equipment

Automated and semi-automated equipment shall provide a complete set of data necessary for detecting, locating and sizing flaws and a permanent record of the examination in the shortest time to minimize radiation exposure and meet ALARA requirements. Semi-automated equipment is a manually positioned scanner that utilizes the same transducers, data acquisition and recording system as the automated equipment.

8.2.2 Calibration Blocks

Calibration blocks of acoustically equivalent material and reflectors suitable for establishing reference gain settings and repeatability shall be used for the calibration of examination equipment. The equipment shall be calibrated prior to each examination/setup using appropriate calibration block(s) that is within ±25°F of the actual temperature of the component area to be examined. Calibration blocks shall satisfy site specific QA program requirements.

9.0 Examination Procedure Qualification and Approval

Examination procedures shall be developed, qualified and demonstrated using appropriate mockup(s).

9.1 MSB Mockup

An unsecured mockup of the MSB shall conform to the following requirements:

9.1.1 Configuration

The mockup components and structural lid to shell weld shall be constructed to the configuration of the MSBs to be examined.

9.1.2 Materials

The mockup shall be constructed of the same material type(s) as the MSBs to be examined.

9.1.3 Implanted Flaws

Flaws consisting of welding process discontinuities and cracks of varying sizes (both length and depth) shall be implanted in the weld and weld HAZ of the mockup at representative locations.

The flawed specimen layout and details for the mockup used in the development of examination processes and techniques are described in References 2.7 and 2.8.

9.1.4 Mockup Temperature

The mockup temperature during examination procedure qualification shall bound the expected temperature of the MSBs to be examined.

9.2 MTC Mockup

The mockup shall represent the configuration of the actual MTC used during loading.

9.3 VCC Mockup

The mockup shall represent the configuration of the actual VCC used during loading.

9.4 Examination Procedure Requirements

The examination procedure shall address the essential variables described in Attachment 2.

9.5 Examination Procedure Qualification Criteria

The procedure is considered to be qualified if implanted flaws are detected, length and depth sized in accordance with 8.1.1 and 8.1.2.

9.6 Examination Equipment Demonstration

The examination equipment shall be demonstrated in the configuration that the actual examinations will be performed using an appropriate mockup combination as follows:

- The MSB mockup shall be installed in the MTC mockup to assure that the examination equipment can perform satisfactorily under the operational constraints of this configuration, including shielding.

- The MSB mockup shall be installed in the VCC mockup to assure that the examination equipment can perform satisfactorily under the operational constraints of this configuration, including shielding.

9.7 Examination Procedure Approval/Modification/Revision

The VSC-24 Owners shall review and approve the examination procedure.

A modification to an approved procedure that constitutes a change to an essential variable described on Attachment 2, requires requalification. A qualified examination procedure may be modified without requalification provided the modification does not change an essential variable and compliance with the requirements is maintained. Editorial, clarification and format changes are examples of procedure modifications which may be made without having to requalify an approved procedure. Examination procedure requalification, when required, shall be in accordance with the requirements contained in this guideline document.

Modifications to an approved procedure which affect the essential variables shall be concurred with by all the VSC-24 Owners. Modifications that do not affect the essential variables may be controlled on a site specific basis.

10.0 Examination Personnel Qualification

10.1 Experience

Personnel performing the examination shall be qualified and certified as ultrasonic testing (UT) Level II (minimum) to a program that meets the requirements of SNT-TC-1A, Reference 2.5.

10.2 Performance Qualification Demonstration

10.2.1 General

10.2.1.1 Personnel performing data acquisition and data analysis shall demonstrate proficiency by participation in a performance demonstration developed and administered by the EPRI NDE Center.

10.2.1.2 Test data used in the personnel analysis demonstrations may be from previous demonstrations, an ongoing data acquisition demonstration or data that has been collected by the EPRI NDE Center.

10.2.1.3 Personnel demonstrations for data acquisition and data analysis will be performed with no prior knowledge of flaw type, size or location (e.g., blind test).

10.2.1.4 The VSC-24 Owners group will have final responsibility in the acceptance of the demonstration protocol developed by the EPRI NDE Center.

10.2.2 Training

Evidence of personnel training (specific to the inspection of the VSC-24 using the TOFD ultrasonic technique) shall be documented prior to any personnel data analysis demonstration. The training shall a minimum of 40 hours of which 8 hours will be specific to the VSC-24. The training may take place in the classroom and/or on the job.

10.2.3 Test Set Selection

The performance demonstration protocol for the test set developed by the EPRI NDE Center shall address the following: the number of flaws, the size of the flaws, flaw orientation, flaw characteristic/type, unflawed areas within the demonstration mock up and the number of the same flaws allowed from a previous test for a given person. As a minimum the test set shall contain ten flaws equally distributed throughout the examination volume.

10.2.4 Security and Demonstration Surveillance

The grading criteria and answer keys shall remain secure from any person who is in or will potentially be in the demonstration process for the analysis of TOFD ultrasonic VSC-24 data.

10.2.5 Grading

The specific grading criteria will be established within the performance demonstration protocol developed by the EPRI NDE Center. As a minimum the person demonstrating their capability to acquire data shall detect 80% of the flaws within the test set. For the candidate to receive credit for detecting a flaw they must locate at least 50% of the flaw length accurately (i.e. the reported length shall be at least 50% coincident with the actual flaw length) Persons demonstrating their capability to analyze data shall detect 80% of the flaws within the test set and the detected flaws shall be sized with the tolerances described in 8.1.1 and 8.1.2.

10.2.6 Retesting of Personnel

Persons who have failed to meet the requirements of the grading criteria may be allowed to test one additional time. Person's who have failed two tests shall receive additional training specific to the inspection of the VSC-24 using the TOFD ultrasonic technique prior to taking a third test. Areas where the person has demonstrated deficiencies shall be addressed in the additional training.

10.2.7 Documentation and Record Retention

All records produced during the demonstration process shall be retained and distributed by the EPRI NDE Center.

10.3 Expiration and Renewal of Qualification Term

10.3.1 Expiration of Qualification

Personnel qualifications in accordance with 10.2 shall expire three (3) years from the date of qualification for Level II and five (5) years for Level III.

10.3.2 Renewal of Qualification

Renewal of qualification expired under 10.3.1 above shall be in accordance with 10.2.

10.4 Personnel Qualification

Personnel qualifications for this UT process may be transferred among VSC-24 Owners.

11.0 Attachments

Attachment 1 - Flaw Disposition Flow Chart

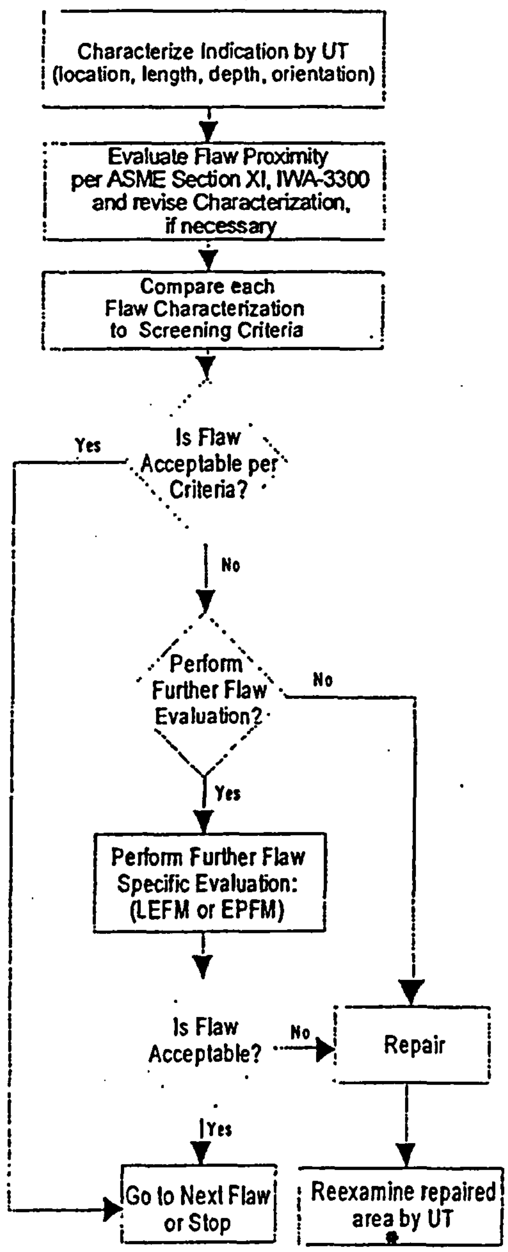
Attachment 2 - Examination Procedure Essential Variables

Attachment 3 - White Paper on Depth Sizing Acceptance Criteria for Time-of-Flight Diffraction Ultrasonic Examination of the VSC-24 Structural Lid to Shell Weld.

Attachment 4 - Screening Criteria for Use During Ultrasonic Examination of VSC-24 Structural Lid to Shell Welds

TITLE: GUIDELINE REQUIREMENTS FOR THE TIME-OF-FLIGHT DIFFRACTION ULTRASONIC EXAMINATION OF THE VSC-24 STRUCTURAL LID TO SHELL WELD

ATTACHMENT 1 - FLAW DISPOSITION FLOW CHART



ATTACHMENT 2 - EXAMINATION PROCEDURE ESSENTIAL VARIABLES

EXAMINATION PROCEDURE ESSENTIAL VARIABLES	
(1)	instrument or system, including manufacturer and model or series of pulser, receiver, and amplifier, and software version
(2)	search units, including: (a) center frequency and either bandwidth or waveform duration; (b) mode of propagation and nominal inspection angles (c) number, size, shape, and configuration of active elements and wedges or shoes
(3)	search unit cable, including: (a) type; (b) maximum length; (c) maximum number of connectors
(4)	detection and sizing techniques, including:
	(a) scan pattern and beam directions;
	(b) maximum scan speed;
	(c) minimum and maximum pulse repetition rate;
	(d) minimum sampling rate (automatic recording systems)
	(e) extent of scanning and action to be taken for access restrictions
(5)	methods of calibration for detection and sizing (e.g., actions required to insure that the sensitivity and accuracy of the signal amplitude and the time outputs of the examination system, whether displayed, recorded, or automatically processed, are repeated from examination to examination)
(6)	inspection and calibration data to be recorded
(7)	method of data recording
(8)	recording equipment (e.g., strip chart, analog tape, digitizing) when used
(9)	method and criteria for the discrimination of indications (e.g., geometric versus flaw indications and for length and depth sizing of flaws)
(10)	surface preparation requirements

ATTACHMENT 3

White Paper on Depth Sizing Acceptance Criteria for Time-of-Flight Diffraction Ultrasonic Examination of the VSC-24 Structural Lid to Shell Weld

White Paper on Depth Sizing Acceptance Criteria for Time-of-Flight Diffraction Ultrasonic Examination of the VSC-24 Structural Lid to Shell Weld

by
Douglas E. MacDonald
EPRI NDE Center
Charlotte, NC 28221

The generic guideline document for the time-of-fight diffraction (TOFD) ultrasonic examination of the VSC-24 structural lid to shell weld contains the following sub-section (8.1.1.3) describing the flaw depth sizing acceptance criteria:

8.1 Examination Process and Technique Requirements

The process and techniques developed for the examination of the MSB structural lid to shell weld shall meet the following requirements:

8.1.1 Circumferentially Oriented Flaws

3. Depth Sizing Acceptance Criteria

The examination shall depth size the detected flaws as follows:

- The mean error in the flaw depth will be calculated and documented. If the mean error is less than or equal to a positive 0.072 inches, the RMS error must be less than or equal to 0.125 inches. If the mean error is greater than a positive 0.072 inches, this contribution to the RMS error will be removed and recorded. The remaining portion of RMS the error must be less than or equal to 0.102 inches.

The purpose of this white paper is to provide the technical basis for the criteria in (8.1.1.3), definitions of the terms used in the criteria, and sample calculations using the criteria.

The industry standard practice for depth sizing acceptance criteria is that the root-mean-squared error (RMSE) be less than or equal to 0.125 inch. For the 52° TOFD data, the criteria on the depth sizing that RMSE ≤ 0.125 inch can be met with no problem (e.g. see Figure 1). However, for the 60° TOFD data, the mean error alone is sometimes as large as +0.125 inch (e.g. see Figure 2). As will be shown below, the mean error is a component of the RMSE, so that the criteria that RMSE ≤ 0.125 inch for the 60° TOFD data cannot be met. The reason for the large positive bias in the depth sizes calculated with the 60° TOFD data is well understood on ultrasonic grounds and will not be addressed here except to mention that it is a conservative error.

The goal of sub-section 8.1.1.3 is to apply the unmodified industry standard (RMSE ≤ 0.125 inch) for the 52° TOFD data where the mean error is small (see Figure 1) and for the 60° TOFD data, to document the large conservative mean error (see Figure 2), account for it, and apply a criteria to the remaining error that is proportional to the industry standard.

To be able to account for the positive bias found in the 60° TOFD data, a short discourse on RMSE is in order. The RMSE can be defined in terms of the sizing data (M_i, T_i), i = 1 ... n by the equation:

$$\mathrm{RMSE}^2 = \frac{\sum_i (M_i - T_i)^2}{n}, \qquad (1)$$

where M_i is a measured flaw dimension and T_i is the "true" flaw dimension. Following the development in NUREG/CR-5410 (see pages 37-39), the RMSE can be expressed in terms of the three parameters of linear regression analysis, i. e.

$$\mathrm{RMSE}^2 = (\beta_1 + (\beta_2 - 1)\mu_T)^2 + (\beta_2 - 1)^2 \sigma_T^2 + \sigma_\varepsilon^2, \qquad (2)$$

where β_1 is the intercept of the regression curve, β_2 is the slope of the regression curve, and σ_ε^2 the variance in the error in the regression curve. It is the minimization of the variance in the regression error that establishes the parameters β_1 and β_2. The term σ_ε is also known as the standard error of estimate and represents the part of the variance in the measured values that can not be explained by regression analysis (i.e. random error).

In equation (2), the mean of the true sizes is given by, $\mu_T = \frac{\sum_i T_i}{n}$; and the variance of the true sizes is given by, $\sigma_T^2 = \frac{\sum_i (T_i - \mu_T)^2}{n}$. Introducing the mean of the measured sizes as $\mu_M = \frac{\sum_i M_i}{n}$ and expressing in terms of the mean of the true sizes using the regression curve; i.e. $\mu_M = \beta_1 + \beta_2 \mu_T$, the expression for the RMSE can be written as,

$$RMSE^2 = (\mu_M - \mu_T)^2 + (\beta_2 - 1)^2 \sigma_T^2 + \sigma_\varepsilon^2 \qquad (3)$$

We now recognize the first term as the square of the mean error (μ_M- μ_T). From the formula in equation (3), the RMSE can only be zero when ideal regression results are obtained, i.e. the mean error is zero, (μ_M- μ_T) = 0, the regression slope is one, $\beta_2 = 1$, and the standard error of estimate is zero, $\sigma_\varepsilon = 0$. Paraphrasing from NUREG/CR-5410: 'A small root mean squared error forces the sizing bias (mean error, (μ_M- μ_T)), the deviation from ideal trend (slope error, (β_2 - 1)) and the random error (estimation error, σ_ε) to be small. Therefore, RMSE summarizes the deviations of the regression parameters from the ideal.'

The expression in equation (3) allows the calculations necessary to account for the positive mean error (bias) in the sizing results of the 60° TOFD data. It also provides a rational basis for establishing the threshold criteria on the mean error before removing it from the RMSE and setting the tighter criteria on the remaining slope error and estimation error components of the RMSE.

The purpose of the threshold criteria on the mean error is to separate the depth sizing measurements into data sets with and without a systematic positive bias. The magnitude of the threshold value should clearly delineate the data sets and not allow for a random separation of the data. In order to meet these goals, the threshold value on the mean error was taken to be equal to its contribution to the limiting value of the RMSE (0.125 inch) assuming equal contributions from the three components of RMSE, mean error, slope error, and estimation error. From equation (3)

$$RMSE^2_{Limit} = (0.125)^2 = 3(\mu_M - \mu_T)^2_{Threshold},$$

$$(\mu_M - \mu_T)_{Threshold} = \frac{+0.125}{\sqrt{3}} = +0.072.$$

Setting the threshold of the mean error at 0.072 inch assures that the data separation will not be arbitrary but associated with the physical differences in the flaw depth measurements.

When the threshold is exceeded, the positive mean error value is recorded and then removed from the RMSE. The new limiting criteria on the remaining components of the RMSE (slope and estimation error) is reduced proportionally from the original value of 0.125 inch, since one out of the three components of the RMSE has been removed. Again from equation (3)

$$\left[RMSE^2 - (\mu_M - \mu_T)^2\right]_{Limit} = \left[(\beta_2 - 1)^2 \sigma_T^2 + \sigma_\varepsilon^2\right]_{Limit} = \frac{2(0.125)^2}{3}$$

$$\sqrt{\left[RMSE^2 - (\mu_M - \mu_T)^2\right]_{Limit}} = \sqrt{\frac{2(0.125)^2}{3}} = 0.125\sqrt{\frac{2}{3}} = 0.102 \cdot$$

The limiting criteria on the remaining error of 0.102 inch is well within the capability of the 60° TOFD data. The 60° TOFD data shows good sizing trend and compact grouping of points about the regression curve (see Figure 2).

Listed below is a version of the depth sizing criteria in (8.1.1.3) annotated with the equations developed in this white paper.

- The mean error (μ_M- μ_T) in the flaw depth will be calculated and documented. If the mean error (μ_M- μ_T) is less than or equal to +0.072 inch the RMS error must be less than or equal to 0.125 inch. *That is,*

  If $(\mu_M - \mu_T) \leq +0.072$ *inch, then* $RMSE \leq 0.125$ *inch.*

If the mean error ($\mu_M - \mu_T$) is greater than +0.072 inch, this contribution to the RMS error will be removed and recorded. The remaining portion of the RMS error must be less than or equal to 0.102 inch.

That is,

If ($\mu_M - \mu_T$) > +0.072, *then* $\sqrt{(\mathrm{RMSE}^2 - (\mu_M - \mu_T)^2)} \leq 0.102$ *inch.*

Sample calculation #1: 52° TOFD data (see Figure 1)

Mean Error = ($\mu_M - \mu_T$) = 0.025 inch (see Figure 1),
Therefore ($\mu_M - \mu_T$) ≤ +0.072 inch,
then RMSE ≤ 0.125 inch.
RMSE = 0.045 inch (see Figure 1),
Therefore RMSE ≤ 0.125 inch and the depth sizing criteria has been met.

Sample calculation #2: 60° TOFD data (see Figure 2)

Mean Error = ($\mu_M - \mu_T$) = 0.125 inch (see Figure 2),
Since ($\mu_M - \mu_T$) >+0.072 inch, the mean error of 0.125 inch is recorded for the 60° TOFD data, it is removed from the RMSE and the remaining error must satisfy $\sqrt{(\mathrm{RMSE}^2 - (\mu_M - \mu_T)^2)} \leq 0.102$ inch.

$\sqrt{(\mathrm{RMSE}^2 - (\mu_M - \mu_T)^2)} = 0.035$ inch (see Figure 2),

Therefore $\sqrt{(\mathrm{RMSE}^2 - (\mu_M - \mu_T)^2)} \leq 0.102$ inch and the depth sizing criteria has been met.

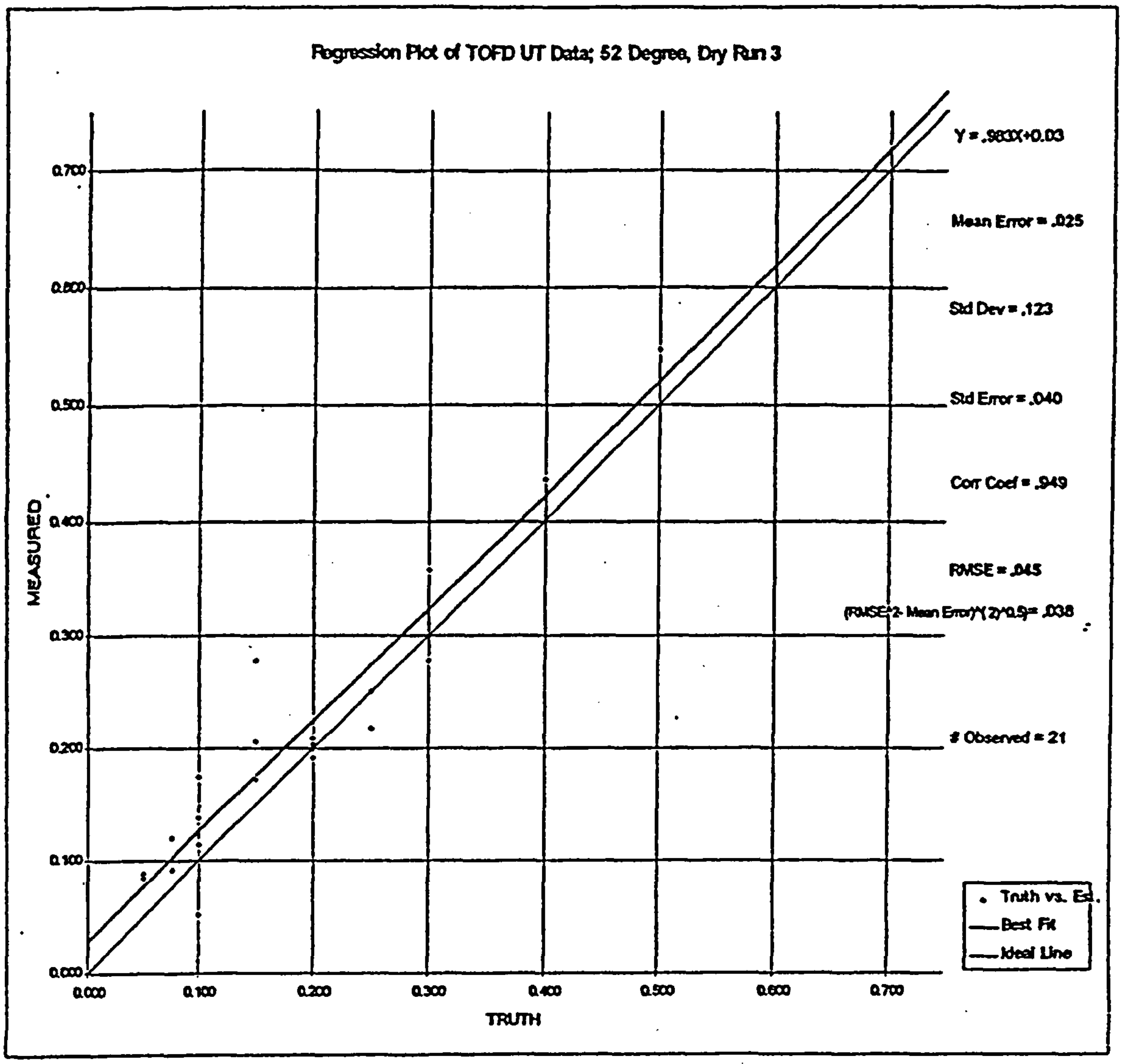


Figure 1. Regression plot of 52° TOFD data (dry run 3).

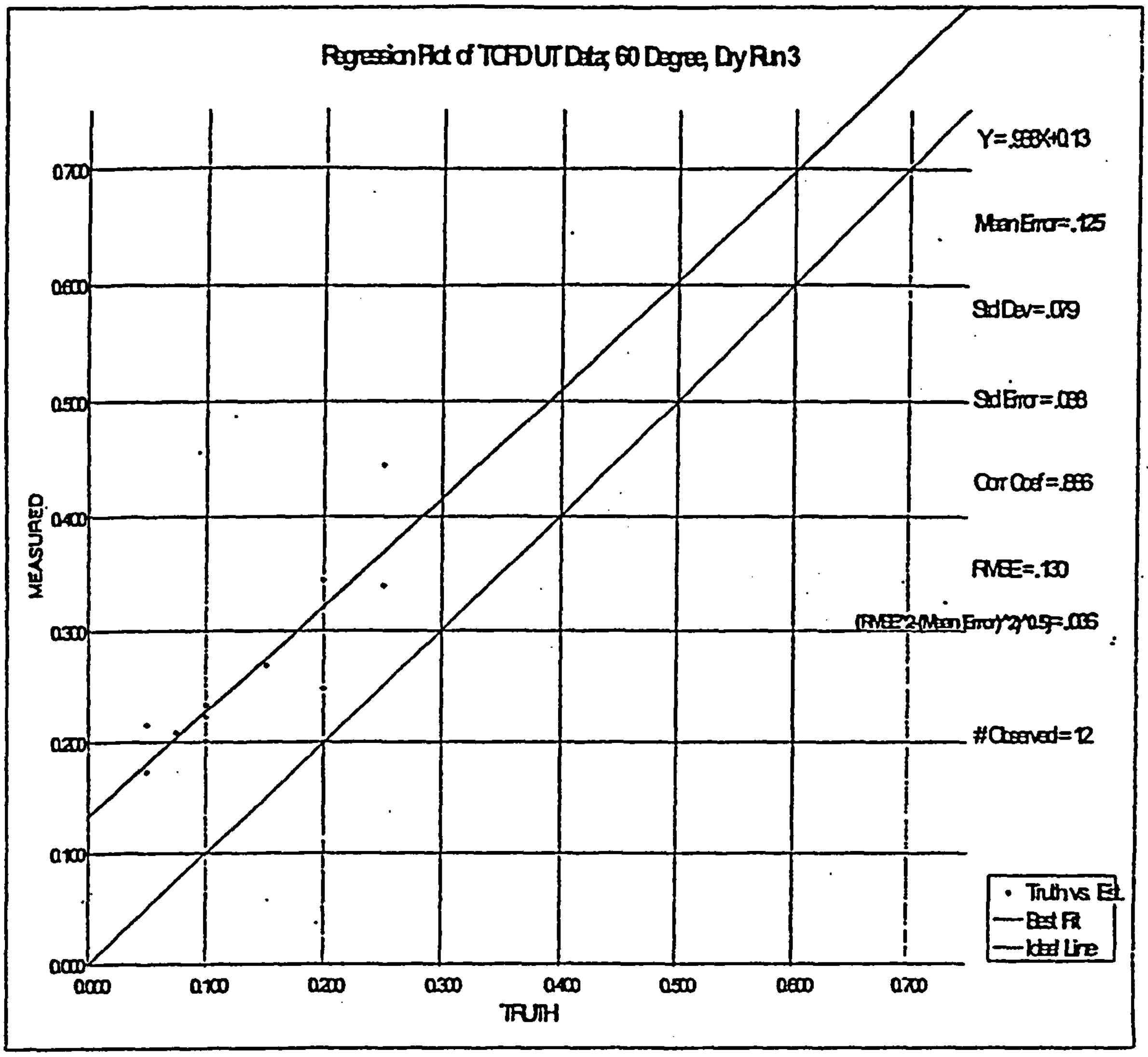


Figure 2. Regression plot of 60° TOFD data (dry run 3).

ATTACHMENT 4 - Screening Criteria for Use During Ultrasonic Examination of VSC-24 Structural Lid to Shell Welds

1. The lower bound fracture toughness of 75 ksi-$\sqrt{in}$ at 0°F was used in these calculations. This value was determined from the lower bound of material toughness (K_{IC} -type value, calculated from J integral testing performed per ASTM E-1737-96). The arrest toughness ($K_{IA} = K_{ID}$) was calculated from the measured (K_{IC} type result) using the methods of ASME Section XI, Appendix A. The value of 75 ksi-$\sqrt{in}$ at 0°F is compatible with that calculated from the toughness requirement of 15 ft-lb at -50°F (CVN).

2. A constant tensile residual stress of 38 ksi, corresponding to the specified minimum yield of SA-516 Grade 70 material, was used in the calculation.

3. For semi-elliptical flaws, the greater of the calculated stress intensity factors at the deepest point of the flaw and at the surface contact point of the flaw was used to develop screening criteria. The deepest point of the flaw governs the calculation, except for very short, deep flaws (aspect ratio of approximately 0.5), where the surface point governs.

4. For long flaws, evaluation of primary stress limits per ASME Section III, NC-3200 continue to be met for the structural lid-to-shell weld if the flaw depth is less than 0.16 inch assuming that weld minimum design thickness remains at 0.75 inches. Screening criteria maintain this limit for long flaws.

5. The above calculations assume that the minimum weld temperature at which the horizontal drop event could occur is 0°F. Increasing this minimum temperature results in increasing toughness, and therefore increasing allowable flaw size. For temperatures above about 30°F, the allowable flaw size is limited by primary stress criteria rather than brittle fracture limits (see item 4 above).

The screening criteria which have been developed using the above assumptions and methods are summarized in Table 1. It should be noted that these are intended as screening criteria, and not as final acceptance criteria. Flaws that are identified as meeting these criteria following review of UT results are acceptable without further evaluation. Flaws that exceed these criteria may be subjected to further evaluation, utilizing the same analytical techniques and limitation, before making a repair or accept decision.

Table 1
Flaw Screening Criteria

WELD TEMPERATURE	FLAW DEPTH (L<0.7 IN)	FLAW DEPTH (L>0.7 IN)
0°F	0.34 IN	0.11 IN
10°F	0.37 IN	0.13 IN
20°F	0.37 IN	0.14 IN
30°F and Greater	0.37 IN	0.16 IN