Docket No. 50-219

ATTACHMENT H

OYSTER CREEK NUCLEAR GENERATING STATION

EXPANSION OF THE DRYWELL CONTAINMENT VESSEL

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OYSTER CREEK NUCLEAR POWER PLANT

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OYSTER CREEK NUCLEAR POWER PLANT

EXPANSION OF THE

DRYWELL CONTAINMENT VESSEL

1. SCOPE

The purpose, material selection, testing, installation and the compressing of the inelastic compressible material applied to the drywell containment vessel to provide for expansion of the vessel are described herein.

2. PURPOSE

2.1 Necessity for Separation of Steel and Concrete

Containment and radiation shielding of the Oyster Creek Plant are provided by separate structures: Containment, the "pressure suppression" system, is provided by steel pressure vessels; a "drywell", housing the reactor and recirculation system and consisting of a 70 foot diameter sphere surmounted by a 33 foot diameter cylinder, and an interconnected absorption chamber containing the water volume necessary for pressure suppression. Radiation shielding is provided by a concrete wall outside the drywell vessel with a minimum thickness of 4 feet 6 inches. The pressure, 62 psig, associated with the postulated mca requires a relatively thin walled (about 3/4 inch) steel vessel. The vessel has relatively little capability to resist concentrated jet forces or the impact of missiles. Such loads are, however, readily accepted by the massive concrete shield. Accordingly, the space between the steel drywell vessel and the concrete shield outside must be sufficiently small that, although local yielding of the steel vessel may occur under concentrated forces, yielding to the extent causing rupture would be prevented. Some space must be provided since, if it is to function as a pressure container, the vessel must be allowed to expand when in its stressed condition. The vessel is also subject to thermal expansion since it will be exposed to operating and accident temperatures significantly higher than an ambient temperature practical to maintain during construction.

2.2 Methods of Separation

The maximum acceptable space, in the order of 3 inches, (further defined below) precludes the use of a conventional forming system for the inner face of the concrete wall. That face of the concrete wall could be formed with a material spaced away from the vessel and suitable to remain permanently in place (the many penetration pipes projecting from the vessel would prevent slipping forms out) provided its support was independent of the vessel or if supports between vessel and form were removable. Alternatively, the space could be temporarily filled with a material which could, after placement of concrete, be removed by being broken up and extracted, or by being melted and drained off, or by being sublimated.

Of these methods, those involving the clearing of the space after complete construction of the 80 foot high multiple curved concrete surface are open to question as to whether the material was completely removed. If the material were to be removed in steps as the construction of the shield advanced or if an independently supported form were used, the procedure would be open to question as to whether the completed portion of the expansion space in the lower region had become obstructed during progress of construction above. In either case, the limited width of the space and its curvature and penetrations preclude subsequent inspection to establish whether or not the required clearance exists continuously.

Another approach to the problem would be to fill the space permanently with a material having sufficient compressibility to permit the expected vessel movement. The compression characteristics of a material to be left in place between the vessel and the concrete would necessarily be such that it would not deflect significantly under the fluid pressure of concrete. The fluid concrete pressure can be controlled by limiting the rate of placement of the concrete but a practical lower limit would be about 3 psi. Commercially available compressible materials or practical modifications of them having such stiffness would require a pressure of at least 10 psi to be compressed to the extent equal to the expected vessel expansion and would of course impose that pressure as a reaction on the vessel. While this thin-walled large-diameter pressure vessel is capable of resisting a much larger bursting pressure, it cannot sustain an external pressure of this magnitude unless the external pressure is balanced by a positive internal pressure.

However, the need for a continuous balancing internal pressure within the expanded vessel could be eliminated by creating an air gap into which the vessel could freely expand. This could be accomplished by selecting a compressible material which is inelastic; such a material could be compressed once by, in effect, simulating the conditions postulated as causing the greatest vessel expansion while maintaining a balancing internal pressure. The residual air gap created by the inelastic compression of the material would offer no resistance to subsequent repetitions of vessel expansion.

3. MATERIAL CRITERIA

The material to be used for an inelastic compressible lining would be required to have the following characteristics:

a. Would adhere tightly to a curved, painted steel plate surface in flat, vertical and overhead positions.

b. Would have relatively insignificant deformation under fluid pressure of wet concrete estimated at 3 psi.

c. Would be reduced in thickness inelastically by about one inch from an initial thickness of 2 to 3 inches under a pressure of preferable not more than ten psi. (Since the concrete wall must be designed for the pressure associated with this compression, a pressure approaching 62 psi would require, in effect, the cost penalty of building a redundant pressure containment vessel in reinforced concrete)

d. Would remain dimensionally stable at the reduced thickness without significant flaking or powdering (to avoid the obstruction of the lower region of the gap with detritus from the lining material above.)

e. Would be unaffected by long term exposure to radiation and heat.

f. Should be an economical, commercially available product or practical modification thereof, readily applicable to the vessel.

g. Should be susceptible to minimum damage (consistant with the other requirements) while exposed on the vessel before concrete placement.

4. MATERIAL SELECTION and TESTING

4.1 Available Materials

The field of commercially available insulation, fire proofing and shock absorbing packaging materials was examined: Plastics showed considerable elasticity and a tendancy to flow or decompose at relatively low temperature (about 175°F). Fibrous blankets or boards showed excessive elasticity. Cellular inorganics (foamed glass and expanded aggregate concrete) could not be reduced to acceptable strength and were excessively friable.

4.2 Standard Fire-Bar

The material ultimately used in a modified formulation was a combination of the fibrous and cellular types. The material is a proprietary asbestos fiber - magnesite cement product applied under the trade name Fire-Bar, normally as a spray coat over steel structures for fire protection, by the All Purpose Fireproofing Corporation of New Hyde Park, N. Y. The solid materials; asbestos fibers, magnesite and magnesium sulphate; (roughly 75% asbestos) are premixed and, at the site of the work, are combined in a mortar mixing machine with water and, to control density, with foam to form a slurry suitable for spray application. The foaming agent is Aerosol PK, a proprietary product of the Mearl Corporation, Roselle Park, New Jersey.

The application of this material as fireproofing of structural steel on a building then under construction was observed and finished areas inspected. Although a specific compressibility was not of concern in that use, it was known that compressibility was a function of density which, through frequent periodic checks of wet density and a corelation between wet and dry density, was the control used to insure proper application. Independant laboratory fire resistance tests of the material were available and showed that it had withstood exposure resulting in temperatures of some 900°F in the metal to which it was applied without separating from the metal during the 2-1/2 hour fire test and the subsequent 2-1/2 minute hose stream test.

4.3 Development and Preliminary Testing

Certified Industrial Products, Inc. of Hillside, New Jersey, a firm specializing in test and development of light weight aggregate concrete and insulating materials, was engaged to test and modify the product to suit the requirements. Certified's developments were to reduce the strength of the standard product by reducing its dry density from 12 to 8 pounds per cubic foot through an increase in foam content, to improve its stability by substitution of longer fiber asbestos, and to develop a sequence of application requiring a base coat of 1/2 inch of standard Fire-Bar followed by two coats of reduced density Fire-Bar to achieve optimum adhesion to the vessel and minimum slump before curing on vertical surfaces.

4.4 Commercial Practicability Evaluation

The All Purposes Fire Proofing Company used the mofified formulation with their production equipment to spray test panels and to judge the commercial practicability of the modified product. They experienced no difficulty.

4.5 Final Development Tests

The United States Testing Company was engaged to perform independant laboratory tests of the compression characteristics and stability of the test panels made with the production equipment. Compression characteristics; a 6% reduction in thickness at the 3 psi fluid concrete pressure and reduction in thickness from 2-1/2 inches to 1-1/2 inches under 15 to 20 psi; were satisfactory. Inelastic compression, checked by measuring rebound, amounted to 80% of total compression; continued measurements by United States Testing over 3 months showed stability after the recovery of 20%. Material loss after compaction was measured on panels compressed in a vertical position; loss was about 1% of sample weight, observation indicated loss to be occurring at the break in the samples at the perimeter of the compression shoe, a discontinuity which would not occur in service. These tests were completed in October of 1965.

Although the decision to use the asbestos fiber - magnesite cement product was based on the tests described above, it was considered desirable to accumulate a greater body of test data including compression tests at elevated temperature.

The second series of test results, also obtained by U.S. Testing, available in April 1966, demonstrated that the previousl_ established compression characteristics were also applicable when tests were made on the material at 300°F.

4.6 Rebound Evaluation

The Mearl Corporation, Foam and Chemicals Division, supplier of the proprietary foaming agent was requested to describe the action of the foaming agent with reference to the demonstrated 20 percent rebound. They described their agent as an aqueous protien base material capable of entrapping air and thus imparting a cellular structure but which would be absorbed by the solid materials upong drying, hence would contribute nothing to the strength of the material. The cellular structure imparted by the foam would be maintained by the magnesite cement but upon being compressed would collapseirrecoverably through failure of the brittle cement walls of the cells. The rebound was attributed to recovery of compression of the asbestos fibers. They also noted that wet asbestos fibers would pack under compression and suggested addition of moisture if feasible as a means of reducing rebound.

4.7 Susceptibility to Damage

The question of susceptibility of the material to damage was being considered in the course of the testing program. It had been established in the original development of the material that about 50% of the strength of the material (crystallation of the magnesium compounds) occured in the first 24 hours and 100% would be developed in 7 days. The 50% strength would preclude damage by rain and sufficient drying would take place in that 24 hour period to eliminate the possibility of damage due to freezing in this extremely porous material.

In order to avoid the material drop off characteristic of sharp breaks within the material, it was considered desirable to insure that the material was firmly bonded to the steel surface and free to separate from the concrete

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during the planned subsequent operation of reducing its thickness by compressing it between these two surfaces. Furthermore, the exterior surface of the compressible material, being porous, required a waterproof covering to prevent absorption of grout from the wet concrete to be placed against it.

4.8 Protection and Bond Breaker

Accordingly, protective measures considered necessary were to cover the new work for a 24 hour period with a weather enclosure consisting of polyethylene sheets draped over the scaffolding to permit circulation of air to promote drying. After the initial drying period the polyethylene sheets would be placed against the material with all edges sealed by tape and would be held in place by insulation pins stuck on the steel vessel before application of the compressible material.

Some mechanical damage due to subsequent operations of constructing the concrete shield wall had to be expected and provisions were made in the contract for repair of such damage. The extent of the damage was expected to be minor since the first subsequent operation would be to erect a curtain of reinforcing steel at the inner face of the concrete wall which would provide a "fence" between the material and further operations. This assumption was valid for vertical or near vertical surfaces of the vessel. However, a splice in the wall reinforcing just above the elevation 51' - 3" floor, the delay in construction of the concrete wall there while the floor was being built and the condition that a tangent to the vessel at this elevation was no longer near vertical all contributed to greater opportunity for mechanical damage to the compressible material in this region. Damage sustained was such that essentially all of the material to some 10 feet above the 51'-3" floor had to be replaced. This experience indicates that additional initial cost for protection against mechanical damage, such as for a fabric reinforced sprayed-on resin shell, could probably be justified in this region.

4.9 Conclusion

The tests and evaluation indicated that the foamed asbestos fiber-magnesite cement product had the required compression characteristics and stability, would be unaffected by long term exposure to radiation and heat, would be commercially

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practicable in application, would be as resistant to weather conditions and damage as could be expected considering the required compression characteristics and could be repaired by local replacement in the event of damage. Thus no technical objection to the material was found and it was decided in October, 1965 to proceed with the inelastic compressible material approach to the providing of the desired expansion space around the drywell vessel.

5. DETERMINATION OF REQUIRED THICKNESS OF THE LINING

5.1 Concentrated Load Test of Vessel

To determine the maximum acceptable distance between the steel vessel and the concrete wall, load deflection tests were made by the Chicago Bridge & Iron Co. These tests, described in the CB&I report: "Loads on Spherical Shells", August, 1964, were to determine the maximum deflection consistant with no rupture but accepting yielding, of prototype sections of the vessel, under a load simulating the postulated jet force accompanying the mca.

Two of the three tests run were terminated without rupture (due to limitations of the testing apparatus) at deflections of 3.3 and 3.25 inches of deflection. The third test was terminated with the development of a crack at a deflection of 3.125 inches. Conservatisms in the tests included: Distribution of the load over only 1.08 square feet of plate whereas the pipe, the failure of which is the postulated source of the jet has an area of 2.54 square feet in the cylinder zone of the drywell and 3.14 square feet in the sphere; use of flat insert plates in simulating a penetration for the one test where a crack developed rather than plates dished in the direction of load to conform to the curvature of the main shell plate; and application of load as a static load at normal ambient temperature rather than as an impact load with steel at the higher operating temperature of the vessel.

5.2 Preliminary Vessel Expansion Procedure

In order to determine required minimum thickness of the lining it was necessary to establish the extent to which it would be compressed. This amount would be determined by the expansion of the vessel associated with its highest postulated temperature for any future operating or accident condition not concurrent with high internal pressure or by the procedure planned for expanding the vessel to create the air gap if this procedure would expand the vessel to a greater extent than the future conditions.

The simplest and therefor probably most reliable expansion procedure appeared to be to release steam from a temporary boiler into the vessel until saturation conditions at a sufficiently high pressure to protect the vessel against buckling prevailed and to hold this steam pressure until the vessel metal temperature reached the steam temperature. A suitable internal pressure was 35 psig which is associated with a saturated steam temperature of 281°F. Expansion at this condition would exceed postulated accident or operating expansion, hence it became a criterion for determining lining thickness.

5.3 Lining Thickness

At the most critical location, the point on the sphere most distant from the embedment, thermal expansion at 281°F was expected to be 1.057 inches. Tests on the compressible material reducing its thickness this much, plus that due to compression from the fluid concrete pressure, from an initial thickness of about 2 1/2 inches set the design pressure which would be transmitted to the concrete wall during vessel initial expansion at 20 psi. Some tolerance on thickness of compressible material had to be allowed; a feasible limit was plus or minus 1/4 inch. Since the design pressure on the wall assumed 2 1/2" minimum, a thickness of 2 3/4 inches plus or minus 1/4 was indicated.

5.4 Vessel to Wall Distance

In considering the acceptability of the 3 inch upper limit of tolerance in relation to the maximum acceptable distance between steel and concrete, it was noted that the initial 3 inches would be reduced by; the compression of the material under the fluid concrete pressure, the thermal expansion of the vessel in going from ambient temperature during construction to an operating temperature at which the mca could occur, and the fully compressed thickness of the material.

These conditions were expected to reduce the 3.0 inches to an amount adequately below the 3.125 minimum failure deflection of the CB&I jet load simulation tests, particulary in view of the many conservatisms in those tests.

It was subsequently determined by tests and measurements during the expansion operation that these conditions would reduce a 3.0 inch gap as follows:

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Compression under fluid concrete pressure:	.10 inch
Vessel thermal expansion @ $100^{\circ}F$:	.15
Residual thickness of lining:	.25
TOTAL	.50
Maximum Reduced Thickness:	2.50 inch.

6. APPLICATION OF LINING MATERIAL

6.1 Lower Region

The lower region of the steel drywell containment vessel from its invert at elevation 2'-3" to elevation 8'-11¼" is embedded inside and out, in concrete to form its permanent support. The concrete fill is continued inside up to elevation 10'-0" with a curb to elevation 12'-3". Outside, the vessel is restrained by a sand filled pocket from elevation 8' - 11¼" to elevation 12' - 3" to form a transition zone.

Erection and testing of the drywell steel containment vessel was completed and the first floor construction was scheduled to be started prior to the final testing and decision to proceed with the inelastic compressible material. Since the vessel expansion in the lower region due to increased temperature and pressure is relatively small (in comparison to that at the sphere-to-cylinder transition some 60 feet above the point of embedment) the compression characteristics of a compressible material for this lower region were not as critical. Owens-Corning Fiberglas S F Vapor Seal Duct Insulation had the required stiffness to resist the fluid concrete pressure; an analysis of the containment vessel by the Chicago Bridge & Iron Co. demonstrated that the load imposed on the vessel to compress the Fiberglas (about 6 psi) was acceptable in this lower region of heavier vessel plates without any balancing internal pressure. In order to proceed with the concrete construction through the first floor prior to reaching a decision on the inelastic material, this 2" Fiberglas board was applied to the vessel up to elevation 23'-6". The material was furnished with a factory applied laminated asphalt kraft paper waterproof exterior face, and was attached to the vessel with mastic and insulation pins; joints between boards, and edges and penetrations were sealed with glass fabric reinforced mastic.

6.2 Access for application to the Vessel

It had been anticipated that the material application would proceed step-wise with construction of the concrete shield wall. The general contractor with whom negotiations for the concrete work were being conducted advised that his schedule would be a month longer if the work were to proceed in this manner. Burns and Roe's Construction Management in discussions with All Purposes Fireproofing and a scaffolding specialist, the Chesebro Whitman Division of Patent Scaffolding, developed an arrangement whereby the material could be applied in the latter stage of the Reactor Building First Floor construction contract thus reducing the time required for construction above by a month.

The radial steel trusses spanning from the center drywell support pedestal to the exterior foundation walls of the building, erected above the first floor to support the first floor forms, provided support and anchorage for scaffolding at a base elevated above the floor thus avoiding significant interference with the first floor construction. The scaffolding all around the vessel extended from that base up to the vessel flange and was cantilevered in, following the curvature of the top hemisphere, to provide access to all parts of the sphere and cylinder without support from the vessel.

6.3 Application

The mixing and foam injection was done at grade and the slurry was pumped to the point of application starting at the top flange. The material was built up in 3 coats in accordance with the procedure developed by Certified Industrial Products, the first coat 1/2 inch of standard Fire-Bar, the balance, 2 coats of Fire-Bar of reduced density to make up the total specified thickness of 2-3/4" ± 1/4 inch for the upper hemisphere and 2-1/2 inches ± 1/4 inch for the lower hemisphere and the cylinder. The actual application of the material was completed in about two weeks during the latter part of May and early June, 1966, and proceeded without difficulty other than some washing off of inadequately protected new work by rain. On that occasion inspection of other exposed work which had cured 24 hours or more showed no damage.

6.4 Bond Breaker

It was desirable from the schedule point of view to apply the bond breaker as soon as possible to permit removal of scaffolding. Development test samples were essentially dry in about 2 weeks but, as noted above, the cementing reaction was complete in 7 days and was 50% complete in 24 hours. Since the lightest density material which had been found to be practicable required a 15 to 20 psi load to be compressed the necessary amount rather than the ideal 10 psi, there was no need to be concerned with achieving gain in strength after 24 hours. Leaving the surface unsealed to facilitate removal of excess water from the material was not particularly desirable since rebound would be less if the material were to be compressed in a moist condition. The only disadvantage to early covering would be the reduction in value of the damp material as insulation during the operation of expanding the vessel by heating. Schedule being of paramount importance, the bond breaker was applied after a minimum period of 48 hours. Material used was Griffolyn 4 mil clear polyethylene sheet reinforced with glass fibers, attached by means of speed washers on the nylon insulation pins previously stuck on the vessel at 4 foot intervals each way. Seams were sealed with pressure sensitive fabric tape. Some consideration was given to providing further protection from wind in the form of a light wire mesh (chicken wire) however, the first areas done demonstrated that the reinforced polyethylene, thoroughly taped, provided a stable,tight cover, and no further measure appeared to be justified. Prolonged exposure through the winter resulted in stripping of the polyethylene from the cylinder in high winds; loss of compressible material was limited to spots where insulation pins were pulled from the vessel; the spots were patched with previously cured plugs of compressible material and the covering was replaced as the concrete construction proceeded.

6.5 Repairs

As noted above, extensive mechanical damage was sustained above the 51'-3" floor level due to the circumstances of extraordinary exposure to other construction operations there. The damage involved not loss of material but a reduction in thickness from the pressure of workmen and reinforcing steel leaning against it. Repair was accomplished by stripping the compressed outer layers but leaving the base coat from which the required thickness was again built up by spray application in layers as specified for the original work. Testing of production samples described below had shown greater strength than previously anticipated hence in the replacement work, wet density was held at the lower limit of the range used in the original work and thickness was increased to the upper limit.

7. PRODUCTION INSPECTION

The United States Testing Company, having previous experience with the material and having an operation at the jobsite (for concrete testing) was engaged to provide inspection services.

7.1 Density

The development tests had demonstrated that the desired compression characteristics were achieved by the formulation producing a material having a dry density of 8 pounds per cubic foot and that this dry density corresponded to a wet density at the spray nozzle of 29 pounds per cubic foot. Hence the principal inspection effort was directed toward monitoring wet density and of course, the gaging of thickness. Density was checked approximately hourly ; at the infrequent deviations from the acceptable range of 27 to 31-1/2 pounds per cubic foot, work was stopped and the variables affecting density, the foam and/or water content, were adjusted until satisfactory density was demonstrated by another check

7.2 Thickness

Thickness was gaged during the spraying by observing the projection of the uniform length insulation pins stuck on the vessel at 4 foot intervals and was checked by probe by United States Testing. Deficient or excess thicknesses were corrected as the work progressed. Thickness was subsequently checked by Burns and Roe before release to the general contractor for each concrete placement against the material; no out-of-tolerance thickness was found in these subsequent inspections. Initally no record of actual thickness was made other than that it conformed to the specified thickness within the tolerance. It was later decided, after about a third of the concrete wall height had been placed, that a knowledge of actual material thickness might serve some future purpose; hence a record of measured thickness at about 3 foot intervals was kept but only at and above elevation 47 feet.

8. PRODUCTION SAMPLING AND TESTING

There was little question that the material, properly formulated and applied, would have sufficient strength to resist the load to be applied during the placing of wet concrete against it without excessive deformation since the development testing had shown that resistance to compression associated with vessel expansion in the order of twice the ideal would have to be accepted. However, with the concrete wall designed for a 20 psi load expected during the operation of compressing the material, some check was indicated to insure against greater resistance to compression.

8.1 Samples

Twenty-one samples of the material were obtained as the work progressed by spraying into 18 inch square plywood boxes located on the work platform at the point of application, to the depth in the box equal to the thickness being applied. The samples were taken at intervals such that each would represent the material applied to a specific area of the vessel, and were labeled with elevation and azimuth to identify that area.

8.2 Tests

Since the concern was to determine stress-strain characteristics at maximum strength, the compression testing of these production samples was deferred until they were thoroughly cured and dried. Tests were performed in August, 1966 by United States Testing using the same procedures and equipment previously employed in testing of the development samples.

The variation in strength between different samples was wider than expected considering that the previous development samples had been made with the same equipment; resistance of 9 of the 21 samples at 1 inch of compression exceeded the 20 psi maximum observed in the development samples and used as a design load for the concrete wall.

8.3 Off-Wall Samples

A question of whether the samples were representative of the work in place was largely dispelled by subsequent test of two samples cut off the wall of the vessel. These two tests also demonstrated the variation shown by the production samples and the more resistant of these two also exceeded the maximum strength of the development samples.

8.4 Penetrometer

The production samples, their resistance to compression having been established by the tests, provided a means of calibrating a hand penetrometer which was used to spot check the initially applied material and to check the strength of replacement material applied to areas where the original lining was damaged and removed.

9. EVALUATION OF PRODUCTION SAMPLE TESTING

In order to evaluate the effect of the greater indicated strength of the material, vessel expansion, as it would vary with distance from the vessel embedment, was calculated - still assuming the heating of the vessel to the 281°F which would permit the relatively simple vessel expansion by steam heating. Comparing vessel expansion at sample location with strength of the sample for that location and discounting a particularly high-strength sample because the material it represented was damaged and replaced, the maximum load on the wall was indicated to be 28 psi.

Although 20 psi had been established as a design criterion for the concrete wall, this criterion was not controlling in the design. An analysis of the reinforcing provided to resist the loading condition at mca; dead and live load, thermal gradient and jet force; showed a capacity to accept a pressure of 31 psi without exceeding normal allowable stresses. (An increase in allowable stress on the order of 33 percent would be consistant with accepted practice for this temporary condition.)

While the numbers resulting from the material tests supported the preliminary plan to expand the vessel with saturated steam, the margin for error was small and the disparity between individual test results was large. Under these circumstances it was prudent, from the viewpoint of protecting the vessel and the concrete wall from overstress, to consider alternate means of heating and pressurizing which would control the heating to the lower temperature actually required.

10. REQUIRED VESSEL EXPANSION CONDITIONS

In order to consider means of heating and pressurizing the vessel alternative to the preliminary selection of saturated steam, it was necessary to determine the amount of vessel expansion required.

The minimum extent to which the drywell vessel would be required to be expanded would be that expansion which would equal the thermal expansion associated with the conditions causing the greatest difference in vessel temperature postulated for any future operating or accident condition not accompanied by concurrent high internal vessel pressure plus some allowance for possible inaccuracies in assumptions.

10.1 Maximum Vessel Temperature Change

Conditions not concurrent with a concurrent with a high internal drywell vessel pressure such as a malfunction of the containment cooling system could cause the temperature of the drywell atmosphere to rise to such a level that it would be necessary to shut down to correct the condition. While the shutdown temperature had not been established it would be in the order of 160° to 170°. The drywell atmosphere temperature which was expected to persist after the relatively rapid (17 minute) rise and fall of temperature and pressure expected to accompany the mca fill within this range, at 162°F. This temperature, 162°F, was used as a basis for determining the minimum extent to which the drywell vessel would be required to be expanded.

The most severe temperature difference would occur if the abnormal increase in temperature were to be experienced during start-up from a completely cold condition at the coldest time of the year. It was considered adequately conservative to assume that the temperature of the vessel and surrounding concrete shield wall within the completely enclosed Reactor Building would not be lower than 50°F.

With the insulating effect of the compressible material and the air gap that will have been created before start-up, the concrete wall temperature would not have increased materially before tha assumed abnormal increase in temperature at start-up, hence the vessel thermal expansion to be provided for must be that associated with a change in vessel temperature from 50°F to 162°F. It would, of course, not be necessary to start the expansion operation at 50°F or any specific temperature but only to provide for a temperature difference of the 112°F.

10.2 Allowance for Rebound

Since the selected compressible material is not perfectly inelastic, an allowance for rebound had to be added. As demonstrated by the tests described above, inelastic compression stabilized at 80% of the reduction in thickness of the material. With temperature and expansion a linear relation, the required expansion, in terms of temperature difference, would be 112/0.80 or 140°F.

10.3 Internal Vessel Pressure Criteria

It was intended that the pressure to be maintained within the vessel during the expansion operation to protect it against buckling be substantially greater than the external pressure imposed on the vessel by the compressing of the asbestos-cement material.

The pressure would of course be limited by the design pressure for the vessel. However, the discontinuity stress at the point of embedment due to internal pressure would be additive to discontinuity stresses at this point due to thermal expansion and to the external load to be imposed by the resistance of the lining. Hence the pressure should also be subject to the limitation of maintaining discontinuity stress in the embedment zone to within the allowable consistant with the criteria for the vessel, ie with ASME Section VIII and Nuclear Code Case 1272N. Furthermore, net positive internal pressure would expand the vessel and therefore the thermal expansion need not be that of the entire 140° F difference derived above but some lesser amount which with the expansion due to pressure, would be equivalent to 140° F thermal.

Thus, in order to assure that external pressure did not exceed internal pressure, to determine discontinuity stress and to evaluate the excess internal pressure available to expand the vessel, it was necessary to evaluate the external pressure which would be expected to be imposed by the compressible material during the expansion operation.

10.4 Evaluation of External Pressure

External pressure would, of course, depend on the extent to which the material would be compressed and on its resistance to compression to that extent.

The maximum movement of the vessel at the critical point of sphere-to-cylinder transition caused by a 140°F thermal expansion or its equivalent, taking into account upward accumulation of expansion due to the lower region of the vessel being embedded, was calculated to be 0.67 inch. Of the several compression tests described earlier, those on the samples removed from the vessel were considered to be more reliable than tests on samples not actually a part of the work and more reliable than the penetrometer readings since those were tests of a smaller area. The more resistant of the two off-wall samples was in the upper range of strength of all tests hence use of its compressive strength would be conservative.

Using that test and considering the increased resistance due to the precompression resulting from fluid concrete having been placed against it, its resistance to compression at the calculated deflection of 0.67 inch was 23 psi.

Deflection and thus load was expected to decrease from this amount at the sphere-to-cylinder transition to zero at the embedment.

The fiberglass applied to the vessel between embedment at elevation 12'-3" and first floor at elevation 23'-6" had a lower resistance to compression than the asbestos-cement material; in this region of expected relatively small vessel deflection, the stress-strain characteristics of the two materials were assumed to be the same for the purpose of evaluating external pressure.

10.5 Selection of Internal Vessel Pressure

To select an internal pressure consistant with allowable discontinuity stress at the embedment, the stress due to this load from the compressible material, with the other concurrent loads, other than internal pressure, was combined with stresses due to a range of internal pressures.

From this range, a value of 40 psig was found to produce with the other concurrent loads, a discontinuity stress within allowable. The other concurrent stresses included those due to the fluid pressure of concrete (this being considered a residual stress since no opportunity prior to formation of the air gap had existed which would allow the deflection of the vessel induced by that load to be relieved) the thermal expansion and the normal dead loads.

10.6 Expansion Due to Pressure

Having this selected an internal pressure to be used during the expansion operation and having evaluated the external pressure, it was then possible to make a judgement as to how much expansion due to excess internal pressure would be considered as making up a part of the required equivalent of 140°F of thermal expansion.

For this vessel the radial growth caused by one psi of internal pressure is roughly equal to the thermal radial growth due to 1°F of temperature increase or about 0.003 inches. However, due to such factors as the restraint on mechanical expansion imposed by the heavy plate at the sphere-to-cylinder transition and the uncertainty as to the actual resistance of the compressible material, the amount of expansion due to pressure to be considered effective was arbitrarily set at the low value of 10 psig or the equivalent of 10°F. Thus the temperature difference required to be achieved in expanding the vessel was reduced to 130°F.

10.7 Conclusion

As developed above, the conditions required to be achieved in the operation of expanding the vessel were established as a 130°F increase in temperature of the metal over the concrete shield wall temperature during the operation, at a vessel internal pressure of 40 psig.

11. SELECTION OF METHOD OF EXPANSION

Expansion temperature and pressure were established at 130° F over ambient or about 180° F, and 40 psig. To accomplish the expansion using saturated steam at the 40 psig pressure desired would result in heating to 287° F, the saturation temperature of steam at this pressure, i.e. more than 100° F above the temperature actually required.

Pressurizing with air was thus indicated and various methods of heating the air were investigated.

It was desirable to accomplish the expansion operation over a weekend to minimize disruption of other construction activities. To allow time within the weekend for checking, pressurizing and cooldown after heating; it was desirable to limit the heating period to about 15 hours. A preliminary calculation of the heat input required to bring the drywell metal temperature to 180° F in this period showed minimum heat required to be in the order of 24 million BTU.

This required heat input eliminated the possibility of the compression of the air providing sufficient heat as a practicable procedure. The use of oil or, less objectionably, gas-fired heaters within the vessel would be complicated by the necessity for remote operation, operation under pressure, providing oxygen, and the handling of combustion products. Such heaters outside the vessel involved a rather extensive, relatively high pressure duct system.

Electrical heating within the drywell appeared to have none of these disadvantages other than that of remote operation which was least objectionable with this method and the power requirement, indicated to be in the order of 500 kw, was well within the 2000 kw of temporary power available.

Electrical heating of the compressed air atmosphere within the drywell was selected and a detailed equipment list and operational procedure were developed.

12. EXPANSION EQUIPMENT AND ARRANGEMENT

12.1 Pressurizing

Compressed air was provided by a bank of three 600 cfm, engine driven portable compressors located outside the building and connected to a common 6 inch line. The line was extended into the vessel through an existing 10 inch vessel penetration (No X-67) just above outside grade, some 17 feet above the concrete fill floor inside the drywell. Valves for bleeding off air were installed, a 3 inch at the supply and a 6 inch at another penetration (No. X-3A) just below the top flange of the vessel. Pressure guages, 0-100 psig, 6 inch dial, were installed at the two bleed points and in another penetration (No. X-45) opposite the supply point at about that level.

12.2 Heating

Eight General Electric duct heaters, GE No. 2A 699 G 5, 60 kw, 3 phase, 480 volt, 60 cycle, were spaced uniformly around the interior of the drywell on the platform provided by planking on the radial structural steel beams at elevation 23 feet, 6 inches. These were mounted in unistrut channel frames strapped down to the planking.

Four Chromalox duct heaters, Type TDH 600, 60 kw, 3 phase, 480 volt, 60 cycle were available as spares.

Eight American Coolair Corporation fan units, Model No. C36M, propeller type, 36 inch diameter, for V-belt drive were positioned in the drywell, one behind each heater. Each fan was driven by a General Electric motor, 5 hp, 460 volt, 3 phase, 60 cycle, 184T frame size, Class B insulation, ball bearings, open drip-proof, for belt drive, GE 700 Super Standard Line, SF 1.15. The standard grease for the motors was replaced with Dow DC-44 silicone grease to allow operation in the high temperature environment; the standard lubricant for the fans was suitable for up to 212° F. The fan and drive units, were also strapped down to the planking.

The fans and heaters were oriented so that the discharge would impinge obliquely on the vessel wall, this to promote circulation and to avoid having the motor for the next-in-line fan in the path of the air stream directly off the heater.

The power cables from all heaters and fans were routed to one existing 16 inch diameter vessel penetration (No. X-66) and through two 3 inch conduits welded into the penetration closure plate. Vessel leak tightness was maintained through use of silicone putty injected into Crouse Hinds Type EYS sealing fittings on the conduits.

A separate fused disconnect switch was installed outside the vessel for each heater and for each fan drive since it was anticipated that if might be necessary to operate the fans without the heaters in the event of uneven temperature distribution or to disconnect individual fans and heaters, in case of malfunctions, without shutting down the entire operation.

12.3 Monitoring Temperature

A General Electric Multipoint Temperature Recorder was used to monitor vessel metal and inside air temperatures. Twenty-nine copper constantan thermocouples were placed inside the drywell, twenty four taped to the metal surface and insulated from the drywell atmosphere, five suspended in exposed locations to read air temperature. Those to read air temperature were located at three elevations, two at elevation 23 feet, two at 64 feet and one at 85 feet. Those to read metal temperatures were placed in 8 levels with levels spaced at 8 to 12 feet aprat, 3 per level at 120 degrees apart with those in each level rotated 30 degrees from those in the level below to form a uniform spiral pattern over the entire surface of the vessel exclusive of the head.

The wires from all thermocouples were routed to the vessel penetration used to bring out the power cables and were brought through in a separate conduit welded into the penetration c losure plate and sealed in the same manner as for the power cables.

12.4 Monitoring Expansion

The existing vessel penetrations, being pipes welded into the vessel and extending out through the concrete shield wall through sleeves (thus not in contact with the concrete) provided accessible points at which vessel expansion and contraction could be measured.

Fourteen dial indicator extensometers were bracketed to the outside face of the concrete shield wall, two at each of seven vessel penetrations to monitor horizontal and vertical components of expansion and contraction of the vessel. Flat plates were tacked to the penetration pipes to provide true horizontal and vertical surfaces to contact the extensometers.

The seven penetration pipes used were selected to provide a range of elevations and locations as tabulated below:

Penetration No.	Elevation	Azimuth
X-66	27'	38°
X-2A	27'	171°-15'
X-32	36'	125°
X-36	44'	290°
X-63	62'	340°
X-12A	62'	240°
X-19	86'	190°

The temperatures at the outside ends of the penetrations were observed, by means of insulated thermometers taped to the pipe. These, averaged with the temperatures at the inside end (the vessel temperature), would provide a basis for correction of the indicated vessel movement to compensate for thermal expansion of the penetration pipes.

13. PREPARATION FOR EXPANSION OPERATION

The personnel airlock which had been removed to allow use of the larger concentric equipment hatch for construction purposes, was reinstalled. The top head gasketed manhole cover was bolted in place. Several penetration pipes had been opened, the principal ones being the main steam, feedwater and vacuum breaker connections; except for main steam and feedwater, the penetrations were closed to maintain pressure and a reasonable degree of leak tightness by rewelding on the original caps. To avoid the extensive welding operation of replacing the dished head closures for main steam and feedwater, a stiffened 3/4 inch flat plate with 3/16 inch rubber gasket was placed against the inside end of each 30 and 36 inch penetration pipe and was held in place by a 1 inch threaded rod extended out through the penetration to an assembly of 6 inch steel channels spanning the diameter of the pipe at its outside end. In the subsequent pressurizing operation the substitute closure plate proved to be structurally adequate but it was apparently not possible to apply sufficient seating pressure on the gasket; one of the four blew out at below 5 psig and all 4 were replaced by seal welding the plate to the penetration pipe.

Penetration closures were intended to be structurally adequate for the pressure and without gross leaks which would significantly reduce internal pressure, however minor leaks would not affect the planned operation hence inspection before pressurizing was limited to a visual check.

The equipment and thermocouples were installed in the arrangements described above and were individually checked for operation and the thermocouples were calibrated.

Both inner and outer gasketed airlock doors were closed.

14. EXPANSION OPERATION PROCEDURE

14.1 Pressure Test

Before starting the heating operation it was desirable to obtain, by pressure test, assurance that the replaced penetration and access closures were safe and free of gross leaks, hence the first step in the operation was intended to be to pressurize without heat, initially to 10 psig at which point the replaced closures would be inspected and soap bubble tested and then, if satisfactory, to increase the pressure to 50 psig, 25 percent over the pressure intended to be maintained during heating, as an overload test. The pressure was to be increased to the 50 psig in increments of 10 psig, holding at each increment to monitor expansion reflected by extensometer readings to assure, before proceeding further, that the vessel was free to expand in response to the internal pressure.

14.2 Pressure

A satisfactory overload test would be followed by bleeding air to reduce pressure to 30 psig anticipating that expansion of the air due to heating would increase pressure to a level approaching the intended 40 psig with final adjustment to that pressure to be made by pumping or bleeding off as required.

14.3 Heating

With the heaters and fans in operation it was intended to interupt the operation once to experimentally determine the metal temperature below the desired maximum at which heat input should be cut off in order that continued heat transfer from the air to the metal without further heat input would result in equilibrium at the desired maximum metal temperature. The monitoring of the representative range of temperatures at 15 minute intervals would indicate any necessity to correct uneven temperature distribution; it was expected that operating the fans without the heaters would do this. The monitoring of expansion by local reading of the extensometers initially at 1/2 hour intervals and subsequently hourly (or more frequently if abnormal) would show up deviations from the predicted pattern if and as they developed, to permit evaluation as to whether holding for further investigation or shutdown of the operation was indicated.

14.4 Cool Down

Upon reaching the desired temperature it would be necessary to cool down with pressure on until the vessel had contracted sufficiently (approximately 20 percent of expansion) to assure that the rebound of the compressible material would not impose an unbalanced external pressure on the vessel.

14.5 Initial Computer Program

On the basis of the rated output of the heaters selected, the total weight of material to be heated and assumed conductivities based on the character of the surrounding materials, a computer program to predict the time-temperature behavior of the vessel during heatup was developed and printed out for 10 minute intervals for use as a guide to progress.

The initial computation indicated that the heating of the vessel 130°F to the expected requirement of 180°F would be accomplished in 15 hours.

15. MARCH 3-6, 1967, EXPANSION OPERATION

15.1 Required Conditions

Preparations were completed at 8:20 pm Friday, March 3, at which time the concrete shield wall temperature was observed at mid thickness and over a range of elevations and was found to be at an essentially uniform temperature of 43° F. With the required increase established as 130° F, the objective of the expansion operation was to obtain a vessel metal temperature of 173° F at an internal pressure of 40 psig.

15.2 Pressure Test

(March 3, 8:20 pm to March 4, 1:00 pm)

15.2.1 Pressure

Pumping started at 8:20 pm but was shut off at 10:00 pm when the pressure, then less than 5 psig, was lost due to the forcing out of the gasket on the temporary closure of one of the main steam and reactor feedwater penetrations. The gaskets on all four were then removed and the closure plates at the inside ends of the penetration pipes were seal welded to the pipes.

The pressure test was restarted at 2:40 am, March 4; with the three 600 cfm compressors in operation, pressure increased at a rate of 6 to 7 psig per hour. The full overload test pressure of 50 psig was reached at 11:00 am and was reduced by bleeding off to 30 psig at 1:00 pm.

15.2.2 Temperature

Minor increases in temperature were obtained from the warm (98° F) air introduced over the 8 + hour pumping period; air from 50 to 54° F, metal from 40 to 47° F.

The bleeding operation (expansion of the remaining atmosphere) resulted in decreases in temperature, air to 39° F, metal to 43° F. Pressure was reduced at a rate of 10 psig per hour.

15.2.3 Expansion

Extensometers were read and recorded at 5 psig increments and decrements of pressure (approximately 45 minute intervals). Movements corresponded reasonably well with predictions except for vertical movement at elevations 62'-0" where 0.12 inch vertical movement at 40 psig was calculated. Penetration No. X-12A at azimuth 240° showed essentially no vertical movement while Penetration No. X-63 showed 0.32 inch at this pressure. Another inspection of the space between Penetration X-12A and its sleeve through the concrete wall assured that the pipe was completely clear of restraint from the wall. The other observation points, particularly the one above, Penetration X-19 at elevation 86', confirmed general vessel movement in accordance with predictions. No explanation was apparent other than the general observation that these penetrations were immediatly below the 2-5/8 inch thick sphere to cylinder transition which, as a restraint, would locally influence the curvature of the expanding vessel. To attribute the apparently abnormal readings to response of the vessel discontinuities to pressure loading, requires that the different size and different reinforcing details for these two penetrations, both at elevation 62'-0", explains their different response. The 9' length of pipe between vessel and gauge point as a lever arm would magnify the effect of a change in vessel curvature perhaps enough to obscure actual vessel movement.

Since the vessel itself had previously been successfully overload tested, it was considered enough, for the purpose of this operation, to verify that "abnormal" readings were not due to restraint imposed by the wall; the other observation point readings and the inspection established reasonable assurance of no restraint hence the pressure test was continued to completion. Movements of these points during the subsequent heating operation were more in line with predictions thus providing a further indication that the "abnormal" readings were characteristic of the manner in which the vessel responded locally to pressure.

15.2.4 Leakage

The penetrations which had had test caps removed and replaced or modified were soap bubble tested starting at 10 psig. Small leaks were observed in all of the replaced vacuum breaker to vent pipe penetration closure welds and in the weld of the conduit for thermocouple leads through the cap on Penetration X-66, at 10 psig. At 25 psig a small leak developed in one of the main steam seal welds made at the beginning of the test and in the other main steam and one feedwater at 40 psig. The leaking welds were inspected and judged to be of no consequence to the expansion operation.

15.3 Heating with 480 kw Capacity

(March 4, 1:12 pm to March 5, 12:40 pm)

15.3.1 Temperature

All heaters (8 at 60 kw) and fans were started at 1:12 pm and were all operated continuously over this period. Initial conditions were air at $39^{\circ}F$, metal at $43^{\circ}F$. Metal temperature increased at $3^{\circ}F$ per hour until early

March 5 (about 1 am) then dropped to 1° F per hour. Heating was stopped at 12:40 pm, March 5 to install additional heaters since the rate of progress indicated an impractical length of time to complete. Conditions at shutdown were air at 107° F, metal at 92° F.

15.3.2 Pressure

Compressors were not operated during this period. The pressure increase due to heating over the roughly 24 hours and 68° F change in air temperature was from the initial 30 psig to 35 psig. To shutdown the operation for installation of additional heaters it was not considered necessary to cool down before reducing pressure since metal temperature was only 52° F above the initial condition hence vessel contraction due to pressure reduction and the expected temperature drop during blowdown would exceed rebound of the lining material. Pressure was reduced from 35 to 0 psig between 12:43 and 2:00 pm.

15.3.3 Expansion

Extensometers were read and recorded at intervals of 1/2 hour during the 1st 6 hours of the heating operation and hourly thereafter. Movements corresponded reasonable well with predictions, including those at the points at elevation 62' where the apparently abnormal movement during the pressure test was previously observed, thus reinforcing the conclusion that the previous readings were characteristic of the manner in which the vessel responded locally to pressure, as noted above under "Pressure Test".

15.3.4 Other Observations

Snow began to fall on the exposed top head at about midnight, roughly the time when rate of temperature increase dropped from 3° F per hour to 1° F per hour. Arrangements were made to cover the head in the morning and tarpaulins over planking were in place at 10 am, March 5.

15.4 Heating with 720 kw Capacity

(March 5, 12:40 pm to March 6, 8:30 am)

The operation was suspended for 4½ hours while the 4 spare 60 kw Chromalox heaters were installed at alternate locations of the eight 60 kw GE heaters.

15.4.1 Temperature

Metal temperature at 5:15 pm when heating was resumed was 84° F, a drop of 8°F during the shutdown. Considering this temperature level, the rapid pressure increase to be expected, and the slow temperature increase, it was not considered necessary to await pressure build-up before starting heating. The 92° F maximum metal temperature reached before shutdown was recovered in 3-1/4 hours (pressure at that time had reached 25 psig and air inside the vessel was at 122° F.) After compressors were off (input of relatively cold air stopped), rate of temperature increase was 4° F per hour briefly, until 11 pm when it dropped to 2 to 2-1/2 F° per hour. Heating was interrupted for one hour, 4 am to 5 am, to repair a smoking connection on the #1 main power cable.

At 8:00 am Monday, March 6, the metal temperature was at 112° F and was increasing at a rate of 2° F per hour. The extent of time which would be needed to complete the operation at this rate and the consequent continued suspension of other construction activities coupled with the changes which experience had shown would improve the rate and which could be made if the operation were to be interrupted led to the conclusion that the operation should be suspended at that time and be resumed the following weekend.

15.4.2 Pressure

Compressors were started at 5:15 pm and, in order to observe what improvement in rate of temperature increase the additional heaters would produce, the input of relatively cold air was stopped at 8:30 pm when the pressure reached 25 psig. If the rate justified optimism about completing this weekend, pumping would be resumed to reach 35 psig. Pumping was not resumed. Pressure had reached 26 psig when the operation was discontinued at 8:40 am March 6. It was not considered necessary to cool down before reducing pressure; the metal temperature was now 72°F above initial conditions; vessel contraction due to pressure reduction and temperature drop during blowdown would exceed rebound of the compressible material.

15.4.3 Expansion

Extensometers were read and recorded hourly; movements corresponded reasonably well with predictions.

15.4.4 Other Observations

Voltage was observed to be extremely low: readings at time were:

March 5,	9 pm	421 volts
	10 pm	421.5 volts
	11 pm	430 volts
March 6,	2 am	400 volts
	3 am	400 volts
	5:30 am	420 volts

16. CONCLUSIONS FROM THE MARCH 3-6, 1967 OPERATION

The failure to achieve the predicted rate of progress, heatup to 173° F in 14 hours, was concluded to be basically attributable to moisture in the compressible material and to the wetting of the exposed top head causing greater than anticipated heat loss.

16.1 Moisture in the Compressible Material

The condition of excessive moisture in the compressible material became apparent when compression forced water out through the sleeves around several of the penetrations. Probable sources of moisture were: mixing water from the spray application sealed in by the polyethylene covering; rain to which the upper areas of the lining were exposed when the covering was damaged; drainage entering the material at the top flange of the vessel and; locally at the control rod drive penetrations, the wet drilling operation performed to clear the space around those penetrations. Other than to assure no penetration of grout during the concreting operation, no particular effort had been made to exclude moisture since its effect on compression characteristics would be a moderate improvement through a slight reduction in strength and a lesser rebound.

The moist condition of the material, contributing to loss of heat by decreasing the value of the asbestos lining as an insulator and by absorption of latent and sensible heat, was not susceptible to change in any reasonable time hence the alternative of increasing heat input was indicated. Four 60 kw Chromalox heaters in addition to the 4 already on the job as spares were available in time to be used the next weekend.

16.2 Heat Loss Through Vessel Head

The risk of greater heat loss through the top head due to its becoming a wet surface, as it did in the snow of March 4 and 5, had been eliminated by covering it with tarpaulins; the condition could be further improved by insulation.

16.3 Voltage

Another contributing factor to the slow rate of heatup was the effective operation of the heaters at less than rated capacity due to low (400 volt) voltage. This condition could be improved by changing the transformer taps.

16.4 Conclusions

It was expected that the operation could be completed in the next weekend in view of the conditions that: 1) the 17 hour pressure test phase had been completed and need not be repeated 2) the total heater capacity was doubled from the original installation by the addition of eight 60 kw heaters 3) the top vessel head, previously exposed, was insulated and protected from the weather 4) voltage to the heaters would be up from 400 volts to 480 volts 5) an air gap had been formed between the lining and the concrete which would provide additional insulation in the early phase until expansion to that extent was recovered.

16.5 Revised Computer Program

To determine whether this expectation was justified, the computer program of time-temperature performance was revised to conform to the experience curve developed with the original 480 kw heating capacity. The revised computer program was run for the new 960 kw heating capacity. The new run predicted 42 hours to reach a metal temperature of 173° F, or well within a weekend. Furthermore, the 42 hour time was an outside limit, barring major disruptions, since it took into account no improvements other than the additional heaters and assumed a 45° F starting metal temperature whereas actual starting temperature would be found to be 58° F.

17. MARCH 10-12, 1967 EXPANSION OPERATION

17.1 Required Conditions

Preparations for resumption of the heating operation were completed at 3:00 pm, Friday, March 10, at which time the concrete shield wall temperature was observed and again found to be 43° F hence the objective remained to obtain a vessel metal temperature of 173° F at an internal pressure of 40 psig.

17.2 Heating with 960 kw Capacity

17.2.1 Temperature

It was not considered necessary to delay start of heating for the pressure build-up since the vessel had already been expanded to the extent associated with conditions of 112°F and 26 psig. All heaters, sixteen at 60 kw and fans were started at 3 pm March 10. Initial air and metal temperature was 58°F.

Initial heat up rate was about 10° F per hour metal temperature increase which produced a rather wide range of metal temperature, about 45°F; highest at the heater level and decreasing upward. The heaters were turned off for 20 minutes between 6 and 7 pm with fans remaining on to promote circulation and reduce the metal temperature variation. The result was a rapid drop in air temperature with only a 5°F reduction in the spread. Since the variation was fairly uniform and temperature within each level of thermocouples reasonably close, the effort was abandoned with the reservation that it would be pursued again if the variation did not narrow in the course of heating.

The metal temperature had reached 100° F, 12°F below the maximum reached previously, when the pressure build-up was to 32 psig at 8:18 pm.

After passing the maximum conditions attained the previous week, heat up rate dropped gradually to about 3° F per hour.

One pair of heaters was out of service between 3:20 am and 4:15 am March 11 to replace a burned out fuse. Voltage, initially 480, had increased to 500; transformer taps were dropped; voltage at 5:00 am was back to 480.

Main breaker, thus all heaters, went out at 5:25 am March 11 due to short in No. 1 main switch. A brief electrical fire required the No. 1 bank (half the heaters) to stay out temporarily for repairs. No. 2 bank was back on at 5:40 am; 2 pairs of heaters in No.1 bank were back on at 7:50 and all heaters were in service at 10:30 am. Probable cause was moisture being forced out of the drywell inside the cable insulation; the condition became so pronounced that by 8:00 am water was dripping out at the switches. Metal temperature, at 144°F at 5:25 am, dropped and did not recover to that level until about 5 hours later. Temperature rate of increase returned to 3°F per hour when all heaters were back in service.

With average metal temperature at about 170°F at 6:27 pm March 11 the temperature variation was still about 28° F. All heaters were then shut off for 45 minutes. With fans left on during this period the spread was reduced to about 18° F with the 2-5/8 " thick plate at the sphere to cylinder transition being low at about 165°F. It was considered desirable to get the transition up to the minimum objective of 173°F if this could be accomplished with overall average not more than about 180°F.

Heating was resumed at 7:10 pm. With the operation approaching completion, the concrete shield wall mid-thickness temperature was checked at 8:30 pm and was found to be still at the starting condition of 143° F. Overall average metal temperature reached 180.5° F at 9:53 pm at which time the transition was at 172°F. Heating was then terminated.

Cool down and pressure reduction were accomplished as described below under "Pressure". Temperature conditions at the time the airlock was opened were air and metal at 140° F.

17.2.2 Pressure

Compressors were started at 4:15 pm March 10; pumping was stopped when pressure reached 32 psig 4 hours later. Pressure increased with temperature at a much lower rate than previously experienced, possibly due to the additional leakage through the cables between wire and insulation; increase was only 2 psig while air temperature had increased from 58 to 206°F. Pumping was resumed at 3:30 pm March 11 when metal temperature was at 159°F and stopped when 38 psig was reached at 4 pm. Further pumping was not required; temperature increase caused pressure to ultimately override the intended 40 psig by 2 psig. This moderate excess was accepted to avoid the temperature drop which would accompany bleeding. After the termination of heating at 9:53 pm, pressure reduction was deferred for an initial cool down period, then performed in steps alternating with cool down and gauging of contraction to assure adequate internal vessel pressure to balance any external pressure due to rebound of the material. When temperature was down from 180.5 to 168° F pressure was reduced to 30 psig. When temperature was down to 160°F pressure was reduced to 20 psig. At 12:10 am March 12 average temperature was 155°F or approximately 20% less than maximum temperature increase. The extensometer readings showed a range of 28 to 38 percent reduction from maximum expansion due to combined cooling to 155°F and pressure reduction to 20 psig indicating no further need for concern regarding rebound of this material since it had been established as not exceeding 20%. Pressure reduction to 0 psig followed and the airlock was opened at 1:25 am, March 12.

17.2.3 Expansion

Extensometers were read and recorded hourly. As maximums were approached a pattern somewhat different from the prediction developed in that, while horizontal movement was in good agreement, the upward accumulation of expansion expected due to the embedment of the lower region was at all points less than predicted. (Therefore vessel discontinuity stress at embedment would have been less than calculated and load on the concrete wall would have been more uniformly distributed and with a lower maximum) All gauge locations had been expected to rise, actually the one near the vessel equator moved essentially horizontally, those 10 feet below the equator moved out and slightly down while the high guage points moved up and out but with vertical component less than predicted, since the calculated rise assumed a contribution from expansion below the equator.

The gauge readings were continued through the cool-down - pressure reduction phase and were used to advantage to confirm vessel contraction to safe limits before final pressure reduction as described under "Pressure" above.

Maximum measured vessel expansions compared with the calculated expansions at each gauging point are tabulated below:

Drywell Movement at Time of Maximum Average Temperature, & Pressure, 180.5°F; 42 psig; 9:45 pm, March 11, 1967.

Penet. No.	Elev.	Azi	Movement (inches)					
			Calculated			Measured		
			Hor.	Vert.	Total *	Hor. **	Vert.	Total *
X-66	27'	38°	.42	.22	.48	.46	-.01	.46
X-2A	27'	171°-15'	.42	.22	.48	.40	.05	.40
X-32	36'	125°	.42	.34	.54	.43	.02	.43
X-36	44'	290°	.43	.44	.61	.38	.20	.43
X-63	62'	340°	.31	.66	.73	.32	.50	.59
X-12A	62'	240°	.31	.66	.73	.36	.10	.37
X-19	86'	190°	.21	.93	.95	.31	.52	.61

* $(\text{Hor}^2 + \text{Vert}^2)^{\frac{1}{2}}$

** Dial readings corrected for 140° F avg. penetration pipe temp.