Data Storage Transmittal - X97

01d

DATA NO. 143F-~~143F~~
~~N8110: TM 1722~~

DATA TITLE THERMAL NETWORK SOLUTIONS
FOR TRANSIENT ANALYSES

PROJ. NO.
143 F

PAR. NO.
~~143 F~~

CAT. NO.
5J

NO. OF PAGES
14

PROJECT MGR.
SHURLEY

OPS. MGR.

BACK-UP DATA: IDENTIFY TYPES INCLUDED IN PACKAGE

AS ATTACHED

BRIEF DESCRIPTION OF DATA PACKAGE

Document contents reflect:

1. "INITIATE" PROGRAMING FOR
DETERMINATION OF THERMAL TRANSIENTS
CHARACTERISTICS AS DEFINED
IN W/S 143f1d
2. SOLUTIONS AVAILABLE WITHIN
SINDA COMPUTER CODE TO PERFORM
ANALYSES AS DEFINED IN 143f 5

DATA CONTROL SIG.

DATE

4/17/72

STORAGE BOX NO.

AGC-18

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MASTER

TO: C. M. Kawashige 3 August 1971
FROM: O. J. Demuth JDM:jm N8110:TM1722
Project 143
SUBJECT: Transmittal of Report No. N8110R:71-008 Pertaining
to Project 143f, Work Statement 5
DISTRIBUTION: D. T. Buchanan, L. B. Claassen, W. L. Garrett, L. A. Kimura,
J. D. Mockenhaupt, L. A. Shurley, E. A. Thomas, W. R. Thompson,
P. P. Ventura, J. J. Williams
ENCLOSURE: (1) Evaluation of Thermal Network Solutions Available with
the SINDA Computer Code, ANSC, N8110R:71-008, 29 July 1971

A report containing a short evaluation of the SINDA execution subroutines for solution of the nozzle extension thermal network is attached as Enclosure (1). This study was conducted in support of the thermal analyses required by Project 143f, Work Statement 5.

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CLASSIFICATION CATEGORY	
<i>Unclassified</i>	
<i>O. J. Demuth</i>	<i>8-4-71</i>
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Enclosure (1)

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N8110R:71-008

ENGINEERING OPERATIONS REPORT

EVALUATION OF THERMAL NETWORK
SOLUTIONS AVAILABLE WITH THE
SINDA COMPUTER CODE

PROJECT 143f, WORK STATEMENT 5

29 JULY 1971

J. D. MOCKENHAUPT

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EVALUATION OF THERMAL NETWORK SOLUTIONS

AVAILABLE WITH THE SINDA COMPUTER CODE

I. INTRODUCTION

The SINDA-70 computer code offers a number of different solutions for transient thermal network solutions. A brief survey study was conducted to establish some criteria for selection of the best execution routine for use in the transient thermal analyses required by Work Statement 5.a for Project 143f. The selection must consider possible trade-offs between solution accuracy and computer run time, as well as the size of the computer storage required. This study was undertaken because of accuracy problems previously encountered in some preliminary transient analyses for the nozzle extension effort.

Two short sample problems were created to evaluate the various execution subroutines. The first contained a sharp discontinuity in the initial temperature distribution to provide a severe test for the finite-difference solutions. The second sample problem more closely simulated conditions that would be typical of the nozzle/nozzle-extension flange. This report presents the results obtained for these two problems with the available SINDA-70 subroutines.

II. SUMMARY/CONCLUSIONS

For the two sample problems considered, it was found that the full explicit transient solution gave accurate results for minimal computer time. It was possible, however, to reduce the computer time somewhat for the typical nozzle problem by taking large time steps with an implicit method. Relatively poor accuracy was obtained with the exponential prediction methods and hence their use is not recommended for the nozzle calculations. For steady-state problems, the network solution CINDSL, which requires the long pseudo-compute sequence (LPCS), was found to be the faster and more reliable.

From the results of this study, it is recommended that the first choice for the nozzle/nozzle-extension transient solution be the straight explicit method, CNFRWD or CNFRDL. If resulting computing times are too large, CNDUFR

could be used to increase the step size, with the maximum size determined from comparison of results with those from the explicit method.

If a few nodes have a very small value for $C/\Delta G$, CNFAST would be the best routine to use since a steady-state solution would be obtained for these nodes, and the minimum time step (CSGMIN) would then be determined by more representative nodes.

In some cases in which large temperature gradients are not expected, an implicit method may allow the use of step sizes an order of magnitude larger than required by the explicit methods. This can only be determined by direct comparison with explicit results for a short, but significant, time period before extending the solution to the desired final time value. If an implicit method is used, CNFWBK appears to be somewhat better than the full implicit CNBACK.

For problems in which large gradients may be present, it is recommended that the change in temperature during a time step be limited by the use of the control constant DTMPKA (for diffusion nodes).

For steady-state problems, CINDSL is recommended. If CINDSS must be used, some damping could be necessary by specifying values less than 1.0 for DAMPD and/or DAMPA (for diffusion and/or arithmetic nodes). These control constants determine the weighting between old and new temperature values in the iteration process, e.g.,

$$T_g = \text{DAMPD} * T_{\text{new}} + (1 - \text{DAMPD}) * T_{\text{old}}$$

where T_g is the temperature to be used as the next guess in the iteration process, T_{new} is the temperature just calculated in the current iteration step, and T_{old} is the T_g for the step just completed. Since computer time increases as the damping becomes greater, it is recommended that DAMPD and/or DAMPA be initially set at 0.5 for a specified number of steps and then increased to 1.0.

Although the results quoted from this brief study are strictly applicable only to the particular cases considered, it is felt that these cases covered a broad enough range to give a good indication of the trends expected for the nozzle/nozzle-extension solution.

III. TECHNICAL DISCUSSION

A. DESCRIPTION OF AVAILABLE EXECUTION SUBROUTINES

The two basic types of finite-difference solutions to partial differential equations are the explicit and the implicit methods. The explicit method calculates new values of the dependent variables as a function only of old values of the same variables. For example, in a thermal problem the temperature of a given node at time t depends only on surrounding node temperatures at the previous time step ($t - \Delta t$). Hence, node temperatures are calculated from the straight algebraic solution of the finite-difference equations.

The implicit method, however, utilizes the final temperature values at surrounding nodes to calculate a given node temperature. The simultaneous solution of a number of finite-difference equations, as well as an iteration process, is required to find the final node temperature. The computer time per step with the implicit method is therefore greater than with the explicit method, but a larger step size can be taken with the implicit. The maximum step size with an explicit method is limited by stability considerations, while the full implicit method is always stable (but not necessarily accurate) for any step size.

The selection of the method to be used for a given problem must consider the trade-off of the accuracy, but possible long computer run times, of the explicit method versus the shorter run times, but possible inaccuracies, of the implicit method. The results of such a trade-off will vary depending on the particular problem to be solved.

An additional factor that can be significant for a large problem is that the implicit method requires approximately 3 times the computer storage of the explicit routines.

A third general solution method available with SINDA is an exponential-prediction method, which is essentially an explicit-type of solution using an integrated exponential form of the heat conduction equations. Details are given in Reference (1). This method does not have the stability limitations of the straight explicit solution, and hence can take larger time steps.

The transient thermal network solution subroutines available with SINDA are listed in the table below.

Table I: SINDA Network Solution Subroutines

Subroutine	Solution Method	Significant Control Constants	Comments
1) CNFRWD	Explicit	DTMPCA, NLOOP, ARLXCA (for arithmetic nodes only)	Uses SPCS (short-pseudo-compute-sequence); time step calculated as $0.95 * (C/\leq G)_{\min}$.
2) CNFRDL	Explicit	Same as above	Same as above except LPCS is used.
3) CNFAST	Explicit	Same as above plus DTIMEL	Uses SPCS; minimum step size specified by DTIMEL; if $(C/\leq G)$ less than DTIMEL for any node, steady state solution used for that node.
4) CNDUFR	Explicit (DuFort-Frankel)	Same as CNFRWD plus CSGFAC	Uses SPCS; unconditionally stable; calculated time step can be increased by multiplication by CSGFAC.
5) CNBACK	Implicit	DTIMEI, NLOOP, DRLXCA and/or ARLXCA, DTMPCA	Uses LPCS; time step used specified by DTIMEI; convergence criteria by DRLXCA for diffusion nodes, ARLXCA for arithmetic nodes; maximum no. of iterations by NLOOP.
6) CNFWBK	1/2 Explicit + 1/2 Implicit (Crank-Nicholson)	Same as above	Same as above.
7) CNVARB	β Explicit + $(1-\beta)$ Implicit	Same as above	Same as above with $\beta = (C/\leq G)_{\min} / \Delta t$
8) CNEXPN	Exponential	Same as CNDUFR	Same as CNDUFR; for first step, the output time step (OUTPUT) must be specified such that $\left(\frac{\leq G}{C} \right)_{\max} * \text{OUTPUT} \leq 88.2$

Subroutine	Solution Method	Significant Control Constants	Comments
9) CNQUIK	Explicit + Exponential	Same as CNDUFR	Same as above; 1/2 CNDUFR + 1/2 CNEXP

In the above table the subroutines use either the short- or long-pseudo-compute sequence (SPCS or LPCS), which refer to method used by the SINDA pre-processor to organize and store the thermal network information. The LPCS stores more information than the SPCS and hence is more flexible in the type of iteration that can be used.

When a problem contains arithmetic nodes, even explicit solutions must include iterative techniques to calculate the effective steady-state solutions required by arithmetic nodes. Hence information such as the maximum number of iterations (NLOOP) or the convergence criteria (ARLXCA) must be specified for such cases.

The control constant DTMPCA limits the change in temperature of any diffuser node for each time step. If the calculated temperature change is greater than DTMPCA, the step size is reduced and the calculation repeated.

For unconditional stability in the explicit routines, the ratio $\sum G \Delta t / C$ must be less or equal to 1.0, where G is the conductance value of each conductor attached to a node ($G = KA / \Delta x$) and C is the node capacitance ($C = \sum V C_p$). Thus the maximum step size $(\Delta t)_{\max}$ must be equal to the minimum value of $C / \sum G$, called CSGMIN in the program.

In the exponential-prediction methods, the term $\exp(\sum G \Delta t / C)$ appears. In the first pass of the first step, the time step specified for the printout of results (OUTPUT) is used as Δt . Since OUTPUT is usually much greater than the calculating time step, the term $\sum G * \text{OUTPUT} / C$ can be much greater than 1.0. If this ratio exceeds 88.2, the run will abort in the 1108 computer since $e^{88.2}$ is the maximum value the computer can accommodate. It therefore may be necessary when using CNEXP or CNQUIK to set OUTPUT to a small value for the first few steps and then increase it to the desired magnitude.

For steady-state problems, three subroutines are available:

- 1) CINDSS, which requires SPCS;
- 2) CINDSL, which requires LPCS;
- 3) CINDSM, for radiation-dominated problems (requires LPCS).

CINDSL can utilize a better iteration technique for diffusion nodes since more information is retained with the LPCS. CINDSL also contains a convergence acceleration feature.

B. RESULTS FOR TEST CASES

To evaluate the various subroutines, two very different test cases were used.

Case A, or the "pulse test case", consisted of 101 nodes connected in a one-dimensional chain and insulated on either end. All conductor values were equal and remained constant with time. The initial temperature of the first node was specified as 100°F, with the remaining nodes starting at 0°F. For Case A1, all nodes were diffusion nodes having the same capacitance, except for the first and last nodes with one-half the capacitance of the others. In Case A2, the 50 even-numbered nodes were replaced by arithmetic nodes, and the capacitance of the remaining diffusion nodes doubled.

Case B is more representative of a typical nozzle problem. It consists of 50 internal nodes connected two-dimensionally and representing two different materials having temperature-varying properties. These nodes are connected to fluid boundary nodes at 1000°F on one side and by radiation conductors to a 0°R boundary node on the other side. The initial temperature of all internal nodes was 70°F.

Results obtained from the various SINDA subroutines for these cases are presented in Table II and Figures 1 and 2. For cases A1 and A2, analytical results are available from Reference (2) for comparison with the finite-difference calculated temperatures. The computer times listed in Table II refer only to the time required for the actual calculation and thus does not include the SINDA processing steps. The latter amounted to approximately 24 seconds for these particular cases.

All real times in Table II are non-dimensionalized by $C/\epsilon G$, the maximum Δt for stability in the explicit solutions.

T_1 in Table II is the temperature of the first node, which starts out at 100°F for Cases A1 and A2, and which is one of the more sensitive nodes in Case B, being located adjacent to the fluid boundary.

Figure 1 shows the calculated temperature decays for the first node in Case A1, and thus offers a direct comparison between analytical and finite-difference results over a significant time period. The lengthwise temperature distributions at a given time value are shown in Figure 2 for the same case.

Steady-state results listed in Table III were evaluated only for Case B, since Cases A1 and A2 were not properly posed for a steady-state solution. Steady-state results are obtained from the solution of either Laplace's or Poisson's equation, depending on whether internal sources are present, and such a solution requires that at least one temperature be specified, usually on the boundary.

The results shown in Table II and III and Figures 1 and 2 are summarized in the following statements.

1. For the same time step, implicit methods required more than twice the computer time of explicit methods.

2. For Cases A1 and A2, representative of cases which have initial or boundary conditions containing large gradients, temperatures calculated by implicit methods tended to diverge from the correct values as the time step was increased.

3. For Case B, typical of a nozzle section without any large gradients in the initial or boundary conditions, a large enough time step could be taken with implicit methods to reduce the computer time to values less than that required by explicit methods, and still maintain accuracy.

4. The Crank-Nicholson method, half implicit and half explicit, appeared to give slightly more accurate results with approximately the same computer time when compared to the fully implicit method.

5. The exponential-prediction method gave less accurate results with approximately the same computer time as explicit methods for the same time step.

6. The combination of explicit and exponential-prediction methods (CNQUIK) gave more accurate results than the straight exponential method (CNEXPN) for Case A1, but at the expense of greater computer time.

7. For Case A1, the explicit time step could be doubled if the DuFort-Frankel Method was used (CNDUFR), but not with the straight explicit (CNFAST).

8. When using CNFAST, special care should be taken to assure that the nodes given a steady-state treatment are relatively few in number and are not critical to the solution (such as node #1 in Case A). The poor results shown in Table II for Case A1 with CNFAST illustrate this effect.

9. For Case B, the explicit time step could be quadrupled with little loss in accuracy.

10. For Case A2 with alternating arithmetic nodes, it was necessary to limit the calculated temperature change in successive steps to 1.0°F for all methods.

11. The explicit method utilizing the SPCS (CNFRWD) gave the same results as the LPCS explicit method (CNFRDL) with slightly less computer time.

12. The smaller the convergence criteria (DRLXCA and/or ARLXCA), the greater the accuracy and the larger the computer time for all methods and cases.

13. For steady-state solutions, CINDSL (requiring the LPCS) appears to be far superior to CINDSS (used with the SPCS) based on accuracy and minimum computer time.

14. CINDSS required damping (weighting of old and new calculated temperatures) to reach a solution.

IV. REFERENCES

1. Gaski, J. D., Fink, L. C., and Ishimoto, T., "Systems Improved Numerical Differencing Analyzer Users Manual", TRW Systems 11027-6003-RD-00, September 1970

2. Carslaw, H. S., and Jaeger, J. C., Conduction of Heat in Solids, Second Edition, Oxford University Press, 1959

TABLE II: COMPARISON OF TRANSIENT RESULTS FROM SINDA

Case A1: Pulse Test Case with Diffusion Nodes Only
Case A2: Pulse Test Case with Diffusion and Arithmetic Nodes
Case B: Nozzle Sample Problem

$$\bar{t} = t / \left(\frac{C}{\dot{E}G} \right)_{\min}$$

Case	SINDA Subroutine	Network Solution Method	DRLXCA and/or ARLXCA (°F)	DTMPCA (°F)	$\Delta \bar{t}$	$\bar{t}_{\max}$	Computer Time (sec)	$T_1 @ \bar{t}_{\max}$ (°F)
A1	-	Analytical	-	-	-	2000	-	0.901
	CNFRDL	Explicit	0.001	-	1.0	↓	47	0.892
	CNFRDL	↓	0.001	1.0	1.0		50	0.892
	CNFRWD		0.001	-	1.0		44	0.892
	CNFRWD		0.010	-	1.0		39	0.892
	CNDUFR		0.001	-	1.0		55	0.892
	CNDUFR		0.001	-	2.0		32	0.891
	CNFAST		0.001	-	2.0		26	2.63
	CNFAST		0.001	-	4.0	↓	16	3.57
	CNBACK	Implicit	0.001	-	1.0	~1800	96	-
	CNBACK	↓	0.001	-	4.0	2000	37	1.053
	CNBACK		0.010	-	4.0	2000	28	1.130
	CNFWBK		0.001	-	1.0	~1800	96	-
	CNFWBK	↓	0.001	1.0	8.0	2000	95	0.986
	CNEXPN	Exponential	0.001	-	1.0	2000	51	1.110
	CNQUIK	Exponential/Explicit	0.001	-	1.0	2000	73	1.003
	CNQUIK	↓	0.001	-	10.0	2000	36	1.763

TABLE II: (Cont)

Case	SINDA Subroutine	Network Solution Method	DRLXCA and/or ARLXCA (°F)	DTMPCA (°F)	$\Delta \bar{t}$	$\bar{t}_{\max}$	Computer Time (sec)	$T_1 @ \bar{t}_{\max}$ (°F)
A2	-	Analytical	-	-	-	2000	-	1.802
	CNFRDL	Explicit	.001/.01	-	1.0	↓	27	.089
	CNFRDL	↓	↓	1.0	1.0	↓	32	1.767
	CNFWBK	Explicit/ Implicit	↓	-	1.0	↓	57	.990
	CNFWBK	↓	↓	-	4.0	↓	31	-1.86
	CNFWBK	↓	↓	1.0	4.0	↓	66	1.963
	CNFWBK	↓	↓	1.0	8.0	↓	68	1.924
B	CNFRDL	Explicit	.001	-	1.0	1000	42	395.9
	CNFRDL	↓	.010	-	1.0	1000	40	395.9
	CNFAST	↓	.001	-	4.0	1000	17	394.4
	CNFWBK	Explicit/ Implicit	.010	-	1.0	~ 900	91	-
	CNFWBK	↓	.010	-	4.0	1000	35	395.8
	CNFWBK	↓	.010	-	20	1000	15	395.9
	CNFWBK	↓	↓	-	100	↓	10	396.1
	CNBACK	Implicit	↓	-	20	↓	14	394.4
	CNEXPN	Exponential	↓	-	1.0	↓	42	392.2
	CNEXPN	↓	↓	-	4.0	↓	16	381.4

TABLE III: COMPARISON OF STEADY-STATE RESULTS

Case	SINDA Subroutine	DAMPA and/or DAMPD	No. of Iterations	Computer Time (sec)	Calculated T_1 (°F)
B	CINDSL	1.0	96	0:08	429.3
	CINDSS	1.0	2000*	1:18	984.6
	CINDSS	0.5	617	0:28	429.3
	CINDSS	0.5 for 100 steps 1.0 after 100	383	0:18	429.3

* Convergence not obtained

Figure 1

PULSE-TEST CASE (A1)

$T_1 (@t=0) = 100^\circ\text{F}$

$\text{DRLXCA} = 0.001$

$\text{CSGMIN} = 2.5 \times 10^{-6}$

$\bar{t} = 2000$

Figure 2