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CONCRETE TEMPERATURE CONTROL STUDY FOR THE OLD RIVER AUXILIARY STRUCTURE

by

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Finite-element method (FEM) computer simulations were made to predict temperature distribution and resulting thermal strains which are possible during construction of the Old River Auxiliary Structure. A FEM computer program computes temperature distributions in the structure during simulated construction resulting from heat of hydration of cement and subsequent heat flows based upon the thermal environment and boundary conditions. A second FEM computer program

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20. ABSTRACT (Continued).

computes thermal strain distributions based upon the volume changes that are proportional to the temperature changes, gravity loads, and the mechanical boundary conditions.

The objective of the simulations is to provide information upon which a temperature control plan for construction can be based to reduce the occurrence of thermal cracking.

The variables considered in the simulations included two cement contents, hence two heat production factors, for the 3000-psi concrete strength requirement, three placement temperatures, and pozzolan (fly ash) replacement of cement to reduce heat production. In addition, the effects of passage of a cool front were simulated as well as the effects of restraining thermal expansion of the base to simulate placement between existing monoliths.

The report summarizes the results of the simulations and recommends temperature control measures based upon these results. A series of supplemental computer simulations are suggested to permit flexibility in the specification of temperature control measures.

PREFACE

The investigation described in this report was conducted for the U. S. Army Engineer District, New Orleans, by the Concrete Technology Division (CTD) of the Structures Laboratory (SL), U. S. Army Engineer Waterways Experiment Station (WES). Authorization for the investigation was given in DA Form 2544, No. LMNED-80-18, dated 19 October 1979, subject: Preparation of Source of Construction Materials Design Memorandum for the Old River Auxiliary Structure.

The investigation was performed under the general supervision of Mr. Bryant Mather, Chief, SL, and Mr. John Scanlon, Chief, CTD, and under the direct supervision of Mr. James E. McDonald. Mr. Anthony A. Bombich performed the thermal analyses and prepared this report.

Funds for the publication of this report were provided from those made available for operation of the Concrete Technology Information Analysis Center (CTIAC). This is CTIAC report No. 62.

Commanders and Directors of the WES during this investigation and the preparation of this report were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. Fred R. Brown.

CONTENTS

CONVERSION FACTORS, INCH-POUND TO METRIC (SI) UNITS OF MEASUREMENT

Inch-pound units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
miles per hour (U. S. Statute)	1.609344	kilometres per hour
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic inch	27,679.899	kilograms per cubic metre
pounds (mass) per cubic yard	0.05933	kilograms per cubic metre
pounds (force) per square inch	6,894.757	pascals
pounds (force) per inch	175.1268	newtons per metre
pounds (force) per inch per inch	6,894.7579	newtons per metre per metre
pounds (force) per square inch per minute	114.91262	pascals per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
Btu (International Table) per pound (mass) · degree Fahrenheit	4,186.8	joules per kilogram Kelvin
Btu (International Table) · inch per hour · square inch · degree Fahrenheit	20.7688176	watts per metre Kelvin

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

CONCRETE TEMPERATURE CONTROL STUDY FOR THE OLD RIVER AUXILIARY STRUCTURE

PART I: INTRODUCTION

Background

1. A primary concern during and immediately following completion of mass concrete structures is the control of thermal cracking. During construction, heat is produced by the hydration of cement causing a temperature rise in the concrete. Subsequent thermal gradients occur due to cooling at rates depending on external temperature. Concrete temperature change causes proportional volume change that, if restrained, either externally or internally by the mass of concrete itself will produce thermal cracking. Thermal cracking can occur at any time during construction or after completion of a structure and can be sufficient to cause concern.

2. Various techniques to reduce the potential for thermal cracking have been developed. These include reducing the potential temperature rise of mass concrete by limiting the heat of hydration of cements used, minimizing cement content, or replacing part of the cement with pozzolan. Other measures include precooling the aggregate to reduce placement temperature or insulating surfaces to control thermal absorption or loss. The degree of control specified for a particular structure depends largely upon the size and geometry of the structure, climate, economics, and severity of cracking if controls are not specified.

3. Numerical methods have been developed to predict temperature distribution and resulting thermal stresses and strains in mass concrete structures. The finite-element method (FEM) employed in computer programs to compute temperature stress and strain is the most effective numerical method yet developed since it is completely general with respect to geometry, material properties, and boundary conditions. The FEM programs used in this investigation provide the capability of

simulating incremental construction of mass concrete structures and include those measures considered necessary for thermal strain control.

Purpose and Scope

4. This report presents the results of an investigation to determine the extent of thermally induced strains during construction of the Old River Auxiliary Control Structure and includes recommendations to reduce or control excessive thermal strains.

5. The properties of several concrete mixtures containing materials most available or most likely to be representative of those used in the concrete for the structure were available from tests conducted for a thermal study of Red River Lock and Dam No. 2 or were estimated from other existing data for use in the computer simulations. Special purpose finite-element method (FEM) programs calculate temperature distribution histories and resulting thermal stresses and strains considering several combinations of concrete mixtures and placement temperatures. Tensile strains are compared with tensile strain capacity for the appropriate age of the concrete used in the study. These comparisons are the basis for the thermal strain control recommendations.

PART II: FINITE-ELEMENT METHOD COMPUTER PROGRAMS

6. Two two-dimensional FEM computer programs were used in this study. The first program, developed by Dr. Edward Wilson of the University of California at Berkeley[1] and modified for use at the WES, calculates temperatures within a mass concrete structure. A second program, written by R. S. Sandhu and associates also at Berkeley[2] and modified at WES, calculates the thermal stresses and strains within the structure resulting from gravity and the thermal loads produced by the temperature calculation program.

7. Both programs use the same FEM model of the structure. The model subdivides the structure into a grid pattern in which the intersection points are called nodes and the enclosed areas are elements. Lift and material interfaces must correspond to an element boundary.

Temperature Calculation Program

8. The temperature program calculates temperatures at each node in the FEM model. Temperature calculations are based upon concrete placement temperature, hydration heat generated, and the thermal properties of the concrete which govern heat flow within and loss or gain from the structure due to ambient conditions controlled by a surface heat transfer coefficient. Calculated temperatures are output at prescribed intervals for all nodes in the model at the particular stage of construction.

Stress and Strain Calculation Program

9. This program calculates the displacements at each node and the strains and stresses developed in each element in the FEM model due to thermal and gravity loads. When creep is considered, stresses at each time step in the analysis are modified for stress relaxation allowing no strain for the interval up to the next analysis time. The creep parameters are stored and the change in stress stored as residual stress to

be included in the next time step analysis. When these stored values are applied during the next time step analysis, strains are then also modified for creep.

10. Since creep removes those strains due to inelastic deformation, the remaining strain should be completely elastic. Then to determine whether the strains calculated are sufficient to cause cracking, they are compared with a crack threshold strain.

11. The cracking threshold used is the ultimate rapid-load tensile strain capacity. Rapid-load strain capacity tests are conducted at a rate of loading of 40 psi/min which is sufficiently rapid to not allow significant inelastic strains to occur. Thus, elastic tensile strains calculated in the FEM analysis can be compared with tensile strain capacity for the age of the concrete in the element under consideration. If the tensile strain reaches 100 percent of strain capacity, it can be assumed that the cracking has begun.

12. The stress program simulates construction in the same manner as the temperature program for a given problem solution and uses the nodal temperatures calculated to determine thermal loads. The stress program requires time-dependent material properties for each unique material in the model.

13. The input value that instructs the program when to apply temperature changes as volume changes is the stress-free temperature. A value of stress-free temperature is determined for each element by the temperature program at 8 hr after placement and is the value of temperature at which an element is assumed to be stress free. Stress-free temperatures for an element and calculated nodal temperatures are stored on magnetic tape for subsequent input to the thermal strain analysis program. Subsequent temperature changes produce volume changes proportional to the coefficient of thermal expansion of an element. When differential volume changes are produced, stresses result. Stresses and strains calculated are also functions of initial external forces or displacements applied as boundary conditions.

14. A modification to account for pile restraint was incorporated into the thermal stress computer program as a direct result of

requirements for the thermal studies for the Old River and Red River Projects. The pile element used is a simple one-node element modeled mathematically by tying the node to the external reference system through a spring or stiffness quantities. Actual pile stiffness data are used to determine horizontal, vertical, and off-diagonal stiffness of nodes representing pile ends. The individual stiffnesses of all the piles in a structure are totaled so that the stiffnesses can be applied on an averaged horizontal area basis rather than an individual point basis.

15. A one-dimensional bar element existing in the program since it was written did not account for temperature change. This element used to simulate reinforcement steel was corrected and used during this study for the first time. Since the program is two-dimensional, the rebars parallel to the model are input as the equivalent cross section area per unit depth.

Finite-Element Model

16. The finite-element model used in this study (Figure 1) represents a cross section through an intermediate dam monolith in a direction normal to the flow upstream of the ogee section. Because both heat flow and stresses are symmetric in this plane, only one-half of the cross section is included in the model. The model includes 10 ft of soil to provide a heat sink for the concrete structure and to provide support for the first lift of concrete. All concrete loads after placement of lift 2 are transferred to piles by reducing soil modulus to 10 psi.

17. A pile foundation represented by single-node pile stiffness elements is located in a horizontal row 1 ft into the first lift of concrete as shown in Figure 2. In addition, steel reinforcement parallel to the plane of the model is located near the top and bottom surfaces of the monolith base section as shown in Figure 2. All concrete in the lower seven lifts has a nominal 28-day compressive strength of 3000 psi. Concrete above lift 7 is 6000 psi representing the trunnion anchorage. Reinforcement was not included in the pier stem because of the complex detail. Interpretation of results should take this into account. All lifts were 5 ft high.

PART III: CONCRETE MIXTURES AND OTHER DATA

Concrete Mixtures

18. Thermal and mechanical properties of concrete used as input data to the computer programs are based upon test results of Mixtures A and B (Exhibit A) conducted during a similar study for Red River Lock and Dam No. 2.[3] The mixtures consist of locally available 1-1/2-in. coarse aggregates, Type II cement with heat of hydration limit, and cement contents of 450 lb/yd^3. Mixture B has 25 percent by solid volume of the cement replaced by fly ash. The materials and quantities specified above were to satisfy 3000-psi strength requirements.

19. Additional data were necessary for the 6000-psi concrete in the trunnion pier stem. Because of the complex nature of the highly reinforced trunnion stem, it was felt that a test program to generate concrete data for this mixture could not be justified on the basis of cost. Estimated properties were assumed acceptable. Modulus of elasticity and tensile strain capacity were assumed to be the same as for the 3000-psi fly ash and nonfly ash mixtures, respectively. This assumes that the increase in both properties to the 6000-psi concrete would be proportionately equal, thus producing the same strain versus strain capacity ratios as if the properties were actually changed. Adiabatic temperature rise for the 6000-psi mixture was based upon a cement content of 650 lb/yd^3 and was estimated from existing data. The corresponding adiabatic temperature rise for the 6000-psi mixture with fly ash was compiled to compare to the mixture without fly ash in the same relationship as the adiabatic temperature rise data of the 3000-psi mixture with and without fly ash.

20. One additional set of mixtures was used in the study. These are minimum cement content mixtures that could be expected to produce the required 3000- and 6000-psi strengths. It was determined that the cement contents of Mixture A could be reduced by 25 percent. Mixtures now being developed at WES for Red River Lock and Dam No. 1 are easily attaining the 3000 psi (actually 3720 psi) required at even lower cement contents.

The adiabatic temperature rise for Mixture A was reduced by 25 percent for the minimum cement content mixture (No. AM). Mechanical data were again assumed the same as Mixture A.

21. Figure 3 contains modulus of elasticity versus age data for Mixtures A and B. Figure 4 contains tensile strain capacity versus age data for Mixtures A and B. Figure 5 contains adiabatic temperature rise versus age data used in the study.

22. Creep data were based upon tests conducted at WES in 1958[4] for Port Allen Lock on a concrete mixture virtually identical to Mixture A. The creep data were then fit to McHenry's equation.[5,6]

$$E_c(\sigma,t,T) = \sum_{i=1}^{N} (A_k(T)\ 1-e^{-m_i(t-T)}$$

where

σ = applied stress

E_c = creep strain

t = time after placement

T = age at loading

N = 2 was found to give a satisfactory fit of experimental data. Values of creep relaxation coefficients A1 and A2 versus time are given in Figure 6. Values of constants $m_1 = 0.45$ and $m_2 = 0.0285$ were used.

Input Properties

23. Additional properties data used as input to the computer programs are:

Concrete

Thermal conductivity	0.110 Btu-in./hr-in.^{2}-^oF
Specific heat	0.22 Btu/lb-^oF
Density	0.0835 lb/in.^{3} (144 lb/ft^3)
Coefficient of thermal expansion	7.0 x 10^{-6}/^oF
Poisson's ratio	0.17

Foundation

Thermal conductivity	0.058 Btu-in./hr-in.^{2}-^oF
Specific heat	0.411 Btu/lb-^oF

Density (temperature calculation)	0.0706 lb/in.^{3} (122 lb/ft^3)	
Density (strain calculation)	0.0001 lb/in.^{3}	
Coefficient of thermal expansion	7.0 x 10^{-6}/°F	
Poisson's ratio	0.35	
Modulus of elasticity (To lift 1)	10,000.0 psi	See paragraph 16
Modulus of elasticity (After lift 1)	10.0 psi	

Reinforcement Steel

Density (stress runs only)	0.283 lb/in.^{3} (489 lb/ft^3)
Coefficient of thermal expansion	6.7 x 10^{-6}/°F
Poisson's ratio	0.2
Modulus of elasticity	3 x 10^{+7} psi

Pile Restraint

24. Stiffness is computed for the unit depth of a finite-element model and unit width in the plane of the model. The actual stiffness input represents the area (width) of influence of each "pile" node. Since thermal stress is affected by foundation restraint, it was assumed that the pile stiffness based upon strong subgrade modulii that were provided by the District would affect thermal stress and strain the most. In the transverse orientation of the model, the weak axis horizontal stiffness for the H-piles was used. Lateral and axial stiffnesses provided were 22.7 and 1149.3 kips (10^3 lb)/in., respectively. Taking into account 1:4 and 1:2.5 pile batter, vertical stiffness computed for input was 0.289 kips/in./in. and horizontal stiffness was 0.412 kips/in./in.

PART IV: COMPUTER SIMULATION - CONSTRUCTION PARAMETERS

Placement Parameters and Environment

Lift height and placement rate

25. Five-feet lifts placed at five-day intervals were used throughout the study. Although placement will in all probability progress more slowly, this rate was used as a worst but possible case.

Construction start date, placement temperature

26. The construction start date used in all computer runs was 1 August. This represents the hottest period of the year for placement which will result in maximum concrete temperature and for which maximum danger due to early fall cool weather will be present. Primary placement temperature for all but two runs was 85^{o} F for a period extending until the last week in August upon which placement temperatures were reduced 1^{o} F per 5 days to conform with the cooling fall weather. In two other runs placement temperatures of 70^{o} F and 55^{o} F were simulated for comparison.

Foundation temperature and air temperatures

27. Foundation temperature was assumed to be a constant 66.7^{o} F at a depth of 10 ft (el -35). This is mean annual ambient temperature for the project site. The soil above was allowed to equilibrate to the $\approx 82^{o}$ F mean daily temperatures which are normal on 1 August at the project site.

28. Air temperatures used in this study are representative of the geographic area of central Louisiana. Daily temperature variation has been ignored. Figure 7 contains the air temperature versus time relationship used in the computer runs. In one of the computer runs a cold front was simulated. This consisted of a drop in air temperature of 20^{o} F lasting for a period of 3 days on 1 September. This is a severe but not impossible case.

Boundary Conditions

Thermal boundary conditions

29. The lower boundary of the soil was fixed at 66.7° F. The vertical soil boundaries permitted no horizontal heat flow. Heat flow was also not permitted horizontally through the vertical centerline of the monolith, represented by the left side of the model. All horizontal surfaces of concrete lifts were exposed to a heat transfer coefficient equivalent to a 5 mph wind. The vertical (formed) surfaces were treated similarly except that the insulating effect equivalent to 3/4-in. plywood forms was included for the first 5 days after placement of each lift. After 5 days, no heat flow was permitted simulating the effect of concrete placement in the adjoining monolith.

Mechanical boundary conditions

30. The lower boundary of the soil was fixed vertically and the vertical surfaces fixed horizontally. The centerline of the monolith was fixed horizontally. For all but run 7 no other boundary restraint was applied. In run 7 the vertical monolith interface was fixed in the horizontal direction simulating placement against existing concrete. In the other runs this boundary is assumed free to expand and contract.

PART V: COMPUTER SIMULATION RESULTS

31. The following table contains a summary of the computer runs made, resulting peak temperatures, and cracking potential of each. Specific locations within the model at which tensile strains exceeded 90 and 100 percent of tensile strain capacity for runs 1, 3, 4, 5, and 7 are found in Figures 8a-8e.

Run No.	Placement Temperature (°F)	Primary Concrete Mixture* Cement (lb/yd³)	Primary Concrete Mixture* Fly Ash (lb/yd³)	Peak Temperature (°F) Base	Peak Temperature (°F) Stem	Strain vs Strain Capacity** Ratio (Percent) Base	Strain vs Strain Capacity** Ratio (Percent) Stem
1	85	450	0	130	138	118	159
2	85	450	0	130	138	175†	N.D.††
3	85	338	87‡	126	127	129	>148
4	85	340	0	119	123	90	>121
5	70	450	0	120	132	92	>110
6	55	450	0	110	122	N.D.	N.D.
7	85	340‡‡	0	119	123	45	>121

* Cement content of primary mixture used in base of monolith and lower pier stem.

** Maximum percentage of tensile strain relative to tensile strain capacity in the run.

† After 20° F air temperature drop on 1 September.

†† N.D. - no data produced.

‡ Total volume of cementitious materials equal to that for 450 lb of portland cement.

‡‡ Vertical monolith interface restrained (cast against existing adjoining monolith).

Trunnion Pier Stem Concrete

32. The table above shows that concrete in the trunnion pier stem had a high potential for cracking on all runs made. The problem was most severe in the 6000-psi concrete of the trunnion anchorage above lift 7. Thermal strains are most severe on the horizontal surfaces of these lifts. It could be expected that a long vertical crack may occur

down the centerline of the pier stem. However, extensive reinforcement is planned for this area which would act to control this cracking.

Base or Lower-Monolith Concrete

33. Concrete in the base of the monolith (first four lifts) also showed excessive thermal strains in certain areas when placement temperature was 85° F and the concrete contained the solid volume equivalent of 450 lb of cement per cubic yard (Mixture A or B). Surprisingly, run 3 which included Mixture B with fly ash replacement indicated a slightly larger ratio of thermal tensile strain to tensile strain capacity than did run 1 which included Mixture A without fly ash. The inclusion of fly ash in mass concrete has for years been an accepted temperature control measure. To date concrete with and without fly ash replacement has not been subjected to as rigorous a thermal analysis as was done in this study. Well documented thermal and mechanical properties existed for Mixtures A and B. Examination of the properties of Mixtures A and B may indicate the reason for the results seen. The data show that although the rate of adiabatic temperature rise in Mixture B was less than that of Mixture A, so was the rate of tensile strain capacity gain. Therefore, the benefits of less heat production and lower thermal strain are more than offset by lower tensile strain capacity in Mixture B. With both Mixtures A and B maximum tensile strain with respect to strain capacity occurs about four days after placement and coincides with the occurrence of peak temperature in the new concrete lift.

34. Concrete placement of Mixture A at 70° F (run 5) did reduce most areas of tensile strains below tensile strain capacity throughout the first six lifts, however, cracking probably could be expected when daily or weekly temperature variations are considered. The reduced cement content mixture (340 lb cement per cubic yard) simulated in run 4 was placed at 85° F. Maximum tensile strains below lift 6 were no higher than 75 percent of tensile strain capacity in all lifts except the top surface of lift 2 which reached 90 percent of strain capacity.

Effects of Boundary Parameter Variation

Effect of cool fronts

35. Run 2 was identical to run 1 (Mixture A placed at 85° F) except that the effects of a cool front equivalent to a drop in mean air temperature of 20° F beginning on 1 September and lasting for 3 days was simulated. The temperature drop started 5 days after placement of lift 4. A mean air temperature drop of 20° F is somewhat severe for early September, and surface tensile strains were almost doubled. This does indicate that even a less severe temperature drop could easily cause problems if tensile strains existing at the time of the temperature drop were above 50 or 60 percent of tensile strain capacity.

Restrained horizontal expansion

36. Run 7 was identical to run 4 except that horizontal expansion of the monolith was restrained as would be the case if the adjoining monolith was already in place. Maximum tensile strains were 45 percent of tensile strains capacity, and orientation of tensile strains were shifted 90° from horizontal to vertical. It is not known what the total effect of this restraint is on the structure, but it would appear that restraint to expansion in the plane of the model (transverse to direction of flow) will increase tensile strains in the plane parallel to the flow due to Poisson's effect.

Discussion of Plots

Temperature profiles

37. Several plots have been included to give an indication of the effects of the variables used in the computer calculations. Figures 9-12 show vertical temperature profiles through the base section of the intermediate pier monolith during concrete placement for runs 1, 3, 4, and 5, respectively. Figure 13 shows vertical temperature profiles for run 4 for a period of 1 year after concrete placement begins. The cooling of the center mass and the effect of winter and summer temperature are easily seen.

Strain profiles

38. Figures 14a-14d show horizontal strains (ε_x) computed in run 1 along a vertical section through the base of the monolith at a location 10 ft from the adjoining monolith following placement of lifts 1-4, respectively. Because the orientation of principal strains virtually coincide with the x and y axes, the horizontal strains closely approximate maximum tensile strains computed. The temperature distribution from which the strains in Figure 14 were computed are found in Figure 9. Figure 14 does show the effects of incremental construction quite vividly wherein concrete properties are different in each lift and are varying at different rates. At the same time new concrete is being placed upon surfaces experiencing tension due to thermal gradient. The effect is to "lock in" thermal strain. Strains at any time across a section composed of several lifts are a function of the total history of temperature distribution and material properties that have existed to that time. "Locked in" strains can readily be seen in Figure 13d where internal concrete is in tension even though the temperature distribution indicates these areas should be in compression.

39. Because the internal locations of peak tensile strain change (move vertically in this case), it is possible to visualize how a crack originating at an exposed surface may later propagate especially considering that much less strain is required for propagation. The computer simulations conducted during this study also demonstrate the ease at which the conditions necessary to produce cracking can occur during construction as a result of improper temperature control.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

40. When maximum placement temperatures of 85° F were simulated for 3000-psi concrete mixtures containing 450 lb/yd^3 of Type II cement with heat of hydration limit, maximum tensile strains exceeded tensile strain capacity by 18 and 28 percent on horizontal surfaces in the base and pier stem, respectively. Tensile strain exceeded tensile strain capacity in the 6000-psi concrete of the trunnion anchorage by up to 50 percent or more. This area, however, will be highly reinforced which should serve to control cracking.

41. While 3000-psi concrete containing 25 percent fly ash replacement of cement was effective in decreasing temperature rise and severity of thermal gradients, it did not reduce the tensile strains relative to tensile strain capacity.

42. Placement of Mixture A with cement contents of 450 lb/yd^3 at 70° F did reduce tensile strains below tensile strain capacity in most areas where they were excessive when concrete placement was 85° F. Reduction of 3000-psi concrete cement contents to 340 lb/yd^3 did reduce all tensile strains below tensile strain capacity.

43. A drop in mean daily temperature of 20° F as experienced during passage of cold fronts can cause increases in tensile strain of up to 100 percent when occurring within 5 days of placement. Daily temperature variation will also increase tensile strain, but by a much lesser amount. Reducing cement content or reducing placement temperature to 70° F individually will not lower tensile strains sufficiently to prevent exceeding tensile strain capacity at least at one location on each exposed surface due to ambient temperature extremes.

44. The highest tensile strains computed occur during the initial temperature rise in the concrete. It appears that reduced lift thickness would reduce initial peak temperatures, hence reduce the temperature differential causing peak tensile strains.

45. Based on the above conclusions, it is recommended that the lowest possible cement contents be used in all mixtures. This is the best way to control thermal cracking. Largest coarse aggregate size

possible should be used. Under these circumstances 3000-psi concrete mixtures should be possible with cement contents no more than 300 to 340 lb per cubic yard of concrete.

46. The use of fly ash to replace a portion of the cement should not be assumed to reduce the potential for cracking even though temperatures will be reduced. Therefore, fly ash should be used for reasons of economy rather than thermal strain control. No attempt should be made to increase placement temperatures when fly ash is used even if peak temperatures are produced which are equal to that produced from mixtures with no fly ash.

47. In conjunction with use of lowest possible cement contents in the concrete mixture it is recommended that maximum placement temperatures be considered reduced to 70^{o} F since no single control measure studied reduced the potential for cracking in of itself. 70^{o} F should be possible with chilled water and aggregate cooling except during a short period of extremely hot weather normally occurring each summer. The need for reduced placement temperature is more critical in the pier stem. Consideration should be given to reducing lift heights from 5 to 4 ft in lieu of reducing placement temperatures from 85^{o} F to 70^{o} F. Similar thermal studies for the Red River Lock and Dam No. 2 have indicated that 4-ft lifts effectively control tensile strain even when concrete mixtures containing 450 lb/yd^{3} are used.

48. Because tensile strains computed in the 6000-psi concrete of the trunnion anchorage in the pier stem were quite high, it is recommended that use of this concrete be confined to the minimum volumes necessary for the structural design. No area designated to receive 3000-psi concrete in the pier stem should receive 6000-psi concrete for reasons of construction expediency.

49. Based upon the results of this study, it is recommended that Type II cement with heat of hydration limit be used without exception.

PART VII: ADDITIONAL STUDIES

50. The computer simulations conducted in this study were intended to examine probable worst case situations. For example, primary concrete mixtures contained relatively greater amounts of cement than necessary to achieve desired strength, periods of time between placement used were nearly the shortest possible, and even the cold front simulation was more severe than normal for the climate at the construction site. In order to provide necessary supplemental information which will permit flexibility in specification of control measures, supplemental computer simulations are suggested.

51. These supplemental simulations should include the near-surface vertical reinforcement steel in the pier stem. This will eliminate any questions relating to incomplete modeling except for the more complex trunnion anchorage reinforcement, which cannot be included.

52. The following computer runs are suggested to evaluate lift height and placement temperatures.

Run	Placement Tempature (^{o} F)	Lift Height (ft) Base	Stem
A	70	5	4
B	70	5	5
C	70	7-1/2	7-1/2
D	85	5	4
E	85	4	5
F	85	7-1/2	7-1/2

Based on results of these runs, one or more additional runs should be made to evaluate different placement rates, especially in areas of critical tensile strains.

53. Finally, one or more runs are suggested in which insulation is used to control development of critical thermal strains resulting from the initial thermal gradient. The possibility of using insulation to control these early thermal strains without substantially increasing peak temperatures is of primary interest.

REFERENCES

1. Wilson, E. L., "The Determination of Temperatures Within Mass Concrete Structures," Report No. 68-17, Dec 1968, Structural Engineering Laboratory, University of California, Berkeley, CA.

2. Sandhu, R. S., Wilson, E. L., and Raphael, J. M., "Two-Dimensional Stress Analysis with Incremental Construction and Creep," Report No. 67-34, Dec 1967, Structural Engineering Laboratory, University of California, Berkeley, CA.

3. Holland, T. C., Liu, T., Bombich, A. A., "Determination of Properties of Concrete Used in Thermal Studies for Lock and Dam No. 2, Red River Waterway," (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.

4. McCoy, E. E., "Laboratory Tests of Concrete and Reinforcing Steel, Port Allen Lock," Miscellaneous Paper No. 6-297, Dec 1958, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.

5. McHenry, D., "A New Aspect of Creep in Concrete and Its Application to Design," Proceedings, American Society for Testing and Materials, Vol 43, 1943, pp 1069-1087.

6. King, I. P., "Finite Element Analysis of Two-Dimensional Time-Dependent Stress Problems," Report No. 65-1, Jan 1965, Structural Engineering Laboratory, University of California, Berkeley, CA.

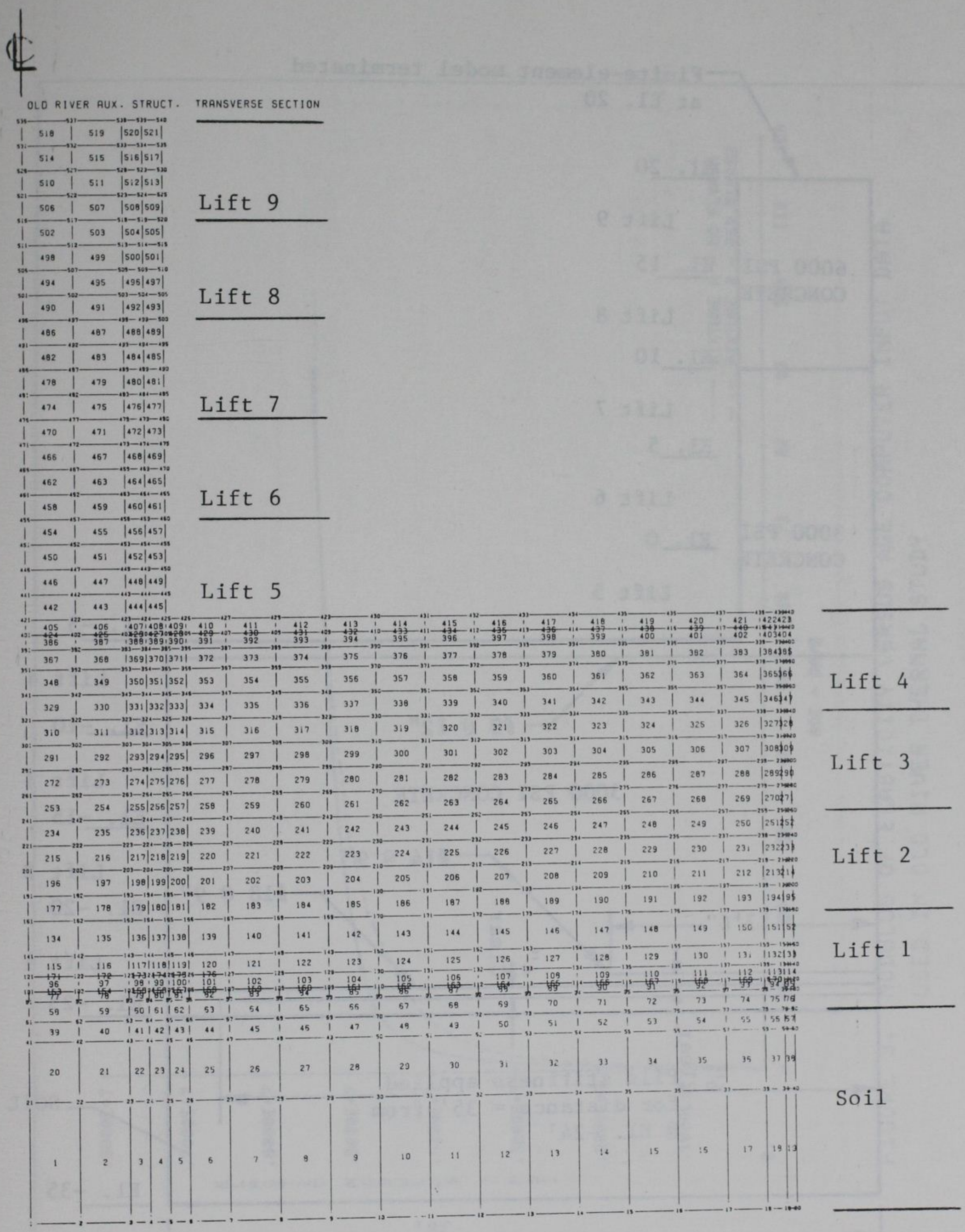

Figure 1. Finite-element model of intermediate pier monolith used in temp control study of Old River Auxiliary Structure

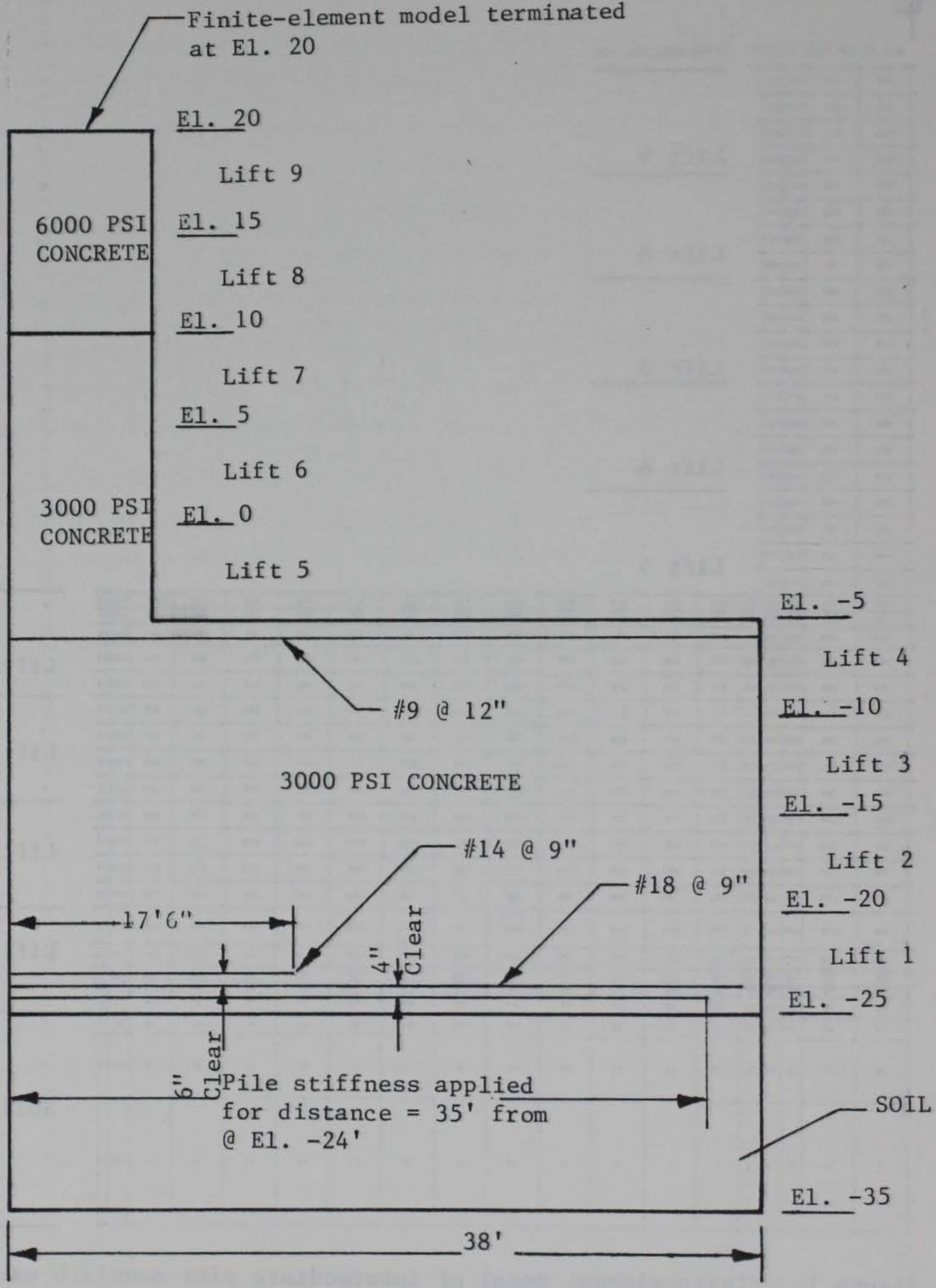

Figure 2. Transverse section of intermediate pier monolith of Old River Auxiliary Structure included in finite-element model

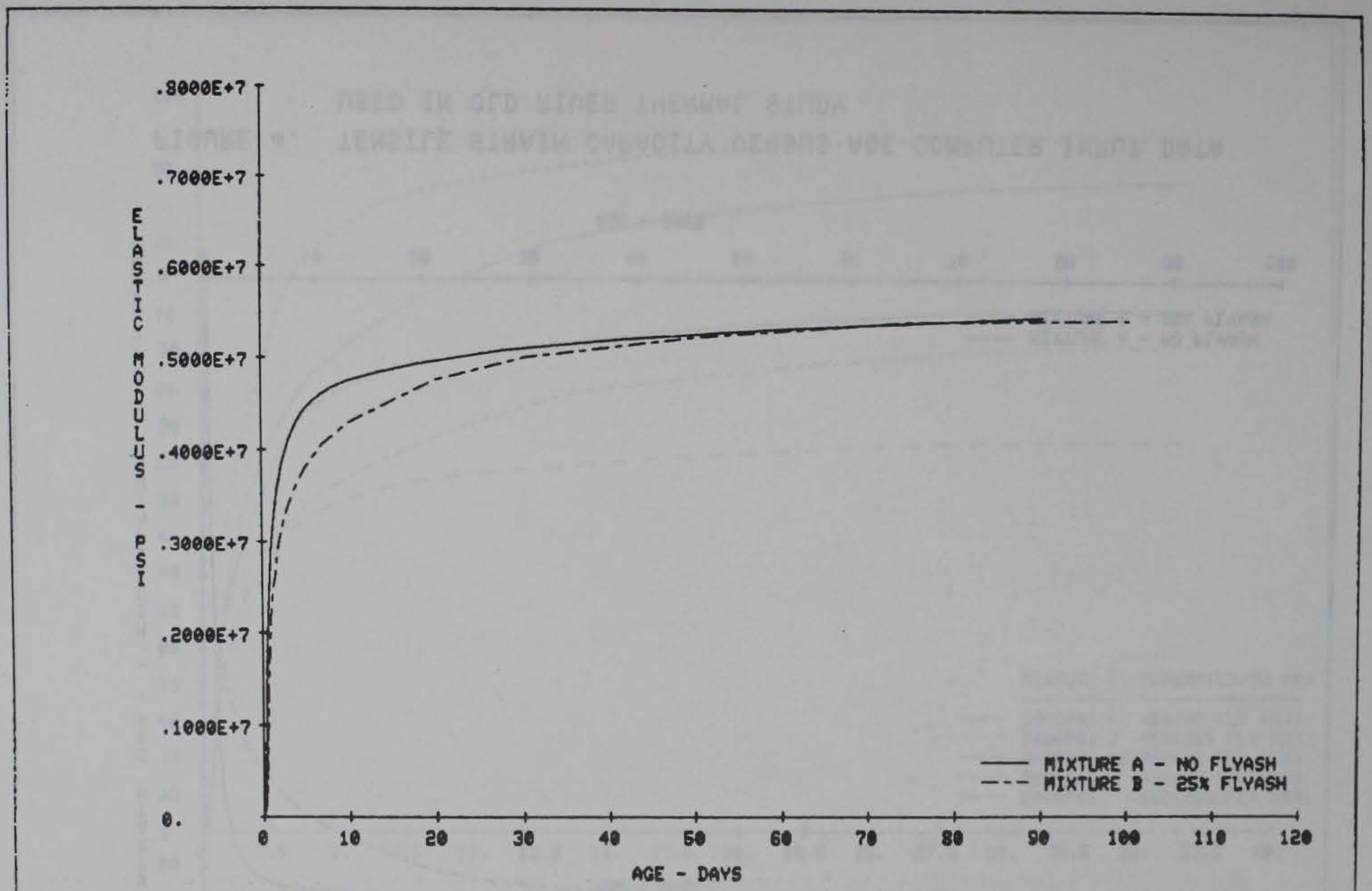

FIGURE 3. MODULUS OF ELASTICITY VERSUS AGE COMPUTER INPUT DATA USED IN OLD RIVER THERMAL STUDY

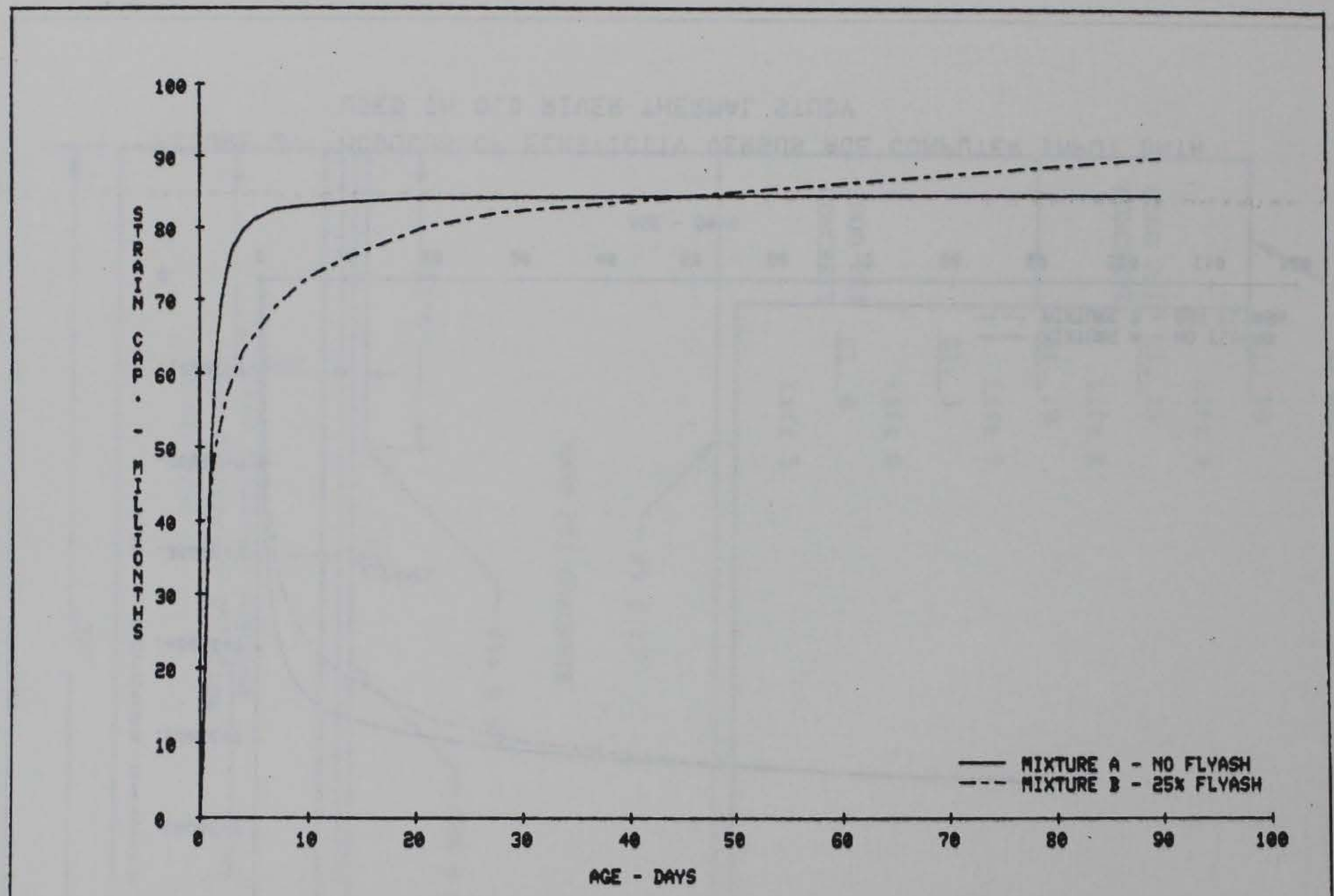

FIGURE 4. TENSILE STRAIN CAPACITY VERSUS AGE COMPUTER INPUT DATA USED IN OLD RIVER THERMAL STUDY

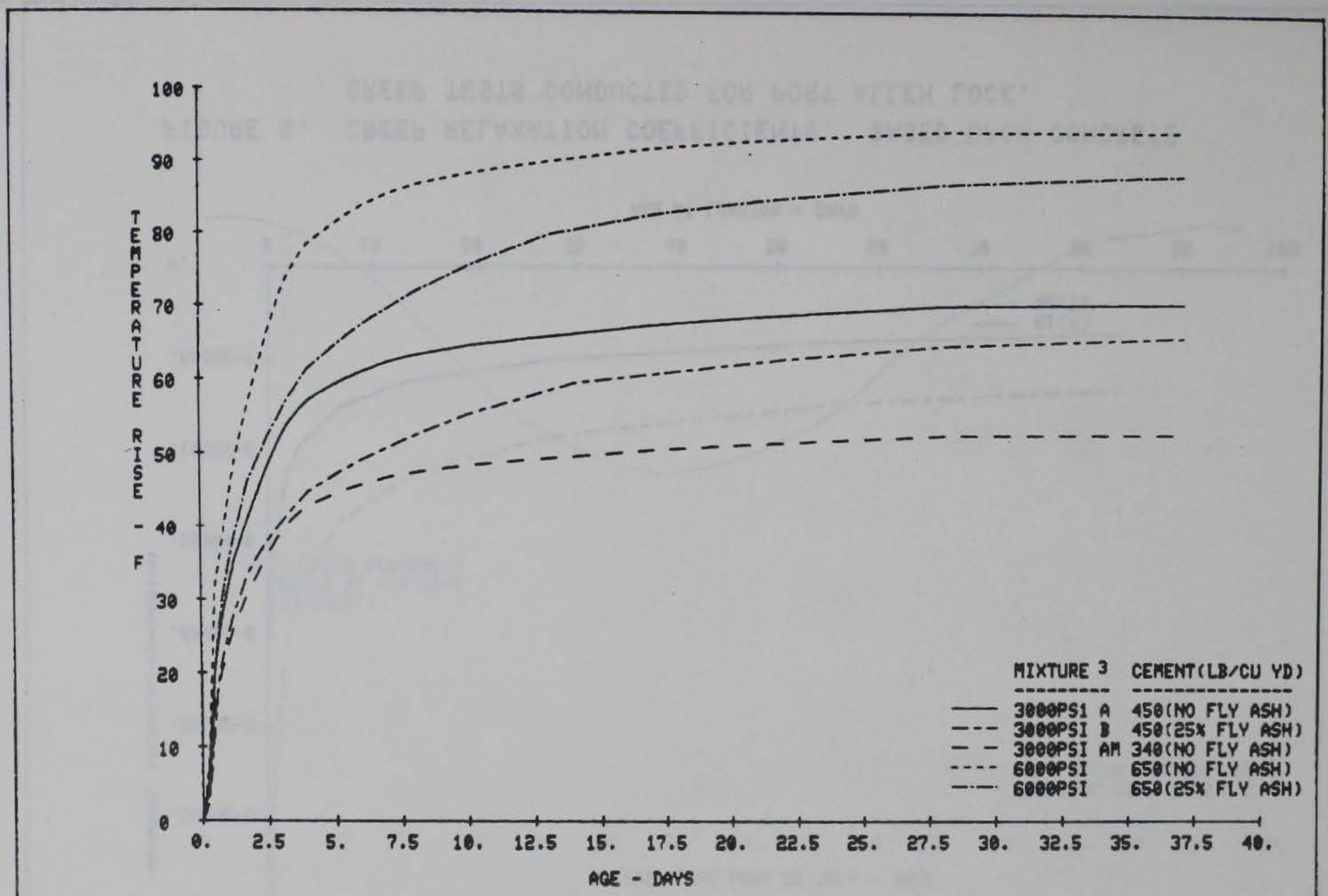

FIGURE 5. ADIABATIC TEMPERATURE RISE VERSUS AGE DATA. COMPUTER INPUT FOR OLD RIVER THERMAL STUDY. DATA FOR MIXTURES A AND B ARE FROM TESTS, THE REST ARE ASSUMED DATA.

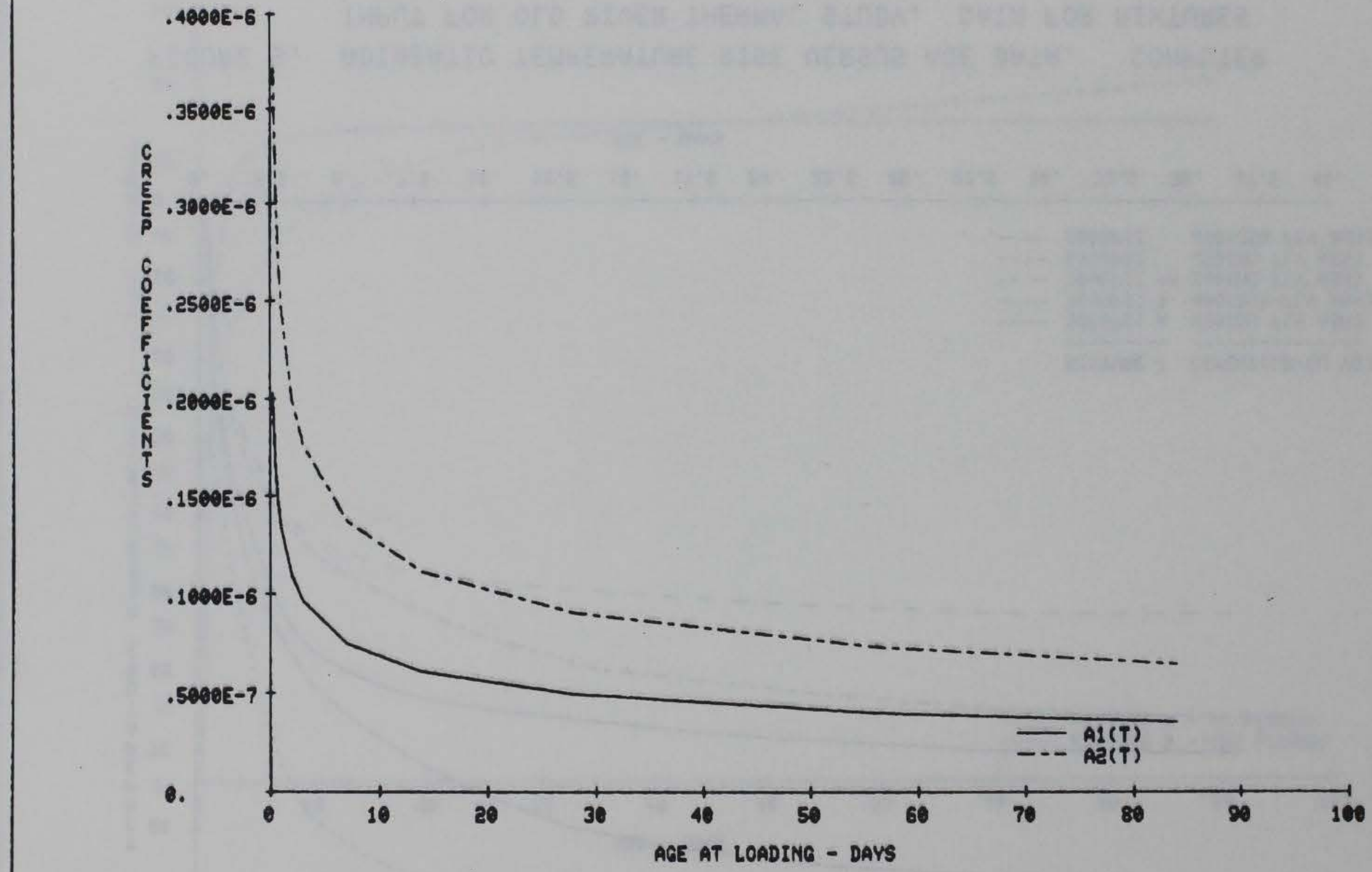

FIGURE 6. CREEP RELAXATION COEFFICIENTS. BASED UPON CONCRETE CREEP TESTS CONDUCTED FOR PORT ALLEN LOCK.

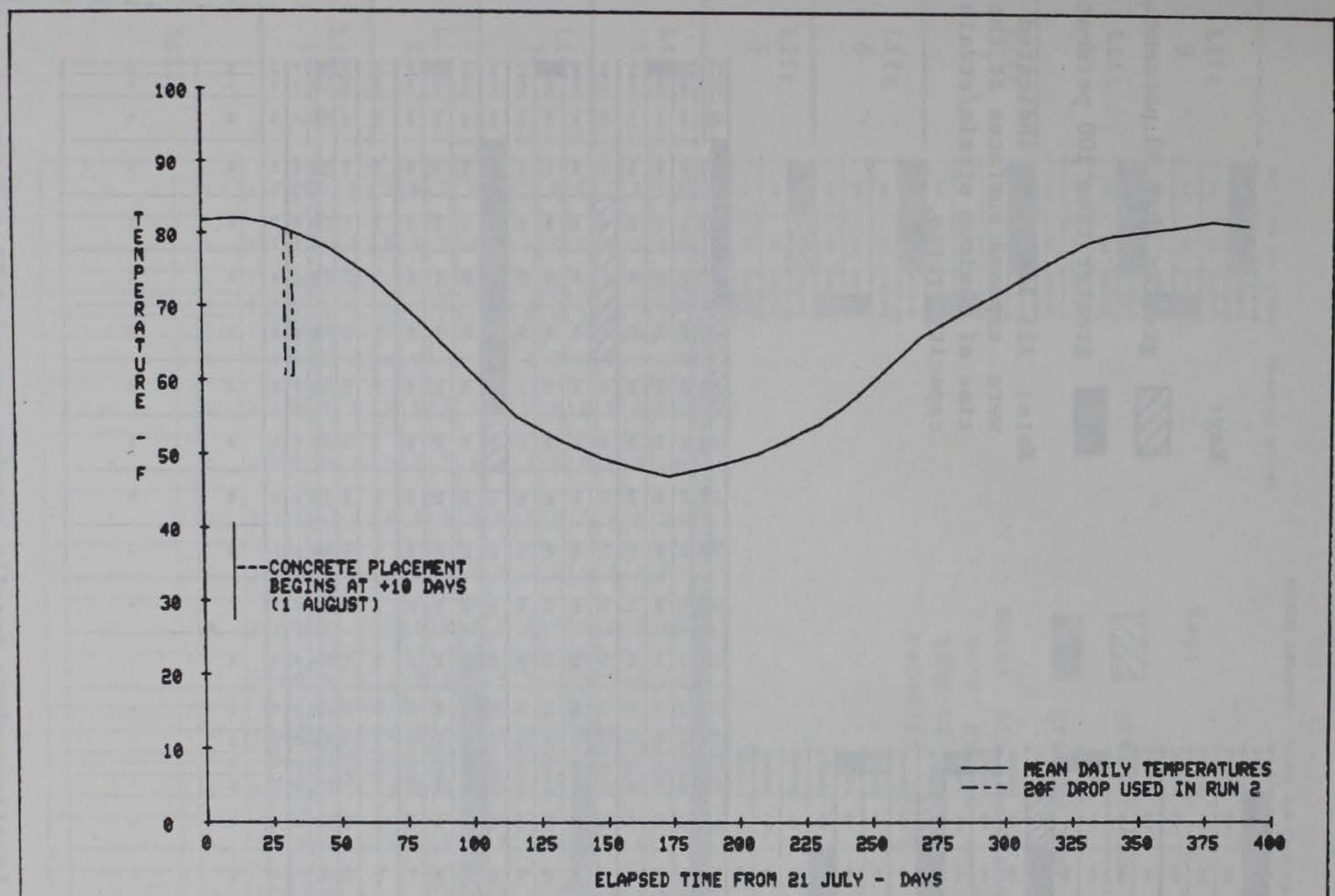

FIGURE 7. AIR TEMPERATURES USED IN OLD RIVER THERMAL STUDY. DATA BASED UPON MEAN DAILY TEMPERATURES NORMAL FOR PROJECT SITE LOCATION.

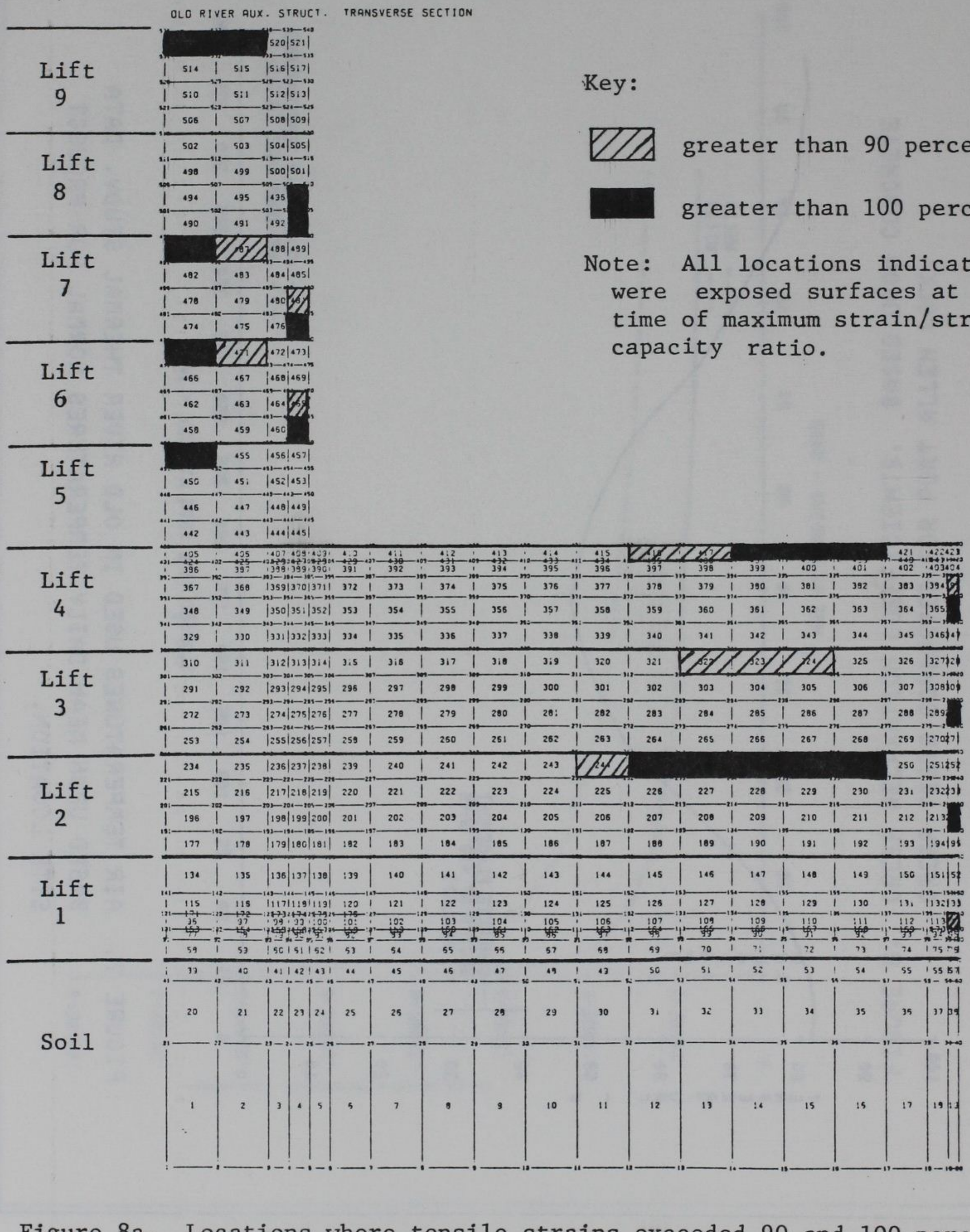

Figure 8a. Locations where tensile strains exceeded 90 and 100 percent of tensile strain capacity - Run #1

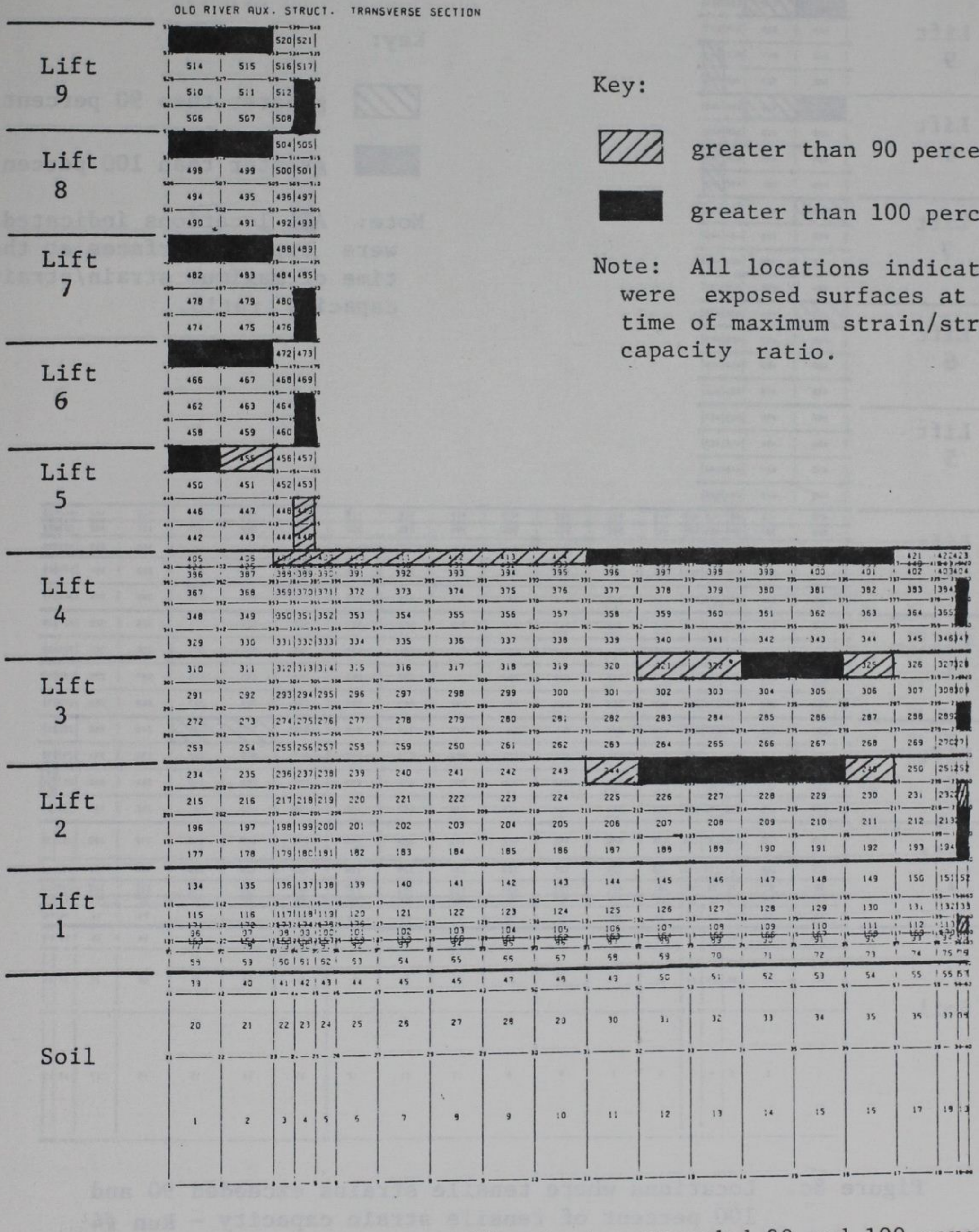

Figure 8b. Locations where tensile strains exceeded 90 and 100 percent of tensile strain capacity - Run #3

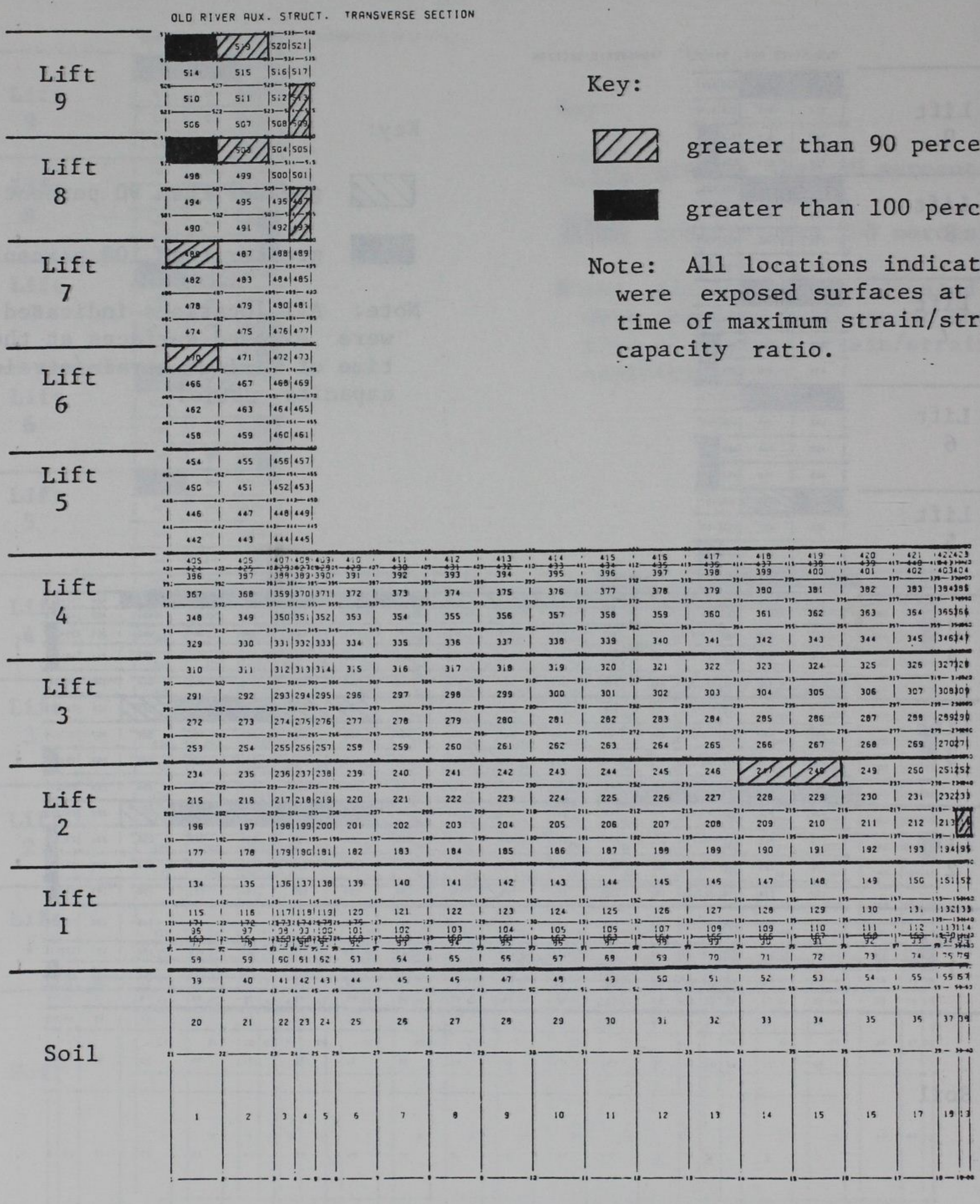

Figure 8c. Locations where tensile strains exceeded 90 and 100 percent of tensile strain capacity - Run #4

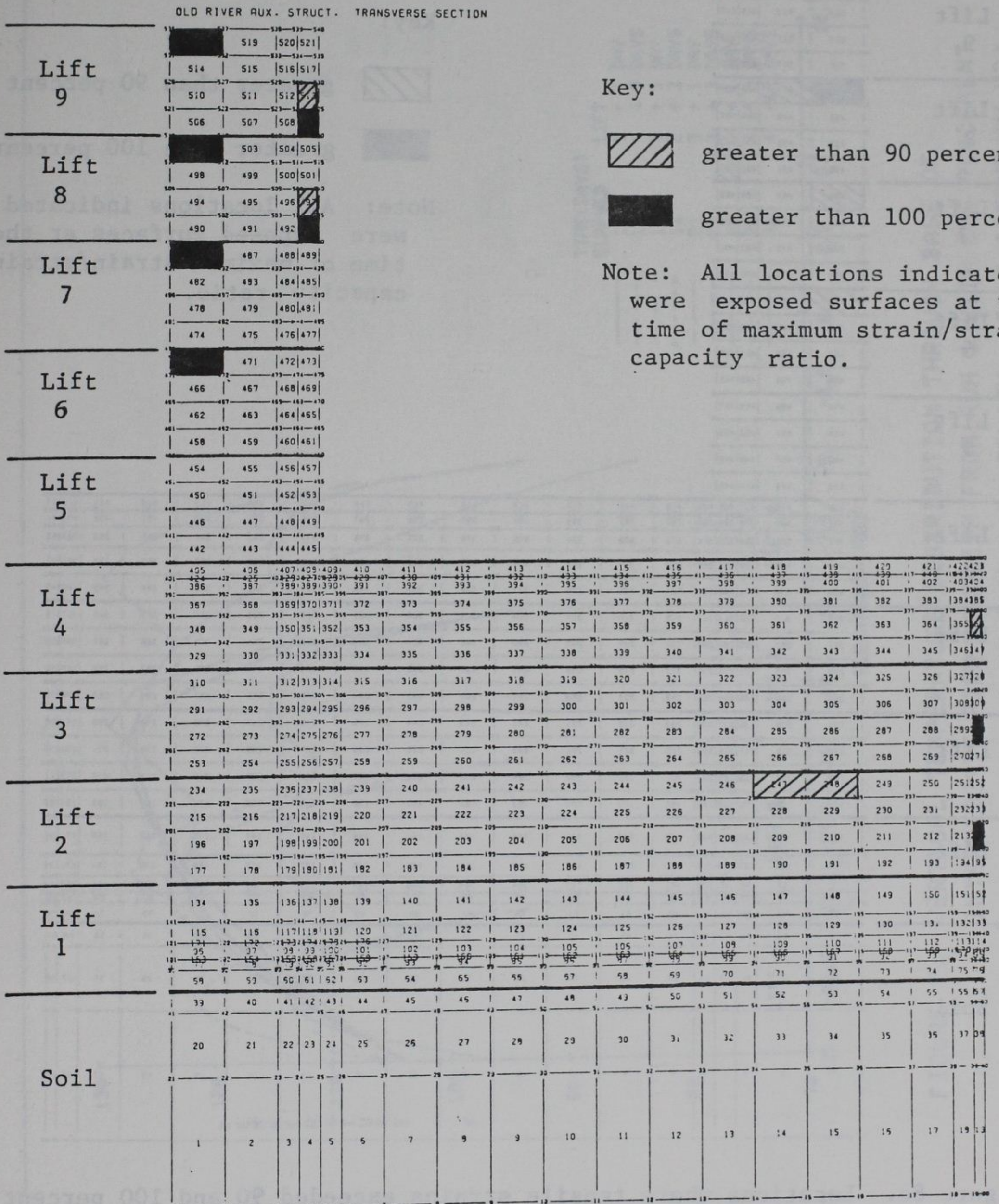

Figure 8d. Locations where tensile strains exceeded 90 and 100 percent of tensile strain capacity - Run #5

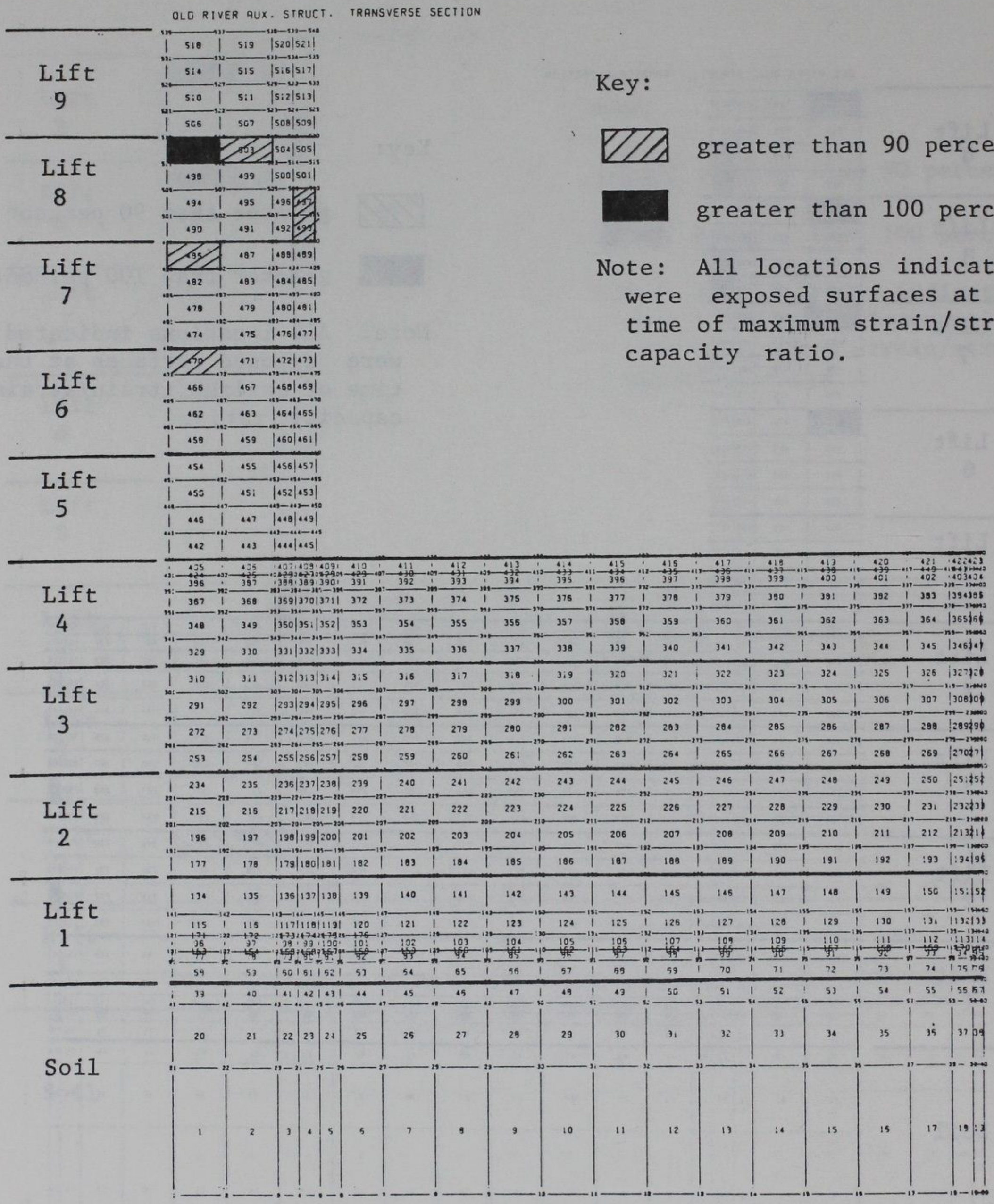

Figure 8e. Locations where tensile strains exceeded 90 and 100 percent of tensile strain capacity - Run #7

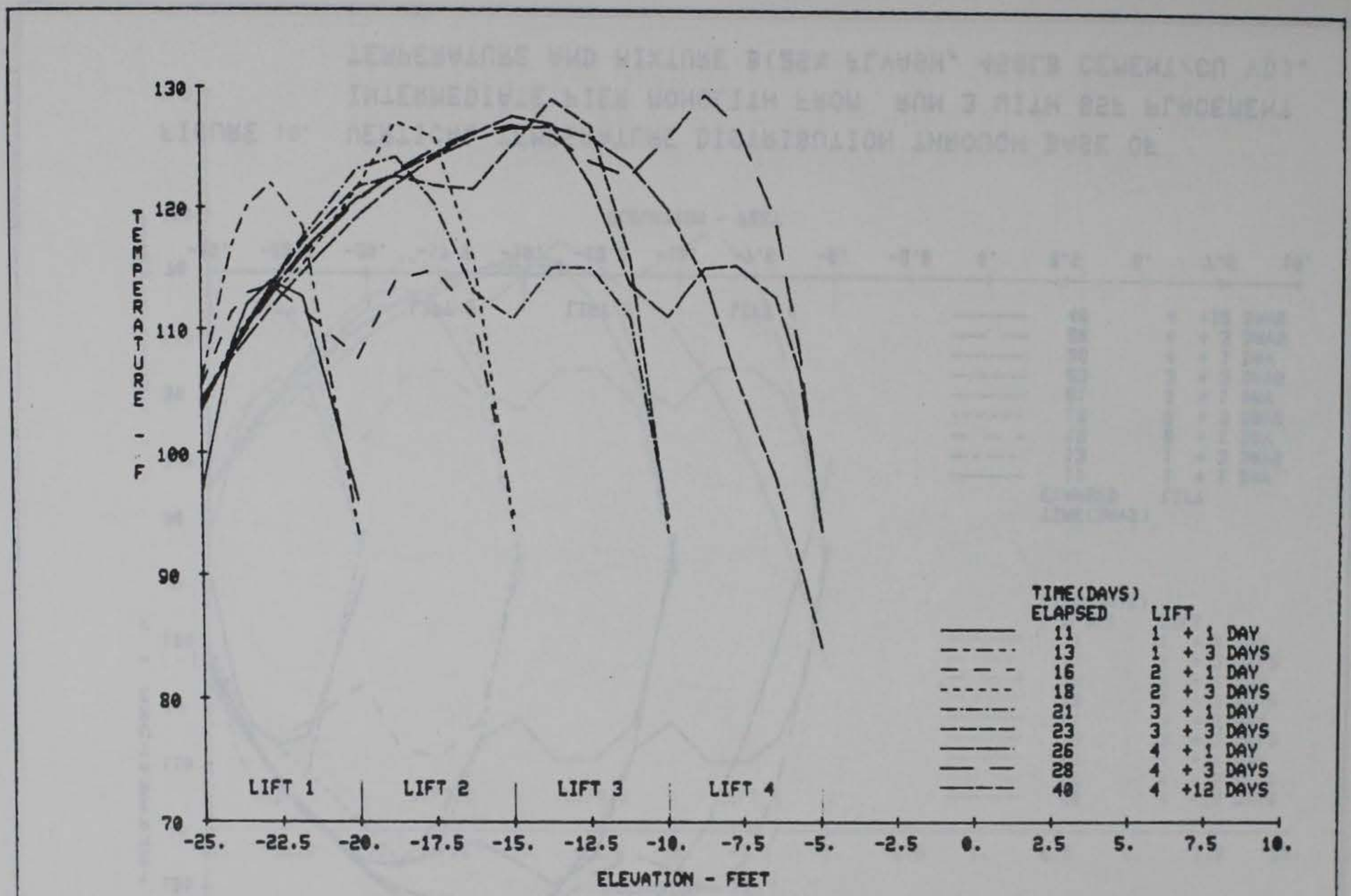

FIGURE 9. VERTICAL TEMPERATURE DISTRIBUTION THROUGH BASE OF INTERMEDIATE PIER MONOLITH FROM RUN 1 WITH 85F PLACEMENT TEMPERATURE AND MIXTURE A(NO FLYASH, 450LB CEMENT/CU YD).

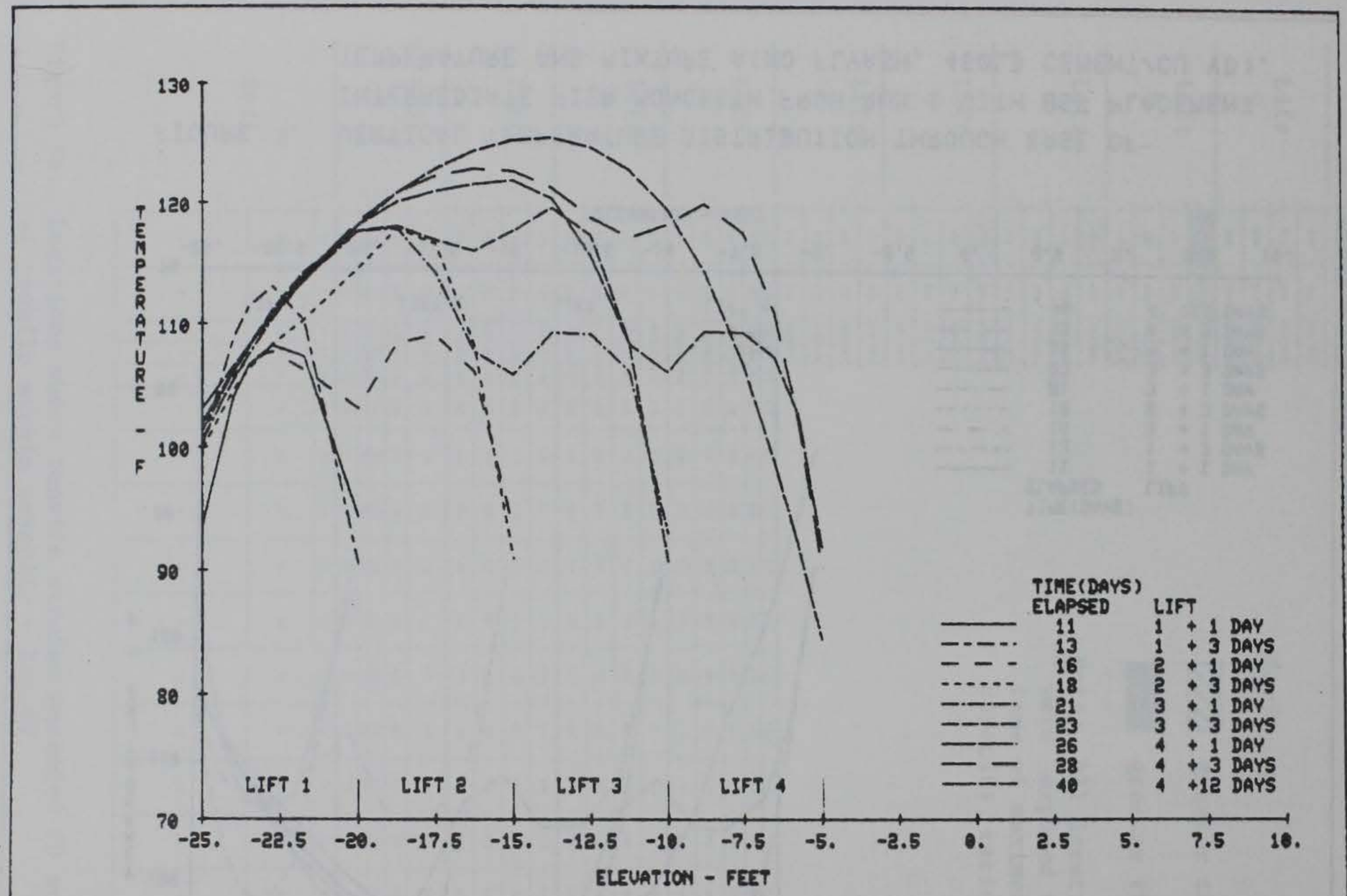

FIGURE 10. VERTICAL TEMPERATURE DISTRIBUTION THROUGH BASE OF INTERMEDIATE PIER MONOLITH FROM RUN 3 WITH 85F PLACEMENT TEMPERATURE AND MIXTURE B(25% FLYASH, 450LB CEMENT/CU YD).

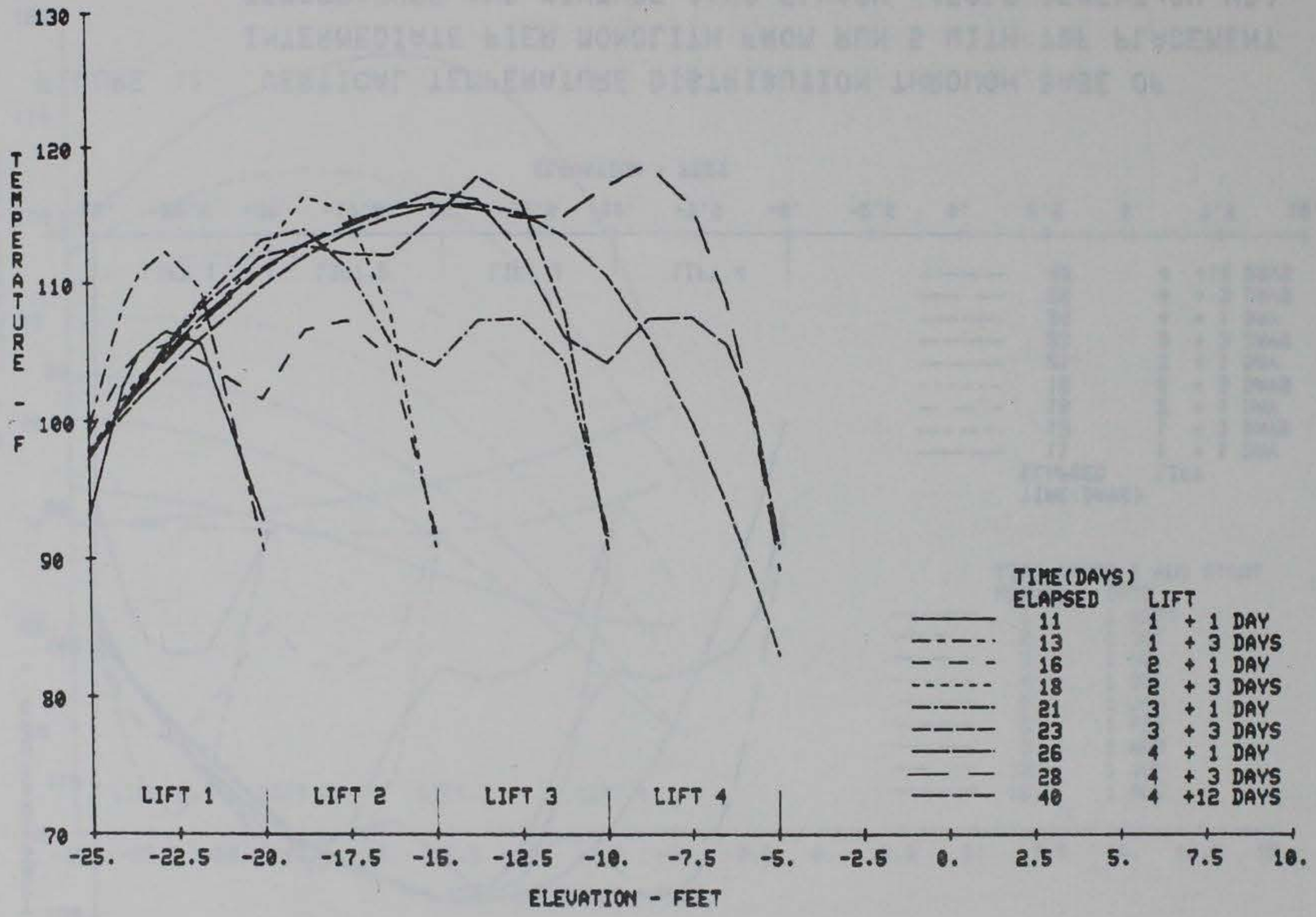

FIGURE 11. VERTICAL TEMPERATURE DISTRIBUTION THROUGH BASE OF INTERMEDIATE PIER MONOLITH FROM RUN 4 WITH 85F PLACEMENT TEMPERATURE AND MIXTURE AM(NO FLYASH, 340LB CEMENT/CU YD).

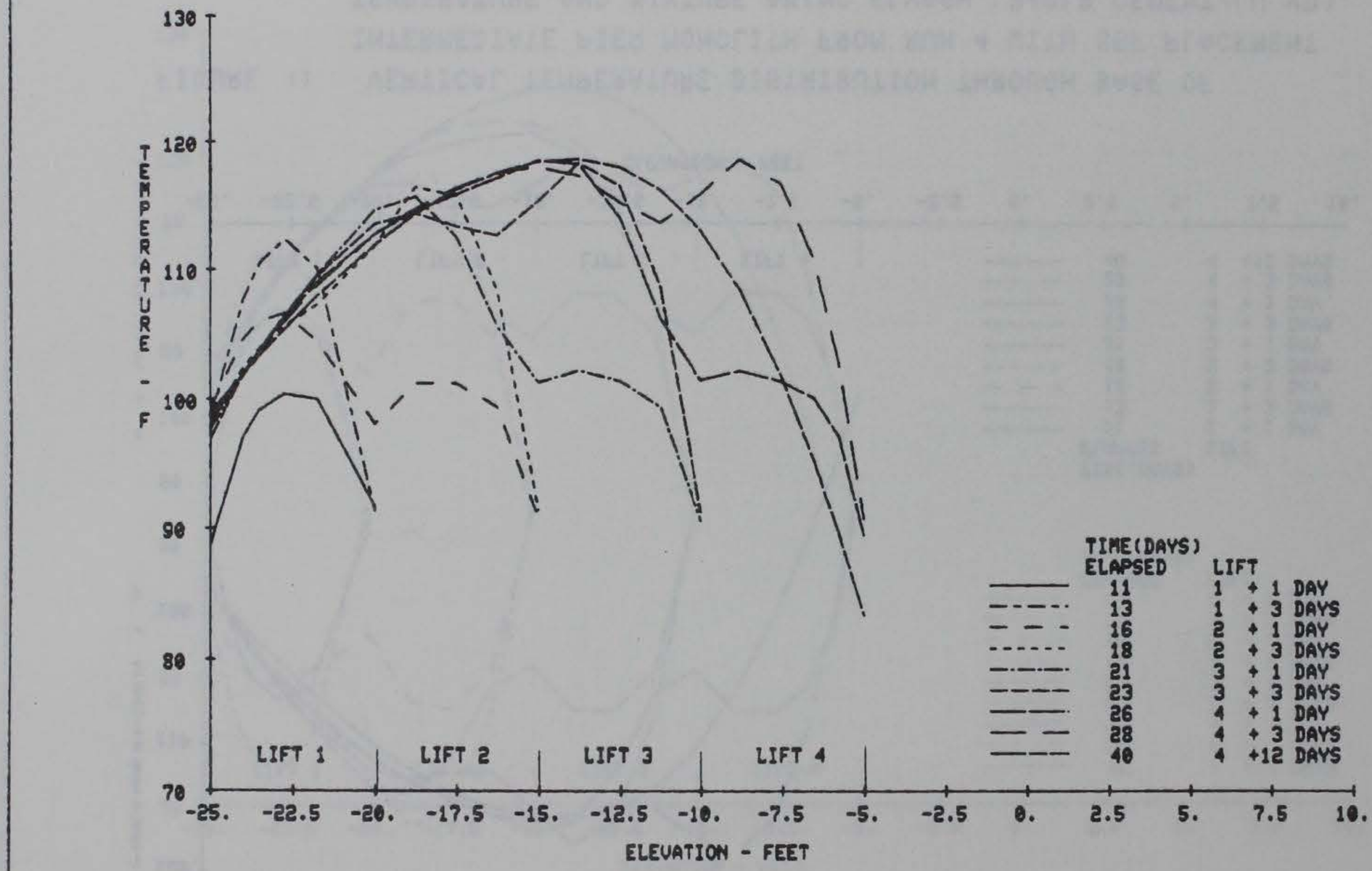

FIGURE 12. VERTICAL TEMPERATURE DISTRIBUTION THROUGH BASE OF INTERMEDIATE PIER MONOLITH FROM RUN 5 WITH 70F PLACEMENT TEMPERATURE AND MIXTURE A(NO FLYASH, 450LB CEMENT/CU YD).

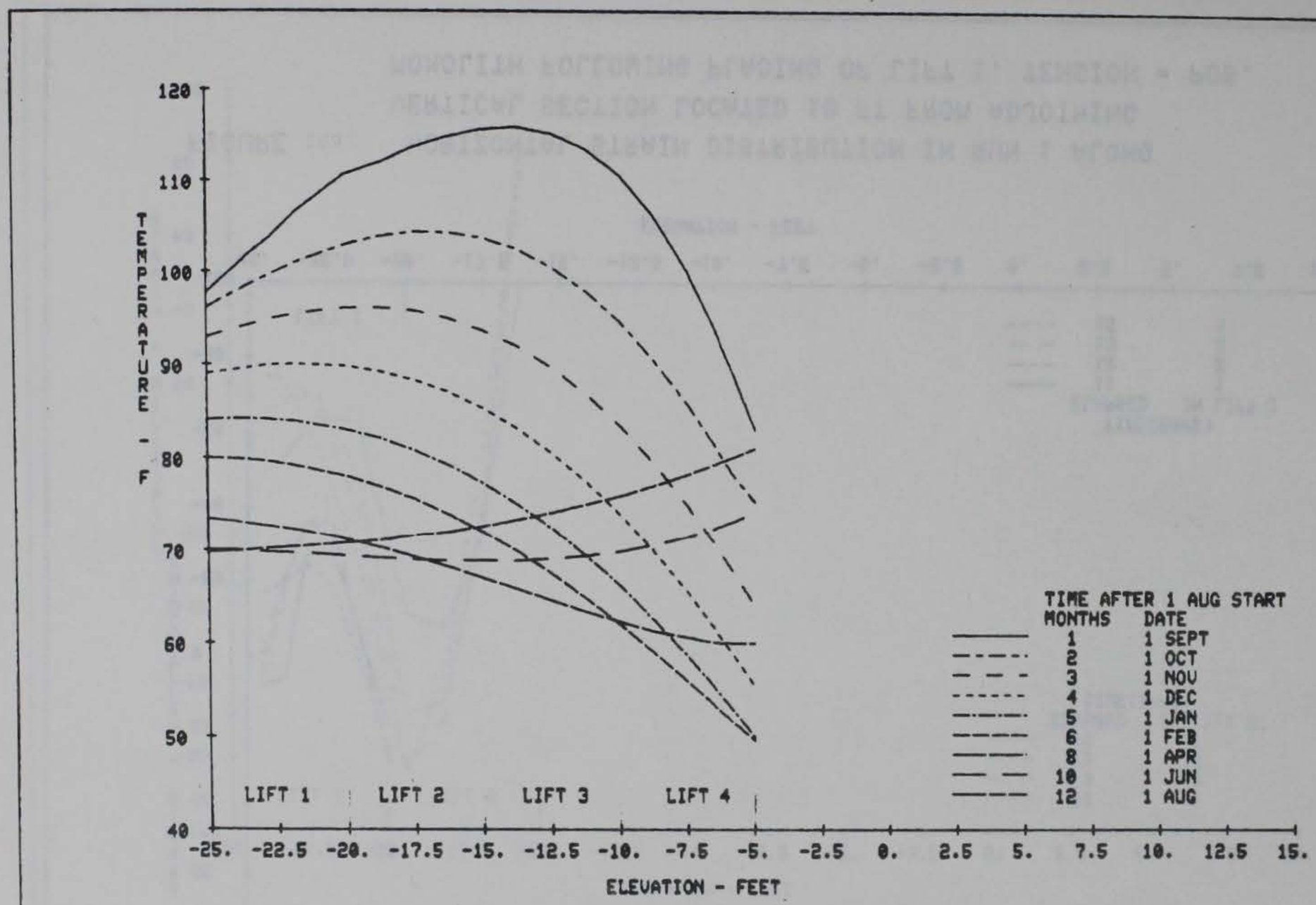

FIGURE 13. VERTICAL TEMPERATURE DISTRIBUTION FOR 1ST YEAR IN BASE OF INTERMEDIATE PIER MONOLITH FROM RUN 4 WITH 85F PLACEMENT TEMPERATURE AND MIXTURE A(NO FLYASH, 340LB CEMENT/CU YD).

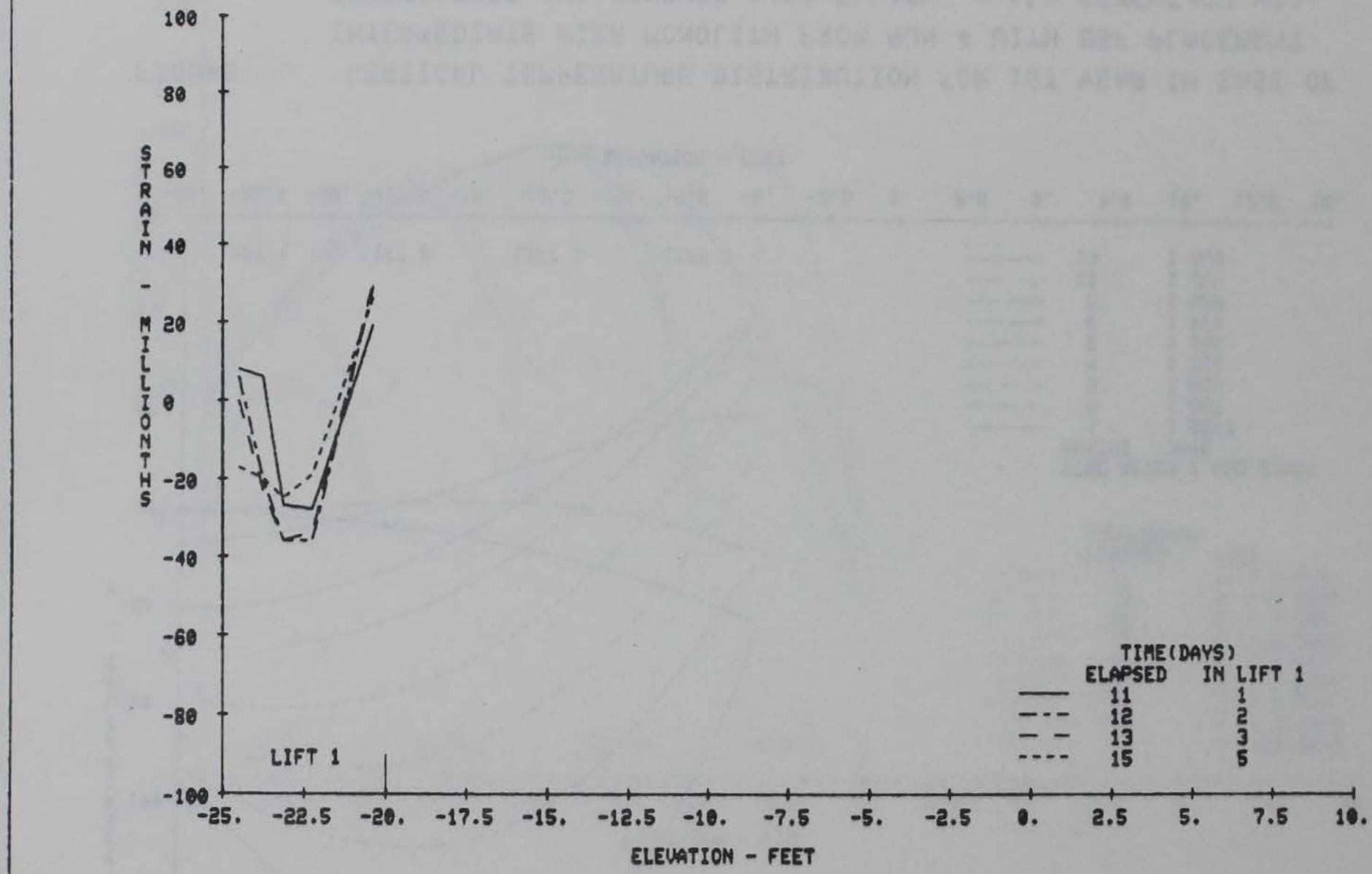

FIGURE 14a. HORIZONTAL STRAIN DISTRIBUTION IN RUN 1 ALONG VERTICAL SECTION LOCATED 10 FT FROM ADJOINING MONOLITH FOLLOWING PLACING OF LIFT 1. TENSION = POS.

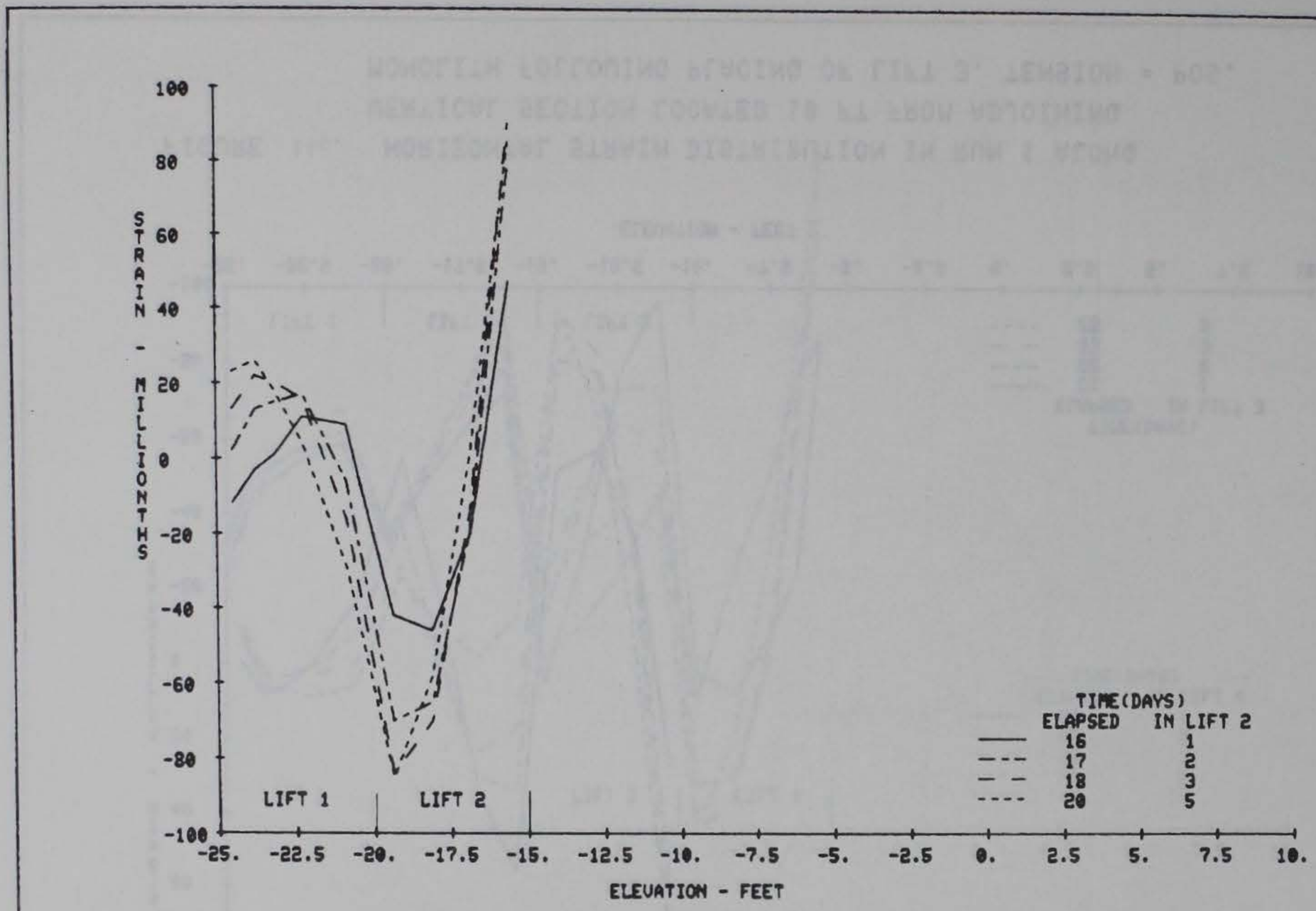

FIGURE 14b. HORIZONTAL STRAIN DISTRIBUTION IN RUN 1 ALONG VERTICAL SECTION LOCATED 10 FT FROM ADJOINING MONOLITH FOLLOWING PLACING OF LIFT 2. TENSION = POS.

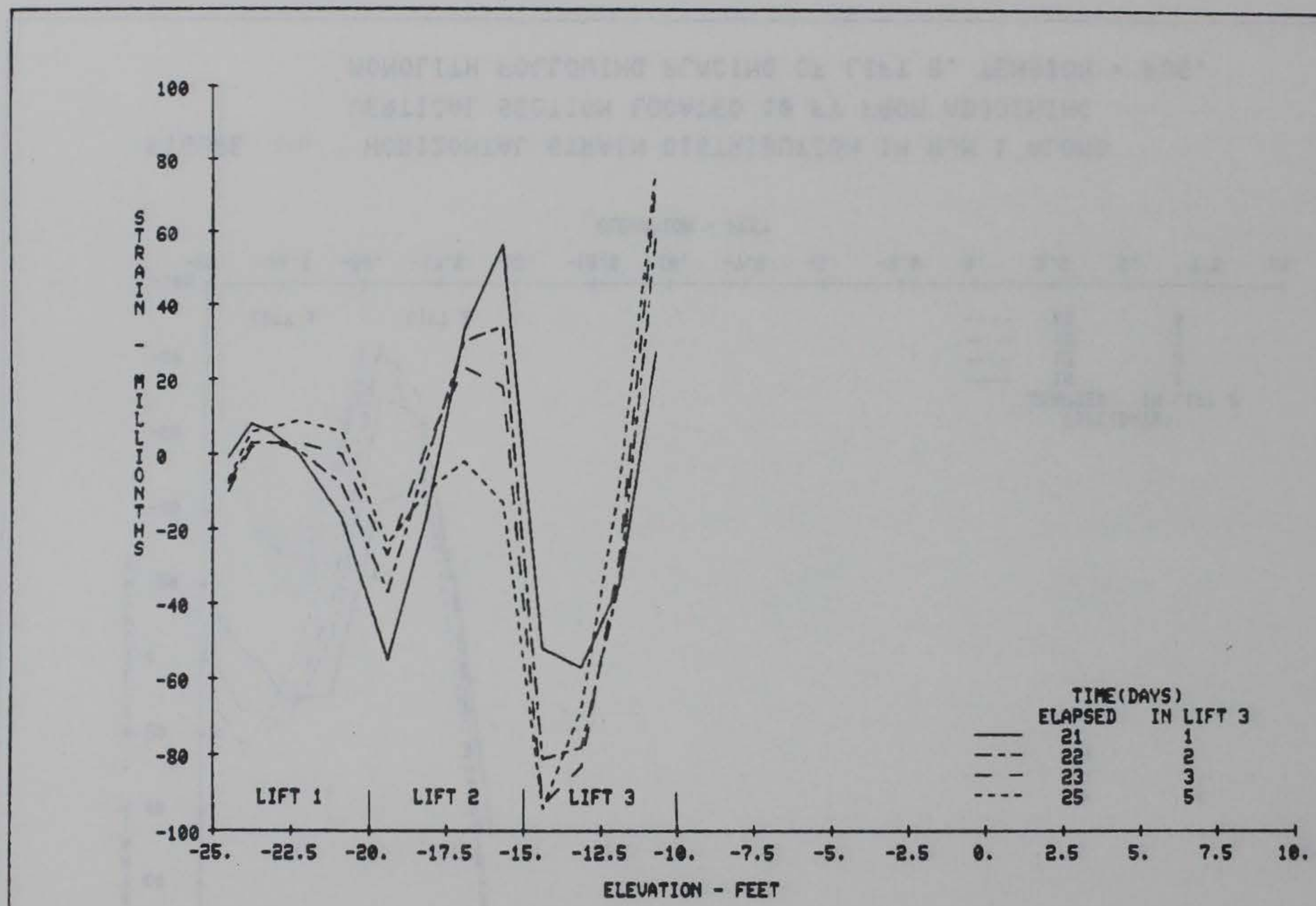

FIGURE 14c. HORIZONTAL STRAIN DISTRIBUTION IN RUN 1 ALONG VERTICAL SECTION LOCATED 10 FT FROM ADJOINING MONOLITH FOLLOWING PLACING OF LIFT 3. TENSION = POS.

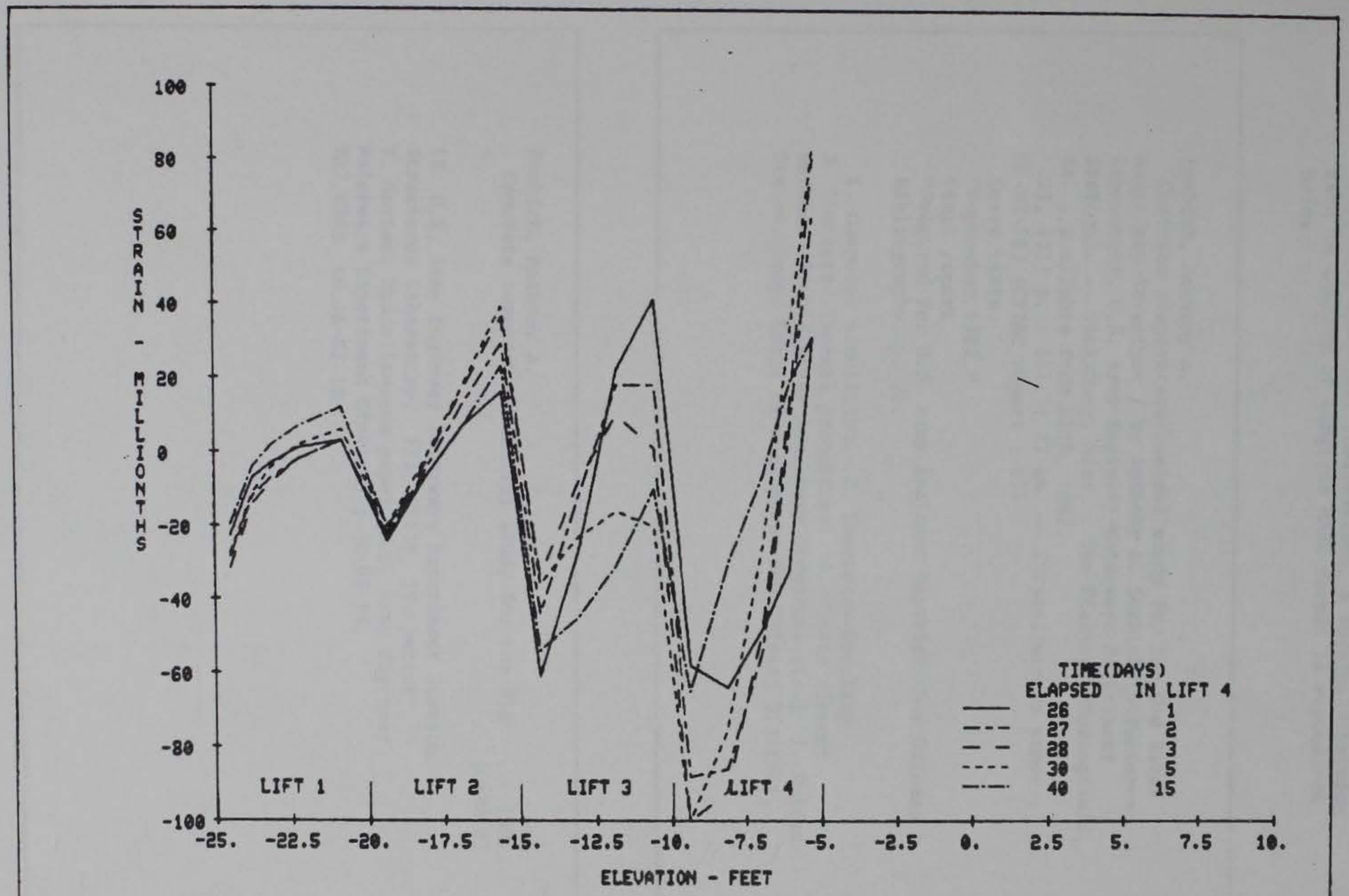

FIGURE 14d. HORIZONTAL STRAIN DISTRIBUTION IN RUN 1 ALONG VERTICAL SECTION LOCATED 10 FT FROM ADJOINING MONOLITH FOLLOWING PLACING OF LIFT 4. TENSION = POS.