DEMONSTRATION OF INNOVATIVE APPLICATIONS
OF TECHNOLOGY FOR THE CT-121 FGD PROCESS

at

Georgia Power's

Plant Yates

Final Report

Volume 3c
Materials Test and Evaluation Program

DOE DE-FC22-90PC89650
SCS C-90-00284

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January 1997

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LIST OF ABBREVIATIONS

AE	acoustic emission
DOE	Department of Energy
ESP	electrostatic precipitator
FEA	finite element analysis
FGD	flue gas desulfurization
FRP	fiberglass reinforced plastic
GPC	Georgia Power Company
GSTT	gypsum slurry transfer tank
ICCT	Innovative Clean Coal Technology
JBR	jet bubbling reactor
LSST	limestone slurry storage tank
SG	specific gravity
SO_2	sulfur dioxide

VOLUME SUMMARY

One of the unique features of the Plant Yates Chiyoda Thoroughbred 121 (CT-121) flue gas desulfurization system is the broad use of fiberglass-reinforced plastics (FRP) in construction of all major process vessels including the jet bubbling reactor, the limestone slurry storage tank, the gypsum slurry storage tank, the inlet duct, the mist-eliminator, a good percentage of the piping, and the wet chimney. The choice of material was based on the excellent corrosion resistance properties of FRP, low life-cycle costs in comparison with other conventional choices, and favorable FRP experience in chemical and pharmaceutical industries. The Yates scrubber facilities were constructed and operated as a demonstration of the extensive use of FRP for future CT-121 FGD designs. A comprehensive FRP test and evaluation program was performed as a part of this program to address the following material objectives:

- Verify that the state-of-the-art in FRP design and construction could support cost-effective construction and reliable operation of the CT-121 process equipment;
- Evaluate the structural reliability of FRP structures as well as the diagnostic tools for evaluating structural integrity;
- Determine the type and extent of routine FRP maintenance and the degree of unscheduled maintenance that could be incurred as a result of FRP construction; and
- Evaluate the design methods and the construction technology for manufacturing larger, more durable FRP scrubber equipment.

The structural design of the FRP process equipment and materials of construction was performed by Ershigs, Inc. using standard design guidelines and formulas. In addition to conventional design approach, finite element analysis was performed to:

- Determine the state of stress and strain in different components of the JBR and the LSST, and
- Better understand areas of design uncertainty and verify design assumptions.

The results showed that the FRP structures vessels, as designed by conventional design techniques, would safely operate under the specified operating conditions. However, the resulting deck deflections at full load would be higher than the tolerances required for the sparger tube alignment. This problem was quickly resolved by minor adjustments in the thickness of laminates and arrangements of the supports.

Following a two-year design and construction phase, the CT-121 FGD system at Plant Yates was placed in operation in October, 1992. Prior to the scrubber start-up, the structural reliability and operability of the JBR and the LSST were tested under hydrostatic loading conditions. Following the startup, routine general inspections were performed to monitor the structural condition, abrasion, and corrosion in various parts. During the first phase of the demonstration program, the pre-existing electrostatic precipitators (ESP) were utilized at full capacity to remove the ash from flue gas entering the process. Shortly after the startup, the color-based abrasion-indicator/coating began to show signs of severe abrasion in the inlet duct. Between March, 1992 and September, 1993, the damaged areas were repaired several times. A technical solution was finally formulated based on high resilience of rubbery materials. To this end, several compliant polyurethane coating systems were evaluated in the inlet duct for their endurance and longevity in this highly abrasive environment. These proved to be successful in controlling the abrasion problem. The only remaining issue in this area is to maintain the bond between the coating system and FRP. The inspections continued during the high-ash phase, when the ESP fields were de-energized to determine the impact of high ash concentration in the slurry on scrubber performance. The CT-121 FRP process equipment has been in operation for nearly four years. With the exception of the inlet duct abrasion, the FRP performance can be classified as very satisfactory. The following specific conclusions have therefore been reached:

- FRP is a suitable material for application to the CT-121 process.
- FRP is prone to abrasion in the areas of high velocity gradient and particulate concentration. In these areas, the FRP surface should be coated with an appropriate coating system, consistent with the nature of flow. The test results show that abrasion due to normal flow can be controlled by compliant coatings. On the other hand, coatings that had a large concentration of fillers worked better in areas of high shear.

- Strain gaging and acoustic emission testing can be effective and valuable tools for verifying the structural integrity of FRP vessels. Acoustic emission was proven successful in locating the structural faults associated with FRP construction.
- Preliminary creep of the material during initial loading can lead to higher than anticipated strains. However, with time, the strain measurements should reach equilibrium and comply with theoretical expectations.
- The design standards for large FRP vessels need to be improved in order to increase product reliability. This can be accomplished by incorporating finite element analysis into the design process. Further, the existing acoustic emission standards appear to be too sensitive for application to large FRP vessels not used in highly corrosive environments. The "knee analysis" combined with "cluster analysis" were found to be a more practical approach for performing diagnostics and quality control experiments.
- Novel FRP construction may be available that could significantly reduce the cost of construction for large cylindrical FRP structures. These construction methods need to be proven under a controlled research environment if they are to be recommended for future CT-121 installations.

1.0 INTRODUCTION

This document describes the results of a three year FRP Test & Evaluation Program conducted as a part of the CT-121 demonstration project at Georgia Power Company (GPC) Plant Yates. This project was one of several environmental control demonstration projects initiated under the Department of Energy's (DOE) Innovative Clean Coal Technology (ICCT) program. The Chiyoda CT-121 FGD system is a limestone-based, forced-oxidation scrubber technology that has been designed to remove over 90% of the sulfur dioxide (SO_2) present in the flue gas from the 100 MWe coal-burning Unit 1 at Plant Yates[1].

One of the unique features of the Plant Yates CT-121 scrubber is its broad use of FRP in construction of all major process vessels. The primary FRP vessels include the jet bubbling reactor (JBR), the limestone slurry storage tank (LSST), the gypsum slurry transfer tank (GSTT), the inlet flue gas duct, the mist-eliminator, a good percentage of the slurry piping, and the wet chimney. The choice of FRP was made based on the following requirements:

- Operational Reliability: Fiber-reinforced plastics are engineered materials. These can be constructed to place a thick layer of highly corrosion-resistance resin next to the process fluids, protecting the load bearing structure from chemical degradation. This would enable the handling and transportation of FGD process products at temperatures up to 140°F[2]. Furthermore, FRP has been widely and successfully used in the chemical, pharmaceutical, and waste treatment industries to contain, control, or transport the production and/or processing of aggressively corrosive chemicals. For example, FRP pipes are well established in the technology of water supply and liquid waste disposal with approximately 1600 miles of FRP sewage piping in use dating back to 1984.
- Lower Cost: FRP was evaluated against several different alternatives: Rubber-lined steel, stainless steel, and other exotic or engineered materials. FRP was found to have a lower construction cost than stainless steel and the other exotic materials. In comparison with rubber-lined steel, it was anticipated that a 10% lower construction cost could be attained with rubber-lined steel. However, the use of rubber-lined steel would have significantly increased the maintenance frequency and maintenance costs since:

- — The rubber lining of the Yates scrubber vessels would have to be performed in situ, under very precise temperature and humidity conditions. This was a difficult and expensive process leading to high upfront construction costs or high maintenance due to construction defects in the rubber lining.
- — There was a strong likelihood that the rubber lining would be damaged during construction, and since there was no easy way of detecting construction defects, the process would become prone to pin-hole leaks and high maintenance.
- — Based on experience in other industries, the rubber lining may also become cracked as a result of chemical aging and embrittlement. If this type of damage occurs, the plant would have to shut down immediately for major repairs. The tanks would have to be emptied and the interior and exterior surfaces treated.
- — Rubber-lined steel vessels require relining every 8 years. In contrast, FRP vessels have a conservative service life of approximately 25 years.

Other factors affecting the decision to use FRP include:

- FRP's good weathering properties eliminates the need for surface coatings.
- FRP's low electrical conductivity and smoothness reduces the risk of deposits.

In summary, FRP was chosen based on its superior performance and lower capital and life cycle cost when compared with other material choices. Table 1-1 shows a more recent economic analysis of FRP scrubber vessels made with epoxy vinyl ester resins, as published by Dow Chemical Corporation. The data in the table support the selection of FRP for construction of the Plant Yates Chiyoda scrubber.

1.1 Objectives

The success of FRP in construction of large process vessels depends largely on the soundness of fundamental design principles, consistency and reliability of construction technology, and the construction workmanship. Other key elements in successful ownership and operation of FRP vessels are to know the operating limits of FRP equipment and to develop a reliable

TABLE 1-1
COST COMPARISON OF FRP SCRUBBER VESSELS VS. ALTERNATE MATERIAL

	4 x 13 meter Historically Installed		12 x 33 meter Historically Installed	
Material	**cost**	**cost ratio**	**cost**	**cost ratio**
FRP made with epoxy novolac vinyl ester resin (Derakane 470-36)	$175K	1.0	$750K	1.0
Rubber-lined Steel	$200K	1.15	$865K	1.5
C-276 Clad Steel	$350K	2.0	$1,300K	1.75
Alloy C-276	$475K	2.7	$1,500k	2.0

[Reference: Derekane News, Vol. 15, Issue 2, October 1996]

scientifically-based maintenance plan. The Plant Yates scrubber facilities were also modeled as the prototype for future CT -121 FGD systems. Therefore, testing wou ld be essential when the elements of FRP design and construction were stretched beyond their existing norms. To this end, a comprehensive FRP test and evaluation program was performed as a part of the Plant Yates CT-121 demonstration project to understand the technical issues associated with the use of FRP.

The primary objectives of Plant Yates FRP Test and Evaluation Program were:

- Verify that the state -of-the-art in FRP design and construction could support cost-effective construction and reliable op eration of the CT -121 process equipment;
- Determine if larger, more durable equipment could be manufactured;
- Determine and evaluate the structural reliability of FRP structures as well as the diagnostic tools designed for evaluating their structural integri ty;
- Determine the type and extent of routine maintenance required in future installations of CT-121 FGD, as well as the degree of unscheduled maintenance that could be incurred due to problems with FRP construction; and
- Evaluate the design methodology and the construction technology for manufacturing larger, more durable FRP scrubber equipment.

2.0 TECHNICAL APPROACH

The technical objectives of FRP Test and Evaluation Program were accomplished by analytical and experimental methods. These were designed based on the recommendations of FRP equipment manufacturers and users, FRP standards and guidelin es, and other available technical expertise. The program focused on two primary goals: FRP Design & Construction, and FRP Performance Evaluation program.

2.1 FRP Design & Construction

Reference 6 contains a list of FRP design and construction codes fo r design of large FRP vessels. These have been developed over many years of design and construction experience in the FRP industry. However, compliance with the guidelines does not necessarily mean that the design will be adequate for the intended service . Sound engineering judgment and the ability to accurately predict structural performance are necessary to design and construct equipment adequate for long-term service.

The structural designs of the FRP process equipment and materials of construction w ere performed by Ershigs, Inc. using specifications provided by Chiyoda Corporation and SCS Inc. The primary design guidelines are shown in Table 2-1. The final design calculations and design procedures were reviewed and approved by SCS engineering and r evised, as necessary, based on the project specific requirements.

2.1.1 Overall Design Criteria

The most complex component of the design process was the JBR, a 42 ft. diameter, 36' - 6" high, filament-wound, glass-vinyl ester composite vessel. This vesse l, shown in Figure 2-1, was designed based on the specifications listed in Table 2 -2. Two horizontal deck plates are used to

TABLE 2-1
STRUCTURAL DESIGN CRITERIA

Design Parameter	Recommended Design Criteria	Units
Max. Ratio of Working Stress to Ultimate Strength	1:10	
Max. Permissible Strain	1000	Microstrains (με)
Max. Ratio of Operating Load to Buckling Load	1:5	
Max. Ratio of Wind Load to Failure Load	1:5	
Max. Ratio of Seismic Load to Failure Load	1:3	

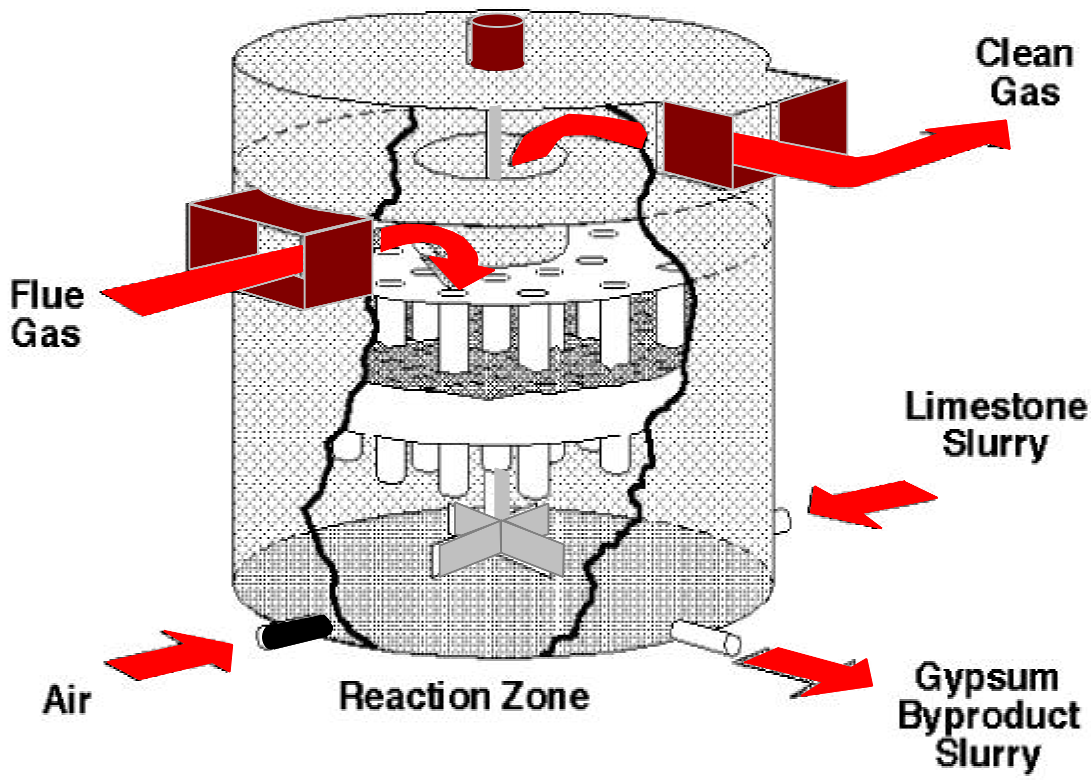


Figure 2-1. Structural Schematic of the Jet Bubbling Reactor (JBR)

TABLE 2-2
JBR DESIGN CRITERIA

Design Parameter	Required Specification	Units
Design Pressure	+43	in of W.C.
Hydrostatic Pressure	+14	ft. of Liquid
Specific Gravity	1.2	
Differential Pressure on Decks	20	in. W.C.
Expected Deposits on Upper Deck	10	psf
Slurry Level on Lower Deck	6 (50)	in. (psf)
Weight of Gas Spargers	20	lb. each
Expected Deposit on Gas Spargers	20	lb. each

divide the JBR into three sealed plenums. The unreacted flue gas enters the middle plenum, the gas inlet plenum, and is forced into a limestone slurry section, the reaction zone. The gas escapes through the gas exhaust plenum into the FRP chimney. The design specifications for the lower deck required the deflections to be less than 0.375" under the maximum operating load. This was necessary to maintain the alignment of the sparger tubes and scrubber removal efficiency.

The other large vessel, the LSST, is a simple 28' diameter storage tank with no internal decks. Several baffle plates were installed axially on the inside wall to improve the mixing of the slurry during the operation.

Other factors considered in the design of the JBR and LSST were buckling, structural stability during a seismic or wind event, thermal stresses, and creep. These design considerations were performed, in accordance with the regional construction codes and standard FRP design requirements, to insure integrity and reliability for the intended long-term service. These are summarized in Table 2-3.

TABLE 2-3
DESIGN AND CONSTRUCTION CODES AND GUIDELINES

Design Codes & Guidelines	Explanation
ASTM D2583	Test for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor
ASTM D2584	Ignition Loss of Cured, Reinforced Resins.
ANSI B16.1	Cast Iron Pipe Flanges and Flange Fittings
ANSI B16.5	Steel Pipe Flanges
NBS PS 15-69	Custom Contact-Molded Reinforced Polyester Chemical Resistant Process Equipment
API 650	Welded Steel Tanks for Oil Storage - Appendix E Only (Seismic Design of Storage Tanks)
ASTM 3299	Filament Wound Glass Fiber Reinforced Thermoset Resin Chemical Resistant Tanks
Ershigs' EPS-601	Quality Assurance and Inspection Procedures
ASTM D4097	Contact-Molded Glass Fiber Reinforced Thermoset Resin Chemical Resistant Tanks
SBC	Southern Building Code
ASTM D2996	Filament Wound Pipe, as Applicable (Except for HDB Testing)
Ashland Chemical Technical Data	Technical Data for Hetron FR 992 Contact Molded Laminates

2.1.2 Composite Design Details

2.1.2.1 Laminate Design

Composites are anisotropic materials. This implies that structural properties vary as a function of orientation relative to the reference coordinate system. This complexity is further amplified in filament wound vessels where the structural thickness profile is generally comprised of several composite sub-layers, as shown in Figure 2-2. These sub-layers, depending on their relative location and chemical exposures, are tasked to perform different structural duties. For example, the composite sub-layers adjacent to the process chemistry are generally designed to provide abrasion and corrosion resistance. While the protective surface protection and corrosion-resistant

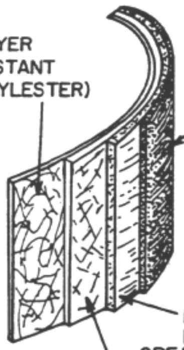


Figure 2-2. Typical Laminate Construction

layers contribute very little to the overall structural strength and overall mechanical behavior, their presence is essential to the structural survival and the reliability of composite vessels. The wall constructions for the JBR and LSST vessels are even more complex and contain many more structural sub-layers. This is illustrated in Table 2-4 which shows the ply schedule and material formulation in JBR. These structural layers introduce different sets of directional structural properties into the design of the wall. Figure 2-3 shows the variation of structural property as a function of radial thickness.

2.1.2.2 <u>Construction Process</u>

The exterior walls of the JBR and LSST vessels were field-fabricated via filament winding process (FW). These vessels, shown as they neared completion, are shown in Figures 2-4 and 2-5, respectively. The materials used in these fabrications were Hetron FR 992 vinyl ester resin and different types of glass fiber.

TABLE 2-4
COMPOSITE WALL LAMINATE SCHEDULE IN JBR

No.	ER PSI	E11 PSI	E22 PSI	G12	NU12	NU21	ANGLE DEG	THICK IN
1	C GLASS	5.00E+05	5.00E+05	4.00E+05	0.200	0.200	0.0	0.10
2	1.5 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.043
3	1.5 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.043
4	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
5		4.30E+06	5.00E+05	4.00E+05	0.200	0.023	-90.0	0.031
6	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
7	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
8		4.30E+06	4.00E+05	4.00E+05	0.200	0.23	-90.0	0.031
9	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
10	FW 90/113YLD	4.303+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
11		4.20E+06	5.003+05	4.00E+05	0.200	0.023	-90.0	0.031
12	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
13	15.6 UNI/FW	4.30E+06	6.00E+05	2.00E+05	0.100	0.014	0.0	0.030
14	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
15	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.23	90.0	0.031
16		4.30E+06	5.00E+05	4.00E+05	0.200	0.23	-90.0	0.031
17	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
18	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
19		4.30E+06	5.00E+05	4.00E+05	0.200	0.023	-90.0	0.031
20	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
21	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
22		4.30E+06	5.00E+05	4.00E+05	0.200	0.023	-90.0	0.031
23	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
24	15.6 UNI/FW	4.30E+06	6.00E+05	2.00E+05	0.100	0.014	0.0	0.030
25	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
26	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
27		4.30E+06	4.00E+05	4.00E+05	0.200	0.023	-90.0	0.031
28	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
29	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
30		4.30E+06	5.00E+05	4.00E+05	0.200	0.023	-90.0	0.031
31	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
32	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
33		4.30E+06	5.00E+05	4.00E+05	0.200	0.023	-90.0	0.031
34	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
35	15.6 UNI/FW	4.30E+06	6.00E+05	2.00E+05	0.100	0.014	0.0	0.030
36	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
37	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
38		4.30E+06	5.00E+05	4.00E+05	0.200	0.023	-90.0	0.031
39	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.15
40	FW 90/113YLD	4.30E+06	5.00E+05	4.00E+05	0.200	0.023	90.0	0.031
41		4.30E+06	5.00E+05	4.00E+05	0.200	0.023	-90.0	0.031
42	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015
43	.75 OZ. MAT	9.00E+05	9.00E+05	4.00E+05	0.200	0.200	0.0	0.015

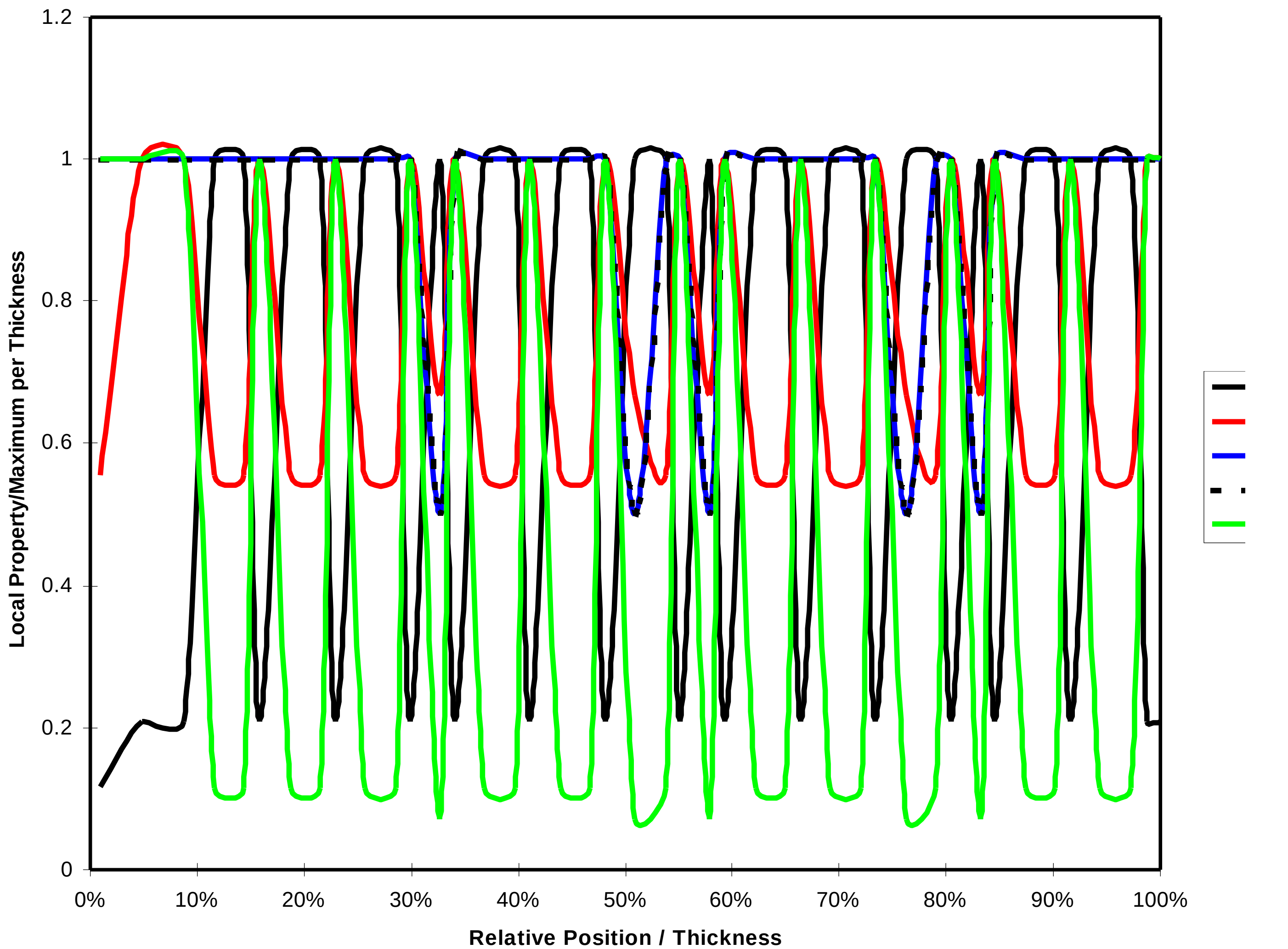


Figure 2-3. **Composite Material Property vs. Radial Thickness**

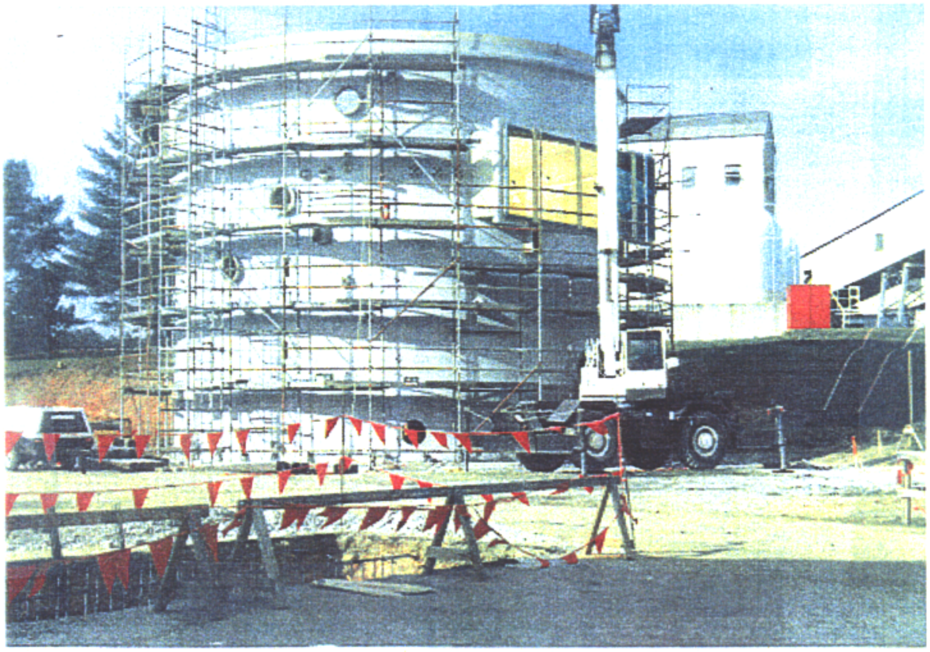


Figure 2-4. Construction of JBR

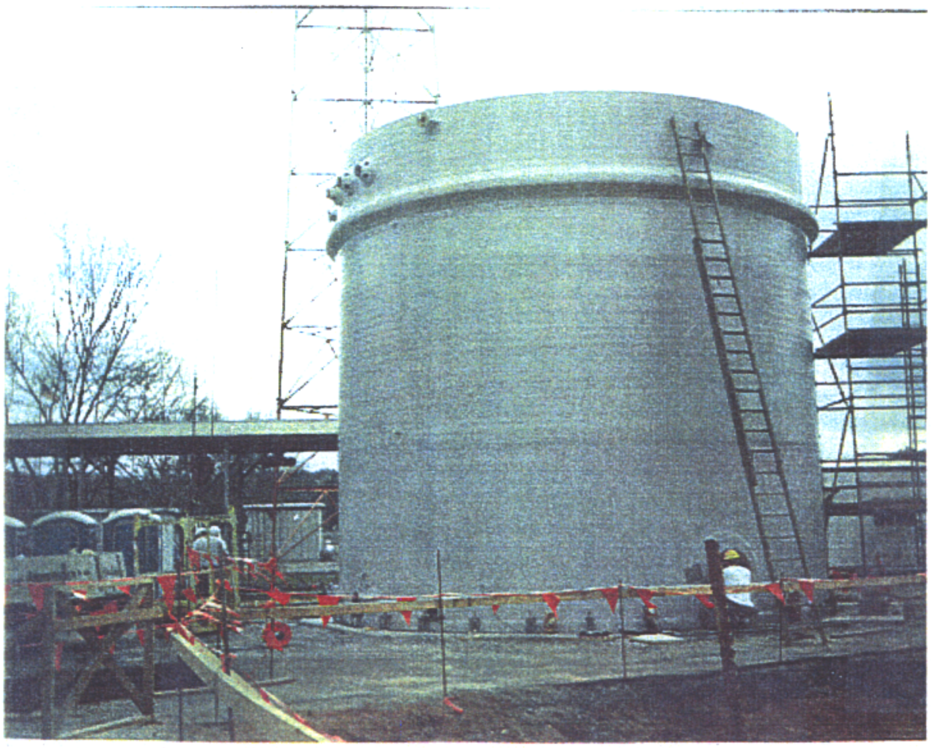


Figure 2-5. Construction of LSST

Because of their size, the vessels were constructed in lengths of 8' to 10'. As the winding on each section was completed, it was raised on the mandrel by about 10' and the next section was fabricated right below it. This process continued until the entire height of the vessels were completed. As a result, the wall thickness in JBR varies from 0.74" at the very top to 1.l" in the lower section. The changes in the wall thickness lead to variations of the ply-schedule and structural properties as a function of the vessel height. The variations in the laminate properties were estimated using the ply-schedule and the overall construction of each vessel. Table 2-5 shows the calculated laminate properties at various heights of the JBR. Similar thickness and property variations are also present in the LSST.

TABLE 2-5
JBR LAMINATE PROPERTIES AS A FUNCTION OF HEIGHT

Height (ft-in)	Thickness (in)	Hoop Modulus (Mpsi)	Axial Modulus (Mpsi)
0' to10'	1.1	3.017	0.939
10' to 20'	0.94	2.911	0.997
20' to 28'-6"	0.82	2.961	0.915
28'-6" to 36'-6"	0.74	2.888	0.949

The JBR deck plates and supporting structural system were designed and built from FRP tiles (hand-lay-up construction). These tiles were constructed off-site and assembled on-site over the deck plate support systems. Additional composite overlays were used around the seams to secure the plates and seal the deck plates to withstand 20" of pressure differential (W.C.).
The lower deck was further reinforced to support the weight the sparger tubes distributed uniformly across the deck area.

2.1.2.3 Structural Reliability

The structural reliability and longevity of the FRP scrubber systems were ensured by using conservative design stress goals for all composite structures. The working stresses in the JBR shell and its components are shown in Table 2 -6 and 2-7. These stresses were calculated by Ershigs, the designer and the manufacturer of the Yates FRP structures, using standard fo rmulas and methods. The details of these calculations are shown in Appendix 6 -B. In certain areas, where higher stresses were expected because of the local property variations or abrupt geometrical design features (manways, bearing plates, nozzles), addi tional hand layup reinforcement was used to lower the stress and improve the safety margin.

TABLE 2-6
OPERATING DESIGN STRESSES IN JBR

Component		Loading Mode	Operating Stress Axial/Hoop	Maximum Allowed Stress (Psi) Axial/Hoop	Critical Buckling Stress/ Pressure	Minimum Factor of Safety
Dish Cover	-Crown-	Internal Pressure	534/387	25200	___________	27.1
	Knuckle		946/686		17.0 psi crit.	26.6
		Buckling	2.55 op. press.			11.5
Shell Wall	0'	Hydrostatic & Deadweight	135/2024	22500/ 25200	1230 psi	9.06
	10'-20'		148/974		1116 psi	7.53
	20'-28'		153/477		894 psi	5.82
	28'-36'		46/48		837 psi	18
Main Support Posts		Deadweight & Internal Pressure	185 psi-tension 21900 lb. comp.	25200	104600	13.6 4.77
Secondary Supports		Deadweight & Internal Pressure	210 psi-tension 5200 lb. comp.	25200	32121 lb.	12 6.17

TABLE 2-7
SEISMIC AND WIND LOAD DESIGN STRESSES IN JBR

Location	Critical Buckling Stress (psi)	Total Axial Stress Seismic	Wind	Factor of Safety
0' (Base)	1230	269	166	4.6
10'	1116	181	166	6.2
20'	894	160	155	5.6
28'	837	48	50	16

2.1.2.4 Finite Elements Analysis Modeling

In addition to conventional design approach, finite element analysis (FEA) was performed to verify the state of stress and strain in different comp onents of the JBR and the LSST. The following parameters were considered in this analysis:

- Orthotropic material properties;
- 20" (W.C) of pressure difference across the deck plates;
- Weight of the sparger tubes on the lower deck;
- Hydrostatic pressure asso ciated with the slurry in the vessel; and
- Large deformation theory (deflections > 1/2 of thickness).

Using a linear FEA approach with the typical 6 plate/shell elements, the stress and the strain field in the JBR deck plates were estimated in a quarter s ymmetric model. As the boundary conditions for the deck plates, the outer circumference of the decks were assumed to be simply supported with the beam ends fixed. Further, the temperature differentials between the plenums were not applied since the edges of the decks were restrained.

The modeling results further verified that the designed vessels would safely operate under the specified operating conditions. The modeling results did identify one area of design improvement --the deflections of the deck plates at full load were found to be higher than allowed by the tolerance specification of the sparger tubes. This problem was quickly resolved by adjustments in the design of the deck laminate thickness and placements of the secondary supports for the l ower deck plate. Figures 2-6 through 2-11 show color contour plots of stress and deflection response in the JBR shell and deck plates.

2.2 FRP Testing and Performance Evaluation

The experimental measurements undertaken during this part of the program were specially designed to verify the structural design and the integrity of FRP equipment in the scrubber process. This was achieved by monitoring potential areas of uncertainty in the performance of the FRP equipment under the actual service conditions. In specific, the test plan consisted of general inspections to detect structural defects associated with the manufacturing process, corrosion tests to quantify structural changes associated with abrasion and corrosion, and the elastic performance test to qualify the FRP vessels under load. These tests were performed to assure that neither the FRP construction defects nor its service wear would hinder the reliability of the FGD process vessels. The overall test program was also synchronized to projected structural needs to address critical structural performance parameters during the different phases of Plant Yates CT-121 scrubber demonstration.

2.2.1 Structural Integrity Tests

The primary objectives of these tests were to address the safety and reliability aspects of the design, construction, and operation of the fiber-reinforced vessels. Two types of tests that were designed and performed are:

- Elastic performance tests which were used as a QC/QA tool to verify the safety aspects of the FRP structural system; and
- Structural reliability tests which were used to monitor, on-line, the rate of change of structural properties in the areas that were exposed to the process chemistry, and monitor dynamic activities that could lead to the detriment of the FRP structures.

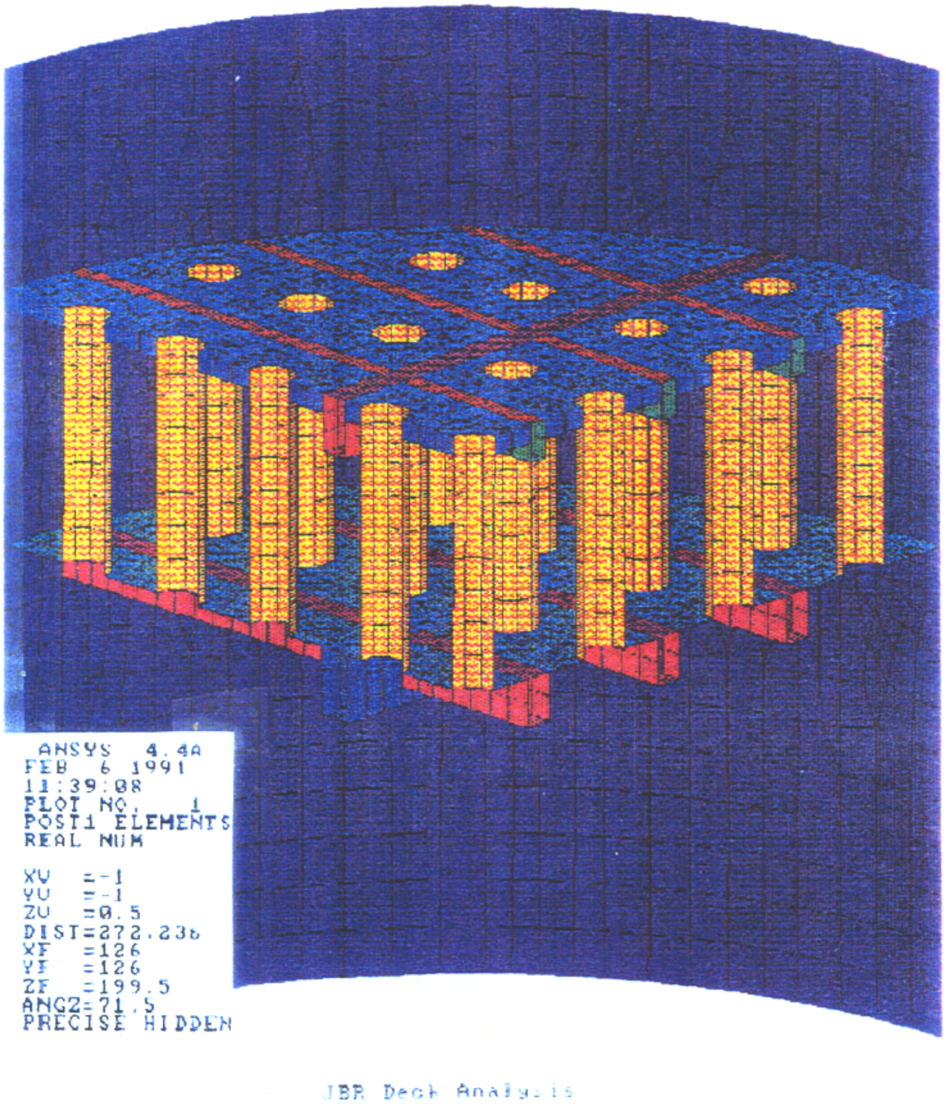
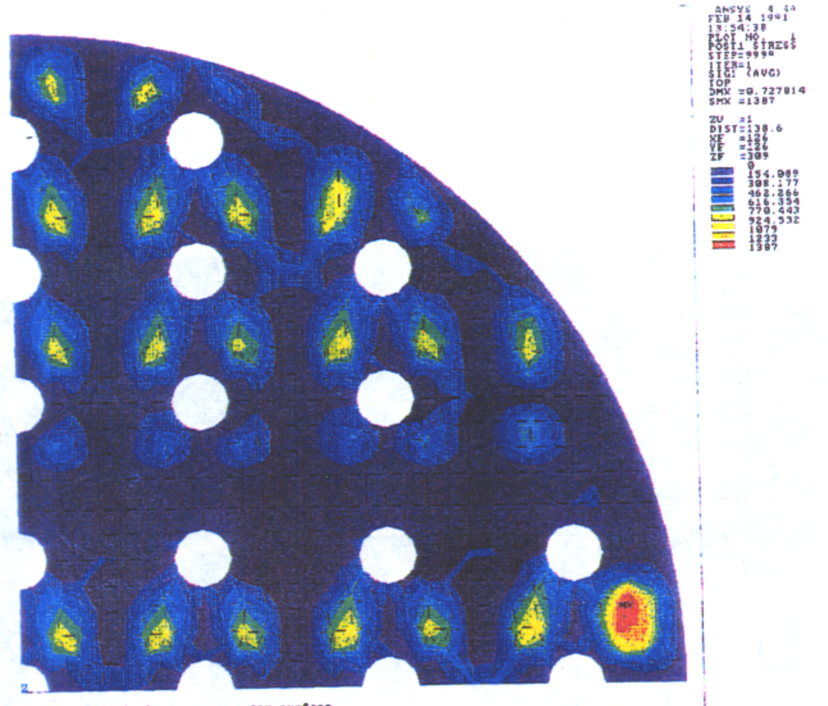
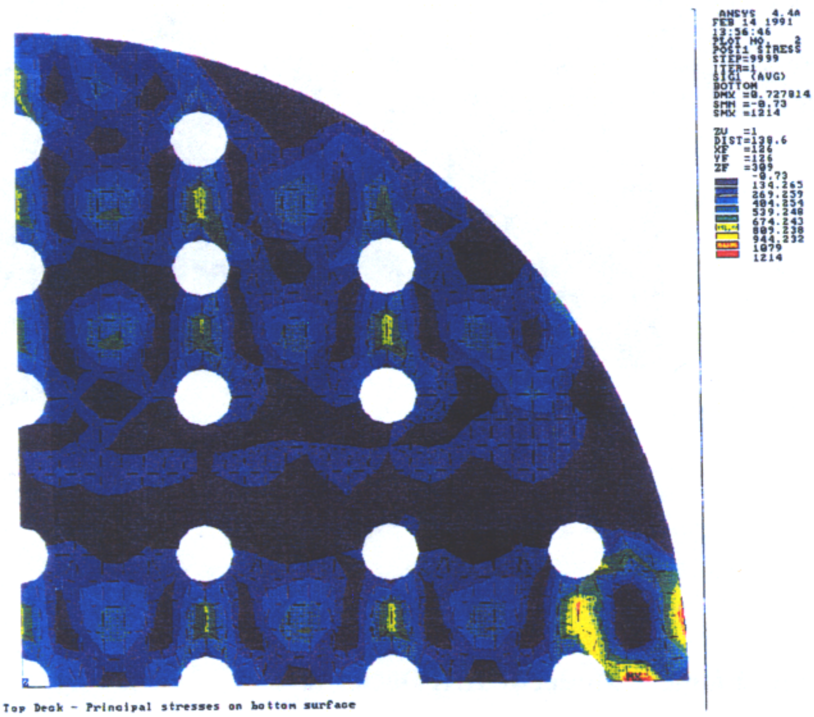


Figure 2-6. Finite Element Model of JBR Deck Plate



Top Deck Principal stresses on top surface



Top Deck - Principal stresses on bottom surface

Figure 2-7. Principal Stresses in Top Deck

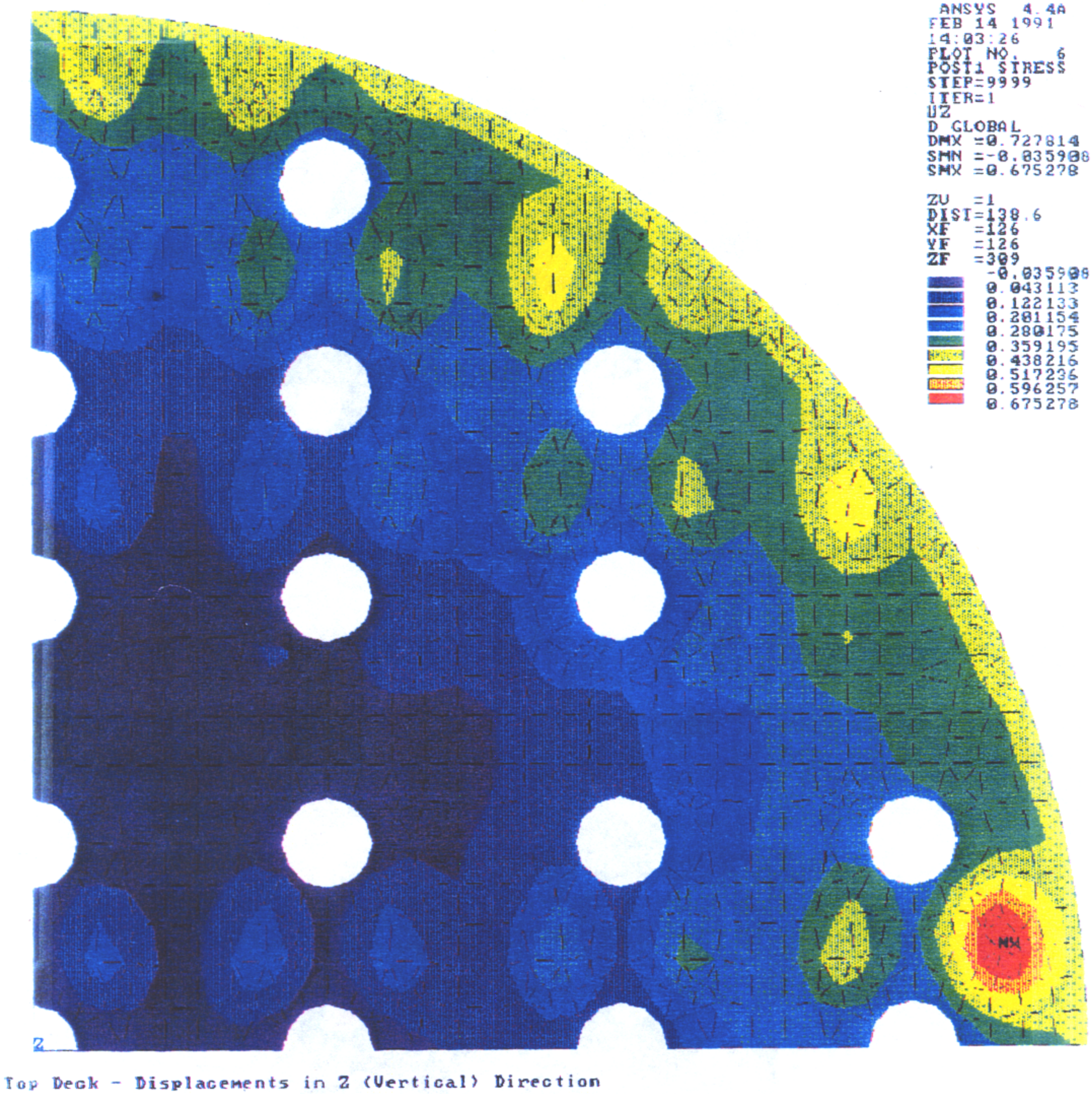
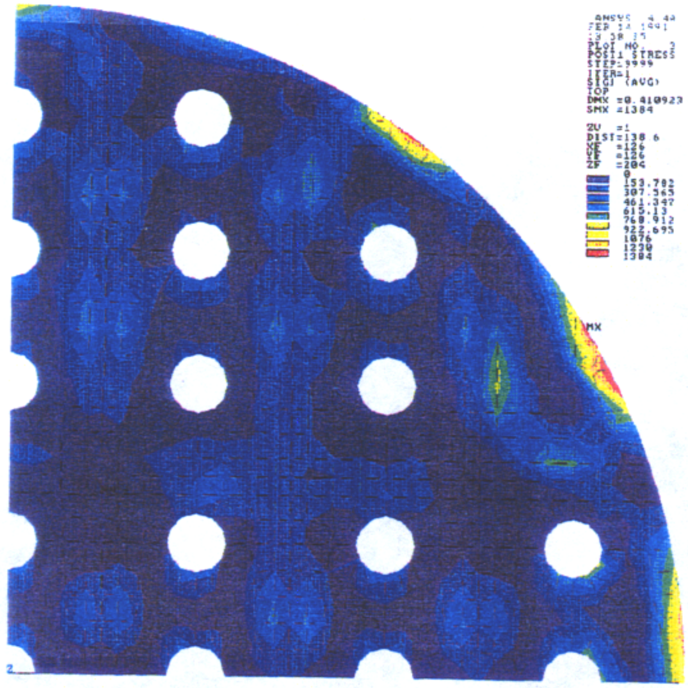
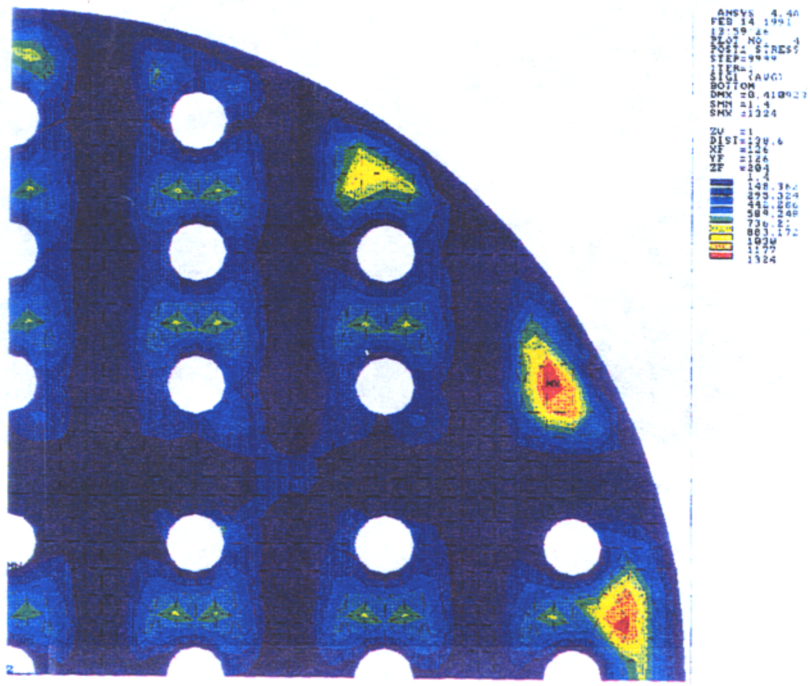


Figure 2-8. Deflection Field in the Top Deck



Bottom Deck Principal stresses on top surface



Bottom Deck - Principal Stresses on bottom surface

Figure 2-9. Principal Stresses in the Lower Deck

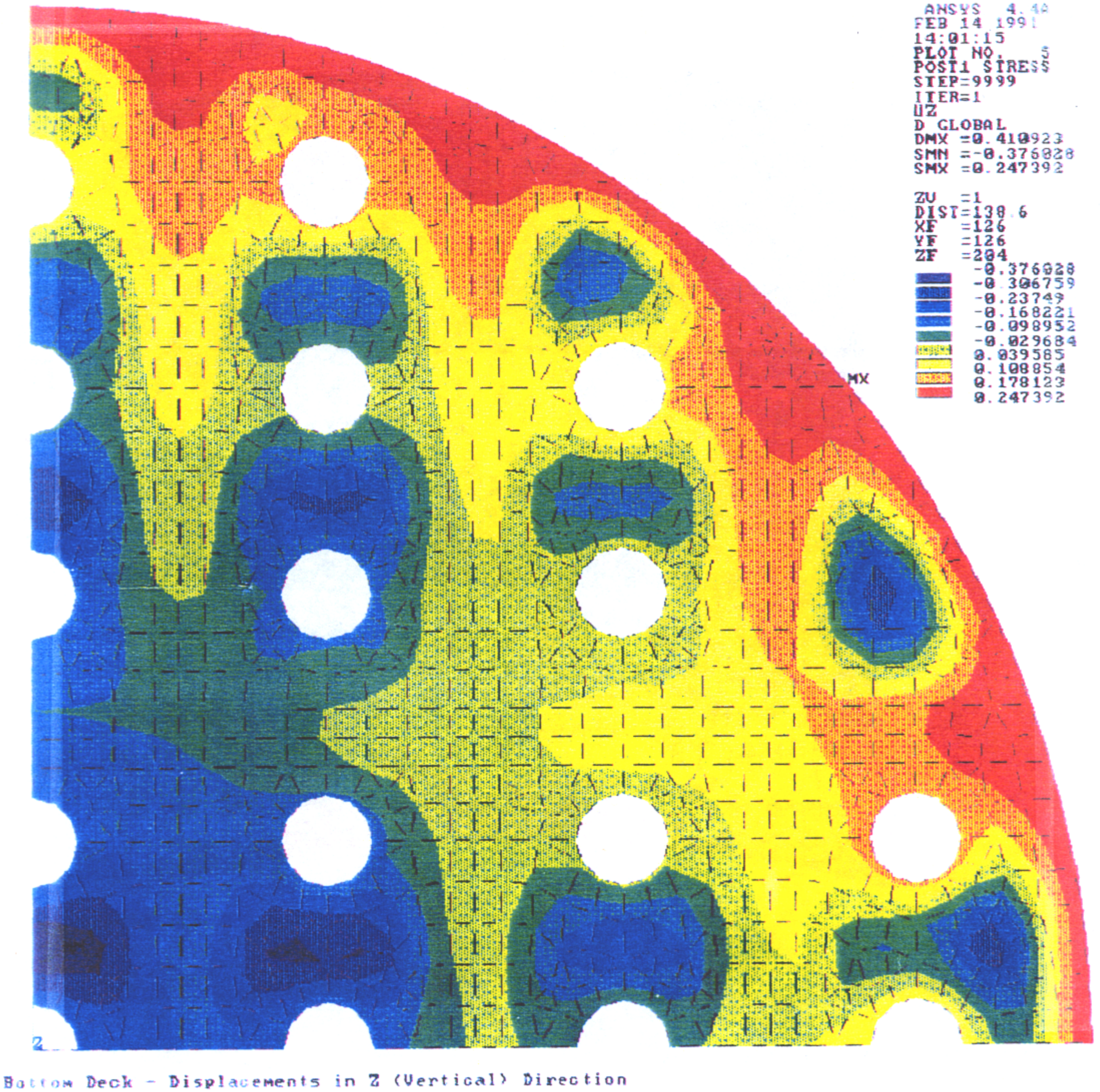


Figure 2-10. Deflection Field in the Lower Deck

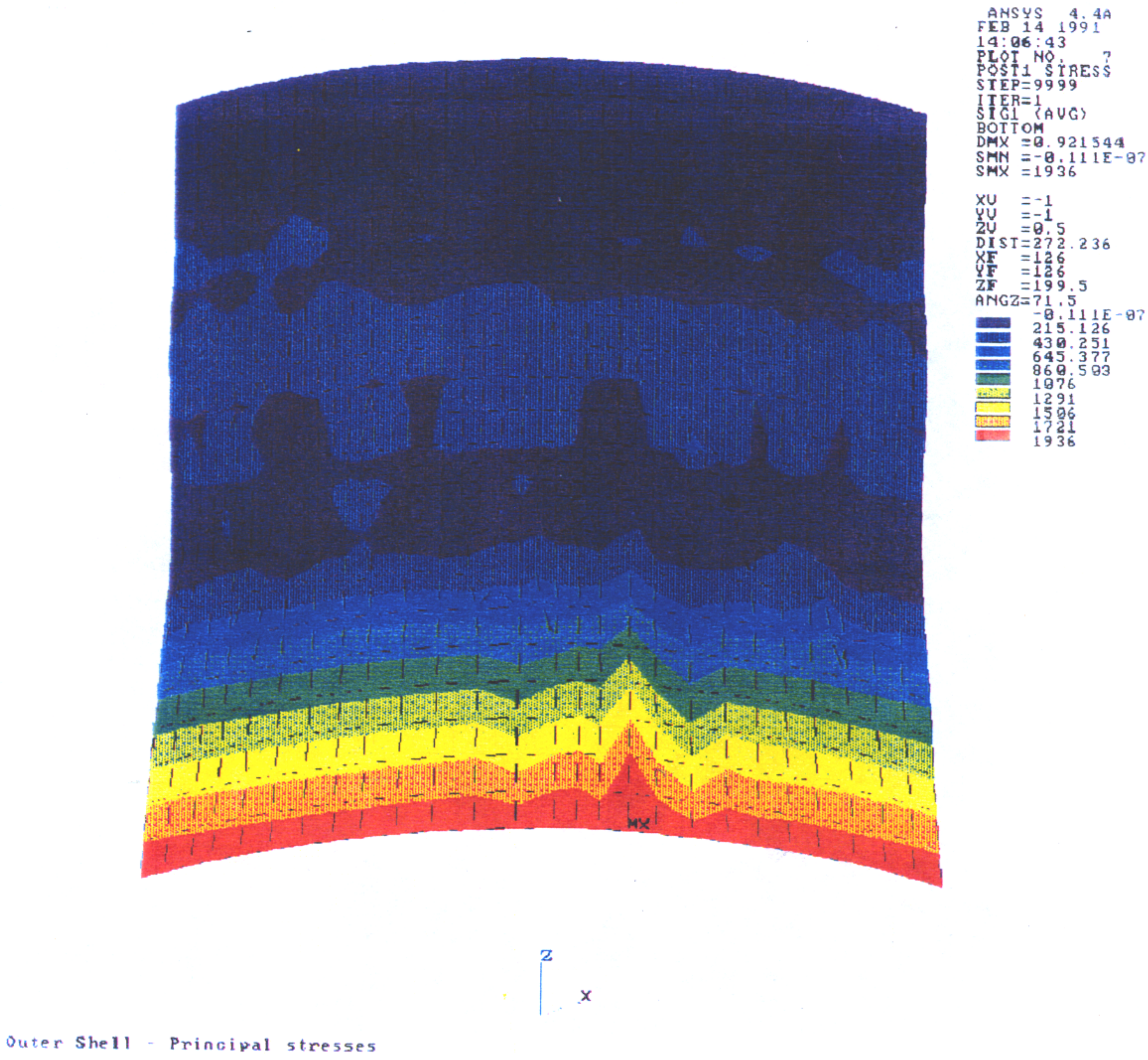


Figure 2-11. Principal Stresses in the Outer Shell of JBR

Acoustic emission (AE) techniques were utilized to detect micro-cracking in the highly loaded structural components. When crack growth was detected, crack locations were identified and marked for repair. The strain gage readings from this test were used to verify the results of finite element computer models used in the structural design of the FRP equipment or future monitoring. The strain fields were measured again during the CT-121 FGD system startup to determine the applied stresses under operating service conditions. The strain gage readings and AE hydrotests were also repeated at the completion of the equipment service to assess the structural changes associated with prolonged exposure to the process environment as well as the overall integrity of the FRP vessels.

2.2.1.1 Elastic Performance Tests

The purposes of the elastic performance tests were, as mentioned before, threefold:

- Determine flaws, if any, in the construction of the FRP vessels;
- Verify the elastic performance of the shell under load in the areas of design uncertainty; and
- Identify areas of structural concern within the FRP vessels, which can be associated with any design or construction anomaly.

The FRP performance was studied by measuring the applied strain fields at key locations in the FRP vessels and monitoring the acoustic emissions of FRP structures under simulated loading conditions. These measurements were obtained through a series of hydrotests. This technique provided a mechanism for simulating strains similar to those experienced during full-load operation. The test simulations were also used to measure the structural integrity of the seals.

The hydro-loading procedures were established by SCS based on the experiences and recommendations of FRP manufacturers and users. These included a series of fill-hold hydro-loadings to relax the FRP structures into their equilibrium states and prepare them for the elastic performance tests, followed by a 24 hour full-hold period to detect growing structural flaws and assess the structural rel iability of the JBR and LSST.

The initial conditioning process was necessary since most FRP structures creep upon their first loading. The creep phenomenon is primarily caused by the reorientation of the molecular chains in the resin when subjected to external load. As the resin creeps, the reinforcing fibers are reoriented. In areas of high stress or manufacturing defects, the overloaded fibers would break causing acoustic emissions in the composite medium. This process continues until the fiber/res in system has reached an equilibrium state with the externally applied load. As such, the acoustic emission activities generally cease with time as the structures set in their final equilibrium state.

At the completion of the conditioning stage, the FRP vessels were filled with water to a height of 1.2 times the normal operating levels to simulate the pressure loading of the vessel. The additional height of water was necessary to account for the difference in the densities of water and slurry (SG=1.2). At different water levels during the hydrotests, the elastic performance of FRP equipment was quantified by measuring the applied strain field at key locations in the vessels and monitoring the acoustic emissions of the loaded structures. Once at full hyd rostatic load, the simulated load was held for a period of 24 to 48 hours while collecting elastic perforce data. The collected information during this stage of testing was used to identify manufacturing defects and/or qualify the structures for their intended use.

2.2.1.1.1 Acoustic Emission

Acoustic emission (AE) refers to a test procedure in which the quality of structure is assessed based on its acoustic response to an applied force field. This acoustic response, which is generated due to a sudden release of stored elastic energy (or transformation into surface energy, heat) and the propagation of the resulting stress wave through the medium (spherical in an isotropic body), is generally called an acoustic emission event. The generated acoustic wa ves travel in the media causing an elastic field response and traveling deflection fields. These can be detected by acoustic emission sensors attached to the elastic medium surface. The signal is then amplified and monitored on specialized machines to determine the scope of acoustic emission activities. Figure 2-12 is a simplistic representation of an acoustic emission test setup.

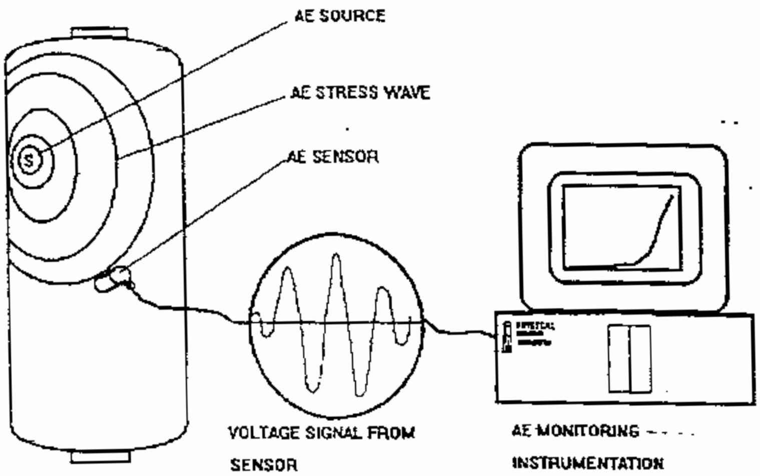


Figure 2-12. Basic Diagram of Acoustic Emission Instrumentation

The specific mechanisms that produce AE events in composites are:

1. Second phase or fiber cracking and failure;
2. Second phase or fiber interfacial debonding;
3. Second phase or fiber plastic deformation;
4. Matrix plastic deformation and cracking;
5. Interlaminar debonding;
6. Rubbing of second phase or fiber against the matrix;
7. Secondary bond failures;
8. Impact noise from loose parts;
9. Friction noise due to relative motion of adjacent loose parts; and
10. Background noise associated with process and the environment.

In the case of the Plant Yates FRP vessels, the expected AE sources were identified as (1), (2), (4), and (6), as described above. There are several codes that apply AE to identify structural flaws and certify FRP equipment for their intended use. A few of these codes are shown in Table 2-8. Per the AE industry, the most applicable code for large FRP tanks is the SPI/CARP. This code, which was developed by the Committee on Acoustic Emissions from Reinforced Plastics (CARP) of the Society of the Plastic Industry (SPI), describes the detailed procedures and guidelines for applying AE to fiber reinforced plastic storage tanks. Compliance with this code also requires compliance with other general AE codes which deal with the AE instrumentation, data presentation, and data interpretation.

Three sets of acoustic emission tests were performed during the course of the four year testing process. Table 2-8 shows the applicable standards for use in AE testing of FRP vessels.

2.2.1.1.2 Strain Monitoring

Conventional strain-gaging was selected as a suitable technique for monitoring of the elastic response of the process vessels during hydrotests. Strain gages are film resistance probes that are attached to the surface of an elastic material. These resistors are connected in a Wheatstone bridge circuit topology to monitor the changes in the electrical resistance when an elastic strain field is applied. Figure 2-13 shows a schematic of a strain gage circuit. There are several ASTM codes for testing and analysis of FRP vessels. The most fundamental practice is, however, that the measured strains are maintained below the recommended working strain and stress levels. To apply this code, special care was taken to apply the strain gages at locations which would facilitate the achievement of the program goals.

TABLE 2-8
APPLICABLE STANDARDS AND CODES FOR USE OF AE IN FRP VESSELS

Issued by	ID	Description
SPI	SPI/CARP	Recommended Practice for AE Testing of Fiberglass Tanks/Vessels.
ASTM	E 1067-85	Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels.
ASME	Section V - Article 11	Guidelines for AE testing of Pressure Vessels.
	Article RT-6	Acceptance Test Procedure for Class II Vessels.
ASTM	E610	Terminology relating to AE.
	E650	Guide for mounting Piezo electric Acoustic Emission Sensors
	E750	Practice for Measuring the operating characteristics of AE instrumentation
	D833	Definitions of terms relating to Plastics.
	E976	Standard guide for determining the reproducibility of AE sensor response.
	E1067	Standard practice for AE examination of FRP resin tanks/vessels.

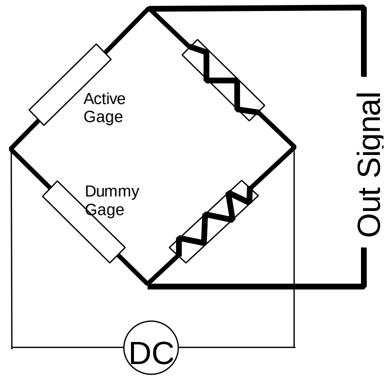


Figure 2-13. Simple Schematic of a StrainGage Circuit

After an initial review of the drawings and calculations provided by Ershigs Inc., several measurement locations on the JBR and th e LSST tanks were selected, and appropriate strain gage and strain gage rosettes were installed. The SCS program also took special account of the effects of the environmental elements—temperature, moisture, chemistry—on the reliability of the measured data and the integrity of the measurement circuits. Figure 2 -14 shows the technical procedure used in the analysis of strain data.

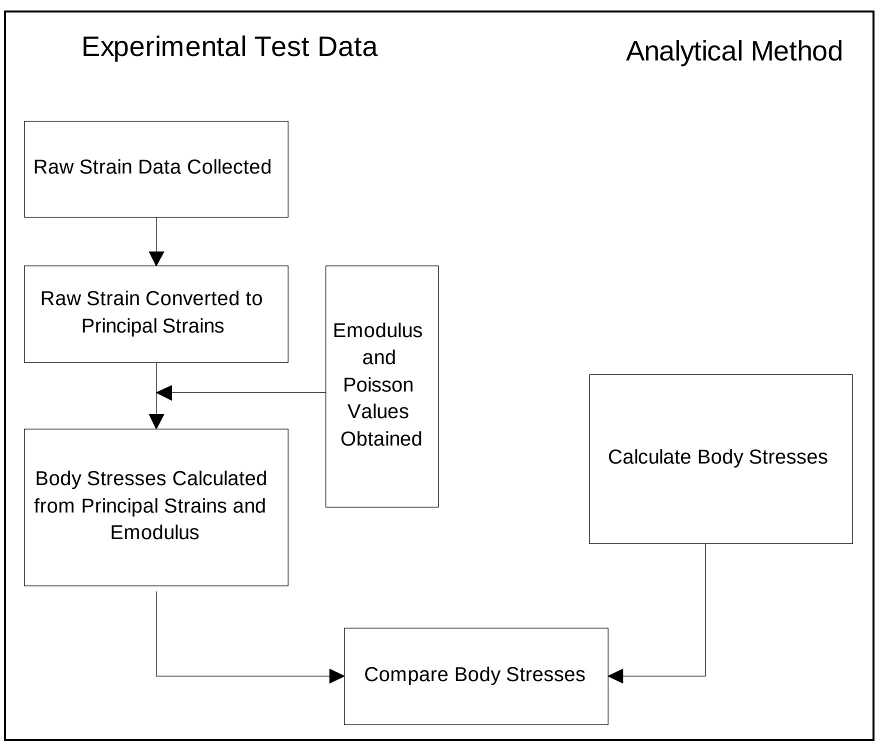
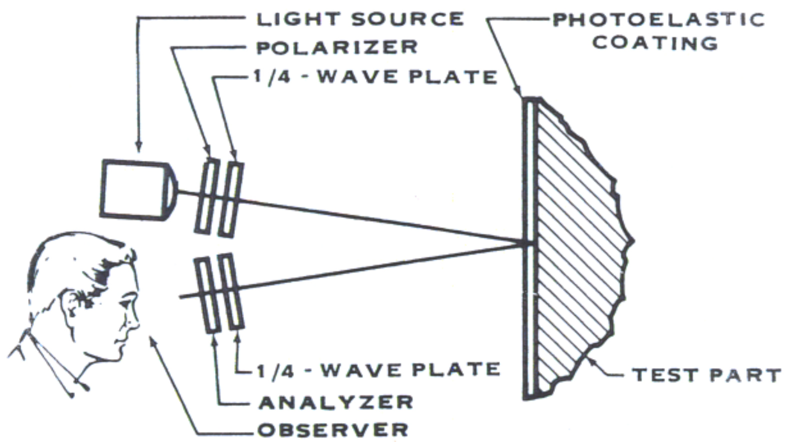


Figure 2-14. Elastic Performance Monitoring Using Strain Measurements

The localized strain gage readings were complemented with field measurements of shear strain around the suspected areas of high stress concentration on the exterior surfaces of the JBR and LSST. This measurement was achieved by using photoelastic laminates formed to fit the exterior surface of the stressed object. The laminates were attached to the surface using epoxy filled with reflective fragments. Once installed, the shear strain field was measured using the arrangement shown in Figure 2-15. As shown, this method provides a larger measure of the strain field which is useful in identification of discontinuities and material imperfections. Figure 2-16 and 2-17 shown the location map of the photoelastic laminates applied to the JBR and the LSST.



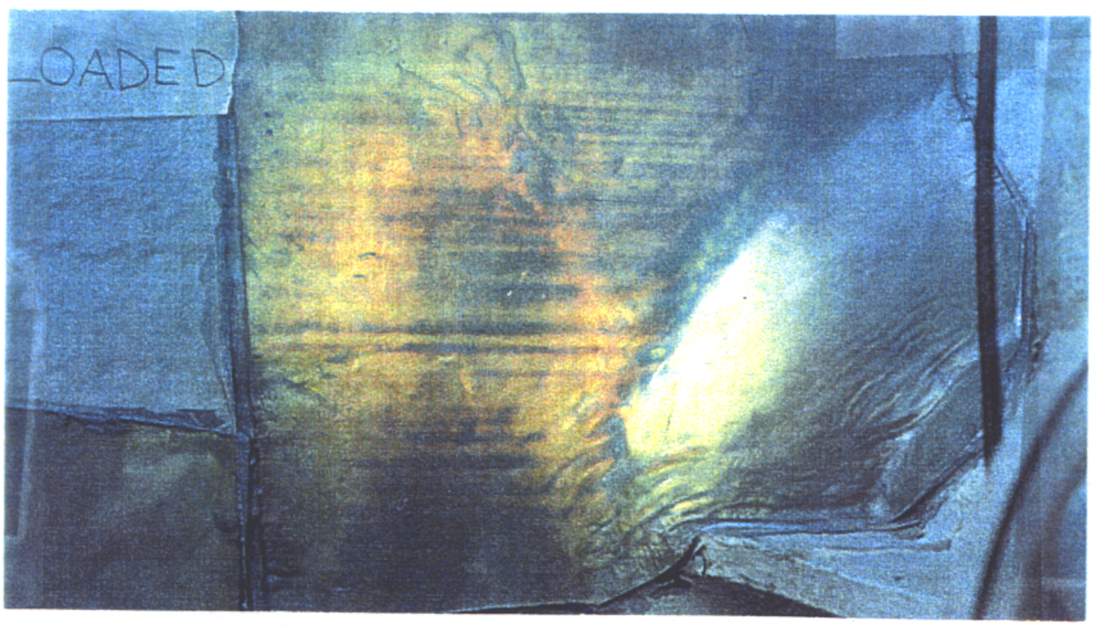
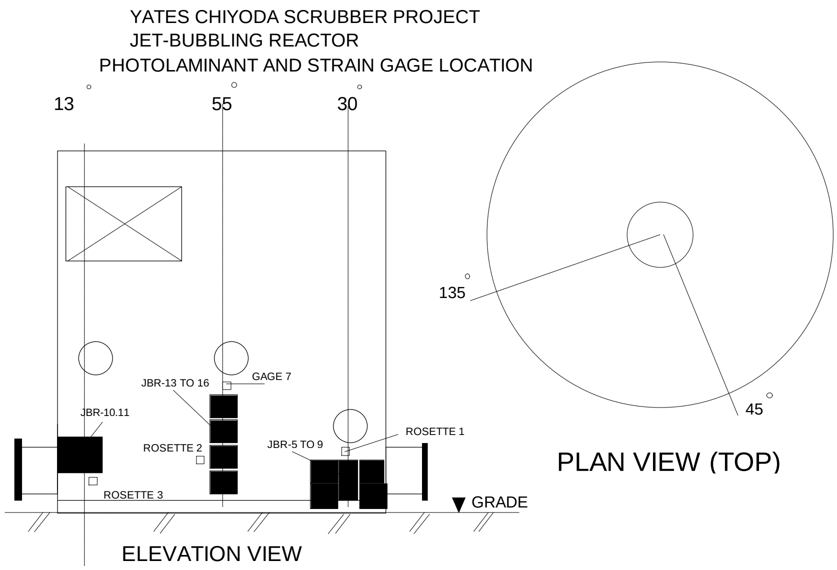


Figure 2-15. Meausring Strain Using Photoelastic Coating and a Typical Strain Field In JBR.



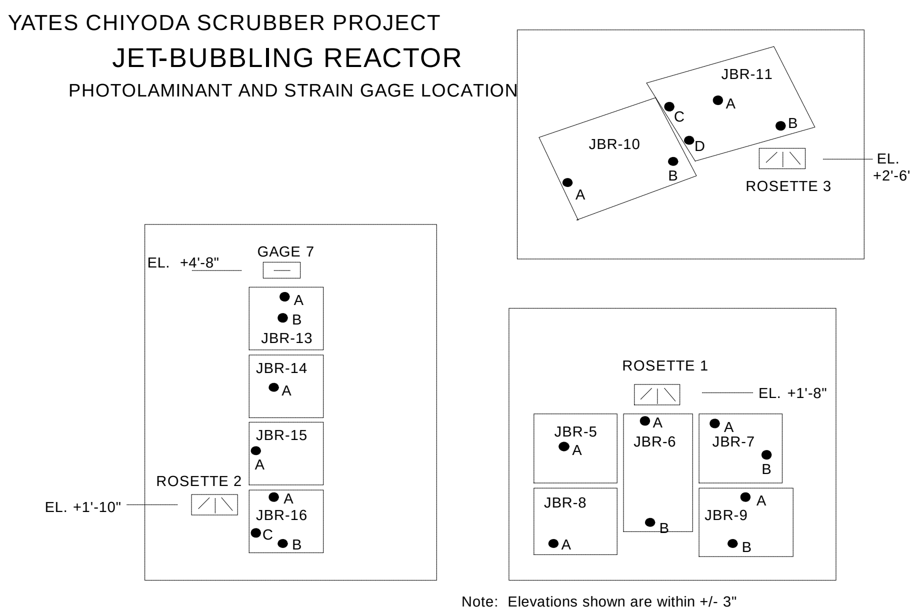


Figure 2-16. Location Map for Strain Gages and Photoelastic Laminates Applied on JBR and LSST

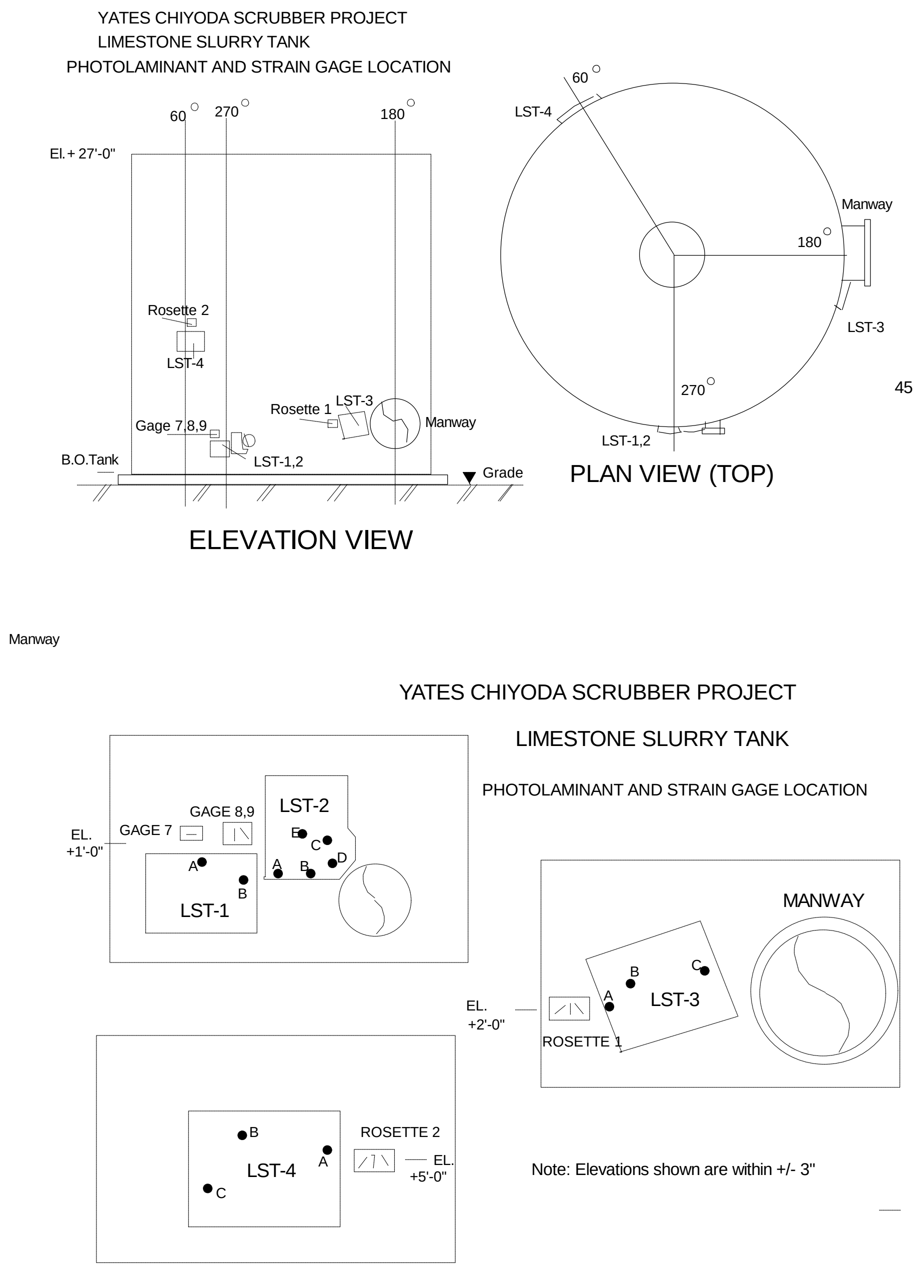


Figure 2-17. Location Map for Strain Gages and Photoelastic Laminates Applied on JBR and LSST

2.2.1.2 Structural Reliability Tests

These tests were performed during short term outages of the scrubber system and on -line while the system was in operation. The purpose of these tests was to monitor the rate of change in the structural properties of FRP system and insure safe operation of the FRP scrubber systems. The scope of the testing is described in the following sections.

2.2.1.2.1 General Inspection

The purpose of the general inspections were to identify and track the progress of structural defects associated with the manufacturing process and operating cycles of the CT -121 FGD process. The inspections were performed by on -site personnel, the employees of Ershigs (equipment manufacturer), and certified FRP specialists/ consultants during routine visits and also during unit outages. A typical general inspection could include a visual inspection of the FRP equipment, and when possible, Barcol hardness measurements of FRP surfaces (per Section 7 of ASTM D-2583).

- Visual Inspection: Each inspection included a thorough examination of the interior and exterior surfaces of the FRP vessels to identify all visible defects including blisters (caused by osmotic pressure acting at the concentrations of unreacted material in the laminate), delaminations (caused by weak bond at a secondary overlay or within a laminate that has an exposed cut edge), interior cracks (due to thermal expansion or chemical corrosion or severe flexing of t he wall), exterior cracks (due to thermal expansion or over -stress or resin embrittlement), overload (axial and circumferential cracking), or severe flexure of the wall (random cracks), and point impact (star cracks).
- Barcol Hardness Measurements: Barcol hardness measurements were made on the surface of the structural laminate by the equipment manufacturer to determine if the surface was softening (due to corrosion and abrasion).

2.2.1.2.2 Abrasion Monitoring

It is generally believed that exposure of the structural laminates to a chemically corrosive environment may lead to excessive corrosion, cracking, and eventual failure of the load bearing structure. Consequently, the structural laminates in the CT-121 FGD process system were lined with corrosion resistant overlays. However, due to the particulate-laden nature of the process environment at the JBR inlet, it was suspected that the corrosion resistant overlays would be subject to excessive wear and abrasion damage. Therefore, to ensure the integrity and reliability of the FRP vessels and components, the rate of degradation of the protective liner on surfaces exposed to the process environment was monitored during the operation of the CT-121 FGD system. The abrasion was monitored in two ways.

A green-color pigment was mixed in the resin and used in the construction of the inner protective layer of the FRP equipment. This provided a color-based depth gage by which the abrasion effects at an arbitrary location can be quantified and monitored. This color code was used effectively in monitoring the abrasion in the JBR and the slurry piping. Figures 2-18 and 2-19 shows the colored resin and its effectiveness in measuring abrasion.

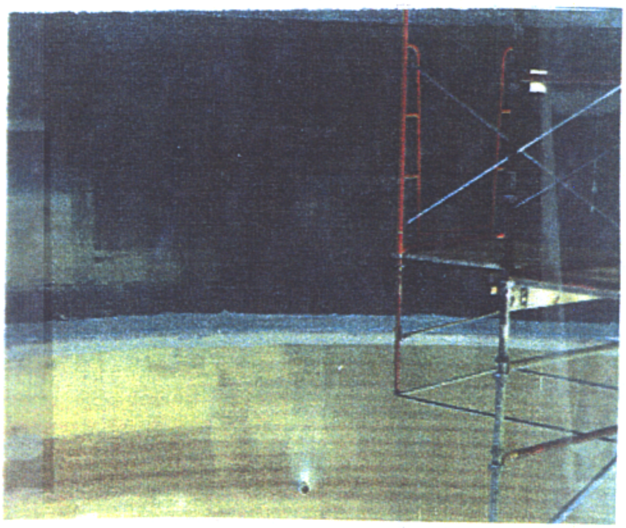


Figure 2-18. Color-Coded Abrasion Monitoring in LSST

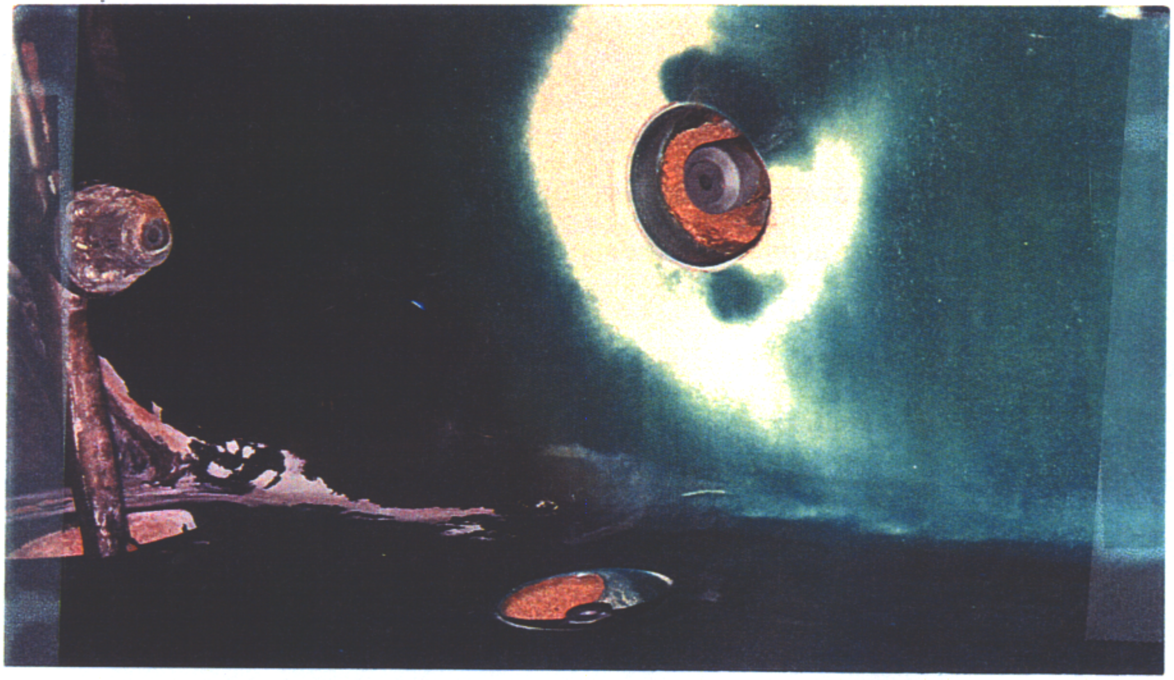


Figure 2-19. Color-Coded Abrasion Monitoring in the JBR Inlet Duct

In addition to the green-color abrasion monitoring resin system, test coupons were also prepared to study the abrasion resistance of other type of material formulations for future use. The pre-fabricated test samples, illustrated in Figure 2-20, were designed and prepared in cooperation with Ershigs Inc. and Ashland Chemical Company using different abrasion resistant formulations, including those used in construction of the protective lining in the critical process areas. A unique feature of the abrasion test samples was the two-color construction that allowed visual inspection and measurement of the abrasion depth in different samples. Figure 2-21 shows a photograph of the depth coding in an abraded test sample.

The abrasion samples were prepared in the shop by Ershigs according to the design dimensions and specifications, and installed by SCS at the designated locations before system start-up. Table 2-9 and Figure 2-22 show the material formulation and the location of abrasion test

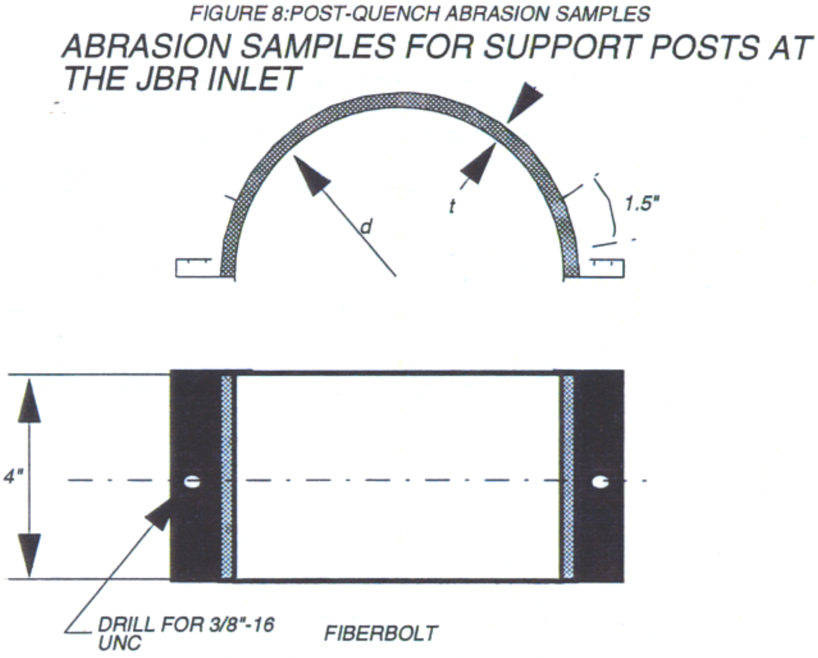


Figure 2-20. Schematic of Abrasion Test Coupons

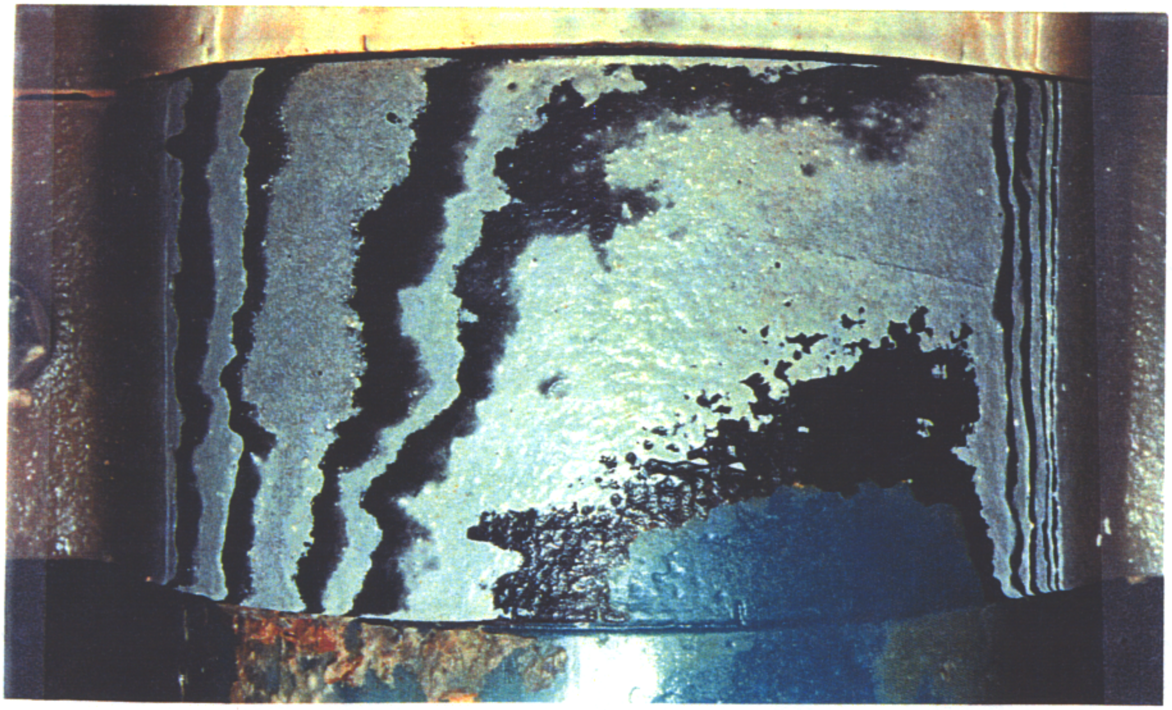


Figure 2-21. Abrasion Depth Monitoring Using Color-Coded Coupons Depth

TABLE 2-9
LAMINATE PLY-SCHEDULE FOR ABRASION TEST COUPONS

ID	Resin/Comments	Reinforcement	Inlet to JBR	JBR Reaction Zone
			# of Samples	
992-C	Hetron FR992	"C" (10 Layer Glass Veil)	12	6
992-CV	Hetron FR992	Carbon Veil	12	6
992-CVMF	Hetron FR992	Carbon Veil and Milled Fibers	12	6
992-CAR	Hetron FR992	"C" + Abrasion Resist. Dust	12	6
1619-CVMF	Hetron D-1619	Carbon Veil and Milled Fibers	12	
1619-CAR	Hetron D-1619	"C" + Abrasion Resist. Dust	12	6
1620-C	Hetron D-1620	"C"	12	
1620-CVMF	Hetron D-1620	Carbon Veil and Milled Fibers	12	6
1620-CAR	Hetron D-1620	"C" + Abrasion Resist. Dust	12	
197-C	Hetron 197AT-T15	"C"	12	
197-CVMF	Hetron 197AT-T15	Carbon Veil and Milled Fibers	12	6
197-CAR	Hetron 197AT-T15	"C" Abrasion Resist. Dust	12	

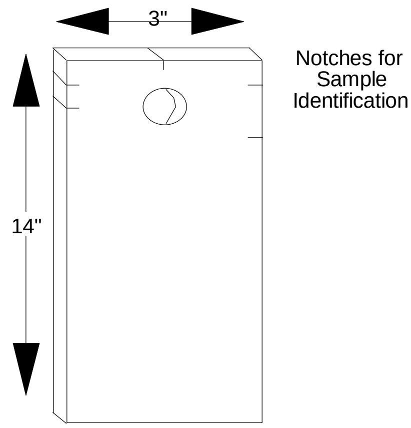


Figure 2-22. Schematic of ASTM C-581 Test Sample

coupons in Plant Yates scrubber. These were to be routinely monitored during the general inspections of the scrubber vessel to measure abrasion damage. However, due to the high abrasion rate in the JBR inlet zone, the abrasion resistant coupons testing proved to be a short-term experiment.

2.2.1.3 Structural Property Monitoring

It was desirable to gain first-hand knowledge of the FRP performance and property changes as well as the same for other applicable resins. This would help improve the process of selecting the appropriate resin for future Chiyoda CT-121 constructions. To meet this objective, several sets of ASTM C-581 tensile test coupons (230 coupons in total), shown in Figure 2-22, were prepared by Ershigs using the formula used in construction of the vessel wall and other suitable formulas.

The test samples, listed in Table 2-10, were prepared using resin provided by Ashland Chemical Company. Additional test sample sets were also prepared and provided by Dow Chemical Company and Morrison Molded Fiber Glass Company. Each set of test samples consisted of five double-sided ASTM C-581 corrosion coupons for each sample construction formula. Each

TABLE 2-10
LIST AND LOCATION OF CORROSION COUPONS

ID	Resin Material	Reinforcement	Inlet Duct	Inlet Plenum	Reaction Zone	Exhaust Plenum
			# of samples			
992C	Hetron 992	"C" Glass Veil	6	6	6	6
1619C	Hetron 1619-D	"C" Glass Veil	6	6	6	6
1620C	Hetron 1620	"C" Glass Veil	6	6	6	6
992MCMV	Hetron 992	Milled Carbon, Carbon Veil	6	6	6	6
1619MCCV	Hetron 1619-D	Milled Carbon, Carbon Veil	6	6	6	6
1620MCCV	Hetron 1620	Milled Carbon, Carbon Veil	6	6	6	6
992CV	Hetron 992	Carbon Veil	6	6	6	6
1620CV	Hetron 1620	Carbon Veil	6	6	6	6
1619CV	Hetron 1619-D	Carbon Veil	6	6	6	6

sample was marked according to its designated location and measured accurately for size and weight. The samples were then installed in the inlet duct, the inlet plenum, the JBR reaction zone, and the exhaust plenum, per the location schedule shown in Table 2 -10. Figure 2-23 shows photogra phs of corrosion sample racks in the exhaust plenum.

After given exposure times, designated samples were retrieved from the process, and tagged for identification. The removed samples were sent to their resin manufacturer for tensile property and hardness examination and results were tabulated to reflect the effects of the exposure time on the mechanical properties of FRP samples. It is important to note that one complete set of

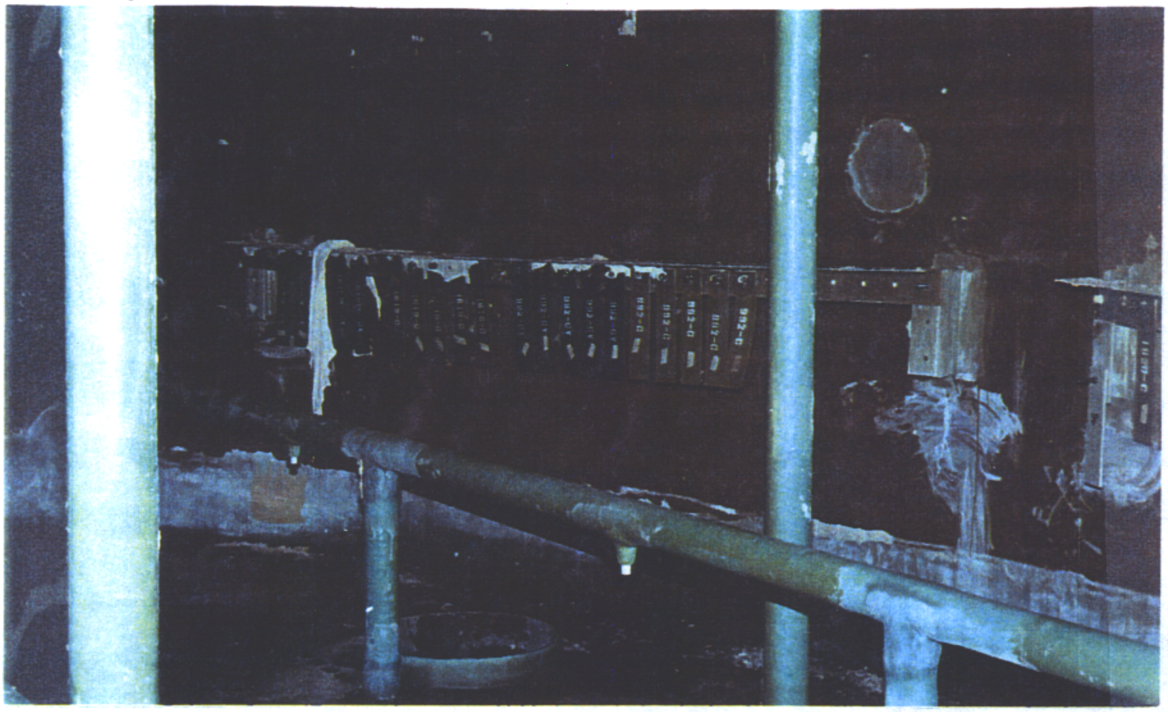


Figure 2-23. Photograph of the FRP Corrosion Coupon Rack

corrosion samples which were installed in the JBR broke shortly after the startup, indicating significant turbulent forces in this area. As such, the in-situ measurement of property degradation in the reaction-zone area was abandoned.

In addition to the FRP samples, it was also necessary to study and document the reliability of various metals for construction of scrubber components. Therefore, a corrosion sample rack containing metal samples of F255, A441, C276, C22, Ti Gr.5, A516-60, 317L, 316L, AL6XN, AND AL-6X were installed in the inlet duct section of JBR. Figure 2-24 shows a schematic of the metal sample rack and a photograph of the rack in place. The rack was removed every six months and analyzed to determine the rate of corrosion in various metals. The results of this analysis were documented and reported. Appendix 6-B contains further details of this work.

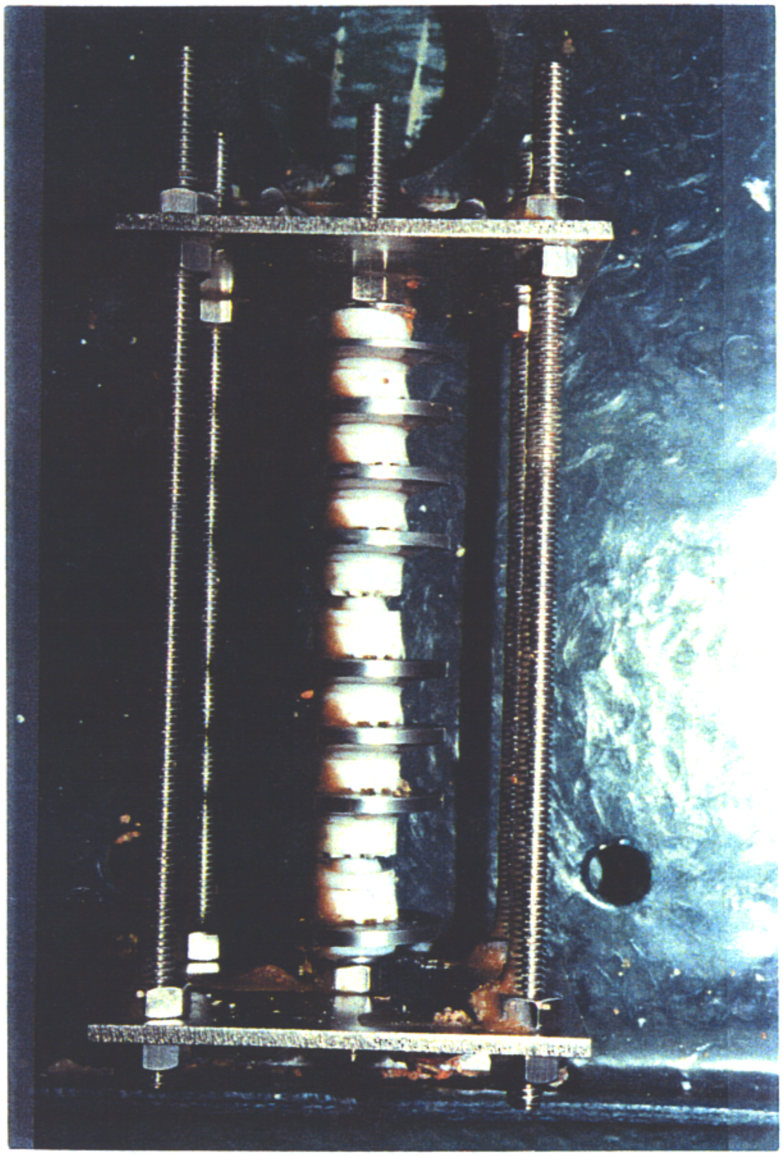


Figure 2-24. Metal Corrosion Coupon Rack

3.0 RESULTS AND DISCUSSION

Following a two-year design and construction phase, the CT-121 FGD system at Plant Yates was placed in operation in October 1992. The JBR vessel, after it was manufactured, was among the largest and most complex field-manufactured filament-wound FRP vessels in the world. As such, the design and construction of the FRP vessels for Plant Yates CT-121 FGD scrubber incorporated several new concepts. The construction process had to also account for the local climate and its effects on the quality of the manufactured products. These uncertainties proved to be time-consuming and costly.

Prior to this start-up, the JBR and the LSST were evaluated for structural integrity and elastic performance under simulated hydrostatic loading conditions. The maximum loads experienced by these vessels during the simulation were to be equal or greater than those applied on the vessels during the operation. The primary objectives of these tests were to identify and correct major manufacturing defects, verify the elastic performance of the shell under load, verify the theoretical understanding of the equipment performance in areas of design uncertainty, and structurally qualify the vessels for their intended operation. These pre-operation tests occurred during April 1991 and September 1991.

During the first phase of scrubber demonstration, the pre-existing electrostatic precipitators (ESP) were fully energized to remove the ash from flue gas entering the process vessels. As such the scrubber FRP systems experienced a lower rate of structural abrasion and chemical attack. The structural integrity tests in this phase included routine general inspections of FRP equipment during short term outages to monitor and assess the conditions of FRP systems including those in LSST, JBR and the adjoining ducts, and various other FRP components. In addition, the pre-fabricated FRP corrosion samples installed at pre-determined locations were routinely removed and tested under standard tensile testing conditions to evaluate the rate of change in material properties.

The ESP fields were de-energized during the second phase of the demonstration program, causing a heavier load of fly ash and slurry to pass through the inlet duct and plenum system. All the abrasion-damaged surfaces were repaired with the proposed new abrasion resistant coatings prior to the start of this phase. However, the structural integrity tests for this phase of operation required more frequent general inspections of the exposed FRP systems to monitor and control any further damage. The testing of the corrosion samples continued in this phase as scheduled and samples tested to determine further changes in their physical properties.

Following the completion of the high-ash phase of the demonstration program in December 1994, the Yates scrubber FRP systems were re-inspected to identify abrasion and/or other damage. The FRP elastic performance was also measured to verify structural reliability and determine the magnitude of change in the structural properties. At the completion of these tests, the FRP systems were refurbished, all damages were repaired, and the scrubber was placed back in service as a part of Plant Yates production equipment.

3.1 FRP Material Concerns

Among the other key objectives of Plant Yates “FRP Test and Evaluation Program” were to evaluate if:

- The state-of-the-art in FRP design and construction could support cost-effective construction and reliable operation of the CT-121 process equipment;
- Larger, reliable, and more complex FRP scrubber equipment could be manufactured in the future; and
- The design and the manufacturing technology could be improved to make more durable FRP scrubber equipment at a lower cost.

3.1.1 Lessons in FRP Design

The finite element analysis results showed that the FRP vessels would safely operate under the specified operating conditions. However, these structural models identified one area of design improvement for control of the lower deck deflections. The analysis showed higher deck deflections at full load than was allowed to maintain the alignment of the sparger tubes. As discussed earlier, this problem was quickly resolved by minor adjustments in the thickness of laminates and arrangements of the secondary supports. These result highlight the importance of finite element analysis in design of larger jet bubbling CT-121 reactors particularly to meet the tolerances specified for alignment of sparger tubes and to avoid costly modifications at a later time. Based on this experience, FEA technique was successfully applied in the structural design of a Chiyoda scrubber for Georgia Power Company's Plant Wansley (1991 proposal to U. S. Department of Energy) and the design and construction of the SUNCOR Chiyoda process. Further, it is strongly recommended that finite element modeling be always used as a complementary tool to conventional design methods to design and verify the performance of complex FRP structures in future CT-121 systems.

In the final analysis, the use of FRP as construction material in the Plant Yates CT-121 Scrubber has demonstrated the merits of this material as a viable alternative for full-scale scrubber vessels. Naturally, the extensive FRP research currently underway throughout the engineering community would lead to further verification of FRP as a viable structural material. However, several significant issues need to also be considered in the use of FRP in future construction of scrubber process vessels:

- Design requirements for FRP structures are not widely controlled as traditional construction materials. Since FRP laminates are constructed as a series of many layers of resins, fiber glass, and coatings, the quality assurance of the raw materials and bonding procedures, and curing has many variables.
- The construction of two identically designed vessels, if constructed at different times or by different construction personnel, could potentially have a much different quality of workmanship. In summary, quality assurance requirements are

much more important for a FRP material than a traditional material of construction.

- FRP does not have the application experience in massive structures as do steel and concrete structures. Aerospace and automotive industry design personnel have a much more extensive experience base in the use of composite plastic materials. Lack of confidence and knowledge in the use of a material is a self-perpetuating problem which prevents quick acceptance of a new material.
- Specifications should be written to include the evaluation of the material and performance of the constructed component. Specifications for a product to be constructed of FRP require an extreme effort on the part of the specifying engineer. Not only do the materials have be tightly specified, but also the construction of the component and the performance requirements for the completed system should also be mandated. This requires a tremendous investment on the part of the owner to enter into a proposal in which the terms of the specification may be very controversial.
- Another area of design uncertainty which has not been fully understood or quantified is the effects of large temperature excursions on the life and durability of FRP vessels. Based on Plant Yates operational experience, these short term events could occur as the result of a malfunction in the gas quenching system and have the potential to damage FRP if they are neglected in the design of FRP systems.
- Finally, the use of FRP as an engineering material has many aspects that require a more deliberate effort on the part of the owner, the engineer, and the construction party. In certain cases, as is demonstrated by the environment required to construct and operate wet SO_2 scrubbers, only the use of very expensive alternative materials to FRP are acceptable. In these types of applications, the FRP material has tremendous promise.

3.1.2 FRP Structural Performance

Normally, the engineer must make many simplifying assumptions about boundary conditions and physical situations that are difficult to quantify with exact numbers. Therefore, the design data provided by testing can both lead and support the analytical assumptions used in normal design practice. The elastic strain response, as a part of the Plant Yates FRP testing program, was designed especially to verify the design calculations and the structural reliability of structural FRP vessels. The plots of measured strain and stress as a function of water-height during hydrostatic loading are shown in Appendix 6-B. Figures 3-1 and 3-2 demonstrate two typical strain response

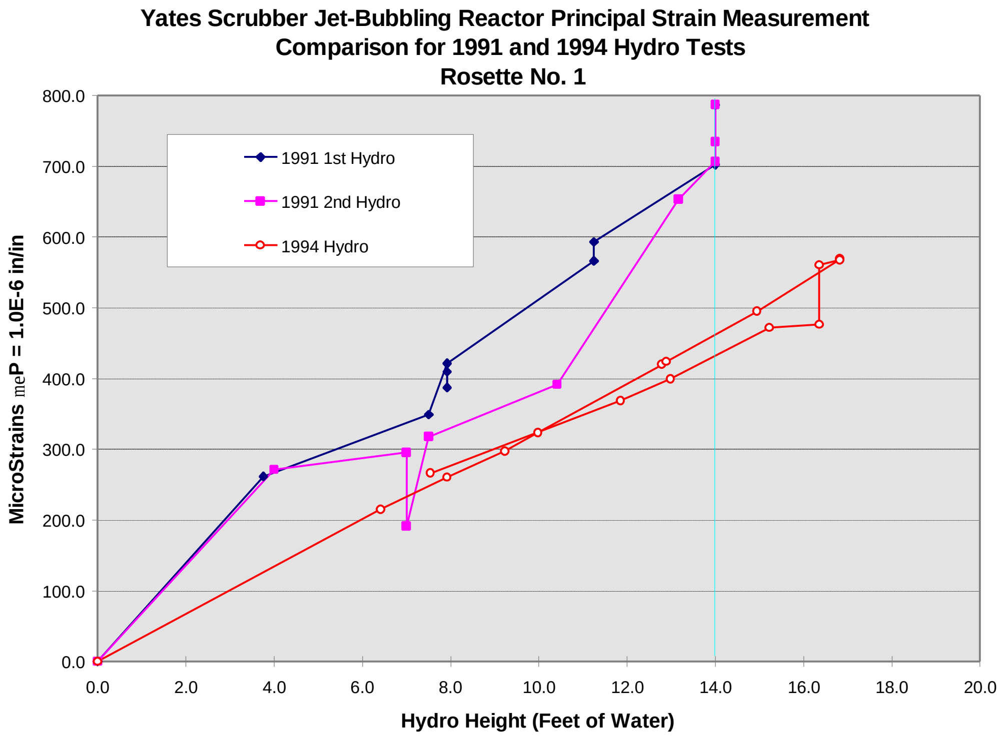


Figure 3-1. Major Principal Strain as a Function of Water Height in JBR

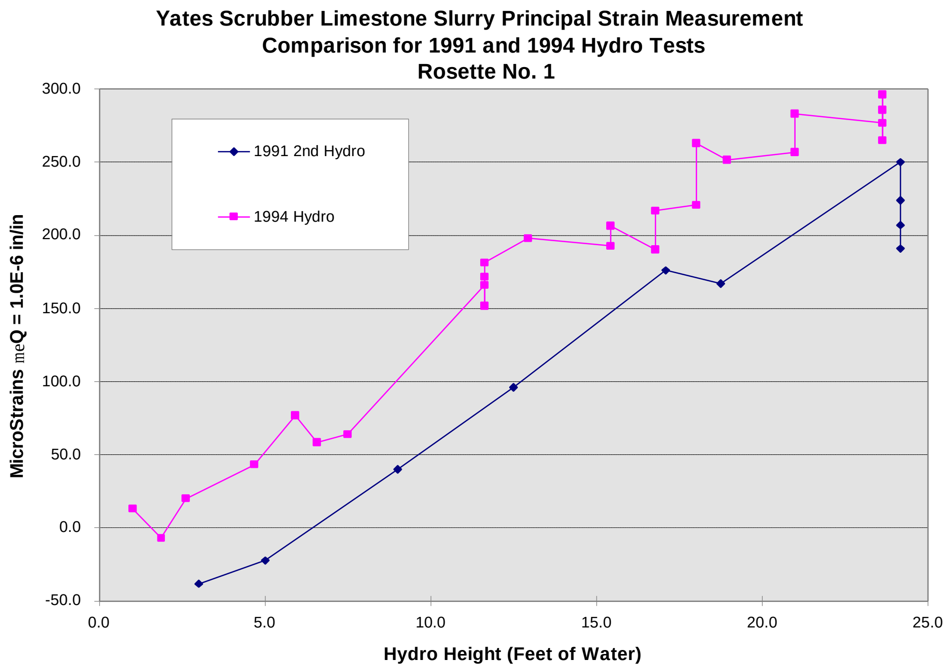


Figure 3-2. Minor Principal Strain as a Function of Water Height in LSST

curves, measured on JBR and LSST respectively. The test measurements also confirmed that the maximum strains occur predominantly in the hoop direction, but that there are significant strains in the vertical direction. It is our assumption that since the strain gages were applied after the majority of the vertical loading were in-place, no considerable vertical strains could be measured by the gages under hydrostatic loading.

These figures also demonstrate the linear relationship between principal strains and load (water height). This linear relationship was typical of all measurement locations indicating an elastic response to load. Furthermore, the slope of strain response to load remains constant indicating no stiffness degradation, or no loss in elastic moduli as a function of time or exposure to chemical environment of the Chioda vessel.

The strain results also indicated that the principal strain directions and corresponding body stress directions occur generally in the hoop and vertical directions. Further, the test data compared well with the predicted stress levels and material properties, as provided in the manufacturers design calculations. Figures 3-3 and 3-4 show the experimentally measured and predicted stresses as a function of water height. According to these figures, the strains measured during the earlier experiments were higher than those predicted by the design calculations. However, the stress-strain response became consistent with theory in the later measurements. The data discrepancy can be attributed to the primary creep strains associated with the initial loading of FRP vessel. It is generally understood that FRP vessels will undergo permanent deformation with time as the primary creep sets in and material relaxes to its optimal equilibrium state. The magnitude of creep will ultimately depend on the type and nature of resin used in construction of FRP. While the differences between predicted and measured strains on Plant Yates scrubber vessels were not large enough to cause an alarm, their root source needs to be accounted for in the future design and maintenance of large FRP vessels.

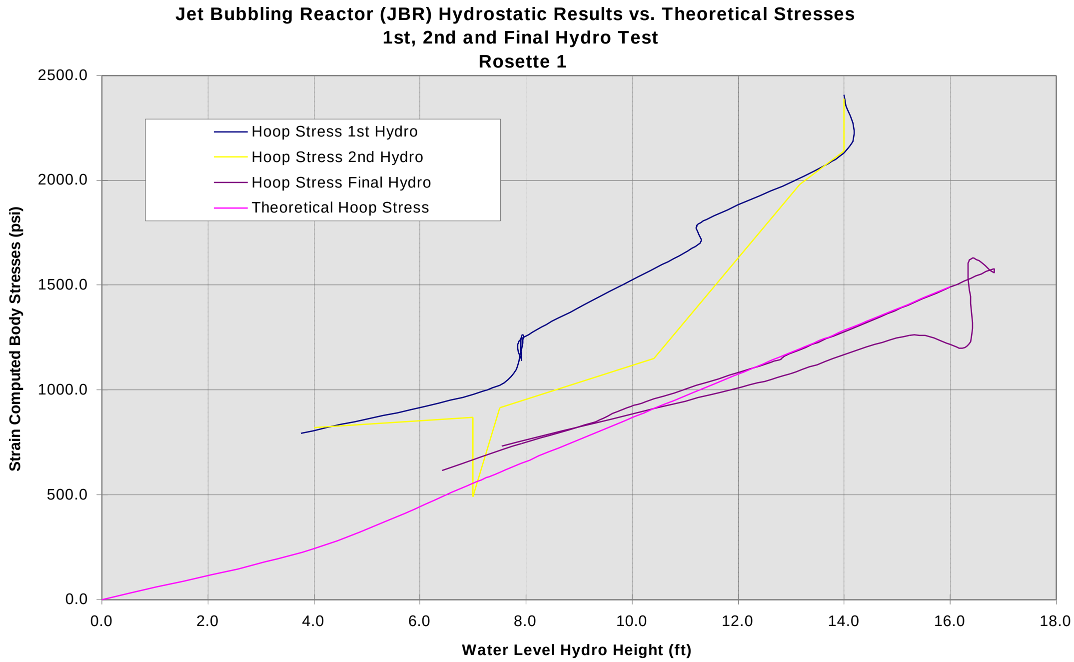


Figure 3-3. Typical Stress Response in JBR

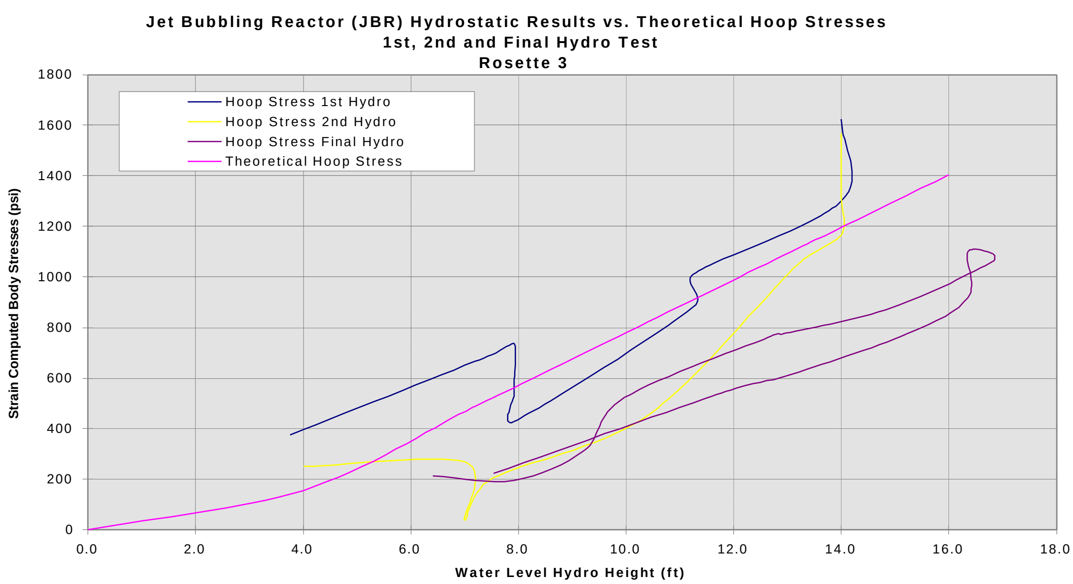


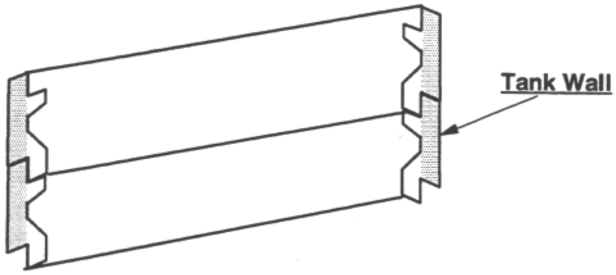
Figure 3-4. Typical Stress Response in LSST

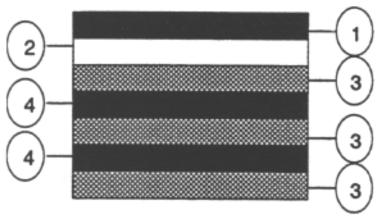
3.1.3 New FRP Tank Construction Technology

Motivated by the technical limitations and high cost of the filament winding (FW) FRP construction at Plant Yates, SCS identified an innovative low-cost approach for construction of large cylindrical FRP vessels. Developed by Goldsworthy, this method would combine conventional pultrusion machinery with a special cylindrical tank fabrication machinery to construct, on-site, large FRP storage tanks. In 1975, a prototype of the construction machinery was built and used to fabricate a 20' diameter-10' high FRP storage tank at Ft. Belvoir, Virginia. The entire construction was completed in less than 4.5 hours, a sharp contrast to what it would take to construct a similar FW vessel.

This technology uses a single pultruded profile with matched tongue-and-groove interlocking sections on both sides similar to the profile sketched in Figure 3-5. As in the case of filament wound vessels, the pultruded profile would consist of several layers (plies). Each ply in this construction would serve a special purpose; the glass roving gives the part strength in the longitudinal direction, the continuous strand mat ply provides flexural stiffness and cross-axis strength, the surface veil improves the weatherability and appearance, and a two-sided bondable Tedlar film would ensure that the tank would not leak. The resin will also contain special additives for optimum performance in pultrusion processing and appropriate pigmentation to produce the desired exterior or interior color.

The continuously pultruded profile is curled around in a continuous vertical spiral to form the single-skin side wall of the tank. The tongue-and-groove sections positioned at the top and bottom of the profile width are zippered and bonded together as the side wall is built up, as shown in Figure 3-6. The tanks is installed directly into the concrete foundation and the seams between the foundation and the vessels are filled with polymer cement to seal the vessel. The concrete foundation will also be used as the tank floors and require coating with an appropriate polymeric material to prevent concrete degradation. The foundation and the anchoring system





Ply No.	Ply Material	Total Thickness
1	Surface Veil	3 mils
2	Tedlar Film	5 mils
3	Continuous Strand Mat 1.5 Oz. (3 X 33 mils)	99 mils
4	Roving 113/Y (3 X89 mils)	267 mils
Total Ply Thickness		0.374 in.

Figure 3-5. Interlocking Pultruded Profiles

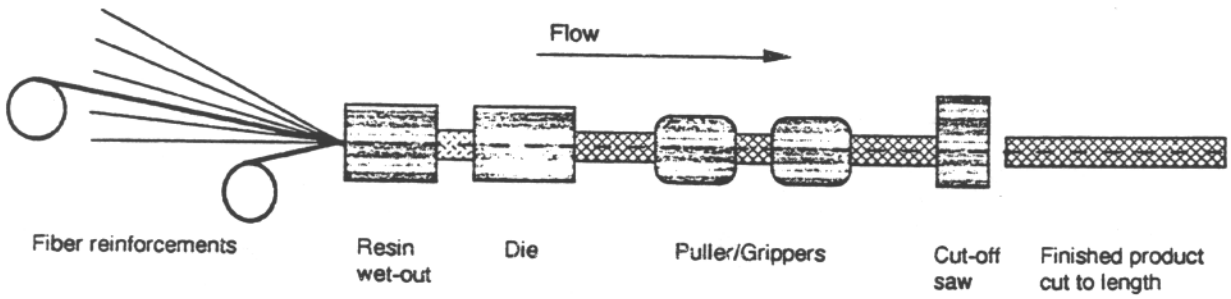


Figure 3-6. Pultruded FRP Construction Technique

should be designed to support the full service loads of tanks and meet the seismic and wind load design requirements.

The Goldsworthy's on-site FRP tank builder system presents several possible advantages over the conventional filament winding systems:

- Improved Quality Control: Utilization of pultrusion in FRP tank construction may lead to improved product quality. This would be achieved by the environmentally-controlled FRP pultrusion machinery.
- Lower Construction Costs: Based on a preliminary analysis, the construction cost of a 28' diameter by 28' high pultruded FRP tank will be at least 50% less than a similar-sized tank produced by filament winding. These savings are due to the highly automated nature of pultrusion and elimination of weather-related intrusions realized during the filament-winding process.
- Greater versatility: Theoretically, no limits are perceived to exist on the diameter of pultruded FRP tank.
- Weatherability: Resin system additives and surface films and veils are pultruded directly into the part to improve weatherability, eliminating additional construction steps.

As an option for the proposed gypsum dewatering process for Plant Yates scrubber system, SCS also proposed to demonstrate the on-site pultruded FRP tank construction technology for future FRP construction applications. Under this proposal, the gypsum slurry storage and reclaim tanks would be fabricated using the pultruded tank technology. After construction and installation were completed, the demonstration program would focus on the technical evaluation and economic assessment of this technology in comparison with other more conventional technologies. However, despite its favorable initial reviews, the proposal did not materialize due to timing and scheduling constraints.

3.2 Structural Reliability Monitoring

Another set of key program objectives included tests and monitoring practices that were designed to:

- Evaluate the structural reliability of FRP structures
- Evaluate and verify the accuracy of diagnostic tools designed for evaluating their structural integrity; and
- Determine the type and extent of routine maintenance required in future installations of CT-121 FGD and the degree of unscheduled maintenance that could be incurred due to problems with FRP construction.

As discussed previously, the tests in this part of the program included test sets focused on verification of structural integrity, abrasion monitoring, and corrosion.

3.2.1 Structural Integrity Tests

In addition to measurements of elastic performance with strain gages as a key performance parameter for structural reliability, acoustic emission measurements were also performed during the hydrotests of 1991 and 1994 to identify structural design flaws and construction imperfections in the FRP structures. The acoustic emission criteria are provided in Table 3-1. These tests were used as a screen to qualify the FRP structures for the intended follow-on service. The following summarizes the results of AE tests as it relates to structural integrity of the FRPO vessels. The AE test reports are available in Appendix 6-B for further reference.

- In April 1991, an initial AE test was performed on the limestone storage tank to determine the applicability of AE to large FRP storage tanks. This test was successful in detecting two major structural failures: delamination of the FRP floor and over-stress conditions in the LSST baffle support tabs. Figure 3-7, which shows the time history of AE activities at one of the sensors, shows the exact time and, within reasonable accuracy, the nature of failure. This floor delamination problem was subsequently corrected. The random level of AE activity at 100% load did not decay with time, as anticipated. Although the AE activity level was relatively low, there was still ample amount of AE such that a standardized test criterion could not be applied. However, the diagnostic information obtained by capture of the burst type activity would not have been obtained if a standardized acceptance criterion was applied to this vessel.

- The limestone slurry and JBR vessels were hydrotested in September of 1991. The data files resulting from these tests represented 11 hours of full loa d hold for JBR and 60 hours of full load hold for LSST. The tests results for LSST also showed indications of delamination and failure at the location of the baffle support tabs (Figure 3-8). Upon closer inspection, visual signs of delamination and discoloration were detected at the location of the tabs (Figure 3 -9). This finding prompted Ershigs to modify the design and construction of the baffle support tabs in LSST. The LSST showed similar trends of AE activity with time.
- Further, the AE data in both tanks showed evidence of prolonged relaxation, as indicated by the continuously decaying rate of AE activity, shown in Figure 3 -10. If the existing AE-CARP criterion were applied, both vessels would fail the approval test for service. However, based on the recommendations of AE consultants and the FRP manufacturer, the low intensity levels and the decaying rate of AE activity did not constitute an alarm for a major failure event. The AE time trend poses a concern since, according to stress strain data, the elastic performance in the JBR and LSST had nearly stabilized; therefore, these activities could not be narrowed down to a specific source.
- The AE tests were performed again in November 1994 to verify structural reliability and measure changes in the structural performance of LSST and JBR. These tests showed continuing low level AE activity throughout the test periods. The data were also evaluated according to the CARP criteria and the results are shown in the table below:

TABLE 3-1
ACOUSTIC EMISSION CRITERIA FOR FRP QUALIFICATION

Acceptance Criterion	Significance Criteria	LSST Results	JBR Results
Hits during holds < 2 min	Measure of continuing damage	Fail-2221	Fail-1, 499
Felicity ratio > 0.95	Measure of Severity of previously induced damage	Fail-0	Fail-0
Total counts < N/2 (3868)	Measure of the overall Damage during a load cycle	Fail-90, 856	Fail-429, 966
Hits above 75dB < 5		Pass-2	Fail 9

The tests also confirmed that the existing SPI/CARP procedures may be too sensitive for testing tanks not intended for highly corrosive materials. The AE tests also detected a cracked nozzle in JBR and several areas of high activity that need to be examined during the next extended outage [6-7]. Figures 3-12 and 3-14 show a cluster analysis of areas of acoustic emission activity in JBR, as measured during the November 1994 tests.

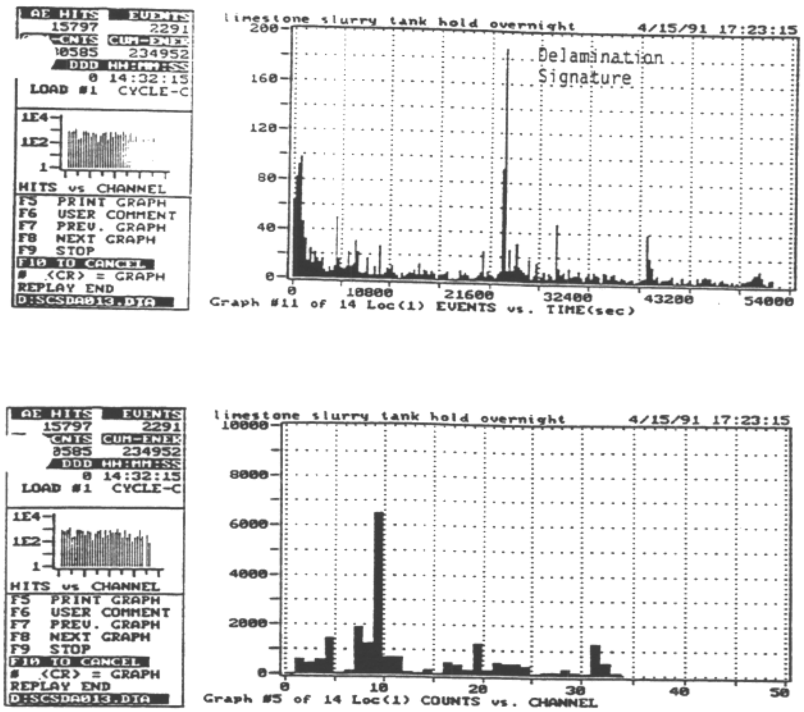


Figure 3-7. LSST Floor Delamination in April 1991 Tests

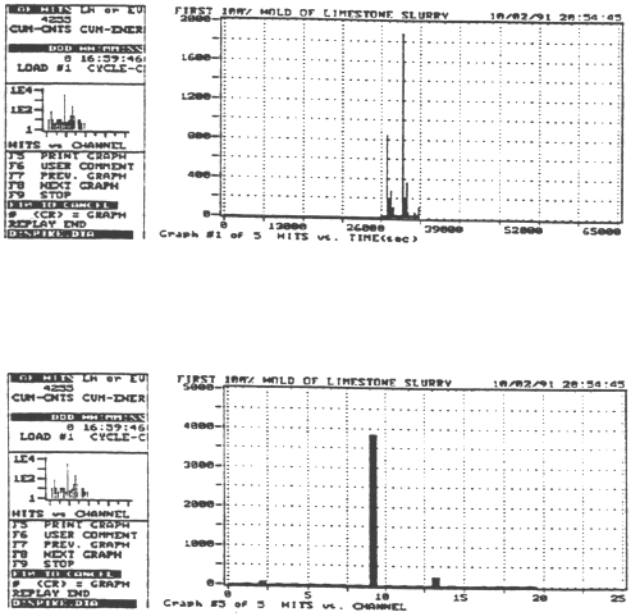


Figure 3-8. Over-stress in LSST Baffle Support Tabs in September 1991 Tests

(Figure Not Available)

Figure 3-9. Photograph of Over-stressed-damaged Baffle Support (September 1991)

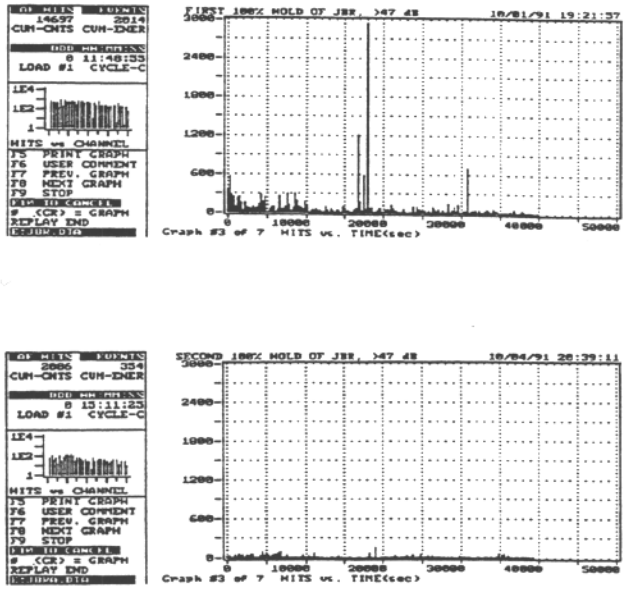


Figure 3-10. Contiguously Decaying Rate of AE Activity in JBR (September 1991)

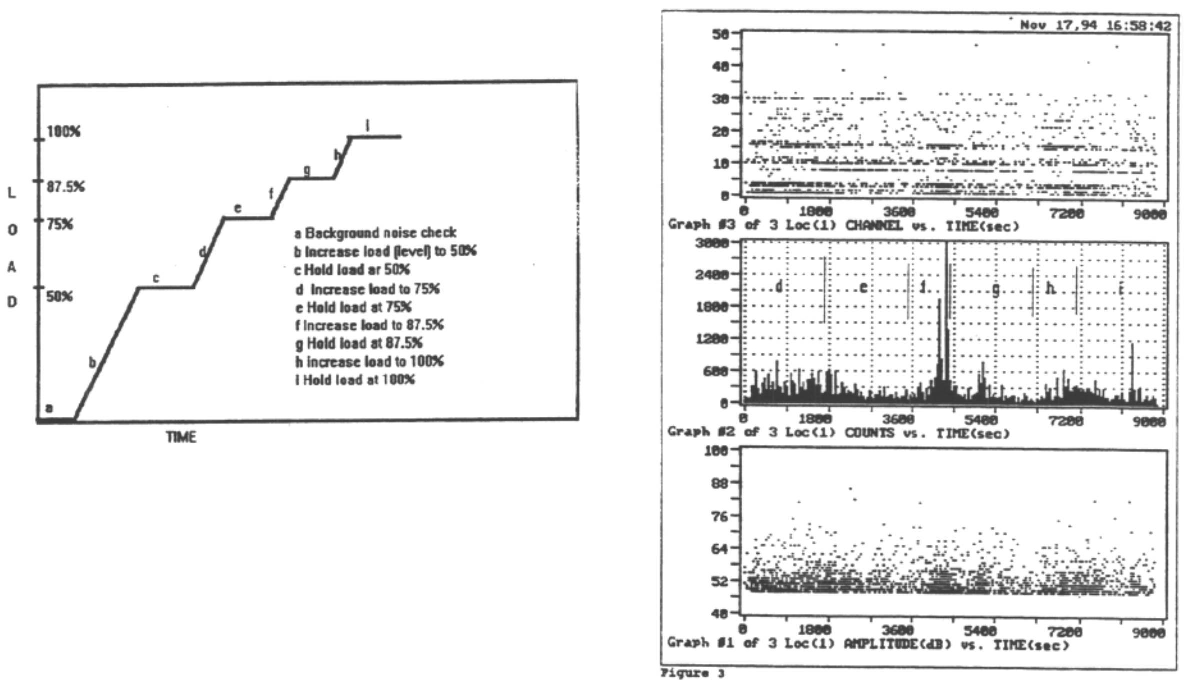


Figure 3-11. Acoustic Emission Data in JBR (September 1994)

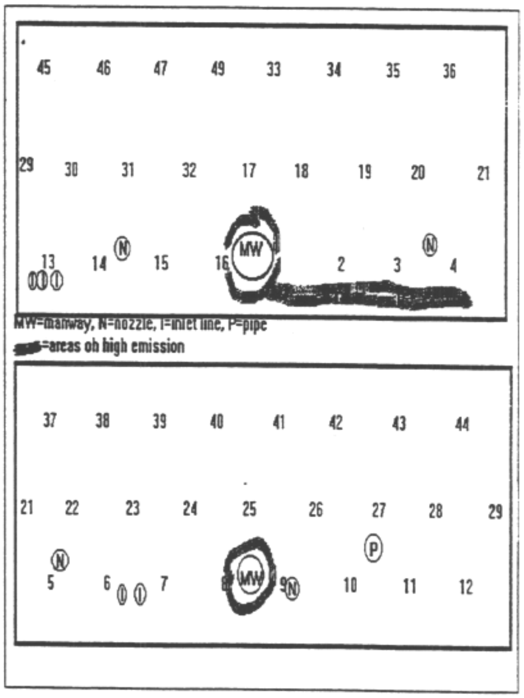


Figure 3-12. JBR Areas of High Acoustic Emission Activity (September 1994)

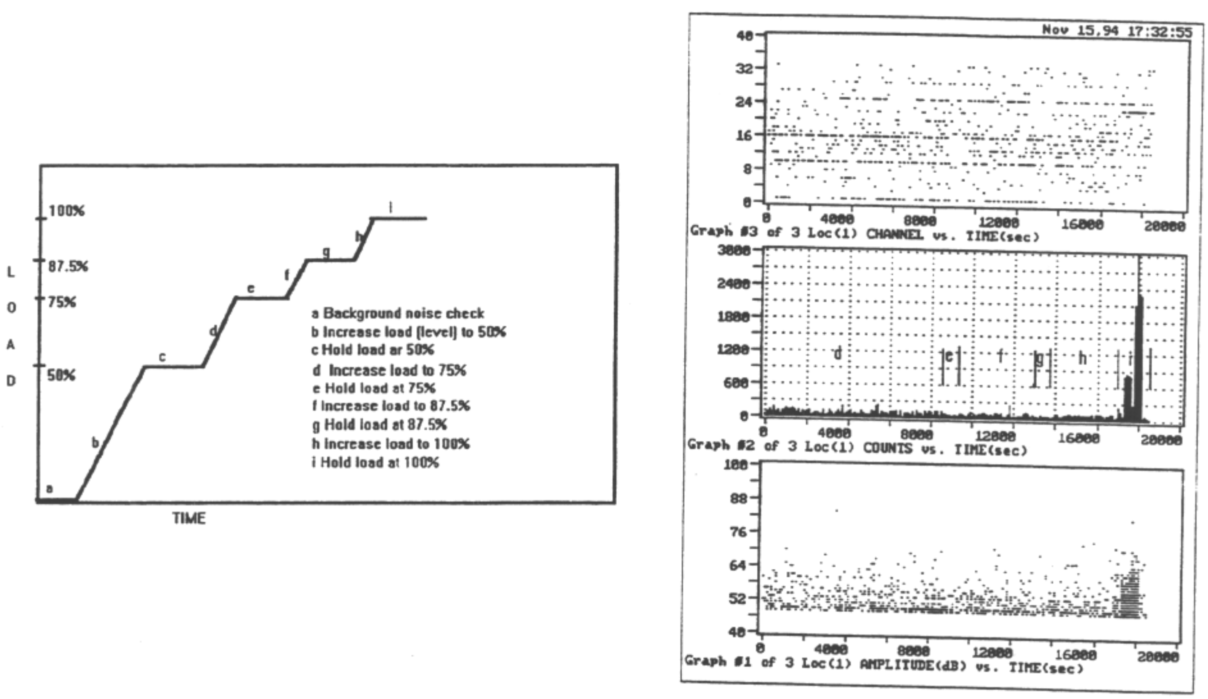


Figure 3-13. Acoustic Emission Data in LSST (September 1994)

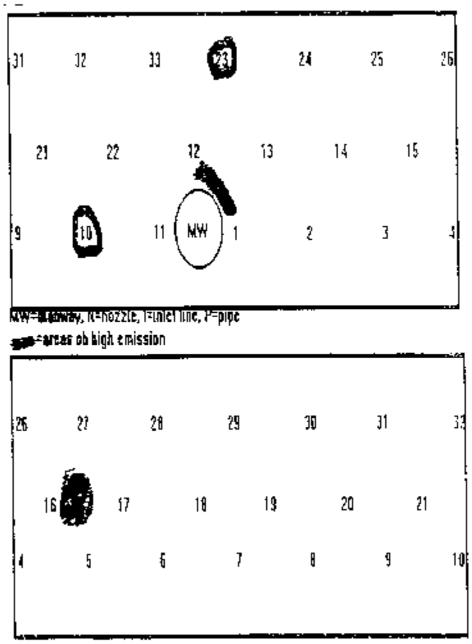


Figure 3-14. LSST Areas of High Acoustic Emission Activity (September 1994)

3.3 Structural Monitoring and Maintenance

3.3.1 Abrasion Monitoring

Shortly after the scrubber startup, the color-based abrasion-indicator/coating began to show signs of severe abrasion in the inlet duct and its internal FRP structures exposed to incoming gypsum-laden flue gas. Abrasion was detected on the upper-deck drains, FRP support columns at the inlet to JBR, trough surfaces of the inlet duct drain, the JBR gas-risers at the inlet, end-caps of the lower deck wash-system headers, the upper-deck drains exposed to incoming gypsum-laden flue gas, and the high temperature transition duct prior to the quenching system. Abrasion damage was also discovered in the high-temperature FRP transition duct right before the flue-gas quenching sprayers. Figures 3-15 and 3-16 show the damage area near a spray-header in the inlet duct.

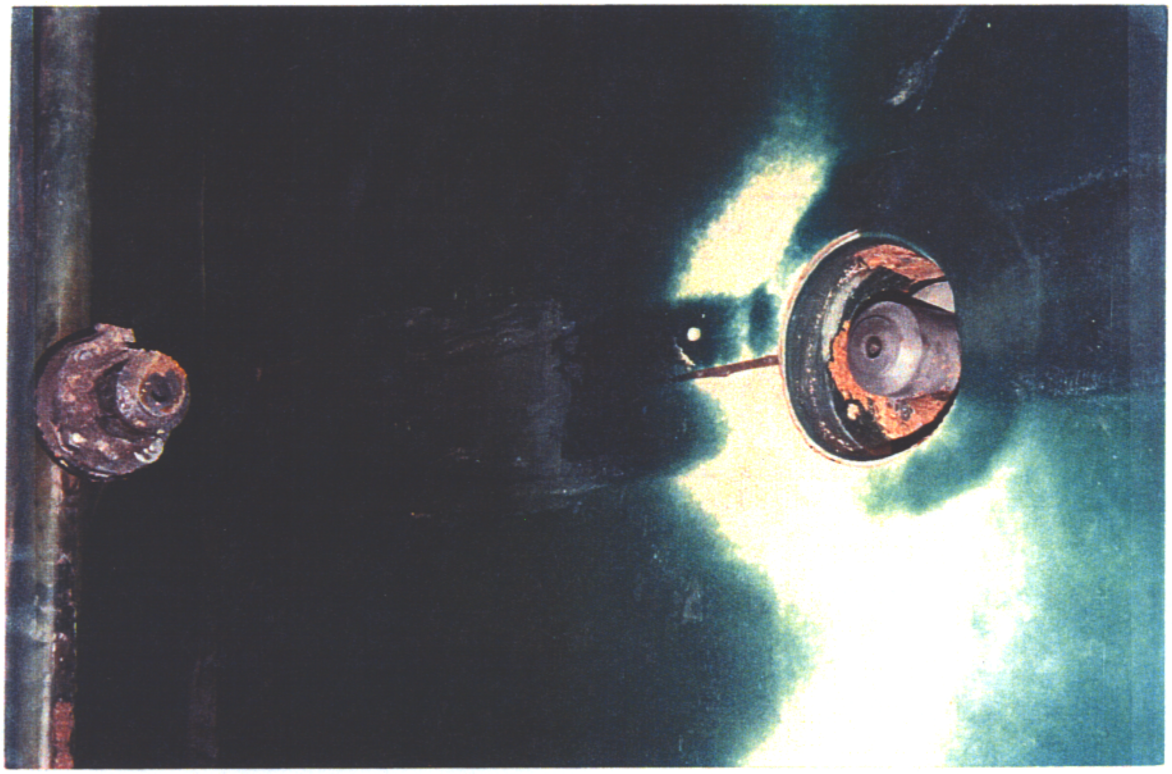
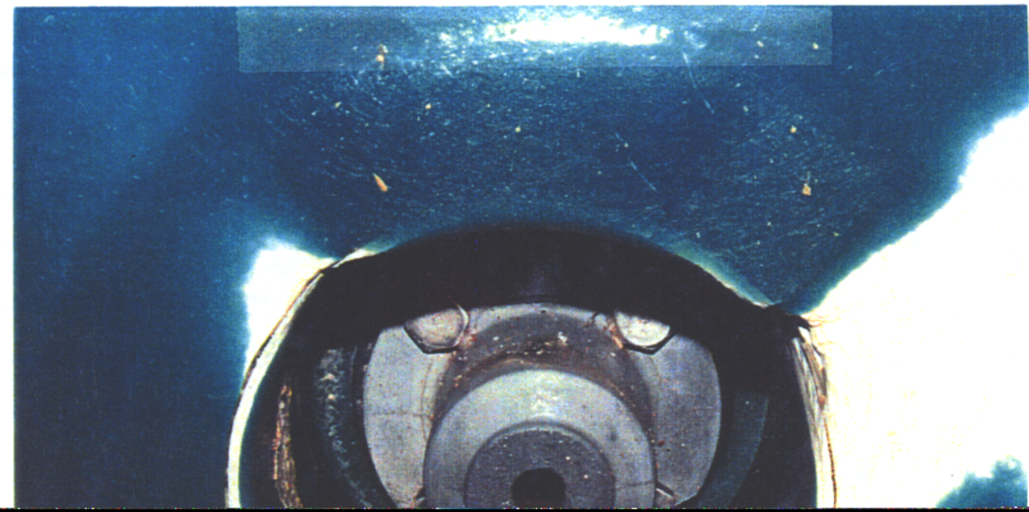


Figure 3-15. Duct Wall Damage Near a Spray Header



Between March 1993 and September 1994, the damaged areas were repaired and new formulations of protective coatings were applied to control the problem. During each solution step, the damaged surfaces were repaired using stiffer abrasion coatings (adding carbon fibers or silica-based additives). These attempts were not successful and the abrasion damage continued to occur in the rebuilt sections. Further, the results from the abrasion test coupons indicated that composite materials incorporating brittle thermoset resins and glass (or carbon mat) would not provide the ultimate abrasion-resistant solution in the areas of high velocity gradient. Figure 3-17 shows the abrasion in the specially designed abrasion coupons located at the gas inlet to the JBR.

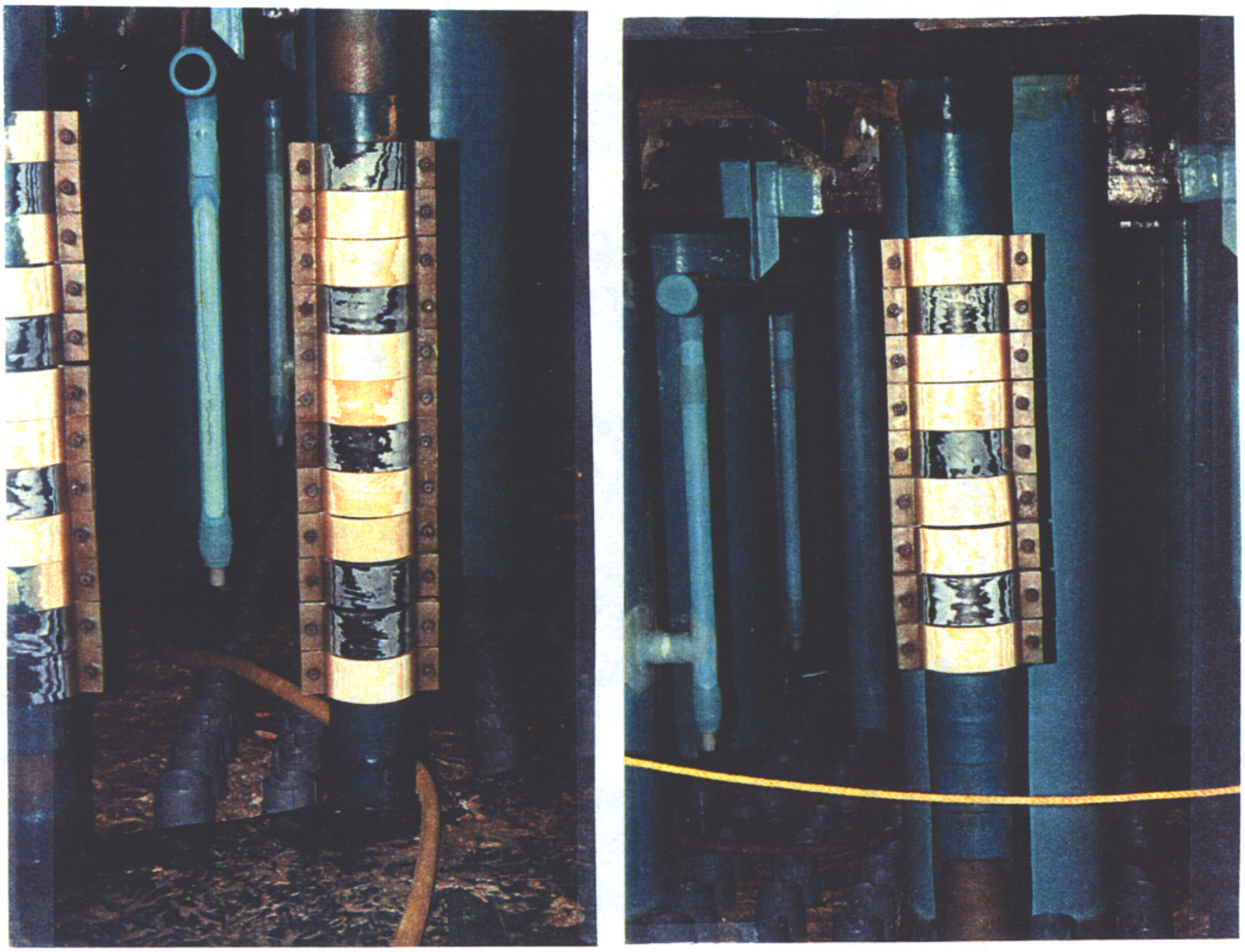


Figure 3-17. Abrasion Damage in Abrasion Resistant Coupons

These events were particularly disturbing since the abrasive nature of the gas flow in the damaged areas would hinder the scrubber reliability while adding substantially to the cost of scrubber maintenance. Finally, a tough rubbery mat used to temporarily wrap a damaged column provided the ultimate solution. This material showed no signs of wear or abrasion after several months of exposure. Since not much was known about use of foam or rubbery material for abrasion control, SCS with assistance from Composite Construction Company installed several compliant polyurethane coating systems were installed in the inlet duct and tested for abrasion resistance evaluation. The test materials included the following:

a) Polyurethane Family
   i) Duramix polyurethane coatings
   ii) Duroform coatings

b) Wear-resistant Ceramic tiles
   i) Coors tiles with Duramix 4188 polyurethane;

c) Nexus veil/Hetron 992
   i) Nexus veil/Hetron 992/AlH3 composite;
   ii) 1.5 Oz Glass mat/Hetron 992/AlH3 composite;

Figure 3-18 shows several of these solutions after installation and again after several months of operation. It is important to note that each solution proved to be effective in controlling a particular type of abrasion attack. For example, abrasion in areas of high shear flow have been better controlled by coatings that have large amounts of fillers. Abrasion due to normal flow, on the other hand, were controlled by more compliant polyurethane mixes. The only remaining issue in this area has been the control of adhesion between the coating system and the FRP. The difficulty is associated with control of humidity, temperature, and surface cleanliness. It is anticipated that the adhesion problem may not exist if the coats are applied in a controlled construction setting prior to scrubber start-up.

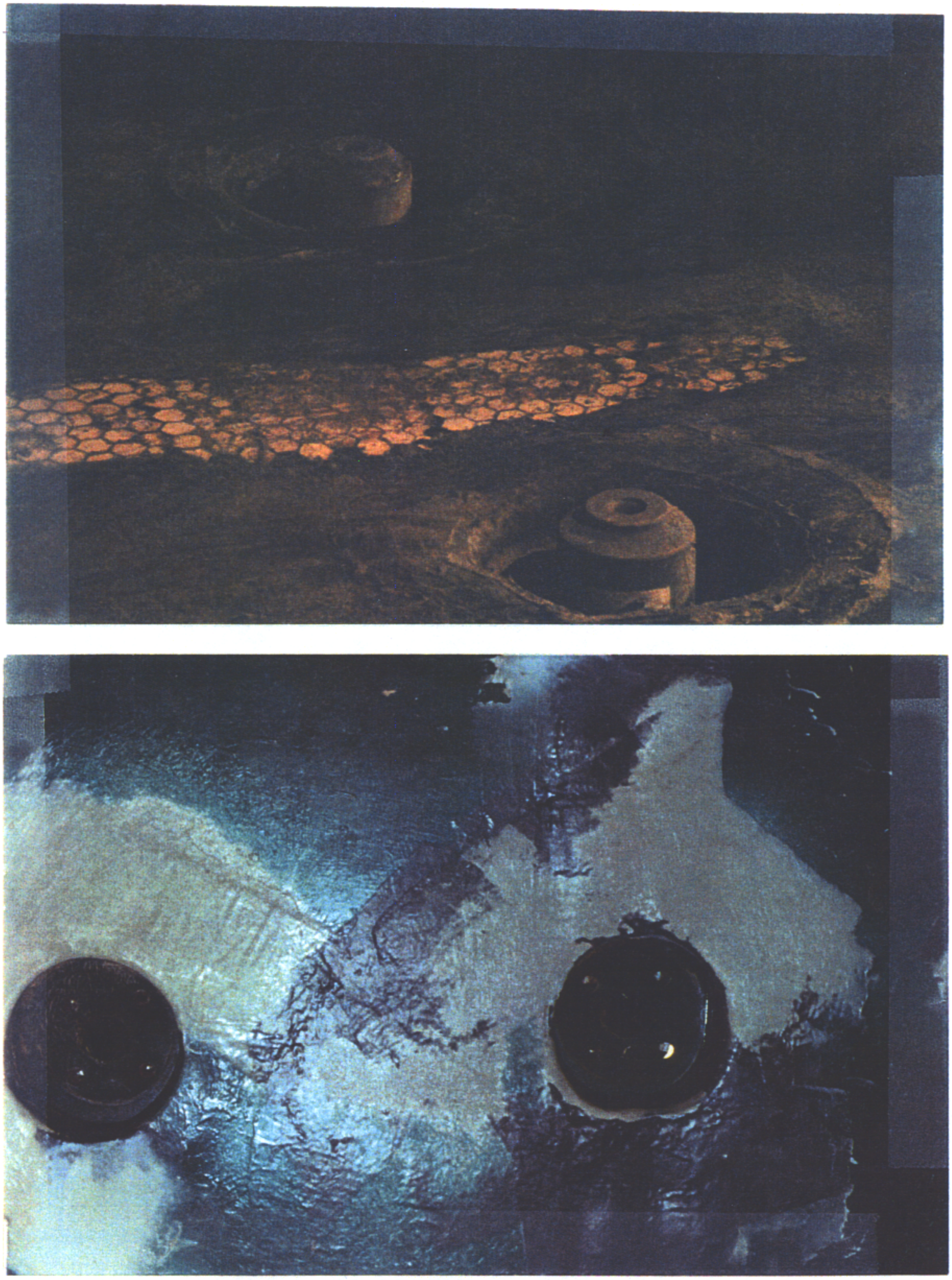


Figure 3-18. Abrasion Resistant Coatings in the Inlet Duct Area

3.3.2 Structural Property (Corrosion) Monitoring

These test results have been summarized in Table 3 -2 below for the three key chemistry areas. As discussed earlier, many of the corrosion coupons installed in the reaction zone of JBR broke shortly after unit start -up. Subsequently, all samples in this area were removed to prevent damage from broken samples to the rubber lined impellers in the slurry pumps. Further details of the tests are shown in Appendix 6 -B.

As shown in this table, the same materials behaved differently in different chemical environments. Further, the different materials provided by th e material suppliers also behaved quite differently under the same chemistry. Figures 3 -19 and 3-20 show the changes in tensile strength in the inlet duct to JBR These results reinforce the importance of material corrosion test data for design of FRP structures in chemical applications. In general, however, most FRP sample materials lost stiffness and hardness with exposure time to the chemical environment of the CT -121 scrubber.

3.4 Status of Diagnostic Tools and Monitoring

3.4.1 Acoustic Emission

Application of AE for QA/QC testing of FRP vessels encountered strong initial resistance from the manufacturer of FRP equipment, Ershigs. The controversy involved vendor's past experiences with AE, especially in the interpretation of AE results and the reco rded inconsistencies between the measurements and field observations. Because of these concerns and the future FRP QC/QA needs in the scrubber industry, the scope of AE measurements was focused on a) first -level screening/detection of incipient structural failures, and b) development of a reliable QC/QA test criterion for FRP scrubber systems of equal to or greater size and complexity than those at Plant Yates. With this mission in perspective, the AE experience at

TABLE 3-2
SUMMARY OF CORROSION COUPON TESTING

Material	Property	Inlet Duct	Inlet Plenum	Exhaust Plenum
992-C	Hardness	• +20% in 375d • -..% after		• +16% in 325d • final < initial
	Tensile Strength	• -20% in 600d • +..% after		• -0.014% per day
992-CV	Hardness	• +0.009% per day	• +14% in 325d, ... ↓ • final < initial	• +14% in 325d .... ↓ • final <Initial
	Tensile Strength	• - 0.02% per day	• -8% in 700d, ... ↑ • final < initial	• -21% in 475 d.... ↑ • final<initial
992-MCMC	Hardness	•	• +22% in 375d, ... ↓ • final < initial	•
	Tensile Strength	•	• -18% in 525d, ... ↑ • final < initial	•
1619-C	Hardness	• +38% in 375, ... ↓ • final < initial		• +21% in 450d.... ↓ • final > initial
	Tensile Strength	• -7% in 450 d, .. ↑ • final < initial		• -22% in 450 d ...level
1619-CV	Hardness	•	• +32% in 425d, ... ↓ • final >initial	• +11% in 450d • final > initial
	Tensile Strength	•	• +31% in 450d, ... ↓ • final < initial	• -25% in 450 d, .. ↑ • final < initial
1619-CVMC	Hardness	• +28% in 400d, ... ↓ • final >initial	• +14% in 325d, ... ↓ • final >initial	•
	Tensile Strength	• +2% in 250d, ... ↓ • final < initial	• +30% in 500d, ... ↓ • final < initial	•
1620-C	Hardness	• +28% in 400d, ... ↓ • final >initial	• +22% in 325d, ... ↓ • final >initial	• +20% in 325d .... ↓ • final < initial
	Tensile Strength	• +2% in 250d, ... ↓ • final < initial	• +16% in 6500d, ... ↓ • final < initial	• -13% in 450d.... ↑ • final , initial
1620-CV	Hardness	•		• +9% in 325d .... ↓ • final < initial
	Tensile Strength	•		• -7% in 525d,.... ↑ • final < initial
1620-CVMC	Hardness	•		• +24%/325d .... ↓ • final < initial
	Tensile Strength	•		• -0.02% per day
Derakane 470-36	Hardness	• +2% in 225 d, ... ↓ • final < initial	• -0.029% per day	• -0.034% per day
	Tensile Strength	• - 12% in 300d, .. ↑ • final > initial	• -32% in 275 days, . ↑ • final > initial	• -0.025% day
MMFG	Hardness	• - 0.037% day	• - 0.024% day	• -0.024% per day
	Tensile Strength	• +0.017% per day	• -0.01% per day	• -0.02% per day

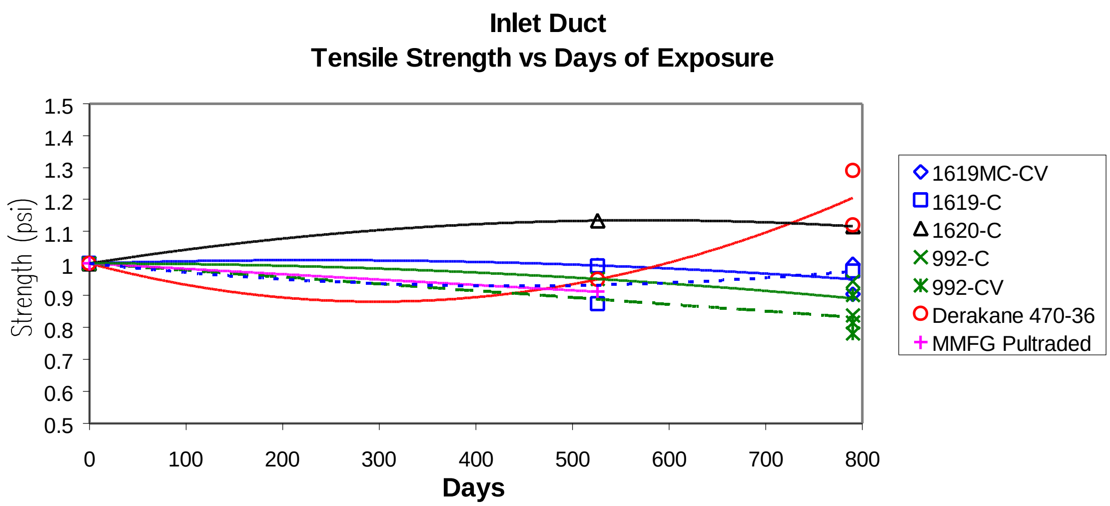


Figure 3-19. Changes in Tensile Strength of Different Materials in the Inlet Duct Area

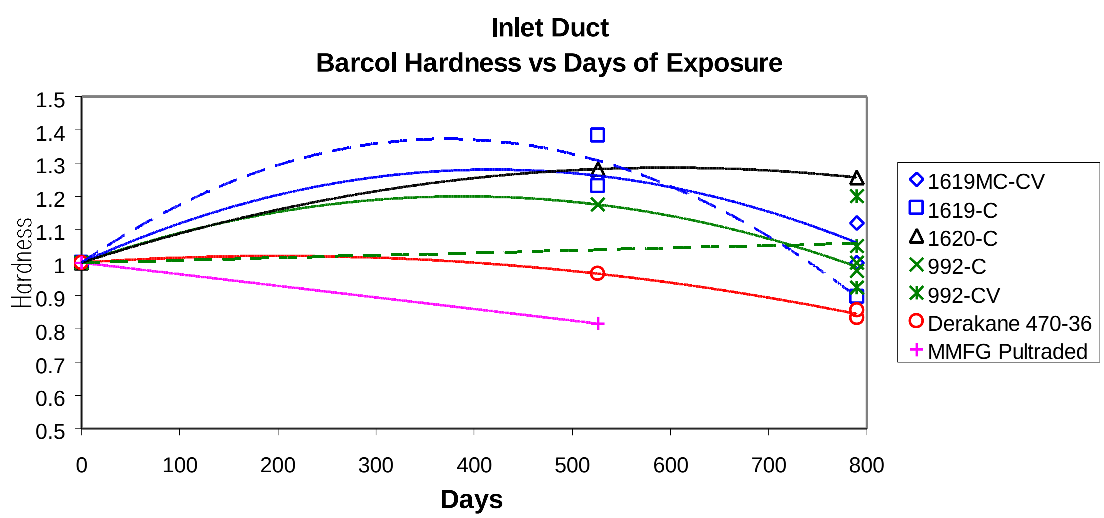


Figure 3-20. Changes in Hardness of Different Materials in the Inlet Duct Area

Plant Yates proved to be extremely successful in detecting major structural flaws in the limestone slurry storage vessel. AE tests detected major design faults in the LSST baffle supports and a major floor/side-wall delamination prior to equipment start-up. Had these equipment problems been left unnoticed, costly unanticipated downtimes with significant slurry spills could have resulted. The tests also confirmed that the existing SPI/CARP procedures may be too sensitive for testing tanks not intended for highly corrosive materials. A revised QC/QA strategy has been proposed which identifies the location of AE events (Cluster Analysis and the rate of change of activity on an individual AE channel (Knee Analysis)). The latter method flags growing faults by monitoring the rate of change of AE activity, as shown in Figures 3-10 and 3-21. It is believed that this method may be more appropriate candidate for applications to larger, more complex FRP vessels. These two techniques concentrate on detection of growing flaws and their location. Therefore, their results can be used as a corrective diagnostic tool and not a pass/fail quality control and acceptance criterion.

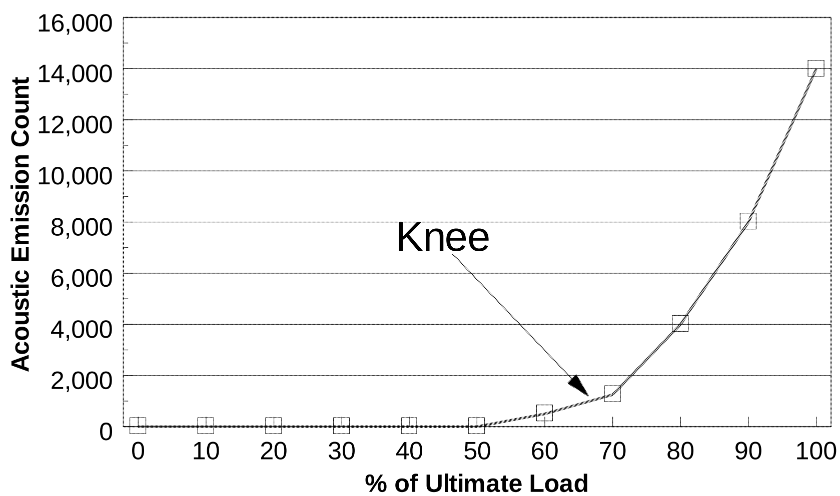


Figure 3-21. Knee Analysis Method for AE Diagnostics of Large FRP Vessels

3.4.2 Strain Gaging

Strain gage testing provided a reliable method for comparison of strain and stress levels and verification of engineering properties used in the design calculations. In general, the measured hoop stresses correlated well with the theoretical. Further, the test data in differ ent experiments trended similarly, although there appeared to be small differences in principal strain magnitudes and angles. On the other hand, the strain gage monitoring system was not successful in measuring time-dependent creep strains, particularly i n the presence of a varying load. The current state of instrumentation technology does not seem to support a cost -effective means of measuring these creep strains in real time. Therefore, the accuracy of strain gaging methodology as a QC/QA tool is hampered by the amount of creep strain experienced during the initial equipment startup.

3.4.3 Photostress

Photostress was primarily used to detect stress concentrations around manways and nozzles. This method was quite effective. Further, based on the co mparison of strain gage data and the photostress measurements shown in Figure 3 -22, photostress can be qualified as a reliable optical method of obtaining the strain state.

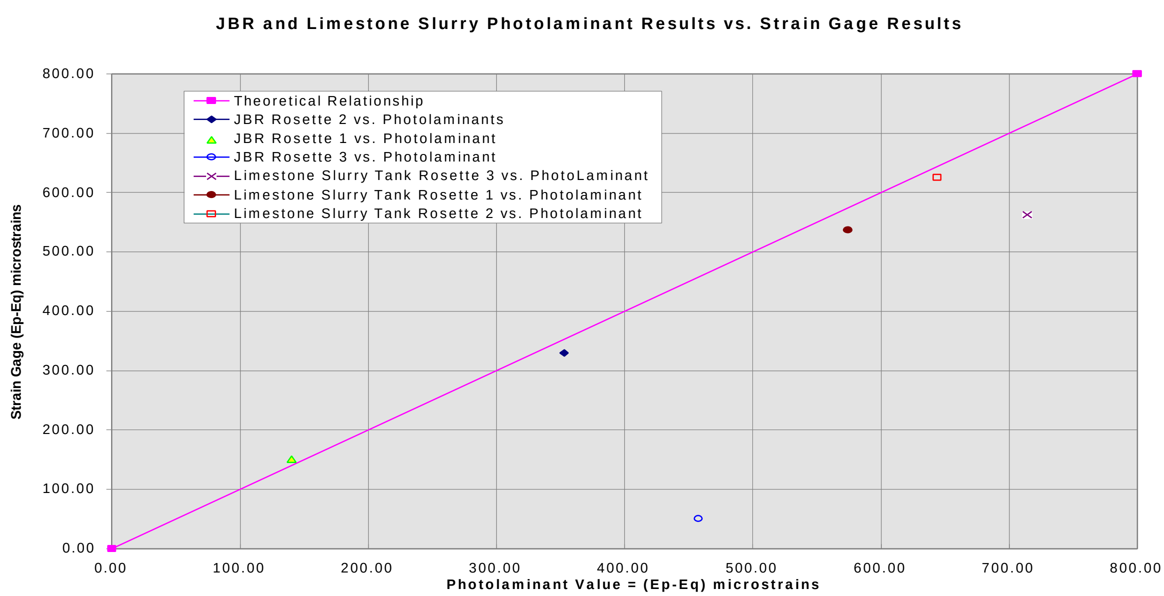


Figure 3-22. Accuracy of Photostress vs. Strain Gage Measurements

3.5 FRP Elbow Vibration Characterization

After the initial startup of the CT-121 scrubber facility at Plant Yates in October 1992, it was discovered that the FRP duct-drain piping and the attached elbow were experiencing visibly high levels of vibration. The vibration was a cause for concern since it could threaten the structural integrity and reliability of the FRP JBR and the nozzle/shell attachment. On October 19, 1992, personnel of Southern Company Services performed a series of tests to characterize the cause and magnitude of vibration. This investigation showed the cause of vibration to be the turbulent flow of the quenching slurry fluid into the down-comer piping. Using the vibration mode shape and amplitude data, the average dynamic bending stress in the nozzle/shell attachment was estimated to be 3190 psi. The dynamic strain on the vessel wall away from the attachment was measured to be approximately 30 microstrains peak-to-peak which does not pose any structural reliability concerns. However, the average dynamic stress in the nozzle/shell attachment is 30% higher than the desired design levels. Further, the estimated dynamic stress does not account for any stress intensification at stress-risers (notches, manufacturing defects, etc.). Therefore, to improve the structural reliability of the FRP assembly, it was recommended that additional structural support be added to the duct-drain piping and elbow assembly to reduce the piping vibration and the dynamic stress levels.

This recommendation was rejected by the project management team as the source of vibration was eliminated during the investigation. Thus, there was no further need for modification of the FRP elbow.

4.0 CONCLUSIONS

Composite materials provide significant benefits over traditional materials. However, due to the limited experience with composites such as FRP, construction with these materials is difficult to specify. As a general rule, however, FRP requires additional surveillance during the design, manufacturing, construction, operation, and maintenance of the subject structure. The FRP process equipment in the Plant Yates scrubber has been in operation for nearly four years. With the exception of the inlet duct abrasion, the FRP performance can be classified as very satisfactory. The following specific conclusions have also been reached:

- FRP is a suitable material for application to the CT-121 process.
- FRP is prone to abrasion in the areas of high velocity gradient and particulate concentration. In these areas, the FRP surface should be coated with an appropriate coating system, consistent with the nature of flow. The test results show that abrasion due to normal flow can be controlled by compliant coatings. On the other hand, coatings that had a large concentration of fillers worked better in areas of high shear.
- Strain gaging and acoustic emission testing can be effective and valuable tools for verifying the structural integrity of FRP vessels. Acoustic emission was proven successful in locating the structural faults associated with FRP construction and aging.
- Preliminary creep of the material during initial loading can lead to higher than anticipated strains. However, with time, the strain measurements should reach equilibrium and comply with theoretical expectations.
- The design standards for large FRP vessels need to be improved in order to increase product reliability. This can be accomplished by incorporating finite element analysis into the design process. Further, the existing acoustic emission standards appear to be too sensitive for application to large FRP vessels not used in highly corrosive environments. The “knee analysis” combined with “cluster analysis” was found to be a more practical approach for performing diagnostics and quality control experiments.
- Novel FRP construction may be available that could significantly reduce the cost of construction for large cylindrical FRP structures. These construction methods need to be proven under a controlled research environment if they are to be recommended for future CT-121 installations.

- Design requirements for FRP structures are not widely controlled as traditional construction materials. Since FRP laminates are constructed as a series of many layers of resins, fiberglass, and coatings, the quality assurance of the raw materials and bonding procedures, and curing have many variables.
- The construction of two identically designed vessels, if constructed at different times or by different construction personnel, could potentially have a much different quality of workmanship. In summary, quality assurance requirements are much more important for a FRP material than a traditional material of construction.
- FRP does not have the application experience in massive structures as does steel and concrete structures. Aerospace and automotive industry design personnel have a much more extensive experience base in the use of composite plastic materials. Lack of confidence and knowledge in the use of a material is a self-perpetuating problem which prevents quick acceptance of a new material.
- Specifications should be written to include the evaluation of the material and performance of the constructed component. Specifications for a product to be constructed of FRP require an extreme effort on the part of the specifying engineer. Not only do the materials have be tightly specified, but also the construction of the component and the performance requirements for the completed system should also be mandated. This requires a tremendous investment on the part of the owner to enter into a proposal in which the terms of the specification may be very controversial.
- Finally, the use of FRP as an engineering material has many aspects that require a more deliberate effort on the part of the owner, the engineer, and the construction party. In certain cases, as is demonstrated by the environment required to construct and operate wet SO_2 scrubbers, only very expensive alternative materials to FRP are acceptable. In these types of applications, the FRP material has tremendous promise.

In the final analysis, the FRP vessel used at Georgia Power Plant Yates for the Chiyoda Wet Scrubber has demonstrated its merit as a viable alternative material for full-scale scrubber vessels. Additional strain testing and research is ongoing throughout the engineering community, to make FRP structures viable, trustworthy materials, that can be used without hesitation by design engineers.

5.0 RECOMMENDATIONS

5.1 Design Standard Improvements

The investigation performed prior to the system startup showed that finite element analysis is a prudent and cost-effective method of optimizing the structural design of JBR. Therefore, in future designs of Chiyoda CT-121 systems, it is recommended that finite element analysis be used to verify the following parameters:

- Lower and upper deck stress and the deflection fields due to the applied structural and thermal loads;
- Operating deflection mode and stresses in the internal support structures and joints due to applied loads and thermal growth/temperature gradients;
- Operating stresses and deflection fields in the vessel wall resulting from the applied load and temperature gradients;
- Maximum operating stresses and deflections during cold startups; and
- Maximum stresses and deflections during thermal transients.

It is recommended that the material properties for a proposed laminate be computed by rational engineering methods. Currently, there does not appear to be an engineering standard that has been adopted as a legal basis for an FRP design. Continued monitoring of industry working groups within the area of composites and FRP design is advisable. Also, the use of finite element analysis provides many useful capabilities including good visual methods of quickly determining critical stress locations on or in composite vessels and structures, design optimization of cross sections, and quick loading simulations.

5.2 Construction Methodology

It is recommended that, in future construction of CT -121 FRP vessels, quality assurance requirements be specified such that controls during the fabrication of the FRP are documented as much as possible, and that the materials and material properties are tested according to at a minimum ASTM D3039-76. Further, it is recommended that hand layup details be documented to determine and monitor on-line the quality of workmanship and any concerns during the actual construction. This documentation would include environmental conditions such as weather, resin mix designs, mixing times, and quality assurance testing of field connections, to try and determine the workmanship concerns during the actual construction.

FRP was also found to be prone to abrasion in the areas of high velocity gradient and particulate concentration. In these areas, the FRP surface should be coated with an appropriate coating system, consistent with the nature of flow. The test results show that abrasion due to normal flow can be controlled by compliant coatings. On the other hand, coatings that had a large concentration of fillers worked better in areas of high shear.

Furthermore, novel FRP construction may be available that could significantly reduce the cost of construction for large cylindrical FRP structures. These construction methods need to be proven under a controlled research environment if they are to be recommended for future CT-121 installations.

5.3 Testing & Structural Monitoring

AE was found to be a valuable diagnostic tool for detecting major structural flaws and incipient failures. The pre-operation test results from the Plant Yates scrubber project has also shown strain gauge monitoring and acoustic emission tests to be valuable tools in verifying the FRP design assumptions and detecting significant structural damage and/or incipient failures. However, the existing AE criteria for acceptance of FRP vessels do not appear to adequately characterize the relaxation characteristics of FRP vessels. This deficiency needs to be resolved if

AE is to be accepted as a QC/QA standard in future CT -121 FGD systems. The following recommendations need to be considered in future CT-121 FRP structures:

- The testing on fiber-reinforced plastics becomes much more important due to the additional uncertainties and requirements induced by the non-isotropic nature of the composite laminate;
- As a trending tool, strain testing provides a way of quantifying the behavior of the vessel over time. As such, a monitoring program of every five years may be advisable. Also, as more and more test data are collected, the trend interval could be expanded or reduced based on the results of the testing.

Finally, there are new instrumentation technologies, involving the embedding of continuous fiber optic tendons inside composite materials, which have the potential for providing either a global or local sensor for strain monitoring.

5.4 Maintenance Frequency

For operations and maintenance, it is recommended that a computer log of repairs, replacements, painting, cleaning, etc. be developed and made available to maintenance and engineering personnel. This log should also include excursions from normal operating conditions that could impede the integrity of FRP components in specific areas. Further, the loading history of the vessel would be important for determination of significant cycling of the loading on the structure.

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