Advanced Energy Systems Division

**LIGHTWEIGHT CONCRETE MATERIALS
AND STRUCTURAL SYSTEMS FOR
WATER TANKS FOR THERMAL STORAGE**

FINAL REPORT

Prepared by
**R.W. Buckman, Jr.
G.G. Elia
Y. Ichikawa**

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**Westinghouse Electric Corporation
Advanced Energy Systems Division
P.O. Box 10864
Pittsburgh, Pennsylvania 15236**

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ABSTRACT

Thermally efficient hot water storage tanks were designed, fabricated and evaluated. The tanks were made using cellular concrete at a nominal density of 100 lb/ft^3 for the structural elements and at a 30 lb/ft^3 density for the insulating elements. Thermal performance testing of the tanks was done using a static decay test since the test procedure specified in ASHRAE 94-77 was not experimentally practical. A series of composition modifications to the cellular concrete mix were investigated and the addition of alkaline resistant glass fibers was found to enhance the mechanical properties at no sacrifice in thermal behavior. Economic analysis indicated that cellular concrete provides a cost-effective insulating material. The total portability of the plant for producing cellular concrete makes cellular concrete amenable to on-site fabrication and uniquely adaptable to retrofit applications.

1.0 INTRODUCTION

This report describes the design, fabrication and testing of hot water storage systems using lightweight cellular concrete as the construction material. The lightweight concretes are prime candidates for hot water-containing structures that can be designed to incorporate structural as well as insulating layers for thermal efficiency. Hot water storage systems were designed and evaluated that could be assembled from the pre-cast elements or cast and assembled on site.

Lightweight concrete structures of the size necessary to contain volumes of water up to 2000 gallons are quite substantial. It is apparent that the most efficient use of the lightweight concrete technology could be achieved by fabricating on-site and thereby taking advantage of the high mobility of the self-contained lightweight foamed concrete plant.

Five-hundred-gallon sized tanks were fabricated and evaluated for thermal performance. Investigations into composition modification of state of the art cellular concrete were undertaken to ascertain what improvements could be made in thermal and mechanical properties. A cost analysis was made for water storage systems made using lightweight concrete technology and compared with more conventional insulated water tanks systems.

2.0 MATERIALS SELECTION AND COMPOSITION MODIFICATION

2.1 MATERIAL SELECTION

Foam or cellular concrete was the material selected to fabricate the hot water storage tanks. Based on the results of a state of the art survey⁽¹⁻²³⁾ on lightweight concrete materials and inquiries on the availability of lightweight aggregates, it was concluded that cellular or foam concrete offered the best combination of mechanical and thermal properties for the hot water storage tanks. A lack of general availability of lightweight aggregates precluded evaluation of this material. Also, comments from the Lightweight Aggregate Producers Association indicated retrenchment in this industry because of the impact of environmental regulations and rising fuel costs.

Foam or cellular concrete incorporates encapsulated air bubbles as the medium to control the density of the bulk concrete material. The encapsulated air bubbles in the wet concrete slurry upon solidification leave a matrix of a closed cell structure. Cellular or foam concretes made with wet cement (without sand) contain 5 to 10 sacks of cement per cubic yard and have densities in the range of 15 to 45 lbs/ft³. Structural cellular concretes made with varying proportions of cement-sand-foam can be tailored to obtain a wide range of densities from 55 to 110 lbs/ft³ with mechanical properties at the higher densities similar to regular weight concrete. Of the three main processes for making cellular concrete: a) aluminum process (Siporex type)^(a), b) protein process and c) gas/foaming agent process^(b), the protein process as practiced by Celcore Systems, Inc., Ft. Lauderdale, Florida, was selected on the basis of reproducibility and cost.

(a) Requires autoclave (high pressure steam @ 150-200 psi) for 14-18 hrs to achieve mechanical strength. Pore structure is open cell.

(b) Foaming agent added to concrete and expanded with butane or propane. No longer available because of hazard associated with combustible gases used.

The Celcore concrete plant (Figure 1) is self-contained and mobile and is designed for the manufacture of lightweight cellular concrete, both structural and insulating, with the use of Celcore preformed foam^(c). The concrete plant is powered by a 391 cubic inch industrial engine driving five hydraulic pumps which power the hydraulic motors for operation of the air compressor, mixer, concrete pump and a separate cement screen and sand belt materials feeding apparatus.

The loading and mixing operations are controlled from a single operator's position, as is the concrete pump which permits placement at substantial distances (up to 400 ft), both horizontally and vertically at a rate of 25 yd³/hr. Proportioning of water, cement, sand and foam is controlled by a weigh-type mixer, a water meter, and foam injection timer.

2.2 COMPOSITION MODIFICATION

The standard composition for lightweight foamed structural and insulating concrete produced at Celcore is given in Table 1 along with typical properties.

To determine if mechanical strength of the standard mix could be improved without sacrificing thermal properties, a series of experimental mixes were prepared. Additions which were evaluated included a polymer latex addition and alkaline resistant glass fibers. The polymer latex modifier selected was Rhoplex[®] MC-76, a product of Rohm and Haas. MC-76 is an acrylic emulsion designed for modifying cementitious compositions and is reported to enhance strength and durability.⁽²⁴⁾ Alkaline resistant glass fibers, 1/2-in long, with a filament dia of 0.00050-in (0.0127 mm) containing 204 filaments per strand were added to improve crack propagation resistance. The experimental compositions (see Table 2) were prepared as one cubic yard size mixes in the concrete plant described earlier. The use of production size equipment was considered desirable to avoid anomalies which may occur when handling laboratory

(c) Proprietary to Celcore Systems, Inc., however, selection of foaming agent and process of foaming prefoamed foam for cellular concrete is outlined in ANSI/ASTM C869-77.

Figure 1. Celcore Mobile Self-Contained Plant for Making Foamed Concrete.
(Capacity 25 yd³/hr)

TABLE 1: MIX COMPOSITION FOR LIGHTWEIGHT
STRUCTURAL AND INSULATING CONCRETE

	Concrete Type	
	Insulating (lbs/cu. yd)	Structurals ⁽¹⁾ (lbs/cu. yd ³)
a) Portland Cement (Type I)	601	846
b) Water	217	384
c) Sand (Oolitic limestone screenings)	-	2,135
d) Foam (3.75 pcf)	<u>78.8</u>	<u>12</u>
TOTAL	896.8	3,377

Properties (nominal)

Wet Density	33 pcf	125 pcf
Compressive Strength	200 psi	3,000 psi

(1) Also contain 40 oz/yd³ of sugar-free calcium lignosulfonate (water reducing agent).

TABLE 2: EXPERIMENTAL LIGHTWEIGHT CONCRETE MIX COMPOSITIONS

BATCH I.D.	Mix Composition ^(a) lbs/yd ³					Density lb/ft ³			
						Calculated		Measured	
	Cement	Water	Fine Aggregate	Foam	Glass Fiber	Wet	Dry	Wet	Dry
1	846	406	1,420	27 ^(b)	-	100	80	112	103
2	846	440	2,078	10 ^(b)	7	125	104	121.6	113.5
3	846	440	2,078	10	7	125	104	123.6	103.7
4	846	440	2,078	10	14	125	104	119.9	107.6
5	500	180	-	80.9 ^(b)	-	28	20	26.7	16.4
6	378	136	-	85.9 ^(b)	-	22	15	23.0	15.0
7	500	180	-	80.9 ^(b)	7	28	20	34.1	25.3

(a) Cement - Universal-Atlas Type I Portland
 Fine aggregate - Oolitic limestone screenings
 Batches 1-4, 40 oz/yd³ sugar-free calcium lignosulfonate (water-reducing agent)

(b) MC-76 added to mix.

size batches. Thermal conductivity shrinkage, compressive strength, splitting tensile, and modulus of elasticity were determined on 6-in dia x 12-in long cylinders and 6-in x 6-in x 36-in beams were used to measure flexural strength.

Pouring of the samples from the experimental batches is shown in Figure 2. After the concrete samples were poured and had set up, the samples were bagged in polyethylene film to maintain high humidity during shipment to the test labs for physical and mechanical property evaluations. The mechanical property evaluations were performed at Wingerter Laboratories, Inc., in North Miami, Florida, which was conveniently located to Florida Celcore, in Fort Lauderdale. The thermal property evaluation specimens were shipped to AESD for testing.

The mechanical property data for the experimental batches are given in Table 3. Both the MC-76 and glass fiber addition were beneficial to the mechanical properties of the structural foamed concrete compositions, but minimal effects were observed on the strength of the lightweight cement foams (see Figures 3-5). From the standpoint of compatibility of the glass fiber addition with the concrete pumping system, glass fiber additions were limited to 7 lbs/yd³ or less.

Thermal conductivity of the lightweight concrete was determined using a modified hot wire technique with the specimen configuration shown in Figure 6. The thermal conductivity specimen was formed by casting a 6-in dia x 12-in long cylinder which has an instrumented cartridge heater positioned concentrically along the axial diameter.

Thermocouples are located on the heater and at the outer surface of the specimen. By measuring the power input and the temperature T_1 and T_2 , thermal conductivity is determined using the following relation:

$$k = \frac{Q \ln r_1/r_2}{\pi L \Delta T}$$

(a) Cylinder and beam molds.

(b) Filling molds.

(c) Samples bagged with polyethylene film to control curing during shipment to test laboratory.

(d) Samples bagged with polyethylene film to control curing during shipment to test laboratory.

Figure 2. Preparation of Experimental Mix Compositions.

TABLE 3: MECHANICAL PROPERTIES OF EXPERIMENTAL BATCHES^(b)

BATCH ^(a)	Flexural Strength ^(c) psi (28 day)	Compressive Strength psi		Splitting Tensile psi (28 day)	Modulus of Elasticity ^(d) psi x 10 ⁻⁶ (28 day)
		(7 day)	(28 day)		
1	435				3.6
	385	2,900	3,643	356	1.7
	390	2,936	3,714	339	2.8
	415		3,661	200	2.5
	<u>325</u>				
	Avg. 390	2,918	3,673	298	2.65
2	400				
	425				
	425			462	3.6
	410		3,855	332	4.0
	535	3,466	3,750	363	4.7
	<u>500</u>	<u>3,360</u>	<u>3,891</u>	<u>409</u>	<u>3.0</u>
	Avg. 454	3,413	3,832	392	3.8
3	500				
	415				2.5
	435		3,572	323	5.0
	490	2,882	3,537	382	4.2
	<u>550</u>	<u>2,830</u>	<u>3,466</u>	<u>362</u>	<u>2.8</u>
	Avg. 478	2,856	3,525	356	3.6
4	490				
	550				5.9
	460	3,077	3,962	438	9.4
	440	3,183	3,820	288	3.5
	<u>425</u>		<u>3,926</u>	<u>373</u>	<u>2.9</u>
	Avg. 473	3,130	3,903	366	5.4
5	10				
	15				0.084
	10		129	-	0.032
	10	53	55	-	0.062
	<u>10</u>	<u>52</u>	<u>96</u>	-	<u>0.081</u>
	Avg. 11	52	93		0.065
6	10				
	10			-	0.039
	10		44	-	0.038
	10		68	-	0.050
	<u>10</u>	<u>61</u>	<u>68</u>	-	<u>0.038</u>
	Avg. 10	61	60		0.041
7	45				
	35		232	-	
	40		203	-	0.071
	35		91	-	0.034
	<u>50</u>	<u>201</u>	<u>211</u>	-	<u>0.023</u>
	Avg. 41	201	184		0.043

(a) Batches 1-4 are lightweight structural concretes and 5, 6, and 7 are insulating foam cements.

(b) All specimens maintained at 73.4 ± 3°F and 99% relative humidity prior to testing.

(c) Per ASTM C-78-64

(d) Per ASTM C-469-65.

Figure 3. Properties of Lightweight Structural Concrete with MC-76 and Glass Fiber Additives.

705535-3A

Figure 4. Effect of MC-76 and Glass Fiber Addition on 28-Day Compressive Strength of Lightweight Structural Concrete.

705535-2A

Figure 5. Effect of MC-76 and Glass Fiber Additions on 28-Day Compressive Strength of Insulating Foam Concrete.

$$K = \frac{Q \ln \frac{r_2}{r_1}}{2 \pi L \Delta T}$$

Figure 6. Thermal Conductivity Test Specimens.

where

Q = heat input

k = thermal conductivity

l = length = $r_2 - r_1$

$\Delta T = T_2 - T_1$

r_1 = inner radius

r_2 = outer radius

Below ambient outside temperatures were achieved by placing the specimen in a cryogenic chamber. Power into the heater was derived from the voltage and amperage from a regulated power supply. The thermal conductivity data obtained are in Table 4. To allow repeatable thermal conductivity measurements, the thermal conductivity specimens were oven dried at 125°C for 8 hrs and then encapsulated in polyethylene film. This prevented changes in moisture content during testing. At comparable densities, the foamed concrete has essentially similar thermal conductivities as lightweight aggregate concretes at densities below 40 lb/ft³ while the foamed concrete has somewhat lower k values at densities of 90-120 lb/ft³ (see Figure 7).

TABLE 4: THERMAL- CONDUCTIVITY OF MODIFIED LIGHTWEIGHT CONCRETE COMPOSITIONS

BATCH/ SPECIMEN NUMBER	MEAN TEMP. (°F)	k BTU/ft ² -in-hr-°F	Density, lb/ft ³		
			As Received	Pretest ^(a)	Post-Test
1-1	168	3.04	113.7	102.5	102.5
	110	3.06			
	66	3.08			
	100	3.21			
1-2	238	3.24	113.8	102.9	102.9
	133	3.06			
	80	3.08			
	45	3.24			
	26	2.90			
1-3	141	2.94	114.1	103.3	103.3
	117	3.03			
	72	3.06			
	76	3.12			
2-1	150	3.47	124.7	113.8	113.8
	104	3.60			
	52	3.63			
2-2	125	3.72	124.6	113.8	113.8
	88	3.89			
	66	3.82			
	58	3.78			
2-3	178	3.54	122.8	112.9	112.9
	107	3.62			
	171	3.60			
	39	3.54			

TABLE 4: THERMAL CONDUCTIVITY OF MODIFIED LIGHTWEIGHT CONCRETE COMPOSITIONS (Continued)

BATCH/ SPECIMEN NUMBER	MEAN TEMP. (°F)	k BTU/ft ² -in-hr-°F	Density, lb/ft ³		
			As Received	Pretest ^(a)	Post-Test
3-1	156	3.26	114.5	103.3	103.3
	106	3.32			
	53	3.57			
3-2	127	3.38	115.1	104.3	104.3
	88	3.26			
	70	3.55			
	60	3.51			
3-3	194	3.40	114.2	103.5	103.5
	112	3.51			
	178	3.44			
	41	3.78			
4-1	156	3.56	117.7	110.1	110.1
	108	3.58			
	63	3.71			
	93	3.57			
4-2	134	3.56	118.6	107.1	107.1
	97	3.54			
	76	3.67			
	44	3.64			
	25	3.87			
4-3	121	3.61	117.2	105.8	105.8
	73	3.79			
	78	3.71			
	134	3.50			

TABLE 4: THERMAL CONDUCTIVITY OF MODIFIED LIGHTWEIGHT CONCRETE COMPOSITIONS (Continued)

BATCH/ SPECIMEN NUMBER	MEAN TEMP. (°F)	k BTU/ft ² -in-hr-°F	Density, lb/ft ³		
			As Received	Pretest (a)	Post-Test
5-1	160	0.34	23.4	16.2	16.2
	100	0.30			
	64	0.32			
	172	0.35			
5-2	133	0.32	23.7	16.2	16.3
	65	0.42			
	54	0.39			
	88	0.34			
5-3	114	0.34	24.0	16.9	17.0
	86	0.32			
	58	0.32			
6-1	116	0.31	23.3	15.3	15.3
	202	0.36			
	136	0.38			
	90	0.34			
	44	0.41			
6-2	151	0.40	21.9	14.8	14.8
	104	0.28			
	69	0.28			
	163	0.31			
6-3	174	0.39	30.3	20.7	20.8
	108	0.36			
	65	0.42			
	65	0.44			
	51	0.46			
	82	0.40			

TABLE 4: THERMAL CONDUCTIVITY OF MODIFIED LIGHTWEIGHT CONCRETE COMPOSITIONS (Continued)

BATCH/ SPECIMEN NUMBER	MEAN TEMP. (°F)	k BTU/ft ² -in-hr-°F	Density, lb/ft ³		
			As Received	Pretest ^(a)	Post-Test
7-1	107	0.38	33.1	24.3	24.3
	182	0.42			
	146	0.35			
	82	0.43			
	39	0.60			
	43	0.61			
	102	0.43			
	60	0.46			
	19	0.54			
	3	0.80			
7-2	116	0.40	35.2	26.2	26.1
	140	0.44			
	90	0.45			
	46	0.60			
7-3	116	0.44	34.3	25.3	25.3
	142	0.44			
	92	0.45			
	62	0.48			

(a) Samples baked at 125°C for 8 hours and then sealed in polyethylene film prior to test.

Figure 7. Effect of Density on Thermal Conductivity of Lightweight Concrete.

3.0 FIVE-HUNDRED GALLON WATER STORAGE TANKS

3.1 DESIGN

Three 500-gallon water storage tanks were evaluated and are shown conceptually in Figure 8. The lightweight concrete tanks are identified as LWC-1, LWC-2 and LWC-3. LWC-1 was the design by Florida Celcore, Inc. and represents a state of the art configuration that could be mass produced and shipped locally with final assembly at the site. The tank consists of an inner and outer structural shell of reinforced lightweight structural concrete of nominal 100 pcf* which are separated by a layer of insulating cement of nominal 18 pcf.* The inner tank details are shown in Figure 9.

Structural strength is provided by a 5/8-in dia reinforcing bar and an 18-mesh reinforcing screen. The outer tank shell is essentially the same except the structural rib member is positioned on the I.D. surface of the shell (see Figure 10). The tank was designed to withstand 5 psi, a force equivalent to 11.6 ft of hydrostatic head. The inner tank I.D. surface was to be coated with a monomer coating which was to seal the I.D. concrete surface. The seal at the flange was accomplished with a 1-in dia Neoprene O-ring.

LWC-2 was designed to take advantage of increased concrete insulation thickness to minimize heat loss. Thermal analysis indicates that increasing the thickness of the insulating foam concrete beyond about 12 in in thickness provides a diminishing return (see Figure 11). The majority of benefit is derived at an insulation thickness of about 8-9 in. The tank for LWC-2 is identical to LWC-1 except that alkaline-resistant glass fibers were added to the structural concrete mix to enhance crack propagation resistance. The shape of the final assembly was octagonal and this shape was selected to give

*Oven dry density.

615449-1C

Figure 8. Lightweight Concrete 500-Gallon Hot Water Storage Tanks.

Figure 9. Inner Tank Design Details.

Figure 10. Composite Tank Design.

Figure 11. Steady State Heat Loss 500-Gallon Tank as a Function of Insulative Concrete Thickness (18 pcf).

8 in of insulative foam concrete at the plane of the flange (see Fig. 8b). The I.D. surface of the inner tank was coated with a cementitious coating based on the use of (R) MC-76. The flange seal was the same as for LWC-1; i.e., a 1-in dia Neoprene O-ring seal.

LWC-3 was a rectangular configuration assembled from slabs. The tank structure details for LWC-3 are shown in Figure 12. The structural concrete was nominal 100 pcf and reinforced with 5/8-in dia reinforcing bar. Seven lbs of alkaline-resistant glass fiber were added to the concrete mix to provide crack propagation resistance. To provide leak tightness, a membrane liner such as a nylon-reinforced E.P.D.M. would be placed inside the assembled tank.

3.2 FABRICATION

Fabrication of three 500-gallon water storage tanks was done at Florida Celcore located in Ft. Lauderdale, FL, using the mix compositions listed in Table 5. The tank halves for LWC-1 and LWC-2 were cast using plug molds which formed the I.D. surface and fiberglass forms which defined the outside surface contour. Fiberglass molds were also prepared to form the plug molds. Figure 13 shows examples of the molds used for fabricating the inner tank halves. The reinforcing mesh and steel bar were formed and positioned over the plug mold (see Figure 14(a)). For LWC-2, the 18-mesh reinforcing wire was eliminated and alkaline-resistant glass fibers were added to the lightweight structural concrete to provide enhanced crack propagation resistance. The outer fiberglass mold was put in place and then the foamed lightweight structural concrete mix was pumped into the assembled form. Approximately 3-5 min was required to form each tank half. After curing for 24 hrs, the fiberglass mold was removed (see Figure 14(b)), and after an additional 24 hrs, the cast tank half shell was stripped from the plug mold. Prior to assembling, a monomer coating (a polyester resin produced by Koppers) was applied to the I.D. surface of the LWC-1 inner tank. Initially, an alumina tri-hydrate was used as a filler for the monomer, but at the thickness that was applied, the coating spalled upon drying. The initial coating was removed and reapplied by spraying. The purpose of the monomer coating is to provide a barrier against moisture penetration. The inner tank was assembled by bolting (see Figure 15(a)). A 1-in dia Neoprene O-ring provided the seal at the flange surface. The assembled inner tank was

706538-18

Figure 12. Tank Structure Details - LWC #3.

TABLE 5: MIX COMPOSITIONS FOR CONSTRUCTION OF 500-GALLON WATER TANKS

Material (a)	LWC-1		LWC-2		LWC-3	
	Insulating	Structural	Insulating	Structural	Insulating	Structural
Portland Cement Type I	601	846	601	846	-	846
Water	217	384	217	384	-	384
Sand	-	2135	-	2132	-	2128
Foam (3.75 pcf)	78.8	12	78.8	12	-	12
Glass Fibers	-	-	-	3.5	-	7
Expanded Polystyrene	-	-	-	-	8-in. thick	-
TOTAL #/yd ³	896.8	3377	896.8	3377.5	-	3377
WET DENSITY #/ft ³ (Calculated)	33	125	33	125	-	125

(a) Cement - Universal-Atlas Portland Cement, Type I
 Sand - Oolitic Limestone Screenings (40 oz/yd³ of sugar-free calcium ligonsulfonate added to structural concrete (water-reducing agent))

(a)

Figure 13. Fiberglass Molds Being Prepared for:
(a) Inner tank liner and (b) Outer tank liner.

(a)

(b)

Figure 14. Plug Mold for I.D. Surface of Inner Tank Showing:
(a) assembled reinforcement and (b) as-cast inner
tank half with outer fiberglass mold removed.

then positioned inside the bottom half of the outer tank (see Figure 14(b)). The annular space between the inner and outer tank was then filled with insulating foam concrete (see Figure 15(c)). After curing for 24 hrs, the upper half of the outer tank was placed in position and the remainder of the annular volume filled with the insulating foam concrete. The completed LWC-1 tank is shown in Figure 16. The dry weight of the tank was 6,250 lbs. Prior to assembling the inner tank within the outer tank, the assembled inner tank was filled with water and observed for 24 hrs to ascertain the absence of any leaks.

Water inlet and outlet penetrations are 1-in dia plastic pipe located at the top end of the tank. During the pouring of LWC-1, samples of each concrete batch were taken for thermal and mechanical property evaluation.

The I.D. surface of the inner tank for LWC-2 was coated with a cementitious mortar based on MC-76 and had the following formula:

<u>Material</u>	<u>Weight Ratio</u>
Silica Flour	200
Portland Cement (Type I)	100
Rhoplex MC-76 (4%)	63.8
Water	90.0
Anti-foam (B-Dow Corning)	0.3

Two cementitious mortar coatings were evaluated by exposing coated concrete samples to 180°F water for 106 days. The other commercially available mortar is designated SIK121. Both coatings performed equally as well and the MC-76 based mortar mix was selected because of material availability.

The sequence of fabricating LWC-2 is shown in Figure 17. Concrete saddles were cast from structural foam concrete (-125 pcf) (see Figure 17(a)) and are used to support the tank. The bottom half of the tank was placed in the

(a)

(b)

(c)

Figure 15. (a) LWR-1 Inner Tank Halves Assembled; (b) Inner Tank Placed Inside of Outer Tank Half and (c) Placing Insulating Foam Concrete in Annulus Between Inner and Outer Tank.

Figure 16. Completed 500-Gallon Tank (LWC-1) in Position for Testing.

Figure 17. Sequence of Fabrication per LWC-2.

saddle and filled with water to verify the absence of any leaks and also to firmly set the bottom tank half in the saddle. Approximately 6 in of light structural concrete was cast in the bottom to tie the saddle together (see Figure 17(c)). The top half of the tank was set in place, and the flange was bolted together (see Figure 17(b)). The remaining volume of the assembled tank was filled with water to leak check the O-ring seal as well as for any leaks through the concrete shell. The forms were extended and then filled with insulating cement (see Figure 17(e)). After stripping the forms, the exterior surfaces were coated with a skim coat of mortar (see Figure 17(f)) for aesthetic purposes. The completed tank is shown in Figure 17(g). One-inch plastic pipe was used for the water inlet/outlet penetrations located in the top of the assembly. The completed tank positioned on the rear of a mobile lightweight foamed concrete plant is shown in Figure 17(h). The tank was shipped from Ft. Lauderdale, FL to Pittsburgh, PA in this manner.

The third tank configuration, LWC-3, was a modular tank and was assembled from precast slabs. For LWC-3, the lightweight insulating foam thickness of 8 in was replaced with expanded polystyrene board. The cost would have been the same as the insulating foam cement but for a given thickness, the polystyrene has a lower thermal conductivity and hence should give better performance in this situation. The thermal conductivity for the expanded polystyrene board is on the order of $0.24 \text{ BTU/in-ft}^2\text{-hr-}^\circ\text{F}$ which is approximately 50% lower than for the insulating foam cement. The sequence for fabricating the slabs for LWC-3 is illustrated in Figure 18. Wooden forms were placed on a casting bed (see Figure 18(a)). The structural skin was poured using the mix composition described earlier (see Table 5 and Figure 18(b)). The expanded polystyrene boards were then set in place (see Figure 18(c)) and pouring of the lightweight structural concrete completed (see Figure 18(d)). The completed composite slabs with the forms removed are shown in Figure 18(e). The completed slabs were shipped to AESD in Pittsburgh, PA, where they were assembled into the tank configuration.

(a)

(b)

(c)

(d)

(e)

Figure 18. Sequence of Fabrication Slabs for Modular Hot Water Storage Tank - Configuration LWC-3.

3.3 THERMAL AND MECHANICAL EVALUATIONS

Samples taken during the pouring of the three tanks were evaluated for mechanical and thermal properties. The data are presented in Tables 6 and 7, respectively. In Figure 19, the 28-day compressive strength for samples taken during fabrication of the storage tanks are compared with data for the experimental batches. From the data scatter, it is difficult to make a positive statement regarding the effects of either MC-76 or the glass fiber on enhancement of compressive strength. The lone data point at 111 pcf density would indicate that MC-76 is very beneficial but insufficient tests were conducted to determine the repeatability of the observation. The same observations can be made when comparing splitting tensile strength values (see Figure 20).

The thermal conductivity values obtained indicate a sensitivity to both density and moisture content as expected. The influence of both of these variables is illustrated in Figure 21. For curves A, B and C, the samples were oven dried prior to testing and this was done generally to obtain reproducible results. The densities given for all the curves are wet density followed by oven-dry density values. Towards the end of the program, an environmental chamber became available which allowed testing under controlled humidity conditions. Curve D on Figure 21 is for a sample tested at 90% R.H. and the thermal conductivity is approximately 38% greater than for curve C. The only difference is that curve C is for oven dried and curve D is for material tested as received.

3.3.1 THERMAL EVALUATION - LWC-1 AND LWC-2

ANALYTICAL MODEL^(a)

The storage tanks were analytically evaluated using thermal resistance models to obtain an overall conductance. Table 8 lists appropriate equations⁽²⁵⁾ and theoretical conductance values for the concrete vessels.

EXPERIMENTAL TESTING

The basic test arrangement for experimental evaluation is shown in Figure 22. According to the ASHRAE procedure⁽²⁶⁾, the overall thermal conductance may be obtained under quasi-steady state conditions (within the test specifications)

(a) Nomenclature and symbols used are listed in Appendix A.

TABLE 6: MECHANICAL PROPERTY DATA FOR LIGHTWEIGHT CONCRETE TANKS

TANK I.D./ LOCATION	DENSITY		COMPRESSIVE STRENGTH		SPLITTING TENSILE STRENGTH
	(#/ft ³) Wet	Dry	(psi) 7 Day (a)	(psi) 28 Day (b)	(psi) 28 Day (c)
<u>LWC-1</u>					
<u>Inner Tank</u>					
Top	111.8	106.7	2500	3148 ⁺³⁸⁹ ₋₂₄₈	245 ⁺¹⁰ ₋₁₅
Bottom	111	96.8	1742 ⁺⁹⁷	2202 ⁺¹³² ₋₈₀	210 ⁺⁰
<u>Outer Tank</u>					
Top	122	108.2	3077	4258 ⁺⁷⁵ ₋₈₄	408 ⁺⁷ ₋₈
Bottom	118.6	108.5	2193	3090 ⁺⁹³ ₋₈₄	235 ⁺¹⁰
<u>Insulating Cement</u>					
Top	31.3	23.2	129	133 ⁺¹¹ ₋₆	-
Bottom	35.5	26.3	108	168 ⁺¹⁶ ₋₂₉	17 ⁺³
<u>LWC-2</u>					
<u>Inner Tank</u>					
Top	116	107	2334	2830 ⁺¹⁰⁶ ₋₇₁	260 ⁺¹⁵ ₋₃₅
Bottom	125	111	2900	4098 ⁺⁷⁵ ₋₄₈	343 ⁺²⁷ ₋₈
<u>Insulating Foam</u>	NOT DETERMINED				
<u>LWC-3</u>	Structural properties not determined. Following are values on two production-sized batches of same mix used for slabs for LWC-3.				
A	115		2830	3595 ⁺⁸⁴ ₋₅₈	330 ⁺²⁰ ₋₁₅
B	115.2		2848	3980 ⁺⁸⁸ ₋₈₉	322 ⁺¹³ ₋₂₂

(a) Single

(b) Average of four tests

(c) Average of three tests

TABLE 7: THERMAL CONDUCTIVITY VALUES FOR LIGHTWEIGHT CONCRETE TANKS

TANK I.D.	MEAN TEMP (°F)	$k^{(a)}$ (BTU/ft ² -in-°F-hr)	DENSITY #/ft ³		
			AS-RECEIVED	PRE-TEST	POST TEST
<u>LWC-1</u>					
Inner Tank	27.5	2.67	111	96.8	96.8
Bottom Half	42	2.84			
	46	3.24			
	53.5	3.14			
	99	3.02			
	152.5	3.09			
	209	2.92			
Inner Tank	10	4.0	118	106.7	106.7
Top Half	38	4.02			
	79	4.08			
	93	3.99			
	138	3.94			
	187.5	3.80			
Outer Tank	10	5.26	118.6	108.3	108.5
Bottom Half	39	5.28			
	46	4.69			
	89.5	4.02			
	94	4.58			
	100	4.68			
	130	4.40			
	165.5	4.44			

(a) measured on oven-dried samples - 8 hrs at 125°C, then sealed in polyethylene film

(b) k measured on as-received samples in environmental chamber with ambient humidity maintained at 90% R.H.

TABLE 7: THERMAL CONDUCTIVITY VALUES FOR LIGHTWEIGHT CONCRETE TANKS (Cont'd.)

TANK I.D.	MEAN TEMP (°F)	$k^{(a)}$ (BTU/ft ² -in-°F-hr)	DENSITY #/ft ³		
			AS-RECEIVED	PRE-TEST	POST TEST
Outer Tank	15.5	4.30			
Top Half	50.1 92.5 123.5 161.5	4.66 4.50 4.62 4.50	122	108.2	-
Insulating Foam					
Bottom Half	0.5 16 46 82 103 104 135 164	0.50 0.59 0.57 0.61 0.62 0.61 0.58 0.64	35.5	26.3	-
Insulating Foam					
Top Half	-0.5 19 46 84 104.5 106.5 137 173	0.45 0.48 0.48 0.50 0.51 0.49 0.46 0.46	31.3	23.1	-

(a) measured on oven-dried samples - 8 hrs at 125°C, then sealed in polyethylene film

(b) k measured on as-received samples in environmental chamber with ambient humidity maintained at 9% R.H.

TABLE 7: THERMAL CONDUCTIVITY VALUES FOR LIGHTWEIGHT CONCRETE TANKS (Cont'd.)

TANK I.D.	MEAN TEMP (°F)	$k^{(a)}$ (BTU/ft ² -in-°F-hr)	DENSITY #/ft ³		
			AS-RECEIVED	PRE-TEST	POST TEST
<u>LWC-2</u>					
Inner Tank	8 23	3.14 3.65	116	106.7	106.9
Top Half	78.5 125 127 180	4.32 3.65 3.58 3.54			
Inner Tank	8.5	3.86			
Bottom Half	25 80.5 115 125 164	4.18 3.52 4.39 4.38 4.18	125	110.2	111.1
Insulating Foam					
Bottom Half	29	0.45			
Spec 1	51 81 100 131 166	0.50 0.48 0.47 0.48 0.48	28.1	22.6	22.6

(a) measured on oven-dried samples - 8 hrs at 125°C, then sealed in polyethylene film

(b) k measured on as-received samples in environmental chamber with ambient humidity maintained at 90% R.H.

TABLE 7: THERMAL CONDUCTIVITY VALUES FOR LIGHTWEIGHT CONCRETE TANKS (Cont'd.)

TANK I.D.	MEAN TEMP (°F)	k ^(a) (BTU/ft ² -in-°F-hr)	DENSITY #/ft ³		
			AS-RECEIVED	PRE-TEST	POST TEST
Insulating Foam					
Bottom Half	31	0.58	28.4	21.8	21.8
Spec 2	52	0.52			
	82	0.49			
	100	0.48			
	128	0.50			
	167	0.50			
Upper Half	43.5	0.51	29.2	22.4	22.4
Spec 1	63.5	0.48			
	89.5	0.50			
	146.5	0.48			
	182	0.50			
Spec 2	41	0.54	29.4	23.1	23.1
	61	0.50			
	88.5	0.53			
	139	0.50			
	143	0.51			
	177.5	0.52			
<u>LWC-3</u>					
Structural	59	6.20	118	118	117
	87	5.76			
Spec 1 ^(b)	101	6.08			
	121	5.94			

(a) measured on oven-dried samples - 8 hrs at 125°C, then sealed in polyethylene film.

(b) k measured on as-received samples in environmental chamber with ambient humidity maintained at 90% R.H.

TABLE 7: THERMAL CONDUCTIVITY VALUES FOR LIGHTWEIGHT CONCRETE TANKS (Cont'd.)

TANK I.D.	MEAN TEMP (°F)	$k^{(a)}$ (BTU/ft ² -in-°F-hr)	DENSITY #/ft ³		
			AS-RECEIVED	PRE-TEST	POST TEST
<u>LWC-3</u>					
Structural					
Spec 2 ^(b)	58.5	6.34	122.5	122.5	121.9
	85.5	6.04			
	101	6.30			
	122.5	6.25			

(a) measured on oven-dried samples - 8 hrs at 125°C, then sealed in polyethylene film

(b) k measured on as-received samples in environmental chamber with ambient humidity maintained at 90% R.H.

Figure 19. Effect of Various Additives on Compressive Strength of Cellular Foam Concrete.

Figure 20. Effect of Various Additions on Splitting Tensile Strength of Cellular Foam Concrete.

Figure 21. Influence of Density and Moisture on Thermal Conductivity of Cellular Concrete.
(Note: Curves A, B, C for oven-dried samples. Curve D listed is 90% R.H. environment.)

TABLE 8: IDEAL THERMAL RESISTANCE MODELS

Composite Spherical Sections	$R_s = \sum_{i=1}^n \frac{r_{i+1} - r_i}{4\pi k_i r_i r_{i+1}}$				
Composite Cylindrical Sections	$R_c = \sum_{i=1}^n \frac{\ln(r_{i+1}/r_i)}{2\pi l k_i}$				
Composite Planar Sections	$R_p = \sum_{i=1}^n \frac{l_i}{k_i A_i}$				
Surface Convective Resistance	$R_h = \frac{1}{hA}$				
<table> <tr> <th><u>LWC-1</u></th><th><u>LWC-2</u></th></tr> <tr> <td>$U_{total} = 6.4 \text{ watts/K}$</td><td>$U_{total} = 5.4 \text{ watts/K}$</td></tr> </table>		<u>LWC-1</u>	<u>LWC-2</u>	$U_{total} = 6.4 \text{ watts/K}$	$U_{total} = 5.4 \text{ watts/K}$
<u>LWC-1</u>	<u>LWC-2</u>				
$U_{total} = 6.4 \text{ watts/K}$	$U_{total} = 5.4 \text{ watts/K}$				

by measuring the vessel heat loss via flow rates and temperatures. The heat loss rate is given by

$$Q = \dot{m}\bar{c}(T_{in} - T_{out}) \quad (1)$$

Thus, in the ASHRAE test, accurate measurement of the temperature difference across the storage device is imperative. The basic premise is steady state operation; i.e., negligible transient effects.

In the test arrangement (Figure 22) temperature sensors were placed on the piping in close proximity to the vessel inlet and outlet ports. This scheme was used to avoid problems associated with inserting measurement devices into the flow stream; e.g., material deposits, pipe size, turbulence and dynamic effects, as well as cost of the device, etc. Additional thermocouples were mounted along the vessel surface and inside the stored water volume.

ASHRAE TEST RESULTS

LWC-1 was tested for bulk vessel heat loss (and hence conductance) in a steady state operating mode per the ASHRAE test. The tests were conducted at storage temperatures over the intended operating range of the vessel. The results are summarized in Table 9.

As expected, the data show that the heat loss varies directly with storage temperature. The results are also repeatable as indicated by multiple tests at nearly the same mean storage temperature and different flow rates. Note that thermistors having an accuracy of $\pm 0.01^\circ\text{F}$ ($\pm 0.006^\circ\text{C}$) were used to measure temperature since the ΔT is small for low flow rates.

Figure 23 shows typical vessel ΔT data encountered during testing. The thermistor ΔT is approximately 30% less than that obtained using the thermocouples. In fact, several test results showed the thermocouple ΔT reading both higher and lower than the ΔT obtained with the thermistors. The results show that if thermocouples alone were used in the ASHRAE test, the calculated heat losses could be in error. The basic problem here lies in the fact that for highly insulative systems (e.g., the LWC vessel) the measured ΔT is small for realistic flow rates.

Figure 22. Vessel Test Loop - Heating Simulation with Sample Temperature Measurements

TABLE 9: STEADY STATE HEAT LOSS PER THE ASHRAE TEST-LWC-1

STORAGE TEMPERATURE		(INLET-OUTLET) TEMPERATURE DIFFERENCE [Thermistors]		FLOW RATE		HEAT LOSS (watts)
$\bar{T}_w$ (°C)	$\bar{T}_w$ (°F)	$\bar{\Delta T}$ (°C)	$\bar{\Delta T}$ (°F)	(m ³ /sec)	(gal/min)	
80.3	176.6	0.55	0.99	12.6	2.0	282
77.8	172.1	1.04	1.87	6.3	1.0	266
59.5	139.1	0.70	1.26	6.3	1.0	182
49.3	120.7	0.52	0.93	6.3	1.0	135
49.1	120.4	0.52	0.94	6.3	1.0	136

Figure 23. Measured Inlet-Outlet Temperature Difference using Shielded Thermocouples and Thermistors during ASHRAE Test.

Table 10 lists the storage temperature data for each test; i.e., the average storage, surface and ambient temperatures as a function of time during the 1-hr test. Observation of the data show that the average water storage temperature is decreasing during the 1-hr test. While the inlet and outlet temperatures may only vary on the order $\leq 1^\circ\text{F}$ (0.6°C) during the test (satisfying the ASHRAE Specification), the associated heat loss may be significant simply due to the large volume of water; i.e., 500 gallons (1.89 m^3).

CORRECTED ASHRAE TEST

As previously discussed, the average stored water temperature was seen to slightly decrease during the 1-hr test. This temperature change, although small, could represent a significant heat loss. The following is an attempt to correct the ASHRAE results to include the effect of storage temperature change.

Consider the First Law of Thermodynamics and Fluid Continuity⁽²⁷⁾ applied to a control volume.

First Law

$$Q - W_s = \frac{\partial}{\partial t} \int_V e \rho dV + \int_S \rho \left(e + \frac{P}{\rho} \right) \bar{V} \cdot d\bar{S} \quad (2)$$

Continuity

$$Q = \frac{\partial}{\partial T} \int_V \rho dV + \int_S \rho \bar{V} \cdot d\bar{S} \quad (3)$$

For a single inlet/outlet steady state system using a homogeneous fluid, the equations reduce to the ASHRAE test

$$Q = \dot{m} \bar{C} (T_{in} - T_{out}) = \dot{m} \bar{C} (\Delta T) \quad (4)$$

TABLE 10: LWC-1 - ASHRAE TEST DATA SHOWING AVERAGE STORAGE TEMPERATURE DECREASE

TIME (min)	$\bar{T}_w(^{\circ}\text{C})$ (2.0 gpm)	$\bar{T}_w(^{\circ}\text{C})$ (1.0 gpm)	$\bar{T}_w(^{\circ}\text{C})$ (1.0 gpm)	$\bar{T}_w(^{\circ}\text{C})$ (1.0 gpm)	$\bar{T}_w(^{\circ}\text{C})$ (1.0 gpm)
0	80.9	78.2	59.9	49.4	49.3
5	80.8	78.2	59.7	49.4	49.2
10	80.7	78.1	59.7	49.4	49.2
15	80.8	78.1	59.7	49.4	49.2
20	80.5	77.9	59.7	49.3	49.2
25	80.4	77.9	59.5	49.3	49.2
30	80.3	77.8	59.5	49.3	49.1
35	80.2	77.8	59.4	49.3	49.1
40	80.1	77.7	59.4	49.2	49.1
45	80.1	77.7	59.3	49.2	49.0
50	79.9	77.6	59.3	49.2	49.0
55	79.9	77.5	59.2	49.1	49.1
60	79.7	77.4	59.2	49.1	49.0
Avg.	80.3	77.8	59.5	49.3	49.1

However, if the transient term is significant, a corrected heat loss is given by

$$Q_{\text{ASHRAE corrected}} = Q_{\text{ASHRAE}} + (M\bar{c}) \frac{\Delta \bar{T}_w}{\Delta t} \quad (5)$$

The inner vessel mass was included in the total thermal mass since the inner vessel temperature profile closely follows the water temperature transient as evidenced by the relative thermal properties of the materials. Table 11 shows the heat losses obtained with the ASHRAE test and the attempted correction to the ASHRAE test. Clearly, the corrected ASHRAE heat loss is much greater than that measured via the standard test.

The ASHRAE-corrected heat losses may not be very accurate; i.e., the test was not long enough to obtain an accurate decay profile. Still, the ASHRAE data show that the heat loss obtained with the ASHRAE steady state test is not a good measure of the true vessel thermal behavior. Under ideal steady state conditions, the analytical model predicts heat losses on the order of 120-240 watts (400-800 Btu/hr) over the vessel operating range (storage temperature). Under good experimental practice, correction terms should be less than 10% of measured values. Thus, for these heat loss magnitudes, it is necessary to consider temperature decays on the order of 0.006°C/hr (0.01°F/hr). Clearly this specification is difficult to meet. These results indicate that the ASHRAE test is not practical for measuring this magnitude of heat loss.

STORAGE TEMPERATURE DECAY TEST

To overcome the difficulties with the ASHRAE test for these vessels, a static decay test was conducted. The vessel storage temperature was raised to a well-mixed uniform average value of 73.9°C (165°F). The loop pump and heater were then shut off and the vessel temperatures were monitored for 97 hrs.

Basically, the decay of the average storage temperature is a direct measurement of the overall vessel conductance.

TABLE 11: LWC-1 - COMPARISON OF VESSEL HEAT LOSS BY THE ASHRAE
AND CORRECTED ASHRAE TESTS

AVERAGE STORAGE TEMPERATURE		ASHRAE STEADY STATE TEST		ASHRAE CORRECTED FOR TEMPERATURE DECAY
T_w (°C)	T_w (°F)	Q(watts)	(°C/hr)	Q(watts)
76.7	170	266	0.83	2130
60.0	140	182	0.67	1690
48.9	120	136	0.33	880

In conventional terms

$$Q = U\theta \quad (6)$$

where

Q is the heat loss, watts

U is the conductance, watts/K

$$\theta \equiv (\bar{T}_w - \bar{T}_{amb}), \text{ } ^\circ\text{C}$$

The decay test conductance was obtained by fitting a regression equation⁽²⁸⁾ to the following heat balance:

$$(M\bar{c}) \frac{d}{dt} \theta + U\theta = 0 \quad (7)$$

where

$(M\bar{c})$ = thermal mass, Joule/K (based on stored water + inner vessel concrete)

U = overall conductance, watts/K

The behavior of the temperature decay is shown in Figure 24.

The regression fit is

$$\ln(\theta) = A + Bt \quad (8)$$

with results for LWC=1

$$A = 3.738$$

$$B = -1.286 \times 10^{-2}$$

The regression fit with 99% confidence bands is given in Figure 25.

Figure 24. Storage Temperature Decay for LWC-1.

Figure 25. Decay Regression Fit - LWC-1.

From Equation (7)

$$B = \frac{U}{(Mc)} \quad (9)$$

or

$$U = 28.9 \text{ watts/K}$$

VESSEL HEAT LOSS SUMMARY

Table 12 summarizes the vessel conductance as obtained by:

- 1) the analytical heat loss model (Table 8)
- 2) the ASHRAE test results (standard vs. corrected)
- 3) the decay test.

The results show that the vessel conductance as measured by the decay test is much greater than predicted with the steady state model. The corrected ASHRAE data result in a still larger conductance (most likely due to the inaccurate correction data). To investigate the discrepancy between predicted and measured heat loss, various temperature readings were studied. Hot spot areas were noticed at the vessel lower pole and flange (where the two vessel halves are joined). Clearly the areas of higher surface temperature indicate possible heat leaks most likely due to structural discontinuities (possibly during shipping).

In order to substantiate the magnitude of heat loss measured with the decay test, the results were compared to estimated losses using vessel surface temperature measurements. Table 13 shows that the losses based on surface temperatures somewhat underestimate the heat loss calculated by the decay test. The difference is most likely due to choice of surface conductance. However, the calculation indicates that some kind of heat leak occurred in the noted areas of higher surface temperature. The most plausible explanation of the heat leak is a possible breakdown or nonuniformity of the vessel structure in the lower pole and flange areas. Vessel surface cracks and small water leaks were also noticed in these areas which indicate confirmation of the heat leak hypothesis.

TABLE 12: OVERALL VESSEL CONDUCTANCE-LWC-1

ANALYTICAL HEAT LOSS MODEL	ASHRAE TESTS (CORRECTED)		DECAY TEST
U (watts/K)	T_w (°C)	U (watts/K)	U (watts/K)
6.4	49.1	46.6	28.9
	59.5	57.7	
	77.8	44.7	

TABLE 13: LWC-1 COMPARISON OF DECAY TEST HEAT LOSSES AND TOTAL ESTIMATED HEAT LOSSES
BASED ON SURFACE TEMPERATURES TO CALCULATE HYPOTHETICAL HEAT LEAK

Time (hrs)	Storage Temperature (°C)	Heat Loss (Decay Test) (watts)	Surface Losses (watts)	Pole Losses (watts)	Flange Losses (watts)	Total Heat Loss Estimate (watts)	% Pred. vs. Measured
2	71.7	1200	237	567	108	912	-24.0
24	61.1	890	224	424	117	765	-14.0
67	48.1	520	132	210	82	424	-18.5

THERMAL EVALUATION OF LWC-2

Predicted and Measured Results

The analytical thermal conductance for LWC-2 is listed in Table 8. Again, standard techniques were employed for calculating thermal resistances.

The experimental results were obtained with the static decay test. Figure 26 compares the average storage temperature decay rates for LWC-1 and LWC-2. Clearly, LWC-2 is thermally superior to LWC-1. This result is expected due to the additional insulative concrete in the vessel structure. Figure 27 shows the regression fit for the LWC-2 data.

Discussion of LWC-2 Results

The measured thermal conductance for LWC Vessel No. 2 is 30.8% greater than predicted with the analytical model.

U predicted = 5.4 watts/K

U measured = 7.8 watts/K

The difference in the measured and predicted conductance values may be attributed to:

- 1) the concrete conductivity values used in the analytical model, and
- 2) the structural characteristics of the vessel.

The measured concrete thermal conductivity values (dry sample) were adjusted for nominal moisture content. However, the actual water content of the concrete during vessel operation could be greater than assumed, effectively raising the conductivity.

Small structural irregularities or gaps may also exist in the vessel composite structure. Wet spots (small water leaks) were observed at storage temperatures above 65°C. Surface thermocouple measurements showed no outstanding hot spots. However, due to the large surface area, small heat leaks could have gone undetected by the limited number of surface temperature measurements.

Figure 26. Comparison of Decay Rates LWC-1 and LWC-2.

Figure 27. Storage Temperature Decay Regression Fit - LWC-2.

Comparison with LWC-1 Results

Figure 28 shows the heat loss as a function of storage temperature for LWC Vessels No. 1 and 2. The curves are based on the vessel thermal conductance obtained with the experimental decay test. Obviously, LWC-2 has a significantly lower heat loss (conductance) than LWC-1. This result is most likely due to the increased amount of insulative concrete and improved structural integrity of LWC-2.

3.3.2 THERMAL ANALYSIS AND EVALUATION OF LWC-3

Analytical Heat Loss Model

The LWC-3 tank is rectangular in shape (see Figure 8(c)). The walls are constructed with 7-1/2-in thickness of insulating polyboard material surrounded by several inches of structural concrete (~100 pcf).

The vessel thermal resistances are calculated for each section of the cubical structure as follows:

$$R = \sum_i \frac{l_i}{A_i k_i} + \frac{1}{\bar{h} A_0} \quad (10)$$

where

l_i = thickness, ft

A_i = area, ft² (conducting path)

k_i = conductivity, Btu/hr-ft-°F

$\bar{h}$ = external coefficient, Btu/hr-ft²-°F

A_0 = external area, ft²

Since planar sections are involved

$$A_i = A_0 = \bar{A} \quad (11)$$

and

$$R = \frac{1}{\bar{A}} \left[\sum \frac{l_i}{k_i} + \frac{1}{\bar{h}} \right] \quad (12)$$

Figure 28. Comparison of Heat Loss for LWC-1 and LWC-2.

The total vessel thermal resistance is calculated using six resistances in parallel for the top, bottom, side and end sections.

$$\frac{1}{R_{\text{tot}}} = \sum_j \left(\frac{1}{R_j} \right) \quad (13)$$

Table 14 lists the vessel thermal resistance parameters.

Predicted Heat Loss/Conductance

Using the data in Table 14, the total estimated thermal resistance of the vessel is

$$R_{\text{total}} = 1.42 \times 10^{-1} \text{ hr-}^\circ\text{F/Btu} \quad (14)$$

and the vessel conductance is

$$\begin{aligned} U_{\text{total}} &= 1/R_{\text{total}} \\ &= 7.04 \text{ Btu/hr-}^\circ\text{F} \end{aligned} \quad (15)$$

The vessel heat loss at various storage and ambient temperatures is obtained from

$$Q = U\Delta T \quad (16)$$

where

$$\begin{aligned} Q &= \text{heat loss} \\ U &= \text{vessel conductance, Btu/hr-}^\circ\text{F} \\ \Delta T &= T_{\text{storage}} - T_{\text{ambient}} \end{aligned}$$

Table 15 lists the predicted heat loss for various storage and ambient conditions.

TABLE 14: THERMAL RESISTANCE PARAMETERS LWC NO. 3

SECTION	$\bar{A}$ (ft ²)	l_i (ft)	k_i (Btu/hr ft °F)	$\bar{h}$ (Btu/hr ft ² °F)	R (hr °F/Btu)
Top (Styrofoam)	21.1	0.167	0.0417	2.5	0.209
Bottom (Polyboard) (Strct)	21.1 21.1	0.625 0.375	0.0221 0.292	1.0	1.45
Sides (2) (Polyboard) (Strct)	13.3 13.3	0.625 0.375	0.0221 0.292	1.5	2.27
Ends (2) (Polyboard) (Strct)	10.2 10.2	0.625 0.375	0.0221 0.292	1.5	2.96

TABLE 15: PREDICTED HEAT LOSS - LWC VESSEL NO. 3

$T_{\text{storage}}, ^\circ\text{F}$	$T_{\text{ambient}}, ^\circ\text{F}$	$Q, \text{Btu/hr}$
100	60	282
120	60	423
140	60	563
160	60	704
160	70	634
160	80	563

EXPERIMENTAL TESTING

Storage Temperature Decay Test/Conductance

The storage temperature decay test was used to evaluate the vessel thermal behavior and the test setup is shown in Figure 29. The storage temperature was raised to a well-mixed uniform average value of 165°F. A series of temperature measurements were then made for a period of 196 hrs.

Basically, the decay of the average storage temperature is a direct measurement of the overall vessel thermal conductance. The conductance is obtained by fitting a regression equation to the following heat balance equation.

$$(\bar{M}c) \frac{d}{dt} \theta + U\theta = 0 \quad (17)$$

where

$$\theta = (T_{\text{storage}} - \bar{T}_{\text{ambient}}), \text{ } ^\circ\text{F}; \bar{T}_{\text{amb}} = 61.4^\circ\text{F}$$

$$U = \text{vessel thermal conductance, Btu/hr-}^\circ\text{F}$$

$$(\bar{M}c) = \text{thermal mass, Btu/}^\circ\text{F (based on stored water, 480 gallons} \\ \text{+ inner vessel concrete - Reference 1)}$$

$$= M_{\text{water}} \bar{c}_{\text{water}} + M_{\text{vessel}} \bar{c}_{\text{vessel}}$$

$$= (3.94 \times 10^3 \text{ Lb}_m \times 1.0 \text{ Btu/Lb}_m \text{ } ^\circ\text{F}) + 1.05 \times 10^3 \text{ Lb}_m \times 0.15 \text{ Btu/Lb}_m \text{ } ^\circ\text{F})$$

$$= 4.0975 \times 10^3 \text{ Btu/}^\circ\text{F}$$

The thermal mass was chosen to include the inner vessel high density concrete. The temperature of this section follows the storage temperature profile since the thermal resistance of the structural concrete is small compared to the insulating concrete. The thermal mass which includes the effect of the inner vessel concrete will result in a conservatively high conductance value. The data is listed in Table 16. Figure 30 illustrates the storage decay profile.

Figure 29. LWC-3 Tank Static Decay Test Configuration.

TABLE 16: DECAY TEST DATA - LWC VESSEL NO. 3

TIME (hrs)	T _{storage} (°F)	T _{top} (°F)	T _{bottom} (°F)	T _{sides} (°F)	T _{amb} (°F)
0	161.1	76.9	73.6	76.9	70.4
4	156.1	103.6	76.8	79.2	73.8
8	153.1	105.8	77.3	82.1	77.5
12	150.9	100.5	75.9	81.6	73.1
16	148.6	96.3	72.9	78.3	70.6
20	146.6	93.5	72.6	75.7	69.0
24	143.8	97.1	76.5	76.0	72.0
28	141.7	99.9	77.3	78.9	75.0
32	139.0	99.4	77.7	80.5	75.6
36	137.3	97.4	77.5	80.4	74.7
40	135.4	95.3	76.6	79.4	73.8
44	133.6	94.0	76.0	78.4	73.2
48	132.0	94.0	77.3	78.0	73.6
52	130.1	96.3	77.8	79.3	75.3
56	128.4	96.2	77.7	80.7	76.1
60	126.7	94.0	76.9	80.1	74.8
64	125.1	92.5	76.6	79.0	74.2
68	124.1	89.6	74.2	77.3	72.3
72	122.6	90.9	75.6	76.5	73.6
76	121.2	93.4	77.0	78.5	75.7
80	119.8	95.1	76.9	80.4	77.6
84	118.1	90.9	75.2	79.9	75.0
88	117.0	87.1	72.2	76.9	70.9
92	116.0	83.3	70.0	74.5	67.0
96	113.8	84.8	72.6	72.1	70.0

TABLE 16 (Continued)

TIME (hrs)	T _{storage} (°F)	T _{top} (°F)	T _{bottom} (°F)	T _{sides} (°F)	T _{amb} (°F)
100	112.8	89.4	73.9	74.5	73.4
104	111.7	91.6	74.2	77.5	75.4
108	110.2	85.6	71.8	76.6	71.3
112	109.0	81.6	70.0	73.1	67.6
116	108.1	79.0	67.8	70.2	65.3
120	106.5	81.2	71.3	69.6	68.7
128	104.2	89.6	72.3	76.2	75.0
132	103.5	85.6	70.9	76.2	71.3
136	102.3	81.3	69.1	74.0	68.8
140	101.7	78.5	68.9	71.4	67.6
144	101.1	82.5	71.1	71.4	70.6
152	99.9	89.6	72.4	77.9	77.6
156	99.2	85.2	72.4	78.0	73.3
160	98.1	83.4	71.9	76.0	72.6
164	97.5	82.0	71.2	74.4	71.6
168	97.0	83.7	72.1	73.8	72.9
176	96.4	90.0	73.0	79.4	79.1
180	95.8	86.1	74.2	79.5	76.3
184	94.9	83.0	72.7	77.2	73.5
188	94.2	81.4	71.5	75.2	71.9
192	93.7	84.3	73.2	75.3	74.9
196	93.8	86.8	73.4	77.3	76.6

Figure 30. Storage Temperature Decay - LWC-3.

The data was fit to a statistical regression equation as follows:

$$\ln(\theta) = A + Bt \quad (18)$$

with results

$$A = 4.4364$$

$$B = -7.474 \times 10^{-3}$$

From Equation 17

$$B = \frac{U}{(Mc)} \quad (19)$$

or

$$U = (Mc)B \quad (20)$$

$$U = 30.62 \text{ Btu/hr } ^\circ\text{F}$$

The regression fit showing the data points and 99% confidence bands is illustrated in Figure 31. The confidence bands are calculated in the following manner:

$$C = T_{st} \sqrt{V(\hat{y})} \quad (21)$$

where

$C(\alpha)$ is the confidence band

T_{st} is the students T statistic (for various confidence levels)

$V(\hat{y})$ is the variance

$$V(\hat{y}) = \sigma_y^2 \left\{ \frac{1}{N} + \frac{m}{\sum_{i=1}^m} \frac{[1 + \sqrt{1 - r^2(1)}] [X_{(i)} - \bar{X}_{(i)}]^2}{(N-1) \cdot \sigma x_{(i)}^2} \right\}$$

σ_y^2 = standard error of the estimate

N = number of data points

M = number of independent variables

Figure 31. Regression Fit to Decay Data - LWC-3.

$r_{(i)}$ = correlation coefficient between dependent and independent variables

$x_{(i)}$ = independent variables

$\bar{x}_{(i)}$ = mean value of the independent variables

$\sigma x_{(i)}$ = standard deviation of the independent variables

Measured Heat Loss

Table 17 lists the vessel heat losses as a function of storage and ambient temperatures based on the results of the experimental decay test data (conductance).

An alternative heat loss calculation may be made using the measured surface temperatures

$$Q = \bar{h} A_s (T_{\text{surface}} - \bar{T}_{\text{ambient}}) \quad (22)$$

where

$\bar{h}$ = average external coefficient (Btu/hr ft² °F)

A_s = external surface area, ft²

Table 18 lists the various calculation parameters.

The total estimated heat loss via Equation 22 is

$$Q = 1168 \text{ Btu/hr} \quad (23)$$

Converting this result to an overall vessel conductance

$$Q = U(\bar{T}_{\text{storage}} - T_{\text{ambient}}) \quad (24)$$

TABLE 17: MEASURED HEAT LOSS - LWC VESSEL NO. 2

<u>T_{storage}, °F</u>	<u>T_{ambient}, °F</u>	<u>Q, Btu/hr</u>
100	60	1225
120	60	1837
140	60	2450
160	60	3062
160	70	2756
160	80	2450

TABLE 18: SURFACE LOSS CALCULATION PARAMETERS

<u>Section</u>	<u>A_s (ft²)</u>	<u>$\bar{h}$ (Btu/hr ft² °F)</u>	<u>$\bar{T}_s$ (°F)</u>	<u>$\bar{T}_a$ (°F)</u>
Top	21.1	2.5	89.6	73.0
Bottom	21.1	1.0	73.8	73.0
Sides (2)	13.3	1.5	76.9	73.0
Ends (2)	10.2	1.5	76.9	73.0

with

$$\bar{T}_{\text{storage}} = 114.6^{\circ}\text{F}$$

$$\bar{T}_{\text{ambient}} = 73.0^{\circ}\text{F}$$

$$U = 28.07 \text{ Btu/hr } ^{\circ}\text{F} \quad (25)$$

which compares favorably (~8%) to the experimentally measured value of 30.62 Btu/hr $^{\circ}\text{F}$.

Another check calculation may be based on predicted concrete surface temperatures using the theoretical concrete conductivity values and predicted heat losses. In using the concrete top cover, the thermal resistance, heat loss and predicted concrete surface temperature is shown in Table 19.

The average expected concrete surface temperature is approximately 74.1 $^{\circ}\text{F}$, which compares favorably with the measured surface temperatures in Table 18. The fact that the measured temperatures are slightly higher than predicted indicates that the concrete conductivity is a little higher than estimated with the manufacturer's data. This result may be due to nominal moisture content in the concrete. However, the surface temperature comparison clearly shows that the type of concrete used in the vessel structure performs as expected.

Predicted vs. Measured Thermal Behavior

The measured thermal conductance for LWC Vessel No. 2 is four times greater than that predicted with the analytical model.

$$U_{\text{predicted}} = 7.04 \text{ Btu/hr } ^{\circ}\text{F}$$

$$U_{\text{measured}} = 30.62 \text{ Btu/hr } ^{\circ}\text{F}$$

This result is reflected in the predicted and measured heat loss values (Tables 15 and 18).

TABLE 19: PREDICTED CONCRETE SURFACE TEMPERATURE

<u>Section</u>	<u>R(hr °F/Btu)</u>	<u>Q (Btu/hr)*</u>	<u>$\bar{T}_s$ (°F)</u>
Top	1.45	122.3	74.1 °F
Bottom	1.45		
Sides (2)	2.27		
Ends (2)	2.96		

$$^*\bar{T}_{\text{storage}} = 114.6 \text{ °F}, \bar{T}_{\text{amb}} = 73.0 \text{ °F}, \bar{h} = 1.25 \text{ Btu/hr ft}^2 \text{ °F}, \bar{A} = 89.2 \text{ ft}^2$$

The primary reason for the difference between the measured and predicted conductance is convective flows around the styrofoam cover. This is the only logical explanation as the theoretical model correctly predicts the exterior surface temperature.

Secondary reasons for the difference may be because the concrete thermal conductivity may be slightly higher than estimated due to nominal moisture content in the concrete under operating conditions.

Small structure irregularities or gaps may also exist in the vessel composite structure. Surface thermocouple measurements showed no outstanding hot spots except for the higher surface temperature of the styrofoam top cover. However, due to the large surface area, small heat leaks could have gone undetected by the limited number of surface temperature measurements.

Comparison with LWC-1 and LWC-2

Figure 32 shows the heat loss as a function of storage temperature for LWC-1, 2 and 3. The curves are based on the vessel thermal conductance obtained with the experimental decay test. Obviously, LWC-2 has a significantly lower heat loss (conductance) than LWC-1. This result is postulated to be due to the increased amount of insulative concrete and improved structural integrity of LWC-2. LWC-1 had significant heat losses in the lower pole and flange areas accompanied by cracks in the vessel wall.

The conductance for LWC-3 lie in between those for LWC-1 and 2. The results, however, were based on the experimental test data during which a styrofoam sheet was used in place of the vessel concrete top cover. This was necessary to allow for installation the immersion heaters and instrumentation into the tank. If the actual designed concrete top cover were used, LWC-3 would be superior to both LWC-1 and LWC-2.

Figure 32. Comparison of Heat Loss for Three LWC Vessel Designs.

4.0 COST ESTIMATE FOR FIELD-FABRICATED TANKS

An analysis was made to compare the cost of the lightweight concrete hot water storage systems studied under this program with other competing systems. It became obvious during the course of this study that a central plant manufacturing concrete tanks and shipping to local site (i.e. >30-40 miles from factory) would be cost prohibitive. For example, the dry weight of LWC-1 was on the order of three tons and thus shipping costs over great distances would exceed the cost of the tank. A septic tank manufacturer⁽²⁹⁾ indicated that a concrete septic tank of ~2000 gallon volume would be shipped at a rate of \$1.60/mile for every mile greater than 60 miles from the plant site. With the ever-increasing cost of fuel for transportation, shipment of concrete tanks does not appear to be the most cost-effective mode of operation.

Comparing the cost of various insulation materials that could be used (Table 20), cellular concrete compares favorably with expanded polystyrene board and is half the cost of expanded urea formaldehyde. The lowest cost insulating material is fiberglass. However, the cost for the foamed concrete listed in Table 20 is installed cost. Thus, installation costs would have to be added to the cost figures for the other insulating materials listed. Of the insulating materials listed in Table 20, foamed concrete has the advantage of being durable, possessing mechanical strength, and can be used outdoors and underground.

To compare costs of various capacity hot water storage systems, cost estimates were developed for lightweight concrete hot water storage systems which consisted of a right circular cylindrical tank with the I.D. equal to the height and fabricated from nominal 125#/ft³ foamed concrete reinforced with alkaline-resistant glass fibers and steel reinforcing bars. Insulation consisted of 12 in of insulating foam cement giving an R value of approximately 30. The tank is lined with a single piece seamless EPDM liner of 0.045-in thickness. The effect of tank size and production rate on tank cost is shown in Figure 33 and the basis for the estimate is listed in Table 21. The estimate

TABLE 20: COST COMPARISON OF VARIOUS INSULATING MATERIALS

Material	R Value	\$/board ft	\$/R
1. Cellular concrete ^(a) (20 #/ft ³)	2.9	0.07 ^(a)	0.024
2. Expanded polystyrene (2 #/ft ³)	4.17	0.07	0.017
3. Urea formaldehyde (3 #/ft ³)	4.3	0.25	0.058
4. Fiberglass	3.16	0.016	0.01

(a) Installed cost.

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Figure 33. Influence of Tank Size and Production Rate on Cost for Fabrication.

TABLE 21: BASIS FOR ESTIMATING COST OF LIGHTWEIGHT CONCRETE HOT WATER STORAGE SYSTEM^(a)

	1300 TANKS/YR (5 tanks/day)			2600 TANKS/YR ^(g)		
	500	1000	2000	500	1000	2000
Equipment ^(b)	\$ 95,000	\$ 95,000	\$ 95,000	\$ 95,000	\$ 95,000	\$ 95,000
Forms	<u>35,000</u>	<u>38,500</u>	<u>46,000</u>	<u>70,000</u>	<u>77,000</u>	<u>92,000</u>
TOTAL	\$130,000	\$133,500	\$144,000	\$165,000	\$172,000	\$187,000
FABRICATION COST (per tank)						
A. INNER TANK						
1) Labor ^(c)	\$160	\$184	\$212	\$120	\$138	\$160
2) Materials						
a. Concrete ^(d)	35	60	87	35	60	87
b. Reinforcement	60	110	158	60	110	158
c. Liner ^(e)	<u>47</u>	<u>71</u>	<u>113</u>	<u>47</u>	<u>71</u>	<u>113</u>
SUBTOTAL	303	425	570	262	379	518
B. INSULATION						
1) Labor ^(c)	90	110	125	68	82	94
2) Materials ^(f)	<u>234</u>	<u>312</u>	<u>438</u>	<u>234</u>	<u>312</u>	<u>438</u>
SUBTOTAL	627	847	1133	564	773	1050
G&A (20%)	125.40	169.40	226.60	112.80	154.60	210
Profit (20%)	125.40	169.40	226.60	112.80	154.60	210
Equip. Amortization	20.00	20.54	22.00	12.64	13.23	14.38
TOTAL	<u>\$897.80</u>	<u>\$1206.34</u>	<u>\$1608.20</u>	<u>\$802.29</u>	<u>\$1095.43</u>	<u>\$1484.38</u>

(a) 1980 Dollars

(b) Self-contained mobile foam concrete plant

(c) @ \$20/hr which includes FICA, hospitalization, and workmen's compensation.

(d) Includes cost of cement @ \$68/ton, foaming agent, aggregate, water and plant operating cost.

(e) 0.004-in thick EPDM @ 0.60¢/ft²

(f) Includes cost of cement @ \$68/ton, foaming agent, water and plant operating cost.

(g) By doubling production rate, labor content increases 50%.

is listed in Table 21. The estimate is installed cost but does not include the cost of site preparation (i.e. digging a hole in the ground).

The cost for a fiberglass tank of similar capacity is shown in Figure 33. The fiberglass tank, fully insulated is F.O.B. the factory, thus shipping charges would have to be added⁽³⁰⁾. It is apparent that the lightweight concrete tank is a lower cost hot water storage system at these production rates.

Cellular concrete has the advantage of being composed of universally available materials; i.e., sand, cement, water and air. The Celcore concrete plant is designed specifically for the manufacture of lightweight cellular concrete. The plant is totally mobile, providing a flexibility for manufacturing not found in other tank fabricating systems. Two men can operate a lightweight concrete plant and place up to 25 cubic yards of lightweight concrete per hour at substantial distances from the pump (~400 ft) both vertically and horizontally⁽³¹⁾. This feature offers a distinct advantage when considering retrofitting applications. This would allow a tank to be formed inside a basement, without the necessity for handling heavy and bulky sections. Forms can be collapsible and relatively light and the only other access required would be space sufficient to pass a 4-in dia hose. This is a distinct advantage where underground basements have no outside entry access.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation allow the following conclusions and recommendations:

1. Foamed concrete technology is suitable for producing low-cost hot water storage systems.
2. The high mobility of the integrated lightweight concrete plant would make on-site fabrication of hot water tanks a cost effective method of manufacture, plus provide the flexibility of retrofit applications not possible with fixed manufacturing plants.
3. All the tank designs tested could be integrated into a hot water storage system. The conductivity of the lightweight insulating foam concrete provides good thermal resistance which minimizes vessel heat loss.
4. The brittle nature of concrete in general necessitates the use of membrane liner to avoid potential leak problems over an extended operating life (i.e., 30 yrs), and 0.045 in thickness EPDM appears to be a viable candidate for a durable liner material.
5. The ASHRAE 94-77 test for measuring heat loss from storage vessels is not acceptable for very low heat loss vessels such as the lightweight concrete tanks. Two problems exist. The first is that accurate ΔT (inlet and outlet water temperature) measurements must be made because of the small heat loss. The second and most important is that transient effects are significant.
6. To avoid the problems with the ASHRAE test, a stored fluid temperature decay test was developed. The heat loss measured by the decay test method was in general agreement with the loss estimated from surface temperature measurements.

The storage temperature decay test is recommended for low heat loss vessels since:

- a. Highly accurate temperature measurement and flow rate instrumentation are not necessary.

- b. The decay test does not require stringent specifications for steady state operation.
 - c. The results of one test may be applied to a wide range of operating temperatures.
 - d. The overall vessel conductance is easily obtained.
7. Additional testing of the existing tanks, LWC-1, LWC-2 and LWC-3 should be continued to acquire thermal performance and durability data over extended operating times under simulated service conditions.

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APPENDIX A

NOMENCLATURE AND SYMBOLS LISTING USED FOR LWC-1 AND LWC-2 ANALYSIS

NOMENCLATURE

A	Surface area		
B	Regression constant	θ	Temperature difference (storage-ambient)
$\bar{c}$	Specific heat	ρ	Density
e	Specific energy	Δ	Variable difference
h	Convective coefficient		
k	Thermal conductivity		
l	Length		
M	Mass		
$\dot{m}$	Flow rate		
P	Pressure		
Q	Heat loss rate		
R	Thermal resistance		
S	Control surface		
T	Temperature		
t	Time		
U	Conductance		
V	Velocity		
v	Control volume		
W_s	Work		

Subscripts

amb	ambient
c	cylindrical
h	convective
in	vessel inlet
out	vessel outlet
p	planar
s	spherical
w	storage

APPENDIX B

NOMENCLATURE AND SYMBOLS USED FOR LWC-3 ANALYSIS

NOMENCLATURE

A	= area, ft ² (m ²)
$\bar{C}$	= specific heat, $\frac{\text{Btu}}{\text{lb}_m \text{ } ^\circ\text{F}}$ ($\frac{\text{J}}{\text{kg } ^\circ\text{C}}$)
C(α)	= statistical confidence band
D	= diameter, ft (m)
g	= gravitational constant, $\frac{\text{lb}_m - \text{ft}}{\text{lb}_f - \text{sec}^2}$ ($\frac{\text{m}}{\text{s}^2}$)
$\bar{h}$	= convective coefficient, $\frac{\text{Btu}}{\text{hr ft}^2 \text{ } ^\circ\text{F}}$ ($\frac{\text{W}}{\text{m}^2 \text{ } ^\circ\text{C}}$)
k	= thermal conductivity, $\frac{\text{Btu}}{\text{hr ft } ^\circ\text{F}}$ ($\frac{\text{W}}{\text{m } ^\circ\text{C}}$)
M	= mass, lb _m (kg)
Q	= heat loss, $\frac{\text{Btu}}{\text{hr}}$ (W)
R	= thermal resistance, $\frac{\text{hr } ^\circ\text{F}}{\text{Btu}}$ ($\frac{^\circ\text{C}}{\text{W}}$)
r	= radius, ft (m)
r _(i)	= correlation coefficient
S	= surface area, ft ² (m ²)
T	= temperature, °F (°C)
T _{st}	= students T statistic

NOMENCLATURE

$x_{(i)}$ = variable

$\bar{x}_{(i)}$ = mean value of $x_{(i)}$

$v(\hat{y})$ = variance

ϵ = emissivity

F_{1-2} = radiation shape factor

ρ = density, $\frac{\text{lb}_m}{\text{ft}^3}$ ($\frac{\text{g}}{\text{cm}^3}$)

σ = Stephen-Boltzman constant, 0.171×10^{-8} ($\frac{\text{Btu}}{\text{hr ft}^2 \text{ } ^\circ\text{R}^4}$)

$\sigma x_{(i)}$ = standard deviation of $x_{(i)}$

τ = time, hr (s)

Σy^2 = statistical standard error of the estimate