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AN IBM-650 PROGRAM FOR THE COMPUTATION OF THERMAL GRADIENTS IN MASS CONCRETE STRUCTURES

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Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

April 1960

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TECHNICAL REPORT NO. 6-540

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U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

ARMY-MRC VICKSBURG MISS

PREFACE

In Civil Works engineering design studies consideration is always given to the possible, undesirable effects of the thermal gradients which may develop in mass-concrete structures during construction. Paragraph 5-03 of EM 1110-2-2000, Standard Practice for Concrete, includes reference to two analytical methods, the Carlson method and the Schmidt method, which may be used to compute temperature changes in concrete.

The investigation leading to the preparation of the computer program described in this report was authorized by letter from the Office, Chief of Engineers, dated 21 March 1958, subject "FY 1958 Civil Works Investigations - Assignment of CW Item 906." The work was accomplished as a joint project of the Concrete Division, under the supervision of Messrs. Thomas B. Kennedy, Bryant Mather, and E. E. McCoy, and the Technical Services Division, under the supervision of Messrs. C. B. Patterson and D. L. Neumann. This report was prepared by Messrs. McCoy and Neumann. Pvt. Stephen W. Closs, Jr., assisted during the developmental stages of this work and provided several routines which are included in the final program.

Col. Edmund H. Lang, CE, was Director of the Waterways Experiment Station during this investigation and preparation of this report. Mr. J. B. Tiffany was Technical Director.

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SUMMARY

A computer program for the computation of the unsteady state temperatures that develop during the construction of a concrete dam in layers (lifts) is described. Information pertaining to the following ambient and structural conditions and thermal properties is necessary for a computation: ambient air temperature and foundation temperature, concrete temperature at time of placement, lift thickness, number of days between lifts, and adiabatic temperature rise and thermal diffusivity of the concrete. The computation may be continued for fifty lifts.

The computation is based on a numerical procedure for the solution of the heat flow equation for one dimension. The space interval is one-quarter thickness of a lift, and the time interval is one-quarter day. The program is written for the basic IBM-650 computer with a 2000-word drum.

Examples are given to illustrate the types of problems for which the program is suitable. In one example the maximum temperature for 5-day placement of lifts was 6 degrees less than that for 3-day placement, and the maximum temperature for 7-day placement was 5 degrees less than that for 5-day placement. In another example the advantage of use of refrigerated concrete is illustrated. The maximum temperature computed in this example was only 4 degrees higher than the initial foundation temperature.

AN IBM-650 PROGRAM FOR THE COMPUTATION OF THERMAL GRADIENTS IN MASS CONCRETE STRUCTURES

PART I: INTRODUCTION

The Problem

1. Extensive studies of the effects of temperature changes in a dam have seldom been undertaken because to compute the temperatures manually entails so much labor, and the chance of error is so great, that a thorough study by manual computation is impracticable. Also, since comparative data are desired from such studies, it is advantageous to investigate as many conditions as may have an important effect on the temperatures in a dam, but the work is multiplied by each set of conditions that is investigated. Although the problem[6*] of adverse thermal behavior has increased over the past two or three decades, principally because of increased sizes of dams, a thorough study of all the important placement conditions which could affect the temperatures in a dam has never been made for even a single project. In contrast, on completion of development of the computer program described herein it was possible to undertake studies for a dam[5] involving 16 different combinations of concrete-placement scheduling, climatological factors, placement temperature of the concrete, and heat liberation of different types of cement, at a cost estimated to be less than one-tenth that of a manual computation.

Theory and Method

2. The computation of unsteady state temperatures in a dam is most conveniently resolved into the problem of computing temperatures at a sufficiently large number of points and at sufficiently rapid intervals to yield the desired accuracy. Any method of computing the temperature at a point in a solid material or, better, the average temperature of a small unit volume inclosing the point, must take into consideration inflow of

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* Raised numbers refer to References at the end of this report.

heat to the point, outflow of heat from the point, and the net generation of heat due to chemical or physical processes active in the material at the point. Two methods have been extensively used during the past three decades for the computation of temperatures in a structure. They are the Schmidt[4] method, which has been widely applied to problems involving various structures and shapes, and the Carlson[1] method, which was developed specifically for concrete walls and dams. The latter method was used for the program described in this report. This method is "essentially a step-by-step integration,"[3] or convenient "step method"[2] for the numerical solution of the heat-flow equation for one dimension with added term for heat generation within the concrete. Analyses in one, two, or three dimensions can be made,* although the procedure for only one dimension is given in the paper by Carlson.

3. The temperatures of primary interest in a dam are in the lower lifts. Because of the thickness of the dam at the elevations of these lifts, temperatures in them can be effectively controlled by variation of construction practices. Since the thick lifts are relatively self-insulated, lateral heat flow may be considered negligible, and a one-dimension analysis is, therefore, sufficient. The Carlson method for one dimension (the vertical), exactly as described in reference 1, was used in the development of the computer program.

Thermal Properties of Concrete and Other Required Data

4. Computer personnel must be furnished the necessary information pertaining to each computation. This information is normally specified by or supplied by an engineer who is familiar with construction practices and with the determination of thermal properties of concrete. The following conditions define a problem:

a. Ambient temperature. A different value of ambient air temperature T_a may be given for each period of time between lifts (see d on the following page) but not for a shorter period of time. A constant value may be used throughout.

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* See reference 3, author's closure.

b. Concrete temperature. The temperature of the concrete T_c at the time of placement must be given. It may be any value either colder or warmer or equal to the ambient air temperature.

c. Lift thickness. The program can handle any reasonable lift thickness (4X); however, the thickness must be held constant throughout a computation. The lift thickness determines the computational space interval (X) which is one-quarter of a lift thickness for a given computation.

d. Period of time between lifts. The number of days (in whole days) between lifts must be given. The number may be varied to allow for "irregular" placement scheduling, or may be constant. In either case the schedule should represent insofar as possible a realistic placing schedule. (The time interval T used by the computer is the quarter-day and is not affected by the time interval between lifts; but the number of quarter-days M is four times the number of days between lifts. M should be furnished computer personnel.)

e. Adiabatic temperature rise. Adiabatic temperature rise data $\Delta\theta$ are obtained in advance and preferably from laboratory tests of the concrete mixture to be used for the specific job, but may be calculated from a knowledge of heat of hydration of the cement, and quantities and thermal properties of the constituents of the concrete. A separate value is needed for each quarter-day. The computer program provides for 30 days (120 quarter-days) of temperature-rise data. The increment for each quarter-day ($\Delta\theta$) rather than the cumulative rise at the end of each quarter-day is needed.

f. Thermal diffusivity. The value of the thermal diffusivity α is determined from laboratory tests of the concrete, and is assumed to be the same for the rock foundation.

g. Foundation temperature. The foundation-rock temperature (T_R) must be specified, but may be assumed to be equal to the air temperature of the first ambient period.

5. The space interval X , the time interval T , and the thermal diffusivity α are combined into the single dimensionless constant S for use by the computer. Units must be commensurate in the relation of these variables, given by the formula $S = X^2/(\alpha T)$. This quantity (S), and not its components, should be furnished computer personnel. Since T has only one value (0.25 day), $S = 4X^2/\alpha$. Though not likely to occur so in the computation for a dam, S must not be less than unity. The $\Delta\theta$ data are given in a manner similar to the following, but more conveniently in tabular form: 1st quarter-day, 6.2 F; 2d quarter-day, 8.5 F; 3d quarter-day, 4.5 F; 4th quarter-day, 3.4 F;...; 119th quarter-day, 0.1 F; 120th

quarter-day, 0.0 F. Data for less than 120 quarter-days may be given, in which case zeros are used by the computer for the remaining periods.

6. The data required for computer solution of a problem (see paragraph 5 with regard to S) are, therefore, in summary:

a. Ambient (air) temperature (T_a), to hundredths of a degree F.

b. Concrete temperature (T_c), to hundredths of a degree F.

c. Lift thickness (4X), feet to hundredths.

d. Period of time between placement of lifts (M/4), days.

e. Adiabatic temperature rise ($\Delta\theta$), to tenths.

f. Thermal diffusivity (α), square feet per day.

g. Foundation-rock temperature (T_R), to hundredths of a degree F.

Accuracy to hundredths is not required, though all data may be submitted to the accuracy shown above. Computations within the computer are performed to thousandths, to prevent cumulative error which might occur in isolated phases of the computations, but the computer rounds to tenths before printing computed temperature.

PART II: COMPUTER PROGRAM

7. The purpose of the program is to compute temperatures that are expected to be present in a dam during construction for each set of given conditions, and thus to provide a means of investigating, prior to construction, the possible effects of various construction practices on temperature. Temperatures are important because of stresses associated with steep temperature gradients.

The Problem and Method of Solution

8. The problem was to write a program for solution of the heat conduction equation for one dimension modified by the addition of a term for heat generation caused by chemical action of the cement during hydration. As mentioned earlier, the analysis of the problem and method of solution were described by Carlson,[1] and will not be discussed further herein. Parameters are fully discussed in Part I and again with illustrations of their use in Part III, where the accuracy of the method also is discussed.

Description of Equipment

9. The program is written for a basic IBM-650 computer and utilizes a standard utility (8-word) IBM-533 panel. It is computer-optimized by the Symbolic Optimum Assembly Program (SOAP) and operates in fixed point.

Input-Output Data Format

10. The format for the input data and of the output (answer) listing is detailed below, and the specific card form layout is given in the 8-word card form, fig. 1.

Input Data Format

Setup Card (One Card)

Word 1 - Indent - This word may contain any numeric information for identification.

Word 2 - T_R - Temperature of the foundation rock is given.

Word 3 - S - The value of "S" is computed from $X^2/(\alpha T)$ and given herein.

Word 4 - This word gives the value of M when the concrete placing schedule is <u>constant.</u> "M" is the number of quarter-day intervals between lifts. If the placing schedule is variable place zeros in this word.

$\Delta\theta$ Table (1-120 Card)

Words 1, 7, and 8 - $\Delta\theta$ table routine (same for all cards).

Word 3 - Quarter-day.

Word 4 - Heat rise value $\Delta\theta$ at this time.

Lift Cards (1-50 Card)

Word 1 - "This lift number" may vary from one to fifty, and is the identification for each lift to be placed.

Word 2 - Placing temperature of the concrete for this lift.

Word 3 - Air temperature for the period of exposure of this lift.

Word 4 - "M" value when the placement schedule is <u>varying.</u> Word 4 of setup card must be zeros. For constant placement leave this word blank, that is, when word 4 of setup card has "M" value in it.

Output Data Format

Identification Card

Word 1 - The identification word of the input data is given herein.

Word 8 - This card is identified for sorting with a zero in column 80.

Detail Temperature Card

Word 1 - The number of the top lift in place.

Word 2 - The number of this lift for which the following temperatures are given.

Word 3 - Temperature in upper quarter of lift at this time.

Word 4 - Temperature of middle of lift at this time.

Word 5 - Temperature of lower quarter of lift at this time.

Word 6 - Temperature at bottom of lift at this time.

Word 7 - Time of placement of this lift in days (quarter-day increments).

Word 8 - This card is identified for sorting with a 1 in column 80. Columns 71-75 have a card count.

Maximum Temperature Card (One card punched each time the maximum temperature computed in the quarter-day interval exceeds the previous maximum.)

Word 1 - "This lift number" in which maximum temperature occurred during the quarter-day interval.

Word 2 - Time, in days, at which maximum temperature occurred.

Word 3 - The maximum temperature that occurred at this time and lift.

Word 8 - This card is identified for sorting with a 4 in column [illegible].

EIGHT-WORD CARD FORM

PROGRAM NO 1036D

TITLE Thermal Gradients in Mass Concrete Structures

SUBMITTED BY

PAGE ____ OF ____

DATE ____

WORD 1			WORD 2			WORD 3			WORD 4			WORD 5			WORD 6			WORD 7			WORD 8		
1-10			11-20			21-30			31-40			41-50			51-60			61-70			71-80		
1-2	3-6	7-10	1-2	3-6	7-10	1-2	3-6	7-10	1-2	3-6	7-10	1-2	3-6	7-10	1-2	3-6	7-10	1-2	3-6	7-10	1-2	3-6	7-10
OP	D	I	OP	D	I	OP	D	I	OP	D	I	OP	D	I	OP	D	I	OP	D	I	OP	D	I
	Input Format																						
				Setup Card																			
	Ident			TR			S		M or Zeros														
00	1036	0000	00	0000	XX.XX	00	0000	XX.XXXX	00	0000	00XX												
	Delta Theta Table						Quarter-day				Heat Rise												
00	1954	1957				20	0XXX	8000	00	0000	XXX.X							19	0202	1958	31	0002	1953
				Lift Cards																			
	TLN			TC			TA		M or Blank														
00	0000	00XX	00	0000	XX.XX	00	0000	XX.XX	00	0000	00XX												
	Output Format																						
	Detail Card																						
	Top Lift			This Lift			Temp 1			Temp 2			Temp 3			Temp 4			Time (Days)			Card Count	
00	0000	00XX	00	0000	00XX	00	0000	0XX.X	00	0000	0XX.X	00	0000	0XX.X	00	0000	0XX.X	00	000X	XX.XX	XX	XXX0	00CX
	Max Temp Card																						
	TLN	Max		Time (Days)			Temp Max																
00	0000	00XX	00	0000	XX.XX	00	0000	0XX.X															

WES FORM NO 1013
NOVEMBER 1968

Fig. 1

Operating Instructions

11. Operating instructions for the program are outlined below:

Program: THERMAL GRADIENTS IN MASS CONCRETE STRUCTURES - 1036D

IBM-650 Console

Storage entry	70	1951	3000(+) (normal)
	70	1951	990n(-) (alternate punch)
Programmed	Stop		
Control	Run		
Display	Program Register		
Overflow	Stop		
Error	Stop		

Card Input to IBM-533

Program deck (7 per card)

Transfer card to 0200

Setup data card (1 card)

$\Delta\theta$ Table (1-120 cards)

Transfer card to 0201

Lift data cards (1-50 cards)

Start Procedure

New Problem - Load program deck

Trouble stop - Check for error stop number in instruction address of program register and compare this number against listing of error stops for cause and remedial action (page 9).

IBM-533 Control Panel - Standard Utility (8-word)

Tabulating machine control panel - Standard Utility (8-word)

Special operating instructions - Sort output cards on column 80, list 0, 1 and 4 pockets separately.

Error stops

Error No.	Instruction Address	Cause	Action
ERR 0	9000	Transfer to location 0000. Possible only with improper program modification or failure of 650 to read program card.	Operator reload program deck, if same stop persists dump drum and return to programmer for action
ERR 1	9001	M is not defined. Check setup card or lift card.	Return to initiating office for correction.
ERR 2	9002	Address of T_4 exceeds storage in rock. Heat flows into rock to a depth equal 50 lifts of dam height.	Dump drum and return to programmer for action.
ERR 3	9003	TLN exceeds TOPL. Possible only with machine error or improper program modification	Dump drum and return to programmer for action.
ERR 4	9004	I exceeds M. Possible only with machine error or improper program modification.	Dump drum and return to programmer for action.
ERR 5	9005	First lift card read by program is not first lift card.	Operator check sequence of lift cards. Place cards in proper sequence and transfer to 0259 for Read.
ERR 6	9006	Console switches improperly set up for alternate punch routine.	Operator check for sign equal minus and switches equal 70 1951 990(n).
ERR 7	9007	Lift card read is not proper card to be read.	Operator check sequence of lift cards. Reset location 0204 with value equal to next lift card to be read minus one and transfer to 0639 for Read.
ERR 8	9008	T_1 address not equal to top lift address. Possible only with machine error or improper program modification.	Dump drum and return to programmer for action.
ERR 9	9009	L address not equal to lowest lift address. Possible only with machine error or improper program modification.	Dump drum and return to programmer for action.

Note: Unless program has been modified, error stops 3, 4, 8, and 9 are not likely to occur.

Flow Diagram

12. The flow diagram for the program is shown in fig. 2. Modifications of the program to compute slightly different problems from those discussed will require use and understanding of the flow diagram.

Alternate punch routine

13. The program with normal storage entry switch settings 70 1951 3000+ will punch one detailed temperature card for each lift at each time interval. The number of output cards is then approximately equal to but slightly greater than that computed from the formula:

$$S_n = \frac{MN}{2}(N + 1)$$

Where N and M are the maximum number of lifts to be computed and the number of quarter-days between lifts, respectively.

14. The number of output cards punched may be selectively reduced by using the alternate punch routine with storage entry switch settings of 70 1951 990(n) (-). The program will then punch all maximum temperature cards, but only the selected detail temperature cards for each quarter-day computation. (n) in the switch settings indicates the number of intervals (quarter-days) for which detail temperature cards are to be punched; all intervals between these will not be punched. An example of this is given below:

Placing schedule (constant) M = 36 quarter-days between lifts (9 days).

Alternate punch routine in use with (n) set equal to 8, storage entry switch 70 1951 9908(-)

Answer cards punched out

1. Maximum temperature cards are given for all quarter-day time interval computations as they occur even though the detail temperature cards are not punched for that interval.
2. Detail temperature cards are given for the 1st, 9th, 17th, 25th, and 33d quarter-days or the 1st, 3d, 5th, 7th, and 9th days between each lift placement.

Computing time

15. The computing time of a problem is a function of the number of lifts to be computed and the number of days or quarter-days between lifts

and is also affected by the use of the alternate punch routine which reduces the computing time slightly. From the nature of the program no simple equation for calculating computing time can be given; however, running time will normally vary between 2 and 4 hours. Problems 2 and 3 of the Greers Ferry Dam Report[5] required 3.2 and 2.8 hours, respectively.

Other routines

16. A Trace routine (311 TR) and a Seven-Per-Card-Punch routine (315 P7) are included in the program for use in program modification, checking trouble stops, and computing long problems in parts. Reference is made to IBM Library File Nos. 1.4.001 and 1.2.002, respectively, for instructions in the use of these routines.

12

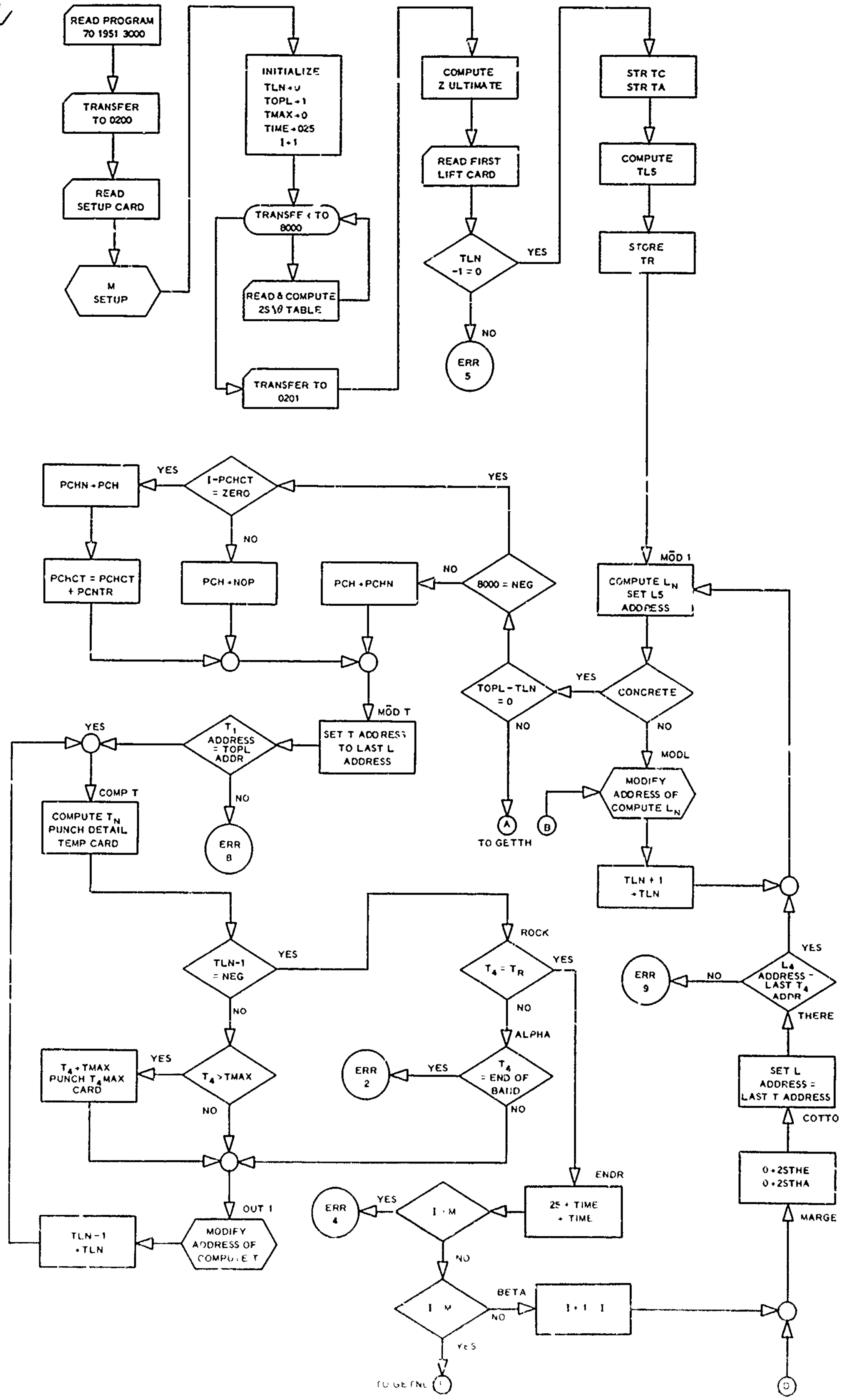

Fig. 2. Flow diagram

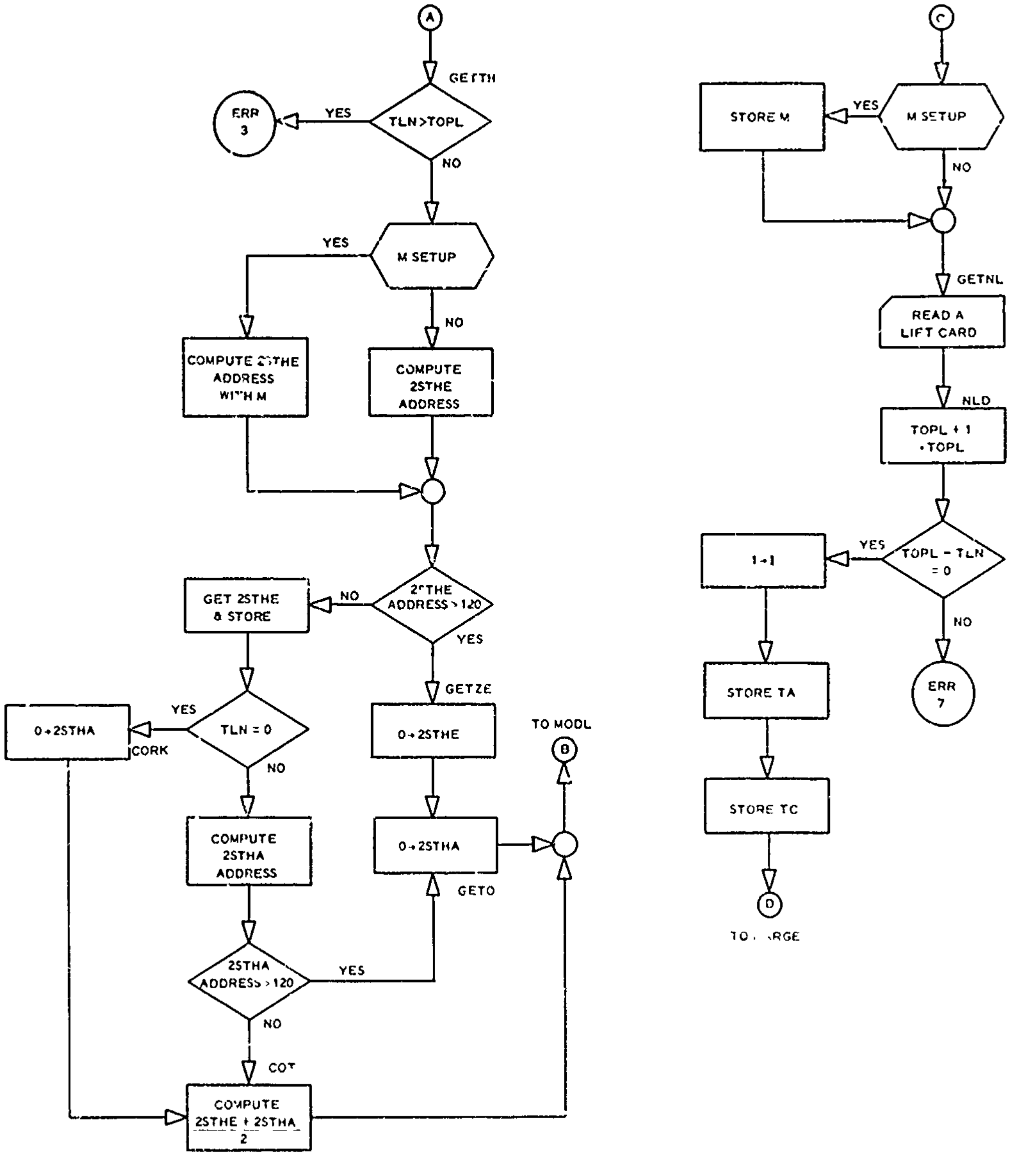

Fig. 2 (Continued)

PART III: EXAMPLES

Check Problem

17. A computation of temperatures in concrete placed in layers, with concrete placement temperature equal to the ambient temperature, was made, first for a given number of days between lifts (3 days), and then for two alternate placement schedules. The number of days between placement of lifts, constant for each computation, was the only placement condition that was varied between computations. The problem was completely defined by the following information (temperatures were shifted to zero for convenience).

Ambient temperature: 0 deg F.

Concrete temperature: 0 deg F.

Foundation-rock temperature: 0 deg F.

Lift thickness: 5 ft (hence 1.25-ft space intervals in the computation).

Time between placement of lifts: 3 days, 5 days, and 7 days.

Thermal diffusivity: 1.00 sq ft per day.

Adiabatic temperature rise:

Quarter-Days	$\Delta\theta$, F
1	6.2
2	8.5
3	4.5
4	3.4
.	.
.	.
.	.
119	0.1
120	0.0

The proper entry of these data on WES Form No. 1053 is shown in fig. 3.

18. During a computation, temperatures are printed for quarter-day intervals and for three positions in a lift and at the boundaries of lifts. The listing for the 168th quarter-day time interval of the calculation for 3-day placement is shown in table 1. This time interval corresponds to 42 days and 14 lifts. The temperatures are shown plotted in fig. 4 (page 18), where also are plotted similar data for 5-day and 7-day placement.

Table 1

Computed Temperatures

TOPL	Lift No.	T_1	T_2	T_3	T_4	Time
14	14	17.2	26.8	30.3	30.1	42.00
14	13	30.0	31.8	34.0	35.5	42.00
14	12	36.4	37.4	38.3	39.0	42.00
14	11	39.6	40.4	41.1	41.7	42.00
14	10	42.3	42.8	43.4	44.0	42.00
14	9	44.5	45.0	45.4	45.5	42.00
14	8	45.5	45.7	45.8	45.8	42.00
14	7	45.8	45.8	45.8	45.8	42.00
14	6	45.8	45.7	45.7	45.7	42.00
14	5	45.7	45.6	45.5	45.3	42.00
14	4	45.1	44.8	44.4	43.9	42.00
14	3	43.3	42.4	41.4	40.2	42.00
14	2	38.7	37.0	35.1	33.0	42.00
14	1	30.7	28.2	25.6	23.0	42.00
14	--	20.4	17.8	15.3	13.0	42.00
14	1M	10.9	9.0	7.3	5.8	42.00
14	2M	4.5	3.5	2.6	1.9	42.00
14	3M	1.4	1.0	0.7	0.4	42.00
14	4M	0.3	0.1	0.1	----	42.00

Note: TOPL is the number of the most recently placed lift of concrete. T_1 is 1/4-, T_2 is 1/2-, T_3 is 3/4-lift thickness from the top of a given lift, and T_4 is at the lower interface. Time is in days. Decimals (as above) are not actually shown in a computer listing. The data shown above correspond to those of the 3-day curve in fig. 4. The computer program output provides a complete temperature history, illustrated by the above data for one time interval, and a separate listing of maximum temperatures. For a complete interpretation of output listings, see reference 5.

THERMAL GRADIENTS IN MASS CONCRETE (1036D)
DATA CARD FORM

Submitted by *Thermal Research and Field Durability Section*	Problem No. *3*	Date *29 July 1959*

Program constants

Lift thickness (4X) *5.00* ft   Space interval (X),

Thermal diffusivity (α) *1.00* ft^2/day   1/4 Lift thickness = *1.250* ft

$S = 4X^2/\alpha =$ *6.25000*

SETUP CARD

Project	Identification 1 10	T_R 17 20	S 25 30	M 39 40
		XX.XX	XX.XXXX	XX.
Check Problem	*001036 0003*	*0000*	*62500*	*12*

LIFT DATA CARDS

Lift 9-10	T_c 17 20	T_a 27 30	M 39 40	Lift 9-10	T_c 17 20	T_a 27 30	M 39 40	Lift 9-10	T_c 17 20	T_a 27 30	M 39 40
	XX.XX	XX.XX	XX.								
01	*0000*	*0000*		20				39			
02	*0000*	*0000*		21				40			
03	*0000*	*0000*		22				41			
04	*(etc.)*	*0000*		23				42			
05		*(etc.)*		24				43			
06				25				44			
07				26				45			
08				27				46			
09				28				47			
10				29				48			
11				30				49			
12				31				50			
13				32							
14				33							
15				34							
16				35							
17				36							
18				37							
19				38							

Key punch operator fill unused columns of words 1-4 with zeros for standard 8-word format. 12 punch columns 10, 20, 30, and 40.

WES Form No. 1053
Revised Nov 1959

Fig. 3

HEAT RISE TABLE											
Type Cement	*Type II, 4 bags/cu. yd*										
	Δθ		Δθ		Δθ		Δθ		Δθ		Δθ
23 26	37 40	23 26	37 40	23 26	37 40	23 26	37 40	37 40	37 40	37 40	37 40
	XXX.X										
0001	*0062*	0021		0041		0061		0081		0101	
0002	*0085*	0022		0042		0062		0082		0102	
0003	*0045*	0023		0043		0063		0083		0103	
0004	*0034*	0024		0044		0064		0084		0104	
0005	*(etc.)*	0025		0045		0065		0085		0105	
0006		0026		0046		0066		0086		0106	
0007		0027		0047		0067		0087		0107	
0008		0028		0048		0068		0088		0108	
0009		0029		0049		0069		0089		0109	
0010		0030		0050		0070		0090		0110	
0011		0031		0051		0071		0091		0111	
0012		0032		0052		0072		0092		0112	
0013		0033		0053		0073		0093		0113	
0014		0034		0054		0074		0094		0114	
0015		0035		0055		0075		0095		01[illegible]	
0016		0036		0056		0076		0096		01[illegible]	
0017		0037		0057		0077		0097		0117	
0018		0038		0058		0078		0098		0118	
0019		0039		0059		0079		0099		0119	*[illegible]01*
0020		0040		0060		0080		0100		0120	*[illegible]00*

Key punch operator
Use load card format below for each card of heat rise table above.

Word 1	Word 3	Word 4	Word 7	Word 8
60 1954 1957 +	20 XXXX 8000 +	00 0000 XXXX +	19 0202 1958 +	31 0002 19[illegible]3 +

Words 2, 5, and 6 may be blank

Fig. 3 (Continued)

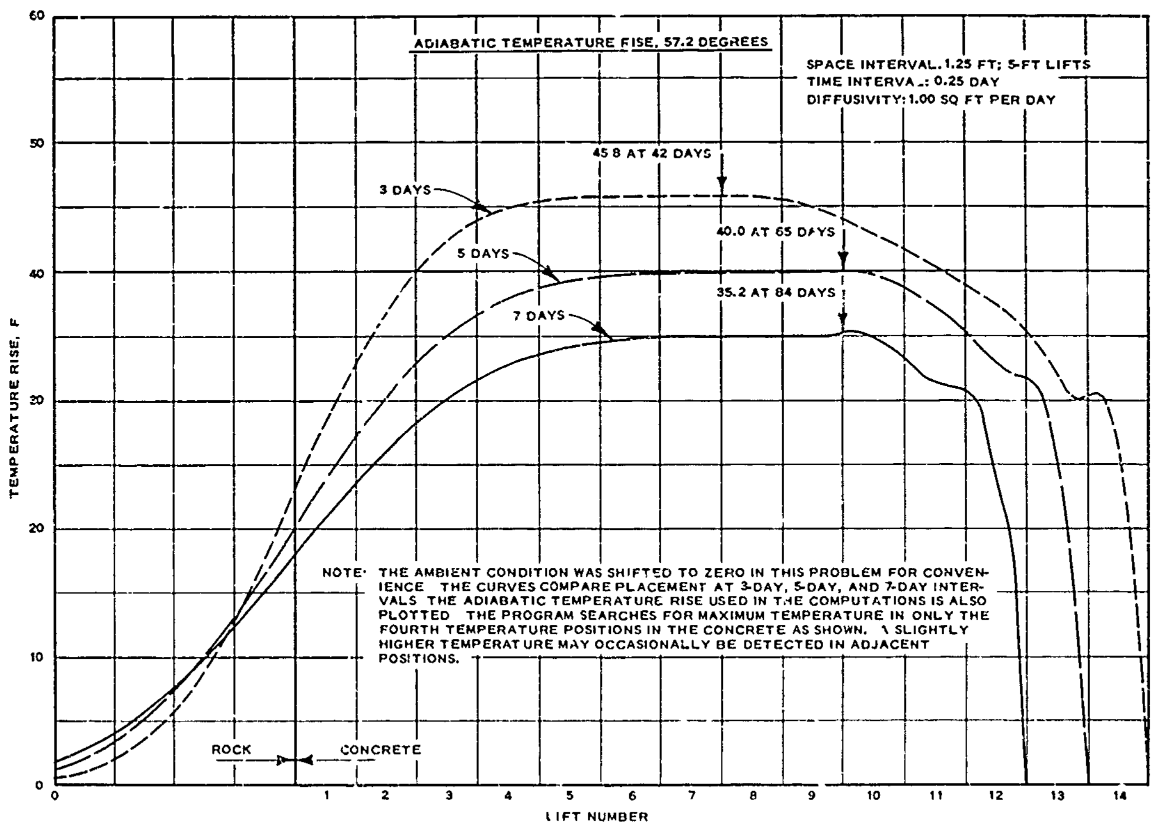

Fig. 4. Electronic computation of temperature rise of concrete placed in layers

A Construction Problem

19. Another reproduction of Form 1053, fig. 5, shows similar data for an actual problem for a construction project.[5] The ambient temperatures shown were taken from a curve that was based on data obtained from Weather Bureau records. The concrete placement temperature (T_c) was 50 F for this problem. The results of this computation are shown plotted in fig. 6. Since the maximum temperature obtained was only 4 F above the foundation temperature, even though placement of concrete continued at 9-day intervals throughout the summer, the advantage of placement at reduced temperature[7] (refrigerated concrete) is well illustrated. This problem is one of 16 such problems, representing 16 combinations of ambient conditions, construction practices, cement type, and thermal properties of concrete which were investigated to determine the influence of these combinations of variables or of the separate variables on the

THERMAL GRADIENTS IN MASS CONCRETE (1036D)
DATA CARD FORM

Submitted by *Thermal Research and Field Durability Section*	Problem No. *12*	Date *2 July 1959*

Program constants

Lift thickness (4X) *7.50* ft Space interval (X),

Thermal diffusivity (α) *1.44* ft^2/day 1/4 Lift thickness = *1.875* ft

$S = 4X^2/\alpha =$ *9.76562*

SETUP CARD

Project	Identification 1 10	T_R 17 20	S 25 30	M 39 40
		XX.XX	XX.XXXX	XX.
Greers Ferry Dam	*0010360012*	*7450*	*97656*	*36*

LIFT DATA CARDS

Lift 9-10	T_c 17 20	T_a 27 30	M 39 40	Lift 9-10	T_c 17 20	T_a 27 30	M 39 40	Lift 9-10	T_c 17 20	T_a 27 30	M 39 40
	XX.XX	XX.XX	XX.								
01	*5000*	*7450*		20		*4640*		39			
02	*5000*	*7720*		21		*4370*		40			
03	*5000*	*7850*		22		*4230*		41			
04	*(etc.)*	*7960*		23		*4150*		42			
05		*8030*		24		*4090*		43			
06		*8080*		25		*4070*		44			
07		*8100*		26		*4090*		45			
08		*8080*		27		*4130*		46			
09		*8000*		28				47			
10		*7880*		29				48			
11		*7700*		30				49			
12		*7400*		31				50			
13		*7050*		32							
14		*6770*		33							
15		*6420*		34							
16		*6050*		35							
17		*5650*		36							
18		*5260*		37							
19		*4950*		38							

Key punch operator fill unused columns of words 1-4 with zeros for standard 8-word format. 12 punch columns 10, 20, 30, and 40.

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Revised Nov 1959

Fig. 5

HEAT RISE TABLE											
Type Cement	*75-25 blend of Portland and fly ash*										
23 26	Δθ 37 40	23 26	Δθ 37 40	23 26	Δθ 37 40	23 26	Δθ 37 40	37 40	Δθ 37 40	37 40	Δθ 37 40
	XXX.X										
0001	0032	0021	0002	0041	0000	0061	0000	0081	0001	0101	0000
0002	0029	0022	0002	0042	0001	0062	0001	0082	0000	0102	0000
0003	0027	0023	0002	0043	0000	0063	0000	0083	0000	0103	0001
0004	0024	0024	0001	0044	0001	0064	0001	0084	0000	0104	0000
0005	0021	0025	0001	0045	0000	0065	0000	0085	0001	0105	0000
0006	0016	0026	0001	0046	0001	0066	0001	0086	0000	0106	0000
0007	0012	0027	0001	0047	0000	0067	0000	0087	0000	0107	0000
0008	0012	0028	0001	0048	0001	0068	0001	0088	0000	0108	0000
0009	0010	0029	0001	0049	0000	0069	0000	0089	0001	0109	0000
0010	0009	0030	0000	0050	0001	0070	0001	0090	0000	0110	0001
0011	0008	0031	0001	0051	0000	0071	0000	0091	0000	0111	0000
0012	0006	0032	0000	0052	0001	0072	0001	0092	0000	0112	0000
0013	0006	0033	0001	0053	0000	0073	0000	0093	0001	0113	0000
0014	0006	0034	0000	0054	0001	0074	0000	0094	0000	0114	0000
0015	0005	0035	0001	0055	0000	0075	0001	0095	0000	0115	0000
0016	0004	0036	0001	0056	0001	0076	0000	0096	0000	0116	0000
0017	0003	0037	0000	0057	0000	0077	0000	0097	0001	0117	0001
0018	0003	0038	0001	0058	0001	0078	0001	0098	0000	0118	0000
0019	0003	0039	0000	0059	0000	0079	0000	0099	0000	0119	0000
0020	0002	0040	0001	0060	0001	0080	0000	0100	0000	0120	0000

Key punch operator
Use load card format below for each card of heat rise table above.

Word 1	Word 3	Word 4	Word 7	Word 8
+	+	+	+	+
60 1954 1957	20 XXXX 8000	00 0000 XXXX	19 0202 1956	31 0002 1953

Words 2, 5, and 6 may be blank

Fig. 5 (Continued)

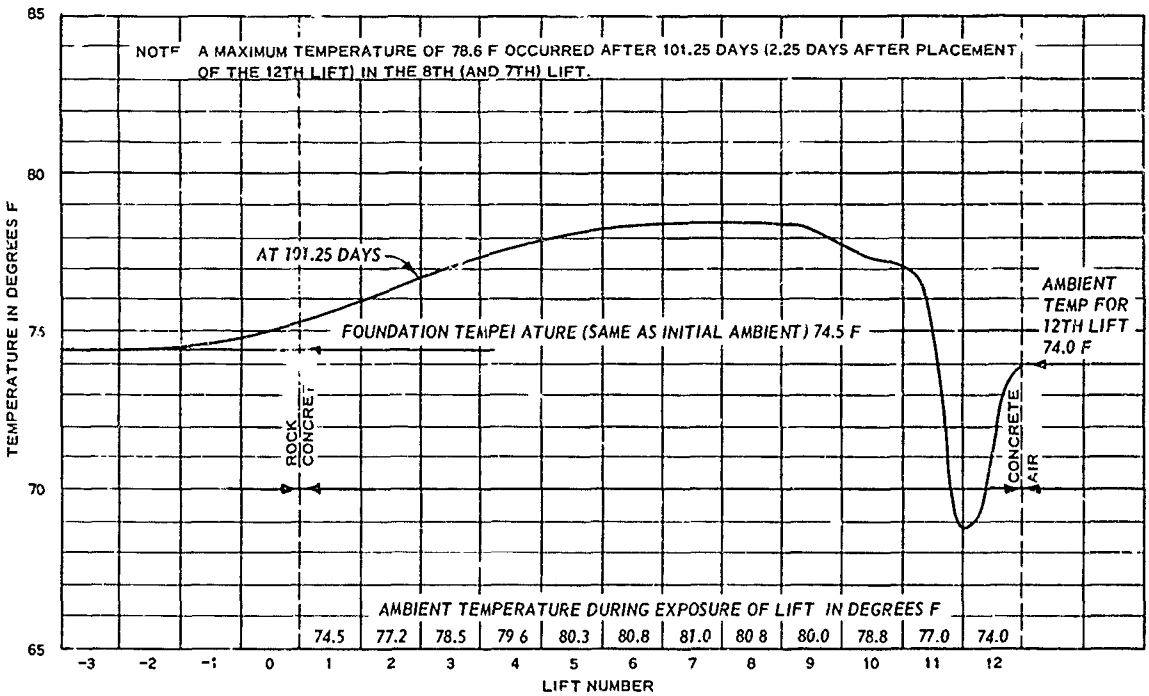

Fig. 6. A prediction for a construction project (Greers Ferry Dam, problem 12)

predicted thermal history of the concrete in Greers Ferry Dam.[5]

Accuracy

20. The accuracy indicated for each item of data in paragraph 6 is satisfactory for a computation. However, before preparations for the Greers Ferry computations (preceding paragraph) proceeded very far, it became apparent that the accuracy of certain data for repetitious use by the computer would have to be increased by several decimal places beyond the accuracy that had been indicated in brief manual computations and also in electronic computations for the "check problem" (paragraph 17). The value of S must be to five significant figures (or six if $S \geq 10.0000$), as shown in completed Forms 1053 (fig. 5) and 1013 (fig. 1), and other data should be as shown in these forms. Although it was impracticable to check a complete problem by manual computation, a satisfactory method of checking the general accuracy of results of a computation was devised and used. The procedure was as follows: a finite increment equation, based on the original differential equation,[2,3] was applied as shown in fig. 7. In this way

close approximation checks could be made at any questionable point on a temperature curve. Several discrepancies were isolated by this method, and necessary adjustments to the program were made. It is believed that sources of systematic error were reduced to a practical minimum.

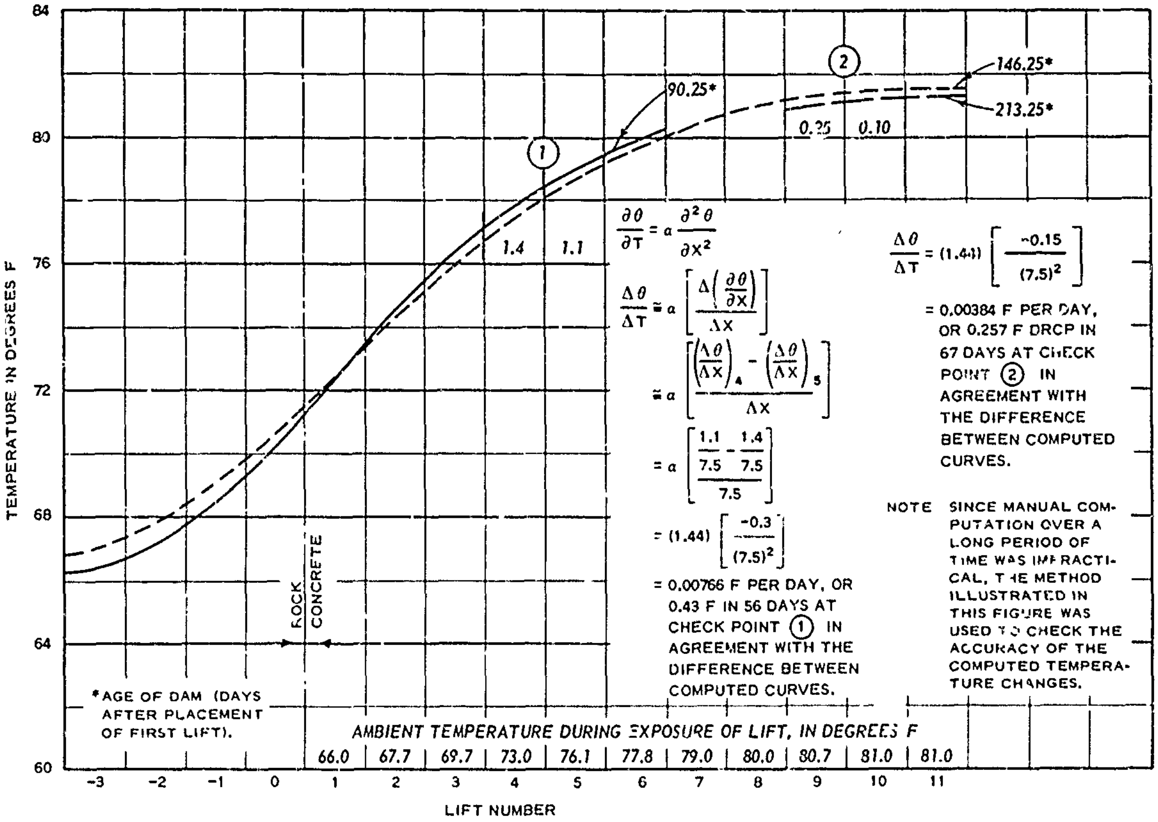

Fig. 7. Check of accuracy of computed temperature changes

Concluding Remarks

21. The cost of electronic computation of temperatures in a dam is reasonably estimated to be less than one-tenth the cost of manual computation. The cost of the electronic computation of temperatures at Greers Ferry Dam was moderate compared with the total cost of the customary thermal investigations that are made for most such projects. Many of the expensive thermal tests, such as those for thermal diffusivity and adiabatic heat rise, have been developed principally because the results of these tests are used in temperature gradient computations; however, because of the cost, manual temperature gradient computations have not been

undertaken very extensively in the past. These thermal properties tests, which hitherto have had only limited usefulness, provide the data that are needed for a complete thermal analysis, as is well illustrated by the results of the computations for Greers Ferry Dam.[5] It appears at the present time that no serious cumulative error is involved in the computer program, and that for comparative purposes temperatures predicted by means of the electronic computations are entirely valid. It is recommended that at least several basic computations be made for all major projects in the future.

REFERENCES

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3. Newmark, N. M., Discussion of Ref 1. American Concrete Institute Proceedings, vol 34, 1938, p 104-1.

4. Rawhouser, Clarence, "Cracking and temperature control of mass concrete." American Concrete Institute Proceedings, vol 41 (1945), p 305. Note: The method is discussed briefly and several other references are given.

5. U. S. Army Engineer Waterways Experiment Station, CE, Electronic Computation of Concrete Temperatures, Greers Ferry Dam, Arkansas, by E. E. McCoy. Miscellaneous Paper No. 6-342, Vicksburg, Miss., October 1959.

6. Waugh, W. R., "Temperature control problem in the construction of mass concrete dams." Western Construction (July 1950).

7. __________, "Experience in controlling temperatures and cracking in mass concrete dams." Sixth Congress on Large Dams, New York (1958).