ANNEX 3: LEVEL 2 THERMAL STUDY MASS GRADIENT AND SURFACE GRADIENT ANALYSIS PROCEDURE AND EXAMPLES

A3-1. Procedure

a. General. This Annex summarizes typical steps in a Level 2 mass gradient and surface gradient thermal analysis of a mass concrete structure (MCS) and provides two examples of the procedure. Example 1 covers a simple one-dimensional (1-D) (strip model) finite element (FE) mass gradient and surface gradient thermal analysis. Example 2 presents a more complex two-dimensional (2-D) mass gradient and surface gradient thermal analysis. This procedure and the examples use FE methodology only because of the widespread availablility and use of this technology. Although other methods of conducting a Level 2 thermal analysis are available, these procedures are most commonly used.

b. Input properties and parameters. The level of data detail depends on the complexity of a Level 2 thermal analysis. Parametric analysis should be routinely conducted at this level, using a rational number and range of input properties and parameters to evaluate likely thermal problems.

(1) Step 1: Determine ambient conditions. Level 2 analyses may be based upon average monthly temperatures for a less complex analysis, or on average expected daily temperatures for each month for a complex analysis. Wind velocity data are generally needed for computing heat transfer coefficients. Extreme ambient temperature input conditions, such as cold fronts and sudden cold reservoir temperatures, can and should be considered when appropriate to identify possible problems.

(2) Step 2: Determine material properties. Thermal properties required for FE thermal analysis include thermal conductivity, specific heat, adiabatic temperature rise of the concrete mixture(s), and density of the concrete and foundation materials. Coefficient of thermal expansion is required for computing induced strain from temperature differences. Modulus of elasticity of concrete and foundation materials are required for determination of foundation restraint factors. Tensile strain capacity test results are important for cracking evaluation. When tensile strain capacity data are not available, the methodology presented in Annex 1 may be used to estimate probable tensile strain capacity performance of the concrete. Creep test results are necessary to determine the sustained modulus of elasticity (or an estimate of E_{sus} is made) if stress-based cracking analysis is used.

(3) Step 3: Determine construction parameters. Construction parameters must be compiled which include information about concrete placement temperature, structure geometry, lift height, construction start dates, concrete placement rates, and surface treatment such as formwork and insulation that are possible during construction of the MCS. To determine concrete placement temperature, a first approximation is to assume that concrete placement temperatures directly parallel the mean daily ambient temperature curve for the project site. Actual placement temperature data from other projects can be used for prediction, modified by ambient temperature data differences between the different sites. The temperature of the aggregate stockpiles may change more slowly than does the ambient temperature in the spring and fall. Hence, placement temperatures during spring months may lag several degrees below mean daily air temperatures, while placement temperatures in the fall may lag several degrees above mean daily air temperatures.

c. Temperature analysis

(1) Step 4: Prepare temperature model. Various temperature analysis methods suitable for Level 2 thermal analysis are discussed in Appendix A. Either step-by-step integration methods or FE models may be used for Level 2 temperature analysis or mass and surface gradients. If step-by-step integration methods are used, the computation or numerical model should be programmed into a personal computer spreadsheet. The decision on whether to use FE 1-D strip models or 2-D section analysis is gen-

erally based on complexity of the structure, complexity of the construction conditions, and on the stage of project design. Often 1-D strip models are used first for parametric analyses to identify concerns for more detailed 2-D analysis.

(2) Compute temperature histories. Once computed, temperature data should be tabulated as temperature-time histories and temperature distributions to obtain good visual representations of temperature distribution in the structure. ETL 1110-2-536 has examples of temperature distribution plots. Appropriate locations can then be selected for temperature distribution histories at which mass gradient and surface gradient analysis will be conducted.

(a) Step 5: Mass gradient temperature analysis. Temperature-time histories, showing the change in temperature with time at specific locations after placing, are generally used to calculate temperature differences for mass gradient cracking analysis. Temperature differences for mass gradient cracking analysis are generally computed as the difference between the peak concrete temperatures and the final stable temperatures that the cooling concrete will eventually reach.

(b) Step 6: Surface gradient temperature analysis. The objective of surface gradient temperature analysis is to determine at desired critical locations the variation of surface temperatures with depth and with time. This can be performed effectively with 1-D strip models or with 2-D analysis. Thinner sections may require temperature distributions entirely across the structure, while large sections often only require temperature to be evaluated to some depth where temperature changes are relatively slow. Ideally, temperature distribution histories are generated for a single lift, tabulated from one surface to the other (or a stable interior) with each distribution representing temperatures for a specific time after placement.

d. Cracking analysis.

(1) Step 7: Mass gradient cracking analysis. The mass gradient temperature differences are used with C_{th} and restraint factors (K_f and K_R) to evaluate mass gradient cracking potential, using Equation A-4 in Appendix A. Computed mass gradient strains are compared against tensile strain capacity to evaluate cracking potential. For a stress-based mass gradient cracking analysis, the sustained modulus of elasticity corresponding to the time frame of the analysis is used to convert strains calculated by Equation A-4 to stresses. The use of the sustained modulus allows for the relief of temperature-induced stress due to creep. These stresses are compared to the tensile strength of the concrete at the appropriate age to determine where and when cracking may occur.

(2) Step 8: Surface gradient cracking analysis. Surface gradient cracking analysis is based on higher temperature differences in the surface concrete compared to the more slowly cooling interior which creates areas of tension in the surface to some depth, H. Tensile strain is calculated based on C_{th}, the temperature difference at some depth of interest, and the degree of restraint based on H.

(a) Temperature differences are calculated using as a basis the temperature when the concrete first begins hardening, rather than a peak temperature as used in mass gradient computations. These temperature differences, with time and depth, allow determination of tensile and compression zones near the concrete surfaces. The point at which tension and compression zones balance is considered a stress-strain free boundary (located at H from the surface) used to compute restraint for surface gradient analysis. This point is generally calculated by evaluating temperature differences at depth with respect to temperature differences at the surface.

(b) Reference or initial temperatures for a surface gradient analysis are defined as the temperatures in the structure at the time when the concrete begins to harden and material properties begin to develop. Generally, this time is established at concrete ages of 0.25, 0.5, or 1.0 day. This age is dependent upon the rate at which the concrete achieves final set, the rate of subsequent cement hydration, and the properties of the mixture. For very lean concrete mixtures at normal temperature, a baseline time of 1.0 days may be reasonable. Mixtures that gain strength more rapidly at early ages may be better approximated by an earlier reference time of 0.25 or 0.33 days (6 or 8 hours).

(c) Internal restraint factors, K_R, are computed using Equation A-5 or A-6 in Appendix A, depending upon the ratio of *L/H*, where L is the horizontal distance between joints or ends of the structure, and *H* is the depth of the tension block. Induced tensile strains are computed at each analysis time from Equation A-8 in Appendix A using the coefficient of thermal expansion, the temperature differences between the surface and interior concrete, and the computed internal restraint factors. These strains are compared with slow load tensile strain capacity (selected or tested to correspond to the time that strains are generated) to determine cracking potential.

(d) Stress-based surface gradient cracking analysis is often handled in a slightly different way, particularly in the way creep is accounted for in the analysis. Commonly, incremental temperature differences at different depths and times are computed. These incremental temperature differences are converted to incremental stresses, including creep effects, using the C_{th}, E_{sus}, and K_R. The incremental stresses generated during each time period are summed to determine the cumulative tensile stress in the surface concrete at various depths. These stresses are compared to the tensile strength of the concrete at the appropriate age to determine cracking potential.

e. *Conclusions and recommendations*. These typically include expected maximum temperatures for starting placement in different seasons, expected transverse and longitudinal cracking without temperature or other controls, recommended concrete placement temperature limitations, anticipated concrete precooling measures, need for adjustment in concrete geometry, properties, joint spacing, and the sensitivity of the thermal analysis to changes in parameters. Typical temperature control measures evaluated might include reduced lift heights, use of insulated forms, and reduction in mix cement content. The potential for thermal shock may be addressed. In addition, recommendations for further or more advanced thermal analysis should be provided and justified.

A3-2. Example 1: One-Dimensional Mass Gradient and Surface Gradient Thermal Analysis

a. *General.* An example of a 1-D mass gradient and a surface gradient analysis in a Level 2 thermal study of an MCS is presented below. This example is based on preliminary 1-D analyses performed during feasibility studies on a proposed large flood control RCC gravity dam on the American River in California. This dam was planned to be 146 m (480 ft) high, 792 m (2,600 ft) long, with a downstream face slope of 0.7H:1.0V.

(1) The 1-D analysis was used as a screening tool only, to provide preliminary evaluation of several concerns and to develop information for more detailed analyses. These studies were conducted to ascertain the general extent of thermal cracking (cracking due to mass thermal gradients and surface thermal gradients), for guidance in selecting an appropriate joint spacing to accommodate transverse thermal cracking, to evaluate the possibility of longitudinal cracking in the structure, and for early planning and cost-estimating purposes. Figure A3-1 illustrates the 1-D strip models employed in this analysis and the overall dam proportions.

(2) FE analysis in this study was used only to determine temperature history for the various schedule alternatives, using the Fortran program "THERM." Stresses were determined by manual computational methods, based on temperature change computed by the FE temperature analysis, the coefficient of thermal expansion, the sustained modulus of elasticity, and the degree of restraint. To account for stress relief due to creep and because the mass concrete modulus of elasticity is very low at early ages, the analysis is segmented into several time spans, 1 to 3 days, 3 to 7 days, and 7 to 28 days. This allows use of changing material properties (modulus and creep) to be used for each time span, as well as changing *h* and *H* dimensions of the surface gradient tension block with time. Consequently, temperature changes were determined for each time span.

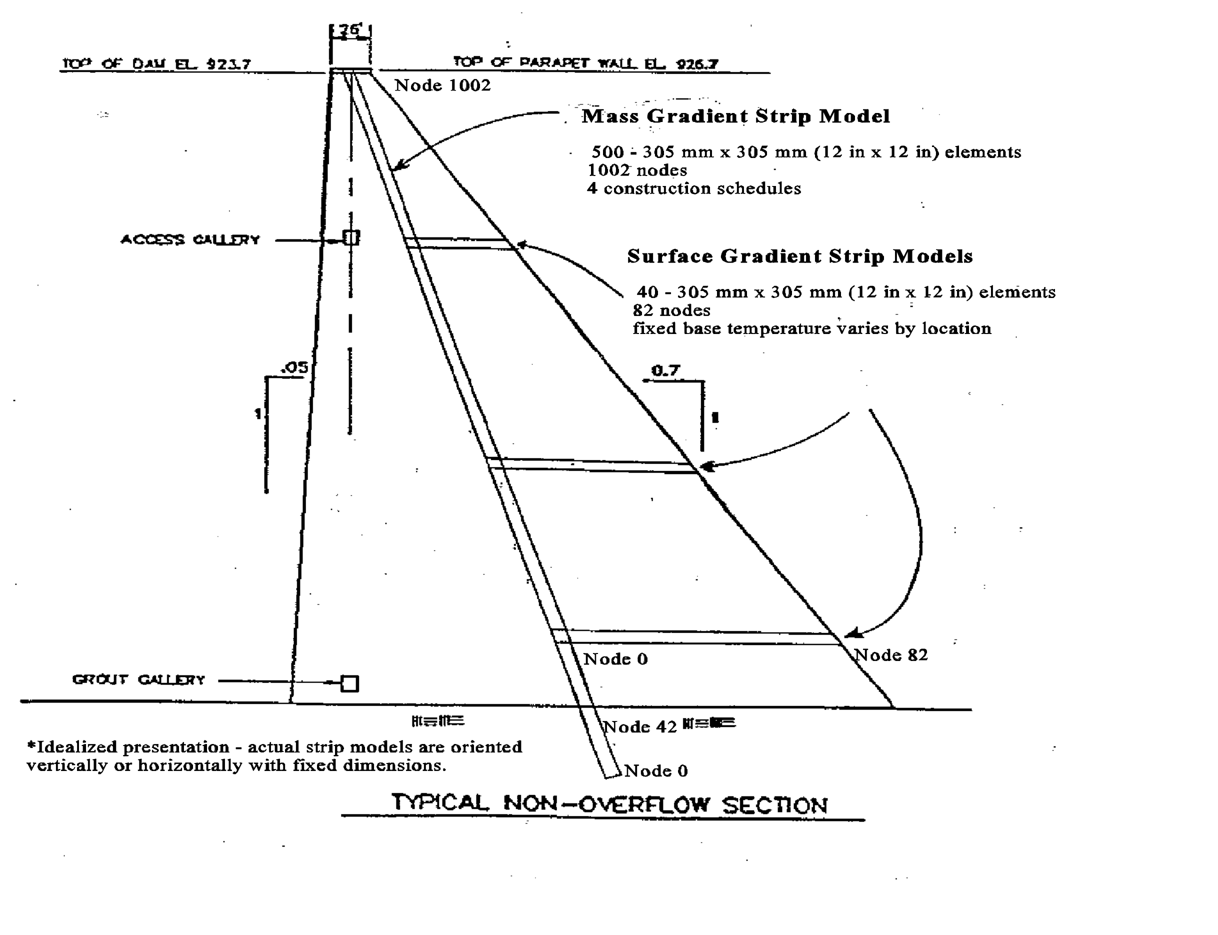

Figure A3-1. FE strip models

b. *Input properties and parameters*. At this early stage in the planning process, many of the details of the structure, materials performance, and placement constraints have not been determined and can only be approximated. It was decided that it would be prudent to make a reasonable estimate of those unknown parameters, and limit the study to evaluating the effects of variations of only a few items. In this study, those items subject to variations are certain material properties and the placing schedule.

(1) Step 1: Determine ambient conditions. Ambient air temperature data were produced from National Oceanic and Atmospheric Administration (NOAA) local climatological data. From these data, seven series of daily air temperature curves (shown in Figure A3-2) were developed, each representing the daily temperature cycle for one or more months. No data were available on how temperatures vary during each day. The curves are an estimate of the daily profile as it varies for each month throughout the year. No means of incorporating heat from solar gain was included in this analysis.

(2) Step 2: Determine material properties. Table A3-1 summarizes the applicable thermal and elastic properties of the materials considered for use in the structure. Most of the properties for the RCC and the foundation rock were estimated, or were the product of laboratory testing. Approximated values used for the modulus of elasticity, tensile strength, and creep rate are shown on Figure A3-3. Three materials were utilized for the analysis of the

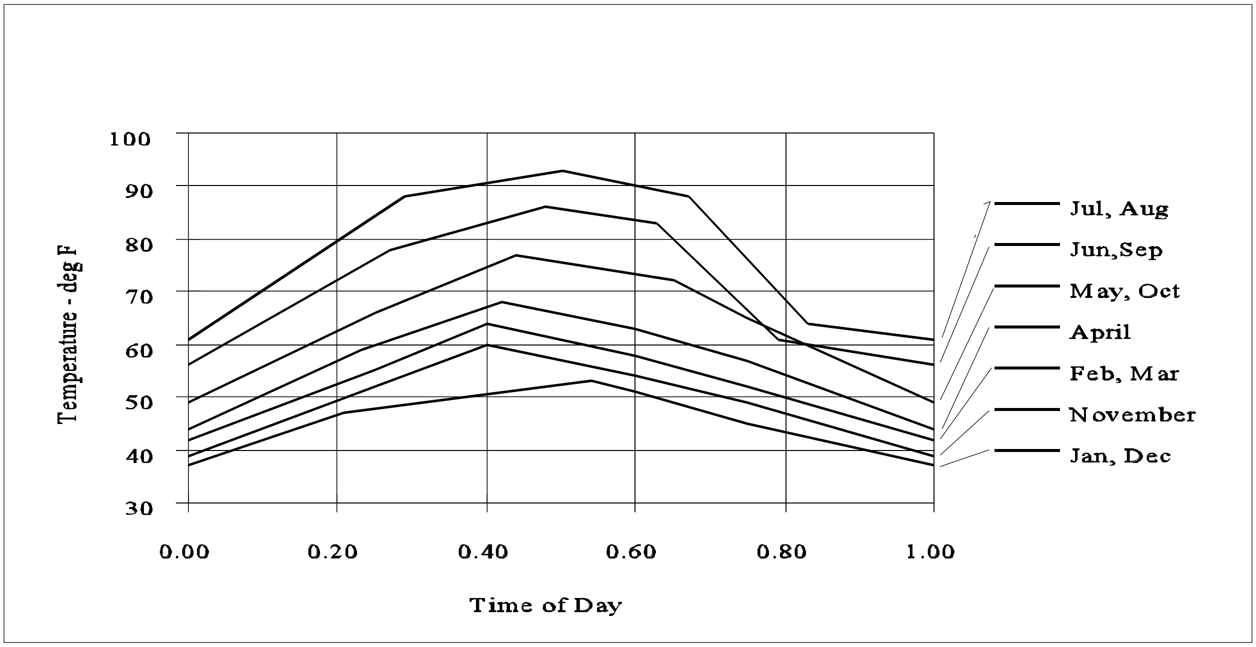

Figure A3-2. Daily ambient temperature cycles

Table A3-1
The RCC Material Properties for Mixtures

Property	Units	Damsite Alluvium	Damsite Amphibolite
Coefficient of thermal expansion (C_{th})[1]	millionths/deg C (millionths/deg F)	7.2 (4.00)	6.9 (3.86)
Thermal conductivity (K)	W/m-K (Btu/ft-hr-deg F)	2.42 (1.4)	2.77 (1.6)
Diffusivity (h^2)	m^2/hr (ft^2/hr)	0.038 (0.041)	0.0039 (0.042)
Specific heat ©	kJ/kg-K (Btu/lb-deg F)	0.92 (0.22)	0.92 (0.22)
Cement content[1]	kg/m^2 (lb/cy)	107 (180)	107 (180)
Flyash content[1]	kg/m^2 (lb/cy)	53 (90)	53 (90)
Adiabatic temperature rise (ΔT_{ad})	deg C (deg F)	15 (27)	15 (27)
Density[1]	kg/m^3 (lb/ft^3)	2,483 (155)	2,643 (165)
Tensile strain cap. (ϵ_{tc}) @ 7-90 day	millionths	100	100

[1] From test results

foundation and the dam construction. The foundation rock was assumed to provide thermal behavior similar to the amphibolite aggregate. The first 200 lifts of the dam use an RCC mixture with damsite alluvium aggregates. The remaining 280 lifts utilize an RCC mixture with amphibolite (metamorphosed sandstone) aggregate from the damsite.

(3) Step 3: Determine construction parameters.

(a) Construction start dates. To evaluate the effects of different construction start dates, the placement of concrete was evaluated during four time intervals. The initiation of RCC placements was set at 1 January, 1 April, 1 July, and 1 October

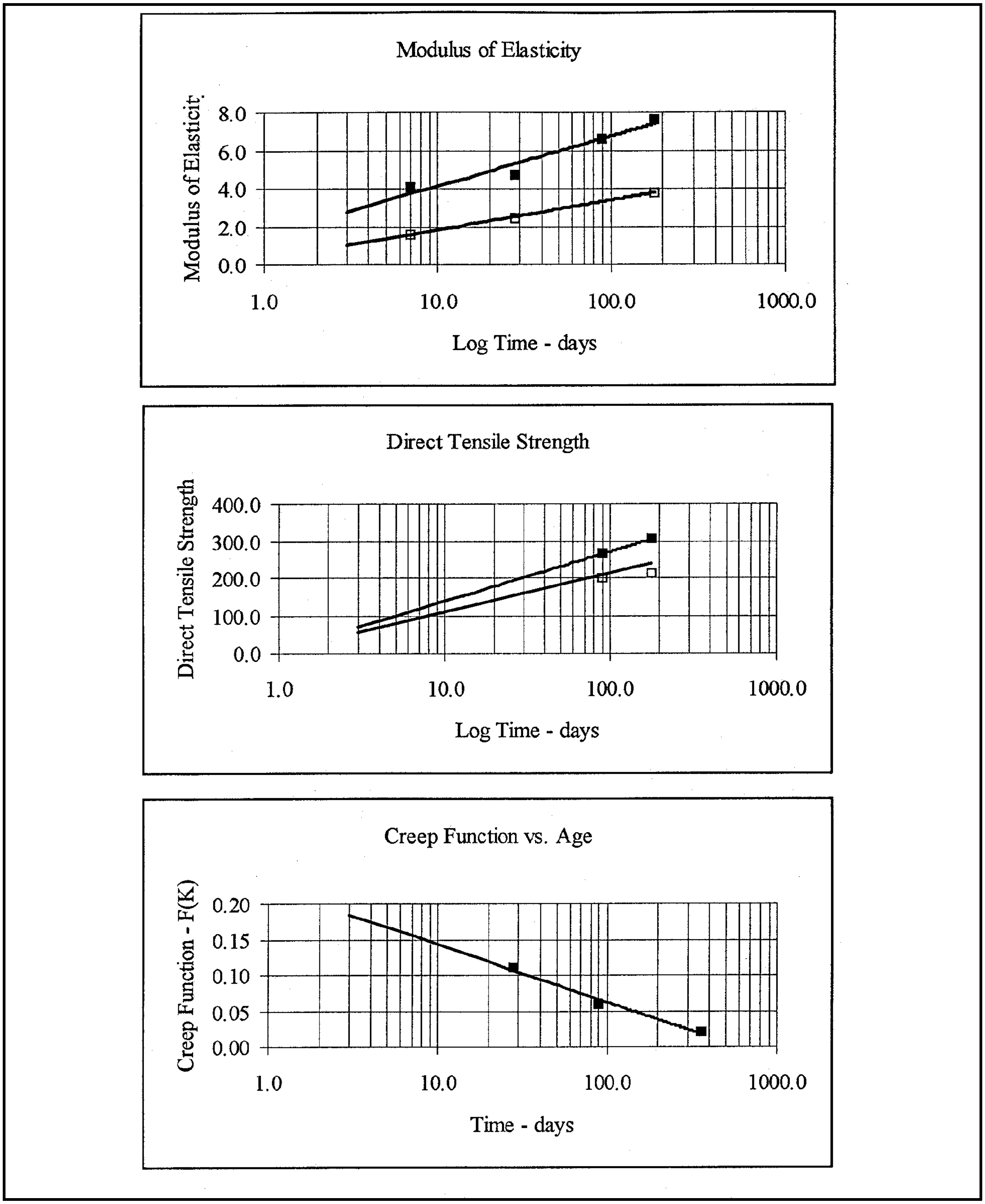

Figure A3-3. Estimated elastic and creep properties

of each year for the mass gradient analysis. For the surface gradient analysis, a 1 January start date was assumed.

(b) Concrete placing temperature. The temperature of the concrete aggregates has the greatest influence on the initial temperature of the fresh RCC. Because of the low volume of mix water, and the minor temperature differential of the water compared to the aggregate, the water temperature has a much less significant effect on overall temperature. Figure A3-4 provides the basis for the placing temperatures used in this study. Since aggregate production will be done concurrently by with RCC placement and regional temperatures tend to be moderate, stockpile temperatures should closely parallel the average monthly ambient temperatures. Some heat is added because of screening, crushing, and transportation activities, as shown in the figure, based on experience.

(c) Placement Assumptions. The RCC structure will be composed of two RCC mixtures, as previously described. The RCC placement will be in a 610-mm (24-in.) lift operation. The FE model is dimensioned having elements 305 mm (12 in.) in height. This allows future evaluations of 305-mm (12-in.) placing schemes, if desired. The RCC placement was assumed to occur on a schedule of 6 days per week, 20 hours per day, for the duration of the placement.

c. *Temperature analysis*.

(1) Step 4: Prepare temperature model (FE).

(a) The Fortran FE program "THERM", developed originally by Wilson (Wilson 1968), was used on a PC for the temperature analysis in this example. An Excel spreadsheet was used for development of an input file for THERM. Output nodal temperatures were imported into Excel spreadsheets for further analysis of cracking and graphical output. The FE grid, termed the mesh, provides more realistic results as it more accurately simulates the geometry of the structure. Since 1-D models (strip models) were used for the mass gradient analysis, heat only flowed vertically in or out of the model. Lateral heat flow in the upstream or downstream direction was not modeled. It is anticipated that actual heat dissipation in the dam over the long term will be at a more rapid rate than the model predicts. Since RCC construction is the continuous placement of relatively thin lifts, it is best modeled with elements of a height equivalent to the lift height or less. Unfortunately, since the American River Dam is a very massive structure, a mesh that provides ample detail would be monumental. A mesh of this magnitude is not necessary for the extent of evaluations to be done at this stage. Consequently, it was determined that a reasonable determination of internal temperatures could be done using strip models. A strip model is simply a vertical or horizontal "strip" of elements, usually only one element wide. Heat flows through the ends of the strip, but no heat flows from the sides. The model is located where necessary to simulate the thermal activity at that location. While the effects of many factors cannot be easily modeled using this method, generalized behavior can be determined.

(b) The primary mesh for mass gradient analysis, shown in Figure A3-1, is composed of 500 elements and 1,002 nodes. It simulates a strip through a cross section of the dam originating 6 m (20 ft) in the foundation rock. Elements 1 to 20 form the rock foundation with the bottom row of nodes set at a fixed temperature of 115.5 deg C (60 deg F), the mean annual air temperature for the area. An arbitrary time of 30 days is allowed to elapse prior to concrete placement to allow the rock temperatures to stabilize.

(c) The RCC at about dam midheight was evaluated for a surface temperature gradient. The surface gradient strip model spans from the exposed surface along a single lift to a point inside the structure where temperatures are assumed to not be influenced by ambient conditions. A small FE model was generated of approximately 82 nodes and 40 elements. Temperature histories of these nodes were then determined. The exterior surface of the surface gradient strip model was assumed to be fully exposed, with no insulation, using a heat transfer coefficient of 28.45 W/m^2-K (5.011 Btu/ft^2-hr-deg F).

Month	Mean Temp	Mean Annual	Diff	2/3 Diff	Sub Total	Crush Add	Stock Temp	Mixing Add	Trans Add	Final Temp
	degC (degF)	degC (degF)	degC (degF)	degC (degF)	degC (degF)	degC (degF)	degC (degF)	degC (degF)	degC (degF)	degC (degF)
Jan	7.1 (44.8)	15.5 (60.0)	-8.4 (-15.2)	-5.6 (-10.1)	9.9 (49.9)	1.1 (2.0)	11.1 (51.9)	1.1 (2.0)	-0.6 (-1.0)	11.7 (53)
Feb	9.2 (48.6)	15.5 (60.0)	-6.3 (-11.4)	-4.2 (-7.6)	11.3 (52.4)	1.1 (2.0)	12.4 (54.4)	1.1 (2.0)	0	13.3 (56)
Mar	10.5 (50.9)	15.5 (60.0)	-5.1 (-9.1)	-3.4 (-6.1)	12.2 (53.9)	1.1 (2.0)	13.3 (55.9)	1.1 (2.0)	0.6 (1.0)	15.0 (59)
Apr	13.2 (55.8)	15.5 (60.0)	-2.3 (-4.2)	-1.6 (-2.8)	14.0 (57.2)	1.1 (2.0)	15.1 (59.2)	1.1 (2.0)	0.6 (1.0)	16.7 (62)
May	17.0 (62.6)	15.5 (60.0)	1.4 (2.6)	0.9 (11.7)	16.5 (61.7)	1.1 (2.0)	17.6 (63.7)	1.1 (2.0)	1.1 (2.0)	20.0 (68)
Jun	21.4 (70.5)	15.5 (60.0)	5.8 (10.5)	3.9 (7.0)	19.4 (67.0)	1.1 (2.0)	20.6 (69.0)	1.1 (2.0)	1.1 (2.0)	22.8 (73)
Jul	25.1 (77.2)	15.5 (60.0)	9.6 (17.2)	6.4 (11.5)	21.9 (71.5)	1.1 (2.0)	23.1 (73.5)	1.1 (2.0)	1.7 (3.0)	25.6 (78)
Aug	24.5 (76.1)	15.5 (60.0)	8.9 (16.1)	5.9 (10.7)	21.5 (70.7)	1.1 (2.0)	22.6 (72.7)	1.1 (2.0)	1.7 (3.0)	25.6 (78)
Sep	22.1 (71.8)	15.5 (60.0)	6.5 (11.8)	4.4 (7.9)	19.9 (67.9)	1.1 (2.0)	21.1 (69.9)	1.1 (2.0)	1.1 (2.0)	23.3 (74)
Oct	17.4 (63.4)	15.5 (60.0)	1.9 (3.4)	1.3 (2.3)	16.8 (62.3)	1.1 (2.0)	17.9 (64.3)	1.1 (2.0)	0.6 (1.0)	19.4 (67)
Nov	11.5 (52.7)	15.5 (60.0)	-4.1 (-7.3)	-2.7 (-4.9)	12.8 (55.1)	1.1 (2.0)	13.9 (57.1)	1.1 (2.0)	0	15.0 (59)
Dec	7.7 (45.9)	15.5 (60.0)	-7.8 (-14.1)	-5.2 (-9.4)	10.3 (50.6)	1.1 (2.0)	11.4 (52.6)	1.1 (2.0)	-0.6 (-1.0)	12.2 (54)

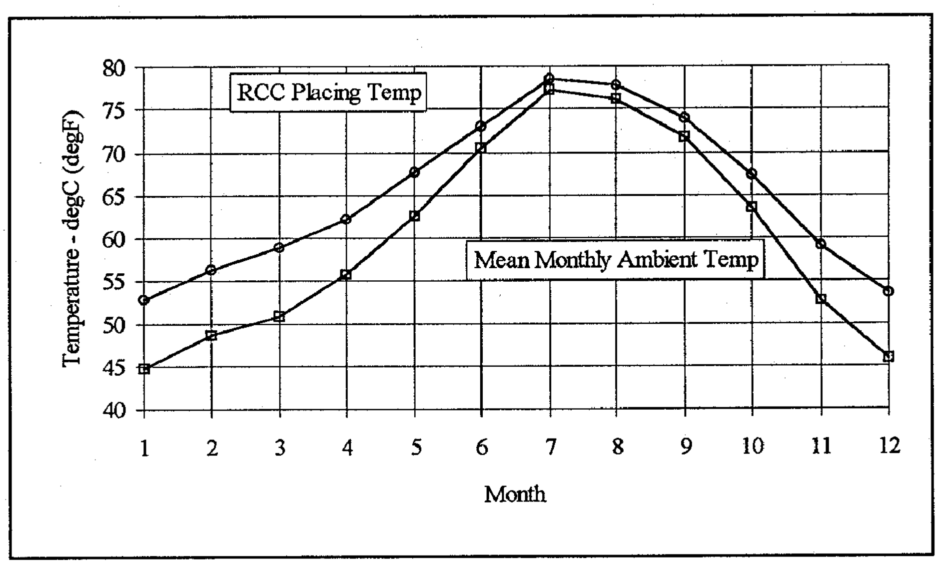

Figure A3-4. RCC placing temperature

(2) Compute temperature histories.

(a) Step 5: Mass gradient temperature analysis. Graphical representations for each of the four cases analyzed (one for each season) are shown in Figures A3-5 through A3-12. The first graph in each set is a time-history of nodal temperatures for selected nodes in the structure. This graph is useful to determine the time when certain zones in the structure reach certain temperatures. The second graph displays the maximum and minimum temperature experienced by each node. Note that these maximums and minimums occur at different times. The minimum temperatures of adjacent nodes fluctuate approximately 4 deg C (8 deg F) because of ambient temperature fluctuations. This graph is useful in determining the maximum temperature differentials, as well as determining the critical zones.

(b) Step 6: Surface gradient temperature analysis. Graphical representation of the single start date case analyzed is shown in Figure A3-13, and is comprised of families of curves representing temperature change with time for different depths from the exterior surface of the MCS. Figure A3-14 shows these temperatures converted to a family of curves of time versus distance from the surface on the x-axis. This conversion is done to ease the subsequent cracking analysis computations.

d. Cracking analysis. It is assumed for the purposes of this study that the initial (baseline) temperatures of the hardened RCC are those temperatures when the RCC is 24 hours old. Any subsequent change in temperature from this base forms the temperature gradient. For surface gradient analysis, the shallowest interior nodes where

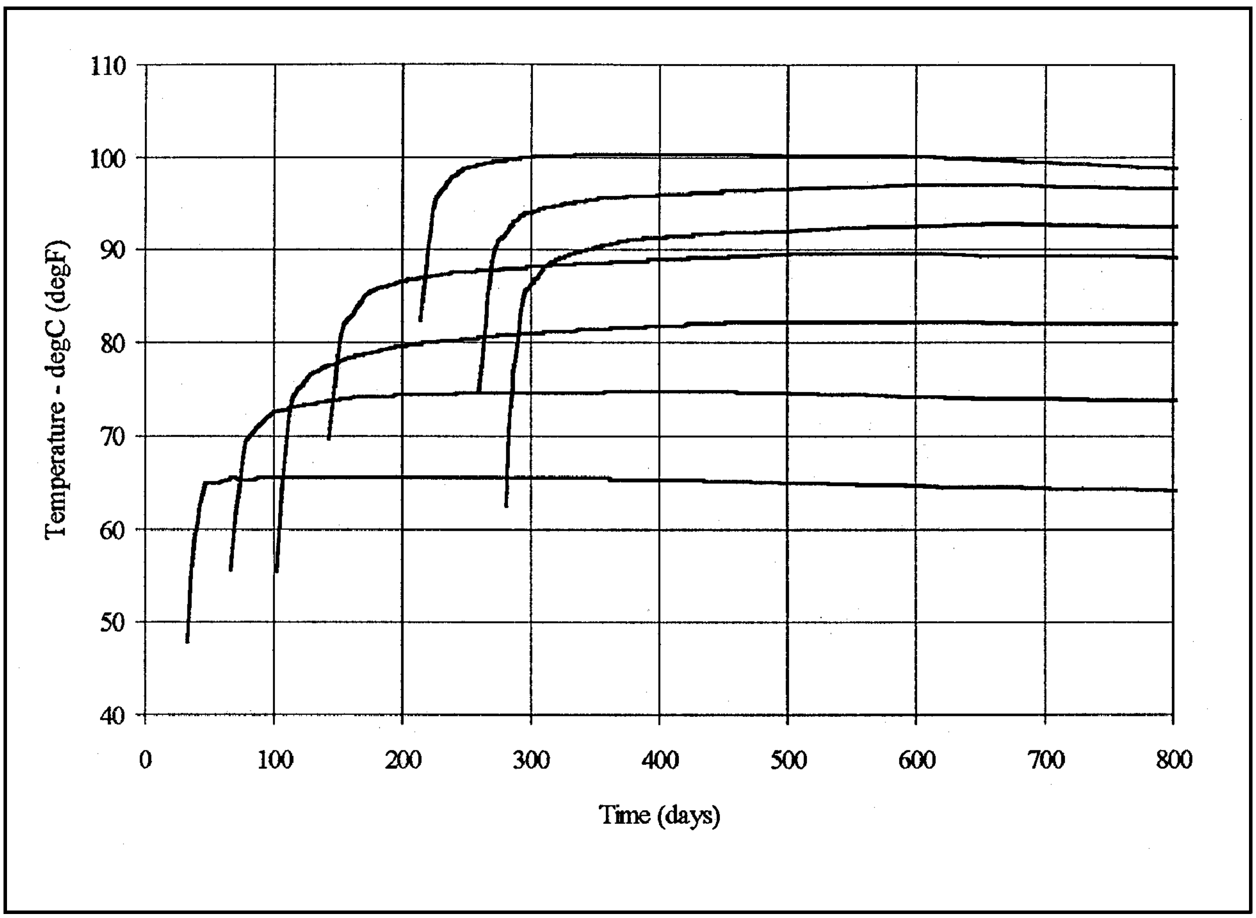

Figure A3-5. Mass gradient temperature histories for 1 January start

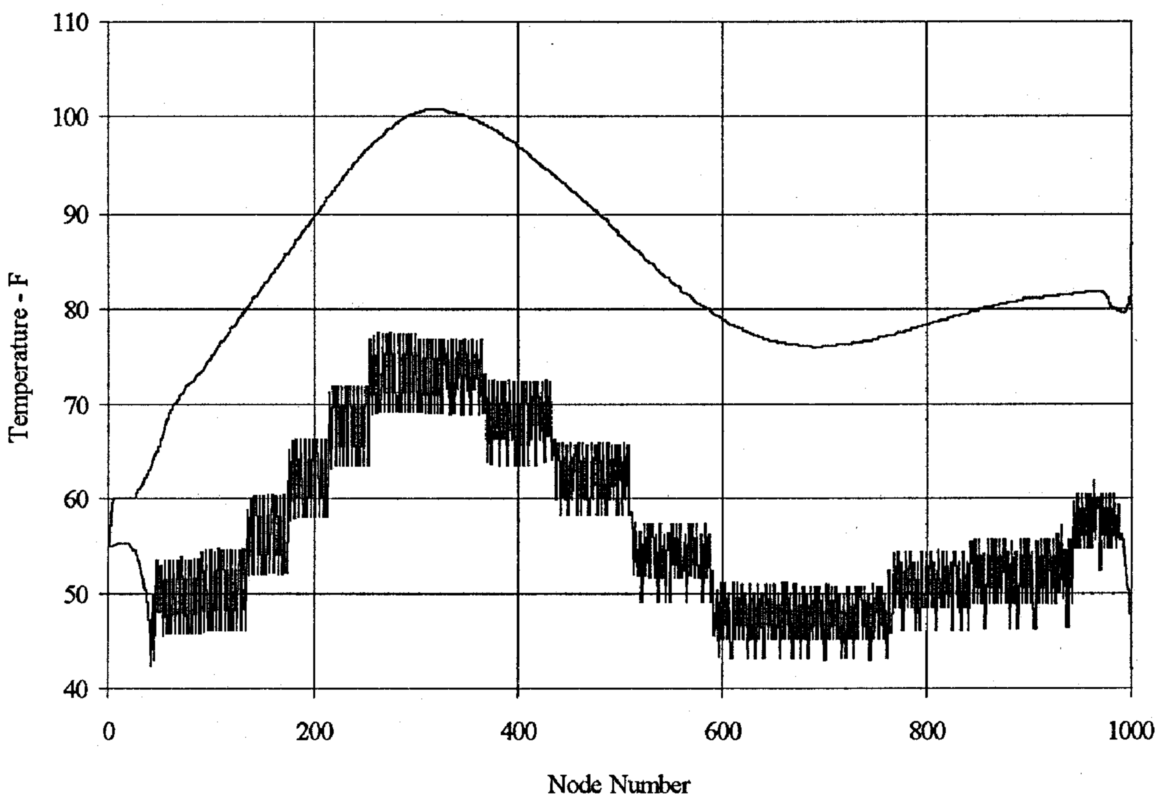

Figure A3-6. Mass gradient peak temperatures for 1 January start

temperatures do not change are assumed to be the location of the stress and strain-free surface. The distance from the surface to the location under consideration is used to calculate restraint factors (K_R) for both surface and mass gradient analysis.

(1) Step 7: Mass gradient cracking analysis. Several general statements can be made regarding the data. At locations low in the structure near the foundation, restraint conditions are the greatest. Consequently, allowable temperature differentials are at a minimum there. Progressing up and away from the foundation, restraint decreases, allowing a greater temperature differential before the onset of cracking. The graphs (Figures A3-6, 8, 10, and 12) in each of the analysis sets represent sections for the full height of the structure. However, the data can be applied to dam sections founded at higher elevations (*e.g.,* the abutments) by merely moving the y-axis to the right to a point corresponding to the appropriate foundation elevation. In this manner, the performance of the entire structure can be evaluated. In general, no cracking is expected if peak temperatures, low in the structure, do not exceed 29.4 deg C (85 deg F); because long-term cooling of the structure to 15.5 deg C (60 deg F) results in a 13.9-deg C (25-deg F) differential. Where nodal temperatures approach 37.8 deg C (100 deg F), they can be expected to remain above 29.4 deg C (85 deg F) for at least 5 years, and final cooling of the interior to 15.5 deg C (60 deg F) may take 15 to 20 years.

(a) Placement start on 1 January (Figures A3-5 and 6). Peak temperatures of 29.4 to 37.8 deg C (85 to 100 deg F) are realized in the part of the structure represented by nodes 200 to 500. This peak occurs during the month of July, after

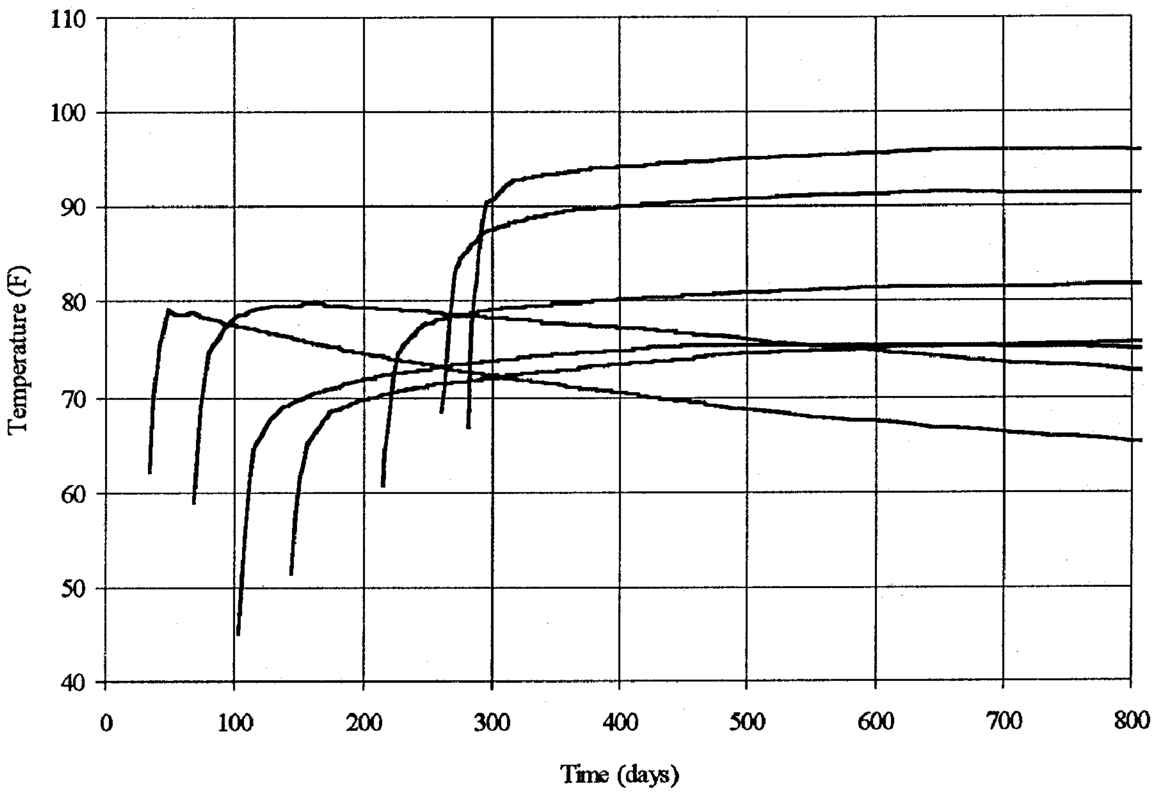

Figure A3-7. Mass gradient temperature histories for 1 October start

approximately 200 days of placement. Initial placements for the large monoliths are performed during the cool part of the year (winter and early spring), resulting in crack-free performance. Higher in the structure, where peak temperatures exceed 29.4 deg C (85 deg F), cracking does not occur because foundation restraint is reduced. The placements generating peak temperatures and resultant strains that may initiate cracking are those placements on the abutments between elevation 90 and 240 for a January start. This can be seen on Figure A3-6. Nodes 200 to 500 exceed 29.4 deg C (85 deg F). These nodes are located 27 to 73 m (90 to 240 ft) above the deepest foundation elevation.

(b) Placement start on 1 October (Figures A3-7 and 8). Peak temperatures of 29.4 to 37.8 deg C (85 to 100 deg F) are realized in the part of the structure represented by nodes 300 to 900. This peak occurs during the month of July, after approximately 300 days of placement. Initial placements for the large monoliths are performed during the cooler part of the year (fall, winter, and early spring), and peak temperatures never reach the critical level of 29.4 deg C (85 deg F). However, higher in the structure, where temperatures do exceed 29.4 deg C (85 deg F), cracking does not occur because foundation restraint is reduced. For an October start, the placements generating peak temperatures and resultant strains that may initiate cracking are those placements on the abutments at elevations 43 to 134 m (140 to 440 ft) from the lowest foundation elevation.

(c) Placement start on 1 July (Figures A3-9 and 10). Peak temperatures of 29.4 to 37.8 deg C (85 to 100 deg F) are realized in the part of the structure represented by nodes 50 to 200 and 500 to 1000.

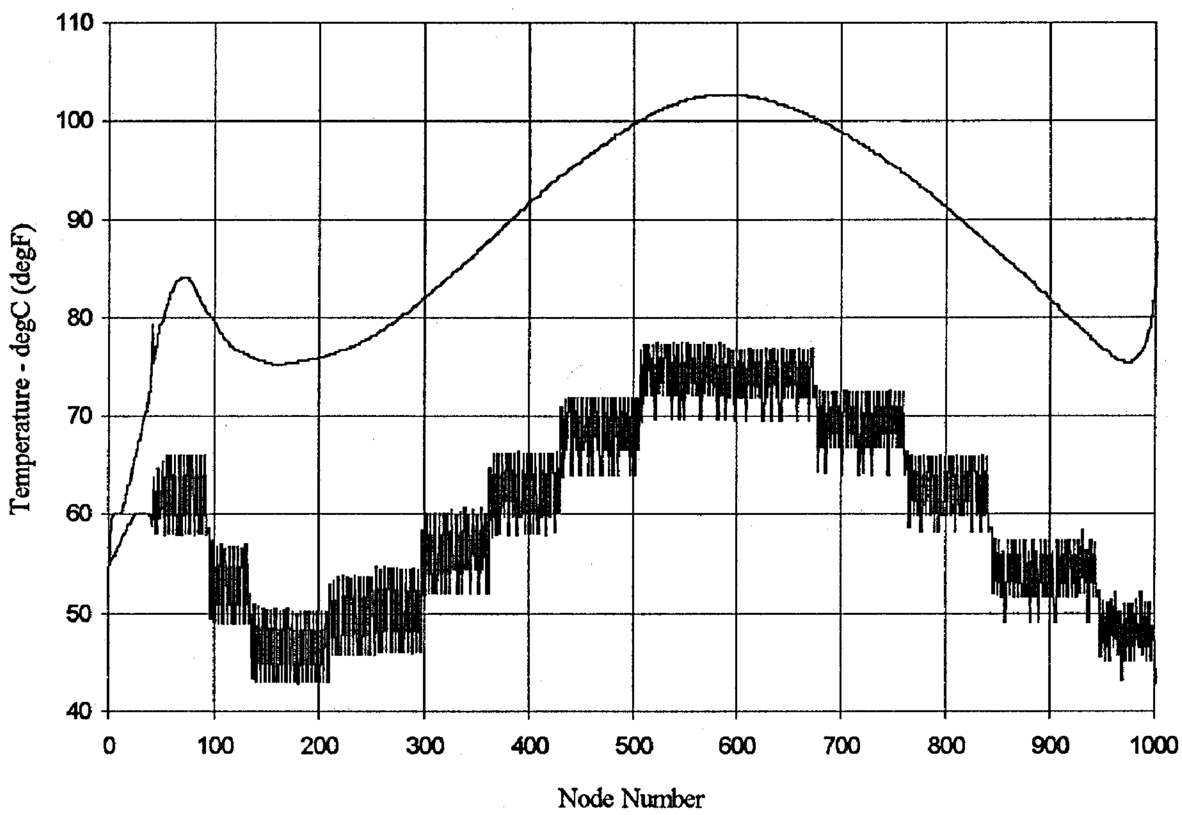

Figure A3-8. Mass gradient peak temperatures for 1 October start

This peak occurs after approximately 100 days of placement (during the month of July) for the early placements; and 1 year later for the upper dam placements. Initial placements for the large monoliths are performed during the warmest part of the year (the summer and early fall months), and peak temperatures exceed the critical level of 29.4 deg C (85 deg F). However, higher in the structure, where temperatures do exceed 29.4 deg C (85 deg F), cracking does not occur because foundation restraint is reduced. For a July start, the additional placements generating peak temperatures and resultant strains that may initiate cracking are those placements on the abutments at elevations 73 to 146 m (240 to 480 ft) above the lowest foundation elevation.

(d) Placement start on 1 April (Figures A3-11 and 12). Peak temperatures of 29.4 to 37.8 deg C (85 to 100 deg F) are realized in the part of the structure represented by nodes 100 to 400 and 800 to 1000. This peak occurs during the month of July, after approximately 100 days of placement for the early placements; and 1 year later for the upper dam placements. Initial placements for the large monoliths are performed during the moderate part of the year (the spring), avoiding cracking. Higher in the structure, where temperatures exceed 29.4 deg C (85 deg F), cracking does not occur because foundation restraint is reduced. Additional placements generating peak temperatures and resultant strains that may initiate cracking are those placements on the abutments from an elevation 12 to 49 m (40 to 160 ft) above the lowest foundation elevation and placements near the top of the dam.

(e) Mass gradient cracking analysis results. The following table summarizes, for each placing

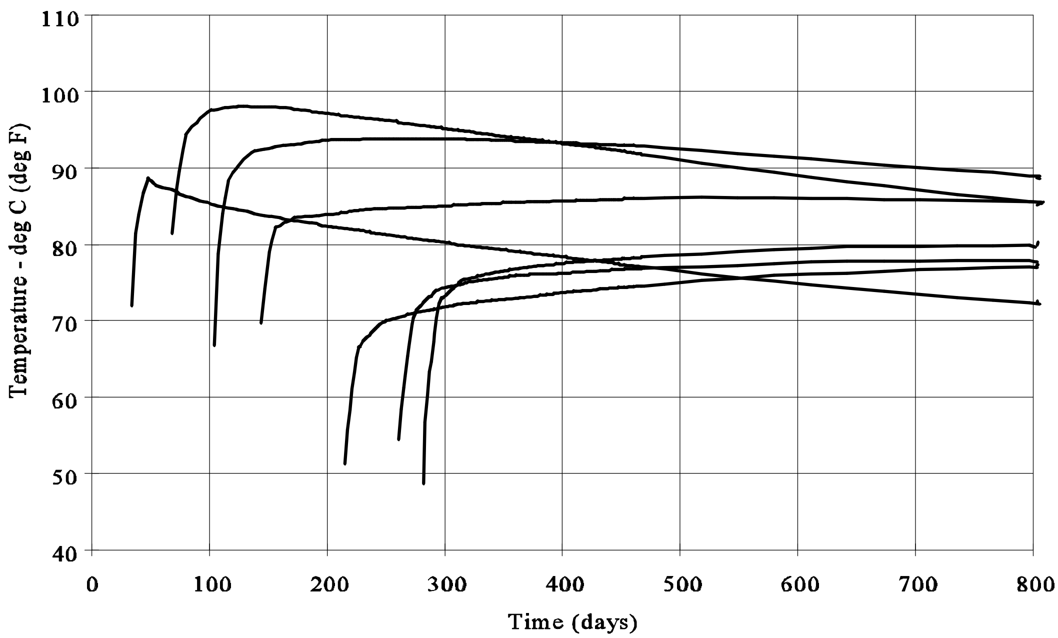

Figure A3-9. Mass gradient temperature histories for 1 July start

schedule evaluated, the nodes and the node locations where mass gradient thermal cracking is expected. The “Height Above Foundation” refers to those abutment foundation locations at elevations above the lowermost foundation elevation. For example, a January-start schedule results in probable cracking of nodes 200 to 400, and foundation elevations located 27 to 73 m (90 to 240 ft) above the lowest foundation elevation.

Uncontrolled RCC placing temperatures will result in peak temperatures of 37.8 deg C (100 deg F) and ultimate temperature differentials of 22.2 deg C (40 deg F). The maximum temperature differential calculated from tensile strain capacity and the coefficient of thermal expansions is 13.9 deg C (25 deg F) for the near term, increasing to near 16.7 deg C (30 deg F) for cooling periods of 15 years. Fall and winter placements result in cool placing temperatures, with peak temperatures for those placements of less than 29.4 deg C (85 deg F). Spring and summer placements result in peak temperatures exceeding 29.4 deg C (85 deg F), making cracking very probable. Cracking is generally induced at the foundation, where full restraint occurs and progresses up until restraint conditions lessen to the point where the driving force behind the crack is reduced. Since the force to propagate an existing crack is less than the force necessary to initiate the crack, it seems appropriate to assume that existing cracks may propagate further. The values shown in Table A3-2 do not include this extra crack height. Longitudinal cracking of the RCC in the large sections is not expected to be a problem when placement is done during the cool periods of the year. If these placements are done during the hot periods of the year, longitudinal

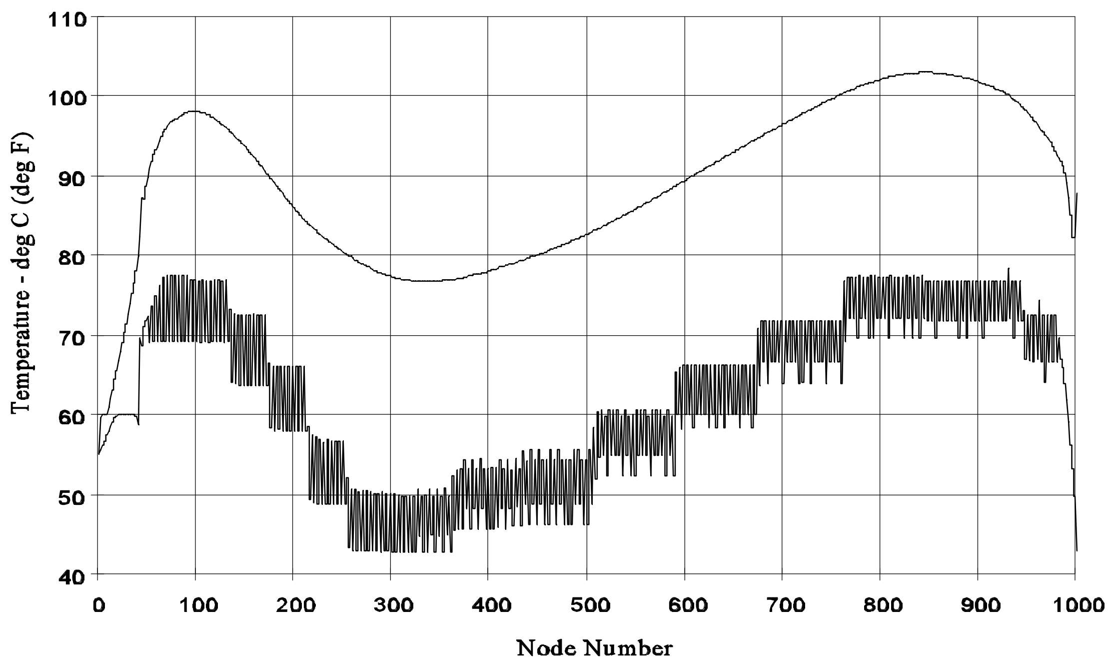

Figure A3-10. Mass gradient peak temperatures for 1 July start

cracking may occur. As construction progresses, placement of smaller RCC sections (those placements founded on rock at higher elevations) during hot periods is unavoidable. Longitudinal cracking of RCC placed against higher elevation foundation areas during these periods may occur. The conditions that may initiate longitudinal cracking may also initiate transverse cracking. The occurrence of transverse cracks can be reduced by installing transverse joints, thereby reducing the restraint.

(2) Step 8: Surface gradient cracking analysis. Surface gradient analysis was performed for several concrete placement start times, including the 1 January start time shown in this example. The effects of transverse joints at three different spacings were evaluated, including 30 m (100 ft), 61 m (200 ft), and 91 m (300 ft). The amphibolite aggregate RCC mixture was used in the evaluation. The procedure described here allows for consideration of changing concrete properties with age, such as *E* and creep, as well as changing *h* and *H* dimensions of the surface gradient tension block with time.

(a) Figure A3-13 presents the temperature data as a time-history plot for the conditions that should create the greatest surface gradient. Replotting the same data, based on nodal locations, yields Figure A3-14. Note that each curve represents the temperature cross section of the structure for a specific time. Each curve extends into the structure until the temperature becomes constant. Temperature differentials at specific locations are selected from Figure A3-14 and listed in Figure A3-15 (for 91-m (300-ft) joint spacing. Two basic assumptions are made in this analysis. First, temperatures of the RCC, at an age of 24 hours, are the baseline temperatures against which temperature change is determined. Second, the stress-strain free surface is assumed to be the depth at which the temperature

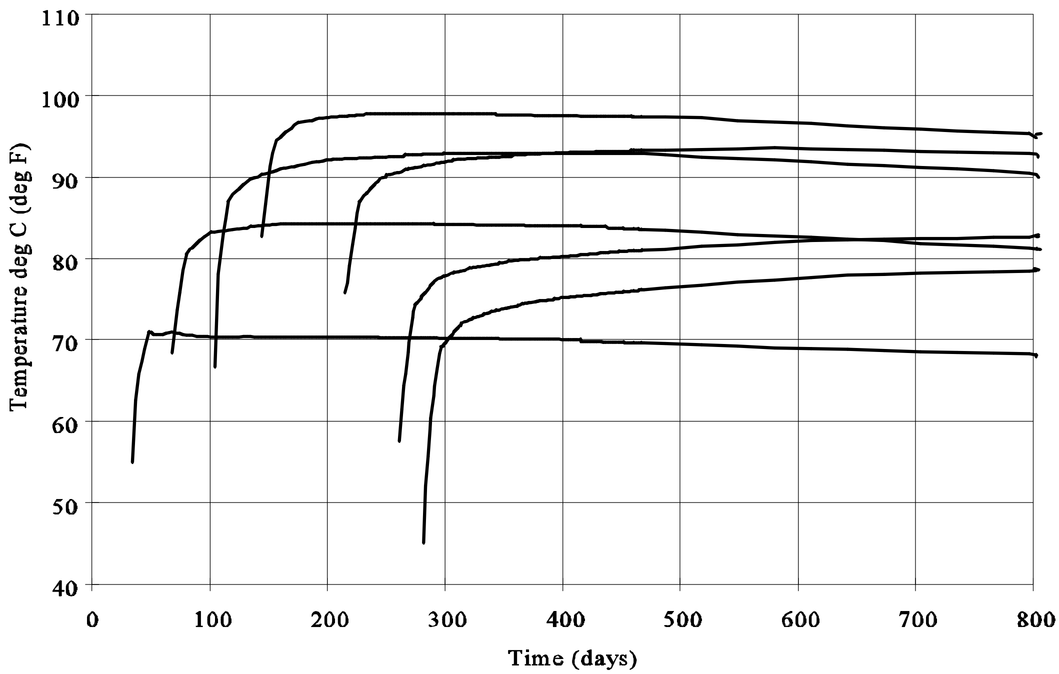

Figure A3-11. Mass gradient temperature histories for 1 April start

change, measured from the baseline temperature, approaches 0. Figure A3-15 shows the temperature deviations (*dT*) from the baseline temperature, as well as the depth at which the temperature gradient approaches 0. The Sum *dT* temperature differences are included on Figure A3-15 as a starting point for calculating induced stresses. "Induced *dT*," or the individual increments of temperature gradient induced with each age period, is calculated from the "Sum *dT*'s." Sustained modulus of elasticity (E_{sus}) is determined in Figure A3-15 for each age increment. To calculate incremental stress generated by temperature gradients:

$$\text{Incremental Stress} = (Ind\ dT)(C_{th})(E_{sus})$$

To determine K_R, Equation A-5 (Appendix A) is used, requiring calculation of *H*, *L*, and *h*. *H* is the distance from the exterior surface to the stress and strain-free surface at each incremental time period and is determined from the Temperature Differential Table in Figure A3-15 (note *H* for each age increment is the same). *L* is the joint spacing. *h* is the distance from the surface to the depth of interest (near surface, 0.6 , 1.5, 3, and 6 m (2, 5, 10, and 20 ft) in the figures), and *h/H* is the proportion of *H* from the surface to the depth of interest. *h/H* largely determines the amount of restraint at any location. K_R is calculated from Equation A-5 (Appendix A) for $L/H \geq 2.5$. The "Adj Stress" is calculated by:

$$\text{Adj Stress} = (K_R)(\text{Incremental Stress})$$

Cumulative stresses are then summed by superposition of stress from each age interval. Crack development is judged by whether the cumulative stress exceeds the tensile strength.

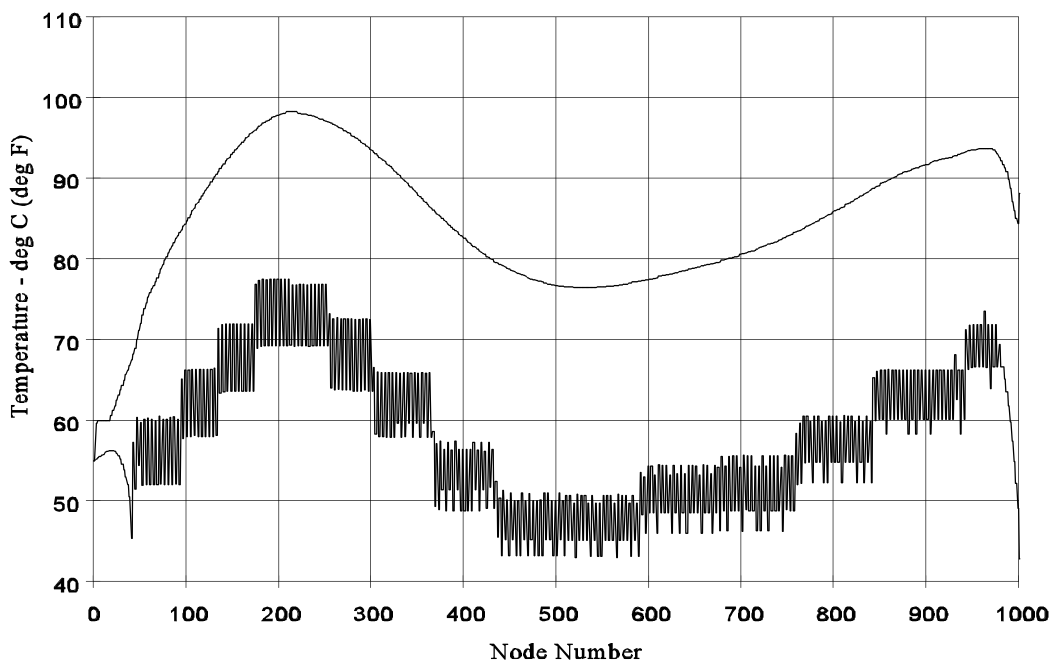

Figure A3-12. Mass gradient peak temperatures for 1 April start

From Figure A3-15 and similar computations for 30-and 61-m (100- and 200-ft) joint spacings, the computations indicate that surface cracking is not likely for a 30-m (100-ft) joint spacing. Surface cracking may increase to a depth of 0.6 m (2 ft) for joint spacings up to 61 m (200 ft) and up to 1.5 m (5 ft) for joint spacings of 91 m (300 ft). The full extent of surface cracking is controlled by the formation of the initial surface cracks. For example, at a joint spacing of 91 m (300 ft), the surface may crack at the midpoint. The analysis shows that this crack may propagate to a depth of 1.5 m (5 ft) after several weeks to months. However, the occurrence of this crack forms a new joint pattern at a spacing of 46 m (150 ft). While the depth of cracking may not be sufficient to change the restraint conditions (*L/H*), it may be enough to relieve induced stresses and stabilize the crack growth to depths of 0.6 m (2 ft). A joint spacing of 61 m (200 ft) may be an optimum spacing for this project based on the occurrence of surface cracking. Evaluation of the combined effects of surface gradient strains with mass gradient strains was not pursued, since the surface gradient strain contribution is not considered to be significant to the overall cracking performance of the structure using joint spacings of 30 and 61 m (100 and 200 ft).

e. *Conclusions and recommendations*. The maximum temperature differential under full restraint conditions (K_R = 1.0) that will not result in cracking of the RCC is 13.9 deg C (25 deg F). Since the final temperature of the RCC will be 15.5 deg C (60 deg F) (the average annual temperature), a crack-free peak RCC temperature is 29.4 deg C (85 deg F). This allowable differential of 13.9 deg C (25 deg F) increases as the distance of the RCC placements from the foundation

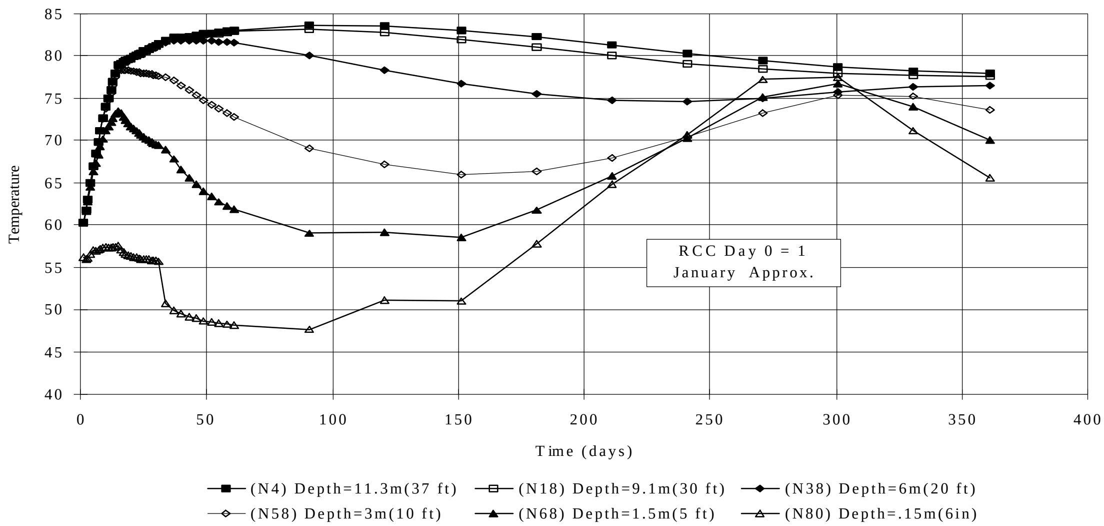

Figure A3-13. Temperature history for selected nodes from surface gradient model

increases. After evaluating several placing schedules, it was apparent that the most beneficial conditions occurred when the RCC placement of the lower third of the dam commenced in the fall of the year and was completed during late spring. This means that, for the larger dam sections, the upper two-thirds would then be placed during a hotter time period. The reduction in foundation restraint at this height in the structure, however, more than offset the effects of the higher temperatures.

Surface gradients were evaluated for several transverse joint intervals. Because the site is located in a relatively temperate area, where cold temperatures are rare, stresses from surface gradients were of little consequence for joint spacings up to 61 m (200 ft). Greater joint spacings increase the depth of surface cracking.

For contraction joints set at a spacing of approximately 61 m (200 ft), transverse cracking of the structure may occur in the lower 6 to 12 m (20 to 40 ft) of the structure. Similarly, longitudinal cracking may occur in the lower 6 to 12 m (20 to 40 ft) of the structure for sections of the dam having an upstream-downstream dimension greater than 61 m (200 ft). Since the occurrence of a longitudinal crack could create serious stability concerns, more rigorous analyses coupling the effects of other simultaneous loadings are necessary to better evaluate the extent of cracking.

An alternate rock source, a nearby quarried limestone aggregate, provides an RCC with a very low coefficient of thermal expansion of 4.5 millionths/deg C (2.5 millionths/deg F). The net effect of using this aggregate instead of the damsite amphibolite is to raise the allowable maximum peak temperature from 29.4 to 37.8 deg C (85 to 100 deg F). It appears that if this aggregate is used, no further control of aggregate temperatures may be necessary. Without this aggregate, measures are necessary to control placing temperatures so that peak temperatures do not exceed 29.4 deg C (85 deg F). This requires a 15.5-deg C (60-deg F) placing temperature for certain placements. This placing temperature could be raised to 23.9 deg C (75 deg F), if the limestone aggregate was used.

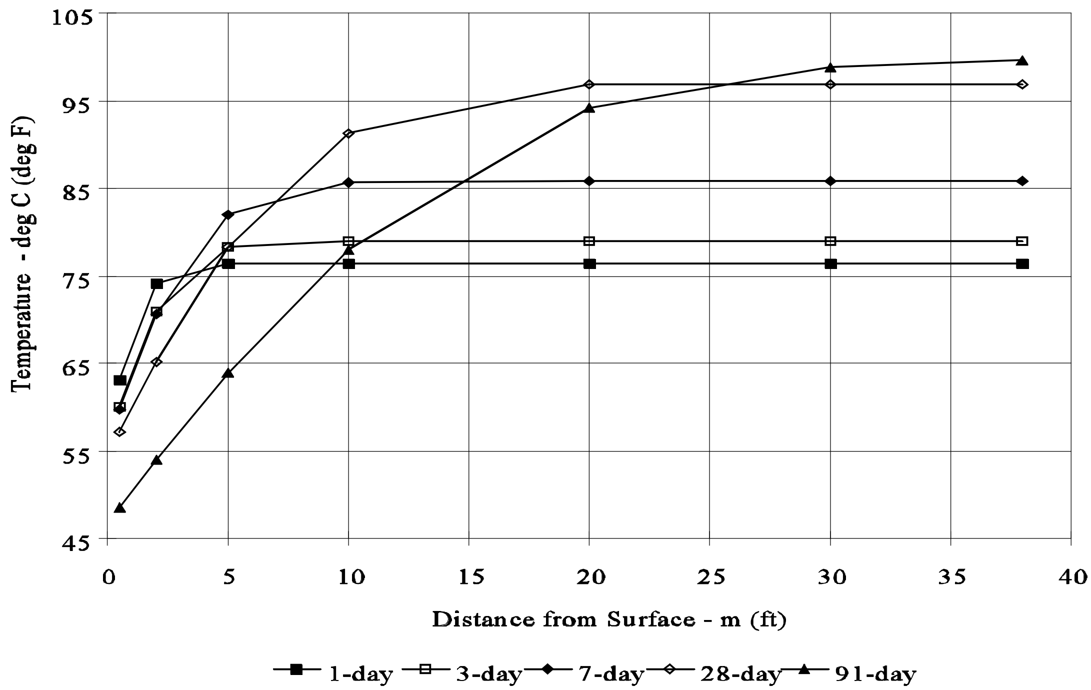

Figure A3-14. Surface gradient temperature distribution

Completion of RCC placements up to a minimum elevation during a fall and winter time period should be required in the construction contract. Otherwise, if these low elevation placements are placed during the spring and summer period, the RCC placing temperature should be specified not to exceed 26.7 to 29.4 deg C (80 to 85 deg F). This will require the use of additional cooling measures. Stockpile sprinkling, water chilling, and possible shading may be sufficient to achieve these temperatures.

The scope of this study was of a limited nature: to identify the potential extent of thermal cracking in the structure. Only generalized conclusions are possible. For a structure of this height, volume, and seismic loadings, a more rigorous study should be performed during design of the structure. Full-section modeling, incorporating foundation properties, restraint conditions, and early-age material properties (time- and temperature-dependent properties) should be done. The structure should be analyzed in sections to ascertain the strain development that may lead to longitudinal cracking and in elevation to ascertain strain development that may lead to transverse cracking. The results of these studies should guide the designer as to whether a three-dimensional (3-D) model is necessary. It is presumed that a 3-D analysis will indicate better cracking performance of the structure than a two-dimensional (2-D) model would indicate. This analysis should quantify the effects of several load conditions in addition to the thermal loads. It may be that the combined action of these factors will initiate cracking.

Table A3-2
Summary of Locations of Mass Gradient Thermal Cracks

Schedule	Peak Temp deg C (deg F)	Critical Nodes	Height Above Foundation, m (ft)
Jan	37.8 (100)	200-400	27 - 73 (90-240)
Oct	37.8 (100)	300-900	43 - 134 (140-440)
July	37.8 (100)	50-200 and 500-1000	73 - 146 (240-480)
April	37.8 (100)	100-400 and 800-1000	12 - 49 (40-160) and near top of dam

A3-3. Example 2: Two-Dimensional Mass Gradient and Surface Gradient Thermal Analysis

a. *General.* An example of each step in the performance of a relatively complex mass gradient and a surface gradient analysis in a Level 2 thermal study of an MCS is presented. This example is based on 2-D analyses performed during design studies for locks and dam facilities on the Monongahela River in Pennsylvania. These studies were conducted to maximize lift heights and determine optimum placement temperatures, to expedite construction and minimize costs. Although numerous lock monolith configurations exist in the project, the most massive section was selected for analysis. Conclusions and recommendations from this analysis could be applied to the other project monoliths. Figure A3-16 shows a cross section representation of the geometry of a river wall monolith with nominal 3-m (10-ft) lifts used in this example analysis. Two-dimensional FE analysis was used to determine temperature histories and temperature distribution during and following construction. FE analysis was not applied for cracking analysis. Cracking analysis was performed using a strain-based criteria similar to procedures described in ACI 207.2R. Slow-load tensile strain capacity test results (which include creep effects) were used to determine the extent of cracking. Analysis was performed on 15 combinations of several parameters, including three lift heights, two maximum concrete placement temperatures, three construction start times, two lift placement rates, and insulated forms for fall placement.

b. *Input properties and parameters.*

(1) Step 1: Determine ambient conditions. These data were gathered from local records. Ambient temperature data are shown in Figure A3-17.

(2) Step 2: Determine material properties. Table A3-3 contains thermal properties used in the example thermal analysis. Adiabatic temperature rise is shown in Figure A3-18. This adiabatic temperature rise is characteristic of the heat generation of an exterior concrete in a mass concrete structure and is not characteristic of interior mass concrete. The foundation material is assumed to be limestone of moderate strength. Table A3-4 contains mechanical properties used in the example thermal analysis modulus of elasticity of concrete and foundation materials are required for determination of foundation restraint factors. Slow-load tensile strain capacity values were developed using Annex 1 methodology for use in mass and surface gradient cracking analysis as discussed later in this annex.

(3) Step 3: Determine construction parameters. Figure A3-17 shows the concrete placement temperatures used in the example thermal analysis. Maximum placement temperature during the summer is 15.5 deg C (60 deg F), and minimum placement temperature during the winter is 4.4 deg C (40 deg F), based on previous specification experience. Placement temperatures are expected to

Sustained Modulus of Elasticity (x 10E6 psi)

Age (T)		E2	E1	Eave	F(k)	Esus
1	3	1.20	2.70	1.95	0.20	1.72
3	7	2.70	4.00	3.35	0.17	2.42
7	28	4.00	5.20	4.60	0.14	2.31
28	90	5.20	6.70	5.95	0.11	2.51

Data from Figure B3

1/Esus=(1/((E1+E2)/2)+F(k)*ln(T2-T1)/2
Esus = Sustained Modulus
F(k) = Creep Function

Temperature Differential (degF)

Surface	.5-ft	2-ft	5-ft	10-ft	20-ft	30-ft
3-day						
dT	3	3	-2	-3	-3	-3
Sum-d	6	6	1	0	0	0
7-day						
dT	3	3	-6	-10	-10	-10
Sum-d	13	13	4	0	0	0
28-day						
dT	6	9	-2	-14	-20	-20
Sum-d	26	29	18	6	0	0
91-day						
dT	15	20	12	-2	-18	-22
Sum-d	37	42	34	20	4	0

Induced Stress at each Depth for 300-foot Joint Spacing

Age days	Sum dT	Ind dT	Incre. Stress	H	L/H	h/H	KR	Adj Stress	Age Range	Cumm Stress	Tensile Str.	Crack
		Cth =	3.86			Length btw Joints=		300 feet				
Near Surface (0.5 ft)												
0-3	6	6	40	10	30	1.00	0.90	36	0-3	36	70	no
3-7	13	7	65	10	30	1.00	0.90	59	0-7	95	140	no
7-28	26	13	116	20	15	1.00	0.81	94	0-28	189	200	no
28-90	37	11	106	30	10	1.00	0.73	77	0-90	266	260	yes
2-Ft												
0-3	6	6	40	10	30	0.80	0.92	37	0-3	37	70	no
3-7	13	7	65	10	30	0.80	0.92	60	0-7	97	140	no
7-28	29	16	142	20	15	0.90	0.83	118	0-28	215	200	yes
28-90	42	13	126	30	10	0.93	0.74	93	0-90	309	260	yes
5-Ft												
0-3	1	1	7	10	30	0.50	0.95	6	0-3	6	70	no
3-7	4	3	28	10	30	0.50	0.95	27	0-7	33	140	no
7-28	18	14	125	20	15	0.75	0.86	107	0-28	140	200	no
28-90	34	16	155	30	10	0.83	0.77	119	0-90	258	260	yes
10-Ft												
0-3	0	0	0	10	30	0.00	1.00	0	0-3	0	70	no
3-7	0	0	0	10	30	0.00	1.00	0	0-7	0	140	no
7-28	6	6	53	20	15	0.50	0.90	48	0-28	48	200	no
28-90	20	14	135	30	10	0.67	0.81	109	0-90	158	260	no
20-Ft												
0-3	0	0	0	10	30	-1.00	1.11	0	0-3	0	70	no
3-7	0	0	0	10	30	-1.00	1.11	0	0-7	0	140	no
7-28	0	0	0	20	15	0.00	1.00	0	0-28	0	200	no
28-90	4	4	39	30	10	0.33	0.90	35	0-90	35	260	no

Data from surface geadient temperature distribution Figure
dT = temperature differential between baseline and specific time curve
Sum-dT = dT adjusted to the difference from the constant interior temperature

KR calculated from earlier Figure. Tensile strength (psi) from earlierFigure.
Sum dT transferred from temp. diff. Table. Ind dT = incremental induced temp. gradient
Incre. stress = (Ind dT)(Cth)(Esus)
H = dist. from face to zero temp. diff. region (from temp. diff. table) L = joint spacing
h = depth of interest (0.5, 2, 6, 10, and 20 ft)
Adj stress = (KR)(Incre. stress)

Figure A3-15. Surface gradient cracking analysis

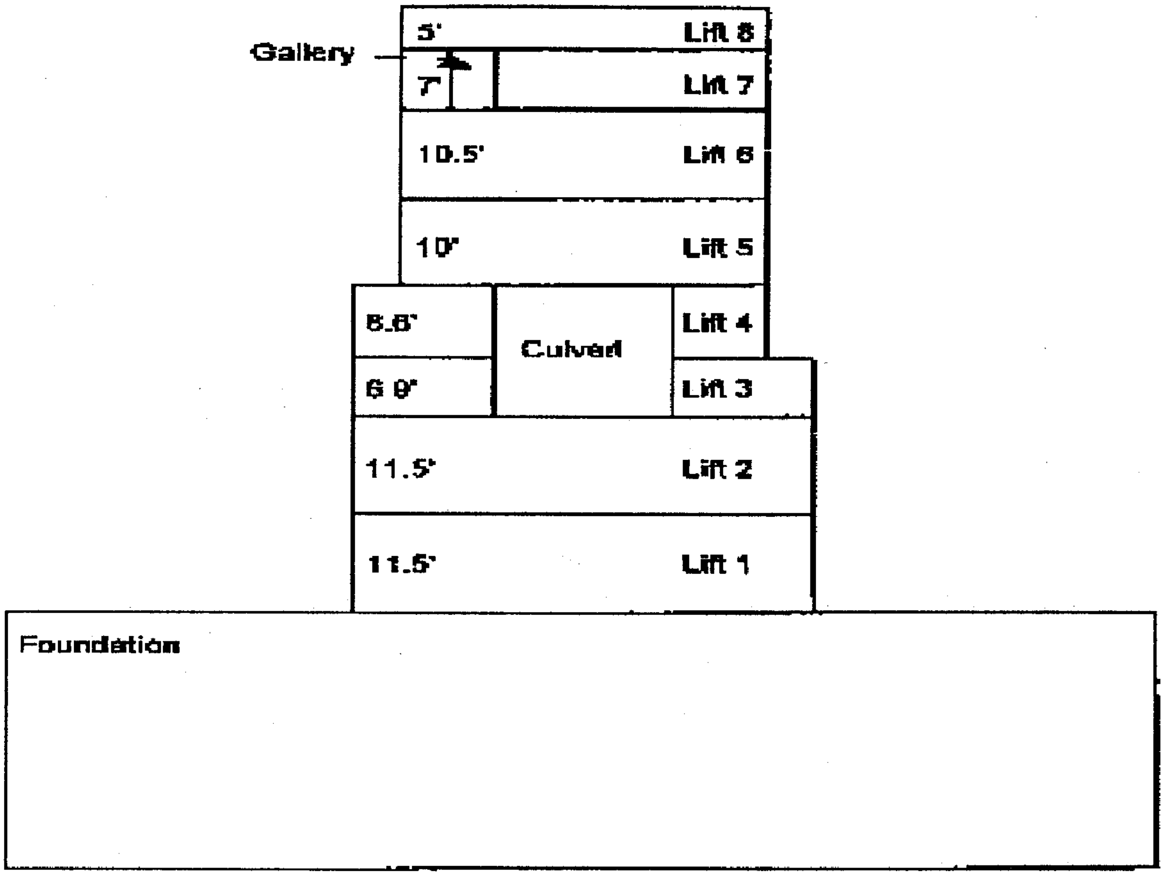

Figure A3-16. Lock wall section used in example

follow mean daily temperatures, except during summer and winter, when temperature controls are typically imposed. Placement temperatures lag mean daily ambient temperatures in the fall by 2.8 deg C (5 deg F), until the 4.4-deg C (40-deg F) minimum placement temperature permitted is reached. Other construction parameters assumed are a nominal lift height of 3 m (10 ft), a construction start date of 1 July, a concrete placement rate of 5 days/lift, with plywood forms removed 2 days after placement, and no insulation.

c. Temperature Analysis.

(1) Step 4: Prepare temperature model. The ABAQUS FE program was used in this example. Details regarding the use of ABAQUS and various ABAQUS and general FE program setup considerations in thermal analyses can be found in ETL 1110-2-365. Figure A3-19 shows the FE model used for the example. These analyses were performed on the Cray at the U.S. Army Engineer Waterways Experiment Station (WES). A time-step of 0.25 days was used to compute

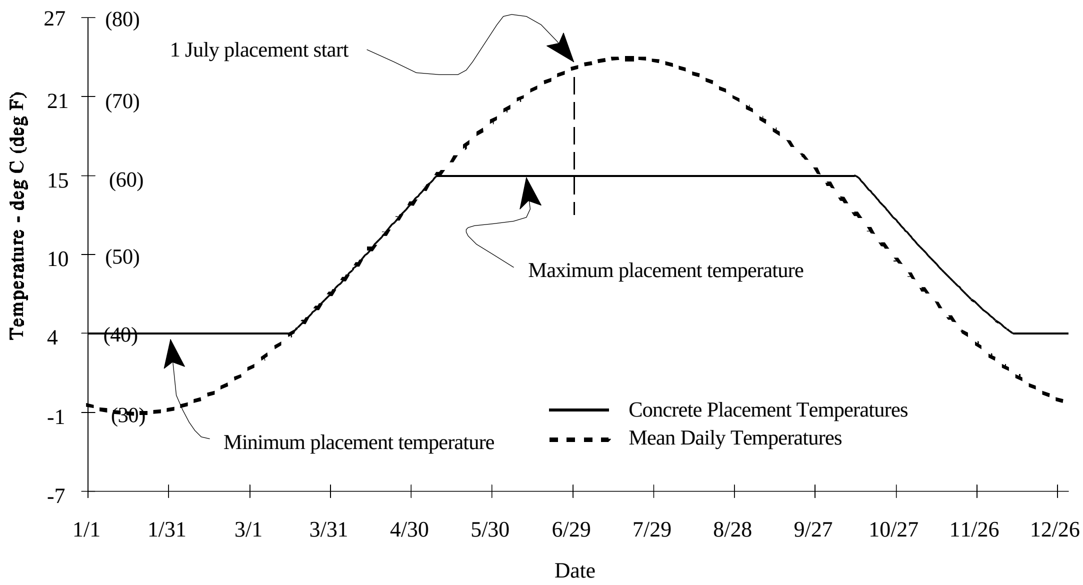

Figure A3-17. Mean daily ambient temperatures and concrete placement temperatures

Table A3-3
Concrete and Foundation Thermal Properties

Material	Thermal Conductivity W/m-K (Btu/hr-ft-deg F) (Btu/day-in-deg F)	Specific Heat kJ/kg-K (Btu/lb-deg F)	Coefficient of Thermal Expansion millionths/ deg C (millionths/deg F)
Limestone foundation	0.86 (0.500)(1.000)	0.96 (0.230)	9.90 (5.50)
Exterior concrete mixture	1.75 (1.012)(2.025)	0.98 (0.235)	10.46 (5.81)

temperature changes, primarily to capture temperature changes during the first 2 days after placement.

(a) Surface heat transfer coefficients computations. Equations A-2 and A-3 from Appendix A were used for computing the surface heat transfer coefficient. Table A3-5 shows surface heat transfer coefficients computed for various surface treatments at several time periods during the year. The heat transfer coefficients used in this example were those computed for wind only or for wind and plywood forms.

(b) Compute temperature histories. Figure A3-16 shows locations of mass gradient and surface gradient analysis in the structure used in the example. A July 1 start date was assumed for placement of the first lift of mass concrete.

(2) Step 5: Mass gradient temperature analysis. Figure A3-20 shows temperature histories at the locations of mass gradient analysis in the example.

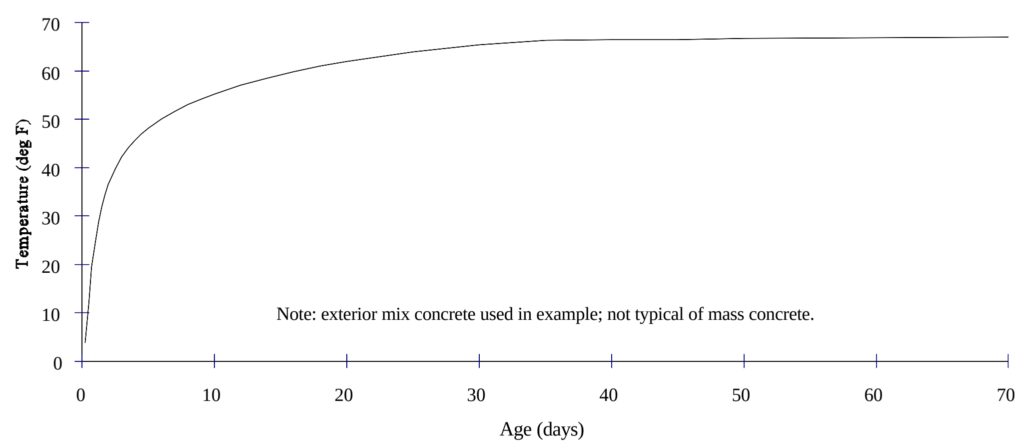

Figure A3-18. Adiabatic temperature rise for Level 2 thermal analysis 2-D example

Table A3-4
Concrete and Foundation Mechanical Properties

Material	Density	Compressive Strength	Modulus of Elasticity
	kg/m^3 (lb/ft^3)	Mpa (psi)	GPa (x 10^6 psi)
Limestone	2,563 (160)	103.4 (15,000)	48.26 (7.00)
Exterior concrete @ 1 day	2,243 (140)	3.93 (570)	12.41 (1.80)
Exterior concrete @ 3 days	same	7.65 (1,110)	20.20 (2.93)
Exterior concrete @ 7 days	same	11.24 (1,630)	23.44 (3.40)
Exterior concrete @ 28 days	same	22.48 (3,260)	33.65 (4.88)
Exterior concrete @ 90 days	same	31.10 (4,510)	35.51 (5.15)

(3) Step 6: Surface gradient temperature analysis. Surface gradient cracking in the example was analyzed at nominal ages of 0.5, 1, 2, 3, 5, 7, 14, 28, 60, 90, 120, 150, and 180 days after placement in lift 6 for this example. Table A3-6 and Figure A3-21 show the surface gradient temperature distributions across lift 6 in the upper portion of the mass concrete structure, determined from FE temperature analysis. Placement time for this lift was 25 days after placement of lift 1.

(a) Calculate surface gradient strains. To calculate surface gradient strains requires determination of the depth from the surface of effective interior restraint. This is performed by evaluating the magnitude of temperature change in the interior versus the surface concrete, thereby defining a surface "tension block" described in Appendix A and earlier in this annex. The following steps illustrate a procedure for determining the distance from the surface where tensile and compressive forces balance, thereby determining the distance from the surface to the point of zero strain, defining the tension block depth. A series of manipulations of temperature history results are used to define the depth, "*H*," of the tension block, where temperature

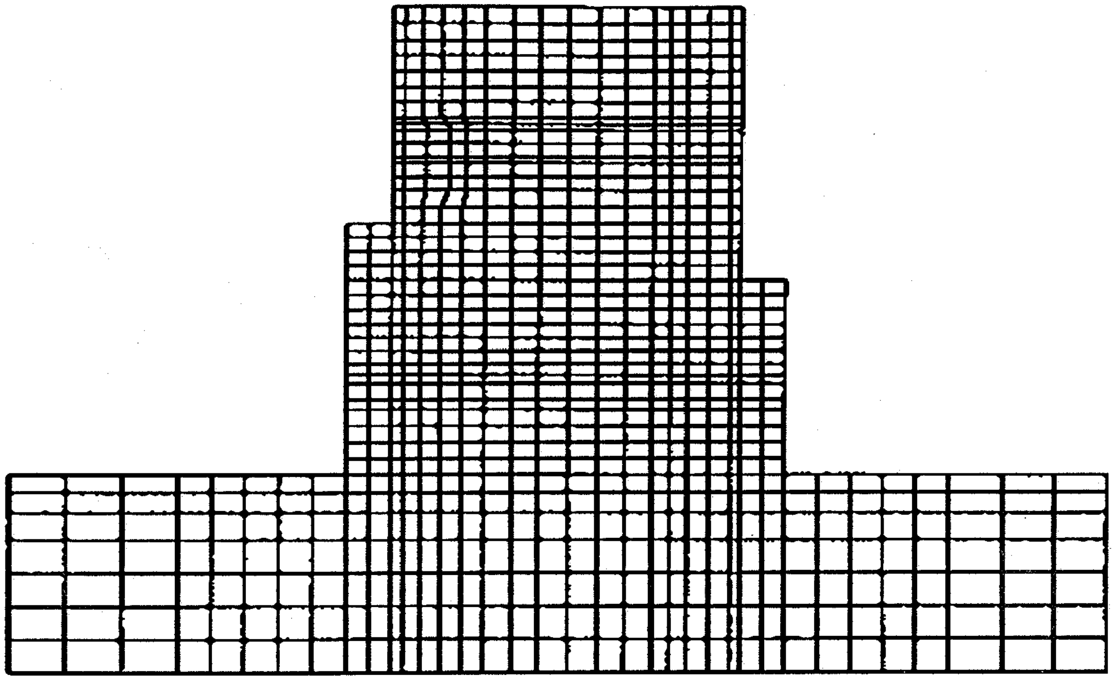

Figure A3-19. Finite element model of lock wall example

Table A3-5
Summary of Surface Heat Transfer Coefficients For FE Thermal Analyses

	Wind Velocity	Surface Heat Transfer Coefficient - *h* W/m^2-K (Btu/day-in^2-deg F)			
Time Span Months	km/h (mi/hr)	Wind Velocity Only	Wind Velocity & Plywood	Wind Velocity & Insulation	Air, Plywood, & Insulation
Nov. - Apr.	16 (10)	25.72 (0.7548)	4.913 (0.1442)	1.345 (0.03949)	1.101 (0.03233)
May - June	13 (8)	22.01 (0.6460)	4.763 (0.1398)	1.333 (0.03914)	1.094 (0.03210)
July - Sept.	11 (7)	19.71 (0.5785)	4.644 (0.1363)	1.324 (0.03887)	1.087 (0.03191)
Oct.	13 (8)	21.88 (0.6423)	4.756 (0.1396)	1.333 (0.03913)	1.093 (0.03209)

changes causing tension and compression are balanced.

(b) Determine reference temperatures. In the example, the reference time was established as 0.5 days after placement of lift 6 (25.5 days after concrete placement start at lift 1). Because the concrete attained a 1-day modulus of elasticity of 12.4 Gpa (1.8×10^6 psi), it was assumed that elastic strains were sustainable in this concrete at an age of 0.5 days.

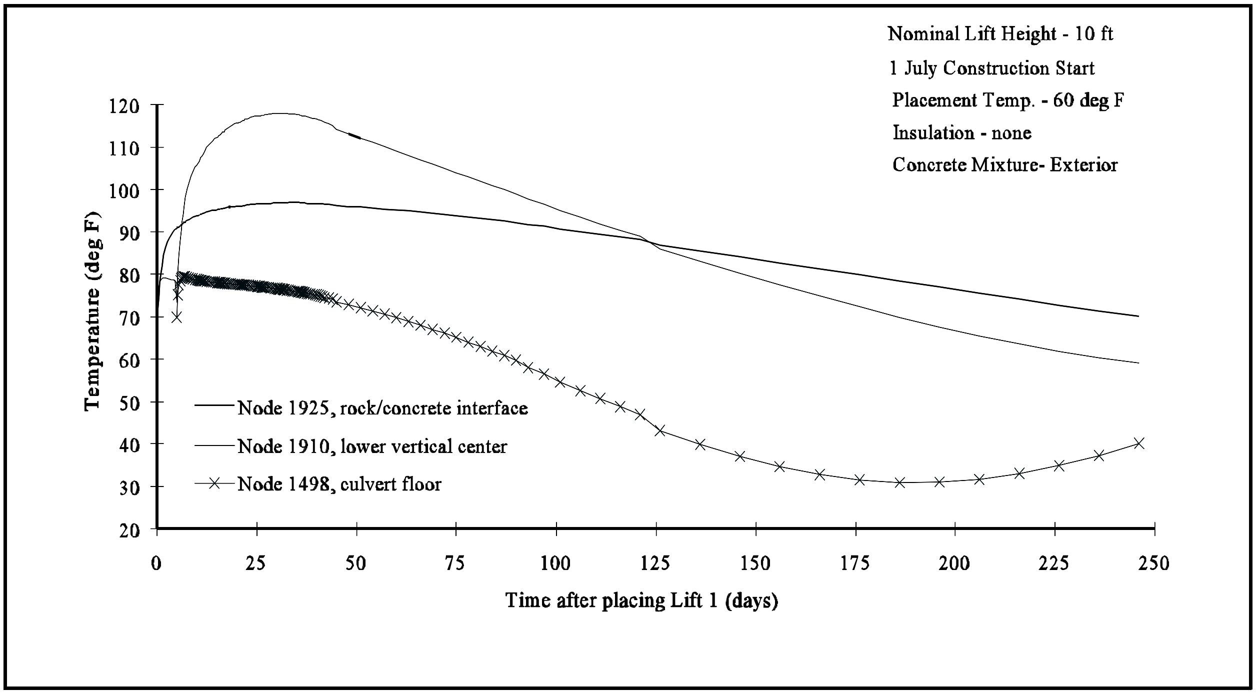

Figure A3-20. Typical temperature histories at locations of mass gradient analysis

(c) Determine temperature change or differences relative to the reference temperatures. Table A3-7 shows distributions of temperature difference at all analysis times relative to the reference temperatures at 0.5 days age of lift 6 (25.5 days after lift 1). These are developed by subtracting all of the temperatures in Table A3-6 from the respective 0.5-day temperatures at the same horizontal coordinates.

(d) Determine temperature differences relative to surface temperature differences, or "normalized" temperature differences. Table A3-8 and Figure A3-22 show temperature differences normalized relative to the surface temperature differences. These normalized temperature differences were developed by subtracting the surface temperature differences (along coordinates 4.0 and 36.0) in Table A3-7 from the corresponding interior temperature differences at the same time intervals in Table A3-7, producing the Table A3-8 normalized temperature differences.

(e) Determine offset balance temperatures. To balance tension and compression zones, a balance temperature, T_0, is determined such that the areas of the normalized temperature distribution above and below T_0 are equal. Table A3-9 and Figure A3-23 show balanced, normalized temperature differences.

(f) The depth of T_0 defines the depth of "*H*" of the tension block. A formula for the sums of individual areas between temperature points of the normalized temperature difference distribution across a section above and below T_0 was used for the determination of *H*. These calculations were solved by extensive computer spreadsheet analysis, resulting in tension block "*H*" values.

d. Cracking analysis.

(1) Step 7: Mass gradient cracking analysis. Mass gradient thermal strains are computed from Equation A-4 in Appendix A. Table A3-10 summarizes the computations.

(a) Foundation restraint factor (K_f). Foundation restraint, based upon relative differences in the

Table A3-6
Temperature Distributions in Lift 6 for Surface Gradient Analysis

Degrees C

Horizontal	Age of Concrete in Lift 6 placed 25 days after Lift 1 (days)												
Coordinate	0.5	1	2	3	5	7	14	29	59	91	121	151	181
(m)	Elapsed Time (T) after Placement of Lift 1 (days)												
	25.5	26	27	28	30	32	39	54	84	116	146	176	206
1.2	23.3	27.8	30.5	26.6	25.8	25.4	24.4	22.3	17.0	10.1	4.1	0.1	-0.9
1.4	23.0	28.5	32.4	30.3	29.2	28.5	26.8	24.1	18.2	11.2	5.1	0.9	-0.4
1.5	22.6	29.2	34.2	34.1	32.7	31.6	29.2	25.8	19.4	12.4	6.2	1.8	0.1
1.8	22.4	29.2	35.4	37.2	37.2	36.2	33.3	28.9	21.6	14.5	8.1	3.3	1.0
2.1	22.4	29.2	35.6	38.3	39.7	39.3	36.5	31.7	23.7	16.3	9.8	4.7	1.9
2.4	22.4	29.2	35.7	38.7	41.0	41.2	39.0	34.0	25.5	18.0	11.4	6.0	2.8
2.7	22.4	29.2	35.7	38.8	41.5	42.3	40.8	36.0	27.2	19.6	12.9	7.3	3.7
3.0	22.4	29.2	35.7	38.8	41.7	42.7	41.9	37.5	28.6	20.8	14.0	8.2	4.4
3.2	22.4	29.2	35.7	38.8	41.8	43.0	42.7	38.8	29.9	22.0	15.1	9.2	5.1
3.5	22.4	29.2	35.7	38.8	41.9	43.1	43.4	40.0	31.2	23.2	16.2	10.2	5.8
3.7	22.4	29.2	35.7	38.8	41.9	43.2	43.9	41.1	32.4	24.3	17.3	11.1	6.6
4.1	22.4	29.2	35.7	38.8	41.9	43.3	44.5	42.6	34.3	26.0	18.9	12.5	7.7
4.5	22.4	29.2	35.7	38.8	41.9	43.3	44.9	44.0	36.0	27.6	20.4	13.9	8.7
4.9	22.4	29.2	35.7	38.8	41.9	43.3	45.2	45.0	37.5	29.1	21.7	15.1	9.7
5.3	22.4	29.2	35.7	38.8	41.9	43.3	45.4	45.9	38.8	30.3	22.9	16.1	10.5
5.7	22.4	29.2	35.7	38.8	41.9	43.3	45.4	46.5	39.9	31.4	23.8	17.0	11.2
6.1	22.4	29.2	35.7	38.8	41.9	43.3	45.5	47.0	40.6	32.1	24.5	17.6	11.7
6.5	22.4	29.2	35.7	38.8	41.9	43.3	45.5	47.2	41.0	32.5	24.9	17.9	12.0
6.9	22.4	29.2	35.7	38.8	41.9	43.3	45.5	47.1	41.0	32.5	24.9	17.9	12.0
7.3	22.4	29.2	35.7	38.8	41.9	43.3	45.4	46.9	40.7	32.2	24.6	17.7	11.8
7.7	22.4	29.2	35.7	38.8	41.9	43.3	45.3	46.4	39.9	31.5	24.0	17.1	11.3
8.1	22.4	29.2	35.7	38.8	41.9	43.3	45.1	45.7	38.8	30.5	23.0	16.2	10.6
8.5	22.4	29.2	35.7	38.8	41.9	43.2	44.7	44.5	37.3	29.1	21.7	15.1	9.7
8.7	22.4	29.2	35.7	38.8	41.9	43.2	44.3	43.6	36.2	28.0	20.7	14.2	9.0
9.0	22.4 •	29.2	35.7	38.8	41.8	43.0	43.7	42.4	34.8	26.7	19.5	13.1	8.2
9.2	22.4	29.2	35.7	38.8	41.7	42.8	42.9	41.0	33.3	25.3	18.2	12.0	7.3
9.4	22.4	29.2	35.7	38.8	41.5	42.3	41.7	39.3	31.6	23.8	16.8	10.7	6.4
9.8	22.4	29.2	35.7	38.7	41.0	41.2	39.7	36.8	29.3	21.6	14.8	9.0	5.1
10.1	22.4	29.2	35.6	38.3	39.7	39.3	37.1	34.0	26.7	19.2	12.5	7.1	3.7
10.4	22.4	29.2	35.4	37.2	37.2	36.2	33.7	30.6	23.8	16.5	10.0	5.0	2.3
10.7	22.6	29.2	34.2	34.1	32.7	31.6	29.4	26.8	20.7	13.6	7.3	2.7	0.8
10.8	22.9	28.9	32.8	31.0	29.5	28.7	27.0	24.7	19.0	12.0	5.8	1.5	0.0
11.0	23.3	27.8	30.5	26.6	25.8	25.4	24.4	22.6	17.2	10.3	4.3	0.3	-0.7

Degrees F

Horizontal	Age of Concrete in Lift 6 placed 25 days after Lift 1 (days)												
Coordinate	0.5	1	2	3	5	7	14	29	59	91	121	151	181
(ft)	Elapsed Time (T) after Placement of Lift 1 (days)												
	25.5	26	27	28	30	32	39	54	84	116	146	176	206
4.00	73.9	82.1	87.0	79.8	78.5	77.7	75.9	72.2	62.5	50.2	39.4	32.2	30.4
4.50	73.3	83.4	90.3	86.6	84.6	83.3	80.2	75.4	64.7	52.2	41.3	33.7	31.3
5.00	72.7	84.6	93.6	93.3	90.8	88.8	84.6	78.5	66.9	54.3	43.2	35.2	32.1
6.00	72.3	84.6	95.7	99.0	99.0	97.2	91.9	84.1	70.9	58.0	46.6	37.9	33.8
7.00	72.3	84.5	96.2	101.0	103.5	102.8	97.7	89.0	74.6	61.4	49.7	40.5	35.4
8.00	72.3	84.5	96.3	101.6	105.8	106.2	102.1	93.2	77.9	64.4	52.5	42.8	37.0
9.00	72.3	84.5	96.3	101.8	106.7	108.1	105.4	96.8	81.0	67.3	55.1	45.1	38.6
9.81	72.3	84.5	96.3	101.9	107.1	108.9	107.4	99.5	83.5	69.5	57.2	46.8	39.9
10.63	72.3	84.5	96.3	101.9	107.3	109.4	108.9	101.9	85.8	71.6	59.2	48.6	41.2
11.44	72.3	84.5	96.3	101.9	107.4	109.7	110.1	104.0	88.1	73.7	61.1	50.3	42.5
12.25	72.3	84.5	96.3	101.9	107.4	109.8	111.0	106.0	90.3	75.8	63.1	52.0	43.8
13.50	72.3	84.5	96.3	101.9	107.4	109.9	112.1	108.8	93.7	78.9	66.0	54.5	45.8
14.75	72.3	84.5	96.3	101.9	107.4	109.9	112.8	111.1	96.7	81.8	68.7	57.0	47.7
16.00	72.3	84.5	96.3	101.9	107.4	109.9	113.3	113.1	99.5	84.4	71.1	59.1	49.4
17.25	72.3	84.5	96.3	101.9	107.4	109.9	113.6	114.6	101.8	86.6	73.2	61.0	50.9
18.58	72.3	84.5	96.3	101.9	107.4	109.9	113.8	115.8	103.8	88.5	74.9	62.6	52.2
19.92	72.3	84.5	96.3	101.9	107.4	109.9	113.9	116.5	105.1	89.8	76.1	63.6	53.1
21.25	72.3	84.5	96.3	101.9	107.4	109.9	113.9	116.9	105.8	90.4	76.8	64.2	53.5
22.58	72.3	84.5	96.3	101.9	107.4	109.9	113.9	116.8	105.8	90.5	76.8	64.3	53.6
23.88	72.3	84.5	96.3	101.9	107.4	109.9	113.8	116.4	105.2	89.9	76.3	63.8	53.2
25.17	72.3	84.5	96.3	101.9	107.4	109.9	113.6	115.6	103.9	88.7	75.2	62.8	52.3
26.46	72.3	84.5	96.3	101.9	107.4	109.9	113.3	114.2	101.9	86.9	73.4	61.2	51.1
27.75	72.3	84.5	96.3	101.9	107.4	109.8	112.5	112.1	99.2	84.3	71.1	59.1	49.4
28.56	72.3	84.5	96.3	101.9	107.4	109.7	111.8	110.4	97.1	82.4	69.3	57.5	48.2
29.38	72.3	84.5	96.3	101.9	107.3	109.4	110.7	108.3	94.7	80.1	67.2	55.7	46.8
30.19	72.3	84.5	96.3	101.9	107.1	109.0	109.1	105.7	92.0	77.6	64.8	53.6	45.2
31.00	72.3	84.5	96.3	101.8	106.8	108.1	107.0	102.7	89.0	74.8	62.2	51.3	43.5
32.00	72.3	84.5	96.3	101.6	105.8	106.2	103.5	98.3	84.8	70.9	58.6	48.2	41.2
33.00	72.3	84.5	96.2	101.0	103.5	102.8	98.8	93.1	80.1	66.6	54.3	44.7	38.7
34.00	72.3	84.6	95.7	99.0	99.0	97.2	92.6	87.1	74.9	61.8	50.0	41.0	36.1
35.00	72.7	84.6	93.6	93.3	90.8	88.8	85.0	80.2	69.2	56.4	45.1	36.9	33.4
35.50	73.3	84.0	91.0	87.8	85.2	83.6	80.7	76.5	66.2	53.6	42.5	34.8	32.1
36.00	73.9	82.1	87.0	79.8	78.5	77.7	76.0	72.6	63.0	50.6	39.7	32.5	30.7

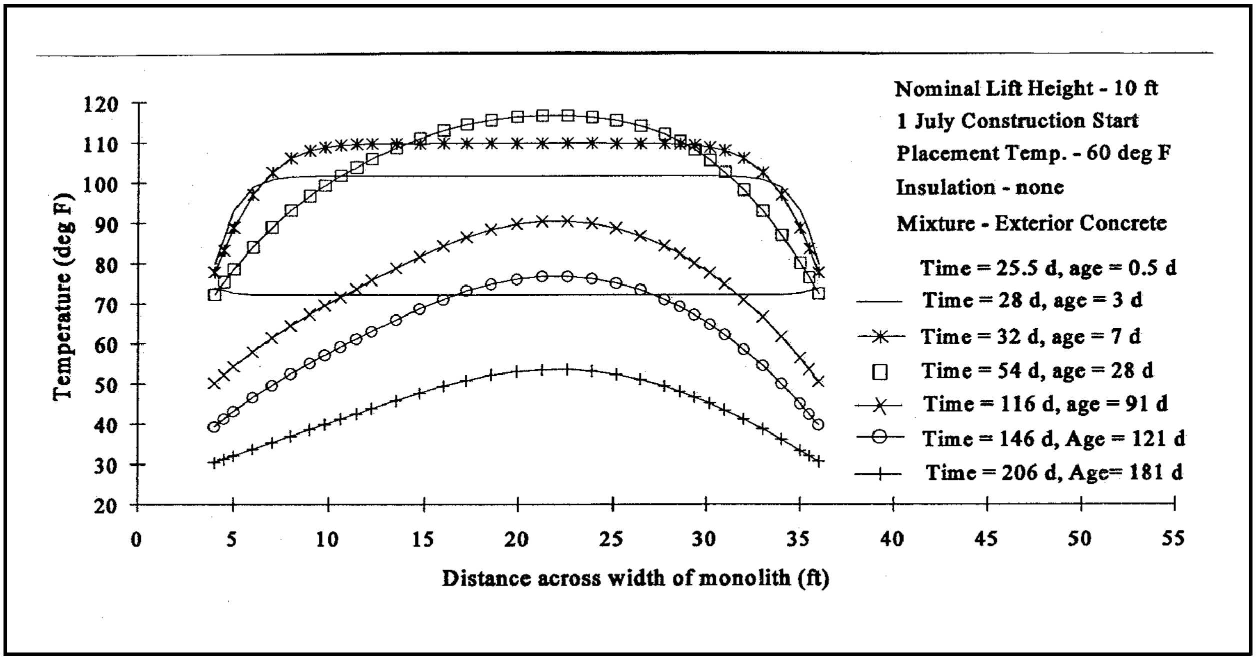

Figure A3-21. Temperature distributions across lift 6 used in surface gradient analysis

stiffness of the foundation material and the concrete, is computed from Equation A-7 in Appendix A as shown below.

$$K_f = \frac{1}{1 + \dfrac{A_g E_c}{A_f E_f}} = 0.64$$

where

A_g = gross area of concrete cross section (relative value) = 1

A_f = 2.5 (area of foundation or zone restraining contraction of concrete, generally as a plane surface at contact, recommended maximum value is 2.5)

E_f = modulus of elasticity of foundation = 48.3 Gpa (7.0 × 10^6 psi)

E_c = modulus of elasticity of mass concrete (mean value during cooling period) = 34.5 Gpa (5.0 × 10^6 psi)

(b) Structure restraint factor (K_R). Structure restraint factors are computed at distances, *h*, along the vertical centerline of the structure at h = 3.5 m (11.5 ft) and at $h = H$ = 7.0 m (23 ft) at the base of the culvert. The length, *L*, of the structure is assumed to be 13.4 m (44 ft) in the axial direction. Note that the mass gradient analysis shown below assumes that the foundation restraint is applied by the foundation material adjacent to the concrete. Therefore, the foundation temperatures used in the analysis are taken at the foundation-concrete interface rather than at the location of constant foundation temperature at a depths of 6.1 m (20 ft) or more.

Using Equation A-6 (Appendix A) for *L/H* less than 2.5

$$K_R = K_f \left(\frac{\dfrac{L}{H} - 1}{\dfrac{L}{H} + 10} \right)^{h/H} = 0.28$$

Table A3-7
Temperature Differences Referenced to Temperature at 0.5 Days

Degrees C

Horizontal Coordinate (m)	Age of Concrete in Lift 6 placed 25 days after Lift 1 (days)												
	0.5	1	2	3	5	7	14	29	59	91	121	151	181
	Elapsed Time (T) after Placement of Lift 1 (days)												
	25.5	26	27	28	30	32	39	54	84	116	146	176	206
1.2	0.0	4.6	7.2	3.3	2.5	2.1	1.1	-1.0	-6.3	-13.2	-19.2	-23.2	-24.2
1.4	0.0	5.6	9.4	7.4	6.3	5.5	3.9	1.1	-4.8	-11.7	-17.8	-22.0	-23.4
1.5	0.0	6.6	11.6	11.4	10.1	9.0	6.6	3.2	-3.2	-10.2	-16.4	-20.8	-22.6
1.8	0.0	6.8	13.0	14.8	14.8	13.8	10.9	6.5	-0.8	-7.9	-14.3	-19.1	-21.4
2.1	0.0	6.8	13.3	16.0	17.4	17.0	14.1	9.3	1.3	-6.1	-12.5	-17.7	-20.5
2.4	0.0	6.8	13.3	16.3	18.6	18.9	16.6	11.6	3.1	-4.4	-11.0	-16.4	-19.6
2.7	0.0	6.8	13.3	16.4	19.2	19.9	18.4	13.7	4.9	-2.8	-9.5	-15.1	-18.7
3.0	0.0	6.8	13.3	16.4	19.4	20.4	19.5	15.1	6.2	-1.5	-8.4	-14.1	-18.0
3.2	0.0	6.8	13.3	16.5	19.5	20.6	20.4	16.4	7.5	-0.4	-7.3	-13.2	-17.2
3.5	0.0	6.8	13.3	16.5	19.5	20.8	21.0	17.6	8.8	0.8	-6.2	-12.2	-16.5
3.7	0.0	6.8	13.3	16.5	19.5	20.9	21.5	18.8	10.0	2.0	-5.1	-11.3	-15.8
4.1	0.0	6.8	13.3	16.5	19.5	20.9	22.1	20.3	11.9	3.7	-3.5	-9.8	-14.7
4.5	0.0	6.8	13.3	16.5	19.5	20.9	22.6	21.6	13.6	5.3	-2.0	-8.5	-13.6
4.9	0.0	6.8	13.3	16.5	19.5	20.9	22.8	22.7	15.1	6.7	-0.6	-7.3	-12.7
5.3	0.0	6.8	13.3	16.5	19.5	20.9	23.0	23.5	16.4	8.0	0.5	-6.3	-11.9
5.7	0.0	6.8	13.3	16.5	19.5	20.9	23.1	24.2	17.5	9.0	1.5	-5.4	-11.2
6.1	0.0	6.8	13.3	16.5	19.5	20.9	23.1	24.6	18.2	9.7	2.2	-4.8	-10.7
6.5	0.0	6.8	13.3	16.5	19.5	20.9	23.1	24.8	18.6	10.1	2.5	-4.5	-10.4
6.9	0.0	6.8	13.3	16.5	19.5	20.9	23.1	24.8	18.6	10.1	2.5	-4.4	-10.4
7.3	0.0	6.8	13.3	16.5	19.5	20.9	23.1	24.6	18.3	9.8	2.3	-4.7	-10.6
7.7	0.0	6.8	13.3	16.5	19.5	20.9	23.0	24.1	17.6	9.1	1.6	-5.3	-11.1
8.1	0.0	6.8	13.3	16.5	19.5	20.9	22.8	23.3	16.5	8.1	0.7	-6.1	-11.8
8.5	0.0	6.8	13.3	16.5	19.5	20.9	22.4	22.2	15.0	6.7	-0.6	-7.3	-12.7
8.7	0.0	6.8	13.3	16.5	19.5	20.8	22.0	21.2	13.8	5.6	-1.7	-8.2	-13.4
9.0	0.0	6.8	13.3	16.5	19.5	20.7	21.3	20.0	12.5	4.4	-2.8	-9.2	-14.2
9.2	0.0	6.8	13.3	16.4	19.4	20.4	20.5	18.6	11.0	3.0	-4.1	-10.4	-15.0
9.4	0.0	6.8	13.3	16.4	19.2	19.9	19.3	16.9	9.3	1.4	-5.6	-11.6	-16.0
9.8	0.0	6.8	13.3	16.3	18.6	18.9	17.4	14.5	7.0	-0.7	-7.6	-13.4	-17.3
10.1	0.0	6.8	13.3	16.0	17.4	16.9	14.7	11.6	4.3	-3.2	-9.9	-15.3	-18.6
10.4	0.0	6.8	13.0	14.8	14.8	13.8	11.3	8.2	1.4	-5.9	-12.4	-17.4	-20.1
10.7	0.0	6.6	11.6	11.4	10.1	9.0	6.8	4.2	-1.9	-9.0	-15.3	-19.9	-21.8
10.8	0.0	6.0	9.9	8.1	6.6	5.7	4.1	1.8	-3.9	-10.9	-17.1	-21.4	-22.9
11.0	0.0	4.6	7.2	3.3	2.5	2.1	1.2	-0.7	-6.0	-12.9	-19.0	-23.0	-24.0

Degrees F

Horizontal Coordinate (ft)	Age of Concrete in Lift 6 placed 25 days after Lift 1 (days)												
	0.5	1	2	3	5	7	14	29	59	91	121	151	181
	Elapsed Time (T) after Placement of Lift 1 (days)												
	25.5	26	27	28	30	32	39	54	84	116	146	176	206
4.00	0.0	8.2	13.0	5.9	4.5	3.8	2.0	-1.7	-11.4	-23.8	-34.6	-41.7	-43.5
4.50	0.0	10.1	16.9	13.2	11.3	10.0	6.9	2.0	-8.6	-21.1	-32.0	-39.6	-42.0
5.00	0.0	11.9	20.9	20.6	18.1	16.1	11.9	5.8	-5.8	-18.4	-29.5	-37.5	-40.6
6.00	0.0	12.3	23.4	26.7	26.6	24.8	19.5	11.8	-1.4	-14.3	-25.7	-34.4	-38.6
7.00	0.0	12.3	23.9	28.7	31.2	30.5	25.4	16.7	2.3	-10.9	-22.6	-31.8	-36.9
8.00	0.0	12.3	24.0	29.4	33.5	33.9	29.9	20.9	5.7	-7.8	-19.7	-29.4	-35.2
9.00	0.0	12.3	24.0	29.6	34.5	35.8	33.2	24.6	8.8	-5.0	-17.1	-27.2	-33.6
9.81	0.0	12.3	24.0	29.6	34.9	36.7	35.2	27.2	11.2	-2.8	-15.1	-25.4	-32.3
10.63	0.0	12.3	24.0	29.6	35.0	37.1	36.7	29.6	13.6	-0.6	-13.1	-23.7	-31.0
11.44	0.0	12.3	24.0	29.6	35.1	37.4	37.9	31.8	15.8	1.4	-11.1	-22.0	-29.7
12.25	0.0	12.3	24.0	29.6	35.1	37.5	38.8	33.8	18.1	3.5	-9.2	-20.3	-28.4
13.50	0.0	12.3	24.0	29.6	35.2	37.6	39.8	36.5	21.4	6.6	-6.3	-17.7	-26.4
14.75	0.0	12.3	24.0	29.6	35.2	37.7	40.6	38.9	24.5	9.5	-3.6	-15.3	-24.5
16.00	0.0	12.3	24.0	29.6	35.2	37.7	41.1	40.8	27.2	12.1	-1.2	-13.1	-22.8
17.25	0.0	12.3	24.0	29.6	35.2	37.7	41.4	42.4	29.6	14.3	0.9	-11.3	-21.3
18.58	0.0	12.3	24.0	29.6	35.2	37.7	41.6	43.5	31.5	16.2	2.7	-9.7	-20.1
19.92	0.0	12.3	24.0	29.6	35.2	37.7	41.6	44.3	32.8	17.5	3.9	-8.6	-19.2
21.25	0.0	12.3	24.0	29.6	35.2	37.7	41.6	44.6	33.5	18.2	4.5	-8.0	-18.7
22.58	0.0	12.3	24.0	29.6	35.2	37.7	41.6	44.6	33.6	18.3	4.6	-8.0	-18.7
23.88	0.0	12.3	24.0	29.6	35.2	37.7	41.6	44.2	32.9	17.7	4.1	-8.5	-19.1
25.17	0.0	12.3	24.0	29.6	35.2	37.7	41.4	43.4	31.6	16.5	2.9	-9.5	-19.9
26.46	0.0	12.3	24.0	29.6	35.2	37.6	41.0	42.0	29.7	14.6	1.2	-11.0	-21.2
27.75	0.0	12.3	24.0	29.6	35.1	37.6	40.3	39.9	27.0	12.1	-1.2	-13.1	-22.8
28.56	0.0	12.3	24.0	29.6	35.1	37.4	39.5	38.2	24.9	10.1	-3.0	-14.7	-24.1
29.38	0.0	12.3	24.0	29.6	35.0	37.2	38.4	36.0	22.5	7.9	-5.1	-16.6	-25.5
30.19	0.0	12.3	24.0	29.6	34.9	36.7	36.9	33.5	19.7	5.4	-7.4	-18.6	-27.1
31.00	0.0	12.3	24.0	29.6	34.5	35.9	34.8	30.5	16.7	2.6	-10.0	-20.9	-28.8
32.00	0.0	12.3	24.0	29.4	33.5	34.0	31.3	26.1	12.5	-1.3	-13.7	-24.1	-31.1
33.00	0.0	12.3	23.9	28.7	31.3	30.5	26.5	20.8	7.8	-5.7	-17.7	-27.5	-33.5
34.00	0.0	12.3	23.4	26.7	26.6	24.8	20.3	14.8	2.6	-10.6	-22.3	-31.3	-36.2
35.00	0.0	11.9	20.9	20.6	18.1	16.1	12.3	7.5	-3.5	-16.3	-27.6	-35.8	-39.3
35.50	0.0	10.8	17.8	14.5	11.9	10.3	7.4	3.2	-7.1	-19.7	-30.8	-38.5	-41.2
36.00	0.0	8.2	13.0	5.9	4.5	3.8	2.1	-1.3	-10.9	-23.3	-34.2	-41.4	-43.2

Table A3-8
Temperature Differences Normalized in Reference to Surface Temperature Differences For Surface Gradient Analysis

Degrees C

Horizontal Coordinate (m)	Age of Concrete in Lift 6 placed 25 days after Lift 1 (days)												
	0.5	1	2	3	5	7	14	29	59	91	121	151	181
	Elapsed Time (T) after Placement of Lift 1 (days)												
	25.5	26	27	28	30	32	39	54	84	116	146	176	206
1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.4	0.0	1.0	2.2	4.1	3.8	3.4	2.8	2.1	1.6	1.5	1.4	1.2	0.8
1.5	0.0	2.1	4.3	8.2	7.6	6.9	5.5	4.2	3.1	3.0	2.8	2.3	1.6
1.8	0.0	2.3	5.7	11.6	12.3	11.7	9.8	7.5	5.6	5.3	4.9	4.0	2.7
2.1	0.0	2.3	6.0	12.7	14.8	14.9	13.0	10.2	7.6	7.1	6.7	5.5	3.7
2.4	0.0	2.3	6.1	13.1	16.1	16.8	15.5	12.6	9.5	8.8	8.2	6.8	4.6
2.7	0.0	2.3	6.1	13.2	16.6	17.8	17.3	14.6	11.2	10.4	9.7	8.1	5.5
3.0	0.0	2.3	6.1	13.2	16.8	18.3	18.4	16.1	12.6	11.6	10.8	9.0	6.2
3.2	0.0	2.3	6.1	13.2	16.9	18.5	19.3	17.4	13.9	12.8	11.9	10.0	6.9
3.5	0.0	2.3	6.1	13.2	17.0	18.7	19.9	18.6	15.1	14.0	13.0	11.0	7.6
3.7	0.0	2.3	6.1	13.2	17.0	18.8	20.4	19.7	16.4	15.1	14.1	11.9	8.4
4.1	0.0	2.3	6.1	13.2	17.0	18.8	21.0	21.2	18.2	16.9	15.7	13.3	9.5
4.5	0.0	2.3	6.1	13.2	17.0	18.8	21.5	22.6	19.9	18.5	17.2	14.7	10.5
4.9	0.0	2.3	6.1	13.2	17.0	18.8	21.7	23.6	21.5	19.9	18.6	15.9	11.5
5.3	0.0	2.3	6.1	13.2	17.0	18.8	21.9	24.5	22.8	21.2	19.7	16.9	12.3
5.7	0.0	2.3	6.1	13.2	17.0	18.8	22.0	25.1	23.8	22.2	20.7	17.8	13.0
6.1	0.0	2.3	6.1	13.2	17.0	18.8	22.0	25.5	24.6	22.9	21.4	18.4	13.5
6.5	0.0	2.3	6.1	13.2	17.0	18.8	22.0	25.7	24.9	23.3	21.7	18.7	13.7
6.9	0.0	2.3	6.1	13.2	17.0	18.8	22.0	25.7	25.0	23.3	21.7	18.7	13.8
7.3	0.0	2.3	6.1	13.2	17.0	18.8	22.0	25.5	24.6	23.0	21.5	18.5	13.5
7.7	0.0	2.3	6.1	13.2	17.0	18.8	21.9	25.0	23.9	22.3	20.8	17.9	13.1
8.1	0.0	2.3	6.1	13.2	17.0	18.8	21.7	24.3	22.8	21.3	19.9	17.0	12.4
8.5	0.0	2.3	6.1	13.2	17.0	18.8	21.3	23.1	21.3	19.9	18.6	15.9	11.5
8.7	0.0	2.3	6.1	13.2	17.0	18.7	20.9	22.1	20.1	18.8	17.5	15.0	10.8
9.0	0.0	2.3	6.1	13.2	16.9	18.6	20.2	21.0	18.8	17.6	16.4	13.9	10.0
9.2	0.0	2.3	6.1	13.2	16.8	18.3	19.4	19.6	17.3	16.2	15.1	12.8	9.1
9.4	0.0	2.3	6.1	13.2	16.6	17.8	18.2	17.9	15.6	14.6	13.6	11.5	8.2
9.8	0.0	2.3	6.1	13.1	16.1	16.8	16.3	15.4	13.3	12.5	11.6	9.8	6.9
10.1	0.0	2.3	6.0	12.7	14.8	14.9	13.6	12.5	10.7	10.0	9.3	7.9	5.5
10.4	0.0	2.3	5.7	11.6	12.3	11.7	10.2	9.1	7.8	7.3	6.8	5.7	4.1
10.7	0.0	2.1	4.3	8.2	7.5	6.9	5.7	5.1	4.4	4.2	3.9	3.3	2.3
10.8	0.0	1.4	2.6	4.8	4.1	3.6	3.0	2.7	2.4	2.3	2.1	1.8	1.3
11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.2	0.2	0.2	0.1

Degrees F

Horizontal Coordinate (ft)	Age of Concrete in Lift 6 placed 25 days after Lift 1 (days)												
	0.5	1	2	3	5	7	14	29	59	91	121	151	181
	Elapsed Time (T) after Placement of Lift 1 (days)												
	25.5	26	27	28	30	32	39	54	84	116	146	176	206
4.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.50	0.0	1.9	3.9	7.4	6.8	6.2	5.0	3.8	2.8	2.7	2.5	2.1	1.4
5.00	0.0	3.7	7.8	14.7	13.6	12.4	9.9	7.5	5.6	5.4	5.0	4.2	2.9
6.00	0.0	4.1	10.3	20.8	22.1	21.1	17.6	13.5	10.0	9.5	8.8	7.3	4.9
7.00	0.0	4.1	10.8	22.8	26.7	26.7	23.5	18.4	13.7	12.9	12.0	9.9	6.6
8.00	0.0	4.1	11.0	23.5	29.0	30.2	27.9	22.7	17.1	15.9	14.8	12.3	8.2
9.00	0.0	4.1	11.0	23.7	30.0	32.1	31.2	26.3	20.2	18.8	17.5	14.5	9.8
9.81	0.0	4.1	11.0	23.7	30.3	32.9	33.2	28.9	22.6	21.0	19.5	16.3	11.1
10.63	0.0	4.1	11.0	23.7	30.5	33.4	34.7	31.3	24.9	23.1	21.5	18.0	12.4
11.44	0.0	4.1	11.0	23.7	30.6	33.6	35.9	33.5	27.2	25.2	23.5	19.7	13.7
12.25	0.0	4.1	11.0	23.7	30.6	33.8	36.8	35.5	29.5	27.3	25.4	21.4	15.0
13.50	0.0	4.1	11.0	23.8	30.6	33.9	37.9	38.2	32.8	30.4	28.3	24.0	17.0
14.75	0.0	4.1	11.0	23.8	30.6	33.9	38.6	40.6	35.9	33.3	31.0	26.4	18.9
16.00	0.0	4.1	11.0	23.8	30.6	33.9	39.1	42.5	38.6	35.9	33.4	28.6	20.7
17.25	0.0	4.1	11.0	23.8	30.6	33.9	39.4	44.1	41.0	38.1	35.5	30.4	22.1
18.58	0.0	4.1	11.0	23.8	30.6	33.9	39.6	45.2	42.9	40.0	37.2	32.0	23.4
19.92	0.0	4.1	11.0	23.8	30.6	33.9	39.6	46.0	44.2	41.3	38.4	33.1	24.3
21.25	0.0	4.1	11.0	23.8	30.6	33.9	39.7	46.3	44.9	41.9	39.1	33.7	24.7
22.58	0.0	4.1	11.0	23.8	30.6	33.9	39.6	46.3	44.9	42.0	39.1	33.7	24.8
23.88	0.0	4.1	11.0	23.8	30.6	33.9	39.6	45.9	44.3	41.4	38.6	33.2	24.4
25.17	0.0	4.1	11.0	23.8	30.6	33.9	39.4	45.1	43.0	40.2	37.5	32.2	23.6
26.46	0.0	4.1	11.0	23.8	30.6	33.9	39.0	43.7	41.1	38.4	35.8	30.7	22.3
27.75	0.0	4.1	11.0	23.7	30.6	33.8	38.3	41.6	38.4	35.8	33.4	28.6	20.7
28.56	0.0	4.1	11.0	23.7	30.6	33.6	37.5	39.9	36.3	33.9	31.6	26.9	19.4
29.38	0.0	4.1	11.0	23.7	30.5	33.4	36.4	37.8	33.9	31.6	29.5	25.1	18.0
30.19	0.0	4.1	11.0	23.7	30.3	32.9	34.9	35.2	31.1	29.1	27.1	23.0	16.4
31.00	0.0	4.1	11.0	23.7	30.0	32.1	32.8	32.2	28.1	26.3	24.5	20.7	14.7
32.00	0.0	4.1	11.0	23.5	29.0	30.2	29.3	27.8	23.9	22.4	20.9	17.6	12.4
33.00	0.0	4.1	10.9	22.8	26.7	26.7	24.5	22.6	19.2	18.1	16.8	14.2	9.9
34.00	0.0	4.1	10.3	20.8	22.1	21.1	18.3	16.5	14.0	13.2	12.3	10.3	7.3
35.00	0.0	3.7	7.8	14.7	13.6	12.4	10.3	9.2	7.9	7.5	7.0	5.9	4.2
35.50	0.0	2.6	4.7	8.6	7.4	6.5	5.4	4.9	4.3	4.1	3.7	3.2	2.3
36.00	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.5	0.4	0.4	0.3	0.2

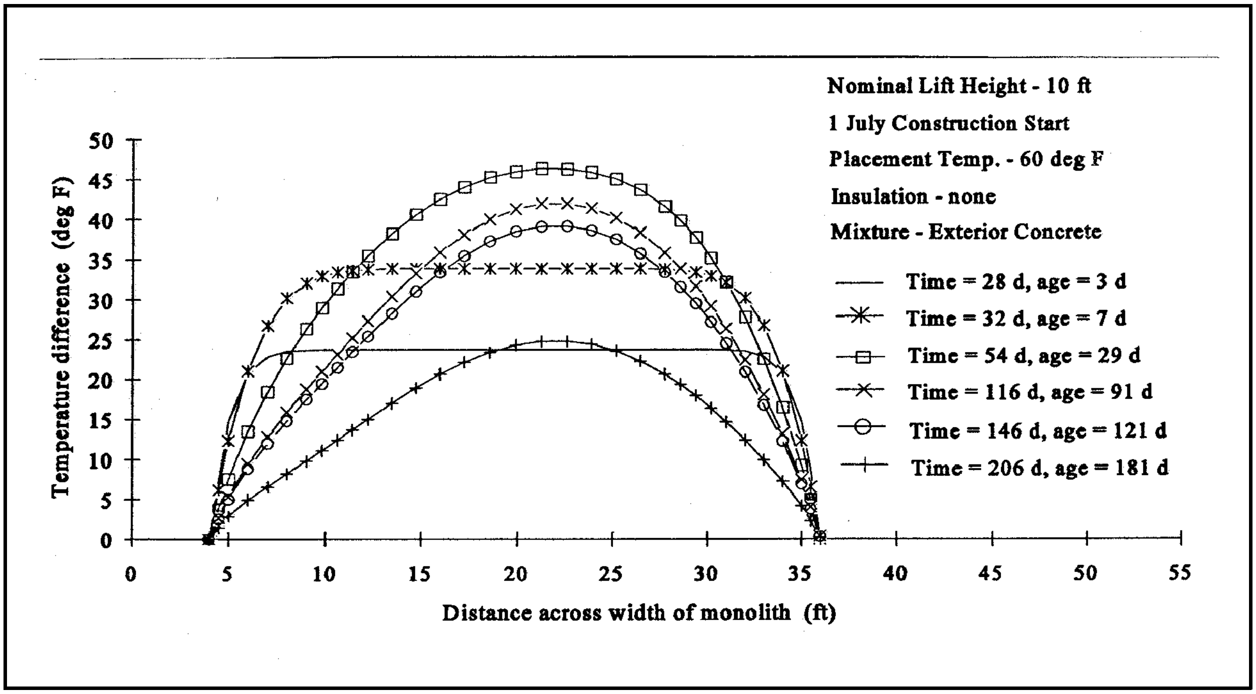

Figure A3-22. Temperature differences in lift 6 for surface gradient analysis

where

L/H = 13.4 m/7.0 m [44 ft / 23 ft] = 1.9

h/H = 3.5 m/ 7.0 m [11.5 ft / 23 ft] = 0.5

(c) Calculate tensile strains.

$\epsilon = (C_{th})(dT)(K_R)$ = 41 millionths

where

C_{th} = 10.5 millionths/deg C (5.81 millionths/deg F)

dT = 13.9 deg C (25 deg F)

K_R = 0.28

(d) Estimate cracking. TSC information is shown in Table A3-11 for various ages. Comparison of mass gradient tensile strains with the slow-load TSC for equivalent time periods indicates no anticipated cracking under the given conditions.

(2) Step 8: Surface gradient cracking analysis. Table A3-11 presents the surface gradient cracking calculations. The upper portion of the table shows the determination of restraint factors based on time and location. The lower portion shows calculation of strains using Equation A-8 from Appendix A, and comparison of calculate strains with slow-load TSC values for the appropriate time period. Figure A3-24 compares the development of tensile strains at the lock wall surface and concrete TSC with time.

(a) Internal restraint factor (K_R). Internal restraint factors are based on the depth of the tension block, "*H*." "*H*" is determined from Table A3-9 by observing the depth where temperatures change from negative to positive, which shows where effective strains are balanced between tension and compression. These depths are shown in Table A3-11 as the tension block width. K_R is calculated based on Equation A-5, as shown in the table.

Table A3-9
Balanced or Effective Temperature Differences to Determine "*H*" and Surface Gradients Strains

Degrees C

Horizontal Coordinate (m)	Age of Concrete in Lift 6 placed 25 days after Lift 1 (days)												
	0.5	1	2	3	5	7	14	29	59	91	121	151	181
	Elapsed Time (T) after Placement of Lift 1 (days)												
	25.5	26	27	28	30	32	39	54	84	116	146	176	206
1.2	0.0	-2.2	-5.8	-12.3	-15.4	-16.6	-17.9	-18.5	-16.6	-15.5	-14.4	-12.3	-8.8
1.4	0.0	-1.2	-3.6	-8.2	-11.6	-13.1	-15.1	-16.4	-15.1	-14.0	-13.0	-11.1	-8.0
1.5	0.0	-0.1	-1.4	-4.2	-7.8	-9.7	-12.4	-14.3	-13.5	-12.5	-11.7	-10.0	-7.2
1.8	0.0	0.1	0.0	-0.8	-3.1	-4.9	-8.1	-11.0	-11.1	-10.2	-9.5	-8.3	-6.1
2.1	0.0	0.1	0.2	0.3	-0.5	-1.7	-4.8	-8.3	-9.0	-8.4	-7.8	-6.8	-5.2
2.4	0.0	0.1	0.3	0.7	0.7	0.2	-2.4	-5.9	-7.1	-6.7	-6.2	-5.5	-4.3
2.7	0.0	0.1	0.3	0.8	1.3	1.2	-0.5	-3.9	-5.4	-5.1	-4.7	-4.2	-3.4
3.0	0.0	0.1	0.3	0.8	1.5	1.7	0.6	-2.4	-4.1	-3.9	-3.6	-3.3	-2.7
3.2	0.0	0.1	0.3	0.9	1.6	2.0	1.4	-1.1	-2.8	-2.7	-2.5	-2.3	-1.9
3.5	0.0	0.1	0.3	0.9	1.6	2.1	2.1	0.1	-1.5	-1.5	-1.4	-1.3	-1.2
3.7	0.0	0.1	0.3	0.9	1.6	2.2	2.6	1.2	-0.2	-0.4	-0.3	-0.4	-0.5
4.1	0.0	0.1	0.3	0.9	1.6	2.3	3.2	2.7	1.6	1.4	1.3	1.0	0.6
4.5	0.0	0.1	0.3	0.9	1.6	2.3	3.6	4.0	3.3	3.0	2.8	2.4	1.7
4.9	0.0	0.1	0.3	0.9	1.6	2.3	3.9	5.1	4.8	4.4	4.1	3.6	2.6
5.3	0.0	0.1	0.3	0.9	1.6	2.3	4.0	6.0	6.1	5.7	5.3	4.6	3.5
5.7	0.0	0.1	0.3	0.9	1.6	2.3	4.1	6.6	7.2	6.7	6.2	5.5	4.2
6.1	0.0	0.1	0.3	0.9	1.6	2.3	4.2	7.0	7.9	7.4	6.9	6.1	4.6
6.5	0.0	0.1	0.3	0.9	1.6	2.3	4.2	7.2	8.3	7.8	7.3	6.4	4.9
6.9	0.0	0.1	0.3	0.9	1.6	2.3	4.2	7.2	8.4	7.8	7.3	6.4	4.9
7.3	0.0	0.1	0.3	0.9	1.6	2.3	4.1	7.0	8.0	7.5	7.0	6.2	4.7
7.7	0.0	0.1	0.3	0.9	1.6	2.3	4.0	6.5	7.3	6.8	6.4	5.6	4.3
8.1	0.0	0.1	0.3	0.9	1.6	2.3	3.8	5.8	6.2	5.8	5.4	4.7	3.6
8.5	0.0	0.1	0.3	0.9	1.6	2.2	3.4	4.6	4.7	4.4	4.1	3.6	2.6
8.7	0.0	0.1	0.3	0.9	1.6	2.1	3.0	3.6	3.5	3.3	3.1	2.7	1.9
9.0	0.0	0.1	0.3	0.9	1.6	2.0	2.4	2.5	2.2	2.1	1.9	1.6	1.1
9.2	0.0	0.1	0.3	0.8	1.5	1.7	1.5	1.0	0.7	0.7	0.6	0.5	0.3
9.4	0.0	0.1	0.3	0.8	1.3	1.3	0.4	-0.6	-1.0	-0.9	-0.8	-0.8	-0.7
9.8	0.0	0.1	0.3	0.7	0.7	0.2	-1.6	-3.1	-3.3	-3.0	-2.8	-2.5	-1.9
10.1	0.0	0.1	0.3	0.4	-0.5	-1.7	-4.2	-6.0	-5.9	-5.5	-5.1	-4.4	-3.3
10.4	0.0	0.1	0.0	-0.8	-3.1	-4.9	-7.7	-9.4	-8.9	-8.2	-7.6	-6.6	-4.8
10.7	0.0	-0.1	-1.4	-4.2	-7.8	-9.7	-12.1	-13.4	-12.2	-11.3	-10.6	-9.0	-6.5
10.8	0.0	-0.8	-3.1	-7.5	-11.3	-12.9	-14.9	-15.8	-14.2	-13.2	-12.4	-10.5	-7.6
11.0	0.0	-2.2	-5.8	-12.3	-15.4	-16.6	-17.8	-18.3	-16.3	-15.3	-14.2	-12.1	-8.7

Negative temperature differences produce tensile strain

Degrees F

Horizontal Coordinate (ft)	Age of Concrete in Lift 6 placed 25 days after Lift 1 (days)												
	0.5	1	2	3	5	7	14	29	59	91	121	151	181
	Elapsed Time (T) after Placement of Lift 1 (days)												
	25.5	26	27	28	30	32	39	54	84	116	146	176	206
4.00	0.0	-3.9	-10.4	-22.2	-27.7	-29.8	-32.2	-33.3	-29.9	-27.9	-26.0	-22.1	-15.9
4.50	0.0	-2.1	-6.5	-14.8	-20.9	-23.6	-27.2	-29.6	-27.1	-25.2	-23.5	-20.1	-14.5
5.00	0.0	-0.2	-2.6	-7.5	-14.1	-17.5	-22.2	-25.8	-24.3	-22.5	-21.0	-18.0	-13.0
6.00	0.0	0.2	-0.1	-1.4	-5.6	-8.8	-14.6	-19.8	-19.9	-18.4	-17.2	-14.9	-11.0
7.00	0.0	0.1	0.4	0.6	-1.0	-3.1	-8.7	-14.9	-16.2	-15.0	-14.0	-12.3	-9.3
8.00	0.0	0.1	0.6	1.3	1.3	0.4	-4.2	-10.7	-12.9	-12.0	-11.2	-9.9	-7.7
9.00	0.0	0.1	0.6	1.5	2.3	2.2	-1.0	-7.0	-9.7	-9.1	-8.5	-7.6	-6.1
9.81	0.0	0.1	0.6	1.5	2.7	3.1	1.0	-4.4	-7.3	-6.9	-6.5	-5.9	-4.8
10.63	0.0	0.1	0.6	1.5	2.8	3.6	2.6	-2.0	-5.0	-4.8	-4.5	-4.1	-3.5
11.44	0.0	0.1	0.6	1.5	2.9	3.8	3.7	0.2	-2.7	-2.7	-2.5	-2.4	-2.2
12.25	0.0	0.1	0.6	1.5	2.9	4.0	4.7	2.2	-0.4	-0.6	-0.6	-0.7	-0.9
13.50	0.0	0.1	0.6	1.5	3.0	4.1	5.7	4.9	2.9	2.5	2.3	1.8	1.1
14.75	0.0	0.1	0.6	1.5	3.0	4.1	6.5	7.3	6.0	5.4	5.0	4.2	3.0
16.00	0.0	0.1	0.6	1.5	3.0	4.1	7.0	9.2	8.7	8.0	7.4	6.4	4.7
17.25	0.0	0.1	0.6	1.5	3.0	4.1	7.3	10.7	11.0	10.2	9.5	8.3	6.2
18.58	0.0	0.1	0.6	1.5	3.0	4.1	7.4	11.9	13.0	12.1	11.2	9.8	7.5
19.92	0.0	0.1	0.6	1.5	3.0	4.1	7.5	12.7	14.3	13.4	12.5	10.9	8.4
21.25	0.0	0.1	0.6	1.5	3.0	4.1	7.5	13.0	15.0	14.0	13.1	11.5	8.8
22.58	0.0	0.1	0.6	1.5	3.0	4.1	7.5	13.0	15.0	14.1	13.2	11.6	8.9
23.88	0.0	0.1	0.6	1.5	3.0	4.1	7.4	12.6	14.4	13.5	12.6	11.1	8.5
25.17	0.0	0.1	0.6	1.5	3.0	4.1	7.2	11.7	13.1	12.3	11.5	10.1	7.7
26.46	0.0	0.1	0.6	1.5	3.0	4.1	6.9	10.4	11.1	10.5	9.8	8.5	6.4
27.75	0.0	0.1	0.6	1.5	2.9	4.0	6.1	8.3	8.4	7.9	7.4	6.4	4.7
28.56	0.0	0.1	0.6	1.5	2.9	3.8	5.4	6.5	6.3	6.0	5.6	4.8	3.5
29.38	0.0	0.1	0.6	1.5	2.8	3.6	4.3	4.4	3.9	3.7	3.5	3.0	2.1
30.19	0.0	0.1	0.6	1.5	2.7	3.1	2.8	1.9	1.2	1.2	1.1	0.9	0.5
31.00	0.0	0.1	0.6	1.5	2.3	2.3	0.7	-1.1	-1.8	-1.6	-1.5	-1.4	-1.2
32.00	0.0	0.1	0.6	1.3	1.3	0.4	-2.9	-5.5	-6.0	-5.5	-5.1	-4.5	-3.5
33.00	0.0	0.1	0.5	0.6	-1.0	-3.1	-7.6	-10.8	-10.7	-9.8	-9.2	-8.0	-6.0
34.00	0.0	0.2	-0.1	-1.4	-5.6	-8.8	-13.8	-16.9	-15.9	-14.7	-13.7	-11.8	-8.6
35.00	0.0	-0.2	-2.6	-7.5	-14.1	-17.5	-21.8	-24.1	-22.0	-20.4	-19.0	-16.3	-11.7
35.50	0.0	-1.4	-5.7	-13.6	-20.3	-23.3	-26.7	-28.4	-25.6	-23.8	-22.2	-19.0	-13.7
36.00	0.0	-3.9	-10.4	-22.2	-27.7	-29.8	-32.1	-32.9	-29.4	-27.5	-25.6	-21.8	-15.7

Negative temperature differences produce tensile strain

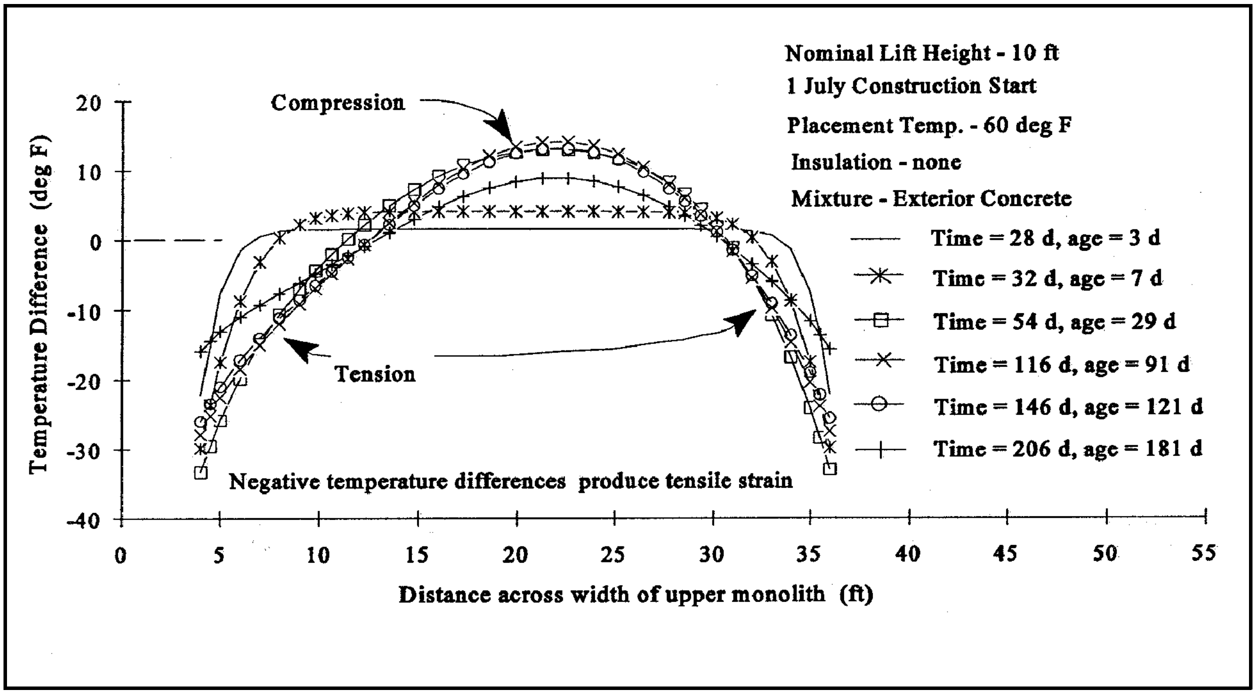

Figure A3-23. Balanced temperature difference distributions in lift 6 for surface gradient analysis

(b) Calculate tensile strains. Surface gradient tensile strains shown on Table A3-11, are based on the use of Equation A-8 (Appendix A), shown below:

$$\epsilon = (C_{th})(dT)(K_R) \quad \text{(A-8)}$$

where

ϵ = induced tensile strain

C_{th} = coefficient of thermal expansion

dT = temperature difference with respect to interior temperature difference

K_R = internal restraint factor

dT is taken from the surface effective temperature differences in Table A3-9, at the exterior surfaces at each time period. These are shown on Table A3-11 for each lock wall face. For this example, only strains at the exterior surface are calculated and are hown on Table A3-11. Exterior surface strains are shown in this Table for K_R = 1.0, for comparison assuming the surface is completely restrained, and for various lengths (L = 11.0, 12.2, and 13.4 m)(L = 36, 40, and 44 ft) between vertical joints in the lock wall, where the surface restraint is less than 1.0. Strain variation with depth from the surface could be developed using corresponding K_R for interior locations.

(c) Estimate cracking. Comparison of strains with slow load TSC provides an estimation of where and when surface gradient cracking may develop, as shown in Table A3-11. The estimated depth of cracking could be evaluated using K_R at varying depths from the surface, and comparing with slow load TSC.

Table A3-10
Mass Gradient Cracking Aanalysis

1 July start, 15.5 deg C (60 deg F) placement temperature, no insulation, exterior mix											
Analysis Location/ Node No.				Rock/Concrete Interface (Node 1925)			*dT*= *dT*(c)- *dT*(r)	Restraint Factor K_r	Thermal Strain	Slow Load TSC	Cracking yes/no
	T(max)	T(min)	*dT*©	T(max)	T(min)	*dT*(r)					
	deg C (deg F)	deg C (deg F)	deg C (deg F)	deg C (deg F)	deg C (deg F)	deg C (deg F)	deg C (deg F)	K_f = 0.64	millionths	millionths	
A / 1910	47.8 (118)	12.8 (55)	35.0 (63)	36.1 (97)	15.0 (59)	21.1 (38)	13.9 (25)	0.28	41	144	no
B / 1498	26.1 (79)	-0.6 (31)	26.7 (48)	33.3 (92)	25.5 (78)	7.8 (14)	18.9 (34)	0.08	16	144	no

Table A3-11
Surface Gradient Cracking Analysis

Example of Surface Gradient Analysis using Temperature Difference Distributions through Center of Lift 6												
3 m (10 ft) lifts, 1 July Start, 15.5 degC (60F) Placement Temperature, No Insulation, Cth = 10.5 millionths/degC (5.81 millionths/degF)												
Construction (days)		27	28	30	32	39	54	84	116	146	176	206
Concrete age (days)		2	3	5	7	14	29	59	91	121	151	181
Tension Block Width:			See Figure A3-9									
H(left)	m (ft)	0.6 (2.1)	0.8 (2.7)	1.0 (3.4)	1.2 (3.9)	1.6 (5.4)	2.2 (7.4)	2.6 (8.4)	2.6 (8.5)	2.6 (8.5)	2.6 (8.6)	2.7 (8.8)
H(right)	m (ft)	0.6 (2.1)	0.8 (2.7)	1.0 (3.4)	1.2 (3.9)	1.5 (4.8)	1.6 (5.3)	1.7 (5.5)	1.7 (5.5)	11.7 (5.5)	1.7 (5.5)	1.7 (5.6)
Monolith	Joint		RESTRAINT FACTORS KR AT SURFACES FOR L									
Analysis	Spacing											
Location	m (ft)		For L/H >= 2.5, Use equation Kr = [(L/H-2)/(L/H+1)]exp(h/H), where h=H at surface									
Left-side	11.0 (36)	0.83	0.79	0.74	0.71	0.61	0.49	0.43	0.43	0.43	0.42	0.41
Outer	12.2 (40)	0.85	0.81	0.76	0.73	0.64	0.53	0.48	0.47	0.47	0.47	0.46
Surface	13.4 (44)	0.86	0.83	0.78	0.76	0.67	0.57	0.52	0.51	0.51	0.51	0.50
Right-side	11.0 (36)	0.83	0.79	0.74	0.71	0.65	0.61	0.60	0.61	0.61	0.60	0.60
Outer	12.2 (40)	0.85	0.81	0.76	0.73	0.68	0.65	0.64	0.64	0.64	0.64	0.63
Surface	13.4 (44)	0.86	0.83	0.78	0.76	0.70	0.68	0.67	0.67	0.67	0.67	0.66
			EFFECTIVE TEMPERATURE DIFFERENCES AT SURFACE									
Eff. Temp. Diff. (Table A3-9)												
dT(left) (deg F)		-5.5 (-10)	-12.2 (-22)	-15.5 (-28)	-16.7 (-30)	-17.8 (-32)	-18.3 (-33)	-16.7 (-30)	-15.6 (-28)	-14.4 (-26)	-12.2 (-22)	-7.8 (-14)
dT(right) (deg F)		- 5.5 (-10)	-12.2 (-22)	-15.5 (-28)	-16.7 (-30)	-17.8 (-32)	18.3 (-33)	-16.1 (-29)	-15.0 (-27)	-14.4 (-26)	-12.2 (-22)	-7.8 (-14)
				SLOW LOAD TENSILE STRAIN CAPACITY								
concrete age (days)		2	3	5	7	14	28	61	90	125	155	185
slow load TSC (millionths)		86	95	104	108	116	124	134	140	144	146	149
Monolith	Joint			SURFACE TENSILE STRAIN CORRECTED FOR INTERNAL RESTRAINT (KR)								
Analysis	Spacing											
Location	m (ft)	(Assume cracking when tensile strains exceed slow-load tensile strain capacity (TSC) for respective age, indicated in bold)										
Left-side	11.0 (36)	50	**102**	**119**	**122**	114	95	75	69	64	54	38
Outer	12.2 (40)	51	**105**	**123**	**127**	**120**	103	83	77	71	60	42
Surface	13.4 (44)'	52	**107**	**126**	**131**	**126**	110	90	83	78	66	46
Right-side	11.0 (36)	50	**102**	**119**	**122**	**121**	119	105	98	91	78	55
Outer	12.2 (40)	51	**105**	**123**	**127**	**127**	**126**	111	104	97	82	59
Surface	13.4 (44)	52	**107**	**126**	**131**	**132**	**131**	116	108	101	86	61

e. Conclusions and recommendations. Some of the recommendations from this thermal study included the following:

(1) Maximum lift height = 1.5 m (5 ft).

(2) Maximum concrete placement temperature = 15.5 deg C (60 deg F) producing a 35.0 deg C (95 deg F) interior temperature.

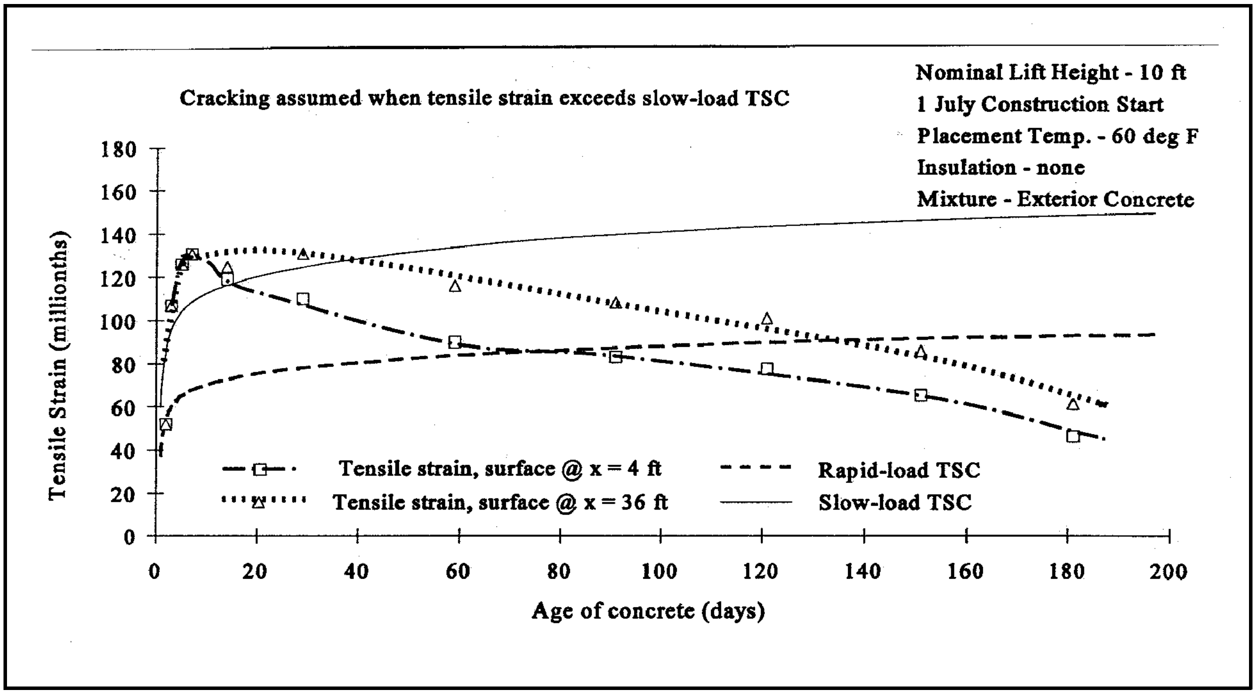

Figure A3-24. Evaluation of surface gradient cracking potential by comparing induced tensile strain with slow load tensile strain capacity

(3) Conduct additional mixture proportioning studies to further reduce the cement content.

(4) Insulate all exposed concrete surfaces placed between 15 October and 1 March.

(5) Remove insulation only when ambient temperatures are above mean daily temperatures, to aid thermal shock.

(6) Open culvert space to cool air slowly, to avoid thermal shock.