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AN APPROACH TO IMPROVING FRP EQUIPMENT RELIABILITY

by

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INTRODUCTION

An important and widely used material of construction in chem-
ical plants is fiberglass reinforced plastics - FRP for short.
This material, which became available for use in our industry
in the 1950's, is made up of glass fibers bound together by a
thermosetting resin which combines to provide strength, light
weight and chemical resistance. The finished product, there-
fore, provides an inexpensive alternative to high cost metals
in construction. These materials of construction are, however,
brittle and do not withstand impact blows as well as their
metal counterparts.

Because of the lack of familiarity with FRP and because it pro-
vided an inexpensive material of construction, this equipment
was used in some applications where it was not well suited.
Safety problems and concerns began to surface and the reputa-
tion of the material suffered. For example, it was difficult
to examine an FRP tank to determine that a weakness or a leak
or some failure from stress was imminent. As a result, fail-
ures occurred followed by accidents and injuries.

The purpose of my presentation today is to review a program
that you may follow to employ the use of FRP equipment that
will permit the welcomed economics as well as protect the occu-
pational safety and health of our employees. I will also re-
view specifically an innovative technique employing acoustic
emissions that we have developed at Monsanto that will allow
you to examine your FRP tank and determine if there are
stresses, strains, weaknesses or cracks - not easily determined
by conventional inspection - so that you may reestablish your
confidence in this type of equipment relative to its ability to
protect the safety and health of our employees as well as prof-
its of our companies.

SUMMARY OF APPROACH

We very quickly found that the key to reliable FRP equipment was <u>attention to detail</u>. All too often this equipment was considered a cheap substitute for metallic equipment and had been treated in a casual manner. Such a casual approach to FRP equipment is guaranteed to fail more often than not.

A concerted program directing attention to all factors which affect performance is necessary. This paper will address five distinct steps to our approach:

1. Materials selection
2. Structural design
3. Procurement
4. Installation
5. Maintenance and repair

It requires the coordinated efforts of many people to assure that proper attention is given to the many details involved in each step. However, we firmly believe that in appropriate applications FRP equipment which is properly designed, fabricated, installed, maintained and repaired can provide years of effective trouble-free service. For those applications where FRP is the preferred material of construction we believe this effort to be a good investment.

MATERIALS SELECTION

Why select FRP for chemical equipment? Like many materials, FRP has advantages and disadvantages. The most significant advantage is its excellent resistance to many chemicals which would otherwise require expensive metals. A common example is a solution of acid with some chloride ion which would require at least a nickel alloy in metal construction. Other advantages are light weight, repairability, economy. Major disadvantages are brittleness - cannot withstand local loads or impacts - and unfamiliarity with the technology of FRP by plant personnel.

The choice of FRP for use in a specific item of chemical plant equipment should be the result of a thorough analysis, such as that outlined in Table 1 - Guide for Materials Selection (FRP). A similar approach is recommended in our organization for all material selection [1], but it is especially important for FRP where subtle variations in service conditions can have a major influence on equipment performance. It may be helpful to identify some of the key points in this guide and to discuss their implications regarding FRP equipment.

Chemical Compatibility

Obviously, if FRP is not resistant to the major chemicals in the application at hand, it would not be considered. It is the more subtle situations which cause problems. For example,

several years ago Monsanto had an unexpected problem with a process fluid to which the resin used would normally be resistant. However, there was a solvent in this fluid at so small a concentration that its presence had not been reported, but this level was enough to rapidly deteriorate the equipment. Although the solvent concentration was low, it selectively diffused into the resin and degraded it. If there is any question at all about the compatibility of specific resins with the environment, they should be tested. We will discuss testing procedures a bit later.

With regard to resin selection and specification, Mallinson [2] makes an observation worth repeating: "It is most important the phrase 'or equal' be stricken from your laminate vocabulary. There is such a great difference in resin systems and their capabilities under varying conditions, particularly to trace contaminants, that unless you have done your homework well and tested all of the possibilities the only system through which success is assured is the one that has produced satisfactory results in your test program." In the past two years we have had at least two failures of equipment which were the direct result of the use of a different but "equivalent" resin system. Also, in at least some applications, change in catalysts or addition of a thixotropic agent to the resin can have a significant effect on performance [3]. We recommend that for any but the most innocuous system, the only resin systems considered be those which have been tested.

Temperature

Compared with other materials, the effective temperature range for FRP is rather narrow; thus it is necessary to precisely define the temperature range that can be expected, especially the upper limit. Since thermal shock can also present problems, the expected rate of temperature change should also be identified. These temperature estimates should be as realistic as possible. Fiddes [4] cites an example where the operating temperature was actually 200°F. However, the person initiating the request gave himself a 10°F cushion and a second individual added another 10°F for safety, making it 220°F. After others had looked at it, the request went out specifying that the material must withstand 240°F. If this had been a metallic design, this change would have had little consequence. However, many of the corrosion resistant resins suitable for 200°F service are not suitable at 240°F. The best resin candidate may have been excluded.

Pressure/Vacuum

Most FRP equipment is designed to operate near atmospheric pressure. With proper design, it can be used for both pressure and vacuum service, but these are special applications and should receive the attention of specialists. Also, in many circumstances, code restrictions make it impractical to design a one-of-a-kind pressure vessel from FRP. This topic will be discussed in more detail in the design section.

Site Environment

The safety aspects of the plant site environment can have a significant influence on materials selection. In a location where occasional acid fumes result in maintenance problems with steel, or where hot chloride vapors might pit or crack stainless steel, FRP may be especially attractive. On the other hand, in a situation where fire is a major concern, the FRP alternative may be eliminated. Suffice it to say, the exterior environment needs to be considered as well as process requirements.

Physical Requirements

If FRP is deemed to be resistant to the process and environmental conditions, it is necessary to make a judgment as to whether FRP can be fabricated into the desired shape with the required quality and integrity. If there are requirements for extensive agitation or heat transfer, the FRP alternative may be less attractive. However, I am aware of a situation where both severe agitation and heat transfer were required, yet FRP was a very attractive alternative. Each application must be evaluated on its own merit.

External Constraints

Constraints external to the process such as codes, company standards or regulations, government regulations, and specific safety requirements must be considered as part of the materials selection. These factors will, at times, require the selection of other materials even though FRP would be adequate from a purely technical standpoint.

Consequence of Failure

Another factor to be considered is the consequence of a failure at the workplace. We know that FRP is more fragile than some metallic equipment. Consequently we have to take into consideration the effect that its failure could have on personnel and other equipment and on the ability of the remainder of the plant to continue to operate if such a failure occurred.

Maintenance/Repair

Another factor which should influence the selection of FRP equipment is the prospect of the equipment being properly maintained and effectively repaired. Not all plants are equally capable. For example, in one of our plants an FRP tank containing warm water developed a leak around the joint between the side wall and the bottom dished head. This leak was ignored and eventually the bottom head fell off. In other locations this equipment would have been repaired when the leak first became evident and there would have been little problem.

FRP repair is generally not difficult if it is done early enough. Obviously, it does require experienced and knowledge-able repair personnel who have appropriate procedures and materials.

In some cases it is not feasible to repair FRP after chemicals have permeated into the resin. This is a concern whenever the contents are highly toxic and where exposure of the repair technicians to the chemical residue in the resin would present a severe hazard. Fortunately, these cases are uncommon.

Economic Evaluation

If the analysis indicates that FRP <u>can</u> be used safely, we are then faced with the question of whether it <u>should</u> be selected. This decision can usually be made largely on economic consider-ations, but note that the <u>total</u> cost of each alternative should be considered, not just the purchase price. It has been our experience that the purchase price of FRP equipment may be small compared with some of the other costs listed in Table 1. In general, FRP equipment should be used only in those situa-tions which are most appropriate considering plant safety and operating requirements. It generally should not be used in those situations where its only advantage is that of incremen-tally lower purchase price of the equipment alone. In most chemical plant applications, other costs are greater for FRP than they are for some other conventional materials of con-struction because of the required attention to detail.

Chemical Compatibility Tests

If your analysis indicates that FRP is an appropriate material of construction, but you have no specific experience with the particular chemical environment -- test! These tests generally need to be of long duration. While rapid attack is easy to spot, slow attack or property loss is difficult to detect. If possible, tests should be conducted for six months or longer.

The results of chemical exposure tests are difficult to eval-uate because a number of somewhat subjective criteria are involved. These include:

1.   Weight change - Weight changes may result from absorption of liquids, production of corrosion products, bleaching of resins, fiber deterioration, or a combination of these factors. Large weight changes, either positive or nega-tive, are undesirable. However, low weight change by itself is not sufficient indication of chemical resist-ance.

2.   Dimensional change - Minor swelling or shrinkage is generally not reason for rejection, provided such dimensional changes will not adversely affect the

performance of the equipment. More swelling could be tolerated in a tank wall than in the volute of a pump or in a valve.

3.   Surface appearance - Charring, chalking, blistering, cracking, and crazing usually result in weakened structure and are indications that the resin is not suitable. Color changes generally indicate some interaction of the plastic and the environment, however it does not necessarily follow that these color changes prohibit the use of the chemical.

4.   Hardness change - Softening or hardening of a resin system may or may not be evidence of prohibited attack. Large changes in hardness should be considered warning signals and other evidence of degradation should be examined. (Low hardness of a new FRP laminate is an indication that the polymerization reaction is incomplete.)

5.   Change in strength properties - Of all the criteria, this is probably the most meaningful. Studies have disclosed that changes in flexural strength, flexural modulus, and tensile strength are the best criteria for evaluating the chemical resistance of glass fiber reinforced plastics.

There are no hard and fast criteria for pass-fail changes in properties. The National Association of Corrosion Engineers [12] has set forth criteria which are reproduced in Figure 1.

These are reasonable, but not absolute criteria. The shape of the property retention vs. time curve is also important. If the data suggest a leveling off of properties with time, we can proceed with more confidence than if the relation is linear (or accelerating!). Obviously, when more than one resin is tested we usually select the one with the highest overall properties retention.

If the preliminary evaluation and subsequent tests show FRP (specific resin) to be the material of choice, we then face the task of translating this selection into a piece of reliable equipment.

STRUCTURAL DESIGN

Methods of structural design of FRP equipment are determined by its properties. FRP is brittle, it creeps, its properties degrade somewhat with time, and it is an isotropic. The first three of these dictate a thorough, cautious approach to design. Anisotropy complicates design, but it can be an advantage. Properly designed FRP equipment should be thicker-walled than corresponding metal equipment, but there should be other differences as well.

Beer cans and bottles illustrate the way material properties
influence good design (Figure 2). The cans and bottles have
the same function but very different shapes. Both hold pres-
sure and need slightly domed ends; but, because glass is weaker
than steel, the bottle's dome is deeper. Steel is ductile, so
it can have sharp corners at the crimped joint between the ends
and sides. Glass is brittle, so the bottom-side juncture must
not have sharp, re-entrant corners, and it is molded, not
crimped. Differences in strength and ductility dictate a radi-
cal difference in geometry. Traditional ways of designing
metal equipment, if applied blindly to FRP, will result in
vessels that resemble thick-walled steel equipment. In many
cases, this is not appropriate.

Because failures have occurred when the material property
differences between FRP and metal were ignored, a specific
design approach which avoids this kind of failure is described
below.

Some FRP properties which influence the design of FRP equipment
compared to the design for metal equipment are:

1.   Lack of definitive creep data

2.   Lack of definitive fatigue data

3.   Lack of ductility

4.   Anisotropy of properties, particularly when filament
     winding or woven roving is used in fabrication.

Design Criteria

Historically, safety factors for FRP have been conservative to
account for material variability, long term creep which has
been difficult to predict, and assumptions in applying design
formulas. Safety factors used [5] have been 10 for vertical
tanks and pipe. This factor compares to 3 or 4 for metal
equipment where properties are better known and material vari-
ability is less.

Recently a brief analysis of the major factors which could
effectively lower the 10 safety factor revealed that the long
term creep of FRP laminates is a major factor. There is little
published data but results of acoustic emission tests at
Monsanto tend to support an effective reduction of 50 to 70%
for creep strength compared to short term ultimate tensile
strength. This would reduce the safety factor to 3 to 5, about
the same as for metal vessels made to the API or ASME codes.

Thus, where stress is an appropriate design criterion, the
allowable working stress is one tenth the ultimate strength of
a given laminate. In filament wound equipment, an allowable

strain design is often used [6]. The maximum allowed strain is ordinarily 0.001 on the basis that ultimate elongation is about 1% or 0.01 and some permanent damage is believed to start at about 0.003 strain.

Hand lay-up or spray-up laminates are approximately isotropic in the plane of the laminate, so a stress criterion for design is appropriate. The allowable stress is obtained from the ultimate strength by equation (1):

$$\sigma_{allow} = \frac{1}{10} \frac{\sigma_{ult}}{F_s} \tag{1}$$

where the safety factor is 10 and F_s is a modifying factor which accounts for high operating temperatures. This factor can be obtained from manufacturer's data. Another way of obtaining F_s is given in the British standard [7]. Let T be the operating temperature and D be the heat distortion temperature, both in °C. If D − T is greater than 40°C, F_s = 1.0. If D − T is less than 20°C, do not use the resin at temperature T. If 20 < (D − T) < 40,

$$F_s = 1.5 - 0.0125 \ (D - T) \tag{2}$$

Thus, when D − T = 20°C, F_s = 1.25, which is its maximum allowed value. Equations (1) and (2) determine the allowable stress. Figure 3 is a graph of this rule.

In general, each point on the vessel shell is in biaxial stress. Therefore some criterion for relating the biaxial stress components to the allowable stress is required. We suggest the following: Let σ_1 and σ_2 be the principal stresses at the point in question. Then the stresses are acceptable at a point if

$$\text{Max} \ \{ \ |\sigma_1|, \ |\sigma_1 - \sigma_2|, \ |\sigma_2| \ \} \leq \sigma_{allow} \tag{3}$$

Equation (3) is the Tresca criterion. Note that Equation (3) applies to every point on the vessel, and that σ_1 and σ_2 include both bending and membrane stresses.

A similar criterion can be stated for strain. Let ε_1 and ε_2 be the principal strains at a point. Then

$$\text{Max} \ \{ \ |\varepsilon_1|, \ |\varepsilon_2| \ \} \leq 0.001 \tag{4}$$

Figure 4 is a graph of the two criteria where $\sigma_{allowable}$ = 700 psi, the modulus is 600,000 psi, and Poisson's ratio is 0.3. Note that they do not agree for uniaxial stress, but under these conditions there is little practical difference between them. Points inside one of the contours satisfy the criterion corresponding to that contour. However, because of temperature effects the relative size of the contours can change, thus making one or the other criterion governing.

Because modulus falls off differently with temperature than strength, a strain criterion may govern at high temperature even though the strength criterion governs at a lower temperature.

Figure 5 is a graph of F_m, a modulus correction factor, for a "Flexiblized" resin. It is obtained by dividing the modulus at 22.8°C (73°F) with the modulus at elevated temperatures and plotting the result vs. temperature. Thus, the modulus at the operating temperature is

$$E = E_{22.8°C}/F_m \tag{5}$$

For example, the heat distortion temperature of the resin is 96°C so that, according to the strength rule, its maximum use temperature is 76°C. At 76°C (170°F), then $F_s = 1.25$ and $F_m = 1.7$. For other resins, the strength factor can be greater than the modulus factor at an elevated temperature. It is seen that the strength and strain criteria are independent.

An advantage to this approach to design criteria is that it limits stress and strain in FRP equipment without forcing any particular design geometry. Its successful application depends on accurate, thorough stress analysis.

For filament wound materials only the strain criterion applies because wound laminates are not isotropic. The strength of such laminates varies with the orientation of the glass fibers. Information for forming a direction-dependent strength criterion is lacking but modulus vs. direction is predictable and known. Thus, the strain in each direction at every point in the shell can be calculated and the strain criterion applied.

Design Approach

There are three parts to our method:

1. Identify and quantify the most severe combinations of load.

2. Calculate in detail the stresses and strains for each combination.

3. Compare the calculated stresses and/or strains to allowable levels using Equations (3) and (4) above.

The approach above could be used to formulate a design standard. Parts 1 and 3 above are pivotal. In a standard, part 1 would be a format by which a purchaser could transmit his precise requirements to the builder. There is no organized, nationally accepted way of doing this now. Part 3 concerns the performance of laminates. Each of the common laminates could have a nominal strength. Temperature factors for each resin can be supplied by resin manufacturers. Engineering theory already exists for doing Part 2. A disadvantage to this

method is that it requires more engineering time than methods
based on membrane analysis only. Once agreement on Parts 1 and
3 is reached, simple design rules for common configurations can
be devised, but trying to define rules without first completing
agreement on Parts 1 and 3 is premature.

PROCUREMENT

Specifications

Prior to ordering a piece of FRP equipment it is necessary to
establish specific and unambiguous specifications. It is
difficult to overemphasize the value of good specifications.
Properly prepared, these specifications provide an unambiguous
communication between the purchaser and the fabricator regard-
ing what is required. Properly prepared and enforced specifi-
cations ensure the purchaser that he obtains the equipment he
needs. These specifications also help the fabricator by defin-
ing precisely what it is he is bidding on and what it is he is
expected to make. The less he has to guess about the pur-
chaser's desires the better he is able to satisfy them. There
are a number of FRP fabricators who sincerely desire to produce
high quality equipment fully meeting the customer's needs as
they understand them. The better that understanding, the more
likely the customer is to be satisfied.

NBS PS 15-69 [5] is a well accepted industry standard and is a
good place to start with hand lay-up designs. However, it is
by no means complete; Mallinson [2] commented in 1975 "If you
want a real education simply specify PS 15-69 and nothing else
from a garage shop operator and you will learn how PS 15-69 can
be circumvented." Similar comments could be made for ASTM
Standard D-3299-74 for filament wound designs.

In light of this observation, supplemental standards should be
prepared. As a minimum, this supplemental specification should
include:

1.   Resin or resins permitted.

2.   Reinforcement combinations permitted or excluded.

3.   Design details for nozzles, gusseting.

4.   Quality/workmanship specifications on permitted inclu-
      sions, dry spots, air bubbles, pin holes, pimples, and
      delaminations.

5.   Specific test(s) required to prove the qualty of the
      finished product.

6.   Shipping instructions.

7.   Records and reports required.

We also find it to be desirable to either perform the structural design ourselves or to provide for detailed design review and approval.

For the specification to be most useful, it should define the minimum acceptable quality. There has been a tendency to specify the ultimate quality obtainable and then, for each order, negotiate the acceptance or rejection of the equipment. This puts the fabricator in the uncomfortable position of having to guess what the purchaser is really willing to accept. Remember, the fabricator is in a very competitive business; if he guesses wrong and incorporates more quality (and higher cost) into the bid than do others, he will probably not get the job. We recommend use of specifications which define the minimum acceptable standards, and then strive to achieve this quality on all units.

This sounds simple and straightforward, but in practice it is proving to be very difficult. Let me elaborate. Several years ago we revised our FRP equipment standards with the thought of creating this minimum acceptance standard. Not being fabrication experts, we sent draft copies to a large number of fabricators asking for their comments and suggestions. We received a number of helpful comments which were incorporated into the specifications. The revised draft was circulated again and this version met with essentially no negative comments. The fabricators assured us that they could meet both the letter and intent of this specification.

This was fine until equipment that was ordered to this specification was found to be significantly deficient with respect to workmanship--specifically air bubble inclusions. When the fabricator found that we intended to reject the equipment for failure to meet this specification, he was appalled. This specification suddenly became "the most arbitrary and unreasonable" specification he had ever heard of. When asked why he had not made that comment earlier he responded "but we didn't believe you really intended to enforce this specification". Further experience led us to conclude most of the fabricators we had contacted had taken the same position, and in fact none of them could meet this specification requirement. We have since revised the specification in line with what the fabricators now say they can do. Time will tell if we have effectively communicated this time around.

It should be noted that there is currently in progress a program jointly sponsored by the Society of the Plastics Industry (SPI) and the Materials Technology Institute (MTI) to develop standards which will improve communications between purchaser

and supplier. In general, we feel there is less likely to be confusion if we can all use an industry-wide standard than with the present system of separate standards from each purchaser.

Fabricator Selection

Chemical plant equipment is a relatively small specialty within the reinforced plastics industry. Standards, designs and materials which are adequate for boats, for example, are not suitable for this specialty. It is unlikely that reliable chemical equipment will be produced in the same shop with the same workers who produce this other equipment. It is our experience that the likelihood of receiving good equipment is much improved if you work with fabricators who specialize in producing chemical plant equipment.

Far too often the scenario described by Brown [9] is the case:

> "Some hungry boat manufacturer hears about the price chemical companies are paying for tanks or duct or pipe made up of polyester resin, and he persuades the purchasing department that he knows all there is to know about this kind of manufacture. He shows the purchasing agent all kinds of pictures of fancy boats and says, 'Look, if I can give this kind of work just think what beautiful tanks I'll make you.' Well it turns out he doesn't know...about corrosion resistant resins, he has never heard of PS 15-69 and wouldn't understand it if he had it. So, what is the result? Well, he has the lowest bid, purchasing buys the vessel, it comes in, it's not right, it has to be reworked, and by the time it's put into place it ends up costing more than if purchasing had bought it from a reliable manufacturer. But unfor- tunately, this is not the end of this story. It probably failed because it was not properly built and then everybody stands around saying, 'That blankey blank fiberglass equipment is no good,' and 'We don't want any more of it in this plant'. It is obvious this is not the way things should be and is not in the best interest of the chemical process industry. Properly built FRP equipment can do the job and save a lot of money."

In our own case, it is inappropriate to place all the blame on the purchasing agent; he had a lot of help from others!

We, as purchasers of FRP equipment, have contributed to the present lack of consistent quality in the industry. Taken as a group, we have systematically purchased equipment with inade- quate specifications, and have consequently gone to the low bidder. The fabricator with high technology and high quality standards has been at a competitive disadvantage because, let's face it, this technology and quality does cost

money. Therefore, the high quality fabricator has either gone
out of business or has adapted and has learned to produce
equipment of lower quality in order to survive.

One of our major challenges is to convince those fabricators
still in the business who are capable of producing high quality
equipment that we are now serious about buying to quality stan-
dards and are willing to pay a fair price for this equipment.
We must stop looking at FRP as a low cost substitute for other
materials and begin to think of it as an engineering material
with unique properties. We should concentrate on using it
where these unique properties are especially advantageous, and
not primarily in places where it might work at lower cost.

Inspection

Having selected a competent fabricator and having assured your-
self that the requirements are known, it is still desirable to
inspect the equipment while fabrication is in progress. If
problems or misunderstandings are detected early in the fabri-
cation process, for example before the components are assem-
bled, they can be corrected at minimum expense to all parties.
Conversely, if the first inspection is a final inspection of
the completed fabrication, there is very little opportunity to
overcome any misunderstanding. It is most helpful if the fab-
ricator has an effective quality assurance program such as de-
scribed by Bernhoft, et al. [10]. In such cases the probabil-
ity of missed communication is much reduced.

Final inspection is the last line of defense to avoid instal-
ling an inadequate piece of equipment. If the unit has been
properly designed and fabricated, there should be no major
problem uncovered at final inspection. Conversely, if inade-
quate attention has been given to any of the factors affecting
equipment reliability, it may be too late to correct them at
the time of final inspection. Remember, you cannot "inspect
in" quality.

The inspection should include as a minimum conformance to de-
sign, proper cure, as indicated by Barcol hardness within the
specified limits, and quality of workmanship [2]. On occasion
we also analyze the nozzle cutouts to confirm that the specific
resin was used. If proper in-process inspection was conducted
there should be no surprises at the final inspection.

Acoustic Emission Testing

A recent innovation has been the use of acoustic emission tests
[11]. This method shows considerable promise as a nondestruc-
tive test to detect structural defects which would eventually
cause failure and create unsafe workplace conditions.

Acoustic emission is accomplihsed by placing acoustic sensors
on the surface of the tank (see Figures 6 and 7) and then
stressing the equipment usually by filling the tank with water
or process fluid. This hydrostatic stress causes structural
defects to grow and thereby emit stress waves. Such defects
could be delaminations, cracks, debonding, etc. The sound
energy is picked up by the sensors and analyzed and displayed
by the electronic equipment. By comparing the results to
acceptance criteria developed from experience we can determine
whether the equipment is structurally sound. Equipment should
also be inspected by other techniques such as visual, hardness
measurement, dimensional, etc. Visual inspection can identify
the defects found from acoustic emission and, if repairable,
they can be repaired and retested using acoustic emission.

It is envisioned that FRP structures will be monitored during
proof load tests during final inspection and at selected inter-
vals thereafter. To date we have used this inspection tech-
nique with new vessels and vessels which had seen varying
amounts of service. The results of these tests are summarized
in Table 2 which shows that AE has identified a large number of
unsafe equipment items before failure. In those cases where
structural deficiencies have been indicated, we have had very
good success in subsequently identifying the defect causing the
problem. Thus, we have become confident of the capability of
acoustic emission to detect structural deficiencies and believe
that it will become a standard method for nondestructive test-
ing of FRP equipment.

INSTALLATION

Equipment damage during installation is frequently cited as a
major cause of failure [2, 4, 9]. This damage may be obvious,
such as a broken flange or nozzle, or it may be subtle as in a
star craze resulting from an impact or mishandling. Although
field repairs of obvious damage are frequently less reliable
than the original fabrication, they may not be as serious as
the subtle cracking of the corrosion resistant barrier which
can go undetected until severe chemical damage has occurred.

It is important that the unique characteristics of FRP equip-
ment be well understood by the construction crew and their
supervision. Brown [9] comments that by several orders of mag-
nitude, more flanges are broken during installation than by any
other causes. Pipe fitters who work with steel are accustomed
to pulling up the lines to flanges by brute force if they don't
fit perfectly. With steel, the pipe yields slightly and no
damage is done. This is not the case with FRP. This material
does not yield and the usual result is that the nozzle or
flange breaks. In like manner, riggers and pipe fitters use
metallic nozzles as steps; this can result in damage to FRP
nozzles.

It is not our intention to provide an encyclopedic list of con-
struction rules, most of which are applied common sense based
on an understanding of the brittle, viscoelastic properties of
FRP described previously. Rather than to provide such a list,
which can never cover all situations, it is probably more
effective to train construction supervision and workers so they
become sensitive to situations which can cause point loads (for
example, impacts and inadequate support of flat bottom tanks)
or creep damage (for example, failure to independently support
valves, pumps, and agitators).

MAINTENANCE AND REPAIR

Inspection

The key to effective maintenance of FRP equipment is early
detection of defects and appropriate repair. This can be
accomplished only by an organized inspection program which
should include all equipment in the plant. Too often equipment
has been ignored for one reason or another and sudden failure
has occurred. An inspection program would have detected prog-
ressive deterioration and could have avoided sudden catas-
trophic failure.

At Monsanto we have experienced two serious catastrophic FRP
failures which luckily resulted in no more than minor in-
juries. One was the hot water tank mentioned above which
leaked for some months before the bottom separated, spilling
hot water and scalding the foot of one employee. The other was
a large weak hydrochloric acid tank which had not been inspec-
ted for seven years. A "minor" quantity of organic material
was known to be present. What was not known was that the
organic content exceeded the expected amount and organics
separated out, floating on the weak acid. Over a period of
time the organic attacked and deteriorated most of the tank
wall. Finally, on a cycle when the tank was full, the wall
gave way spilling over 25,000 gallons of liquid. The acid was
weak enough to cause no harm when washed off within a reason-
able time, but the wall of liquid dashed operating personnel
around causing minor injuries. Again, only fantastic luck
avoided more serious injuries. These two examples helped us to
enforce a tank/vessel inspection policy applicable to all our
plants.

Although inspection should be applied to all equipment, tanks
and vessels were specifically targeted because of the larger
amount of material contained and the greater potential for harm
or damage. This inspection program was for tanks of any mater-
ial including FRP.

The degree and frequency of inspection depends on many factors
including:

1. The nature of the contained material. The potential for harm or damage is greater with toxic, flammable, or hot materials, and tanks containing these materials would be inspected more frequently and in more detail.

2. The amount of contained material. A small tank normally has less potential for harm or damage than a large tank.

3. Location in the plant. If the tank is near personnel or other critical equipment, then it should be inspected more frequently and more extensively.

An inspection is no better than the knowledge and capability of the inspector and the appropriateness and quality of his inspection equipment. The quality of inspection is normally not a major problem at larger plants where trained inspectors and the necessary inspection equipment is available and maintained and calibrated. At small plants an inspection function may not be defined; assistance is available to these plants. Unfortunately the small plants may not recognize when assistance is required. This problem is a continuing one which has not been completely solved yet.

Training of inspectors is a serious problem, also not completely solved. Internal courses in inspection techniques certainly help, but experience is by far the best teacher. How to establish this experience at all our plants is a question not yet satisfactorily answered.

For FRP equipment most problems, at least early in the life of a piece of equipment, are associated with secondary joints, that is, where previously formed and cured components are joined together. Examples are head to shell joints, and nozzle attachments. In most cases these defects can be repaired if they are detected before extensive damage has occurred to the surrounding material.

As shown above and in Table 2, acoustic emission (AE) testing appears to be an extremely useful tool for early detection of damage. If a unit is AE tested again after istallation is complete, it is probable that any significant damage from shipping, handling and installation will be detected. Subsequent periodic tests will detect damage or deterioration of structural integrity resulting from service. One advantage of this test is that it can be conducted with process fluids; therefore, the unit needs to be out of service for inspection only a few hours. Results to date with this tool have been very encouraging, as noted above, and have insured continued safe operation of equipment.

At this point we are not ready to rely exclusively on AE testing for our evaluation of vessel condition. Periodic internal examination by a qualified inspector is still recommended, even

in the absence of AE indications. Obviously, internal inspection is called for if the AE test indicated damage has occurred.

Repair

When repair is required, a very important factor is the experience and expertise of the repair crew. Repair of FRP equipment results in another secondary bond at best; these bonds are weak links in the structure. Therefore the quality of the repair work is critical. It is no more appropriate to have an unskilled worker repair an FRP tank than it is to have him weld a stainless steel tank. The chances of success are poor in both cases.

It may be practical to remove the equipment and return it to a fabricator's shop. There the repair personnel are the most experienced, all the necessary repair supplies and equipment are available, and evnironmental conditions are usually better than in the field. More often, economic or time constraints require field repair.

If a plant has a large amount of FRP equipment, it may be feasible to train a local repair crew. Although this approach is expedient and could increase the awareness of FRP technology in plant personnel, there are valid cautions. First, the number of resins in use is many and increasing. Limited shelf life normally precludes the storage of all the varieties of resins in FRP equipment in the plant. Second, each resin has its own peculiarities, such as gel time variations with temperature, viscosity, exotherm during cure, and sensitivity to air inhibition. An experienced crew should be "qualified" in each resin with which it is going to work. A reasonable compromise is to train plant repair crews in the one or two most common resins in that plant. If this is done, there is a great tendency to allow this crew to repair any FRP equipment, especially in an emergency. Usually, extending an FRP repair crew beyond its experience results in poor quality.

Field repair, although frequently successful, is very frequently botched because repair is done in unacceptable environmental conditions. Excessive moisture or low temperatures (less than 60°F) are common causes for poor quality. These unsatisfactory conditions are sometimes difficult and expensive to modify to acceptable levels, but ignoring these factors will certainly result in early failure.

CONCLUSIONS

In order to have safe and reliable FRP equipment, it must be properly designed, fabricated, installed and maintained. But careful attention to detail is required from the time the material is selected onward. When FRP is viewed as an engineering material with unique properties and is treated accord-

ingly, the chances of a successful application are good. If, on the other hand, the material is viewed as a cheap substitute for some other material, and is treated in a casual manner, failure and safety hazards are predictable.

The approach to using FRP equipment described herein is capable of improving the safety and reliability of this equipment. It involves tedious attention to detail, but for those applications where FRP is the most desirable material of construction, the results are rewarding.

ACKNOWLEDGMENT

TABLE 1

Guide for Materials Selection (FRP)

1. Identify service conditions. (Include normal operations,
    upset conditions which might be encountered and startup/
    shutdown conditions):

    a. Chemicals and their concentration ranges. (Include
        chemicals present in only minor concentrations.)

    b. Temperatures
        1. Maximum
        2. Minimum
        3. Normal
        4. Rate of temperature change expected

    c. Pressure and vacuum requirements

    d. Environment at plant site (external to process condi-
        tions):
        1. Atmosphere
        2. Contamination by other chemicals
        3. Likelihood of fire

2. Identify physical requirements:

    a. Size
    b. Shape
    c. Agitation
    d. Heat transfer

3. Identify constraints external to the process:

    a. Codes
    b. Company standards or regulations
    c. Government regulations
    d. Safety requirements

4. Evaluate the consequences of a failure (consider both a
    small leak or a rupture):

    a. Hazard to personnel and other equipment
    b. Effect of failure on other units or operations. (For
        example, would the failure shut down all or part of the
        plant?)
    c. Economic consequences of failure

TABLE 1 (continued)

5. Evaluate prospects of maintenance and effective repair:

   a. Plant experience in maintaining FRP equipment
   b. Availability of repair service elsewhere in company or through a contractor
   c. Is unit repairable
      1. before chemicals are introduced?
      2. after prolonged service?

6. Evaluate total costs of each alternative:

   a. Purchase price
   b. Design and other engineering costs
   c. Inspection costs
   d. Shipping, storage and installation costs
   e. Equipment downtime costs
   f. Spare equipment costs (if spare is required)

TABLE 2

FRP Vessel Testing Program

Acoustic Emission Tests (Reference 13)

1. New Equipment

   62 vessels tested

   78 AE tests performed (both at fabricator's shop and after
   installation)
      57 accepted by AE
       4 accepted by AE but rejected by visual inspection
     12 rejected initially but accepted after repair
      2 rejected - unacceptable ·

2. In-Service Equipment

   340 vessels tested

   402 AE tests performed
     204 accepted
      80 rejected but accepted after repair
      60 rejected - equipment replaced
      58 rejected - equipment operating at reduced levels or
          out of service

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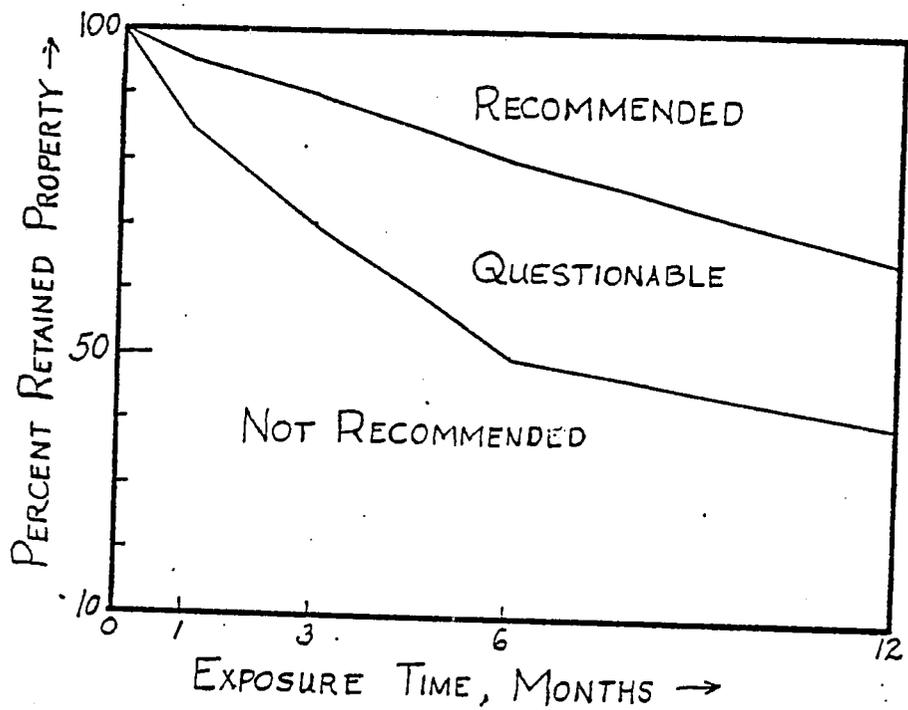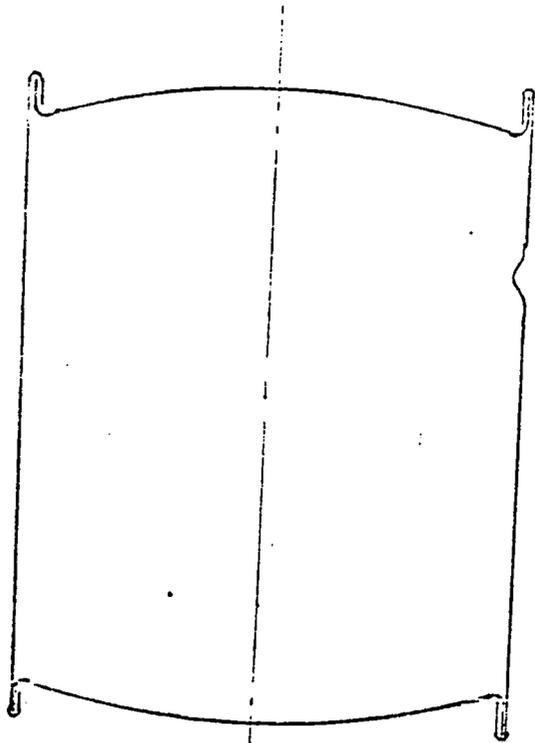
Figure 1 - Criteria for evaluating nonmetallic
materials based on tensile properties
according to the National Association
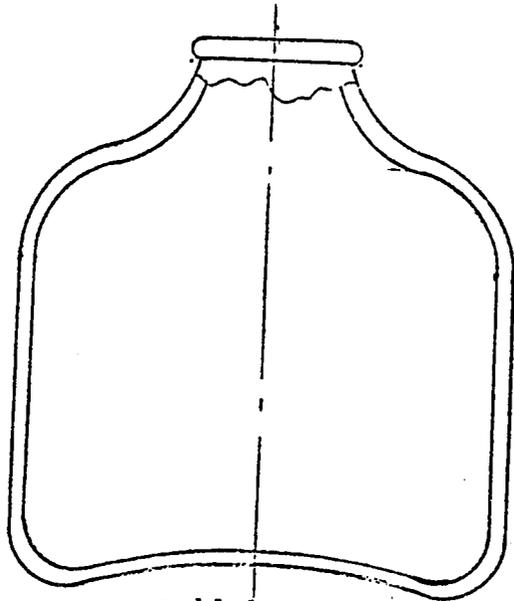of Corrosion Engineers[12]

slight dome

crimped joints

dent

thin walls

sharp corner

BEER CAN

thick wall
(will not dent
successfully)

curved
corner

deeper dome than
can

molded corner
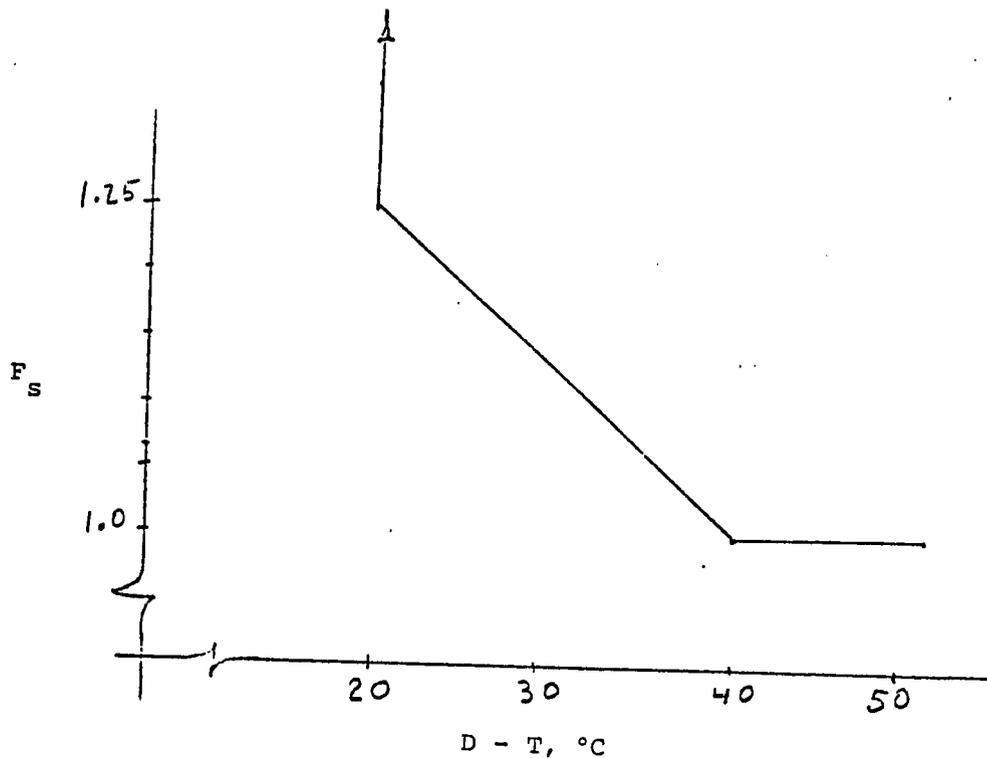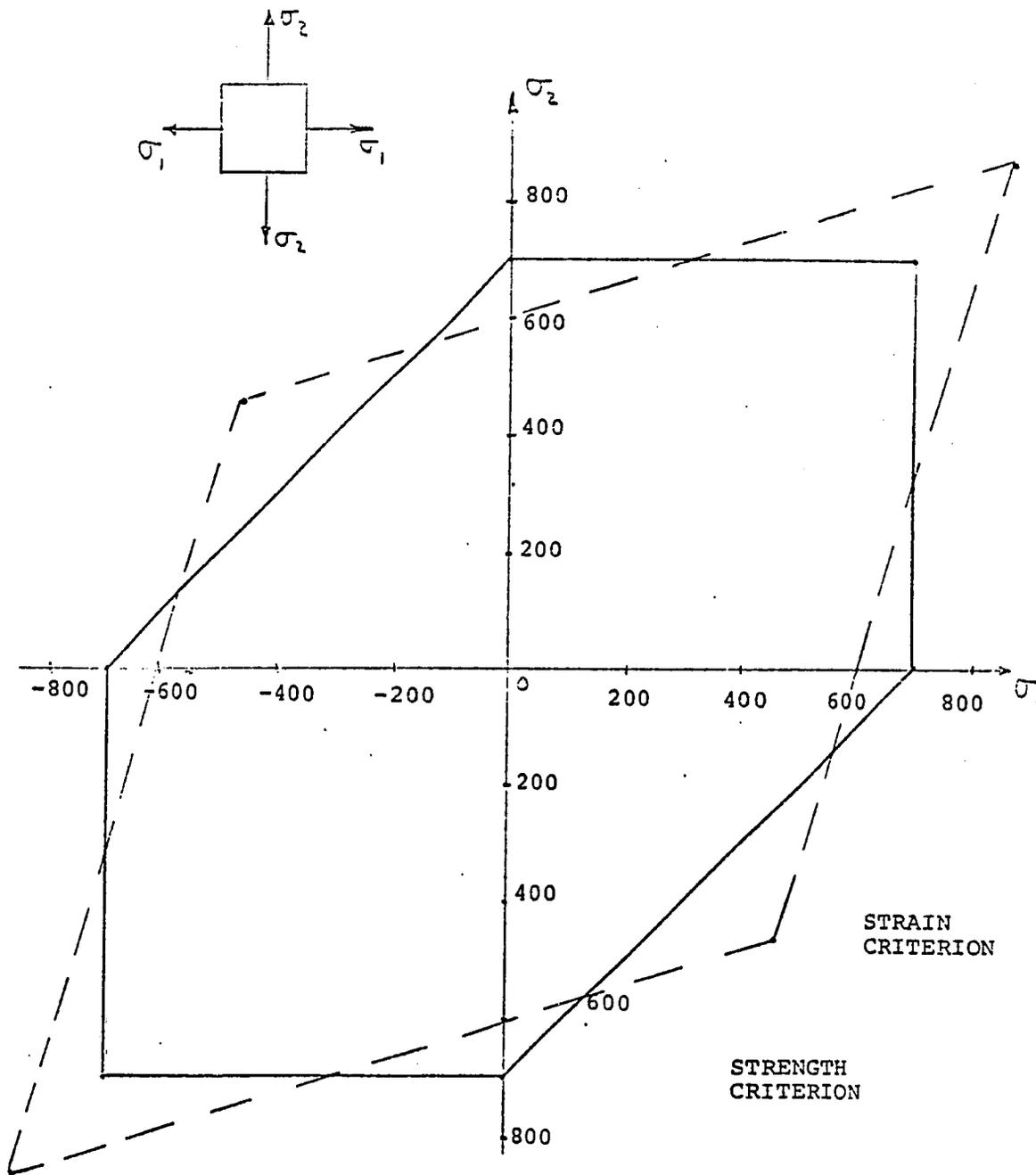BEER BOTTLE

FIGURE 1 - STRUCTURAL EXAMPLE

Figure 3 — STRENGTH TEMPERATURE FACTOR, Fs.

D = Heat Distortion Temperature, °C
T = Operating Temperature °C

$$Fs = \frac{1}{10} \frac{\text{Tensile Strength}}{\text{Allowable Strength}}$$

FIGURE 4 - DESIGN CRITERIA

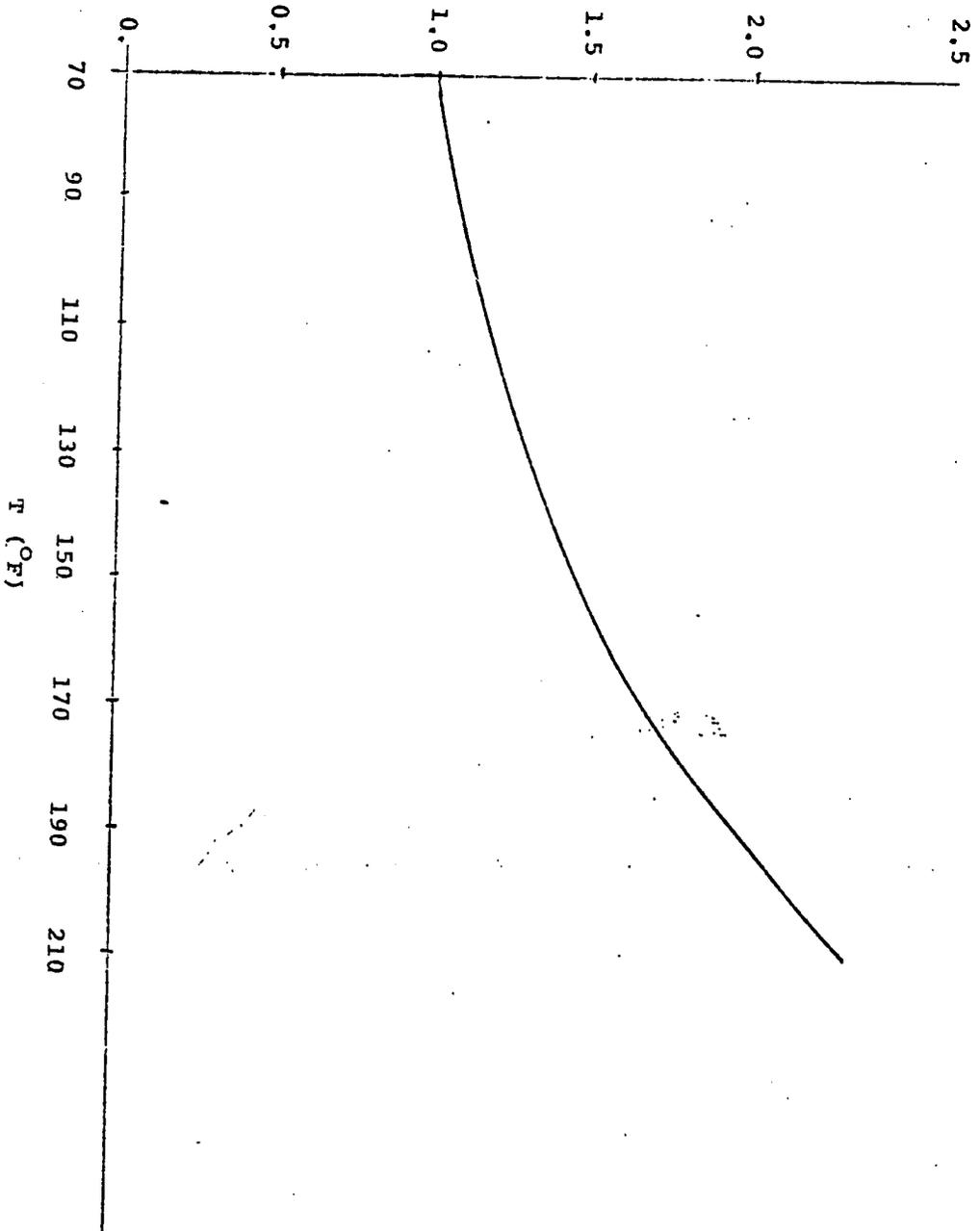$$F_m = \frac{\text{FLEX. MODULUS AT } 70^\circ F}{\text{FLEX. MODULUS AT TEMPERATURE T}}$$

FIGURE 5 — MODULUS TEMPERATURE FACTOR, T_m

Fluid

Sensors (Transducers)

Preamplifiers

→To Acoustic Emission Instrumentation

Defect emitting stress waves

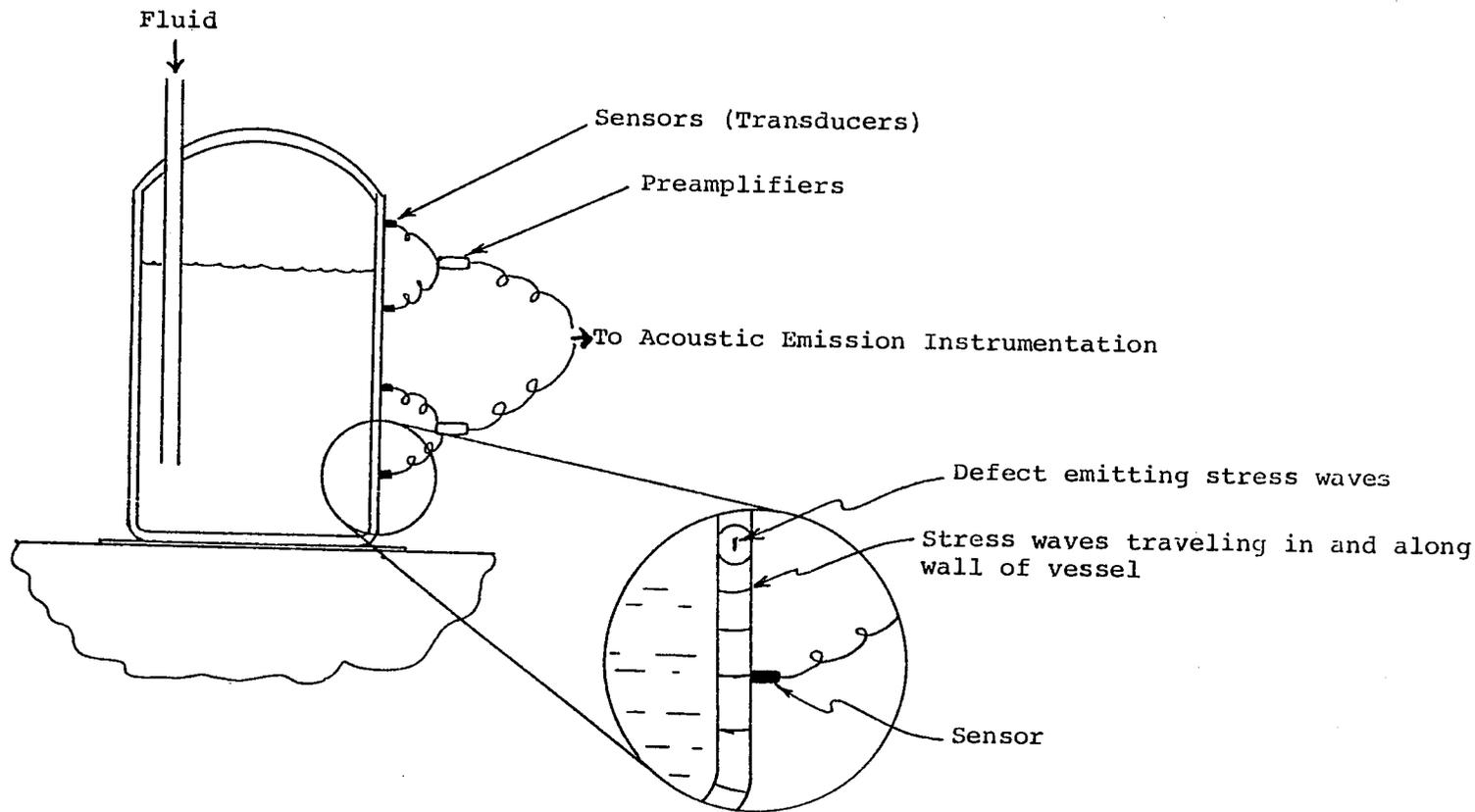Stress waves traveling in and along
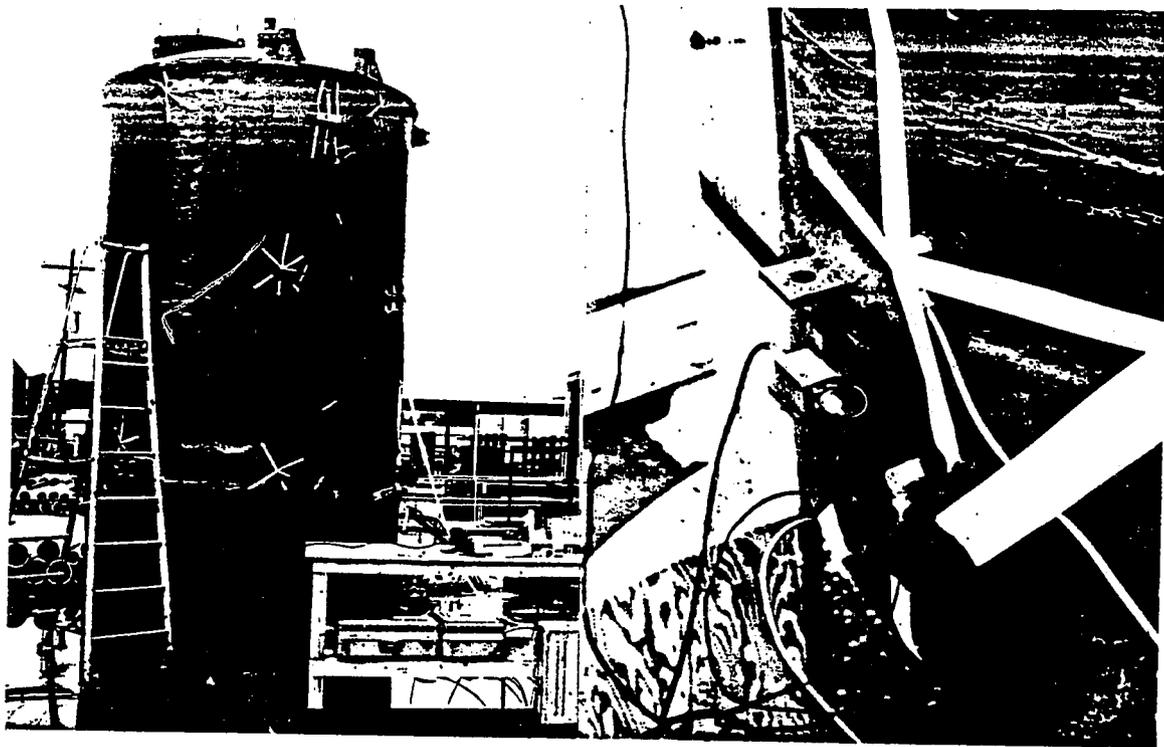wall of vessel

Sensor

Figure 6   Schematic View of Acoustic Emission Test
Setup for a Fiberglass Reinforced Plastic Vessel

Note that stress wave is the same as transient elastic wave.

A   B

Figure 7.   Photos of fiberglass reinforced plastic tanks with
acoustic sensors in place and ready for acoustic emission
test.   A.   Locations of sensors on tank for optimum coverage
of tank wall area.   Note that some premplifiers are also
visible.   B.   Detail photo showing two attached sensors, one
of which is attached to the preamplifier.   (From reference 13)

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