TANK DESIGN

The design history of prestressed concrete tanks has been a matter of using basic shell principles considering the various phases of construction and loading. In general, the construction techniques have evolved from a trial and error basis, as have many other techniques in the construction industry.

The problem of designing and constructing prestressed concrete tanks were generally simple, as long as small tank diameters were involved. However, many items which were ignored in smaller tanks soon became sources of major leakage problems in larger tanks. It became apparent that careful analysis of all factors that may affect the structure had to be considered in the design in order to construct a tank which would perform satisfactorily. In early prestressed concrete tanks (small tanks of 500,000 to 1,000,000 gal.), fixed bases and fixed dome roofs were generally used, and shotcrete (pneumatic mortar) construction preferred.

A fixed tank wall base or a fixed dome has the tank sidewalls monolithic with the foundation and dome ring. This offered radial resistant against inward and outward movements of the wall and the dome. These movements are caused by circumferential prestress, prestresses losses, shrinkage and shrinkage recovery, thermal effects, and water pressure.

Reinforcement

It was thought somewhat erroneously that normal reinforcing steel for the core walls and domes caused excessive shrinkage stresses and should be minimized or avoided. Some well-known trade publications still indicate that this is a proper approach. It was found that by minimizing the vertical reinforcement and by cutting off dowels from the dome or the fixed footing, horizontal cracks generally occurred at the vicinity of the ends of these cut off bars as shown in Fig. 1. These cracks seemed to occur with time even with substantial vertical prestressing.

Since the small tanks performed rather well, if they were constructed properly, it was thought that there was no reason not to step out into the larger tanks. Larger tanks generally made shotcrete uneconomical, and therefore concrete core walls were considered. Problems, such as cold joints, construction joints, and honeycombing, occurred in the initial cast-in-place concrete construction which were not as easily controlled as a good shotcrete application. Today, cast-in-place concrete construction is most used.

Wall bending stress

The first prestressed concrete tanks were generally designed with fixed bases and domes. However, as soon as the tanks became larger, it was found that if fixed conditions were used, high vertical bending stresses occurred in the walls that could not be economically or satisfactorily reinforced. In order to minimize the vertical bending stresses, the wall base was allowed to slide during the prestressing procedure.

Sliding bases were of many types. Concrete footings were treated to permit the radial motion of the wall as the prestressing forces were introduced. However, it was frequently found that friction relieving devices were not dependable. Horizontal cracking of the

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walls occurred during or after prestress, unless a conservative design assumption was made for determination of vertical reinforcement. The early procedure was to release the tank base only for the prestressing operation. After the prestressing operation, the tank base was generally hinged. Based on experience with the smaller tanks, it was thought that the same general design assumptions could be used for larger tanks.

It was found that unless the walls were heavily reinforced vertically, and rather thick, cracking of the nature shown in Fig. 1 often occurred. This cracking has occurred as much as 3 to 5 years after construction. Apparently the volumetric changes caused by temperature, creep, shrinkage and shrinkage recovery, differential temperature, and shrinkage effects, caused moments which were beyond the capacity of the nominal vertical reinforcement and vertical prestressing used. It was found that a predictable base condition could be established by utilizing elastomeric pads which had a predictable radial restraint to the wall and/or dome motion. This resulted in a design criteria compatible with the actual performance of the tank.

The actual design of a prestressed tank would be rather simple if one only had to be concerned with the ring stresses. However, the vertical moments which cause horizontal stresses, and eventually cracking, must be investigated. This takes a rather careful analysis utilizing all the known

Fig. 1—Typical horizontal crack in vicinity of bottom dowels

characteristics of concrete under various temperature differentials, and other volumetric change conditions. The application of these methods is beyond the scope of this paper.

Concrete

Whether regular concrete or shotcrete is used in constructing a prestressed concrete tank, careful planning must be assured in the construction phases to avoid cold joints. It has been found time and again that where cold joints exist in concrete tanks, they will probably leak. A dense concrete which is homogeneous is more important than high concrete strength. Using a dry mix which would result in honeycombing and possible cold joints is not a good procedure for prestressed concrete tank walls. It is necessary to insure as much workability as possible to avoid cold joints and honeycombing.

PRESTRESSING STEEL FOR WATER TANKS

The item which seems to cause the greatest amount of concern, and has had the greatest publicity in recent years, is the problem of protecting the prestressing steel. There have been various incidents of corrosion problems, both in prestressed concrete tanks and in pipe.*

For wire wrapped tanks, the meth-

*Monfore, G. E., and Verbeck, G. J., "Corrosion of Prestressed Wire in Concrete," ACI JOURNAL, *Proceedings* V. 57, No. 5, Nov. 1960, pp. 491-516.

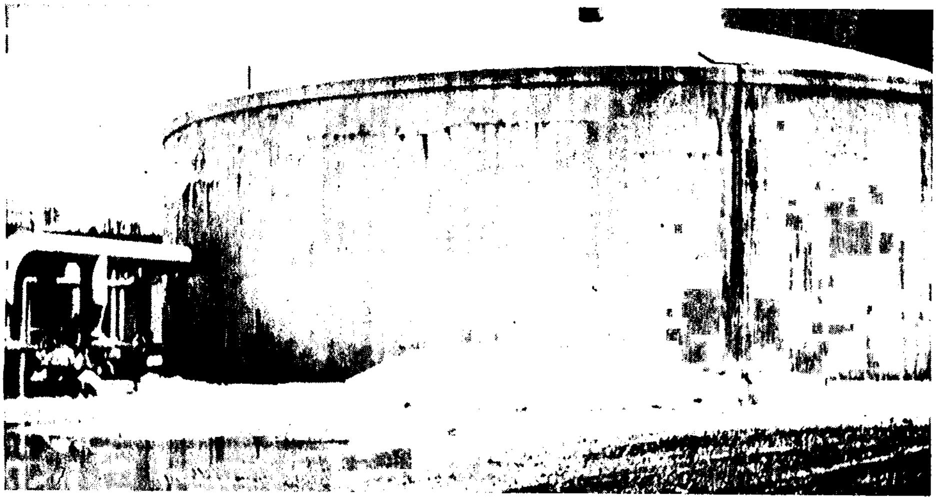

Fig. 2—Water tank, 10 years old, with 16 openings at the worst cracked areas but no corrosion found

od of protecting the wire has generally been the use of shotcrete. It is necessary to completely encase prestressing wire with a rich dense mortar which is bonded to the previous layers in order to insure corrosion protection. If the wire is not completely protected it is likely that corrosion will occur.

Corrosion of properly protected wires will generally not occur, even if a hairline crack exists through the shotcrete, and water from the inside of the tank leaks through (Fig. 2). Proper protection of the wire seems to require a minimum dense mortar cover of ½ in.

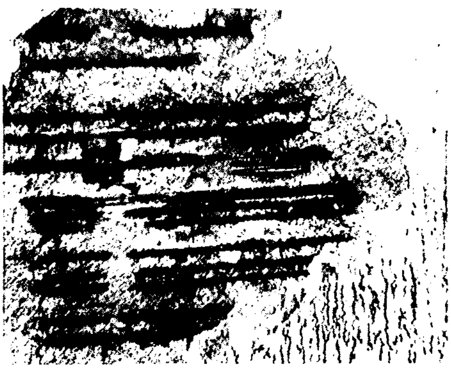

Fig. 3—Surface corrosion of wires where shotcrete cover was less than ½ in.

On one particular water tank inspected recently, it was found that where the shotcrete had spalled off, the wires were corroded on the outside face. By chipping into adjacent shotcrete it was found that wherever the shotcrete was less than ½ in. thick, corrosion existed. Where the shotcrete was more thatn ½ in. thick, the wires were bright and clean (Fig. 3). This particular tank was a slipform tank which had suffered every catastrophe in the construction phases that can happen during a slipforming process. The tank is full of cold joints, and has been leaking for over 11 years. In areas where water seeps through the wall almost constantly, openings were made to expose the wire. It was found that where shotcrete was ½ in. thick or greater, and bonded to the underlayers, the wires were bright and clean. This finding was similar to that found on other tanks examined.

In the various tanks examined by the author, no sign of stress corrosion in water tanks has been found. This, however, does not preclude the possibility of stress corrosion occurring if wires which are improperly protected were subject to an environment conducive to stress corrosion. This could be an environment of a corrosive atmosphere, direct contact of the wires with detrimental chemicals, or a condition which may cause electrolysis. The only means of protection, in a corrosive environment, is to assure that a substantial complete protective coating exists, and that detrimental cracking of the tank walls is avoided by a knowledgeable design approach.

PRESTRESSING STEEL FOR SEWAGE TANKS

The problems which have occurred in sewage treatment tanks have been disconcerting to owners and engineers. The failure of a 2 million gal. sludge tank was one which certainly received much publicity. (It is difficult to see how 2 million gal. of sludge not properly contained could escape publicity.)

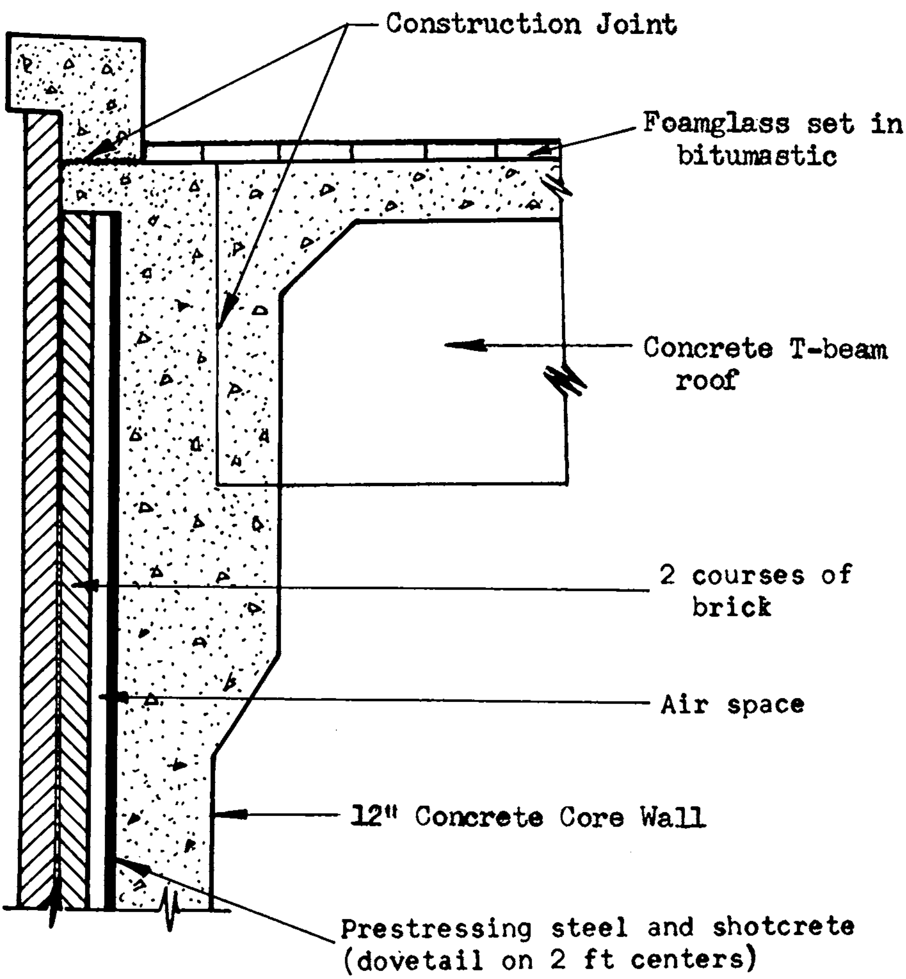

Fig. 4—Roof and wall details of failed sludge tank

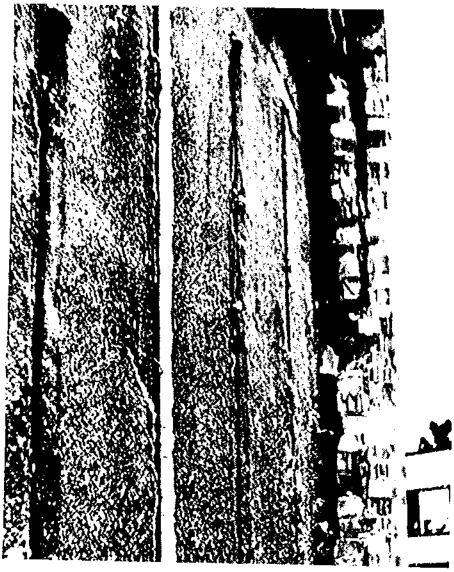

Fig. 5—Wall of failed sludge tank with brick partially removed.

The conditions that existed at this particular structure resulted from a series of unfortunate circumstances. A basic problem which occurred seemed to be an over-all corrosion of the prestressing wire which manifested itself in the forms of ordinary corrosion and stress corrosion. In the one tank that failed out of eight digestors, the corrosion was extremely widespread. It appears from personal limited examination of the other tanks that their prestressing steel is also corroded to varying degrees.

A series of details, which on the surface seemed unimportant, led to this major corrosion problem. As found repeatedly, the points which make problems in structures, are details and not over-all strength. The unbonded construction joint of the roof parapet detail shown in Fig. 4 permitted water to pass through the parapet joint and then find its way between the brick and into the galvanized dovetail. Fig. 5 shows how the parapet has moved on its support pushing the brick and how the water found its way between the previously bonded brick coarses. Most brick in areas of this type of distress were highly deteriorated probably from freeze-thaw action. Note also on Fig. 5, the vertical dovetails which were generally highly corroded.

The prestressing steel wire was placed almost directly against the galvanized dovetails (Fig. 6). Present day good practice would require a minimum of ⅝ in. mortar between dovetail and prestressing wire.

The extent of corrosion on this tank was such that the galvanized dovetails were completely disintegrated in many cases (Fig. 7). Since these galvanized dovetails were not filled with mortar (which is usual practice), they formed

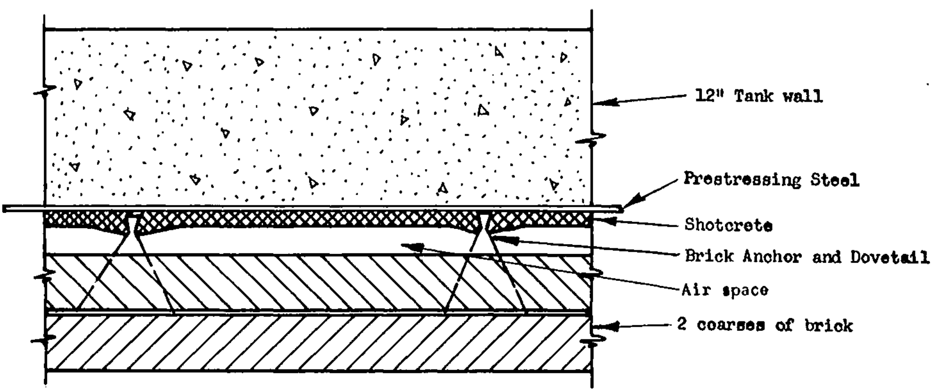

Fig. 6—Horizontal section through failed sludge tank wall

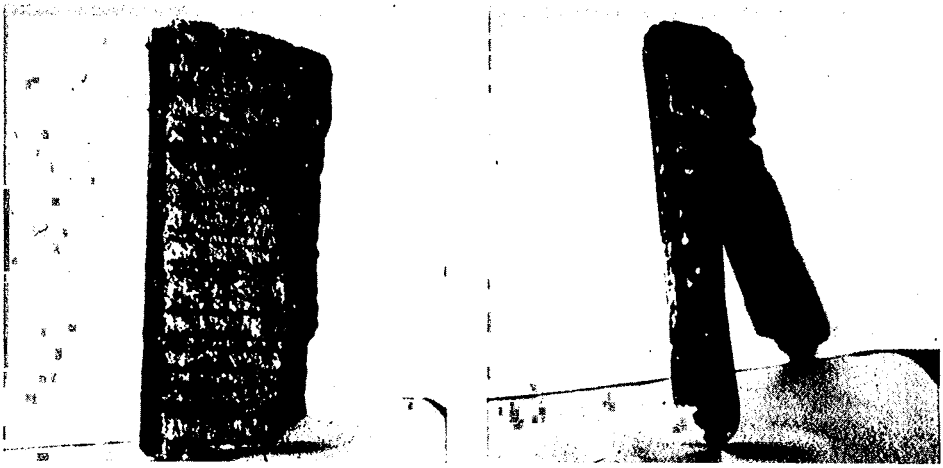

Fig. 7—Section of shotcrete cover coat showing products of corrosion at closely spaced wires (left) and almost completely corroded dovetail (right)

vertical channels for the roof drainage. As a result, the dovetails eventually corroded even though they were galvanized. The drainage water then found its way to the prestressing steel. In some areas the prestressing wires were not spaced sufficiently to insure complete filling of the spaces between the wires. Consequently the water apparently had horizontal passages between dovetail channels. The alternate wetting and drying which occurred on these wires was extremely conducive to corrosive conditions. This is unlike the leakage in the water tank where there is not as much alternate wetting and drying and change of air. It can be seen in Fig. 8 how the corrosion in the vicinity of the dovetails was quite marked whereas the corrosion away from the dovetails diminished.

The failure may not have occurred if the drainage hadn't been subjected to contamination by sewage gas. It is likely that the sewage gas, which was under a pressure of about 13 in. of water, escaped through the concrete roof and mixed with the rain water. The detail of the roof did not include waterproofing (Fig. 4). It was insulated with foam glass and covered with a mastic. This foam glass with a mastic coating did not afford a water or vapor barrier. Therefore, the water probably mixed with the sewage gas and formed a severe corrosive medium.

Fig. 8—Dovetail detail showing corrosion under dovetail

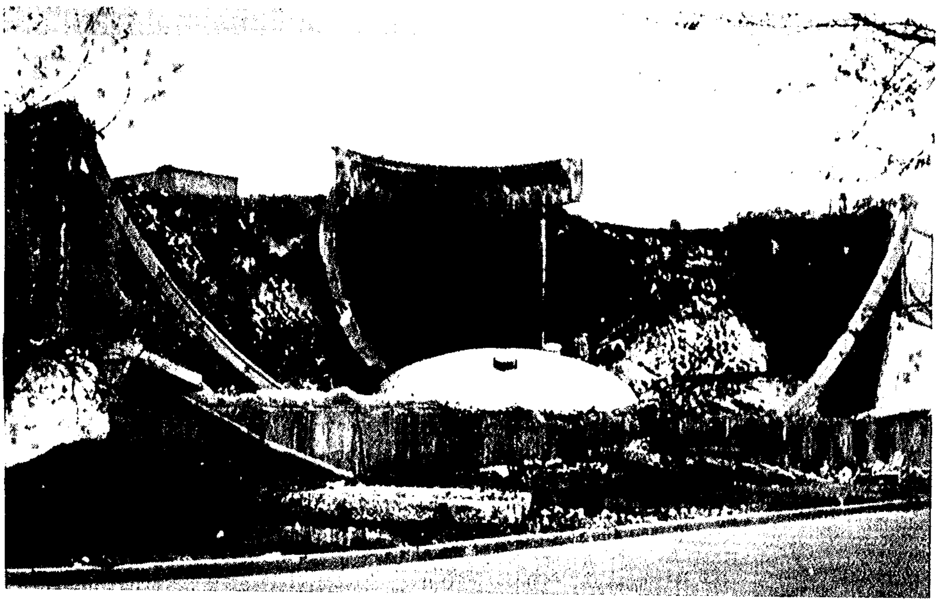

Fig. 9—Failed sewage tank

It is well known that steel under stress in the presence of hydrogen sulfide will suffer stress corrosion. Also, H_2S mixed with water will give either H_2SO_3 or H_2SO_4 which are extremely corrosive to steel. These unfortunate circumstances grouped together resulted in a condition of over-all corrosion, and the consequent failure shown in Fig. 9.

It has been stated that the failure was caused by a basic characteristic of the as-drawn wire: susceptiblity to stress corrosion. The point remains, however, that there are many miles of prestressed pipe, and several thousand prestressed concrete tanks which have not shown this stress corrosion phenonemon.

It is necessary to point out that in a good number of tanks which have been conceived on an inadequate design philosophy have leaked for over 10 years. In these water tanks, generalized corrosion does not exist if proper shotcrete protection has been applied. Some wire corrosion exists, but this generally can be traced to electrolytic corrosion because of aluminum torpedo splices or the use of other dissimilar metals, or where pneumatic mortar cover coat was improperly placed or not bonded. Stress corrosion, as found in the failed sewage tank, has not existed, under these conditions. This again does not imply that stress corrosion cannot occur, but it does indicate that it takes a particular environment to cause stress corrosion. It is felt by the author that a condition of protection against corrosion can be created with the proper construction techniques and materials.

It is also worth mentioning that in another sewage digestor which suffered a failure, but not of a catastrophic type, the corrosion of the wires were generally limited to those areas where the sewage had access to the wire. Fig. 10 shows a crack pattern in a small digestor that manifested this type of failure after about 11 years of use. Note that the failure lines follow approximately the yield lines of a plate ported on four sides. The first in-ction of leakage this tank indicated y the vertical cracks. But during in-ction, the yield line cracks of the te were traced.

An initial crack in this tank was used by the type of vertical pre-essing unit used. The vertical unit s placed on the inside face of the ll and quite often it cracked the l from top to bottom. Generally er circumferential prestressing, these cks were closed up so that they could be found. Apparently, the failure ck did not close up completely and sewage found its way into the crack l apparently, with time, corroded wire in the immediate vicinity of vertical crack.

t was most interesting to note that en one removed the mortar on ner side of the crack, the wires were ght. In this particular instance, the or of the corrosion was black. This parently indicated that a ferric sul-de was produced. The corewall ck itself also indicated that it st have been acted on by some rath-strong acid. The cracked area in-dicated deterioration of the surface of the concrete. This was not so with the inside of the tank wall.

Fig. 10—Sewage tank failure

CAUSES OF CIRCUMFERENTIAL PRESTRESSING STEEL PROBLEMS

As a guide to the designer and de-er and as a construction check list, following is a listing of the prob-e potential causes of prestressing l corrosion or reduced ultimate ngth in circularly prestressing struc-es:

1) Poor design and construction of nhole or pipe openings

2) Voids in mortar between ad-ent wires due to poor wire spacing

3) Bunching of wires sprung around nings resulting in poor mortar cov-ge of wire

4) Poor bond of cover coat to core-l or previously placed shotcrete

(5) Inadequate thickness of mortar cover (minimum specified cover should be ¾ in.)

(6) Improper mix of shotcrete

(7) Stressing methods which cause nicks and notches in wire

(8) Splices of dissimilar material

(9) Additives such as calcium chloride in corewall concrete or shotcrete

(10) Corrosive environment caused by leakage through cracks in the corewall

(11) Excessively delayed cover coating

(12) Inadequate access facilities for shotcrete application

(13) Careless welding in vicinity of wire

(14) Using wire as a ground for welding

(15) Permanent overstressing of wire

(16) Inadequate winter protection, high winds during shooting, and other improper procedures for shotcrete

(17) Inserts of dissimilar metal in contact with prestressing steel

(18) Electrical contact of prestressing steel with pipes or inserts that may carry currents

(19) Horizontal cracks or control joints which move and inadvertently dislodge the mortar protection

(20) Localized restraint of walls to stress and volumetric changes by improperly attached walls, pipes, or other appurtenances

(21) No curing or improper curing of cover coat

PROTECTION OF PRESTRESSING STEEL

There is apparently a much greater need for a fool proof protection of the prestressing steel on sewage tanks than on water tanks. It is not felt that galvanized wire under a detrimental environment would necessarily give an appreciable extended life to the prestressing steel.

It is the opinion of the author that prestressing steel for sewage tanks should be placed only under the most careful supervision. The wires should be accurately spaced and the protective covering should be greater than that required for water tanks. It is also necessary, evidently, to insure that the wall design takes into account all the environmental problems which may effect the cracking performance of the wall.

CONCLUSIONS

In the various tanks inspected, and from the particular experience available in this field, it is evident that prestressed concrete tanks can be designed to perform satisfactorily under many conditions and environments. It is necessary to fully consider all design problems that may not be necessary for the more usual structure. Since there are few other types of structures which are subjected to full load for most of their life, and since any performance characteristic which will create cracks produce an immediately tell-tale failure, it is necessary to fully understand the performance of these structures and to provide details which will assure the assumed structural conditions.

The protection of the wire is most important and it is necessary to assure that complete and sufficient cover be used on the wire. If special requirements such as manhole openings or pipe openings may cause bunching of wires, the details should be conceived so bunching will be avoided. It is also necessary to prevent stray electrical currents from being carried through the tanks into the prestressing wire.

Another item in design which must be considered during the initial stages and then in the operational stages is attachment. No attachments should be made to the tank wall which will change its basic structural action. If the tank is not designed for these attachments, cracking may occur which will be detrimental to the performance of the tank.

In general, it is necessary that prestressed concrete tanks be treated similarly to other structures, with periodic inspections to insure continued proper performance. Because of the belief that concrete is maintenance free, large apparent distress in tanks have been ignored, and consequently, with time, rather major corrective measures were necessary. If these problems were detected at an earlier date, minor provisions could have been made to avoid major problems.

Observations reported here are based on personal field inspection by the author prior to September 1962. Other reported incidents in prestressed concrete tanks have not been described.