NASA CR-165,206

DOE/NASA/0138-1
NASA CR-165206

NASA-CR-165206
19810018018

Extended Development of a Sodium Hydroxide Thermal Energy Storage Module

Richard E Rice and Peter E Rowny
Comstock & Wescott, Inc

and

Barry M Cohen
Consultant

September 1980

JUL ⁇ ⁇ 1981

NOTICE

Extended Development of a Sodium Hydroxide Thermal Energy Storage Module

Richard E. Rice and Peter E Rowny
Comstock & Wescott, Inc
Cambridge, Massachusetts 02238

and

Barry M. Cohen
Newton Centre, Massachusetts 02159

September 1980

N81-26556#

FOREWORD

The program reported herein is a continuation of prior
work under Contract NAS3-20615 from the NASA Lewis
Research Center reported in NASA CR-159465 in December
1978. Both programs were carried out by the same
principal personnel. However, Barry M. Cohen, who
was a member of the Comstock & Wescott staff during
the prior program, has acted as an independent consult-
ant to Comstock & Wescott during the present program.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

SUMMARY

The objective of this work was to extend the prior work
reported in NASA CR-159465, December 1978, on the de-
velopment of a phase-change thermal storage system (TESS)
using modified anhydrous sodium hydroxide and a single,
passive, tube-intensive heat exchanger, for charging
and discharging heat at approximately 584 K by a non-
phase-change heat transfer liquid, Therminol-66.

The three parts of the present program were (1) chemical
analyses on the storage medium used in the experimental
model of the prior work, and examination of its heat
exchanger, (2) production of additional experimental
data using a different non-phase change heat transfer
fluid (Caloria HT-43) to extend the validation of a
computer model of the TESS, and (3) development of a new
computer model of a TESS containing an additional heat
exchanger for the vaporization and superheating of a
power fluid for a Rankine cycle power generator, and the
use of the model to develop a cost optimized reference
TESS design for comparison with the single heat ex-
changer TESS design.

From the results, it was concluded that during the prior
experimental work, no chemical degradation of the medium
occurred, but some physical segregation of components
was observed which had no apparent deleterious effect on
the performance of the system. Physical segregation can
be reversed by fully remelting the medium. No signifi-
cant deterioration of the heat exchanger was found.

A computer model was successfully developed which provides
for 3-way heat transfer, between each fluid and the med-
ium, and directly between the two fluids.

The reference design of the 2-heat exchanger TESS (as
compared to the single heat exchanger TESS) improved
thermal performance, a lower capital cost ($\approx 58\%$) when
credited for the cost of the external heat exchanger
which it displaces, and improved overall system opera-
ting cost.

INTRODUCTION

Background

The work reported herein is an extension of prior work under two completed contracts:

1. The development of a computer model (CM) of a phase-change thermal energy storage system (TESS) under Purchase Order No. 87-5030 from Sandia Laboratories, Livermore, California, completed in December 1976.

2. The development of a phase-change thermal storage system using modified anhydrous sodium hydroxide for solar electric power generation, under Contract NAS3-20615 from NASA Lewis Research Center, which was reported in NASA CR-159465 in December 1978.

This prior work included the design, construction, and testing of an experimental scale-model of a TESS suitable for use in mid-temperature range (approximately 580 K) solar powered electricity generating systems. The model was specifically designed for reliable scaling up to meet the requirements of the Solar Total Energy Test Facility (STETF) operated by the Sandia Laboratories at Albuquerque, New Mexico.

This was used to generate experimental data with which to verify the predictions of the CM, which was modified in several respects until acceptable agreement was obtained.

The TESS studied in the prior work consisted of a tank containing the phase-change medium, and a single "tube-intensive" heat exchanger, which is used both for charging and discharging heat by means of a non-phase-change heat transfer liquid, Therminol-66 (T-66). In the STETF, heat withdrawn from storage is delivered via the T-66 to an external heat exchanger which produces superheated toluene vapor to drive a turbine.

The nominal composition of the phase-change thermal storage medium (Thermkeep*) is:

Anhydrous NaNO, Commercial Grade	91.8% (wt)
$NaNO_3$	8.0
MnO_2	0.2

The commercial grade of NaOH typically contains 1-2% of NaCl and 1/2-1% of Na_2CO_3.

Phase-change TESS using Thermkeep have been under development by Comstock & Wescott for many years in applications using electric heaters and operating at maximum temperatures as high as 725 K (see, for example, Ref. 1). However, the referenced work was outside the range of previous experience in three respects. First, the heat exchanger involved more and smaller tubes which required a different method of support. Second, the cycling mode of the TESS left a portion of the Thermkeep in the bottom of the tank unmelted, and because Thermkeep is a noneutectic mixture, this might lead to segregation of its components. Third, as explained in detail later, for chemical stability in contact with a steel vessel and heat exchanger, the system must have contact with air to prevent reduction of $NaNO_3$ to $NaNO_2$. This was provided by "breathing" during thermal cycling, and since the cycling frequency and temperature range were different from previous experience, it was not known whether the "breathing" would be adequate to maintain chemical stability.

Present Program

The present work continues the prior work by means of a three-part program:

Part I - A number of samples of Thermkeep were
taken from the experimental model for
chemical analysis to determine whether
or not the system remained chemically
stable, and whether or not segregation

---

* Registered Trademark Comstock & Wescott, Inc.

4

of components occurred during the prior testing program. Thereafter, the Thermkeep was melted and partially drained to permit visual examination of the upper part of the heat exchanger.

Part II - The Therminol-66 heat transfer fluid used in the prior program was replaced by Caloria HT43, and an additional set of experimental data obtained for further verification of the computer model with a fluid of different physical properties.

Part III - An earlier study had suggested that TESS and overall system benefits might be obtained in the STETF if a second heat exchanger were incorporated in the TESS in which the toluene vapor for the turbine would be generated, thus eliminating the external toluene boiler. Therefore, a new computer model was developed to predict the performance of such a TESS. This computer model was used to produce a reference design, including construction cost, of a unit suitable for installation in the Sandia STETF. This was compared with the design of the single heat exchanger unit produced in the prior work.

PART I
ANALYSIS OF THERMKEEP SAMPLES
AND EXAMINATION OF HEAT EXCHANGER

The experimental model produced under Contract NAS3-20615 remained in the state in which it was left after several weeks of thermal cycling, as described in NASA CR-159465. During this cycling the thermal gradient causes the Thermkeep in the upper section of the vessel to be predominantly in the liquid state, the Thermkeep at the bottom is predominantly solid, with an intermediate condition between. Since Thermkeep is a non-eutectic composition, segregation of components may have occurred. In addition, some $NaNO_3$ may have been reduced to $NaNO_2$ by the mechanism described below. In order to clarify these points, a series of samples of Thermkeep were taken for chemical analysis.

Chemical Analysis of Thermkeep Samples

The thermal insulation and the external heating shroud (used to control the thermal gradient in the insulation) were removed from one side of the vessel. With the vessel at room temperature, seven 10.8 cm diameter holes were cut along a vertical line on the vessel wall by means of a hole saw. The centers of the holes are 5.1, 32.7, 60.7, 88.0, 116.6, 135.5, 170.8 centimeters from the bottom of the vessel. These locations span the total height of the solid Thermkeep.

The removal of these sections exposed the solid Thermkeep. Approximately 0.23 kg was removed in the form of chips through each hole, after which the holes were temporarily covered to prevent absorption of atmospheric moisture and CO_2.

During the removal of the sample from the third hole from the bottom, a very small penetration accidentally occurred in one of the heat exchanger coils. However, this was in an accessible location and was repaired. This was done by flowing nitrogen through the tube while it was being welded from the outside. This prevented obstruction of the tube bore at the weld. The sampling openings were then sealed by steel patches welded onto the tank wall.

7

Examination of Heat Exchanger

The exposed section of the tank was covered by temporary
insulation. The heating system which is used for charg-
ing the TES unit was activated and the Thermkeep was
completely melted. Approximately 340 kg of Thermkeep
were withdrawn from the tank into a steel drum which
lowered the level sufficiently so that the upper third
of the heat exchanger was uncovered. The Thermkeep in
the drum was covered to prevent absorption of moisture
and CO_2 and allowed to self-cool.

The Thermkeep remaining in the TES unit was allowed to
solidify and cool. The cover of the vessel was removed
and the interior of the exposed interior surfaces were
examined. The heat exchanger was photographed to record
its appearance. Its condition was compared to photo-
graphs made of the heat exchanger at the time of manu-
facture and assembly in the tank. Physically the heat
exchanger appeared to have undergone no significant dis-
tortion. The supporting structure appeared to be in
good condition and was adequate for the planned
experimental work. The metal surfaces which were ex-
posed to air above the highest level of the liquid
Thermkeep were found to have acquired a light coating
of sodium carbonate crystals. This condition has been
found consistently in Thermkeep systems on those sur-
faces which are exposed to ambient air drawn into the
clearance space by cycling. This material was easily
brushed off and the underlying steel showed no abnormal
signs of corrosion.

As a result of the examination it was concluded that no
internal repair or maintenance was required before con-
tinuing with the program.

Heat Transfer Fluid

The original program plan was to use Silicone B as the
heat transfer fluid for the test program. This fluid
is produced by Dow-Corning and has been designated by
three different names: Silicone B, Siltherm 800, and
X2-1162. A quantity of this material was obtained, and
a qualitative test made to determine whether any obvious
interaction occurred when Thermkeep and Silicone B are
in contact at a temperature of 589 K (600 F). It was
found that when a small quantity of either Thermkeep or

8

reagent grade NaOH is dropped into the 589 K (600 F) fluid, a vigorous evolution of gas occurs, and the temperature of the liquid drops promptly. Analysis of the tests indicated that decomposition of the fluid was initiated by the NaOH. The decomposition products are lower molecular weight cyclic molecules such as tetramethyl cyclosiloxane, which are more volatile than the Silicone B. These compounds are reported to be non-toxic.

In view of this instability of the Thermkeep-Silicone B system, the NASA Project Manager directed that a substitute heat transfer fluid which is stable in the presence of Thermkeep at 589 K (600 F) should be identified and substituted, since it is an objective of the program not only to verify the computer model of the system with a second heat transfer fluid, but also to test materials which can be used in a practical system. It was subsequently decided that Caloria HT-43 (a product of Exxon Co.) should be used in the testing program.

Chemical Analysis of Thermkeep

The samples of Thermkeep were analyzed by Skinner & Sherman, Inc. for percentage by weight of NaOH, $NaNO_3$, $NaNO_2$, MnO_2, Na_2CO_3, and NaCl. A copy of Skinner & Sherman's report is included herewith as Appendix A. The values reported are repeated in Table I which also shows the percentage of NaOH and the total of the six constituents for each sample.

Samples 1 and 2 were taken from a previously unopened drum of Thermkeep flakes and represent the batch of material from which the TES unit was originally charged. The remaining samples are the pairs which were taken from the seven openings in the side of the TES unit.

All constituents except $NaNO_2$ were independently determined. $NaNO_2$ was obtained as the difference between a determination of total nitrogen (not shown in the report), and the $NaNO_3$. The reported results are thus based on six independent determinations.

T A B L E   I

ANALYSIS OF THERMKEEP FROM TES VESSEL, AND ORIGINAL MATERIAL
(% by weight)

Sample No.	Location No.	Dist. from bottom, cm	NaOH	NaNO$_3$	NaNO$_2$	MnO$_2$	Na$_2$CO$_3$	NaCl	Total
1	Orig.Mat'l	N/A	86.94	8.467	.0306	.172	2.62	2.03	100.26
2			88.74	7.477	.0307	.171	1.45	1.98	99.85
3	1	172	91.50	4.652	.0020	.101	2.85	1.73	100.84
4			91.55	5.278	.0021	.085	1.48	1.35	99.75
5	2	144	91.17	5.041	.0023	.113	1.55	1.47	99.35
6			91.74	5.326	.0022	.110	1.43	1.63	100.24
7	3	117	91.88	4.503	.0019	.083	1.38	1.68	99.53
8			92.23	4.377	.0023	.110	1.35	1.85	99.92
9	4	89	89.50	5.623	.0023	.102	2.89	1.65	99.77
10			91.66	4.878	.0026	.095	1.36	1.76	99.76
11	5	62	94.30	2.791	.0017	.042	1.44	1.53	100.10
12			---	---	---	---	---	---	----
13	6	34	93.93	2.707	.0021	.057	1.40	1.76	99.86
14			94.59	2.546	.0032	.053	1.32	1.25	99.76
15	7	6	89.17	5.772	.0098	.137	2.88	1.58	99.55
16			89.88	5.138	.0095	.172	2.90	1.43	99.53

The fact that in every case the deviation of the total
of the six from 100% was no greater than 0.65% was an
indication of the precision of the analytical work.
These totals also indicated that the samples absorbed
only an insignificant amount of water from the ambient
air during the sampling procedure.

As previously described, the samples were removed from
the TES unit by cutting 10.8 cm diameter circular sections
from the tank wall. The samples were removed within a
distance of about 5.1 cm from the tank wall. The samples
were not mixed, so that the first sample removed may
represent the material closest to the tank wall, and
the second sample the material taken from the deeper
layer.

Prior to removing the samples, the TES unit was last
operated in the program described in Report CR-159465.
The final tests were simulations of the solar daily
cycle, the results of which are shown in Figs. 91-100
of that report.

Discussion of Analytical Results

A significant result was that the total sodium nitrate
content of the samples taken from the TES unit was sig-
nificantly lower than that in the original material.

Figures 1, 2, and 3 show the averages of the two samples
taken from each opening in the tank, plotted against the
location of the opening. The distance between the cen-
ters of adjacent openings was 27.6 cm.

The curves for sodium nitrate, sodium carbonate, manga-
nese dioxide, and sodium nitrite have similar shapes
in which the percentage of these constituents tends to
be lowest at locations 5 and 6 and highest at location 7
(nearest the bottom of the vessel). This suggests that
in a zone about 5.1 cm thick adjacent to the wall of the
vessel, there was some vertical segregation of these
components of Thermkeep.
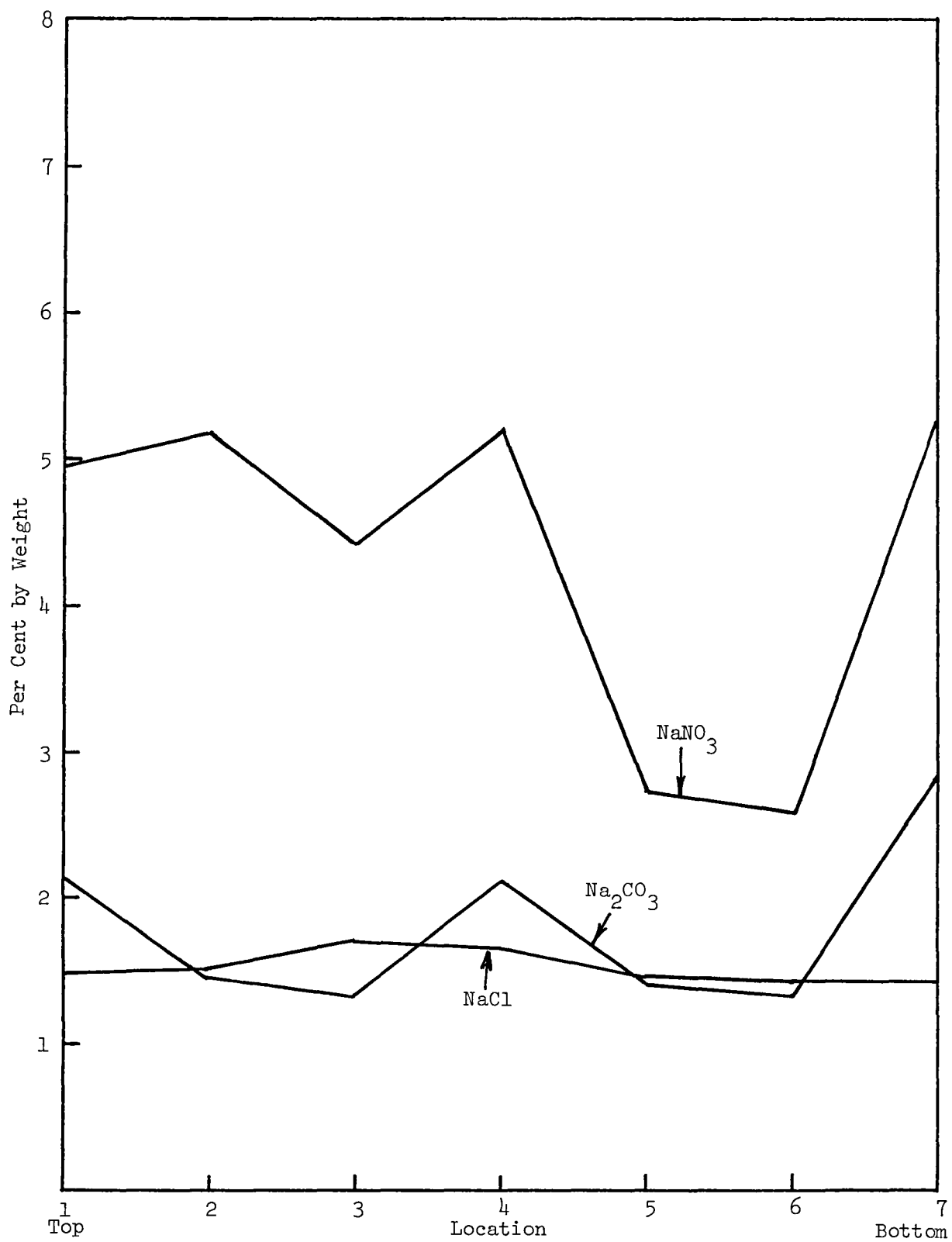
Figure 1. Variation of $NaNO_3$, Na_2CO_3 and NaCl
with vertical location in tank.
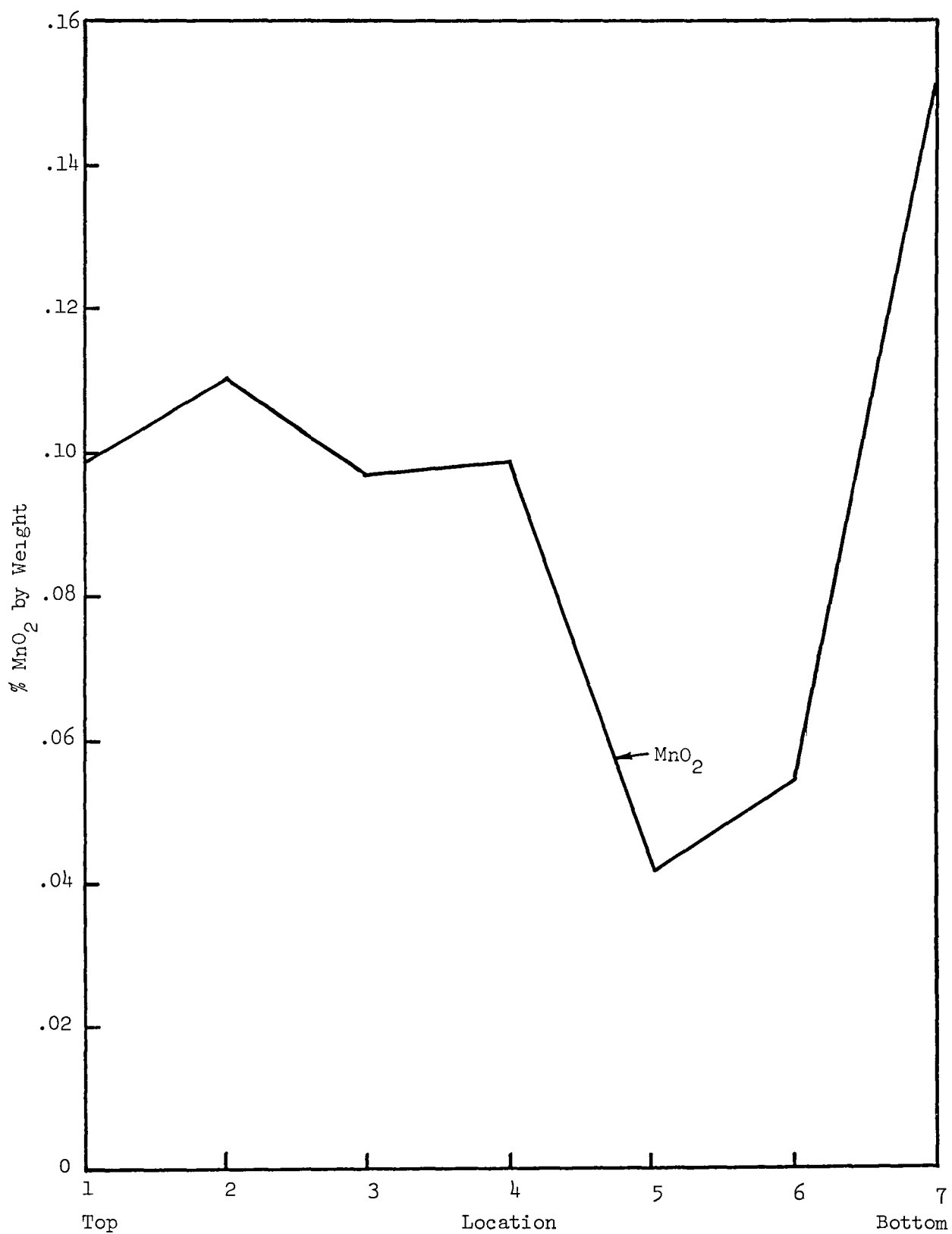
Figure 2. Variation of MnO_2 with vertical location in tank.
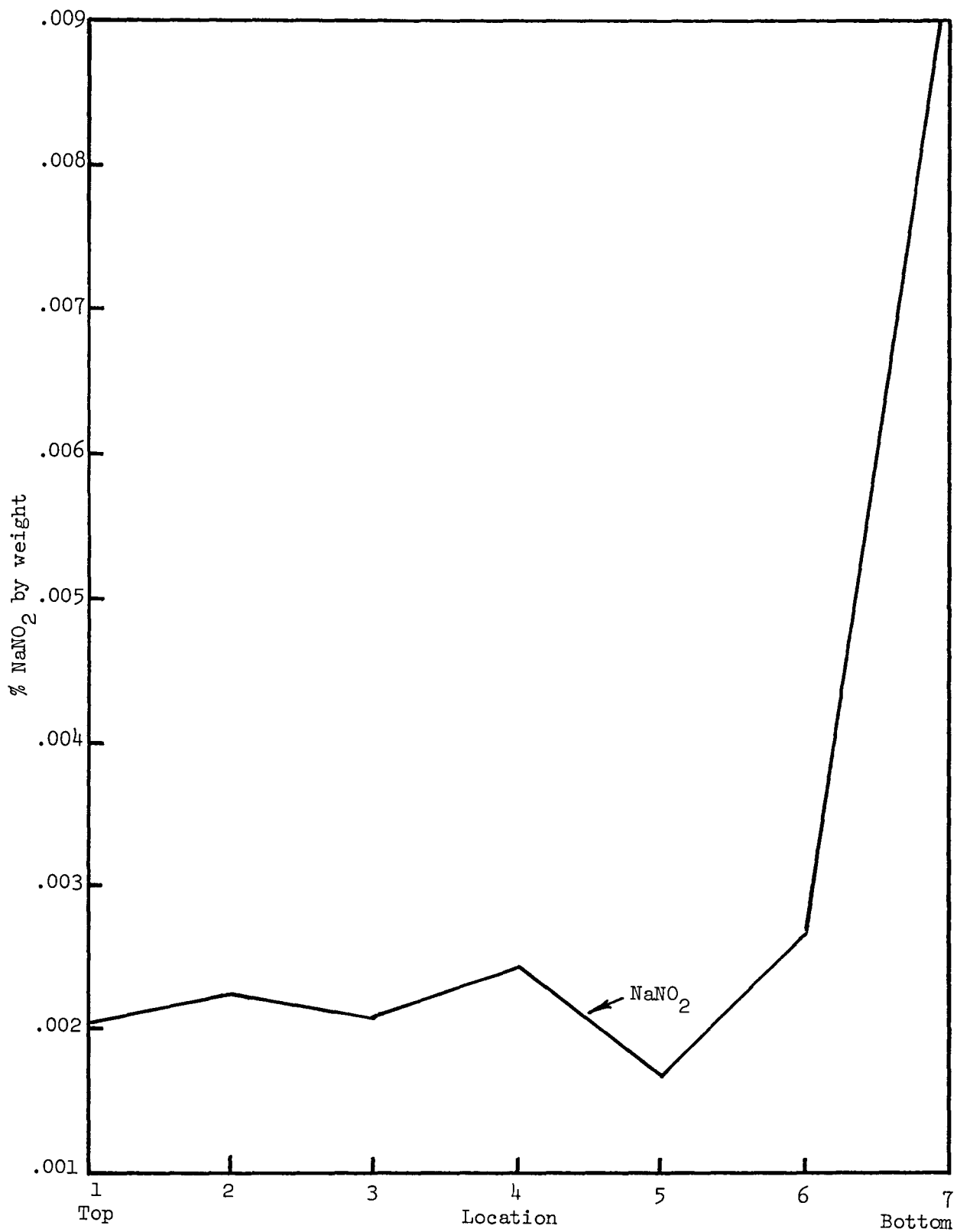
Figure 3. Variation of $NaNO_2$ with vertical location in tank.

In Figure 4 the ratio of the average NaOH content to the average NaNO$_3$ content, for each pair of samples, is plotted against the sampling location, showing that this ratio for all samples is significantly higher than that of the original Thermkeep, and that at locations 5 and 6, it is higher than at the other locations.

Figure 5 is a phase diagram (Ref. 2) for the system NaOH-NaNO$_3$ which shows that the solid which forms upon cooling was higher in sodium hydroxide than was the liquid phase from which it was deposited. Although this phase diagram does not truly represent Thermkeep because of presence of 2-3% of NaCl and Na$_2$CO$_3$, it is probable that during solidification a local variation in composition in the vicinity of the heat exchanger coil would result. The solid close to the tubes would be expected to be lower in sodium nitrate than the solid near the center-line of the heat exchanger coils or in the spaces between the coils. This might also account for the low nitrate content of the Thermkeep which solidified on the vessel walls as a result of heat lost through the insulation.

Chemistry of Thermkeep-Steel System

Studies prior to this contract have revealed some of the chemical characteristics of the Thermkeep-steel system at 756 K (900 F). Chemical stability requires contact with air. This is provided by the "breathing" of ambient air in and out of the clearance space above the Thermkeep during thermal cycling due to the changing volume of the Thermkeep. The reactions which are believed to take place are:

$$2 \text{ Fe} + 6 \text{ NaOH} \rightarrow \text{Na}_2\text{Fe}_2\text{O}_4 + 3 \text{ H}_2 + 2 \text{ Na}_2\text{O} \qquad (1)$$

$$x \text{ Fe} + y \text{ NaNO}_3 \rightarrow \text{Fe}_x\text{O}_y + y \text{ NaNO}_2 \qquad (2)$$

$$y \text{ NaNO}_2 + \frac{y}{2} \text{ O}_2 \xrightarrow{\text{(MnO}_2)} y \text{ NaNO}_3 \qquad (3)$$

$$2 \ Na_2O + 2 \ H_2I \rightarrow 4 \ NaOH \qquad\qquad (4)$$

The net reaction is:

$$(x+2) \ Fe + 2 \ NaOH + \frac{y}{2} \ O_2 + 2 \ H_2O \xrightarrow{\ (MnO_2)\ }$$

$$(5)$$

$$Na_2Fe_2O_4 + Fe_xO_y + 3 \ H_2$$
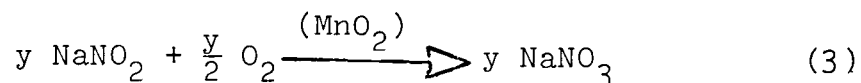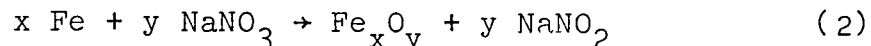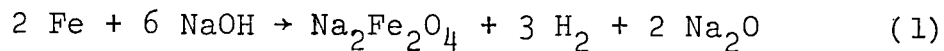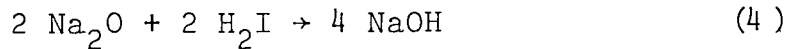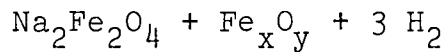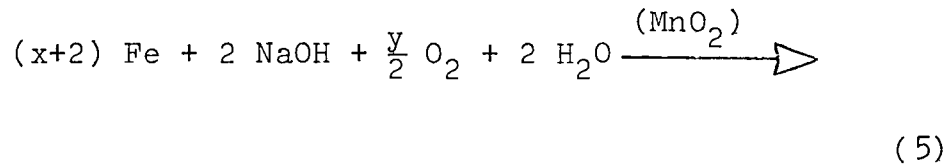
Eq. 1) is the "corrosion reaction." $Na_2Fe_2O_4$ is the principal corrosion product, and has been identified by X-ray diffraction tests. The presence of hydrogen has also been confirmed. Corrosion rates in inches per year (ipy) of penetration at 756 K (900 F) have been measured at less than 2.5×10^{-3} cm/year (0.001 ipy). In the present application at about 584 K (591 F), corrosion is expected to be insignificant in the time of operation, and no measurements were undertaken.

Eq. 2) represents the formation of iron oxide of unidentified composition, by reduction of $NaNO_3$. Salt baths similar in composition to Thermkeep are widely used for metal cleaning, at temperatures of 756-867 K (900-1100 F). These are known to produce oxide coatings on the metal by $NaNO_3$ which is reduced to $NaNO_2$.

Eq. 3) represents the oxidation of $NaNO_2$ to $NaNO_3$ by oxygen from the air. This reaction is catalyzed by MnO_2.

Eq. 4) represents the reaction of the Na_2O formed by Eq. 1) with moisture introduced by the "breathing" of humid air.

16
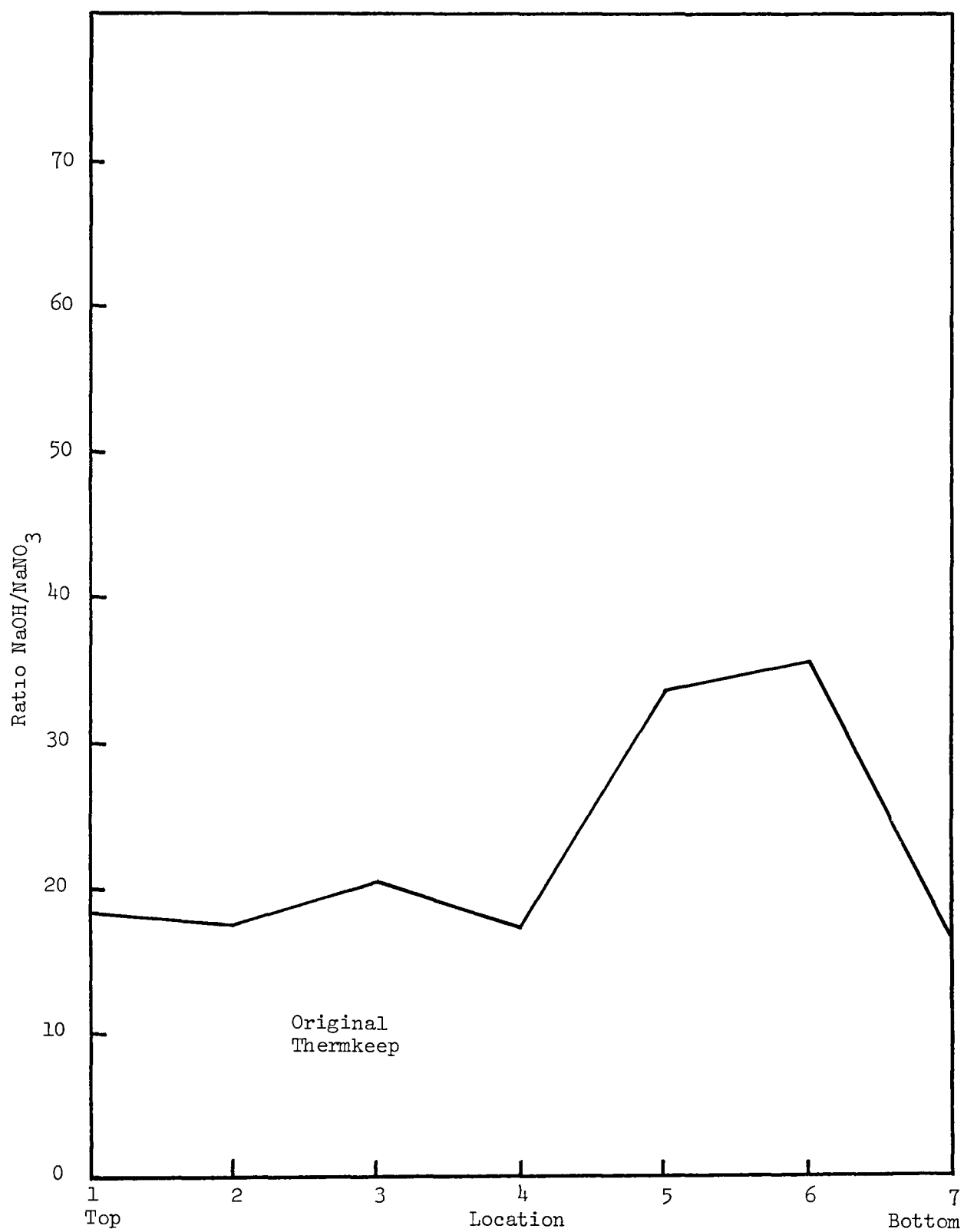
Figure 4. Variation of NaOH/NaNO$_3$ ratio with vertical location in tank.
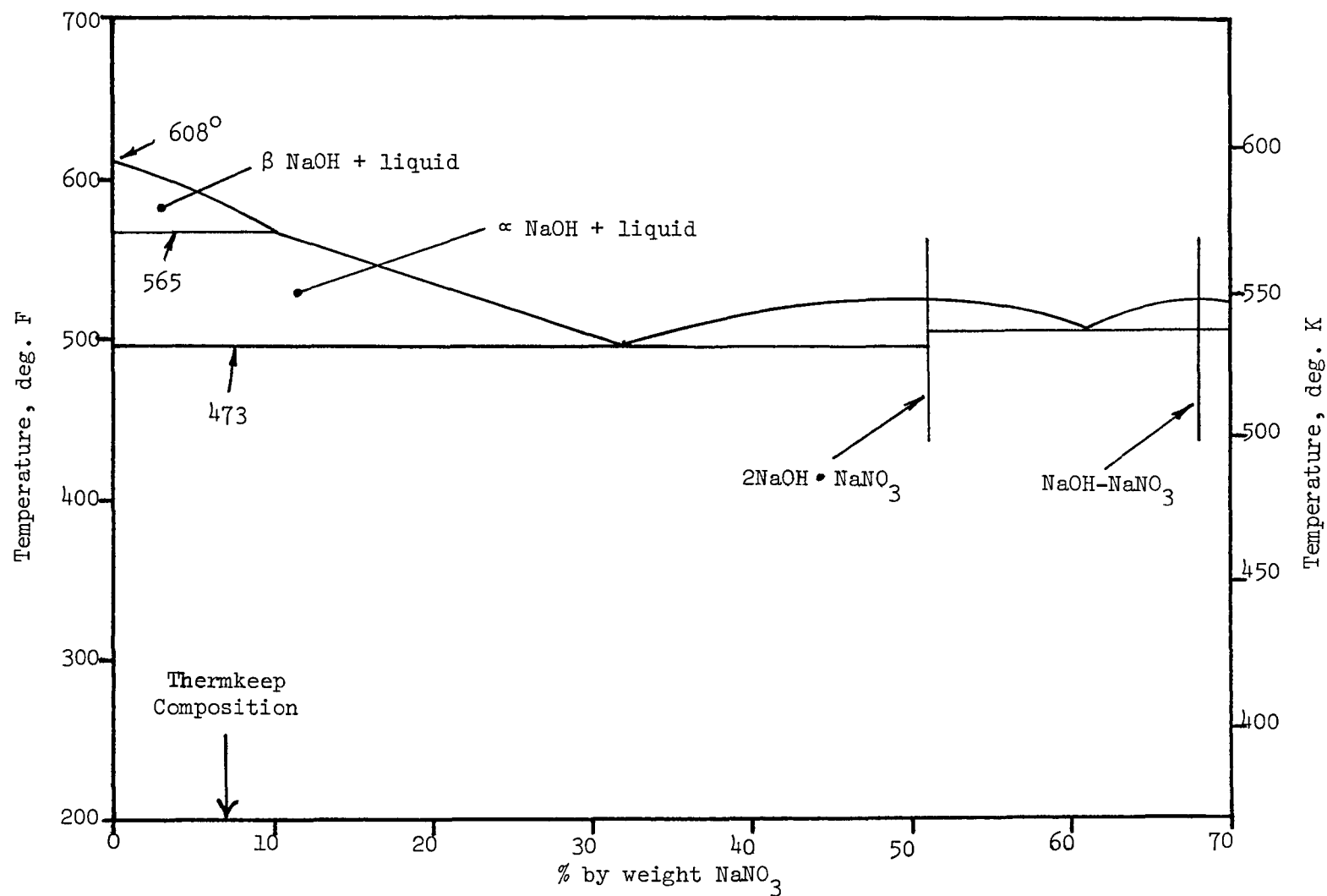
Figure 5. Phase Diagram, NaOH-NaNO$_3$

One purpose of the chemical analyses was to determine whether sufficient oxygen was absorbed by the system to maintain the original level of $NaNO_3$. Since the analysis showed that the $NaNO_2$ in the system was an order of magnitude lower than in the original Thermkeep, it was concluded that the oxygen absorption rate was sufficient to prevent significant conversion of $NaNO_3$ to $NaNO_2$.

The analyses showed that the $NaNO_3$ content of the samples was substantially lower than that of the original Thermkeep. This raises the question of whether or not nitrogen may have been lost from the system. Based upon prior work, it is believed that loss of nitrogen cannot account for this phenomenon.

Prior experiments have been conducted on the Thermkeep-iron system, at 756 K (900 F), in steel containers which were hermetically sealed to prevent entrance of air, in which the pressure was monitored. It was observed that such a system, at 756 K, initially develops a subatmospheric pressure which remains stable for about five days, after which it rises abruptly. The rise in pressure is found to be due to the generation of ammonia. This behavior is due to the sequential reduction of $NaNO_3$ -- first to $NaNO_2$, then to NH_3, according to the following reactions:

$$8 \text{ Fe} + 24 \text{ NaOH} \rightarrow 4 \text{ Na}_2\text{Fe}_2\text{O}_4 + 12 \text{ H}_2 + 8 \text{ Na}_2\text{O} \qquad (6)$$

$$3 \text{ NaNO}_3 + 3 \text{ H}_2 \rightarrow 3 \text{ NaNO}_2 + 3 \text{ H}_2\text{O} \qquad (7)$$

$$3 \text{ NaNO}_2 + 9 \text{ H}_2 \rightarrow 3 \text{ NH}_3 + 3 \text{ H}_2\text{O} + 3 \text{ NaOH} \qquad (8)$$

$$6 \text{ Na}_2\text{O} + 6 \text{ H}_2\text{O} \rightarrow 12 \text{ NaOH} \qquad (9)$$
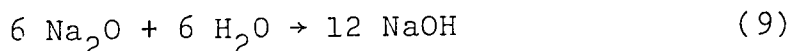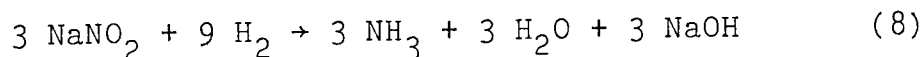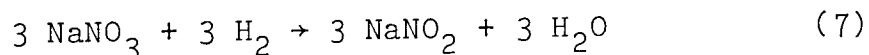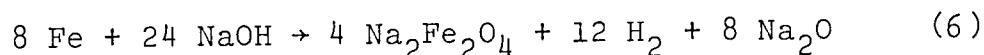
Summing these equations gives:

$$8 \text{ Fe} + 9 \text{ NaOH} + 3 \text{ NaNO}_3 \rightarrow$$

(10)

$$4 \text{ Na}_2\text{Fe}_2\text{O}_4 + 3 \text{ NH}_3 + 2 \text{ Na}_2\text{O}$$
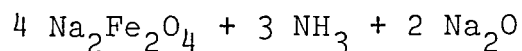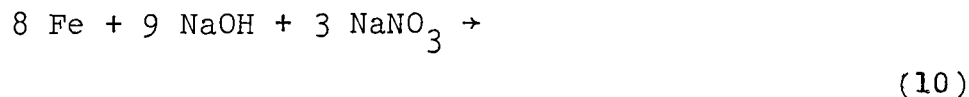
Based upon this chemistry, and the fact that no NH_3 has ever been detected in the clearance space of a cycling system which has had unobstructed access to air, it was concluded that nitrogen had not been lost.

The fact that the $NaNO_3$ content of all samples was substantially lower than that of the original Thermkeep charged into the TES tank has been attributed to segregations of chemical components; a small degree of segregation in the vertical direction and a larger amount in the radial direction.

The radial segregation was believed to be explainable on the basis of the $NaOH-NaNO_3$ phase diagram, Figure 5, which shows that during the thermal discharge cycles the solid which forms on the surfaces of the tubular heat exchanger is richer in NaOH than the liquid from which it crystallizes, or equivalently the solid has a lower percentage of $NaNO_3$ than the liquid. The samples used for analysis were removed through openings in the tank wall and are therefore solid which formed on or close to the wall. Prior to removal of the samples, the last operation of the TES unit (Fig. 100, Report NASA CR-159465) consisted of a thermal discharge which produced a solid layer on the heat exchanger surfaces, leaving liquid in the centers of the tubular helices and near the tank wall.

Upon termination of the test the Thermkeep temperatures in the upper two-thirds of the tank were above 565 K, which as shown by the phase diagram would contain 50% or more of liquid.

20

After completion of the test the circulation of the heat
transfer liquid was stopped and the TES unit allowed to
self-cool by losing heat through the insulation. This
would cause the remaining liquid to solidify starting
at the tank walls. The solid forming at and near the
walls would be low in $NaNO_3$, while the remaining liquid
would increase in $NaNO_3$ until the eutectic composition
was reached at some distance from the walls. This ex-
planation is, of course, over simplified because it does
not take account of the Na_2CO_3 and NaCl which total
approximately 4% of the original Thermkeep composition.

A number of tests were considered which might verify the
presumption that no nitrogen has been lost, and shed
more light on the segregations. However, the opportu-
nity to obtain more information on the system in its
original state was lost when the Thermkeep was completely
melted for draining and examination of the heat exchanger.

Summary of Chemical Analyses of Thermkeep

The following conclusions were drawn as a result of the
observations described above:

1. The accuracy of the analyses was good.

2. There were no significant compounds
    present in the system other than
    those analyzed.

3. The samples were not significantly
    contaminated with H_2O.

4. No significant $NaNO_2$ was present and,
    therefore, 1) no nitrogen was lost
    from the system, and 2) air "breath-
    ing" is adequate to maintain chemical
    stability.

5. Variations in the $NaOH/NaNO_3$ ratio
    were a result of segregation of compo-
    nents during cooling.

6. A small vertical segregation existed as shown by the high $NaOH/NaNO_3$ ratio at locations 5 and 6.

7. Since the $NaOH/NaNO_3$ ratio at all seven sampling locations was less than that of the original material, there must also be a radial segregation from the tank wall inward. These radial segregations had no observed deleterious effect on the operation of the TES system in prior tests, and are probably acceptable if the system had arrived at a stable state as a result of the cycling carried out in the prior program of testing. To determine whether stabilization was achieved will require further testing.

8. If further cycling produces progressive segregation to the point where the performance of the system is unacceptably degraded, this condition could be reversed by periodically over-charging the TES unit and allowing the liquefield Thermkeep to become homogeneous by natural circulation of the liquid.

PART II
VERIFICATION OF COMPUTER MODEL
BY EXPERIMENTAL DATA

Introduction

The purpose of this work was to extend the experimental
verification of the computer model (CM) of the single
heat exchanger TESS, by means of additional data ob-
tained from the experimental scale-model. The new data
were obtained through the substitution of a different
heat transfer fluid for the Therminol-66 (T-66) used
previously. The substitute fluid was to have physical
properties as different from those of T-66 as possible,
in order to demonstrate that the CM could be used with
confidence to predict TESS performance for a range of
fluids.

The program of testing was to duplicate the prior pro-
gram, so far as heat transfer rates were concerned, by
adjusting flow rates to compensate for the different
physical properties of the new fluid. The fluid tenta-
tively selected was Silicone B (a product of Dow-Corning),
because its physical properties are quite different from
those of T-66, and it has superior thermal stability,
although its cost is substantially higher. When, as de-
scribed in Part I, it was found to be reactive with mol-
ten Thermkeep, it was rejected on the basis of safety,
and Caloria HT-43 was substituted.

Heat Transfer Fluid

Caloria HT-43 has a higher specific heat (Cp) but a lower
density (ρ) than T-66, and flow rates are inversely pro-
portional to the product of these values. The following
compares the two fluids at 316 C (600 F):

	ρ g/cm^3	Cp J/(g·K)	$\rho \times$ Cp
T-66	.805	2.63	2.12
HT-43	.649	2.93	1.90

Since ρC_p for HT-43 is 90% that of T-66, the flow rates
necessary to effect the same heat rates at 589 K fluid
temperatures must be increased by about 10%. The high-
est steady state flow rate in the test plan was 0.35
kg/sec (6.6 gpm) for T-66, while the pump is capable
of 0.40 kg/sec (7.6 gpm). The only test in which the
heat rates were not duplicated was the solar cycle, where
during charging the HT-43 will reach the maximum pump
rate sooner than did the T-66. Since the actual flow
rate is a computer input, this was simulated in the com-
puter program.

Experimental Model

The experimental model is described in detail in NASA
CR-159465. Briefly, it consists of a steel cylindrical
thermal storage tank 2.23 m in height and 0.70 m in
diameter containing 1500 kg of Thermkeep. The heat ex-
changer consists of 25 helical steel tubes, 0.635 cm
outside diameter and 23.1 m long, which are manifolded
at the top and bottom of the tank for parallel flow of
the heat transfer fluid, downward during charging, and
upward during discharging. Temperatures are measured
by 20 thermocouples in wells extending through the
side of the tank into the Thermkeep to two different
depths, and additional couples on the outside of the
tank.

The temperature of the fluid entering and leaving the
tank and at other points in the system, as well as
other system temperatures, are also measured by thermo-
couples.

The tank is covered by an inner layer of thermal insula-
tion 0.457 m thick, and an inner steel shroud carrying
a grid of electric heating elements. This is covered by
an additional layer of insulation 0.152 m thick and an
outer steel shroud. The heated shroud is used to
establish a desired thermal gradient in the inner insu-
lation in order to simulate insulation heat loss which
would occur in a larger unit.

The auxiliary equipment provides for the supply of heat
transfer fluid to the TESS at predetermined flow rates
and temperatures for charging and discharging, at con-
stant flow rates and at programmed variable rates to
permit simulation of solar cycles.

The experimental model has approximately one-tenth the capacity of a TESS suitable for use in the Sandia Albuquerque Solar Total Energy Test Facility. The height of the model and consequently the length of each heat exchanger element are of full scale; the cross-section and consequently the number of heat exchanger elements are one-tenth of full scale.

Preparation of Test Unit

After samples were taken from the storage unit, about 430 kg (950 lbs) of Thermkeep flakes were added to replace what had been drained to allow visual inspection of the heat exchanger. During previous testing the liquid level of Thermkeep was about 15 cm lower than necessary to cover the entire heat exchanger at the maximum temperature, since a large portion of Thermkeep usually remains solid at the bottom during normal duty cycles. Therefore, enough Thermkeep was added to increase the average level by 15 cm.

The storage tank was closed and covered with insulation. The heated shroud was then replaced and its heating elements checked and reconnected. The purpose of the heated shroud was to produce an elevated "ambient" temperature for the tank. The shroud was turned on and over a period of ten days was balanced so that the top, sides, and bottom were at an average temperature of about 493 K.

All of the original heat transfer fluid (T-66) was drained from the system and air was blown through the pipes and coils for 24 hours. The system was then charged with 10 gallons of Caloria HT-43 (HT-43) which was pumped through all of the plumbing, collected, and circulated once again. Then the HT-43 was drained and air was pumped through the pipes for 24 hours. The procedure was repeated with fresh HT-43. After draining the T-66 and after each HT-43 flushing, the water-immersed cooling coil was removed, inverted, and drained. This coil was the only location where more than one pint of liquid could collect. The liquid content of the heat exchanger was measured between flushings by balancing its pressure head against a water manometer, on the upper and lower manifolds, and found to be no more than 250 cm^3. Therefore, in the worst case, each 38 liter (10 gal) flush was at least a 100 to 1

dilution, and with the final charge of 265 liters (70 gal), another 1000 to 1 dilution.

The unit was heated to various states of charge and the liquid level of Thermkeep was measured with a dipstick. This showed that the unit contained 1515 kg of Thermkeep, or about 75 kg (165 lbs) more than before disassembly, and that none of the heat exchanger surface was exposed above the Thermkeep level during normal cycling.

Two minor problems were encountered before the start of tests: The cooling water barrel had several leaks and was replaced, and thermal siphoning to the expansion tank became an increasing problem. The siphon pathway was traced to a broken relief valve between the heating reservoir and the expansion tank, and the valve was removed. An alternate escape pathway already exists with a hand-operated valve, and this was fixed in the open position.

All thermocouples were found to be in working order and were connected to a 60-channel "Datalogger" (FLUKE Model 2240B), which automatically records temperatures on paper tape, on a predetermined schedule.

Testing Procedure

The experimental data taken include the flow rate of the heat transfer fluid, HT-43, its temperature entering and leaving the TES unit, and temperatures of the Thermkeep in the TES unit measured by sets of thermocouples in wells extending into the tank, in two vertical rows, one to a depth of 11.0 cm and the other to a depth of 27.3 cm from the tank wall (the tank diameter is 69.9 cm inside).

The temperature data, recorded on paper tape by the Datalogger, were manually transferred to files of a small computer. The computer model (CM) of the TESS required a larger computer located in an outside facility for the CM performance predictions. The results of these predictions were also transferred to the small computer file, which was then used to print graphical displays of the experimental data and superposed CM predictions. In these graphs, the maximum deviation of the printed point from the true point is 2.5°C.

26

Inputs into the CM program include the physical proper-
ties of the heat transfer fluid, and its flow rate.
Twenty-five elements are used in the analysis. The
initial condition data for the CM includes the tempera-
ture of the Thermkeep in each element, as measured at
the start of the corresponding test.

The experimental data and the CM predictions of perform-
ance of Thermkeep temperatures vs. time are shown in
several sets of computer-printed graphs which are to
be found in Appendices B and C. Temperatures were re-
corded and graphed at half-hour intervals, but the data
in Appendices B and C are abbreviated to conserve space.
Superposed on the data are the temperatures predicted
by the computer model. The graphs show the Thermkeep
temperatures vs. the location in the tank, measured
from the top of the tank. Also shown is the location
of the upper surface of the Thermkeep as calculated by
the CM; this location depends upon the temperature vari-
ation within the tank and the fraction of Thermkeep
which is solid.

Enthalpy-Temperature of Thermkeep

The CM uses a table relating the enthalpy and tempera-
ture of the Thermkeep, which is used to determine the
energy of each of the finite elements. Data for the
table were to have been determined under a subcontract
of the preceding contract. This failed to produce use-
ful information and in its place data obtained by
Comstock & Wescott during large scale cooling tests
were used. These data were input to the CM in the form
of a table. The table used in the prior work to corre-
late data and CM predictions is identified as "Table 4"
and is shown graphically in Figure 6.

The ability to produce large numbers of graphical dis-
plays of superposed experimental data and CM predictions
quickly and inexpensively by computer data processing
enabled a more complete analysis of the temperature-
enthalpy relation than was possible during the preced-
ing study. This showed that Table 4 is a less than ideal
temperature-enthalpy representation, and also that some
degree of hysteresis occurs in the latent heat range
during heating-cooling cycles. In order to study these
effects, the enthalpy table was adjusted by trial-and-
error until two new tables were produced, one which

27
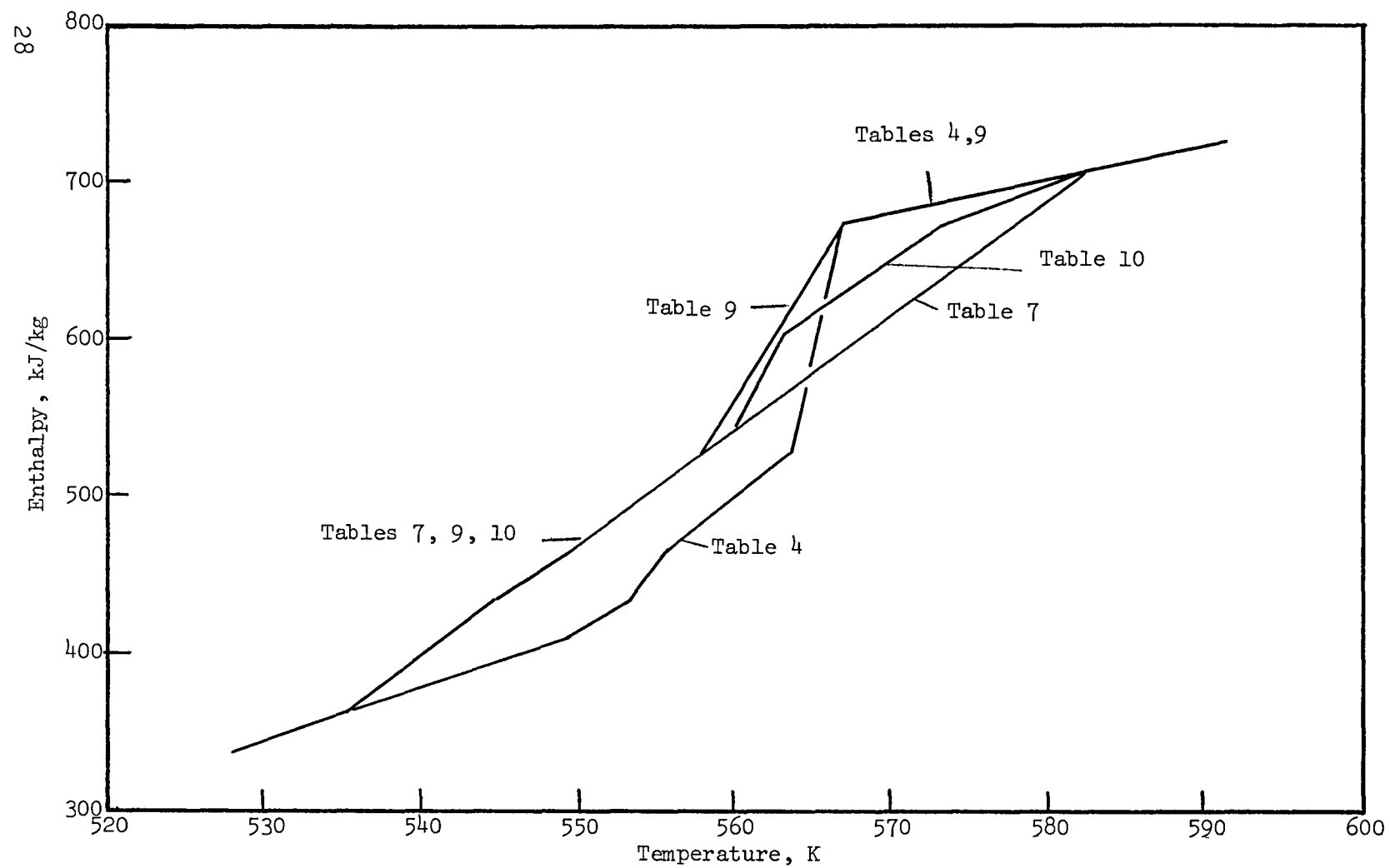
Figure 6. Temperature-Enthalpy Tables for Thermkeep

correlates the CM predictions better with cooling data, and another with heating data. These are shown graphically in Figure 6, where Table 7 is used for heating, and Table 9 for cooling.

In addition, Table 10 was constructed and used as a compromise to correlate both heating and cooling data.

Hysteresis Study

The construction of these new tables was based on CM predictions correlated with experimental data obtained with a constant flow rate of the heat transfer fluid HT-43 at 0.125 kg/sec (3 gpm). Thereafter, correlations at 0.042 kg/sec (1 gpm) for heating and cooling and at 0.305 kg/sec (7.3 gpm) for cooling were produced.

Table II shows the conditions of nine of the tests which were run, each of which ran for a total of six hours, except for No. 9 which ran four hours. Data were taken at the start of each test and thereafter at one-half hour intervals. Correlations for each data set were made with CM predictions. From these, the set showing the greatest deviation, and the starting condition, were selected. The graphs for these are to be found in Appendix B. In these graphs the symbols have the following meanings:

Δ = temperatures measured in deep wells,

o = temperatures measured in shallow wells,

+ = temperatures prediced by the computer model.

Figures B-1 – B-4 show the deviation using Enthalpy Table 4. The effect of hysteresis (which is not accounted for in the CM) is shown by the fact that Thermkeep temperatures in the temperature range of latent heat are higher than predicted during heating, and lower during cooling.

Figures B-5 and B-6 show considerably better correlation for heating through the use of Enthalpy Table 7 in the CM, rather than Table 4.

29

TABLE II

TEST CONDITIONS FOR HYSTERESIS STUDY CORRELATION

Test No.	Figures of Appendix B	Mode	HT-43 Flow Rate	Enthalpy Table
1	B-1, B-2	Charge	0.125 kg/sec (3 gal/min)	4
2	B-3, B-4	Discharge	0.125 kg/sec (3 gal/min)	4
3	B-5, B-6	Charge	0.125 kg/sec (3 gal/min)	7
4	B-7, B-8	Discharge	0.125 kg/sec (3 gal/min)	9
5	B-9, B-10	Charge	0.042 kg/sec (1 gal/min)	10
6	B-11, B-12	Discharge	0.042 kg/sec (1 gal/min)	10
7	B-13, B-14	Charge	0.125 kg/sec (3 gal/min)	10
8	B-15, B-16	Discharge	0.125 kg/sec (3 gal/min)	10
9	B-17, B-18	Discharge	0.305 kg/sec (7.3 gal/min)	10

Figures B-7 and B-8 show better correlation for cooling through the use of Enthalpy Table 9 in the CM, rather than Table 4.

Figures B-13 - B-16 show the maximum deviation obtained with Enthalpy Table 10 used both for heating and cooling.

The remaining figures show the maximum deviations measured at higher and lower flow rates, using Enthalpy Table No. 10.

On the basis of these tests, it appears that the use of Table 10 for both heating and cooling provides an adequate representation of performance for the purposes of this program. Table 10 was subsequently used to correlate all data from the heating and cooling cycling tests, and selected data obtained during the prior program with T-66 as the heat transfer fluid.

Some preliminary consideration has been given to the problems of incorporating into the computer model a means for accounting for the apparent hysteresis effect. However, this appears to be very complex, and to require quantitative information not now available. The true nature of the phenomenon is not understood. A supercooling and/or superheating may be involved in which the temperatures of latent heat effects are elevated during heating, and/or depressed during cooling. The degree of elevation or depression may be functions of the temperature and/or the rate of heating or cooling. A contributing factor may stem from the fact that upon cooling from the liquidus range, the first solid which forms on the heat exchanger is pure NaOH whose melting point is given by literature references as 593 K (cf Fig. 5), which is above the temperature of the heat transfer fluid entering during charging. Upon reheating with a heat transfer fluid whose temperature is several degrees below its melting point, reliquefying must be principally by solution in the liquid phase at the liquid-solid interface rather than at the heat exchanger surface. (The CM is based upon this mechanism.)

Experimentally determined information would be needed relating the rate of change of the enthalpy of the Thermkeep to its temperature, its rate of heating or cooling, and, if necessary, its immediately preceding temperature history. This information may be extractable from the experimental data already in hand, which

31

includes an almost continuous temperature history of
Thermkeep temperatures throughout the TES unit for a
wide range of heating and cooling rates, and for cycles
in which heating is immediately followed by cooling,
and vice versa.

If the necessary information can be obtained, it must
then be introduced into the CM in a way which follows
the first law, the conservation of energy. That is,
when an element of Thermkeep is carried through a cycle
within the temperature range of the hysteresis effect,
the cycle must form a closed loop on the temperature-
enthalpy diagram. This cannot be accomplished simply
by using two tables, one for heating and one for cool-
ing and shifting from one to the other. For example,
with reference to Figure 6, if Table 7 were used for
heating and Table 9 for cooling, and if an element were
heated from 558 K to 573 K along curve 7, then cooled
along curve 9 back to 558 K, more energy would be de-
livered by the element during cooling than would be
received during heating. Upon repeated cycling between
these temperatures, the element would progressively
lose energy.

This might be avoided by introducing a third t-h rela-
tionship such as Table 10 which represents a zero-rate
relation between t and h, and by requiring that the
maximum and minimum temperatures of cycles which are
within the hysteresis temperature range must lie on this
curve.

However, correlations next to be described, in which Enthalpy
Table 10 was used for all cycles are believed to be ade-
quate for the intended uses of the CM.

Data Correlation

The data correlations consisted of comparisons between
experimental data (DATA) and computer predictions (CMP).
The correlations include Thermkeep (TK) temperatures
and the temperatures of the heat transfer fluids enter-
ing or leaving the upper end of the heat exchanger (TU)
and entering or leaving the lower end (TL).

Correlations were made using data for Therminol-66 (T-66) from the prior program and for Caloria HT-43 (HT-43) obtained in the present program. The results are given in Appendix C in graphical form.

Figures C-1 through C-12 show HT-43 inlet and outlet temperatures vs. time. Figures C-13 through C-48 show the corresponding Thermkeep temperature profiles in the tank.

Figures C-49 through C-59 show T-66 inlet and outlet temperatures vs. time. Figures C-60 through C-75 show the corresponding Thermkeep temperature profiles in the tank.

The tests performed consisted of four types:

1. Single discharge, in which the TES is initially charged, and is discharged by a constant flow of fluid.

2. Single charge, in which the TES is initially in a partially charged state, as at the end of a typical cycle, and is charged by a constant flow of fluid.

3. Cyclic, in which a cycle consists of a 4-hour charge and a 4-hour discharge at constant fluid rate.

4. Solar cycle, which conforms to the solar daily cycle described in NASA CR-159465. The solar daily cycle is shown in Figure 7.

The conditions of the tests performed in the present program are given on Table III.

The conditions of the prior tests with T-66 are shown on Table IV. The correlation of the data with CMP is given in NASA CR-159465, which used the original Enthalpy Table 4.

Correlation of the original data for T-66 temperatures with CMP was repeated for inclusion herein, using Enthalpy Table 10, and also TK temperature correlations for Test 018 and Test 023.

33

34
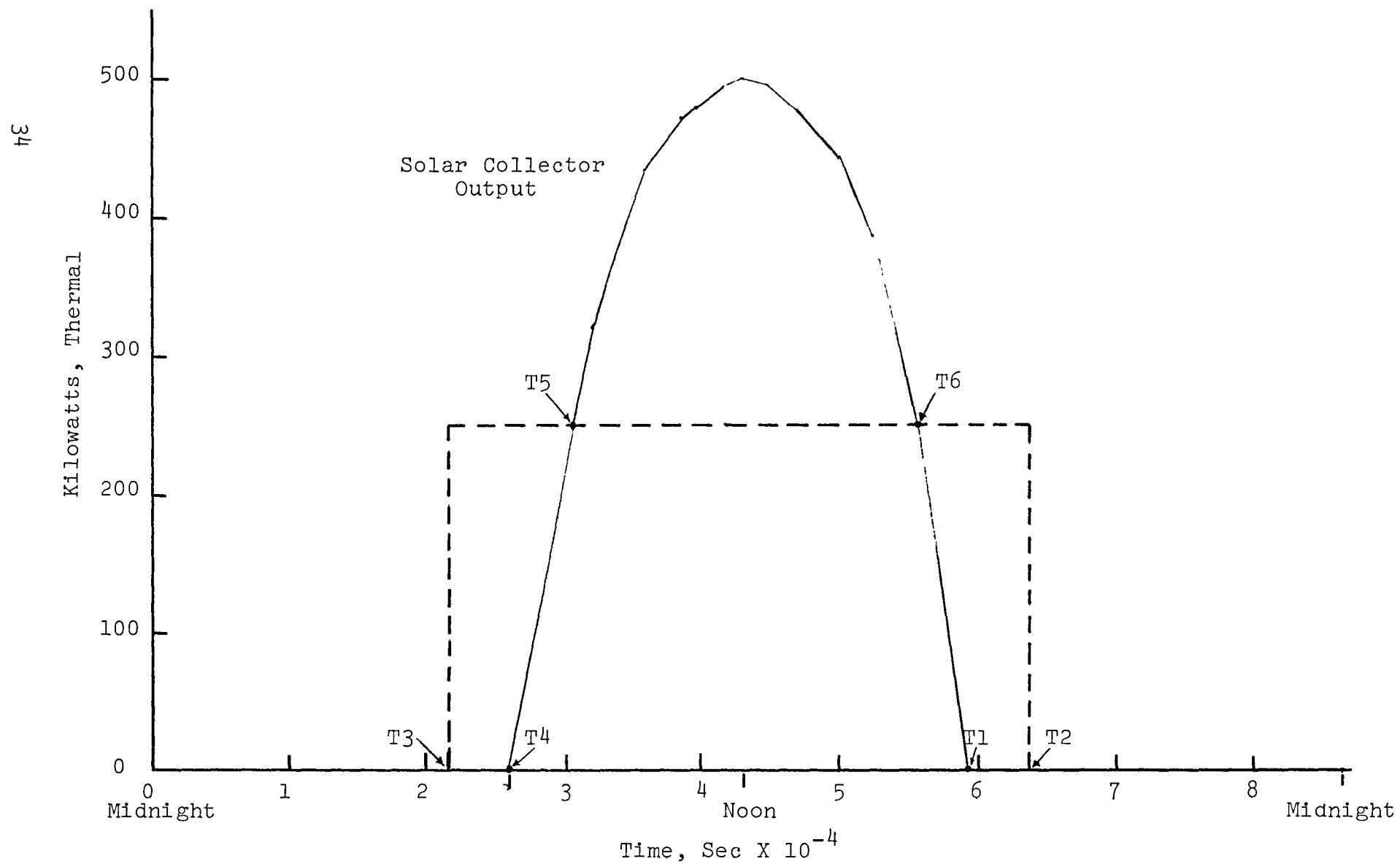
Figure 7. Typical solar daily cycle at Sandia Total Energy Test Facility.

TABLE III

TESTS WITH CALORIA HT-43
UNDER PRESENT PROGRAM

Test No.	Type of Test	HT-43 Flow Rate kg/sec	gpm
201	Single discharge, 6 hrs.	0.14	3.3
202	Single charge, 6 hrs.	0.14	3.3
204	Single charge, 6 hrs.	0.16	3.7
214-2	Single discharge, 6 hrs.	0.046	1.1
215-2	Single charge, 6 hrs.	0.046	1.1
218	Cyclic; 4-8 hr. cycles	0.080	1.9
219	Single discharge, 4 hrs.	0.32	7.7
223	Solar cycle; 2-12 hr. cycles	Variable	

TABLE IV

TESTS WITH THERMINOL-66
UNDER PRIOR CONTRACT*

Test No.	Type of Test	T-66 Flow Rate kg/sec	gpm
001	Single discharge, 6 hrs.	0.15	2.9
002	Single charge, 9 hrs.	0.15	2.8
004	Single charge, 6 hrs.	0.18	3.4
014	Single discharge, 6 hrs.	0.053	1.0
015	Single charge, 6 hrs.	0.053	1.0
018	Cyclic; 3-8 hr. cycles	0.106	2.0
019	Single discharge, 3 hrs.	0.35	6.6
023	Solar cycle; 2-12 hr. cycles	Variable	

* See NASA CR-159465

35

For the constant rate charging and discharging tests
with HT-43, TK temperature profiles are shown for the
initial state, and after 3 hours and 6 hours, except
in the case of Test 219 which was of shorter duration.
After 6 hours, correlation is generally good for flow
rate of 0.14 kg/sec. An exception is noted in the
case of Test 204, at 0.16 kg/sec, which appeared be-
tween the 4th and 5th hours, the cause of which is
unexplained. The correlation of HT-43 temperatures
for all these tests is good, with a maximum discrepancy
t the end of the discharging tests of 6 K (Test 201).
The HT-43 temperature correlation of Test 204 is good
(4 K maximum discrepancy) in spite of the discrepancy
noted above in the TK temperature correlation.

The high constant discharge rate test (Test 219) showed
more discrepancy in the TK temperatures than the lower
rate tests. However, The HT-43 temperature correlation
is exceptionally good, the maximum discrepancy being
only about 1 K.

The cyclic test with HT-43 (Test 218) consists of 4
cycles, each consisting of 4 hours of discharging fol-
lowed by 4 hours of charging at a constant flow rate
of 0.080 kg/sec (1.9 gpm). During the discharge por-
tions of this test, the same type of discrepancy occur-
red as in Test 204. This is reflected in the HT-43
temperature graphs; however, the maximum discrepancies
between DATA and CMP were less than 10 K at the end of
32 hours of cycling.

Test 223 shows the results of the solar cycle test with
HT-43. Although some discrepancy is apparent in TK
temperatures between 6 and 8 hours, they disappear at
10 hours. Deviations between DATA and CMP for HT-43
temperatures are no greater than about 5 K throughout
the 36 hour duration of the test.

The TK temperatures of the cyclic Test 018 using T-66
show better correlation than that of Test 218 using
HT-43, and this is reflected in a very good correla-
tion for the Test 018 fluid temperatures. On the other
hand, the correlation of fluid temperatures for the
Solar Cycle tests (Tests 223 and 023) is better for
HT-43 than for T-66. The Solar Cycle test with T-66
shows approximately the same degree of correlation
with Enthalpy Table 10, as with the previously reported
Enthalpy Table 4.

In view of the generally good correlation of the fluid temperatures of the steady flow rate tests, it is surprising that the discrepancy is so high in the solar cycle with T-66. It is noted that the large discrepancy occurs during the decreasing fluid flow portion of the charge phase of both the first and second cycles, and that the correlation is good during the discharge portion of both cycles (hours 10-12 and 34-36) which follows the charge portions (hours 3-9 and 27-33). Since the fluid flow rate during charging is variable in the solar cycle (starting and ending at substantially zero), it may be that the experimental model does not perform as assumed in the computer model. The latter assumes uniform flow through all 25 heat exchanger elements and that there are no lateral temperature variations within the elements. There is evidence that this was not the case during the periods in which the discrepancy occurs.

Figure 75 of Appendix C shows temperatures at the surface of the tank (□), in the shallow wells (o), and in the deep wells (Δ), at 32 hours of the solar cycle Test 023, using T-66. Temperature variations of as much as 25 K are noted between the surface and deep well locations, and about 13 K between the deep and shallow well locations. Similar variations were recorded at the 9th hour of the test which is the corresponding point in the first cycle. A similar pattern of variations is apparent in the solar cycle test with HT-43.

These temperature variations may result from variations in fluid flow rates through the corresponding elements of the heat exchanger. If this is the case, it will undoubtedly be correctable by manifolding design changes.

Summary

The practical significance of this work lies in the correlation of the measured heat transfer fluid outlet temperature with that predicted by the computer model. For the six constant rate tests of charging and discharging with HT-43, the average difference between experimental and predicted temperatures is 3 K, and the maximum is 6 K. For T-66, the average is 2 K and the maximum is 7 K. For the constant flow cycle tests (218 and 018), the discrepancy at the end of 3 cycles is 6 K for HT-43 and 2 K for T-66. For the solar cycle with T-66, a maximum discrepancy of 14 K was noted, while for HT-43, the maximum was only 5 K.

It is believed that the computer model is reliable enough to be used in the design of phase-change TES systems, using Thermkeep as the heat storage medium, and non-phase-change heat transfer liquids which are generally similar in properties to HT-43 and T-66.

PART III
DUAL HEAT EXCHANGE DESIGN ANALYSIS

Introduction

Early investigations into the use of Thermkeep* as a phase-change heat storage medium for solar power generation systems suggested that a more economical storage unit could be produced if both the collector fluid (T-66) and the working fluid (Toluene) of the power cycle were caused to flow through the storage unit. This would eliminate the cost of a separate boiler but would increase the cost of the heat exchanger within the storage unit.

It was felt that the thermodynamics of the storage and retrieval process would be superior in the case of the two-fluid storage unit because of the inherent irreversibilities and large ΔT's associated with the fluid pinchpoints which occur when heat is exchanged between the non-phase change fluid (T-66) and the phase-change storage medium and power fluid. Early attempts to quantify this did indeed indicate a substantial benefit in terms of overall storage unit size for acceptable performance with the use of a two-fluid storage device.

For this program, an analysis was developed which accounts for the use of two fluids in a typical daily duty cycle according to which the solar collector fluid flows during hours of collection at a rate determined by the insolation intensity. Moreover, the power fluid, which is a vaporizing fluid such as Toluene, flows during the hours of power generation. Consequently, at some times both fluids flow; at other times only one flows.

Approach

There are two ways to approach the analysis and the first effort in the formulation assessed the relative complications and benefits of the two approaches. As might be expected, the approach which is more precise is considerably more difficult to perform.

---

* Registered Trademark Comstock & Wescott, Inc.

39

The simpler approach is to view the heat exchange process as one in which each fluid exchanges heat with the storage medium, but not directly with the other. A heat balance is made on the numerical element of storage medium at the end of a time step during which the temperature of the medium is assumed to remain constant. Then an updated temperature distribution is produced.

The other approach which requires additional simplifying assumptions in order to be made solvable is to consider also the direct heat exchange between the two fluids. This permits a substantial amount of heat transfer from the collector fluid to the power fluid without the intervening resistance of the storage medium. It also reduces the quantity of medium required because the medium need have capacity only for the heat stored, rather than all the heat flowing from the collectors to the power fluid.

Direct heat exchange between the collector fluid and the power fluid, when both fluids are in energy balance, has a clear thermodynamic advantage, albeit one which has not yet been quantified. In the existing system configuration, whereby the boiler and storage system exist as two separate components, collector fluid heats the power fluid directly during a substantial part of the daily cycle. Since all the fluid flow in the system under analysis herein must flow through the storage unit, it seemed that a direct heat exchange path between the two fluids would be preferred over one which imposed the heat transfer resistance of the storage medium.

Therefore, the analysis has been formulated to account for simultaneous heat transfer between the fluids and between each fluid and the storage medium, i.e., three-way heat exchange. The purpose of a parametric study would be to evaluate the effect of changes in the heat transfer path resistances between the three media. Moreover, the results of optimization in this configuration would be compared in terms of cost, performance, and operational characteristics to the current standard design which passes only collector fluid through the storage unit and uses a separate boiler to heat the power fluid.

General Features

The prior analysis may be referred to as a design analysis -- that is to say it includes a rather detailed series of calculations relating to a number of specific characteristics of the storage system. It works from an input set which consists of basic geometry from which it derives heat transfer parameters such as surface areas and pressure drops. It does a cost analysis. It includes axial conduction heat flows and losses to the environment. It is limited, however, to a specific geometry -- that of coiled tubes in a parallel configuration.

At the outset of the present work, it was not known what sort of geometry would be preferred for a three-way system. A determination was made to provide a less detailed analysis which would describe the basic heat transfer and thermodynamic behaviour of the process and to overlook for the moment other effects which have already been shown to be relatively insignificant. On this basis, calculations with regard to geometries, pressure drops, losses to the environment, and axial losses have been put aside.

It will not be difficult to introduce these later if wanted. It will require, however, a clearer, more limiting description of the desired design configuration, one not deemed appropriate at this time. Also, it was not entirely clear at the outset that a problem of such complexity as this would lend itself to a useful solution, and introduction of additional details was not considered prudent.

General Description

The analysis considers variations in the temperatures of the three media to be one-dimensional; temperatures vary only in the direction of flow of the fluid media. The hot end of the unit is the top, as shown on Figure 8. This stabilizes the thermal gradient established in the storage medium by preventing mixing due to natural convection flow.

Heated fluid from the solar collector, assumed to be a liquid with a constant specific heat, C_L, flows through
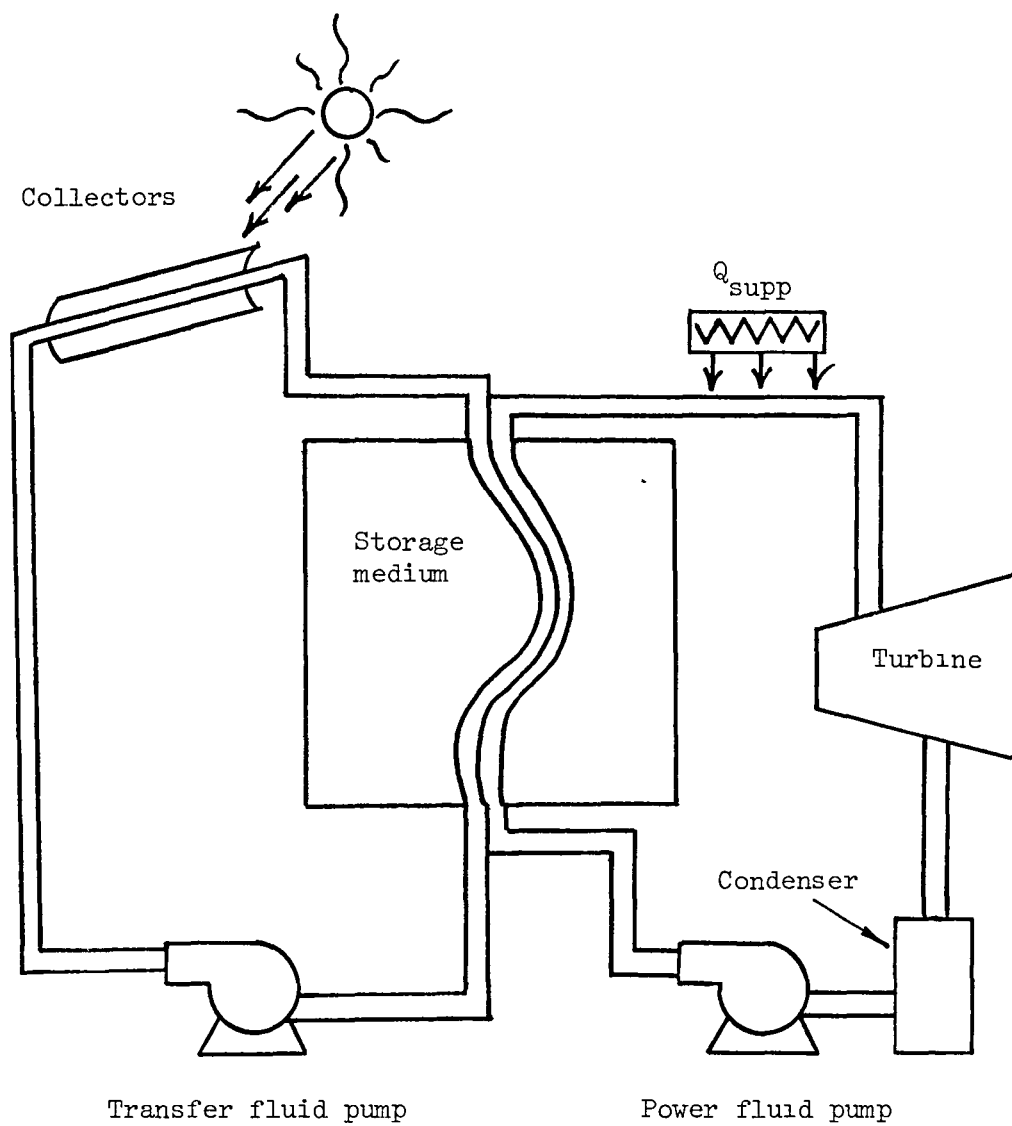
Figure 8. Solar electric power generating system schematic.

the unit from top to bottom. Its inlet temperature,
assumed to be constant, is $T_{L,in}$ while its exit
temperature is $T_{L,out}$. Its flow rate, also a time
variable, is W_L, its value being a function of the col-
lector heat output and the fluid temperature.

Cooled power fluid, assumed to be a vaporizing liquid
with constant specific heats in the sensible regions,
flows into the unit at the bottom and out at the top.
Its liquid phase specific heat is C_S, its vapor phase
specific heat is C_V, its heat of vaporization is Q_T,
its flow rate is W_P (assumed to be constant in time),
its inlet temperature is $T_{P,in}$ (constant in time) and
its exit temperature is $T_{P,out}$ which is a time-varying
output of the analysis.

The power conversion system, however, in order to pro-
duce a constant output, P, requires a constant inlet
temperature, $T_{P,des}$, and a boost heater is assumed to
make up the difference between the desired and the
actual delivery temperatures. In general, this supple-
mental heat is

$$Q_{supp} = W_P C_V \left(T_{P,des} - T_{P,out} \right).$$

The solar collectors produce a scheduled amount of heat,
Q_{coll}, which is assumed to be a function of time of day
but repeatable from day to day. The collector fluid
attempts to absorb this heat by varying its flow rate
according to

$$W_L = \frac{Q_{coll}}{C_L (T_{L,in} - T_{L,out})}$$

At some point, the fluid pump reaches a maximum flow, $W_{L,max}$, and any heat which cannot be absorbed due to this limiation is assumed to be lost through a heat rejection device. It is calculated by

$$Q_{lost} = Q_{coll} - W_{L,max}C_L(T_{L,in} - T_{L,out})$$

Both Q_{lost} and Q_{supp} are important operational characteristics of the system.

The task of the analysis is to use as input the parameters Q_{coll}, P, $T_{L,in}$, $T_{P,in}$, the fluid thermal properties, and the storage unit geometry, and to calculate $T_{L,out}$, $T_{P,out}$, Q_{lost}, Q_{supp}, and the storage medium temperature variation in space and time. The material discussed so far, the parameters external to the storage unit itself, constitutes the essence of the MAIN portion of the computer analysis. The major portion of the computer analysis, a subroutine called ELANAL, deals with the processes within the storage unit. It receives the flows and inlet temperatures of the fluids from the MAIN program.

Heat Exchange Analysis

Description

The analysis of the heat exchange processes within the storage unit rests upon the same assumptions made to develop the heat exchange analysis for the single fluid case. The actual procedure is greatly complicated by the fact that two fluids flow countercurrent and that one fluid exists in three states: subcooled liquid, two-phase boiling fluid, and superheated vapor. This last factor imposes the definition of three distinct spatial regions: Region I where the power fluid is superheated, Region II where boiling is taking place, and Region III where the power fluid is subcooled.

44

Two basic approximations are made in the solution methodology; finite differencing in time, and finite elements in space. With regard to the temporal variation in the parameters, the approximation is made that the time axis is divided into sufficiently small time steps that the system may be viewed as stationary during said time steps.

Heat flows are computed from temperature potentials assumed not to change significantly during the time step. The heat flows contribute to a stepwise change in the thermal state of the storage medium, the result of which is assumed staionary for the next time step. The storage medium is assumed to have the only thermal capacitance of any significance.

Thus, the differential equation

$$Q = MC \frac{dT}{dt}$$

is approximated by

$$\Delta T = \frac{Q}{MC} \Delta t$$

where the ΔT of a piece of storage medium of mass, M, and specific heat, C, is that created by imposing a fixed heat flow Q on it over a time step, Δt. This is the finite differencing in time.

Spacial variation of the temperature of the storage medium is approximated by a stepwise variation in the (vertical) X-direction. The unit is divided in the X-direction into N_E elements of size ΔX and of mass ΔM. Figure 9 describes an element. Each element is assumed to be of uniform temperature, T_i. For each element, heat flows among the media are computed from the knowledge of the inlet temperatures of each fluid, $T_{H, i+1}$ and $T_{C,i}$, the
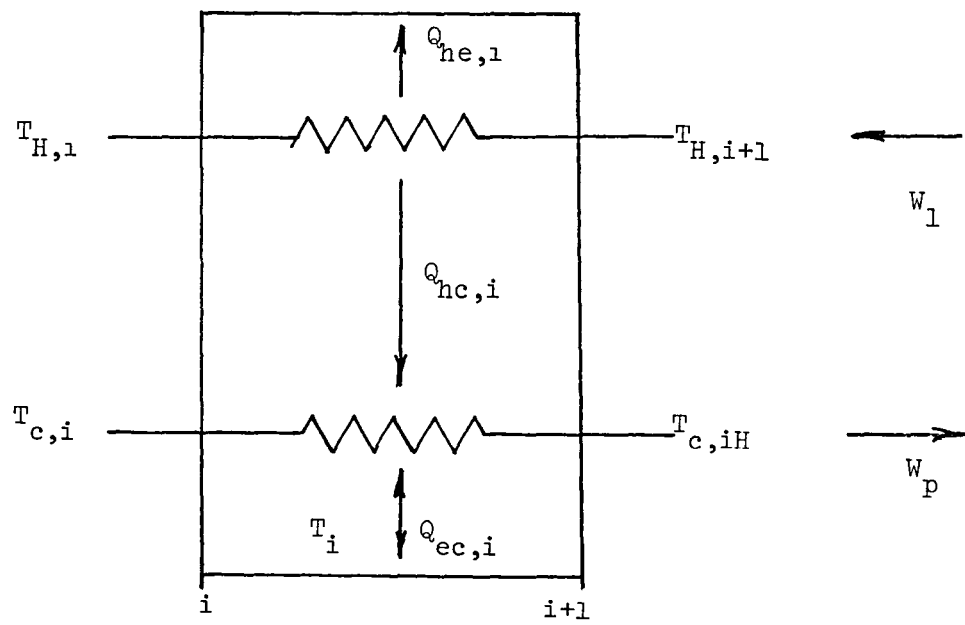
Figure 9. Element for heat exchange analysis.

element temperature, T_i, and the heat flow resistances between the media.

The heat flow between the fluid media, $Q_{HC,i}$, contributes a portion of the heat needed to change the fluid temperatures (or states). The heat flows between the storage medium and each fluid contribute the remainder. These heat flows, $Q_{HE,i}$ and $Q_{EC,i}$, also, when summed together constitute the net heat flow to the storage medium finite element and, when multiplied by the appropriate time step, t, determine the element temperature change. Consequently, the updated set of element temperatures may be calculated to be used in the next time step.

The three-way heat flow analysis for the power fluid is different in the sensible regions, where temperature changes with heat exchange, from that in the boiling region, where quality changes with heat exchange. Consequently, the normally equally sized elements must be divided into fractional elements when a regional transition occurs, each fraction being described by its appropiate relationships.

Governing Equations

For any element with constant element temperature and fluids flowing counter-currently, the following equations describe the heat transfer and thermodynamics:

$$dT_H(X) = -\frac{dQ_{HE} + dQ_{HC}}{W_L C_L}$$

$$dT_C(X) = -\frac{dQ_{EC} - dQ_{HC}}{W_P C_C}$$

$$dQ_{HE} = (UA)_{HE} (T_H - T)dX$$

$$dQ_{HC} = (UA)_{HC} (T_H - T_C)dX$$

$$dQ_{EC} = (UA)_{EC} (T - T_C)dX$$

where $(UA)_{HE}$ is the product of U, the overall heat transfer coefficient, and A, the effective surface area for heat transfer, associated with the heat flow Q_{HE} and likewise for $(UA)_{HC}$ and $(UA)_{EC}$. The UA are derived in the normal way considering the overall heat flow path between the two relevant media.

There are two solution forms of use to this situation. In the general case the power fluid is in the sensible region and T_C is, in fact, a function of X. In this case, the solution is of the form

$$T_C(X) = Z_1 C_1 e^{\left(\frac{\lambda_1 X}{L}\right)} + Z_2 C_2 e^{\left(\frac{\lambda_2 X}{L}\right)} + Z_3 \qquad (1)$$

$$T_H(X) = C_1 e^{\left(\frac{\lambda_1 X}{L}\right)} + C_2 e^{\left(\frac{\lambda_2 X}{L}\right)} + Z_4 \qquad (2)$$

where λ_1, λ_2 are solutions to a characteristic equation; L is the effective element length; Z_1, Z_2, Z_3, and Z_4 are groups of terms formed from the

48

UA, $W_L C_L$, $W_P C_C$, and the element temperature, T, which is constant. C_1 and C_2 are constants determined by substitution of the boundary conditions, i.e., the known inlet temperatures.

For the more specific case of $T_C(X)$ being constant, which describes the boiling process occurring at saturation temperature, the solution for $T_H(X)$ is of form:

$$T_H(X) = Z_5 e^{\left(\frac{\lambda_3 X}{L}\right)} + Z_6. \qquad (3)$$

Heat flows for all paths may be calculated by integration of the heat flow equations once the temperature expressions are known. For example,

$$Q_{HC} = (UA)_{HC} \int_0^L (T_H(X) - T_C(X)) dX \qquad (4)$$

Application

In subroutine ELANAL, the element heat flows are determined from relationships arising from the basic equations discussed above. It is to be noted, however, that the fluid temperatures entering each element are initially unknown. In fact, all that are known are temperatures, $T_{C,1} = T_{p,in}$ and $T_{H,NE+1} = T_{L,in}$ from the external system. Not only that, there are three distinct regions, previously described, the boundaries of which are not known until solution is achieved.

It can be shown that a set of elements totally
composed of fluids in uniquely sensible regions
can be solved for directly through simultaneous
solution of a set of linear equations in the
unknown fluid temperatures at the element
boundaries.

This is suggested by the fact that N_E elements
yield $2N_E$ equations for temperatures of which
there are $2N_E + 2$, of which 2 are the
known inlet temperatures for each fluid.
In fact, the matrix of coefficients, if the
equations are properly arranged, is a tridiagonal
matrix, and special computer subroutine packages
exist for this situation.

The computer analysis proceeds in the following
way:

.. A position is assumed for the point where
   the power fluid reaches a quality of 1.0.
   Here, the temperature is T_{sat}, the satura-
   tion temperature, and all elements above
   this point lie in a region where the sen-
   sible heat equations govern. The inlet
   temperature to this set of elements is
   known for the collector fluid as well since
   it is $T_{H,in}$.

.. The aforementioned solution is used for the
   set of linear equations. This yields all
   the desired fluid temperatures including
   the collector fluid temperature at the X-
   coordinate corresponding to power fluid
   quality of 1.0, hereafter called T_{LF}.

.. Knowing the two associated fluid temperatures
   at the end of the boiling region, the heat
   flow equations for T_C = constant may be used
   to work backwards to the point where quality
   is exactly 0.0. Neither this point nor the
   point where quality is 1.0 necessarily fall
   on an element boundary. Not only will the
   point be determined but also the associated
   collector fluid temperature, called hereafter
   T_{LI}.

.. The region below this point will consist
of power fluid entirely in the sensible
region and may be solved for again by
the set of simultaneous linear equations
and knowledge of T_{LI} and $T_{P,in}$. This will,
however, result in a calculated temperature
for the power fluid at the outlet, where a
quality of 0.0 was expected, which will dif-
fer from T_{sat}. The extent to which it dif-
fers is a measure of the accuracy of the
choice of the point where quality is iden-
tically 1.0.

There are two approaches to the use of this method.
One may be called a closed loop approach and the
other an open loop approach. The closed loop
approach is an iterative approach whereby knowledge
of the error in temperature match where quality is
to be 0.0 is used to adjust the point where quality
is 1.0. Adjustment proceeds until the error falls
within acceptable limits. This iterative approach
is more accurate but more costly in terms of compu-
ter processing time.

The open loop approach uses a method of prediction
of the point where quality is 1.0 and assumes that
by proper selection of the prediction method a
satisfactory accuracy will be achieved. The cost
of such an approach is much less but accuracy is
apt to be sacrificed. This is the approach taken
and results to date are considered satisfactory.
A method of tracing the movement of the saturated
vapor point has been developed which combines a
knowledge of the current error with a predictor of
the expected result of having updated element
temperatures.

Appendix E is a listing of the Fortran program used
for this work.

Performance Analysis

A design is specified by certain limited input parameters.
The surface areas associated with each heat flow path, as
well as heat transfer film coefficients for each fluid
define the geometry. The collector fluid film coefficient
is input as a function subprogram whose value depends upon
fluid flow rate. Since the power fluid flow rate is fixed

over a cycle, the only variation provided by the analysis is a dependence upon quality in the two-phase region.

The duty cycle is, as in the single fluid situation, such that the solar collectors produce a normal daily variation in output, peaking at solar noon. The power system operates for a certain part of the cycle, in the early morning and early evening, when the collector output is zero. Overall the collectors can provide more over a day than the power cycle needs and storage smooths the daily variation in collector output in an attempt to provide constant heat input required.

Each design run is accomplished by setting the unit at full charge, i.e., uniformly at peak cycle temperature, and letting the daily cycles progress until heat input and output are equal within acceptable limits. This stable repetitive operation is the mode of operation assumed to be characteristic of the design. Once stability is achieved, then the important rating criteria can be established.

When equilibrium is established, the capacity of the unit is available as the daily "Storage Output." A "Figure of Merit" is defined as the Storage Output divided by the sum of the Storage Output and the supplemental heat, Q_{supp} which is defined above. The "Specific Cost" of the TES unit is defined as the total cost divided by that portion of the daily output which passes through the storage medium.

An analysis has been used to determine the expected performance of such a system and the results appear in the sections to follow. Also, the optimal design from earlier work for a single fluid system has been rerun with the higher order effects such as insulation heat loss and axial heat conduction within the storage unit eliminated, so that the two systems are compared on a common basis.

The Fortran code of the computer model and notes on its use are to be found in Appendix D.

Results of Computer-Model-Predicted TESS Designs

The purpose of the dual heat exchanger TESS design exercise was to produce a cost optimized design of the dual heat exchanger TESS for comparison with the cost optimized design of the single heat exchanger TESS reported in NASA CR-159465. The single heat exchanger TESS requires the use of an external heat exchanger to vaporize and superheat the power fluid, whereas in the dual heat exchanger TESS this function is incorporated internally and the external heat exchanger is eliminated. Therefore, the cost of the dual heat exchanger design is credited with the cost of the external heat exchanger. This is done in two steps; that is, the specific costs of the two designs are compared with, and without, the external heat exchanger credit. Additional savings in operating costs in the solar-electric system which accrue to the dual heat exchanger design are pointed out, but not credited.

The specifications of the TESS design are as follows:

Storage capacity is 3.1×10^6 kJ when operating over the range 516 K to 584 K. Heat is charged into storage medium (Thermkeep) by the non-phase change heat transfer fluid Caloria HT-43 at a maximum rate of 1.8×10^6 kJ/h at an entering temperature of 584 K $\pm$ 2 K. Heat is discharged from storage by means of toluene which enters as liquid at 473 K, and leaves as superheated vapor at 582 K $\pm$ 2 K and 1,862 kPa. The maximum heat discharge rate is 1.0×10^6 kJ/h. The TESS includes an auxiliary heater which supplies auxiliary heat to raise the temperature of the toluene vapor to the specified temperature as required. The Figure Of Merit (FOM) is the fraction of the heat delivered which comes from storage.

Using the computer program described in Appendix D (Use of Computer Program), trial designs were run on the Solar Cycle running through consecutive cycles to produce stabilization. These were chosen for convenience to have power fluid and heat transfer fluid heat exchangers of equal area, the inside heat exchanger surfaces of each varying from 37.2 m^2 to 148.6 m^2 (400 to 1600 ft^2) in increments of 18.6 m^2 (200 ft^2). Note that these are

the inside areas of _each_ of the two heat exchangers. Thermkeep masses were varied in increments of 1 Mg between 10 and 25 Mg. A limitation imposed upon all designs was that the TESS always furnish power fluid of quality 1.0 vapor at the outlet; if it fell below this, the program was terminated.

For a given heat exchanger design, a minimum Thermkeep mass was found below which the outlet vapor quality dropped below 1.0. For each design a storage specific cost and a Figure of Merit (FOM) were calculated.

For comparison purposes the single-tube heat exchanger design program previously developed (NASA CR-159465) was rerun with several program changes to provide the same operating conditions as in the dual heat exchanger design; viz. axial conduction and insulation loss were eliminated, the Thermkeep properties were taken from temperature-enthalpy Table 10 (see Part II), and a return temperature was calculated for the heat transfer fluid flow from the TESS combined with that from the external power fluid boiler, the results of which are shown on Figure 10. The Fortran code of the modified program is given in Appendix E. As a result of the modifications, the FOM rose from .88 to .92, and the specific cost decreased from $11.20 to $9.57/MJ, as compared with the values given in NASA CR-159465.

The cost of each unit was computed using identical material and fabrication costs, tube wall thickness (.0004 m), insulation thickness (.6096 m), aspect ratio (1.0), and vessel wall and bottom thickness (.0127 m and .0254 m, respectively).

Input data consist of the cost of material for each component and costs for fabrication on the basis of weight and surface area. Material costs were those at the time of construction of the experimental model in 1977. These fabrication costs are based upon the actual manufacturing cost of two experimental prototype "Thermbank" electric water heaters constructed at that time of the type described in the background section of the Introduction. Therefore, they do not include the cost benefits of the "learning curve" which results from converting prototype designs to manufacturing designs nor the cost reductions which result from quantity manufacturing.
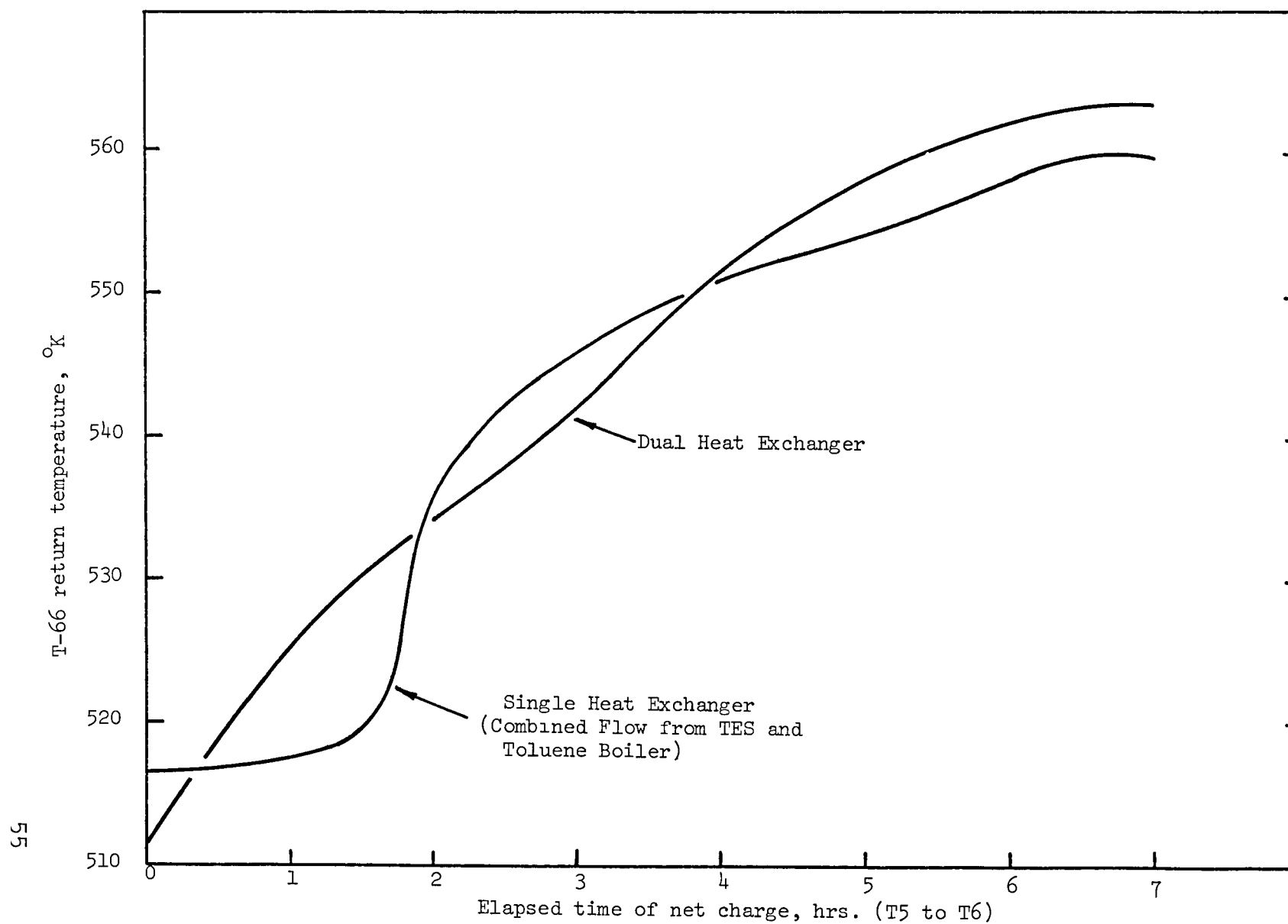
Figure 10. Heat transfer fluid return temperature vs. charge time.

55

Output costs incorporate fabrication factors based on weight, surface area, and the "six-tenths rule" whereby fabrication costs increase as the 0.6 power of the size ratio. These methods are generally accepted for making approximate estimates of costs of industrial equipment such as heat exchangers and vessels.

Graphs were made of the parameters against specific cost. Figure 11 shows the FOM against specific cost for several heat exchanger surface areas. The decreasing FOM seen in the 37.2 m^2 (400 ft^2) and 55.7 m^2 (600 ft^2) lines represent smaller Thermkeep masses, and these lines end when a smaller mass no longer produces quality 1.0 vapor.

Figure 12 shows the FOM against specific cost at constant Thermkeep masses. Here there is great improvement in FOM for relatively small cost increases. The relationships between the two graphs are plotted in Figures 13 and 14 where the surface area and Thermkeep mass are varied at constant FOM. The Reference Design point for the single heat exchanger TESS is also shown on these figures.

The choice of the Reference Design point is somewhat arbitrary, its choice depending upon the relative importance of specific cost and FOM. Figure 11 shows that an FOM as high as .99 can be achieved at a specific cost below that of the single heat exchanger TESS. Therefore -- somewhat arbitrarily -- a Reference Design which betters the single heat exchanger TESS in both specific cost and performance (FOM) is chosen at 55.7 m^2 (600 ft^2) of each heat exchanger, 13 Mg of Thermkeep, and .95 FOM. It should be noted that, while the abso- lute specific costs are subject to the limitations noted above, the relative specific costs and perform- ances are realistic. The characteristics of the Ref- erence Designs are shown in Table V.

The specific costs shown on the figures are computed on the same basis for the single, and dual, heat exchanger designs. However, as noted above, the dual heat ex- changer eliminates the need for an external toluene boiler. A credit for the boiler was estimated as fol- lows. A communication from the Sandia Laboratories at Albuquerque (Ref. 3) showed that the cost of the boiler in the solar total energy system which the TESS is de- signed to match, cost $17,000 in 1974-1975, and would cost approximately $25,000 to replace in 1980.
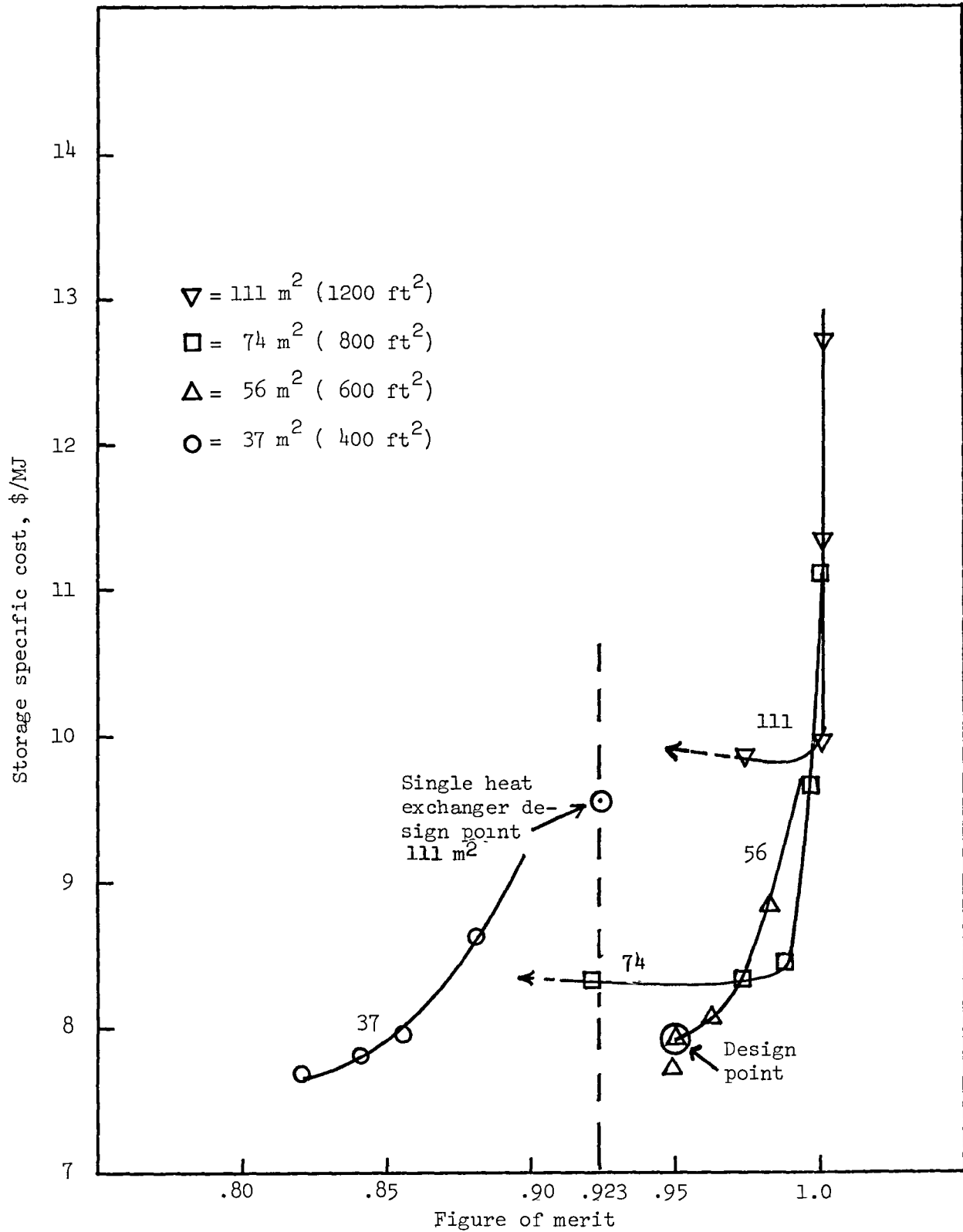
Figure 11. Specific cost vs. Figure of Merit for various heat exchanger areas.
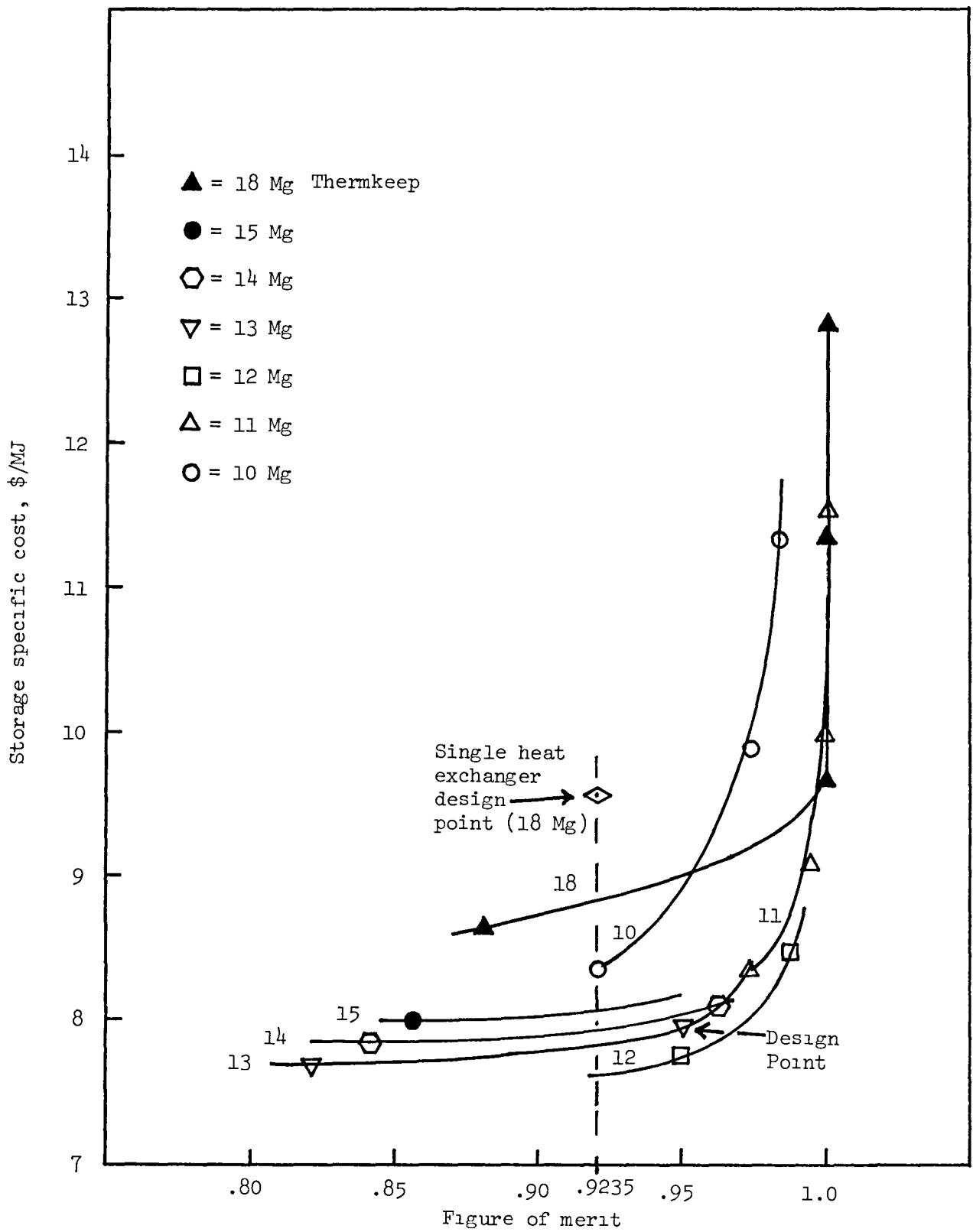
Figure 12. Specific cost vs. Figure of Merit for various Thermkeep masses.
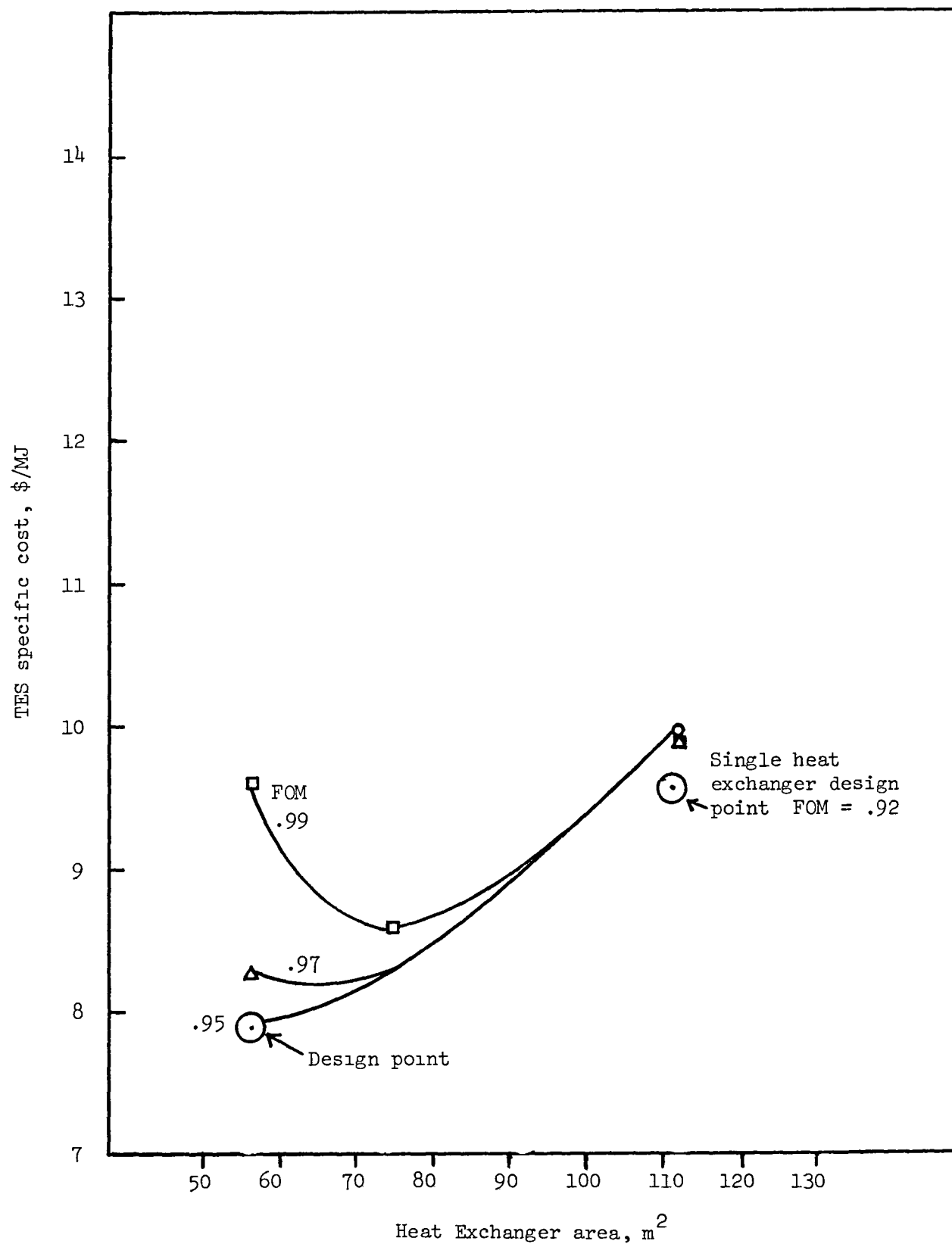
Figure 13. Specific cost vs. heat exchanger
area for various Figures of Merit
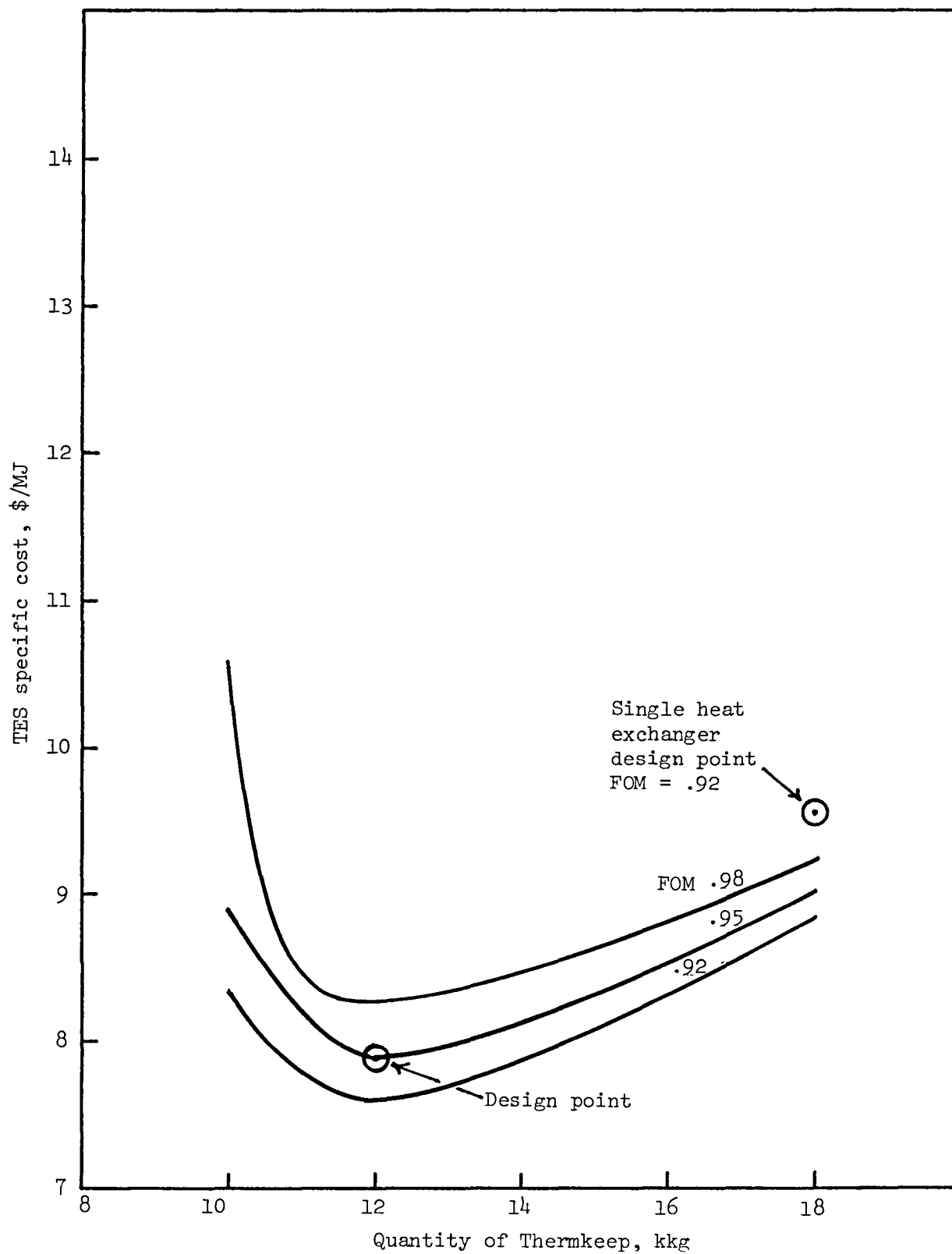
Figure 14. Specific cost vs. Thermkeep mass for
various Figures of Merit.

TABLE V

CHARACTERISTICS OF REFERENCE DESIGN

Cost Calculation Input Data	Dual Heat Exchanger Design Point	Single Heat Exchanger Comparison Point
Shroud material cost, $/kg	.509	.509
Shroud side fabrication cost, $/m^2	10.14	10.14
Shroud side fabrication cost, $/kg	1.038	1.038
Shroud top fabrication cost, $/m^2	77.35	77.35
Shroud top fabrication cost, $/kg	7.92	7.92
Shroud bottom fabrication cost, $/m^2	99.84	99.84
Shroud bottom fabrication cost, $/kg	7.67	7.67
Shroud top thickness, m	1.524×10^{-3}	1.524×10^{-3}
Shroud side thickness, m	1.2192×10^{-3}	1.2192×10^{-3}
Shroud bottom thickness, m	3.4036×10^{-3}	3.4036×10^{-3}
Vessel wall material cost, $/kg	.4718	.4718
Vessel end material cost, $/kg	.4806	.4806
Vessel fabrication cost, $/m^2	615.47	615.47
Vessel fabrication cost, $/kg	2.447	2.447
Tube material cost coefficient	.028	.028
Tube material cost, $/kg	3.9091	5.1998
Tube fabrication cost, $/kg	11.9	11.9
Tube fabrication cost, $/m^2	964.3398	964.3398
Storage material cost, $/kg	.441	.441
Insulation cost, $/kg	.2866	.2866

Cost Calculation Output Data		
Tube material cost, $	1479.	2013.
Total tube cost, $	14331.	15190.
Storage material cost, $	5733.	7938.
Insulation cost, $	992.	1173.
Shroud side material cost, $	173.	199.
Shroud side total cost, $	336.	376.
Shroud bottom material cost, $	120.	138.
Shroud bottom total cost, $	582.	640.
Shroud top material cost, $	54.	62.
Shroud top total cost, $	315.	345.
Shroud total material cost, $	346.	398.
Shroud total cost, $	1232.	1361.
Vessel material cost, $	1321.	1644.
Vessel total cost, $	3271.	3929.
Total materials cost for TES, $	9872.	13166.
Total fabrication cost for TES, $	15687.	16426.
TES total cost, $	25559.	29592.
% OF TOTAL COST, HEAT EXCHANGER	56	51

This represents an annual cost increase over the six years of 6.6%. On this basis the cost in 1977, the year in which TESS comparative costs are based, would have been $20,600. This was subtracted from the computed TESS cost in order to obtain a Storage Specific Cost After Boiler Credit.

An additional benefit would accrue to the dual heat exchanger TESS in the Sandia solar total energy system resulting from the elimination toluene boiler; namely, the heat loss from the boiler during the nighttime system shutdown, especially in winter (Ref. 4). Since this represents an operating cost benefit, no credit is taken in the capital costs reported here.

The side-by-side tube concept was chosen for this study because it is simple to represent mathematically, and a method of constructing such tubing can be easily visualized. For small diameters (.004 - .03 m), the cost per unit weight of tubing decreases as diameter increases and this is reflected in the heat exchanger costs of the Reference Design. A double tube consisting of two identical tubes was considered to have a material cost just twice that of a single tube. These factors may unfairly favor the dual tube costs since they are based upon a tubing configuration which is not known to be readily available. However, it seems probable that such tubing can readily be manufactured. For example, two tubes might be passed side-by-side through a continuous MIG (metal-inert gas) welding machine which lays a fillet between them, or an electric current could be applied across them to cause a continuous line weld between them.

Another concept which might apply would use two coaxial tubes with an annulus between, plus a single tube. One fluid would flow through the annulus, while the other fluid would flow through the inner coaxial tube and through the single tube. This system provides for direct heat exchange between the two fluids, and between each fluid and the storage medium. Coaxial tube configurations are presently available; designs exist with fins and wire in the annulus to promote turbulence or direct heat transfer between the inner and outer walls.

The computation of the single and dual heat exchanger costs on the same material and fabrication cost basis may underestimate the cost of the dual heat exchanger. In order to show the latitude for cost increase, the cost of the dual heat exchanger was modified in the following three cases:

62

Case 1

The material cost of tubing of the dual heat exchanger was fixed at twice that of the single tube exchanger ($10.4/kg vs. $5.2/kg) to eliminate the cost advantage of larger diameters. Then the fabrication costs were allowed to increase 22% until the storage specific cost of the dual heat exchanger TESS was the same as that of the single tube heat exchanger TESS, viz. $9.57/mJ.

Case 2

The material cost was kept the same ($3.9/kg), and it was found that the fabrication costs could be allowed to increase 41% before the storage specific cost of the single tube heat exchanger TESS was exceeded.

Case 3

The material cost was kept the same but the fabrication costs were doubled. This produced a storage specific cost of $11.91/mJ for the dual heat exchanger TESS.

The results of these comparisons are shown in Table VI.

Table VII shows the percentage of total cost of the three cases of the dual heat exchanger TESS described above, and for the single heat exchanger comparison case.

The characteristics of the Reference Designs for the dual and single heat exchanger are summarized on Table VIII where the Case 3 heat exchanger cost has been assumed for the dual heat exchanger TESS in order to present the results on what is believed to be a conservative basis. On this basis the dual heat exchanger TESS has a specific cost which is higher than the single heat exchanger TESS by 25% before the boiler credit, but which is only 58% of the single heat exchanger TESS cost after boiler credit. This cost saving is achieved while the performance as measured by the Figure of Merit is improved from .92 to .95.

TABLE VI

COMPARISON OF THREE METHODS OF CALCULATING
HEAT EXCHANGER COST FOR DUAL HEAT EXCHANGER TESS

	Case 1	Case 2	Case 3
Cost Calculation Input Data:			
Tube Material Cost Coefficient	.0745	.028	.028
Tube Material Cost, $/kg	10.401	3.909	3.909
Tube Fabrication Cost, $/kg	14.518	16.815	23.8
Tube Fabrication Cost $/m^2	1176	1362	1929
Cost Calculation Output:			
Tube Material Cost, $	3934	1479	1479
Total Tube Cost, $	19614	19639	27183
Total TESS Materials Cost $	12327	9872	9872
Total TESS Fabrication Cost $	18515	20995	28540
Total TESS Cost $	30842	30867	38411
Storage Specific Cost, $/MJ:			
Before boiler credit	9.57	9.57	11.91
After boiler credit	3.18	3.18	5.52

TABLE VII

PER CENT OF TOTAL COST OF TESS

	Dual Heat Exchanger		Single Heat Exchanger
	Case 1 and Case 2	Case 3	
Thermkeep	19	15	27
Heat exchanger	64	71	51
Containment	11	9	13
Thermal insulation	3	3	4
Outer shroud	4	3	5

TABLE VIII

SUMMARY OF DUAL AND SINGLE HEAT EXCHANGER
TESS DESIGN POINTS

	Dual	Single
Tank height and diameter, m	2.11	2.35
System height and diameter, m	3.4	3.6
Quantity of Thermkeep, kg	13,000	18,000
Heat exchanger:		
Tube inside diameter, cm	.716	0.457
Number of tubes	150 (prs)	280
Total length, m	5588	7761
Figure of merit	.95	.92
Total cost $	38411	29592
Specific cost, $/MJ	11.91	9.57
Boiler credit $	20600	None
Net specific cost, $/MJ	5.52	9.57

CONCLUSIONS

A program of experimentation and analysis has been carried out to continue and extend the work reported in NASA CR-159465, on the development of a phase-change thermal energy storage system (TESS) using modified anhydrous sodium hydroxide for solar electric power generation.

The phase-change medium used comprises commercial grade anhydrous NaOH modified by the addition of 8% (wt) of $NaNO_3$ and 0.2% MnO_2.

The TESS studied in the prior work utilizes a single heat exchanger and a non-phase-change heat transfer fluid, and is designed to meet the following operating conditions:

> Storage capacity is 3.1×10^6 kJ operating over the range 516 K to 584 K. Heat is charged into the storage medium at a maximum rate of 1.8×10^6 kJ/hr, at a temperature of 584 K $\pm$ 2 K. Heat is discharged from storage at a maximum rate of 1.0×10^6 kJ/hr at a temperature of 582 K $\pm$ 2 K.

The present program consisted of three parts:

> Part I extends the prior work by means of chemical analyses of the storage medium, and examination of the heat exchanger of the one-tenth scale experimental model constructed and tested in the prior program.

> Part II utilized the physical model of the prior program to obtain experimental data with a different heat transfer fluid, Caloria HT-43, for further verification of a computer model of the prior program which used Therminol-66.

> Part III included the development of a new computer model which introduced a second heat exchanger into the TESS for evaporating and superheating the power fluid for a Rankine cycle power generator. This was used to produce a cost optimize reference design of a TESS for comparison with the single heat exchanger design of the prior work.

No chemical deterioration of the medium was found. Some
physical segregation of components was observed, which
is attributed to the fact that the medium is a non-
eutectic mixture, but no corresponding deterioration in
performance was noted. Physical segregation can be
reversed by periodic complete melting of the medium.

No significant physical deterioration of the heat ex-
changer was observed.

The dual heat exchanger TESS was found to be superior to
the single heat exchanger design in performance and in
capital cost, due to savings resulting from the elimi-
nation of an external heat exchanger. Additional ad-
vantages result from system operating cost savings.

Auxiliary heating is used to raise the temperature of
the power fluid vapor to the specified temperature, and
a figure of merit is defined as the ratio of the heat
from storage to the sum of the heat from storage plus the
auxiliary heat. This is used as the measure of performance.

The design comparison is summarized as follows:

	Dual Heat Exchangers	Single Heat Exchangers
Quantity of storage medium, kg	13,000	18,000
Heat exchanger tubing		
Inside diameter, cm	0.716	0.457
Total length, m	5588	7761
Total cost	$38,411	$29,592
Specific cost, $/MJ	11.91	9.57
Boiler credit	$20,600	-0-
Net specific cost, $/MJ	5.52	9.57
Figure of Merit	.95	.92

A P P E N D I X   A

THERMKEEP POST TEST ANALYSIS

(Technical Report - Skinner & Sherman, Inc.

Scientific Services Since 1922

CHEMICAL ▪ PHYSICAL
ELECTRICAL ▪ BACTERIOLOGICAL

TECHNICAL REPORT
prepared for

COMSTOCK & WESCOTT, INC.

CASE NO. 11833

31 July 1979

CLIENT: Comstock & Wescott, Inc.
765 Concord Avenue
Cambridge, MA   02138

Attention: Mr. Richard Rice

CASE NO: 11833

REFERENCE: Purchase Order No. 29519

PROJECT DESCRIPTION:

To analyze fifteen (15) samples of inorganic salt mixture for $NaNO_3$, $NaNO_2$, MnO_2, Na_2CO_3 and $NaCl$.

SAMPLE IDENTIFICATION:

#1	C&W	#1
#2	C&W	#2
#3	C&W	#3
#4	C&W	#4
#5	C&W	#5
#6	C&W	#6
#7	C&W	#7
#8	C&W	#8
#9	C&W	#9
#10	C&W	#10
#11	C&W	#11
#12	C&W	#13
#13	C&W	#14
#14	C&W	#15
#15	C&W	#16

METHODS OF TESTS:

1.   Standard Methods for the Examination of Water and Wastewater, 14th Edition, 1975.

2.   Atomic Absorption Spectroscopy for total manganese.

skinner & sherman laboratories inc.

A-5

New England Laboratories
300 SECOND AVENUE, WALTHAM, MASSACHUSETTS 02254 ● 617-890-7200

31 July 1979

Page 2 of 2

CLIENT: Comstock & Wescott, Inc.

CASE NO: 11833

3. Colorimetric Method, using spectrophotometer, Beckman DB for sodium nitrite.

4. Official Methods of Analysis of the Association of Official Analytical Chemists.

5. Scott's Standard Methods of Chemical Analysis.

RESULTS OF ANALYSIS:

	Sodium Nitrate	Sodium Nitrite	Sodium Carbonate	Sodium Chloride	Manganese Dioxide
			Percent		
Sample #1	8.467	0.0306	2.62	2.03	0.172
Sample #2	7.477	0.0307	1.45	1.98	0.171
Sample #3	4.652	0.0020	2.85	1.73	0.101
Sample #4	5.278	0.0021	1.48	1.35	0.085
Sample #5	5.041	0.0023	1.55	1.47	0.113
Sample #6	5.326	0.0022	1.43	1.63	0.110
Sample #7	4.503	0.0019	1.38	1.68	0.083
Sample #8	4.377	0.0023	1.35	1.85	0.110
Sample #9	5.623	0.0023	2.89	1.65	0.102
Sample #10	4.878	0.0026	1.36	1.76	0.095
Sample #11	2.791	0.0017	1.44	1.53	0.042
Sample #13	2.707	0.0021	1.40	1.76	0.057
Sample #14	2.546	0.0032	1.32	1.25	0.053
Sample #15	5.772	0.0098	2.88	1.58	0.137
Sample #16	5.138	0.0095	2.90	1.43	0.172

Respectfully submitted,

SKINNER & SHERMAN LABORATORIES, INC.

Sidonie Herzfeld, Ph.D.
Chemist

SH/ls

A-6

skinner & sherman laboratories inc.

New England Laboratories

300 SECOND AVENUE, WALTHAM, MASSACHUSETTS 02254 ● 617-890-7200

A P P E N D I X   B

HYSTERESIS STUDY GRAPHS

SYMBOLS

Thermkeep temperatures:

o = Shallow well temperatures vs.
location in tank

Δ = Deep well temperatures vs.
location in tank

+ = Computer model predictions

Figure B-1. Test No. 1

```
310-|  Δ     +o     Δ                                              LOGGER DATA: 020202
   -|          +      Λ                                            DATE/TIME: 002:15:00:00
   -|         +      o                                             TEMP.CORRECTION,°C: -.2
   -|                                                              FORTRAN RUN:H2024 012480
300-|                              o                               ELAPSED TIME: 5    HOURS
   -|                            Δ
   -|                         .      o
   -|            +   +   +   +         Δ
290-|                      +   +   +   +
   -|                          +   +  Δ
   -|                              +   Δ   +  Λ
   -|                            o  +   +   +  +
280-|                                      o   +   +   +   +
   -|                                          o   Λ
D  -|                                                    o
E  -|
G 270-|
R  -|
E  -|
E  -|
S 260-|
   -|
C  -|
   -|
250-|
   -|
   -|
   -|
240-|
   -|
   -|
   -↑
230-T-K LEVEL------------------------------------------------------
    |       |       |       |       |       |       |       |       |
    25      50      75     100     125     150     175     200     225
              DISTANCE FROM TOP OF TES, cm
          THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
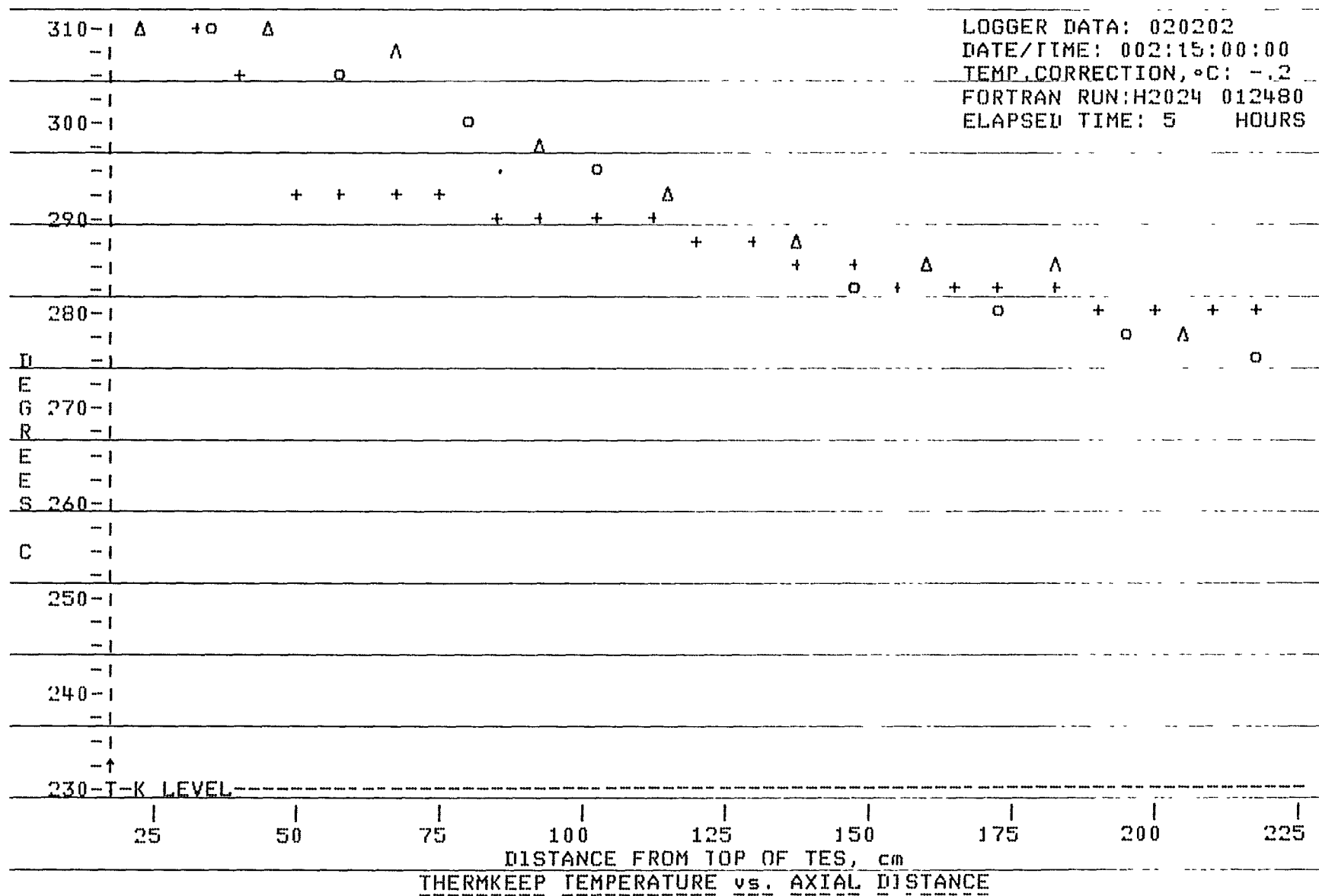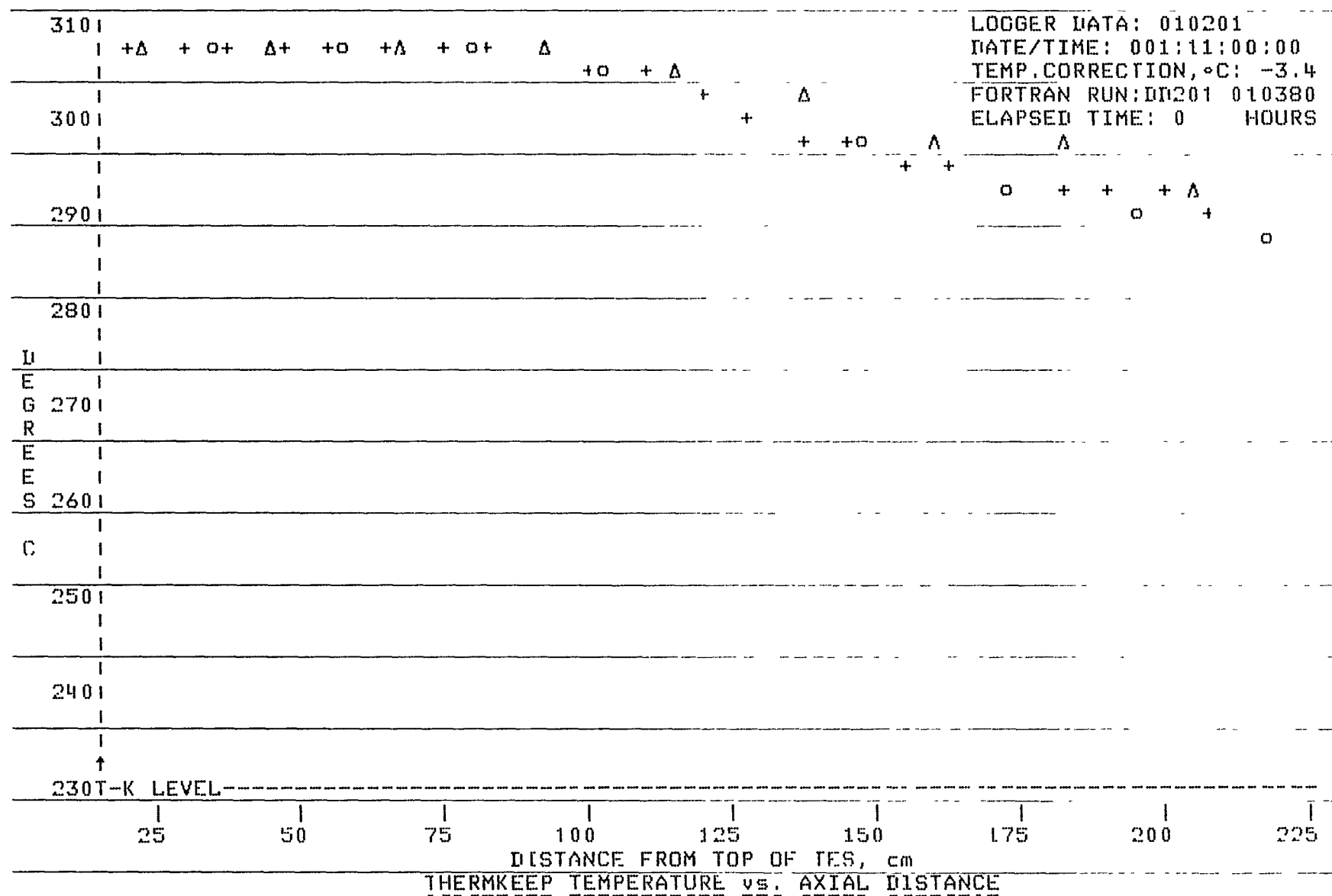
Figure B-2. Test No. 1

Figure B-3. Test No. 2

Figure B-4.   Test No. 2.

Figure B-5. Test No. 3

LOGGER DATA: 020202
DATE/TIME: 002:13:00:00
TEMP.CORRECTION,°C: -2.2
FORTRAN RUN:H202A 011680
ELAPSED TIME: 3   HOURS

310—
— Δ
—
—   +
300—   o   +
—   +
—   +
—   Δ   o   +
290—
—   Δ   o   +
—   Δ +
—   o+
280—   Δ
—   +   + Δ
D —   +   Δ   Δ
E —   o+   +
G 270—
R —   +   +
C —   o   +   +
E —   o + Δ +   +
S 260—   o
—
C —
—
250—
—
—
—
240—
—
—
— ↑
230———T-K LEVEL————————————————————————————————

        25   50   75   100   125   150   175   200   225
                        DISTANCE FROM TOP OF TES, cm
                    THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
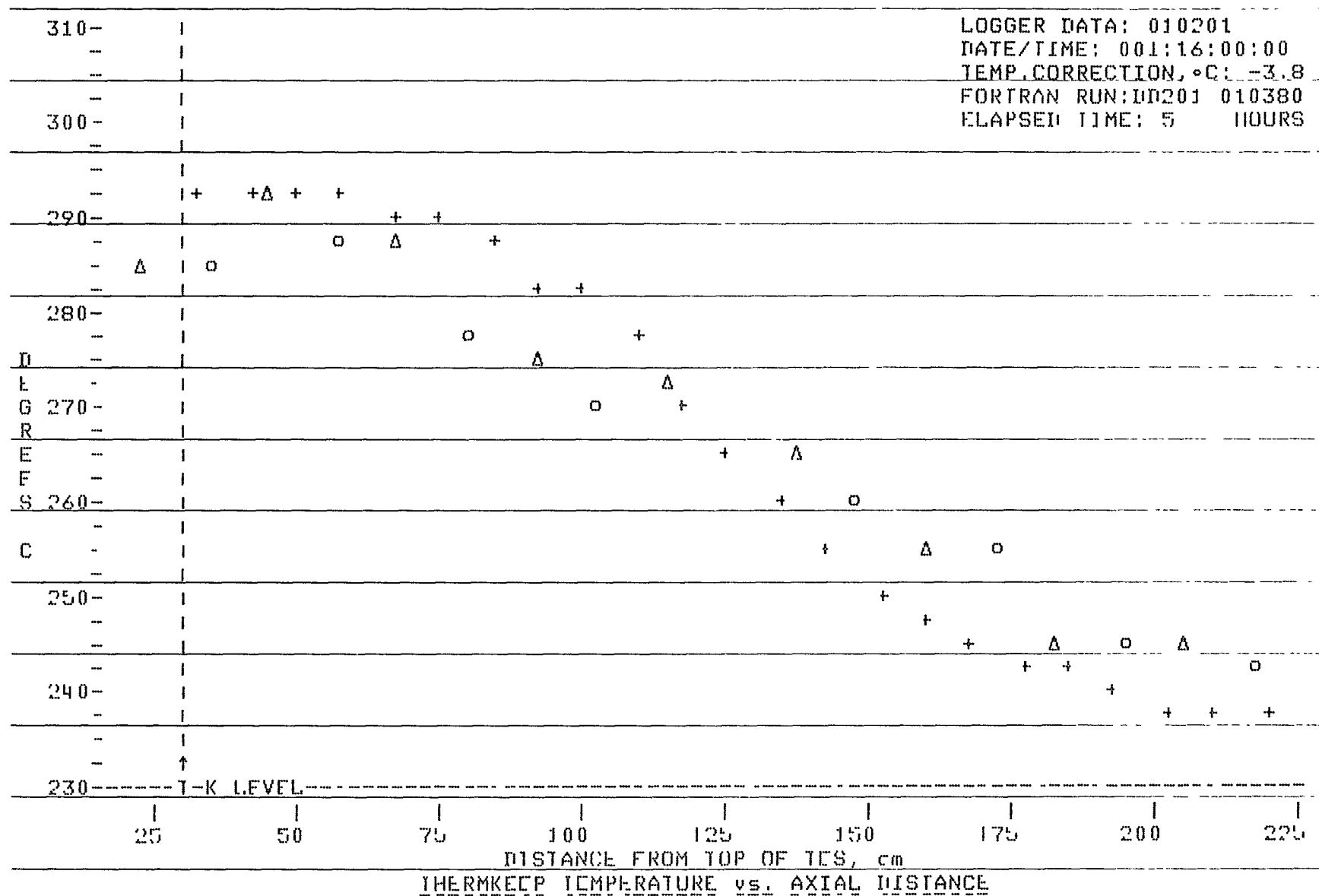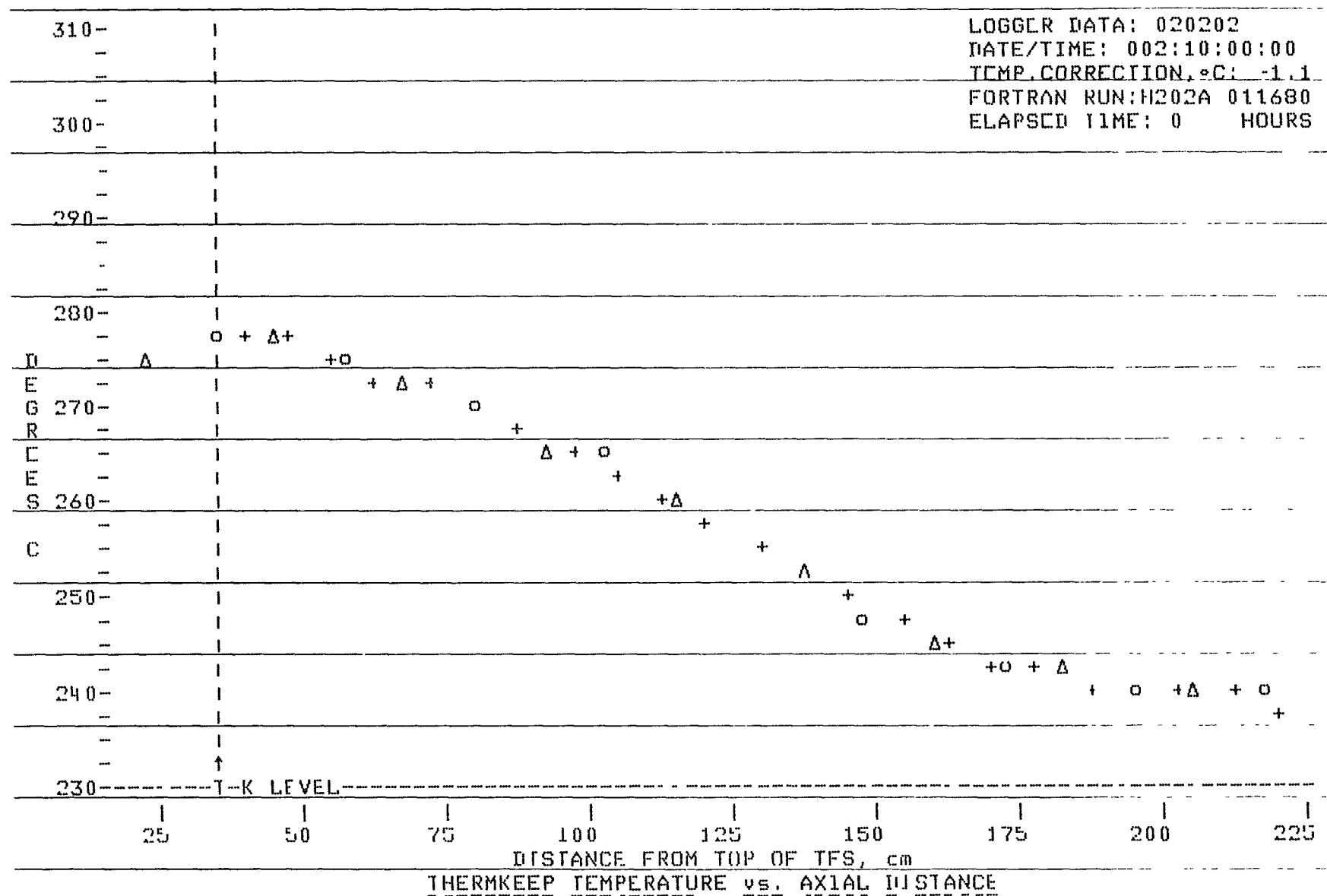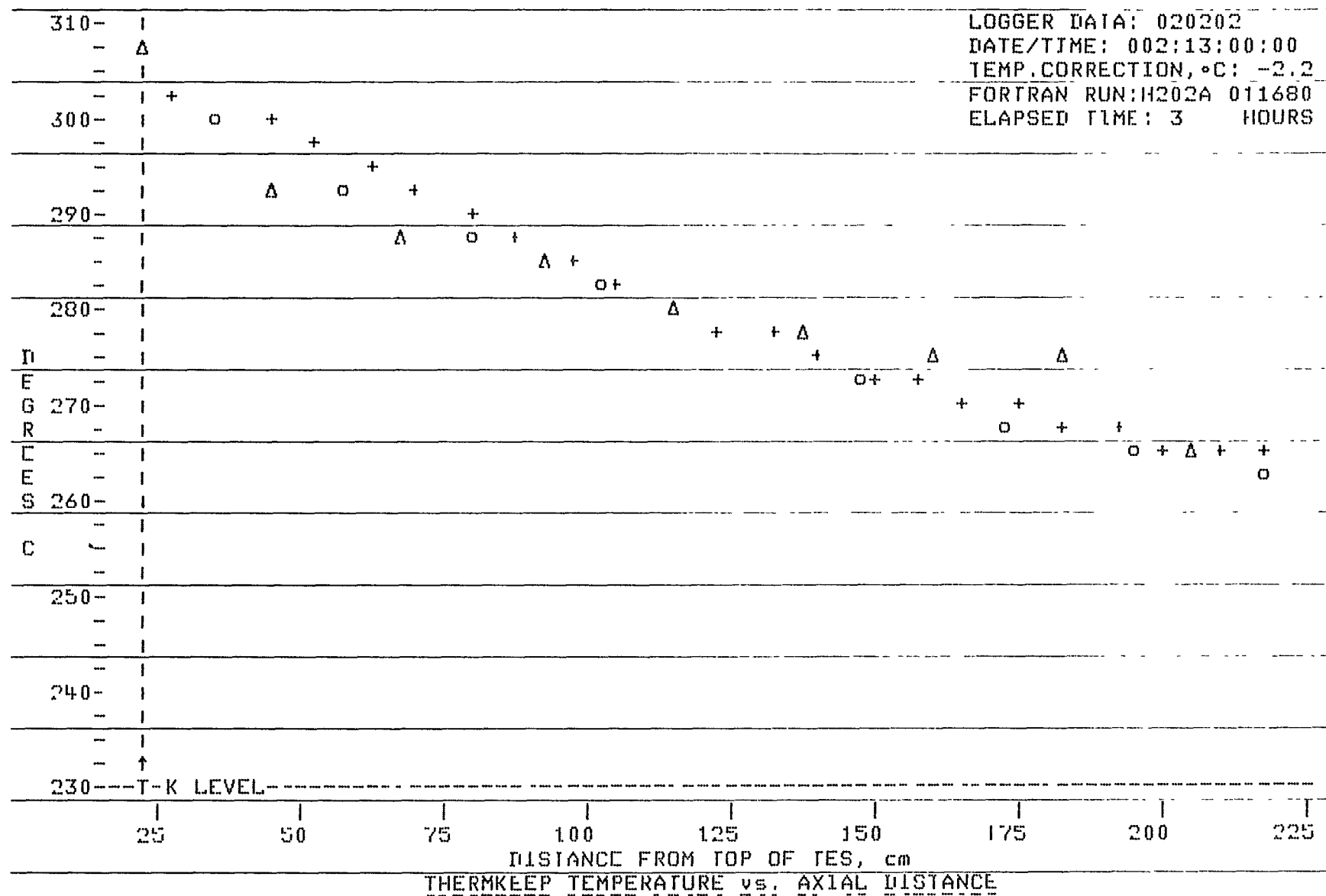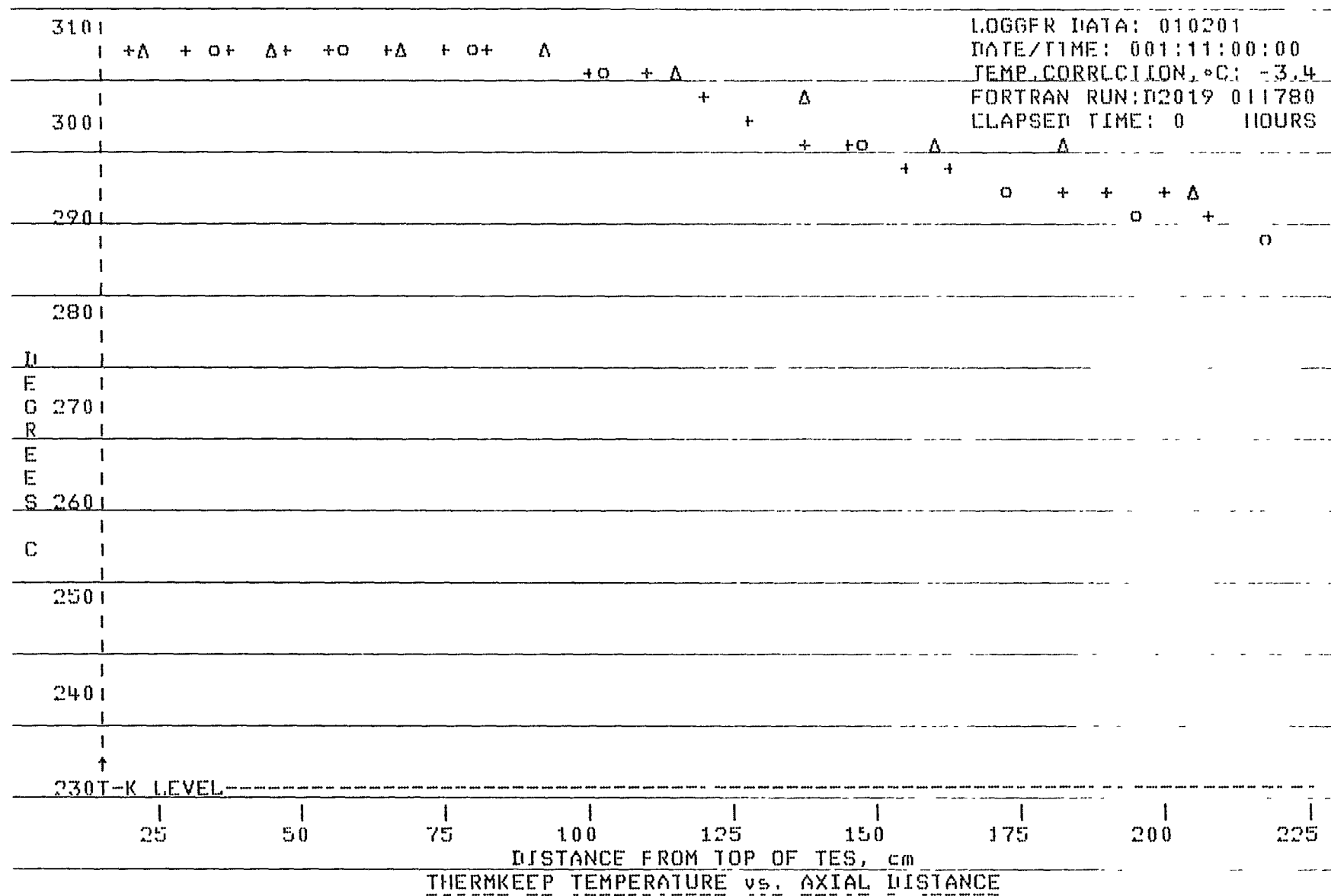
Figure B-6.   Test No. 3

Figure B-7. Test No. 4.
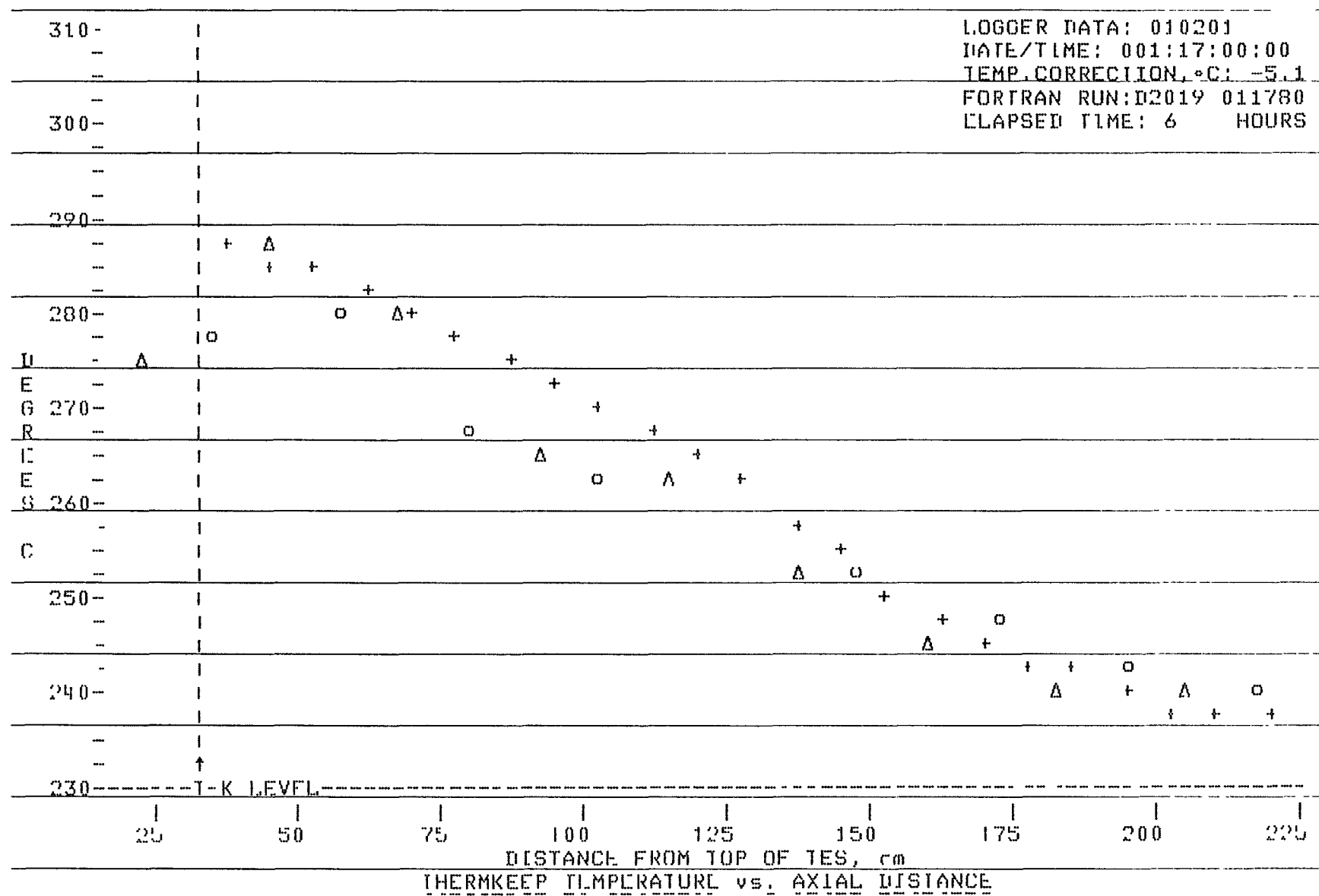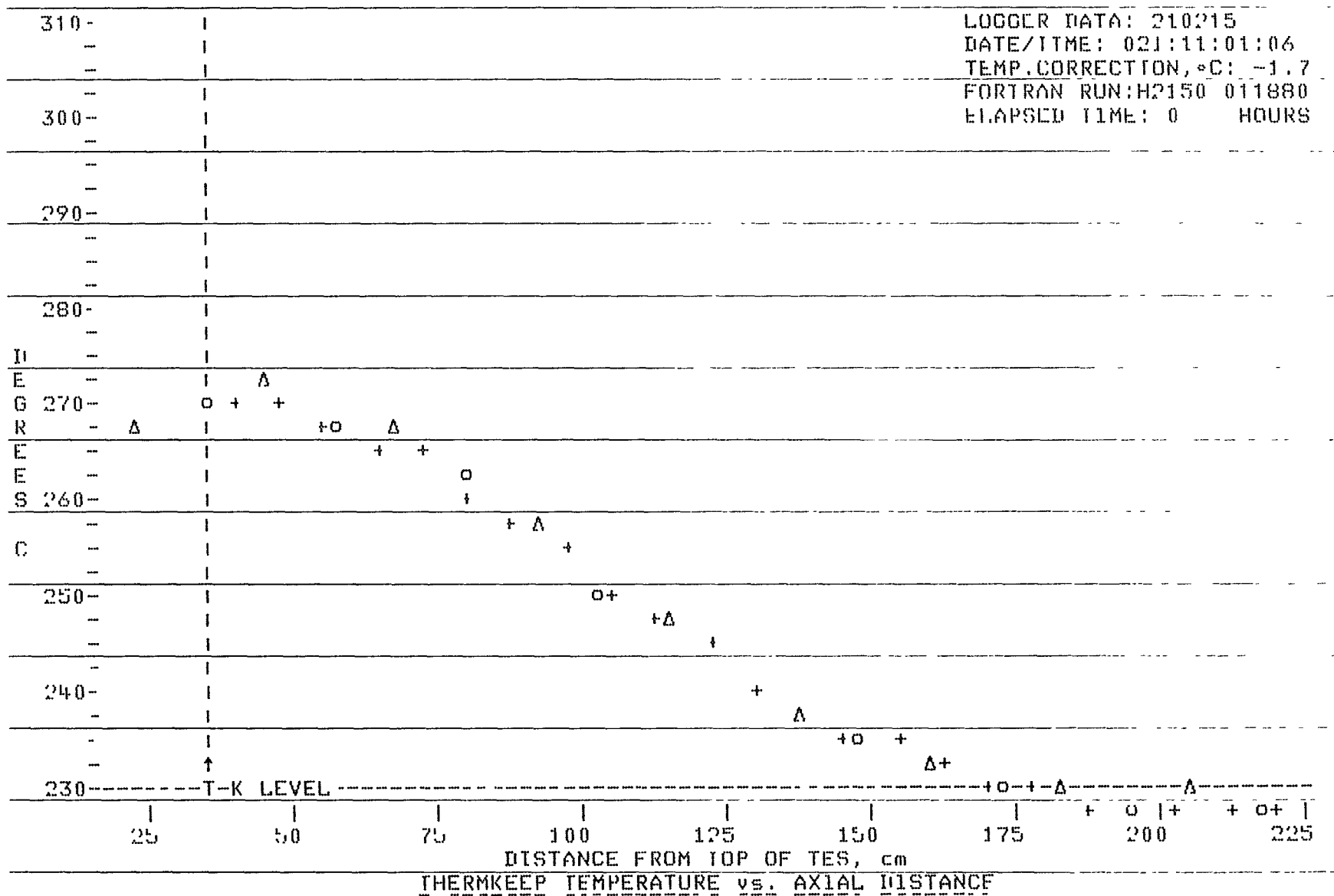
Figure B-8. Test No. 4.
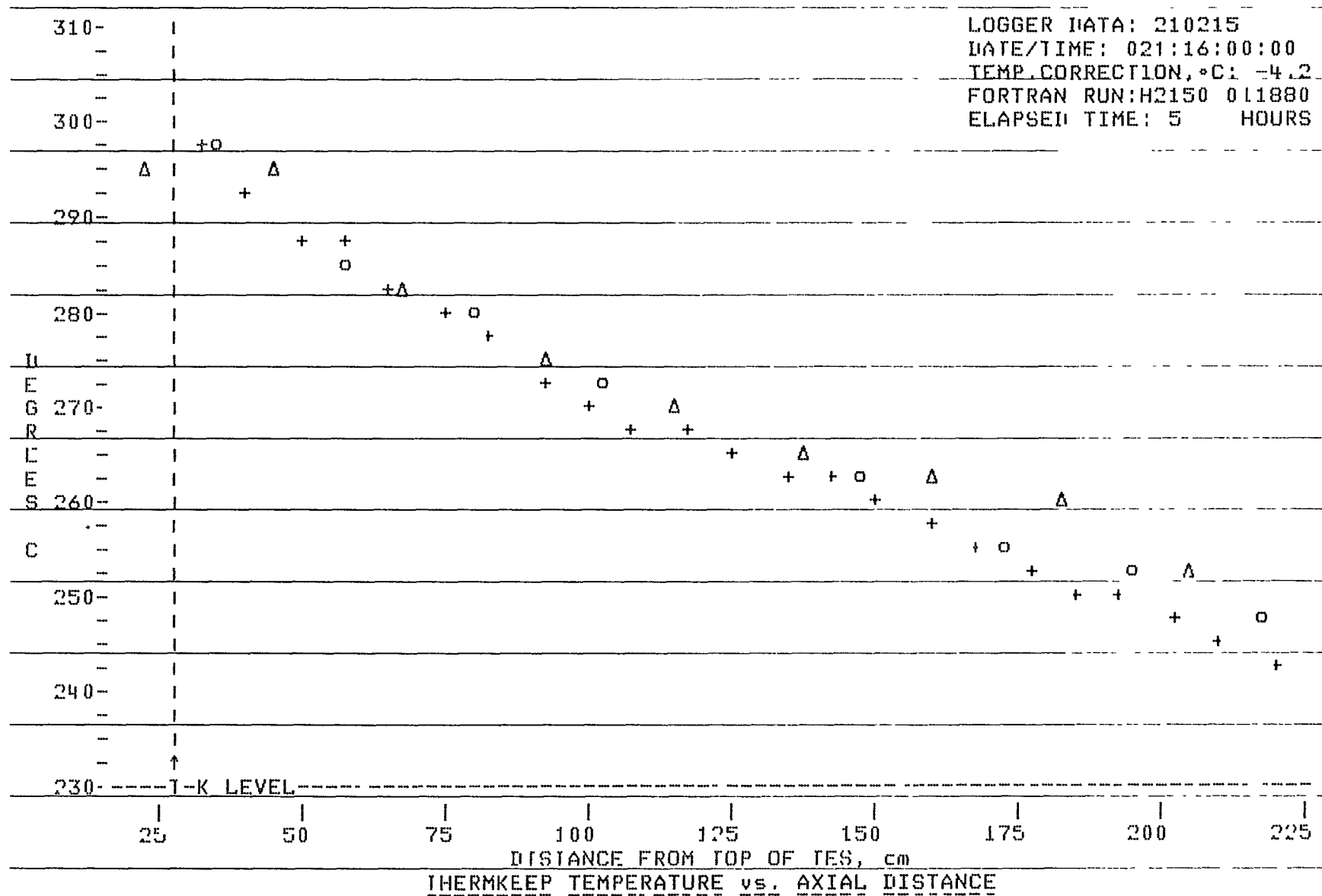
Figure B-9. Test No. 5

Figure B-10.   Test No. 5.

Figure B-11. Test No.6.

LOGGER DATA: 112142
DATE/TIME: 011:17:00:00
TEMP.CORRECTION,°C; -4.4
FORTRAN RUN:D2140 011880
ELAPSED TIME: 6   HOURS

```
310-   |
   --  |
   --  |
   --  |
300-   |
   --  |
   -   |
   --  Λ |
290-   | |  +    +
   -   |   o    Δ+    +    +
   -   |        o    Λ
   --  |            +  o      Λ
280-   |              +    +
   --  |                 +o
II --  |                   +
|  -   |                   +          Λ
G 270- |                     +
R  -   |                        +
E  -   |                          +  o      Λ
E  -   |                             +
S 260- |
   --  |                                +    o
C  -   |
   -   |                                  +    Λ
250-   |
   -   |                                    +    o
   --  |
   --  |                                        +    Λ    o
240-   |                                          +
   --  |                                            +
   --  |                                              +    +
   --  ↑
230-----T-K LEVEL-------------------------------------------------
       |        |        |        |        |        |        |        |
      25       50       75      100      125      150      175      200      225
                     DISTANCE FROM TOP OF TES, cm
              THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

Figure B-12. Test No. 6.

Figure B.13. Test No. 7.

```
310-|  Δ        O      Δ
  -|       +     +                    Δ
  -|                +    O                              TEMP.CORRECTION,°C: -.2
  -|                  +
300-|                                                   FORTRAN RUN:H2020 011880
  -|                           O                        ELAPSED TIME: 5     HOURS
  -|                        +       Δ
  -|                    +            O
  -|                      +       Λ
290-|                         +    +
  -|                            +    +
  -|                              +    +        Λ            Λ         Λ
  -|                                   O
280-|                                       +    +   O
  -|                                          +    +        O    Δ
   -|                                              +    +        O
E  -|                                                        +    +
G 270-|
R  -|
C  -|
E  -|
S 260-|
  -|
C  -|
  -|
250-|
  -|
  -|
  -|
240-|
  -|
  -↑
230-T-K LEVEL
```

LOGGER DATA: 020202
DATE/TIME: 002:15:00:00
TEMP.CORRECTION,°C: -.2
FORTRAN RUN:H2020 011880
ELAPSED TIME: 5   HOURS

```
       25      50      75      100     125     150     175     200     225
```

DISTANCE FROM TOP OF TES, cm

THERMKELP TEMPERATURE vs. AXIAL DISTANCE

Figure B-14. Test No. 7.

```
310|
   |  +Δ   + O+   Δ+   +O   +Δ   + O+   Δ
   |                              +O   + Δ
   |                                +        Λ
300|                                  +
   |                              +  +O    Λ        Λ
   |                                    +  +
   |                                      O   +  +  + Λ
290|                                             O   +
   |                                                    O
280|
D  |
E  |
G 270|
R  |
E  |
E  |
S 260|
C  |
250|
   |
240|
   |
  ↑
230 T-K LEVEL
      25      50      75     100     125     150     175    200     225
              DISTANCE FROM TOP OF TES, cm
           THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

LOGGER DATA: 010201
DATE/TIME: 001:11:00:00
TEMP.CORRECTION,°C: -3.4
FORTRAN RUN:D2010 011880
ELAPSED TIME: 0   HOURS

Figure B-15. Test No. 8.

LOGGER DATA: 010201
DATE/TIME: 001:17:00:00
TEMP. CORRECTION, °C: -5.1
FORTRAN RUN: D2010 011880
ELAPSED TIME: 6   HOURS

DISTANCE FROM TOP OF TES, cm

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE

Figure B-16.   Test No. 8.

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE

Figure B-17. Test No. 9

Figure B-18. Test No. 9.

A P P E N D I X   C

DATA CORRELATIONS

SYMBOLS

Heat transfer fluid (HT-43 and T-66) temperatures:

    o = Experimental data

    - = Computer model predictions

Thermkeep temperatures:

    o = Shallow well temperature vs. location in tank

    Δ = Deep well temperature vs. locations in tank

    □ = Tank surface temperature vs. location in tank

    + = Computer model prediction
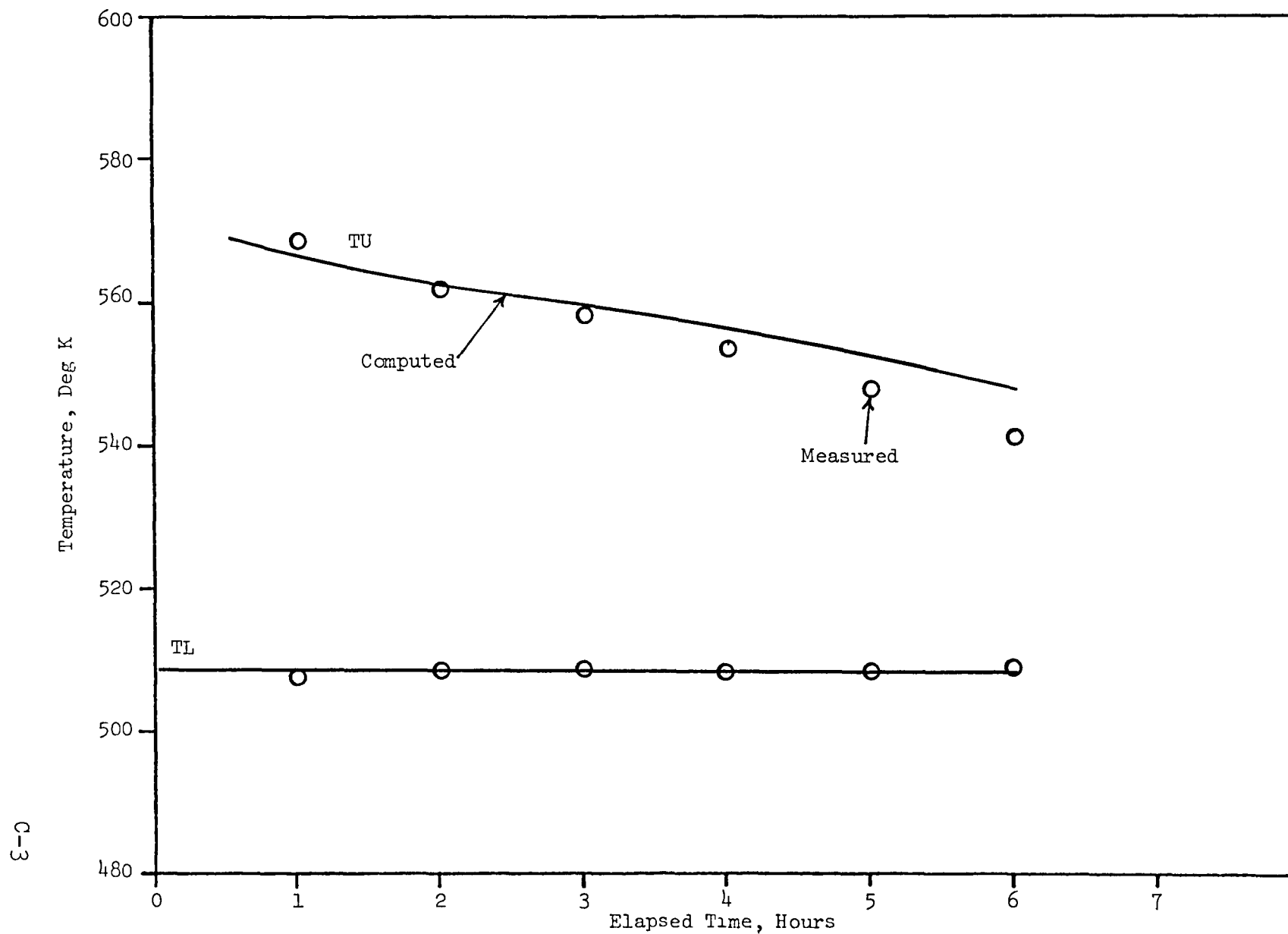
Figure C-1. HT-43 outlet temperature, discharge test 201 (3.3 gpm)
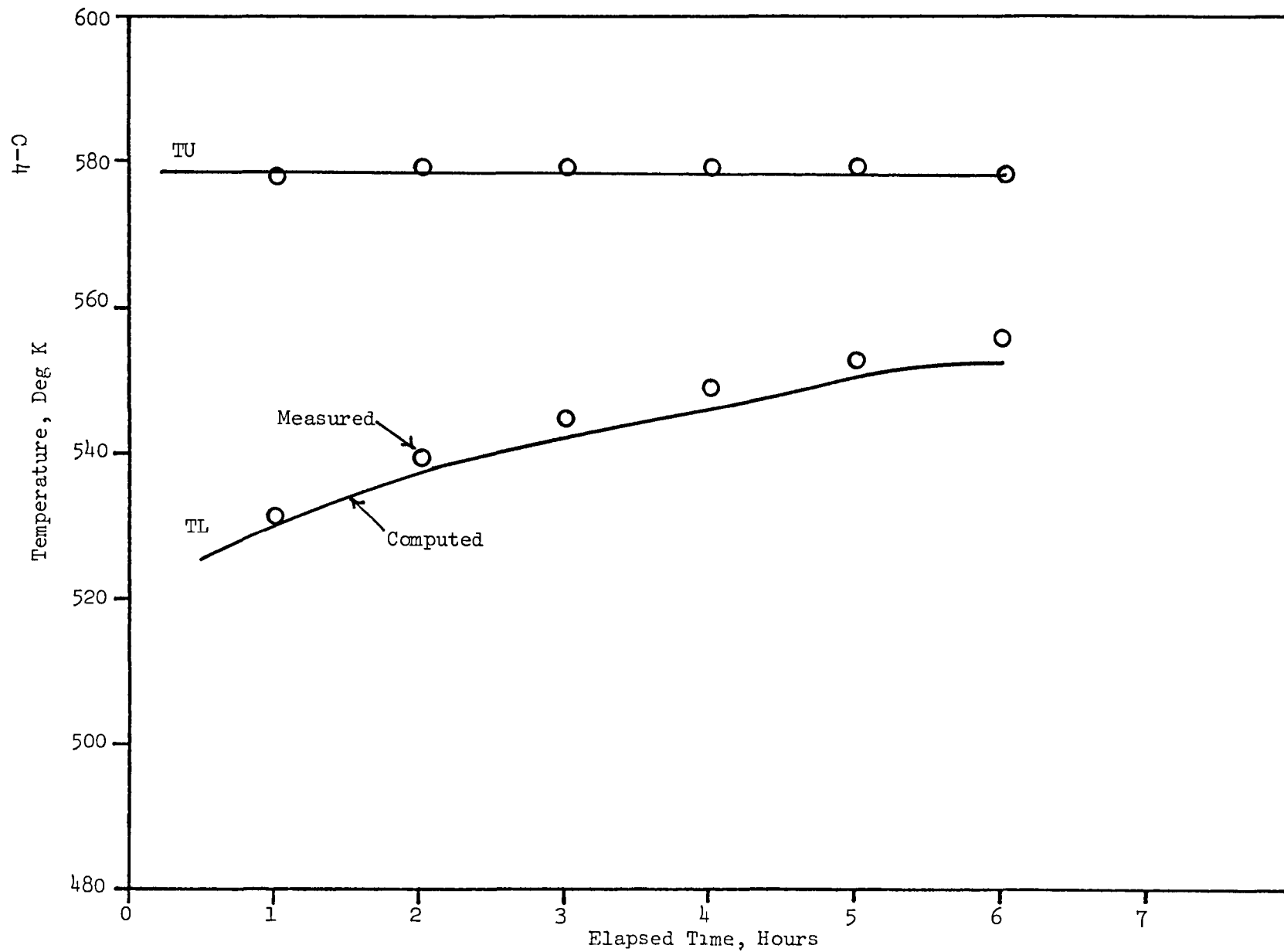
Figure C-2. HT-43 outlet temperature, charge test 202 (3.3 gpm)

C-4
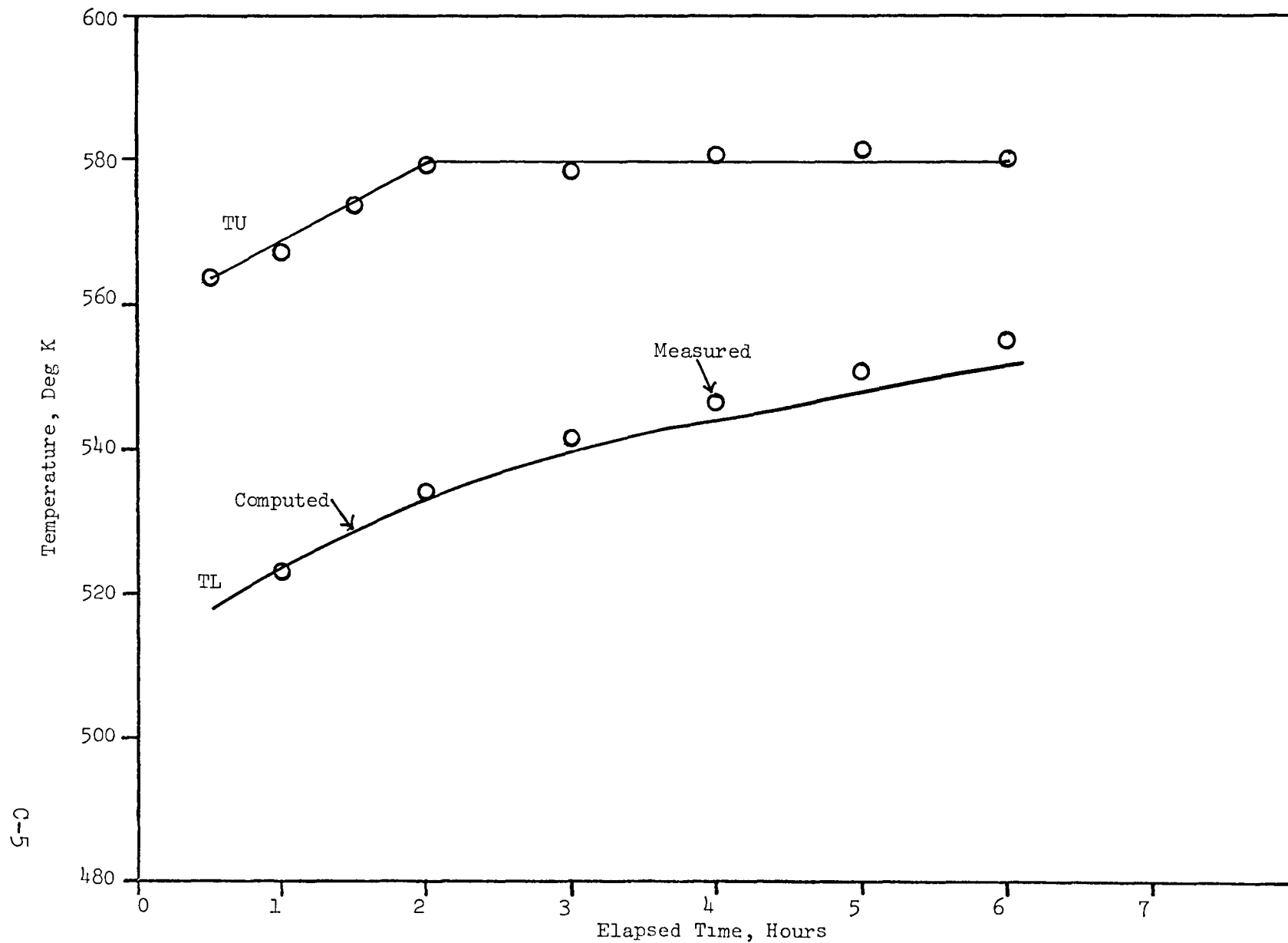
Figure C-3. HT-43 outlet temperature, charge test 204 (3.7 gpm)
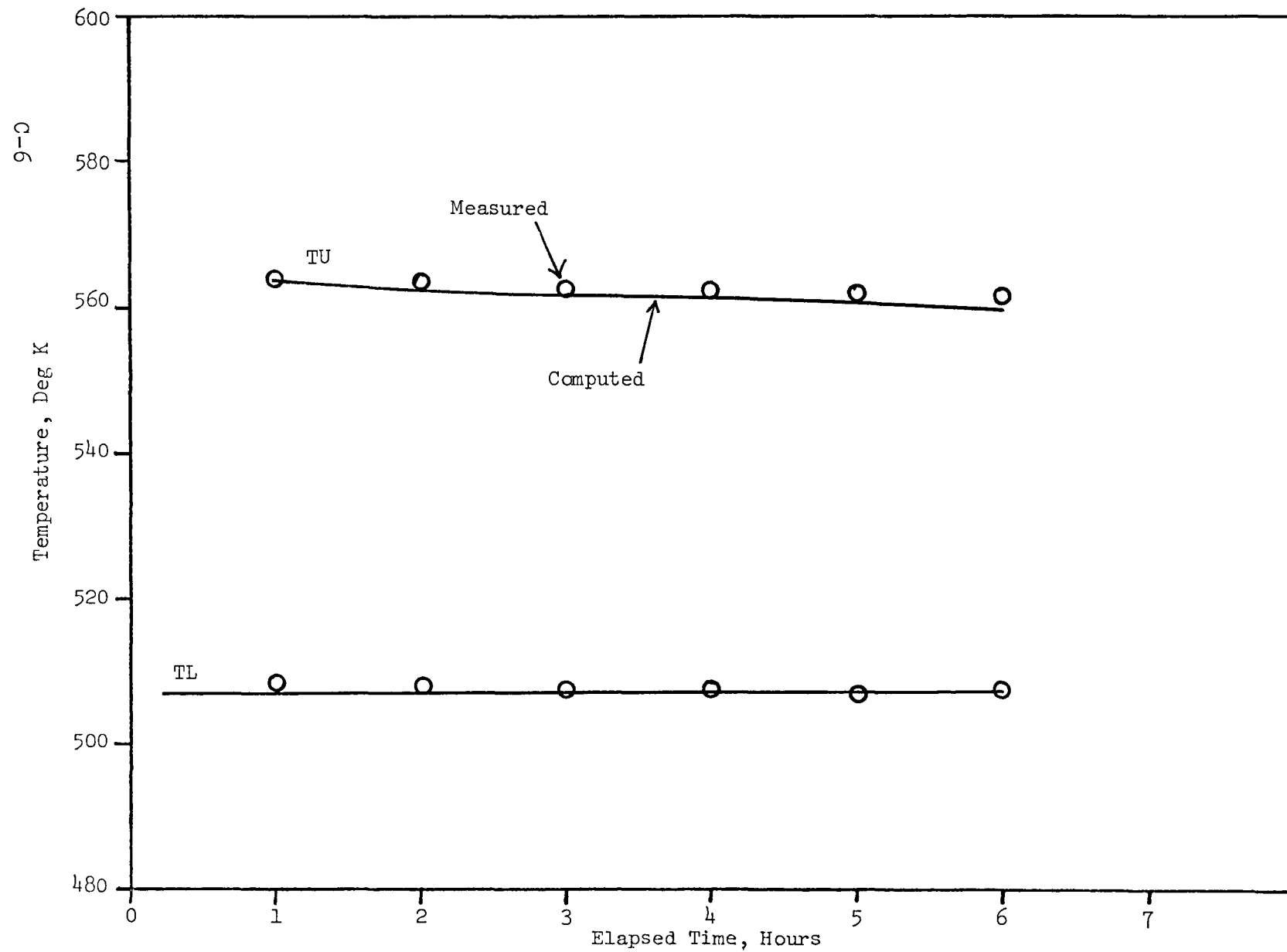
Figure C-4.   HT-43 outlet temperature, discharge test 214-2 (1.1 gpm)
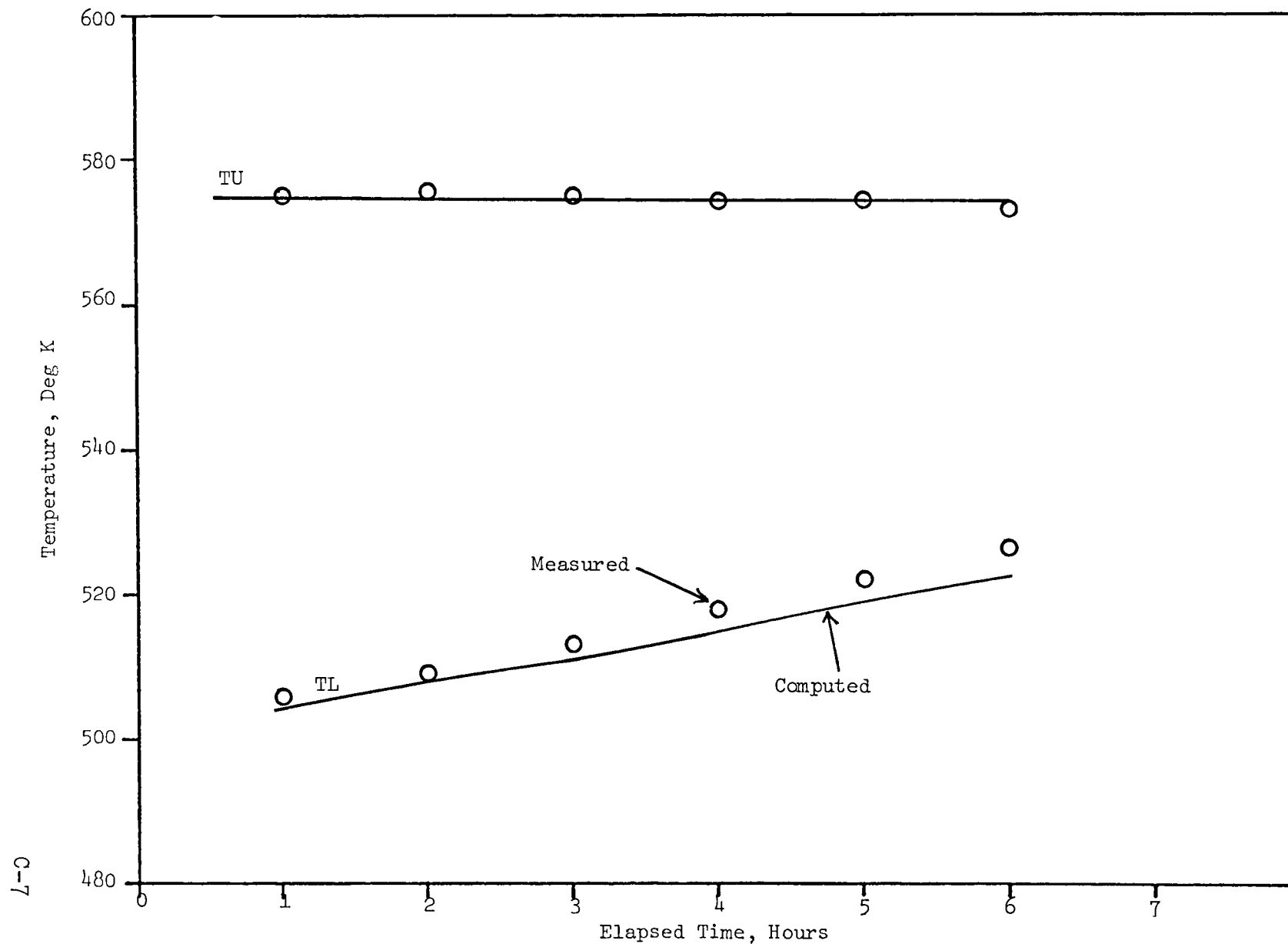
Figure C-5. HT-43 outlet temperature, charge test 215-2 (1.1 gpm)
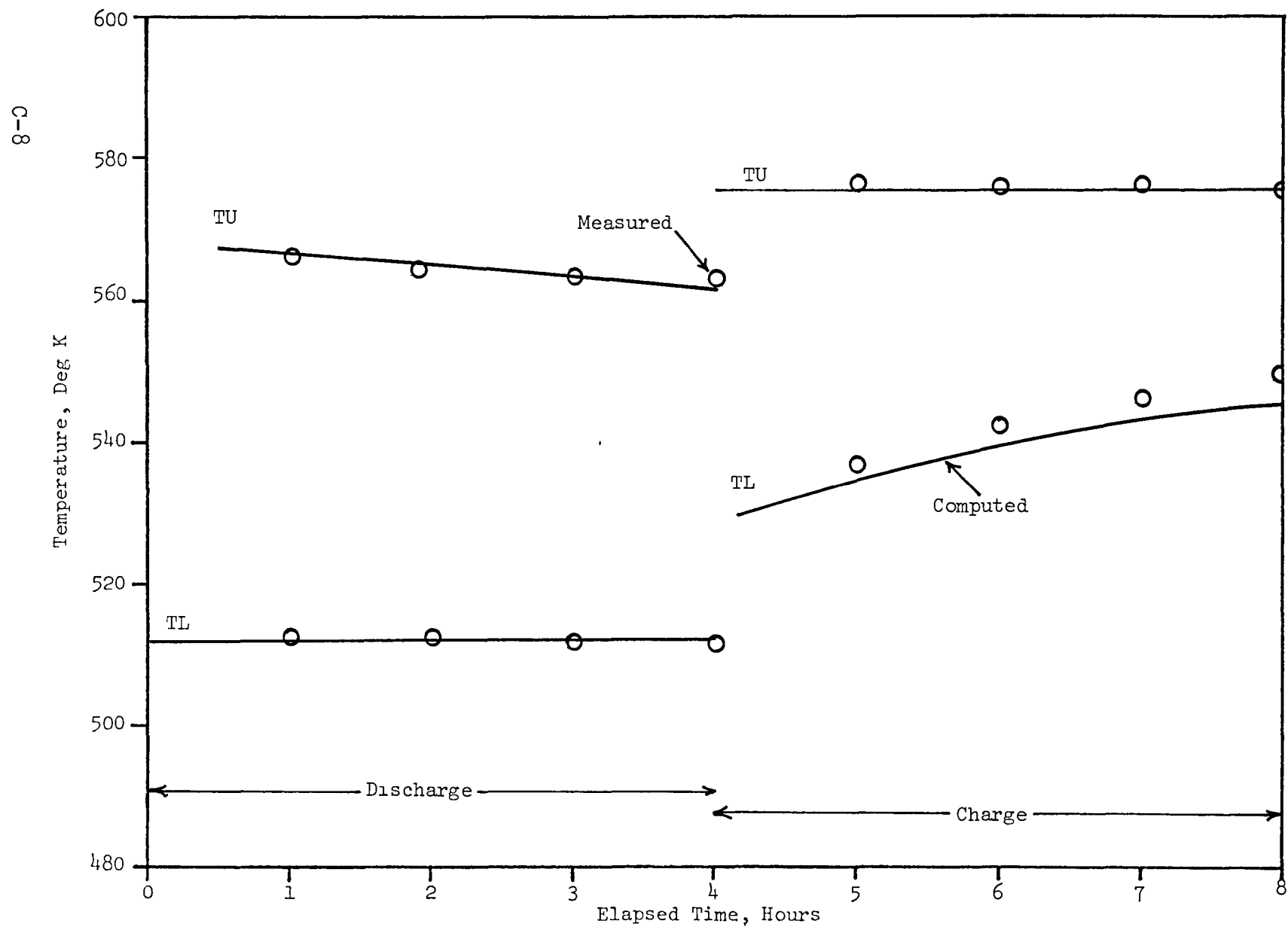
Figure C-6. HT-43 outlet temperature, cyclic test 218 (1.9 gpm), first cycle
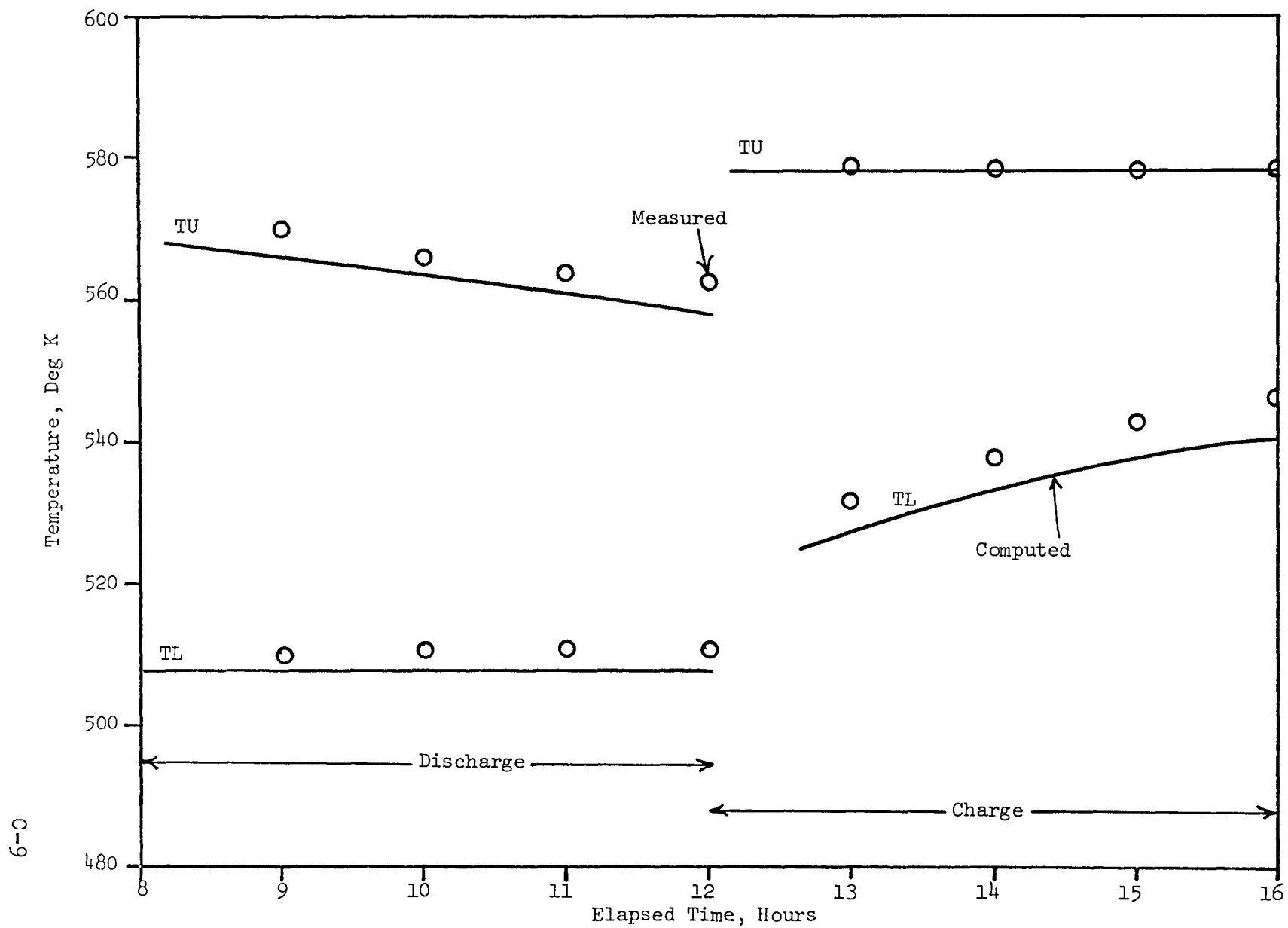
Figure C-7. HT-43 outlet temperature, cyclic test 218 (1.9 gpm), second cycle.
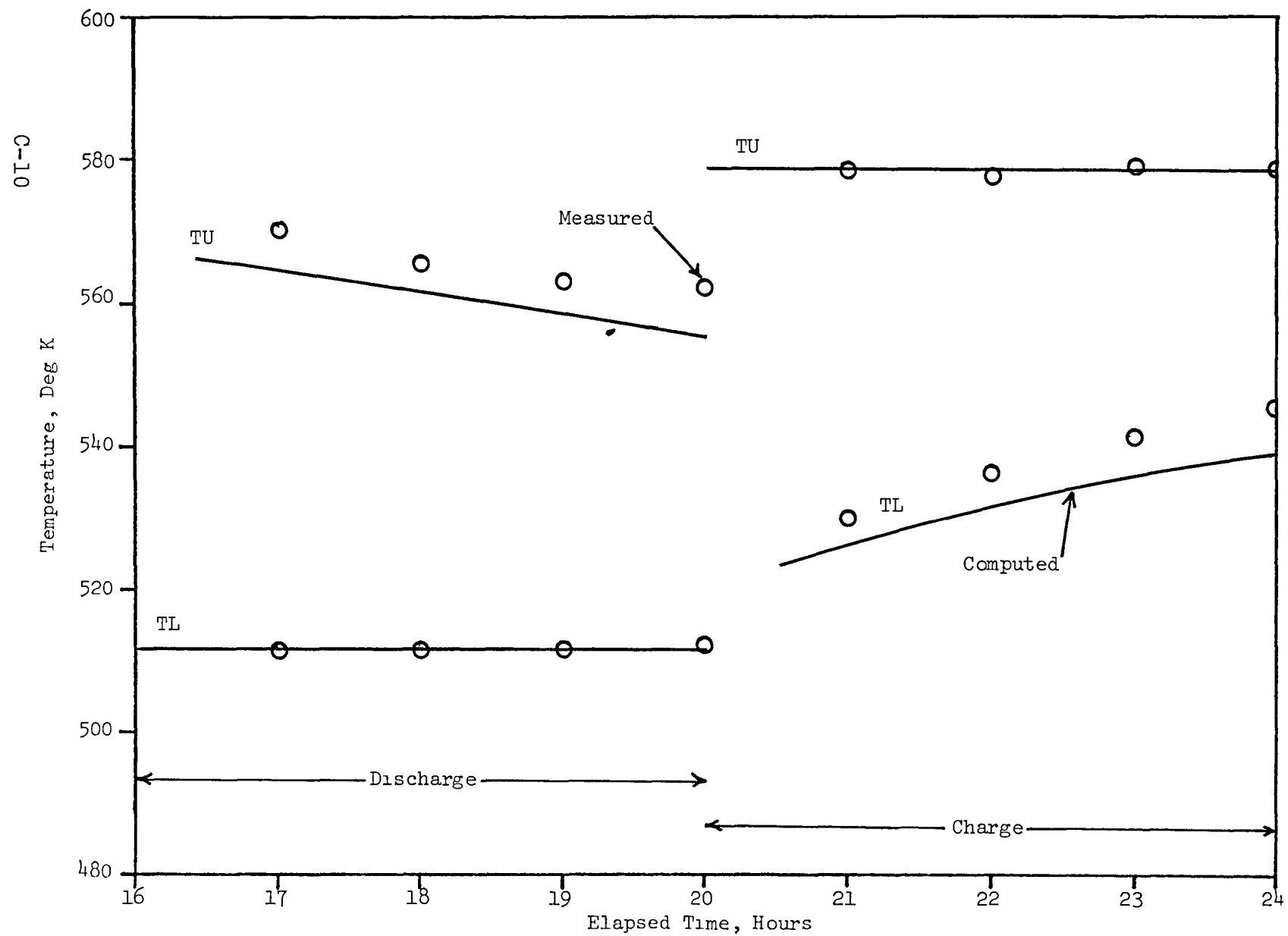
Figure C-8. HT-43 outlet temperature, cyclic test 218 (1.9 gpm), third cycle.

C-10
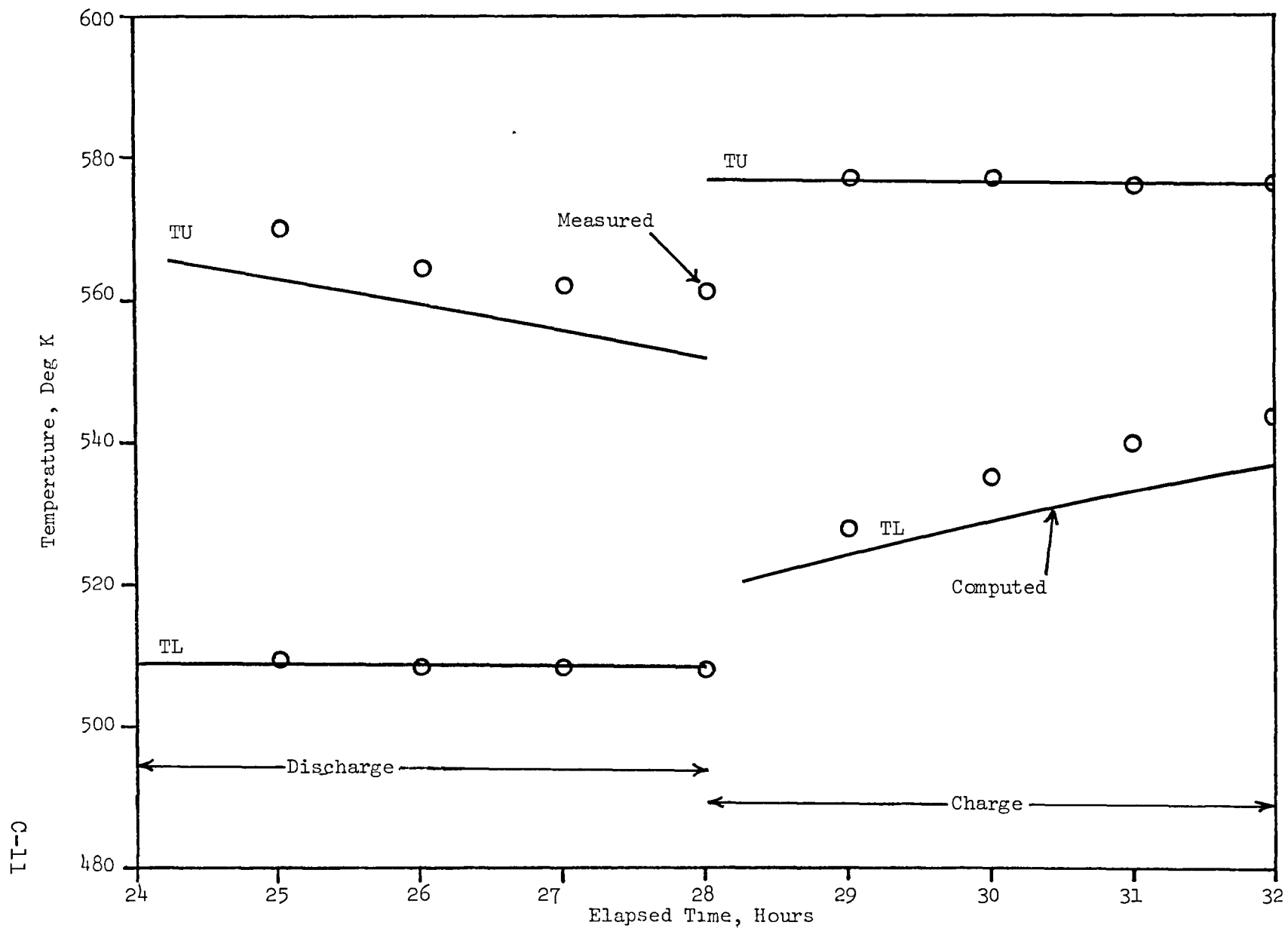
Figure C-9. HT-43 outlet temperature, cyclic test 218 (1.9 gpm), fourth cycle.
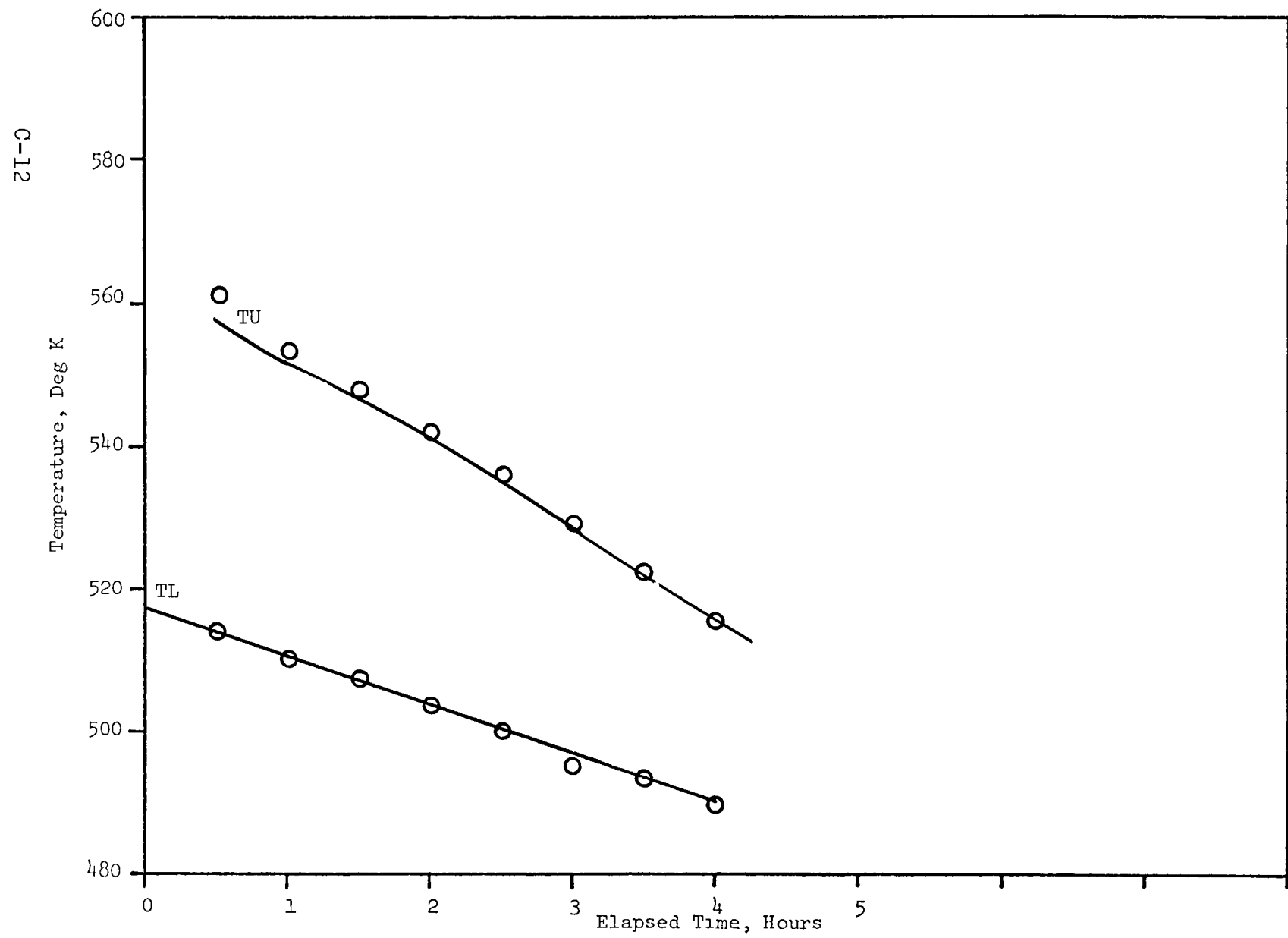
Figure C-10. HT-43 outlet temperature, discharge test 219 (7.7 gpm).
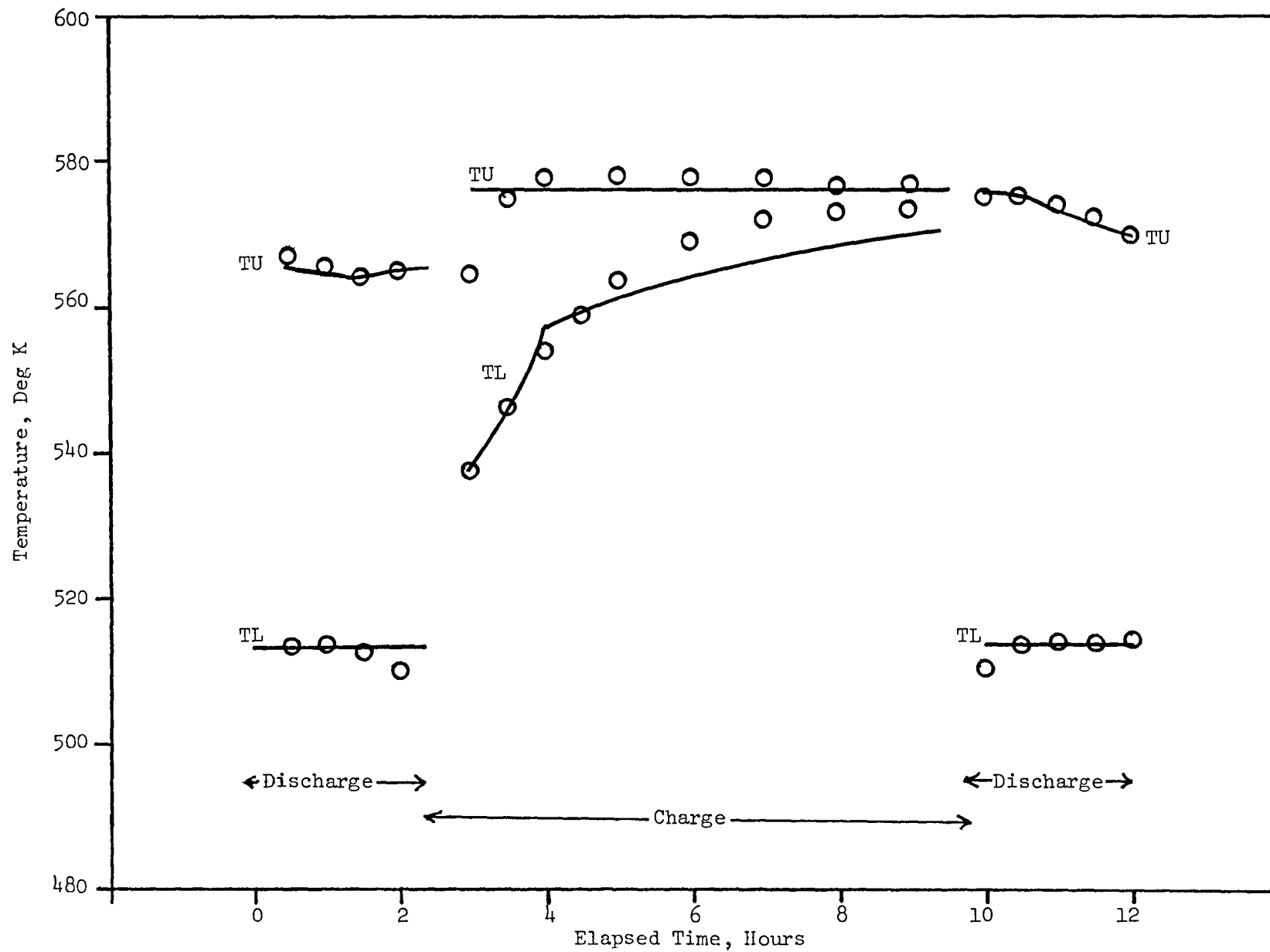
Figure C-11. HT-43 outlet temperature, solar cycle test 223, first cycle.
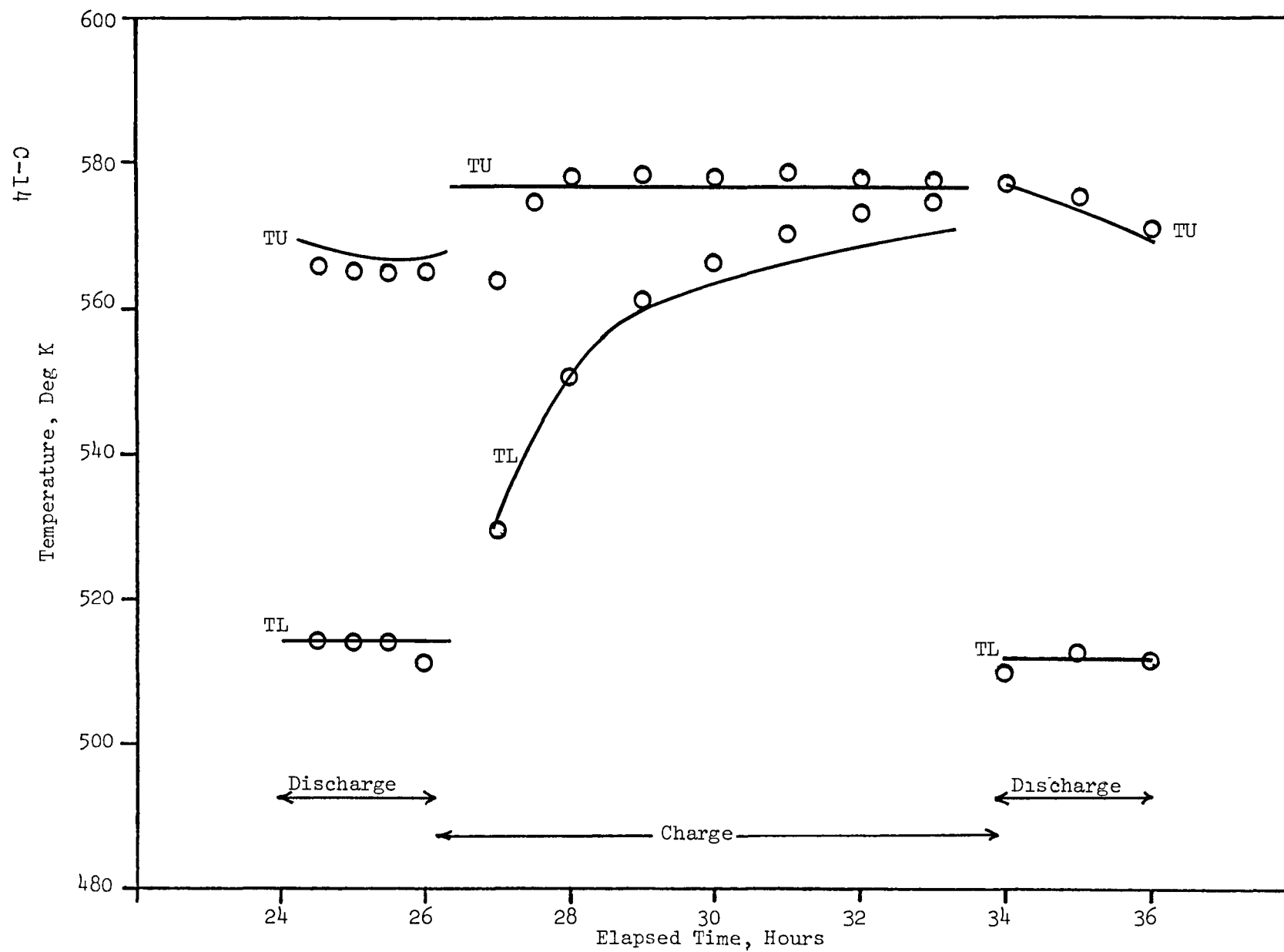
Figure C-12. HT-43 outlet temperature, solar cycle test 223, second cycle.

```
310 |
    |   +Δ   + O+   Δ+   +O   +Δ   + O+    Δ                              LOGGER DATA: 010201
    |                                                                    DATE/TIME: 001:11:00:00
    |                                          +O   + Δ                  TEMP.CORRECTION,°C: -3.4
    |                                              +      Δ              FORTRAN RUN:DD201 022680
300 |                                                +                   ELAPSED TIME: 0     HOURS
    |                                                   + +O    Δ           Δ
    |                                                    +  +
    |                                                          O   +  +   + Δ
290 |                                                              O      +
    |                                                                        O
    |
280 |
    |
D   |
E   |
G 270 |
R   |
E   |
E   |
S 260 |
    |
C   |
    |
250 |
    |
    |
240 |
    |
    |
  ↑
230 T-K LEVEL────────────────────────────────────────────────────────
    |     |      |       |        |        |        |        |        |
         25    50     75      100      125      150      175      200      225
                         DISTANCE FROM TOP OF TES, cm
                   THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

Figure C-13. Thermkeep temperature profile, discharge test 201 (3.3 gpm), starting profile.

```
LOGGER DATA: 010201
DATE/TIME: 001:14:00:00
TEMP.CORRECTION,°C: -4.3
FORTRAN RUN:DD201 022680
ELAPSED TIME: 3    HOURS
```

```
310-  |
  -   |
  -   |
  -   |
300-  |
  -   |
  -   |
  -   Δ  +    +  Δ      Δ
290-  |    o    +   + o +  +    +      Λ        Λ
  -   |              o  +   +  +    +   +
  -   |                          +   +
  -   |                     o        Δ      +
280-  |                                +
  -   |                            o       +
D -   |                                      +
E -   |                              Δ
G 270-  |                                  o    +
R -   |                                        +
E -   |                                          +  Δ
E -   |
S 260-  |                                  Δ            +
  -   |                                          o
C -   |
  -   |                                                 +
250-  |                                                    o
  -   |
  -   |
  -   |
240-  |
  -   |
  -   ↑
230---T-K LEVEL----------------------------------------------------------
      |      |      |      |      |      |      |      |      |
      25     50     75    100    125    150    175    200    225
            DISTANCE FROM TOP OF TES, cm
         THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
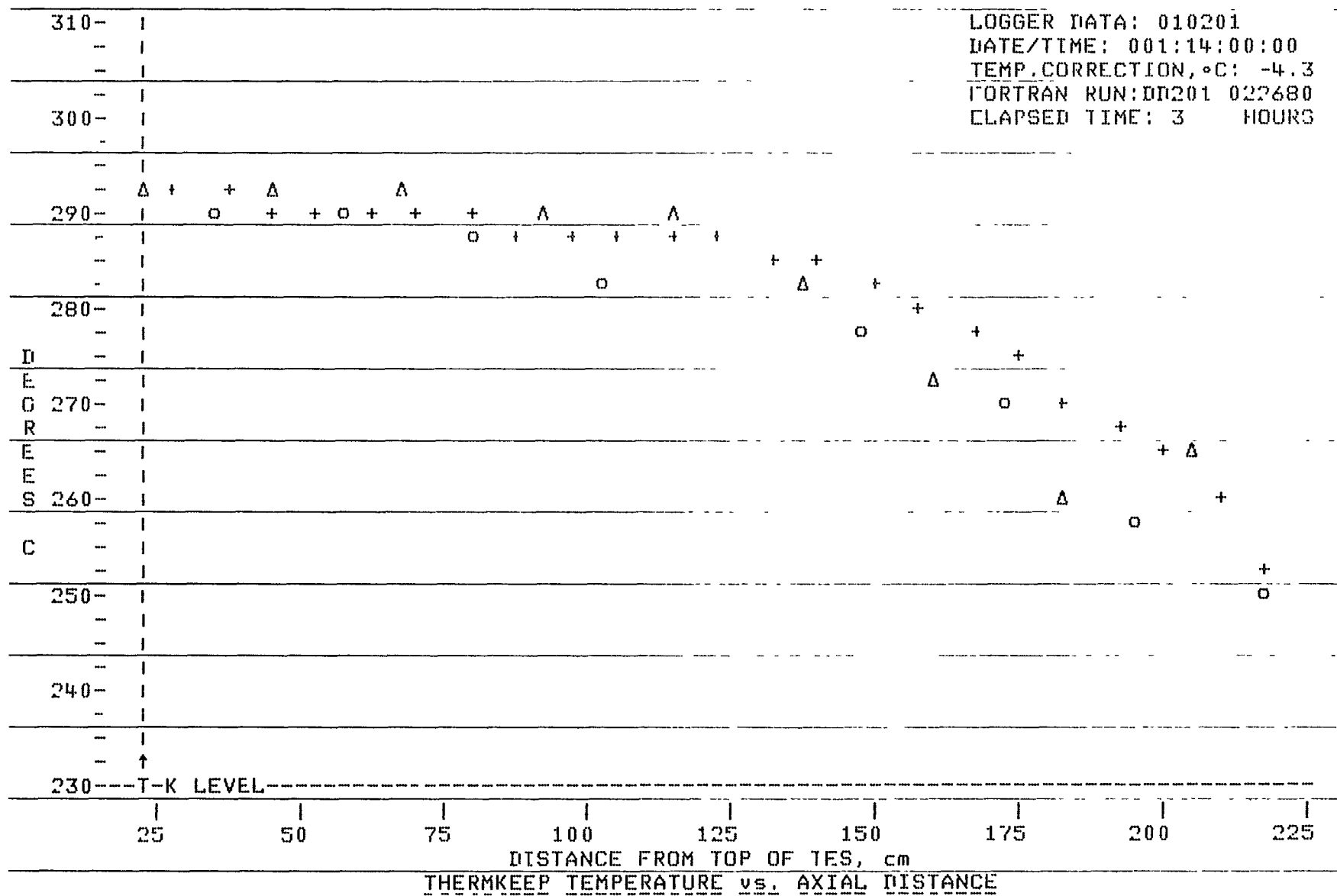
Figure C-14. Thermkeep temperature profile, discharge test 201 (3.3 gpm), after 3 hours.

LOGGER DATA: 010201
DATE/TIME: 001:17:00:00
TEMP.CORRECTION, °C: -5.1
FORTRAN RUN:DD201 022680
ELAPSED TIME: 6   HOURS

310-

300-

290-

280-

D
E
G 270-
R
E
E
S 260-

C

250-

240-

230--------T-K LEVEL--

25   50   75   100   125   150   175   200   225

DISTANCE FROM TOP OF TES, cm

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
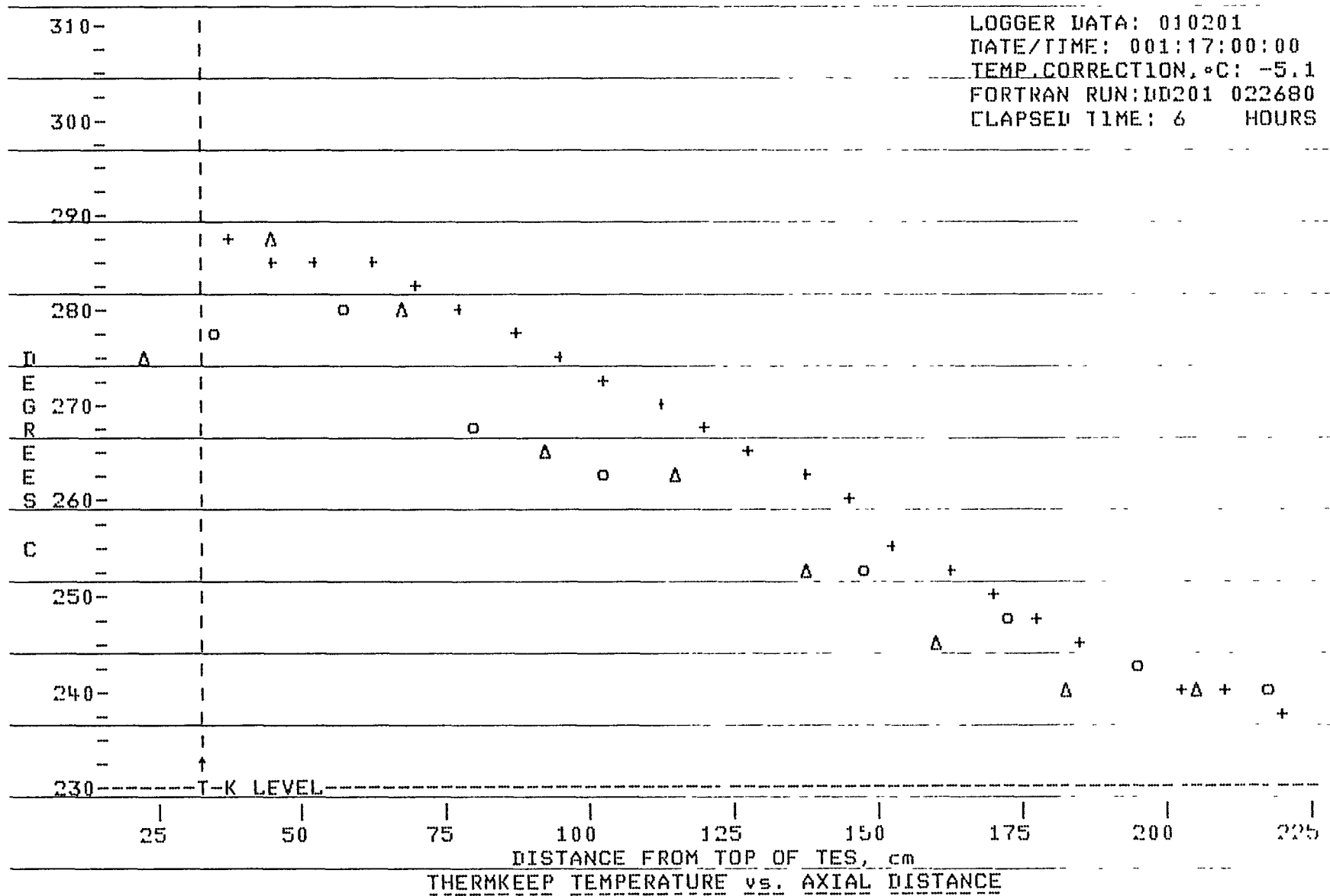
Figure C-15. Thermkeep temperature profile, discharge test 201 (3.3 gpm), after 6 hours.
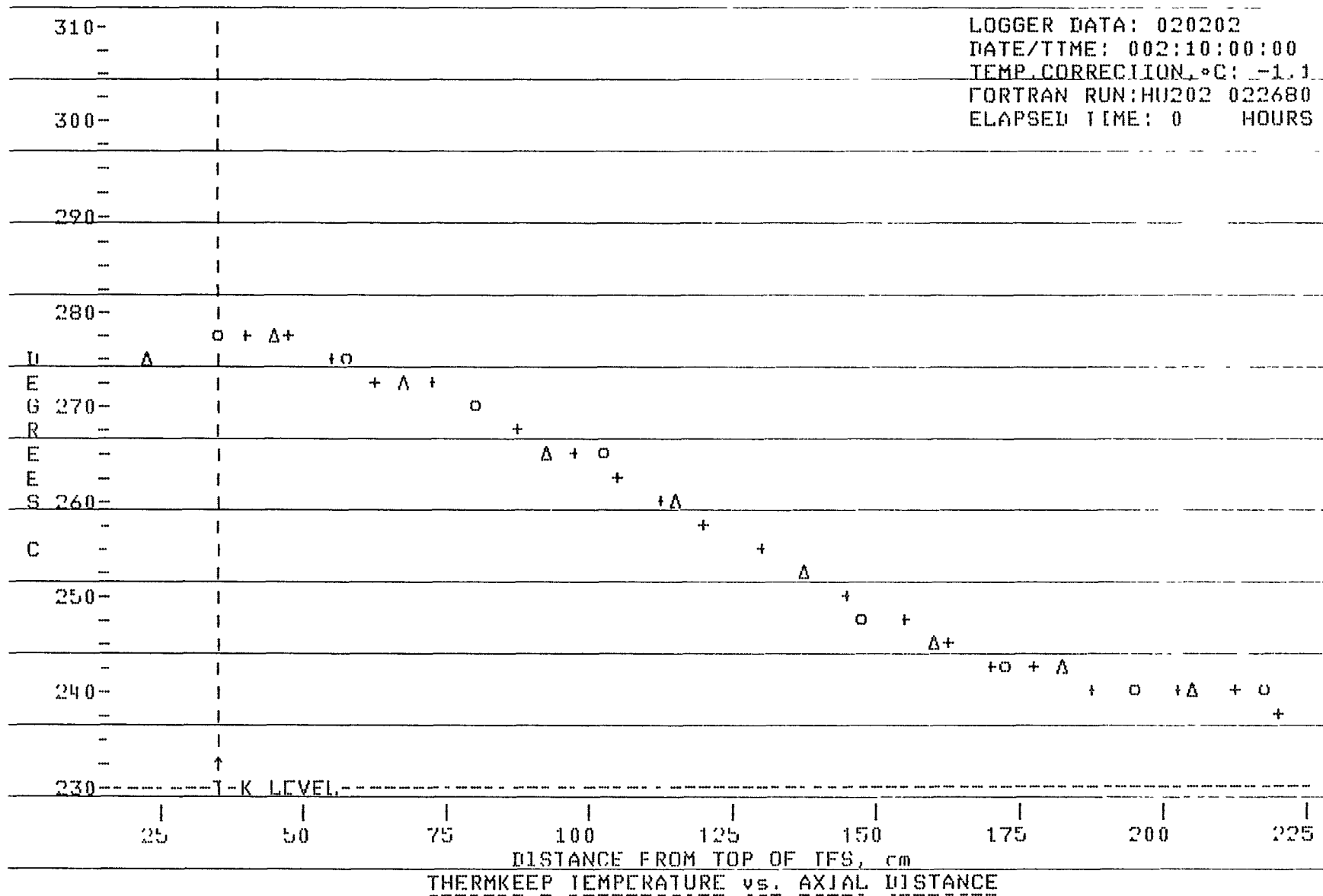
Figure C-16. Thermkeep temperature profile, charge test 202 (3.3 gpm), starting profile.
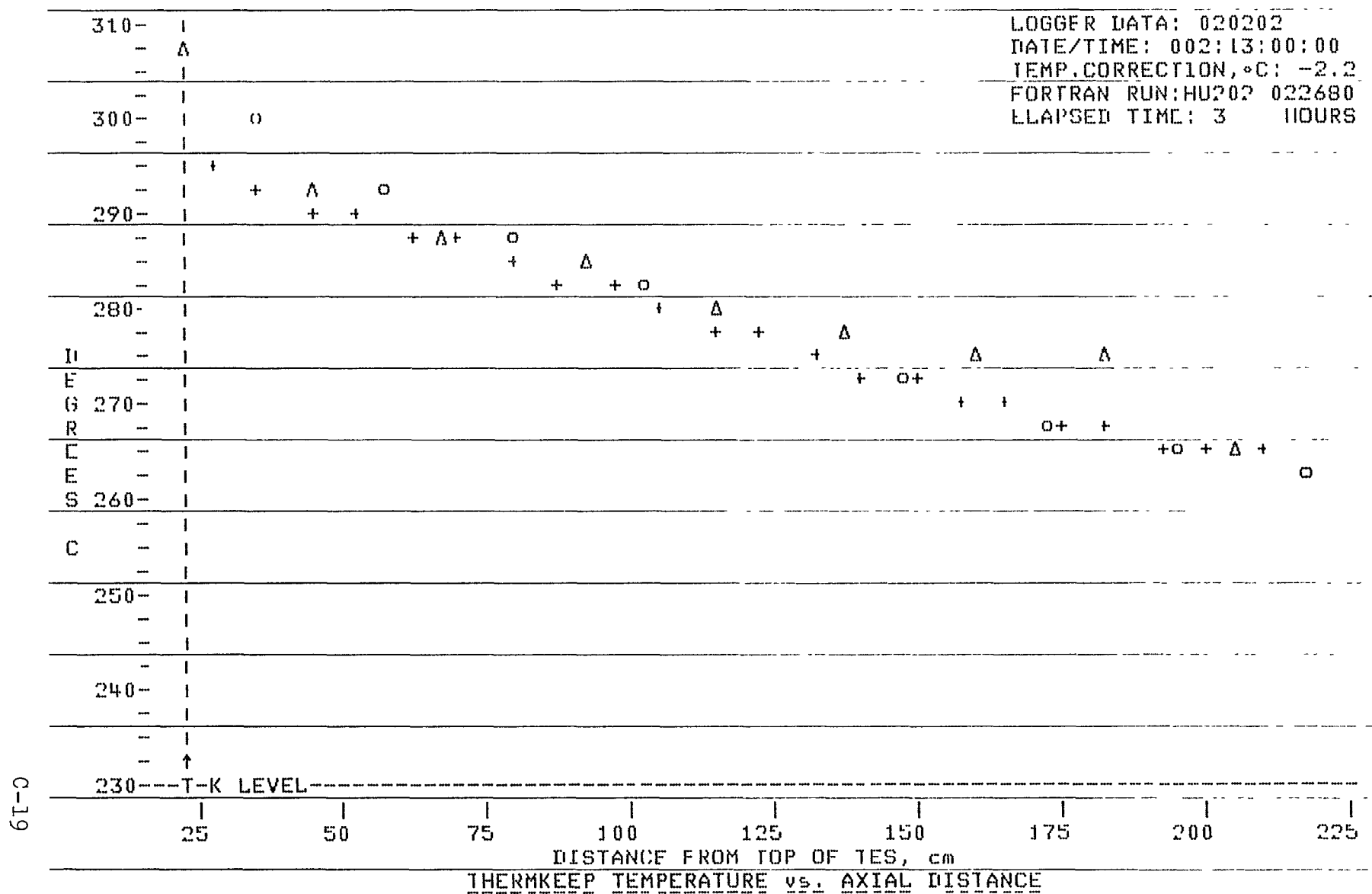
Figure C-17. Thermkeep temperature profile, charge test 202 (3.3 gpm), after 3 hours.

```
310-|
  -| Δ          Δ          Δ
  -|      o          o
  -| +    +                    o    Δ
300-|           +    +
  -|                 +
  -|              +         +         o
  -|                   +    +         Δ
290-|                        +    +         Δ
  -|                            +  +  +
  -|                                   +   o    Δ         Δ
  -|                                      +
280-|                                         +  o
  -|                                              +   + o + Δ
  -|                                                      +   o
E -|
G 270-|
R -|
E -|
E -|
S 260-|
  -|
C -|
  -|
250-|
  -|
  -|
  -|
240-|
  -|
  -|
  -↑
230-T-K LEVEL
     |      |      |      |      |      |      |      |      |
    25     50     75    100    125    150    175    200    225
              DISTANCE FROM TOP OF IES, cm
           THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

```
LOGGER DATA: 020202
DATE/TIME: 002:16:00:00
TEMP.CORRECTION,°C: -4.2
FORTRAN RUN:HU202 022680
ELAPSED TIME: 6    HOURS
```
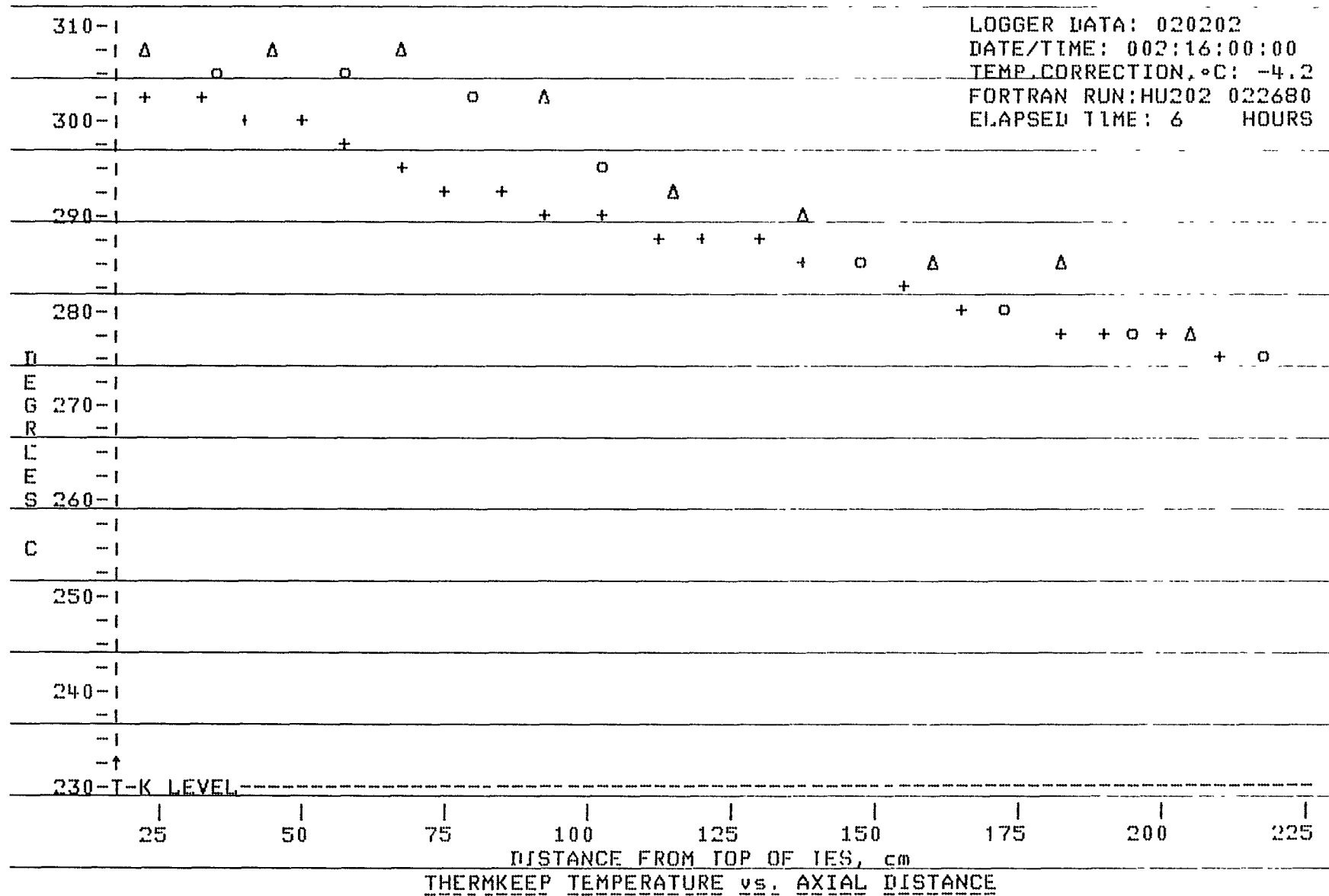
Figure C-18. Thermkeep temperature profile, charge test 202 (3.3 gpm) after 6 hours.

```
310-   |
  -    |
  -    |
  -    |
300    |
  -    |
  -    |
290-   |
  -    |
  -    |
280-   |
  -    |
D -    |
L -    |
G 270- |
R -    |  +  Δ+    +o
E -    o        +Δ  +
E - Δ  |           o
S 260- |
       |           + Δ
C -    |            + o
  -    |              +
250-   |              +Δ
  -    |                +
  -    |                 +
  -    |
240-   |                    Δ   o
  -    |                      +   +
  -    |                        Δ+   +o    Δ
  - ↑  |                              +  +  o
230---------T-K LEVEL------------------------+Δ-- +-o+---
   |         |        |        |        |        |        |        |
   25       50       75      100      125      150      175      200     225
              DISTANCE FROM TOP OF TES, cm
          THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
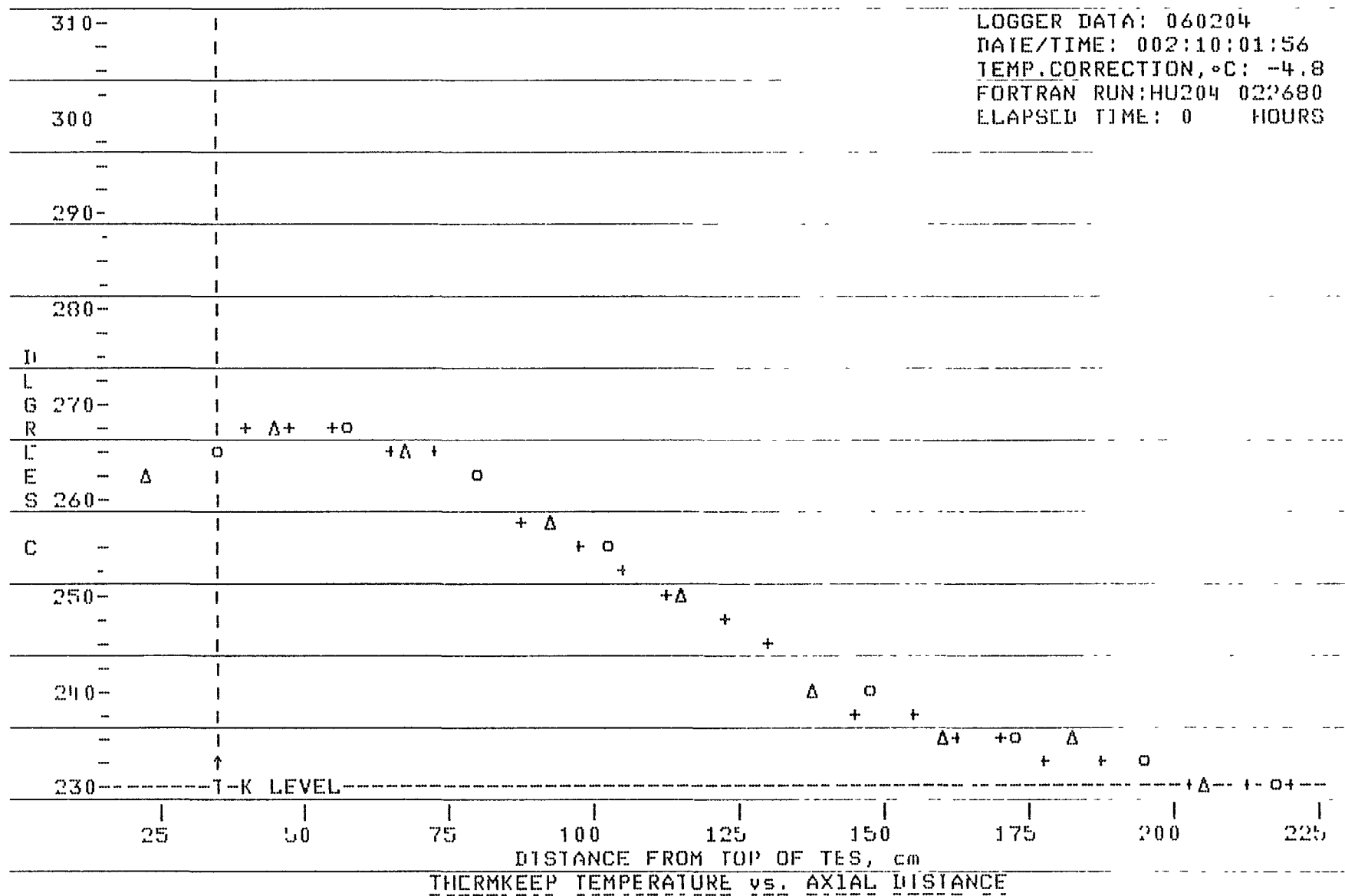
Figure C-19. Thermkeep temperature profile, charge test 204 (3.7 gpm), starting profile.

```
310-      |
  --      |                                    LOGGER DATA: 060204
  --      |                                    DATE/TIME: 002:13:00:01
  --      |                                    TEMP.CORRECTION,°C: -3.1
  --      |                                    FORTRAN RUN:HU204 022680
300-    Δ |                                    ELAPSED TIME: 3    HOURS
  --      |    o
  --      |
  --      |
290-      | +
  --      |    +   +     +
  --      |         Λ      o  +
  --      |           Δ +   o
280-      |              +      Δ
  --      |               +  + o
  --      |                  +  Λ
  --      |                     +  +      Λ                    Δ
270-      |                         +  +  o   Λ
  --      |                            +   +
  --      |                               + o+   +
  --      |                                    +o   +Δ +
260-      |                                              o
  --      |
  --      |
250-      |
  --      |
  --      |
240-      |
  --      |
  --      ↑
230----T-K LEVEL----------------------------------------------
        |       |       |       |       |       |       |       |       |
       25      50      75     100     125     150     175     200     225
                    DISTANCE FROM TOP OF TES, cm
                 THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

DEGREES C
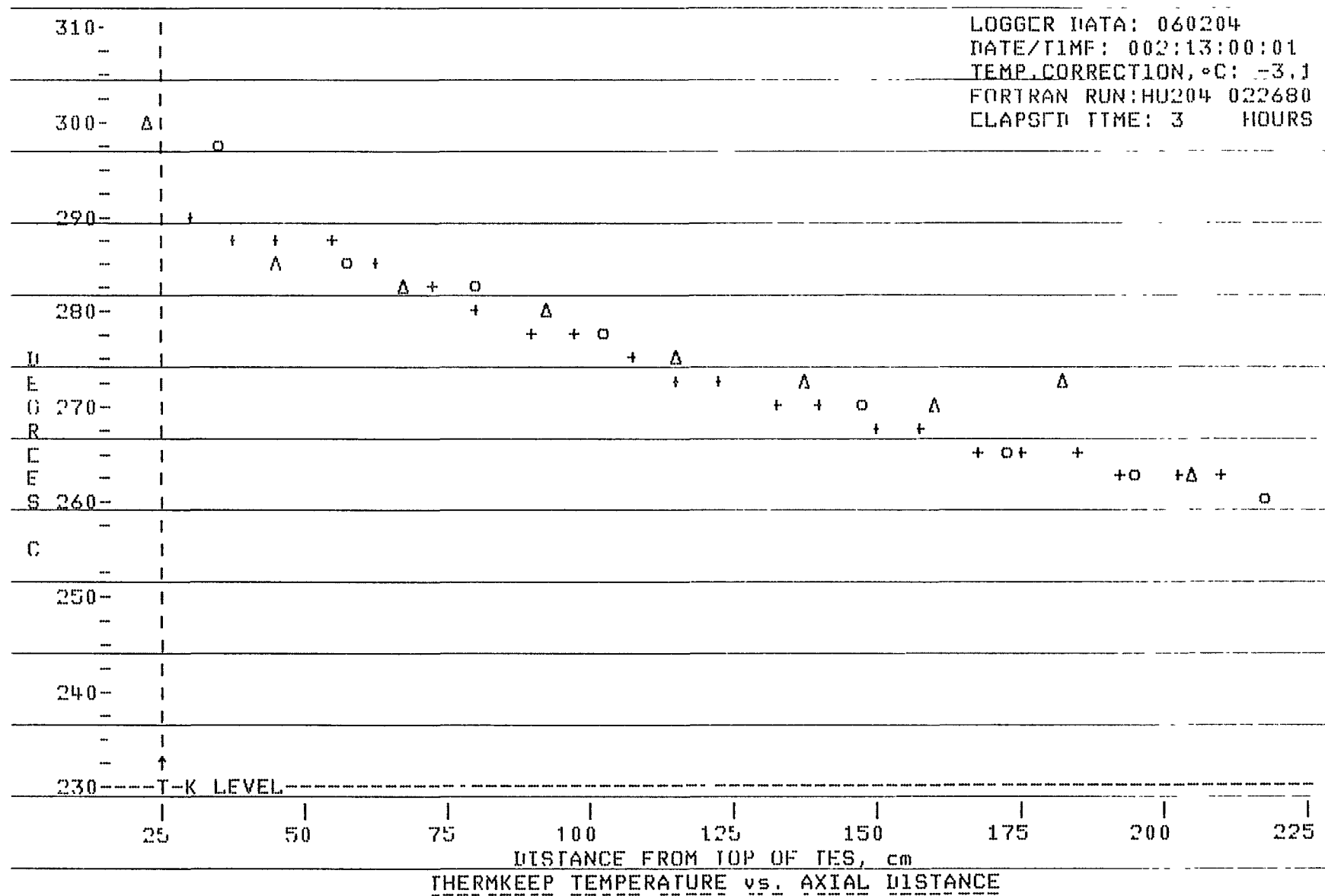
Figure C-20. Thermkeep temperature profile, charge test 204 (3.7 gpm), after 3 hours.

Figure C-21. Thermkeep temperature profile, charge test 204 (3.7 gpm), after 6 hours.

LOGGER DATA: 112142
DATE/TIME: 011:11:00:00
TEMP.CORRECTION,°C: -3.2
FORTRAN RUN:112142 022680
ELAPSED TIME: 0   HOURS

```
310-  |
   -  |
   -  |
   -  |
300-  |
   -  |
   -  |            Δ
   -  Λ+    o    +    +
290-  |              o+    Δ+    +
   -  |                  o    +  Λ+
   -  |                      o+    +Δ
   -  |                          +    +    Δ
280-  |                              +    o      Λ
   -  |                                  +    +      Λ
Θ  -  |                                      o+    +
E  -  |                                              +o  +  Λ
O 270- |                                                  +    +
R  -  |                                                      o
E  -  |
F  -  |
S 260- |
   -  |
C  -  |
   -  |
250-  |
   -  |
   -  |
   -  |
240-  |
   -  |
   -  |
   -  ↑
230---T-K LEVEL-------------------------------------------------
      |      |      |      |      |      |      |      |      |
     25     50     75    100    125    150    175    200    225
         DISTANCE FROM TOP OF TES, cm
```

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
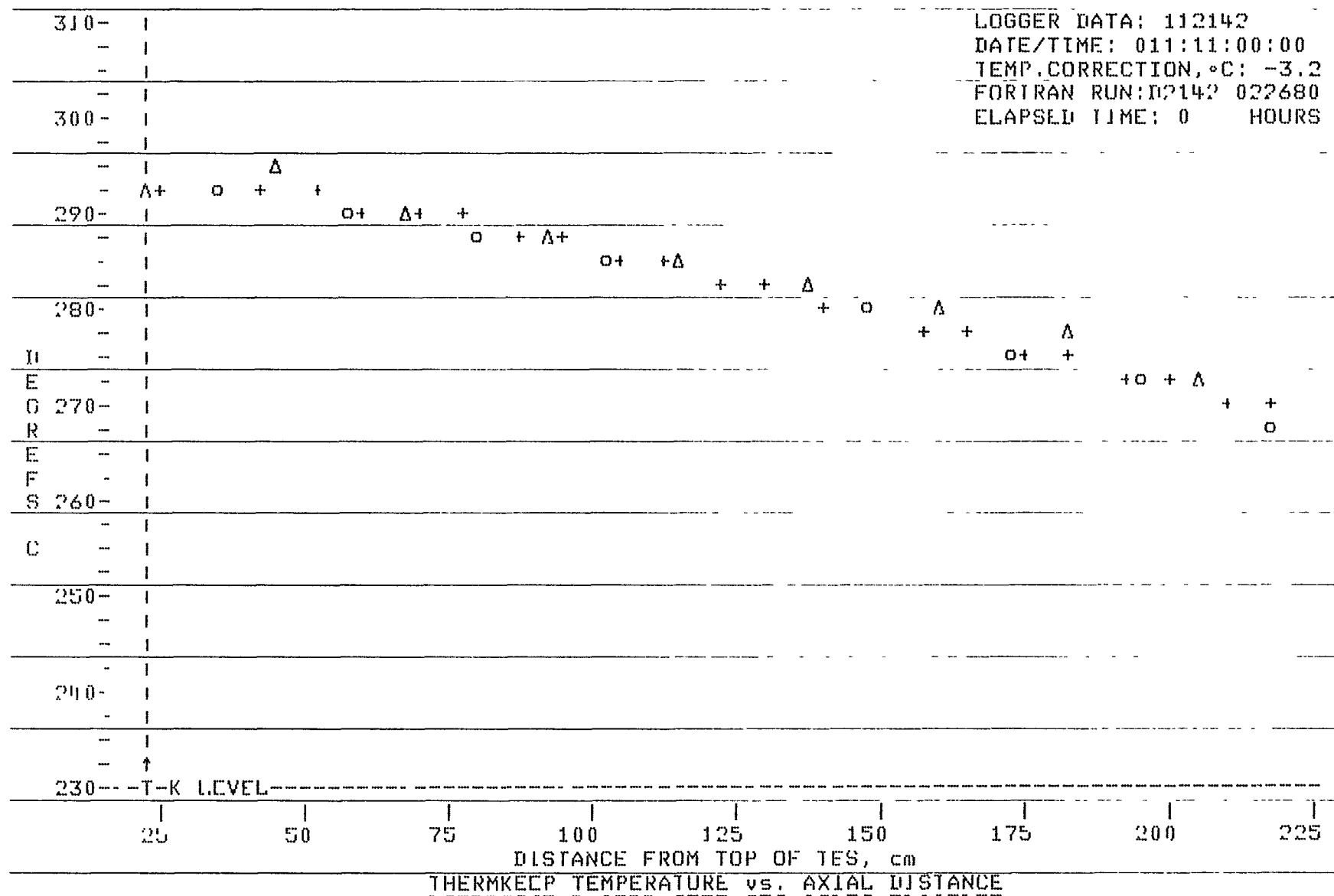
Figure C-22. Thermkeep temperature profile, discharge test 214-3 (1.1 gpm), starting profile.
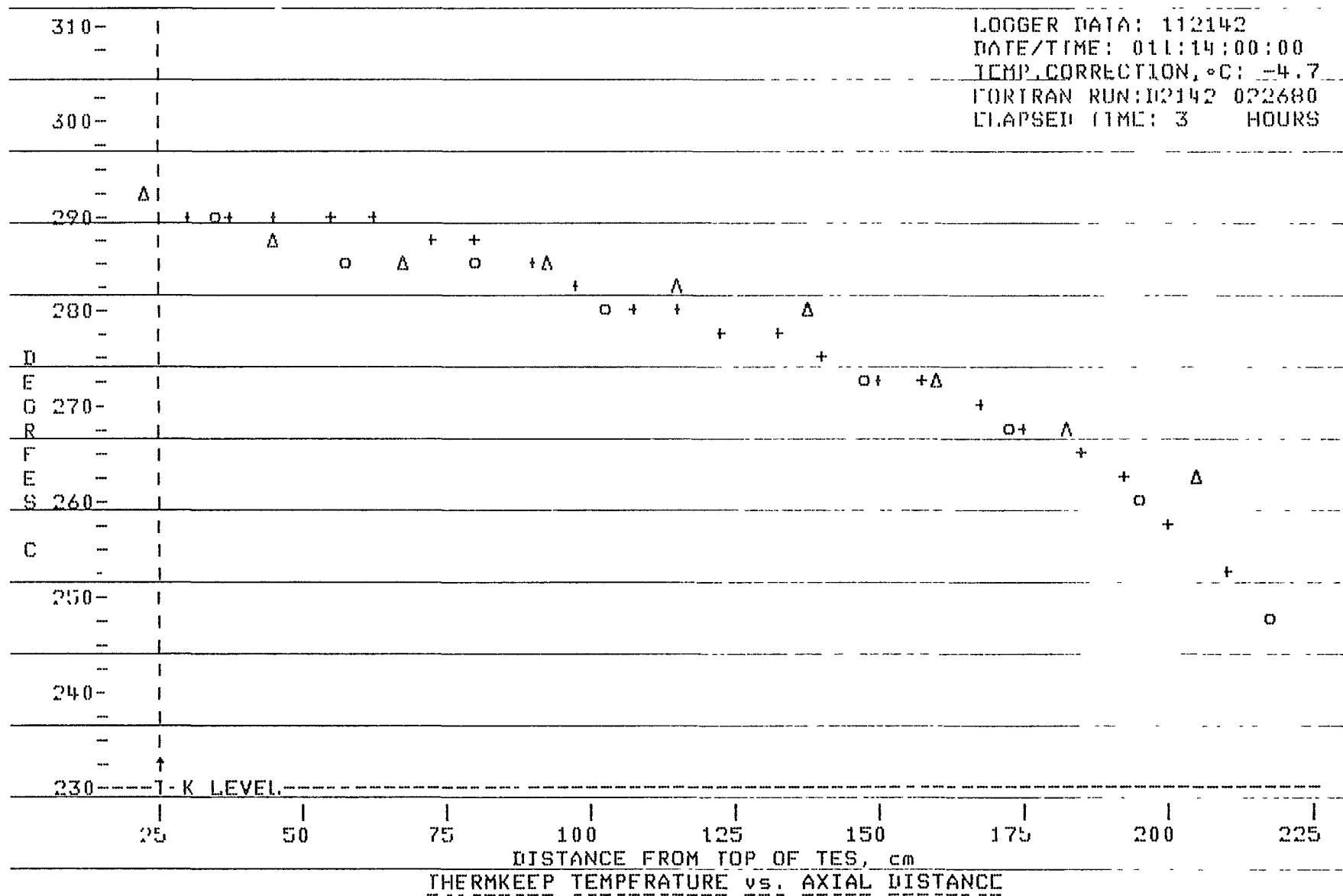
Figure C-23. Thermkeep temperature profile, discharge test 214-3 (1.1 gpm), after 3 hours.

LOGGER DATA: 112142
DATE/TIME: 011:17:00:00
TEMP.CORRECTION,°C: -4.4
FORTRAN RUN:112142 022680
ELAPSED TIME: 6   HOURS

310-

300-

290-

280-

D
E
G 270-
R

C
E
S 260-

C

250-

240-

230----- T-K LEVEL----------------------------

```
     25      50      75      100     125     150     175     200     225
```

DISTANCE FROM TOP OF TFS, cm

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
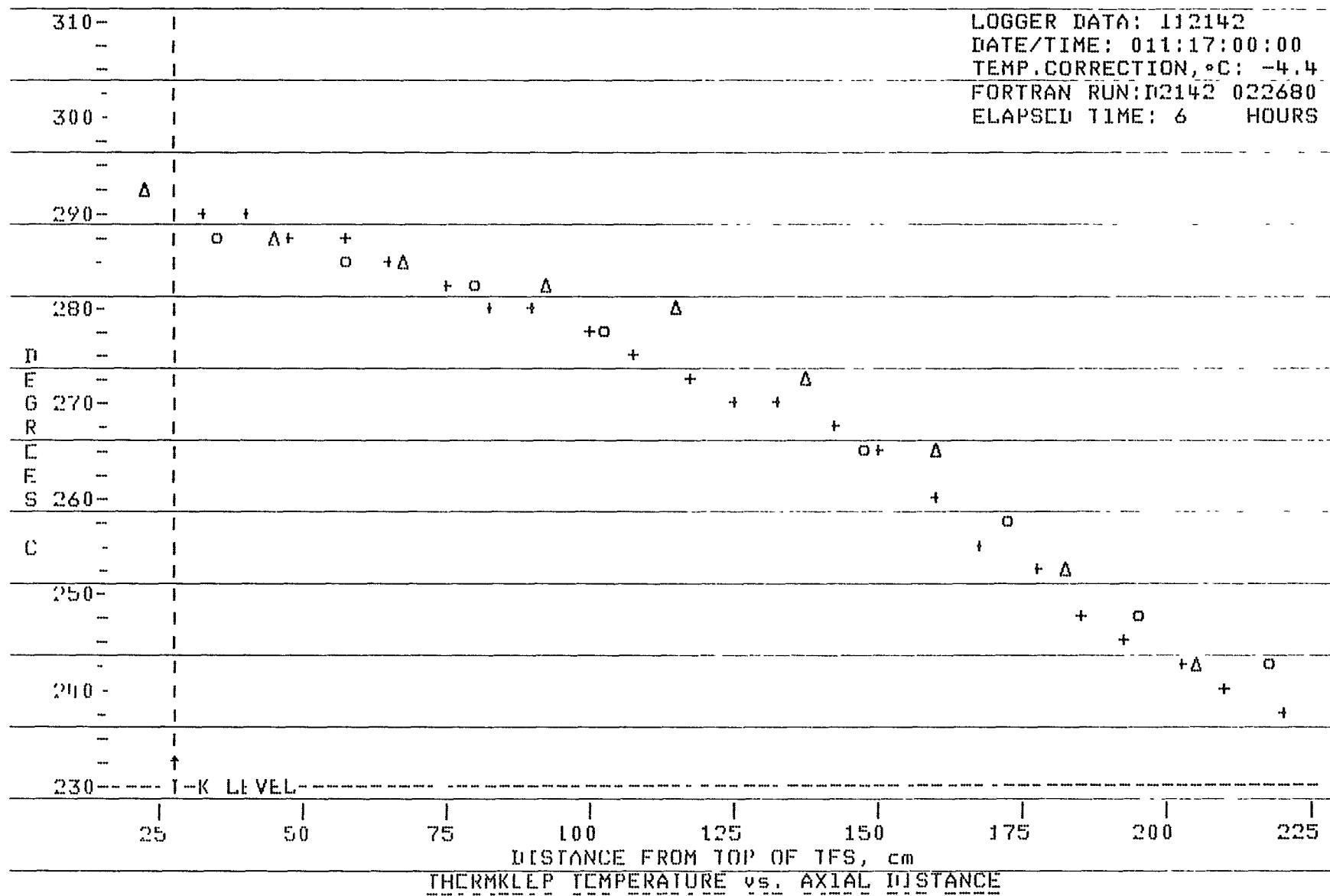
Figure C-24. Thermkeep temperature profile, discharge test 214-3 (1.1 gpm) after 6 hours.

Figure C-25. Thermkeep temperature profile, charge test 215-2 (1.1 gpm), starting profile.

```
                                          LOGGER DATA: 210215
310 -          |                           DATE/TIME: 021:14:00:00
   --          |                           TEMP.CORRECTION, °C: -2.1
   --          |                           FORTRAN RUN:H2152 022680
300 -          |                           ELAPSED TIME: .3    HOURS
   --          |

   --     Δ    |
290 -          |O
   --          |  +
   -           |    Δ
   --          |        +
280 -          |
   --          |            O +  Δ
D  --          |                  +
E  -           |                    +O
G 270 -        |                        +  Λ
R  --          |                           +
E  --          |                              O      Δ
E  -           |                                +      +
S 260 -        |                                         +
   --          |                                          +Δ
                                                            +O
C              |                                               +   Λ
   --          |                                                 +      Δ
250 -          |                                                    +O
   --          |                                                       +
   --          |
   --          |                                                          +      O
240 -          |                                                             +   +Λ
   --          |                                                                +   O+
   --          |
   --          ↑
230 --------T-K LEVEL-----------------------------------------------------------
          |      |      |      |      |      |      |      |      |
          25     50     75    100    125    150    175    200    225
                      DISTANCE FROM TOP OF TES, cm
                 THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
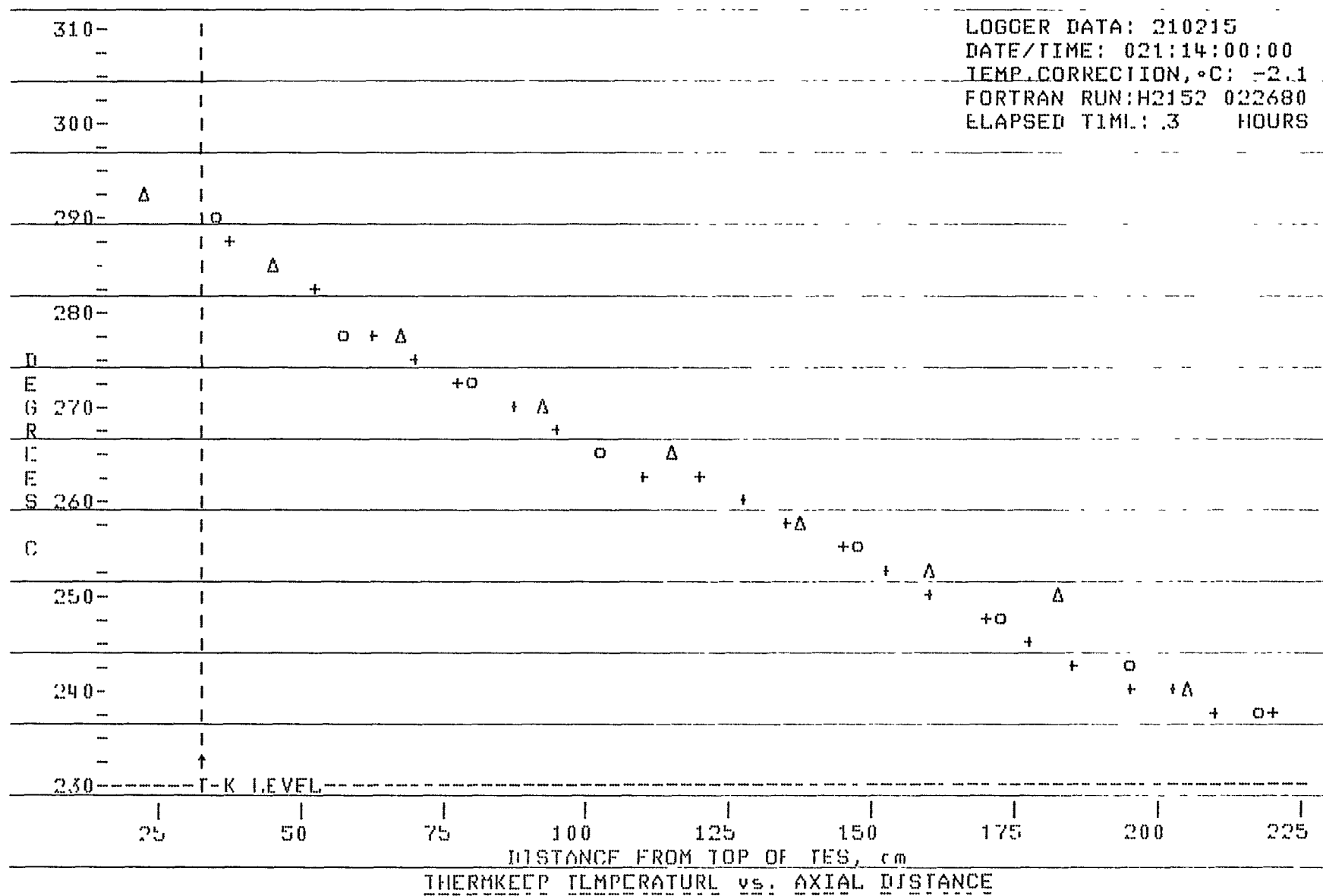
Figure C-26.   Thermkeep temperature profile, charge test 215-2 (1.1 gpm), after 3 hours.
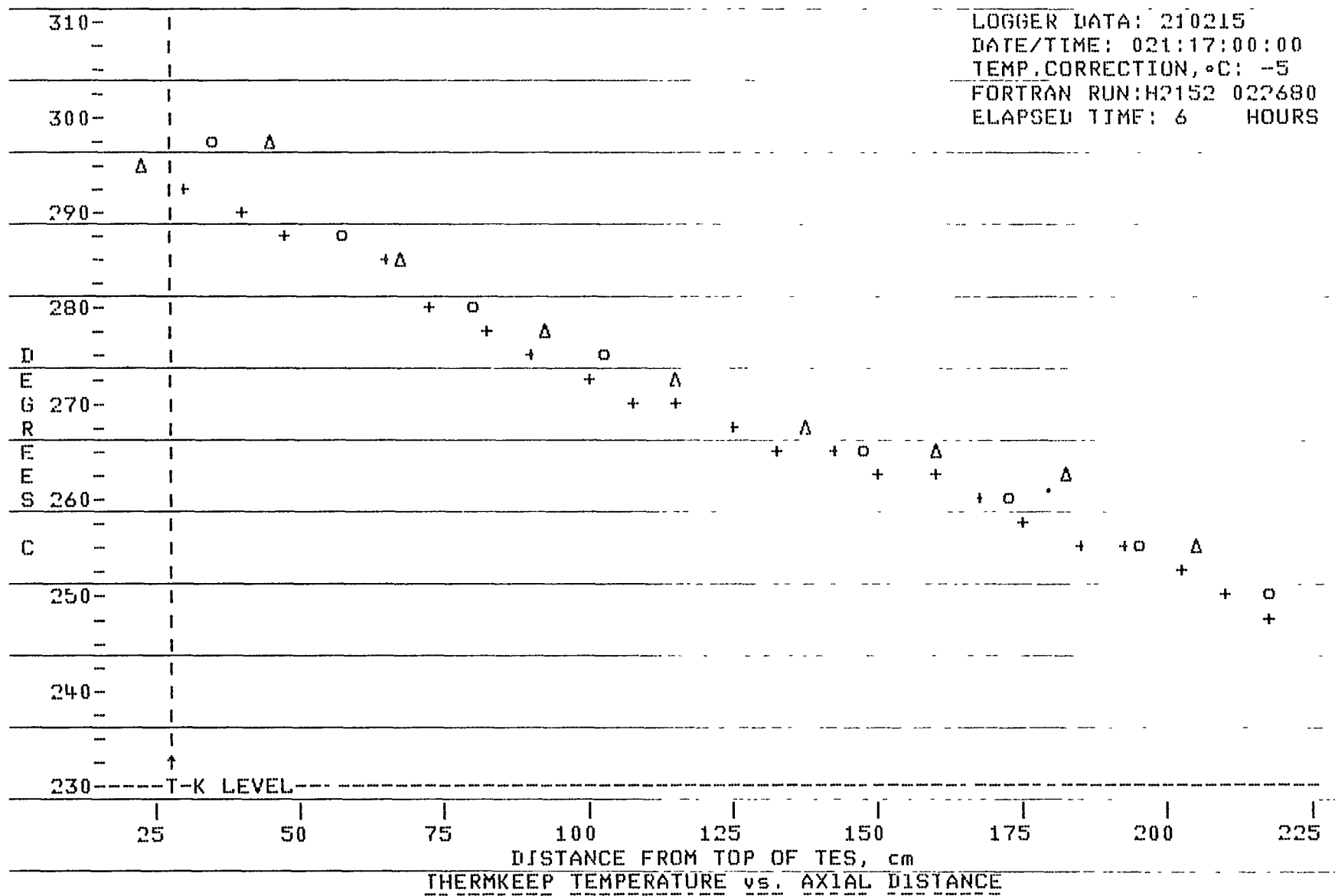
Figure C-27. Thermkeep temperature profile, charge test 215-2 (1.1 gpm), after 6 hours.

LOGGER DATA: 122181
DATE/TIME: 012:08:00:00
TEMP.CORRECTION,°C: -2.6
FORTRAN RUN:CY218 022680
ELAPSED TIME: 0   HOURS

310-
-
-
-
300-
-
-
-
290-
-
-
-
280-
-
D   -
E   -
G 270-
R   -
E   -
E   -
S 260-
-
C   -
-
-
250-
-
-
-
240-
-
-
-
230-T-K LEVEL

25   50   75   100   125   150   175   200   225

DISTANCE FROM TOP OF TES, cm

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE

Figure C-28.   Thermkeep temperature profile, cyclic test 218 (1.0 gpm), starting profile.

```
310-  |                                                          LOGGER DATA: 122181
   -  |                                                          DATE/TIME: 012:12:00:04
   -  |                                                          TEMP.CORRECTION,°C: -.6
   -  |                                                          FORTRAN RUN:CY218 022680
300-  |                                                          ELAPSED TIME: 4     HOURS
   -  |
   -  |
   -  A  +      o      A       + o +    A
290-  |          o      +    + o +    +      o      A          A
   -  |                              +    +       + o
   -  |                                       +              A
   -  |                                    +
280-  |                                          +    +
   -  |                                                   +
D  -  |                                                       A
F  -  |                                              o+
G 270-  |                                                 +
R  -  |                                                    + o
E  -  |                                                        + A
E  -  |                                                           +
S 260-  |                                                              A
   -  |                                                            +
C  -  |                                                    '       o +
   -  |
250-  |                                                              +
   -  |                                                                 o
   -  |
240-  |
   -  |
   -  ↑
230---T-K LEVEL----------------------------------------------------------
      |        |        |        |        |        |        |        |
     25       50       75      100      125      150      175      200      225
                        DISTANCE FROM TOP OF TES, cm
                   THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

Figure C-29. Thermkeep temperature profile, cyclic test 218 (1.9 gpm, at end of first discharge phase.

Figure C-30. Thermkeep temperature profile, cyclic test 218 (1.9 gpm), at end of first charge phase.

Figure C-31. Thermkeep temperature profile, cyclic test 218 (1.9 gram), at end of second discharge phase.

```
310- |
   - |Δ               Δ
   - |     o    Δ   o        o    Δ                          LOGGER DATA: 122184
   - |+                                                      DATE/TIME: 013:03:00:00
300- |      +    +                                           TEMP.CORRECTION,°C: -4.4
   - |            +                          o               FORTRAN RUN:CY218 022680
   - |         +                                             ELAPSED TIME: 16    HOURS
   - |            +              Δ
290- |               +   +
   - |                  +   +          Δ
   - |                      +      o
   - |                     +   +       Δ
280- |                        +          Δ
   - |                         +    o
D  - |                          +            o
E  - |                            +  +
G 270- |                            +    Δ   o
R  - |                                +  +
E  - |                                  +  +
E  - |
S 260- |
   - |
C  - |
   - |
250- |
   - |
   - |
   - |
240- |
   - |
   - |
   - ↑
230--T-K LEVEL----------------------------------------------------------------
      |      |      |      |      |      |      |      |      |
     25     50     75    100    125    150    175    200    225
                      DISTANCE FROM TOP OF TES, cm
               THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

Figure C-32. Thermkeep temperature profile, cyclic test 218 (1.9 gpm), at end of second charge phase.

```
310-
  -
  -
  -
300-
  -
  -
290-
  -
  -
  -
280-
  -
  -
D -
E -
G 270-
R -
E -
E -
S 260-
  -
C -
  -
250-
  -
  -
  -
240-
  -
  -
  -
230----T-K LEVEL
        25    50    75    100   125   150   175   200   225
              DISTANCE FROM TOP OF TES, cm
              THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

LOGGER DATA: 122185
DATE/TIME: 013:08:00:00
TEMP.CORRECTION,°C: -3
FORTRAN RUN:CY218 022680
ELAPSED TIME: 20   HOURS

Figure C-33. Thermkeep temperature profile, cyclic test 218 (1.9 gpm), at end of third discharge phase.

```
310-  I
  -  I Δ            Δ
  -  I     o    Δ    o        o
  -  I +                Δ
300-  I      +
  -  I         +
  -  I          +              o
  -  I             +        Δ
290-  I                +
  -  I              +  +  +          Δ
  -  I                    +
  -  I                      +        o    Δ
280-  I                        +          Δ
  -  I                          +  +        o
D  -  I                              +
E  -  I                                +        o
G 270-  I                                 +  +      Δ
R  -  I                                      +  +        o
E  -  I                                          +  +
E  -  I                                              +
S 260-  I
  -  I
C  -  I
  -  I
250-  I
  -  I
  -  I
  -  I
240-  I
  -  I
  -  I
  - ↑
230--T-K LEVEL--------------------------------------------
     I     I     I     I     I     I     I     I     I
    25    50    75   100   125   150   175   200   225
              DISTANCE FROM TOP OF TES, cm
           THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

LOGGER DATA: 122186
DATE/TIME: 013:13:00:00
TEMP.CORRECTION,°C: -1.4
FORTRAN RUN:CY218 022680
ELAPSED TIME: 24   HOURS

Figure C-34.   Thermkeep temperature profile, cyclic test 218 (1.9 gpm), at end of third charge phase.

Figure C-35. Thermkeep temperature profile, cyclic test 218 (1.9 gpm), at end of fourth discharge phase.

```
310-  |                                                      LOGGER DATA: 122188
  -   |                                                      DATE/TIME:  013:23:00:00
  -   |A    O    A    O    A                                 TEMP.CORRECTION, °C: -3.9
  -   |                      O                               FORTRAN RUN:CY218 022680
300-  | +                                                   ELAPSED TIME: 32   HOURS
  -   |      +
  -   |        +                                A
  -   |          +               O
290-  |                +                    A
  -   |                  +   +  +
  -   |                       +          A
  -   |                         +              O
280-  |                            +        A
  -   |                              +            A
D -   |                                +  +      O
L -   |                                   +              O
O 270-|                                     +  +
R -   |                                        +      A    O
E -   |                                          +  +  +
E -   |                                              +  +
S 260-|
  -   |
C -   |
  -   |
250-  |
  -   |
  -   |
  -   |
240-  |
  -   |
  -   |
  - ↑
230---T-K LEVEL----------------------------------------------------------------
      |      |      |      |      |      |      |      |      |
      25     50     75     100    125    150    175    200    225
                      DISTANCE FROM TOP OF TES, cm
                   THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

Figure C-36. Thermkeep temperature profile, cyclic test 218 (1.9 gpm), at end of fourth charge phase.

Figure C-37. Thermkeep temperature profile, discharge test 219 (7.7 gpm), starting profile.

```
310-    |                                                    LOGGER DATA: 070219
   -    |                                                    DATE/TIME: 007:14:00:00
        |                                                    TEMP.CORRECTION, °C: -1.8
   -    |                                                    FORTRAN RUN:DD219 022680
300-    |                                                    ELAPSED TIME: 2     HOURS
   -    |
   -    |
290-    |        Δ           Δ
   -    |   +    +    +      +
   -  Δ |              o    +      +
   -    |                        +   +Δ         Δ
280-    |   o                        +
   -    |                              +    +
D  -    |              o
E  -    |                              +  + Λ
G 270-  |                        o        +
R  -    |                                    +
E  -    |                              +
E  -    |                            Λ   +   +
S 260-  |                        o          o    +
   -    |                                         +      Δ
C  -    |                                           +
   -    |                                             +
250-    |                                     Δ    o      +
   -    |                                                o
240-    |
   -    |
   - †
230-----T-K LEVEL.----------------------------------------------
     |        |        |        |        |        |        |        |        |
    25       50       75      100      125      150      175      200      225
                      DISTANCE FROM TOP OF TES, cm
              THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
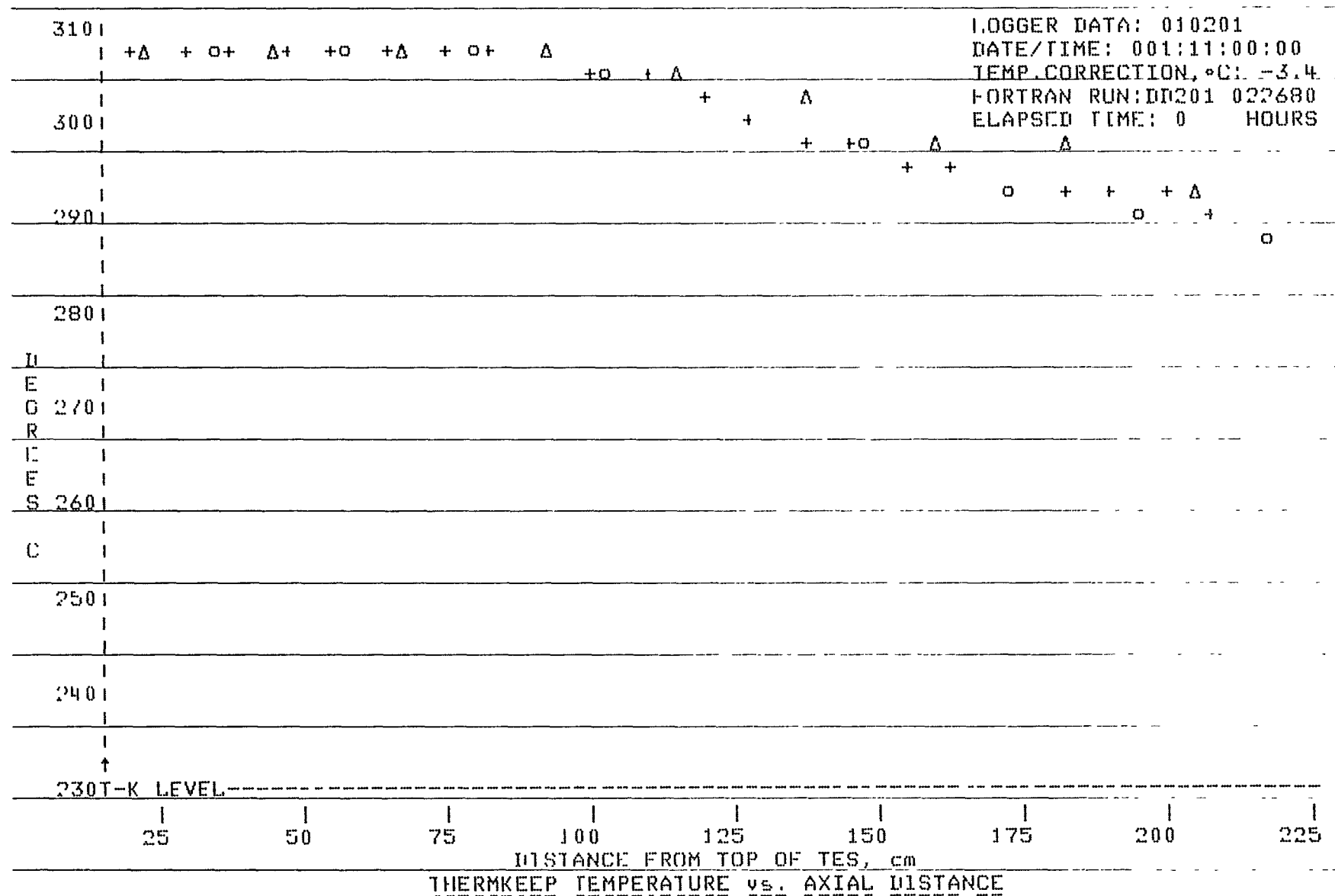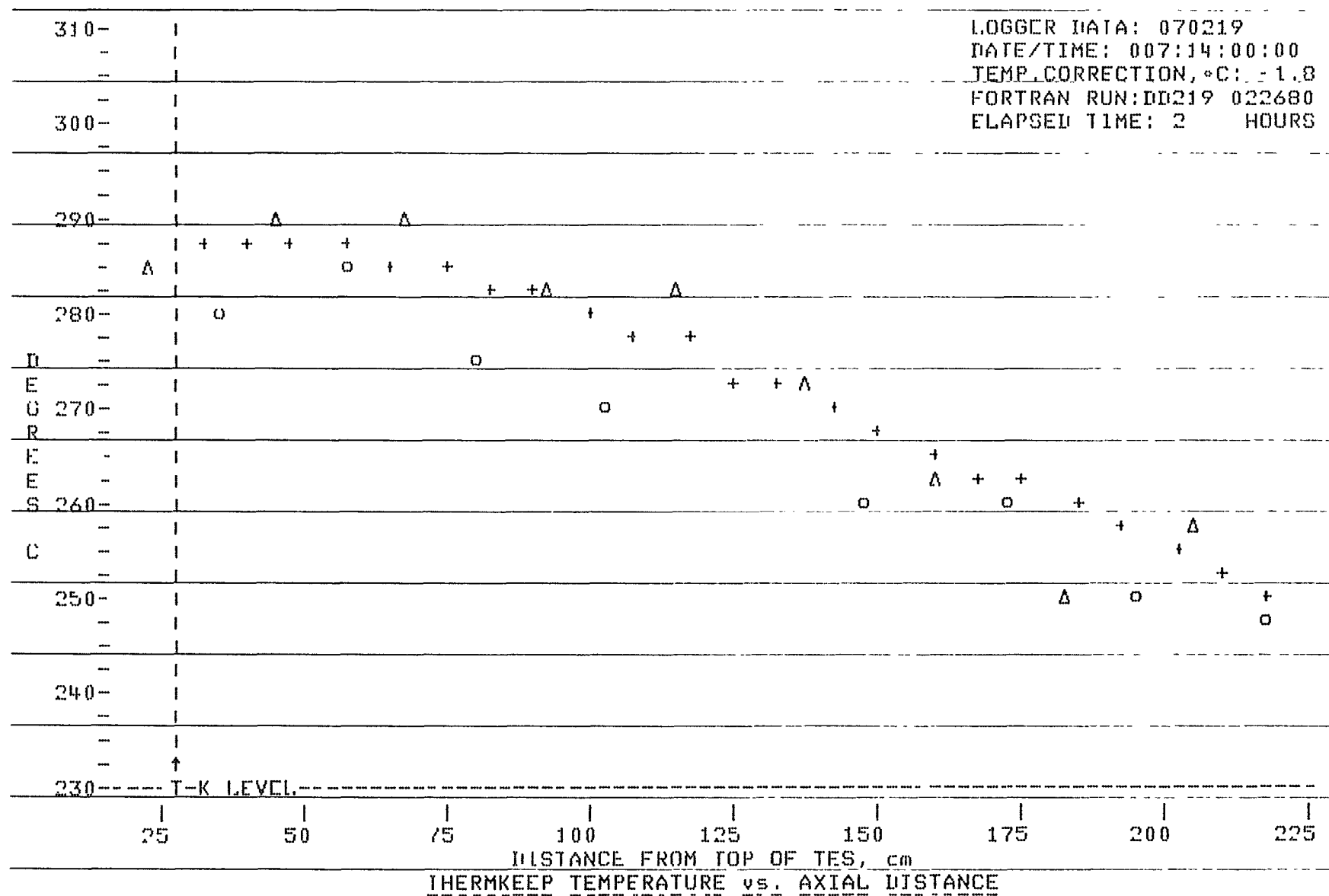
Figure C-38. Thermkeep temperature profile, discharge test 219 (7.7 gpm), after 2 hours.
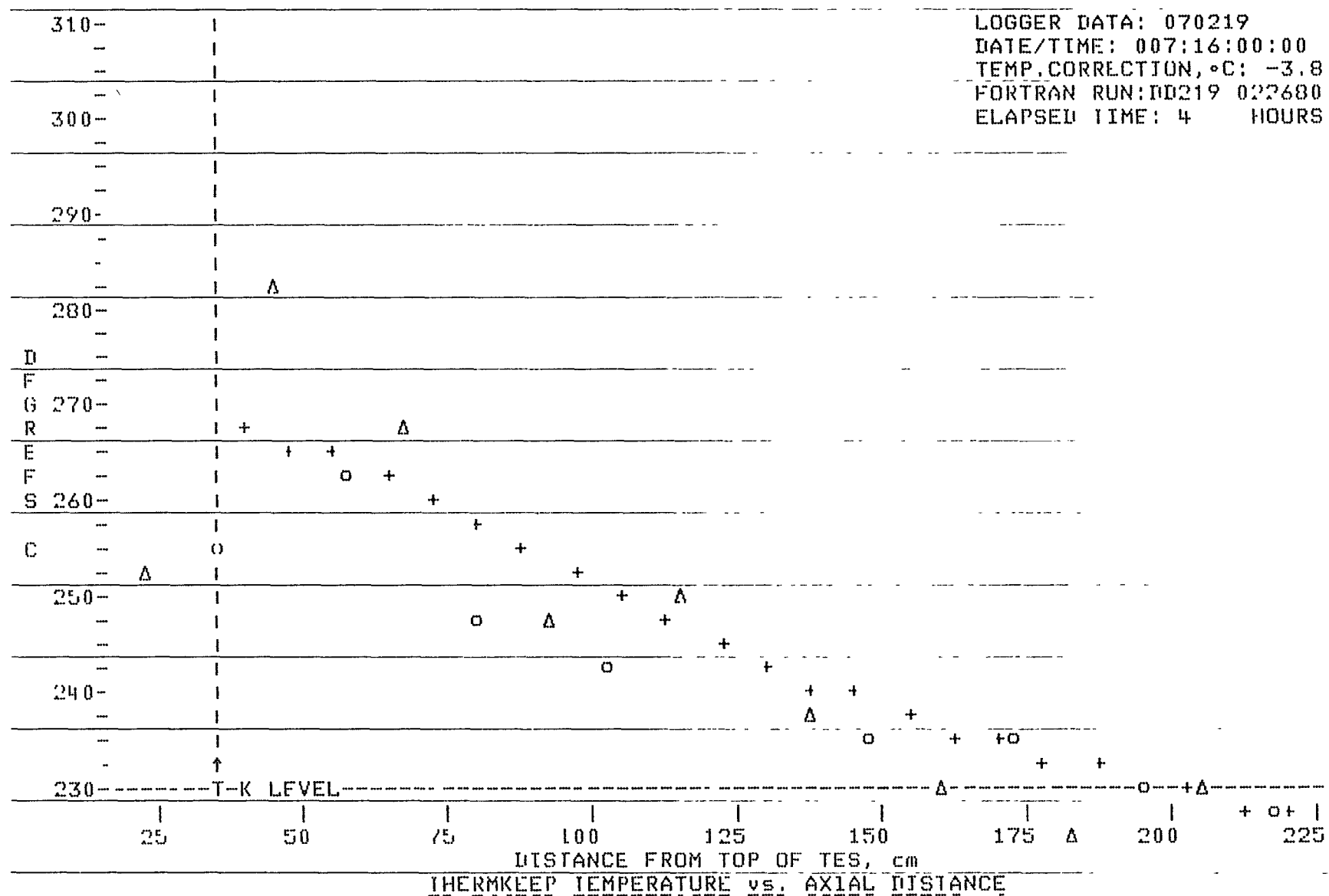
Figure C-39. Thermkeep temperature profile, discharge test 219 (7.7 gpm), after 4 hours.

```
LOGGER DATA: 800223
DATE/TIME: 043:09:00:00
TEMP.CORRECTION,°C: -4.4
FORTRAN RUN:SC223 022680
ELAPSED TIME: 0     HOURS
```

DISTANCE FROM TOP OF TES, cm

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
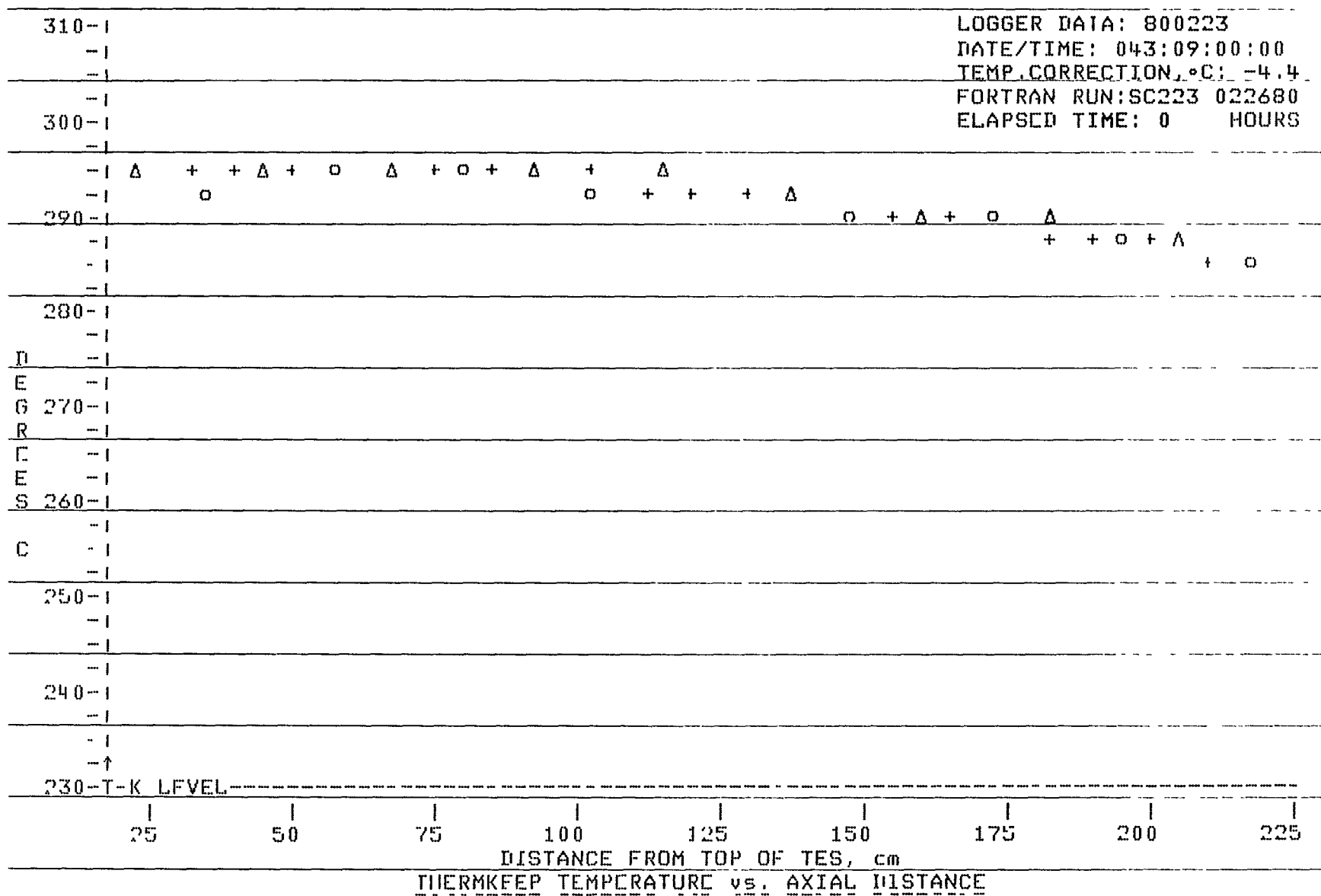
Figure C-40. Thermkeep temperature profile, solar cycle test 223, starting profile, cycle 1.

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
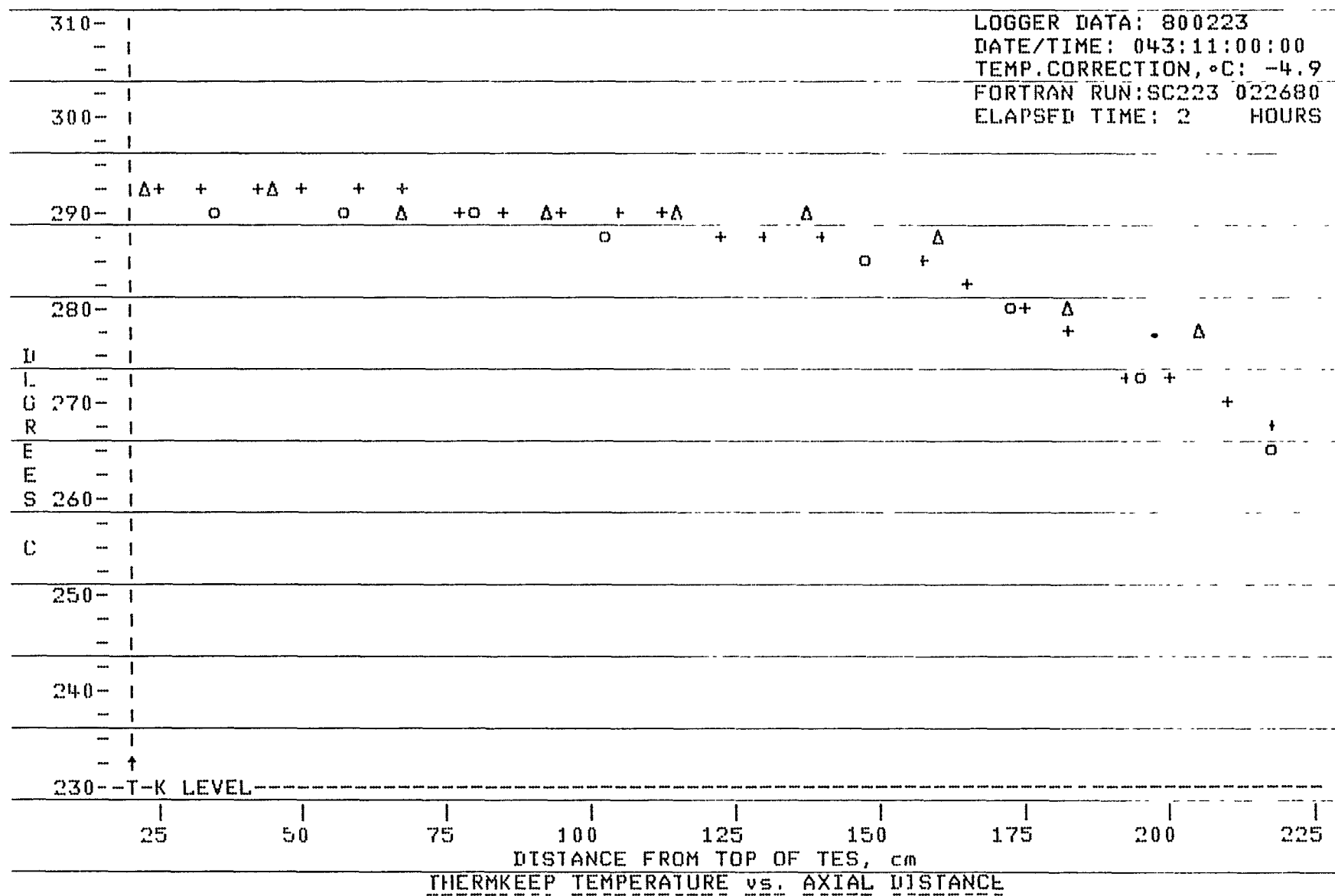
Figure C-41. Thermkeep temperature profile, solar cycle test 223, at end of Phase 1 discharge, cycle 1.

```
310 |
    |                                                    LOGGER DATA: 800223
    |                                                    DATE/TIME: 043:19:00:00
    |                      Δ                             TEMP.CORRECTION,°C: -7.3
    | +Δ   + O+    +   +O   +Δ  + O+   Δ  +O  + Δ +   +   Δ    FORTRAN RUN:SC223 022680
300 |                                              +   +O  + Δ  ELAPSED TIME: 10   HOURS
    |                                                 +   O   Δ
    |                                                       + O + Δ
    |                                                             +   O
290 |                                                                   +

    |
280 |
    |
D   |
E   |
G 270 |
R   |
E   |
E   |
S 260 |

C   |

250 |
    |
    |
240 |
    |

    ↑
230 T-K LEVEL
      |         |         |         |         |         |         |         |         |
      25        50        75       100       125       150       175       200       225
                          DISTANCE FROM TOP OF TES, cm
                     THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
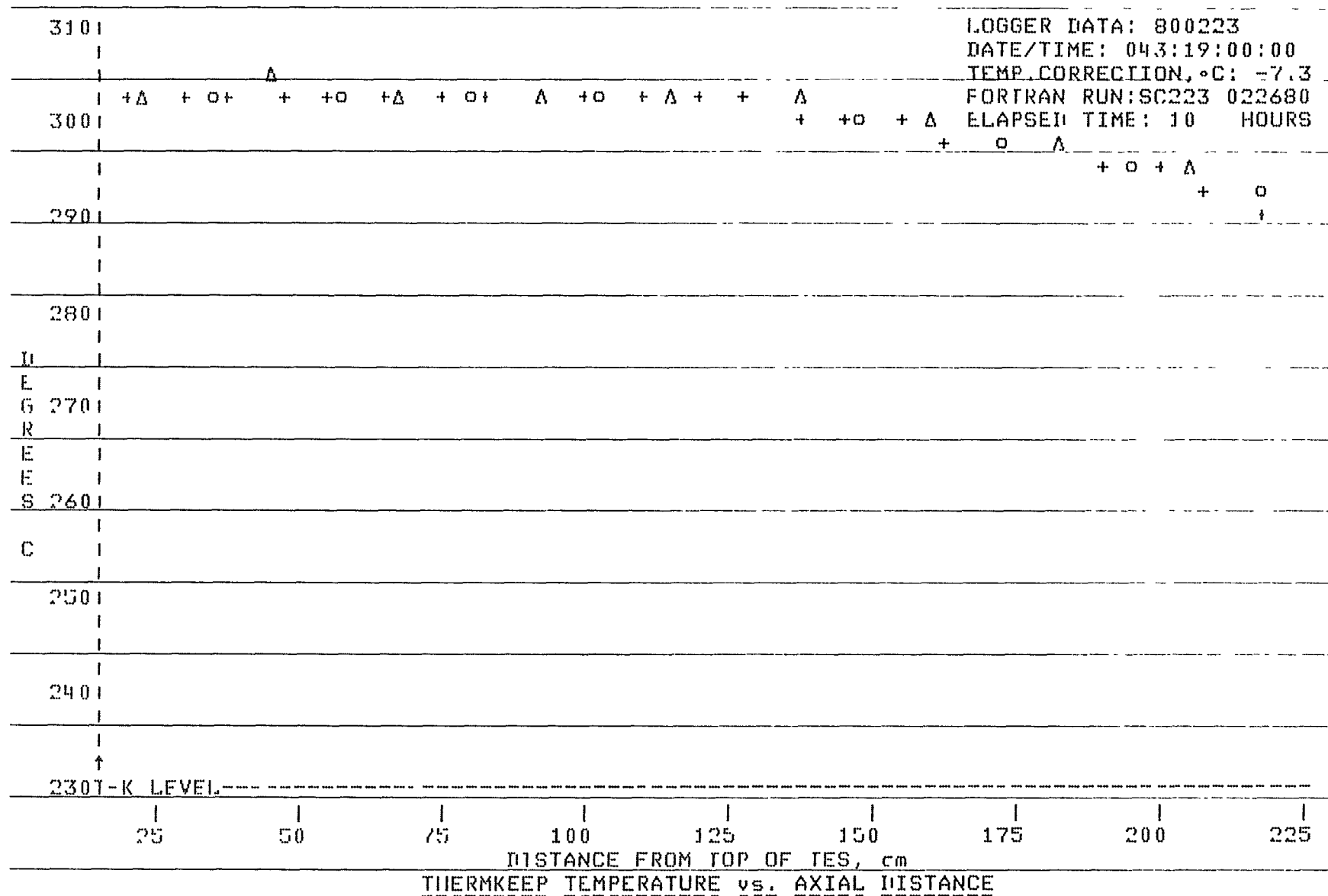
Figure C-42.   Thermkeep temperature profile, solar cycle test 223, at end of Cycle 1, charge.

Figure C-43. Thermkeep temperature profile, solar cycle test 223, at end of phase 2 discharge, Cycle 1.
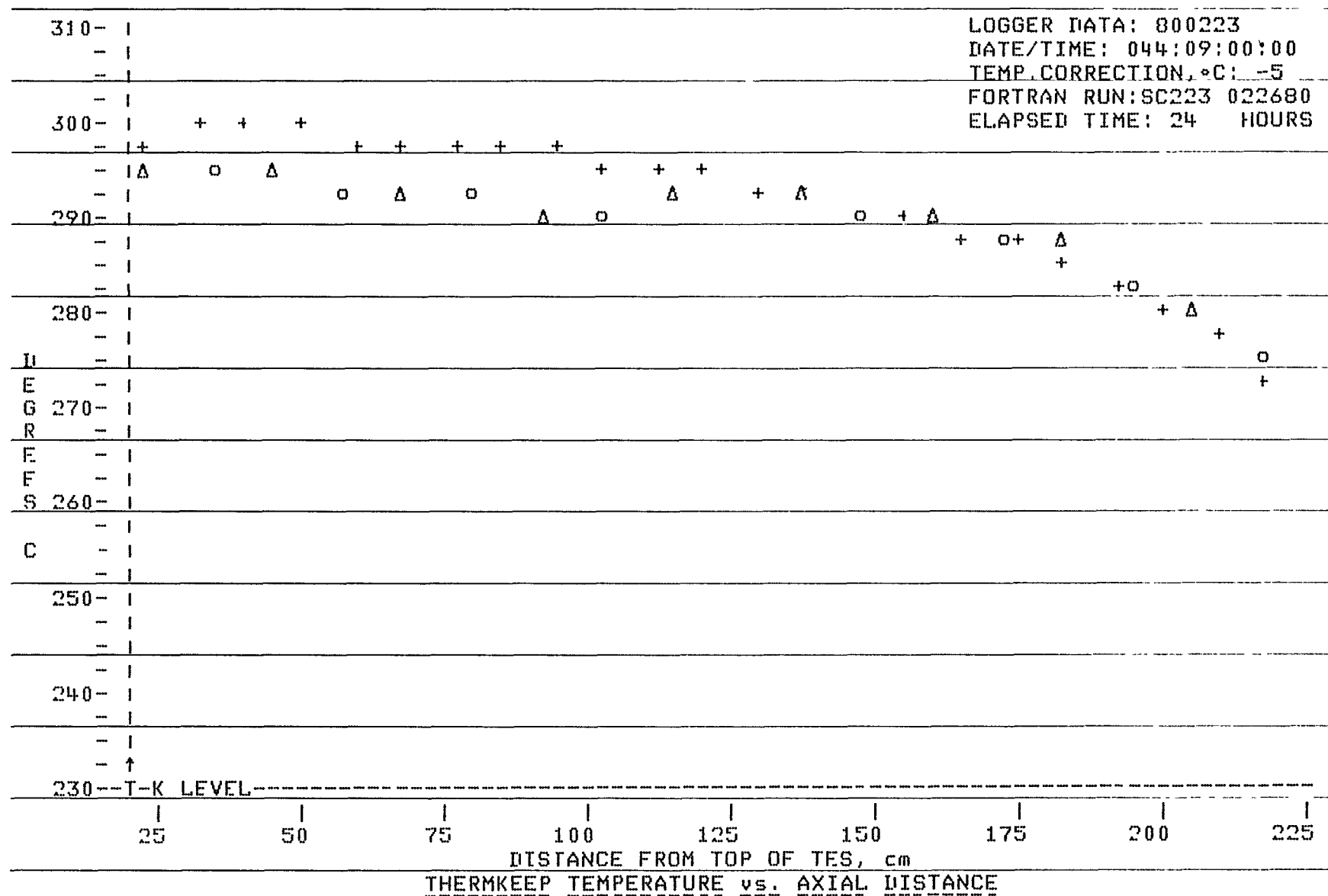
Figure C-44. Thermkeep temperature profile, solar cycle test 223, starting profile, cycle 2.

Chart — Thermkeep temperature profile:

- Y-axis (DEGREES C): 310, 300, 290, 280, 270, 260, 250, 240, 230
- 230---T-K LEVEL---
- X-axis (DISTANCE FROM TOP OF TES, cm): 25, 50, 75, 100, 125, 150, 175, 200, 225

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE

Figure C-45. Thermkeep temperature profile, solar cycle test 223, at end of phase 1 discharge, cycle 2.

310

+Δ + O+ Δ+ +O +Δ + O+ Δ +O Δ Δ

LOGGER DATA: 800223
DATE/TIME: 044:19:00:00
TEMP.CORRECTION,°C: -7.3

+ + + + O Δ FORTRAN RUN:SC223 022680

300

+ + + ELAPSED TIME: 34 HOURS

+ + O

+ + Δ

+ O

290

+

280

D
E
G 270
R

E
E
S 260

C

250

240

↑
230 T-K LEVEL

25   50   75   100   125   150   175   200   225

DISTANCE FROM TOP OF TES, cm

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE

Figure C-46. Thermkeep temperature profile, solar cycle test 223, at end of cycle 2 charge.
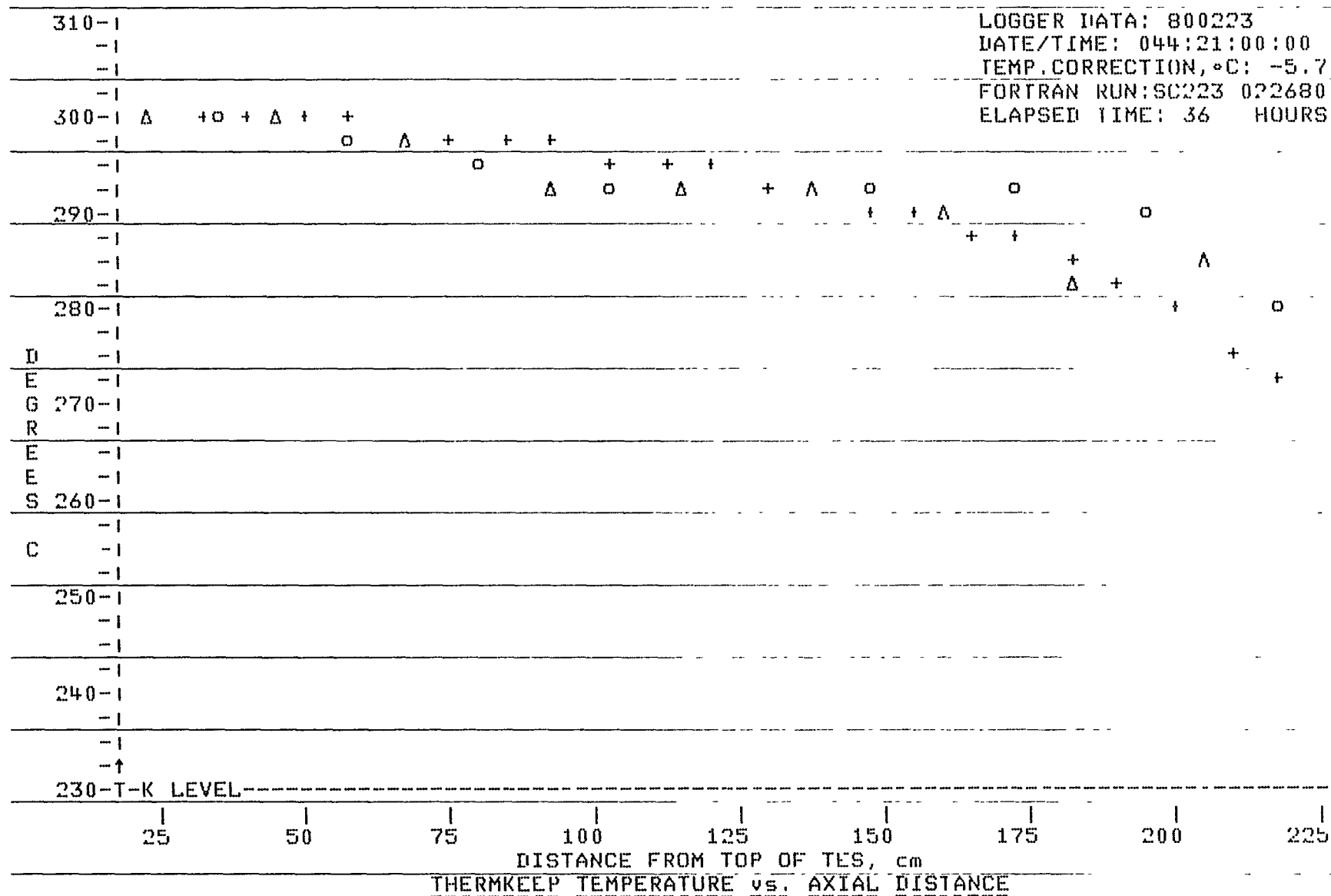
Figure C-47. Thermkeep temperature profile, solar cycle test 223, at end of phase 2 discharge, cycle 2.

```
LOGGER DATA: 800223
DATE/TIME: 045:09:00:00
TEMP.CORRECTION,°C: -4.3
FORTRAN RUN:SC223 022680
ELAPSED TIME: 48   HOURS
```

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE

DISTANCE FROM TOP OF TES, cm
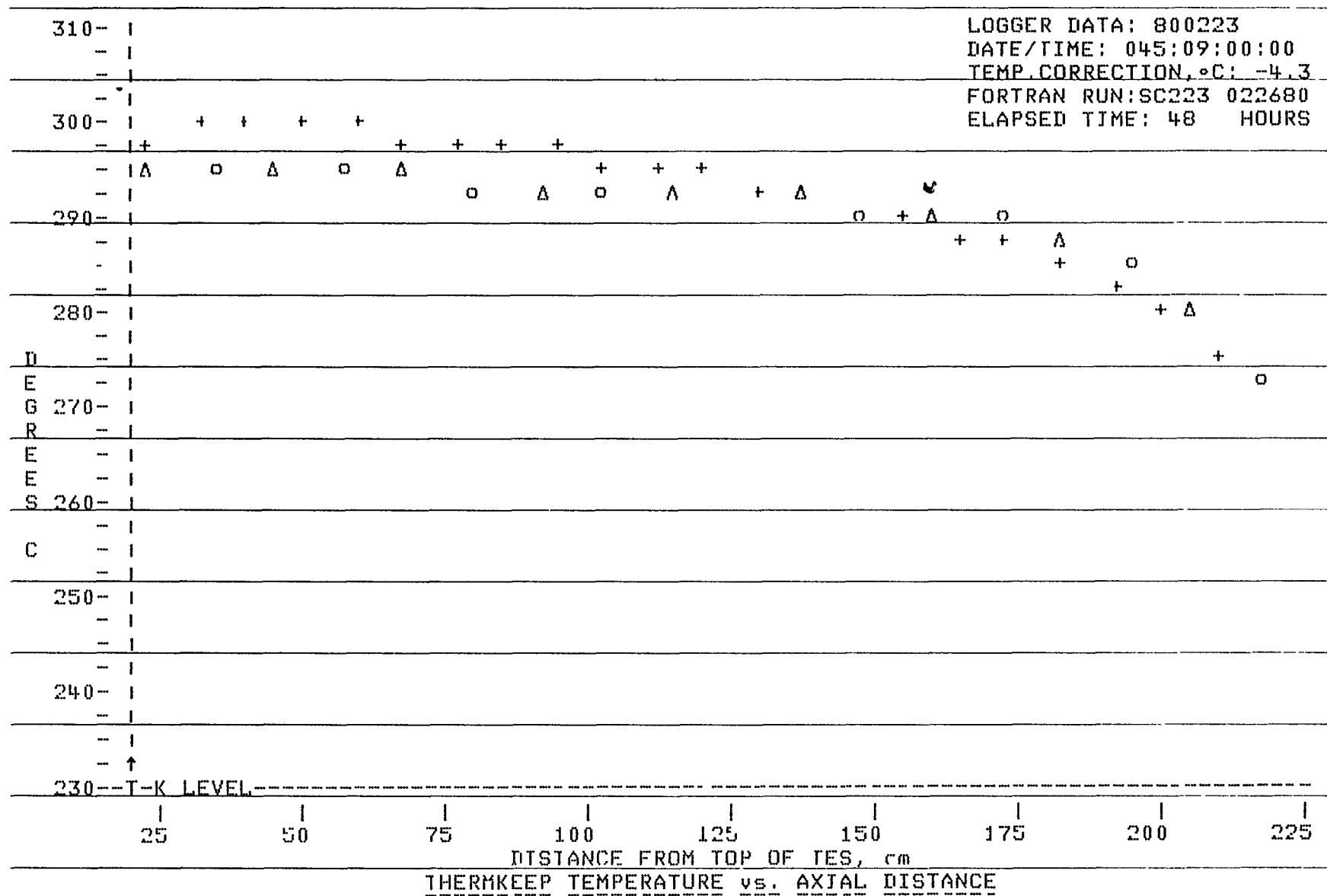
Figure C-48. Thermkeep temperature profile, solar cycle test 223, at end of overnight idle after cycle 2.
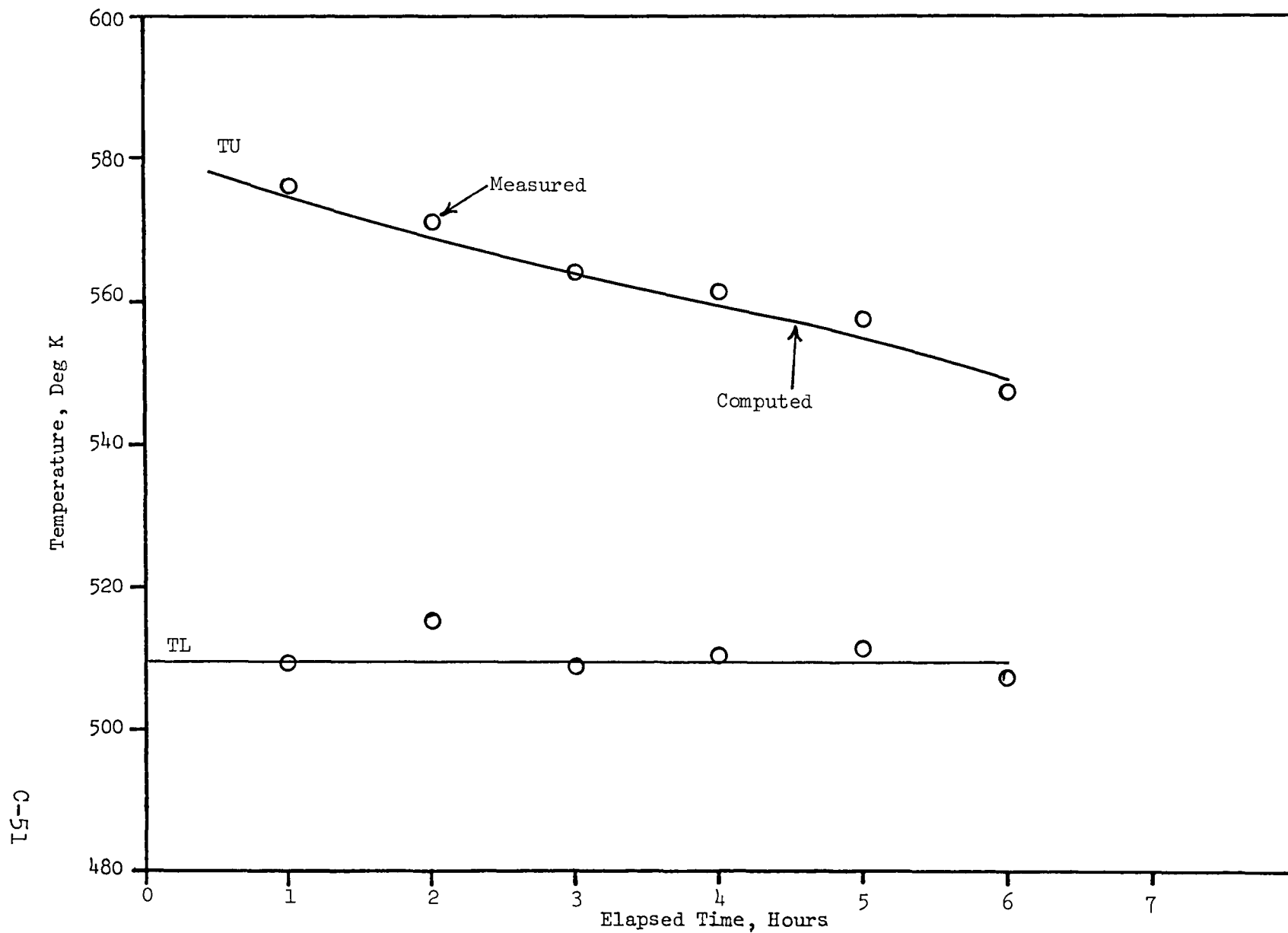
Figure C-49. T-66 outlet temperature, discharge test 001 (2.9 gpm)
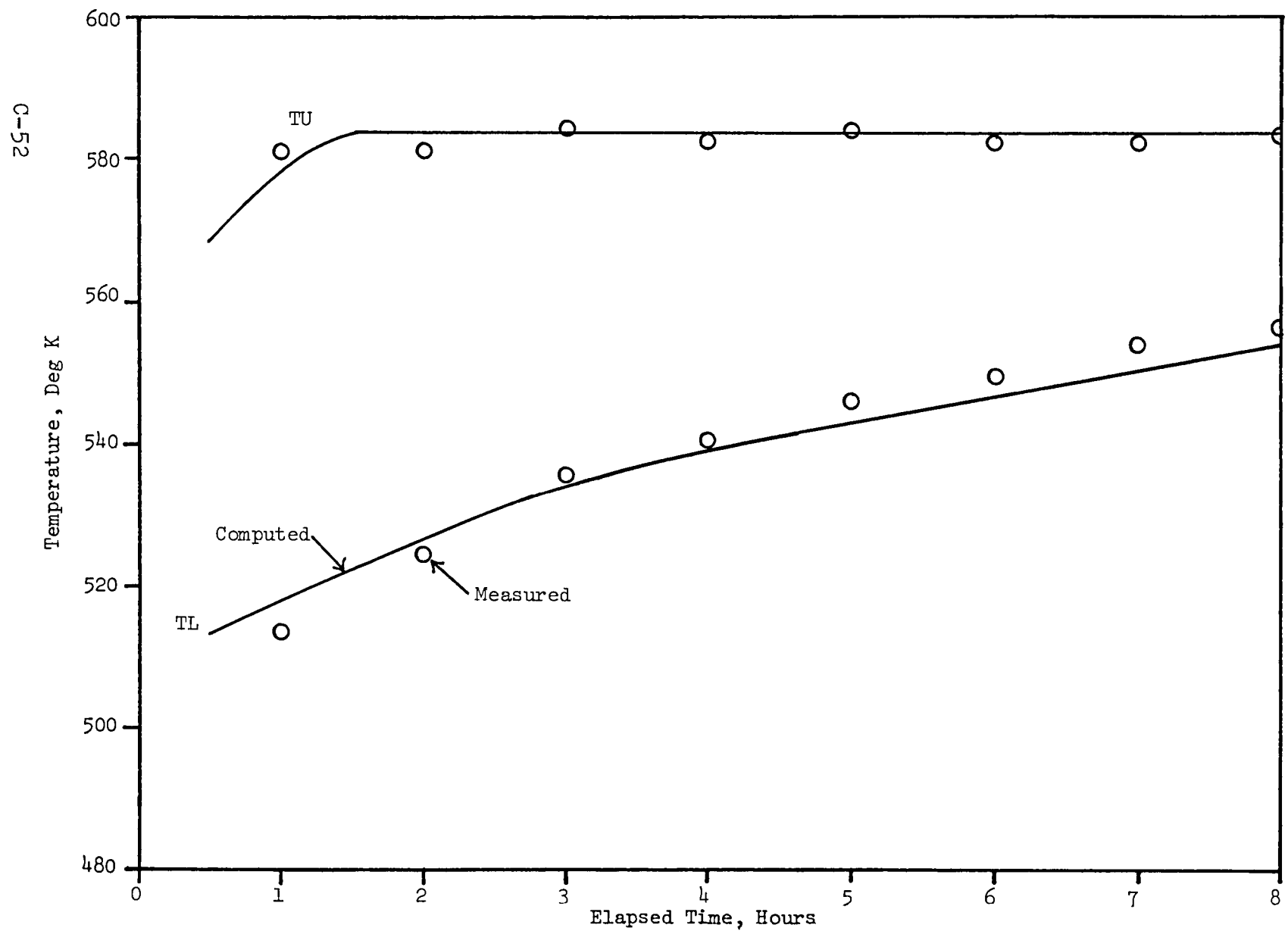
Figure C-50. T-66 outlet temperature, charge test 002 (2.8 gpm).
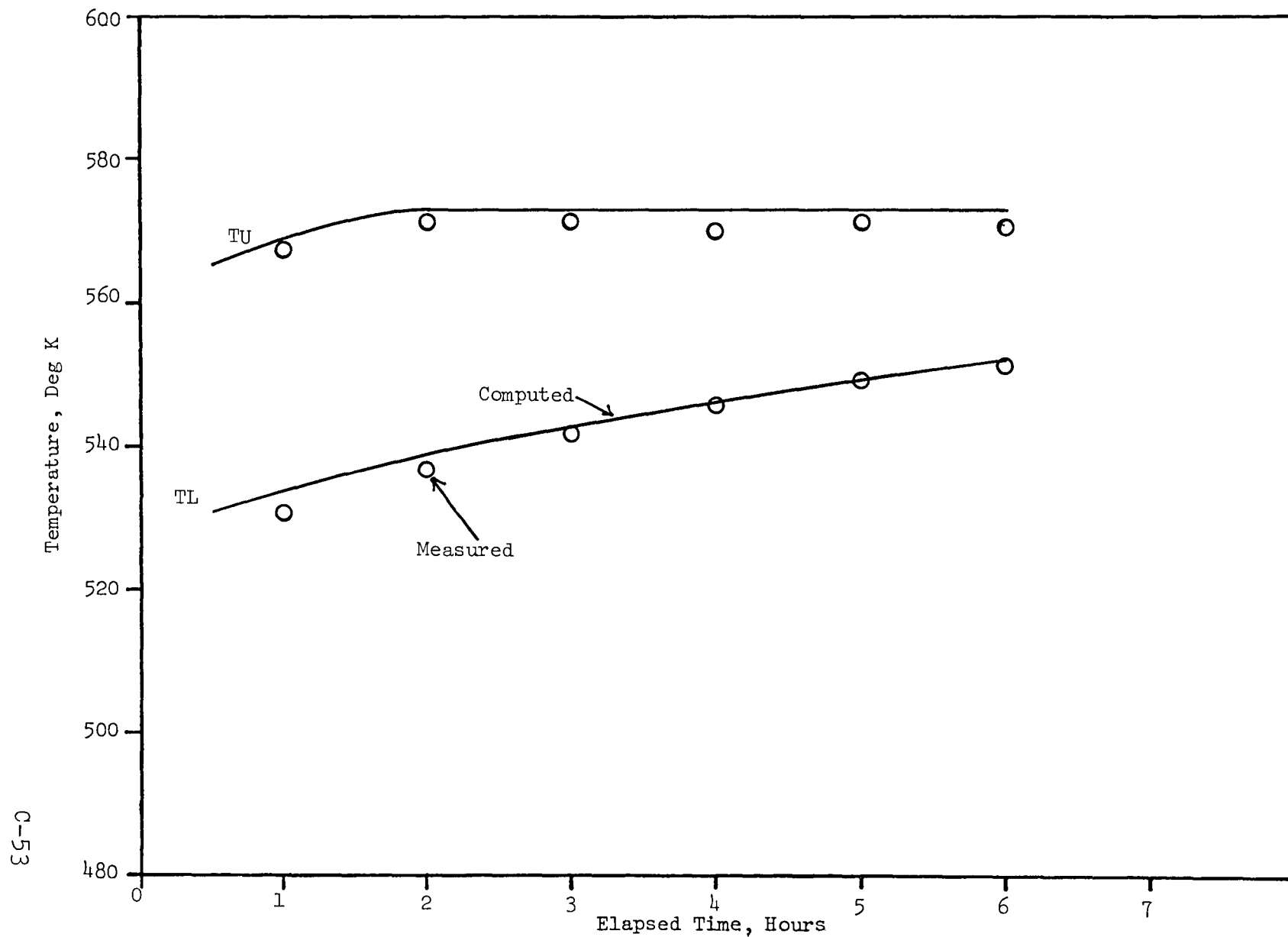
Figure C-51.   T-66 outlet temperature, charge test 004 (3.4 gpm).
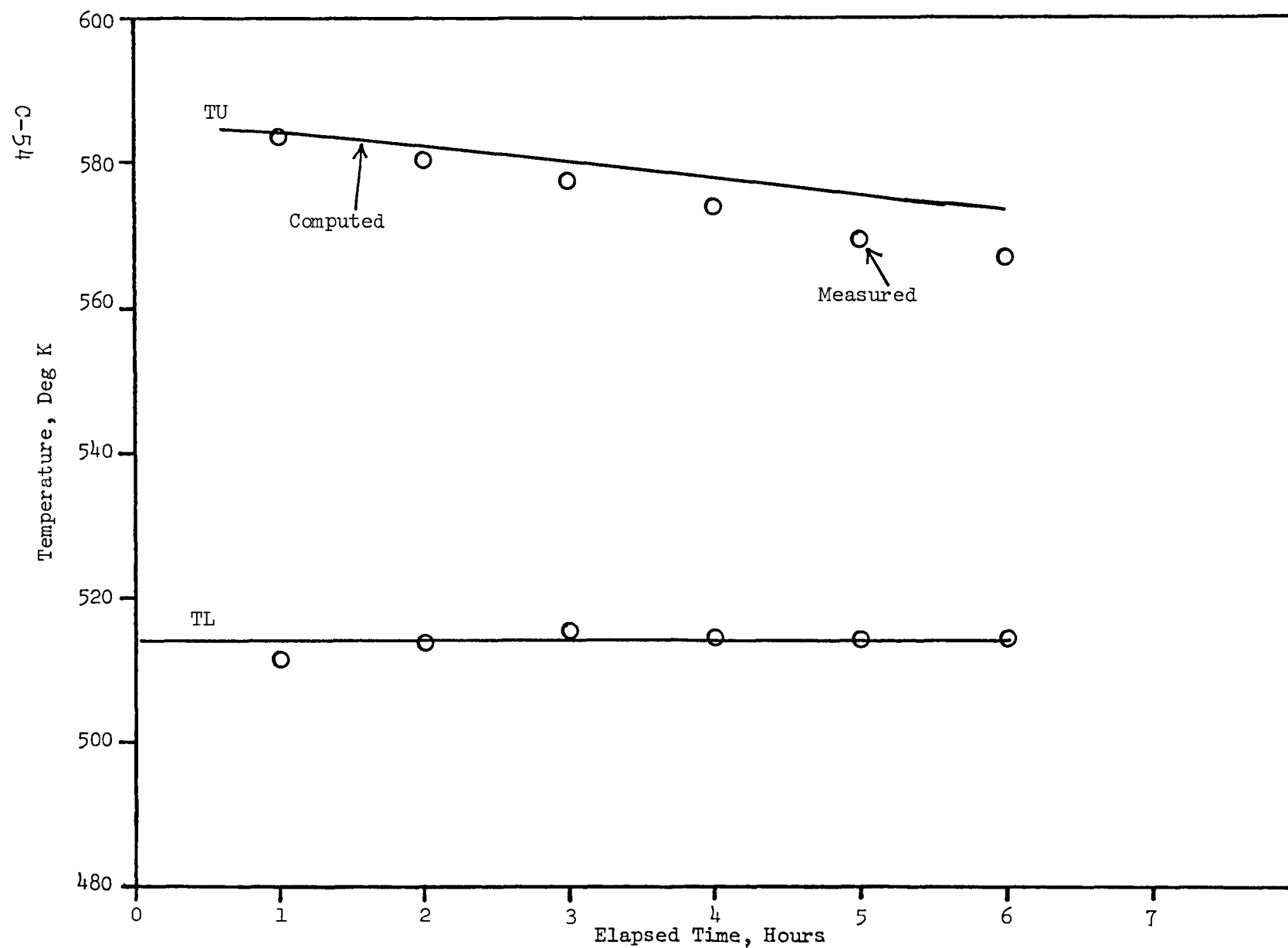
Figure C-52. T-66 outlet temperature, discharge test 014 (1.0 gpm).
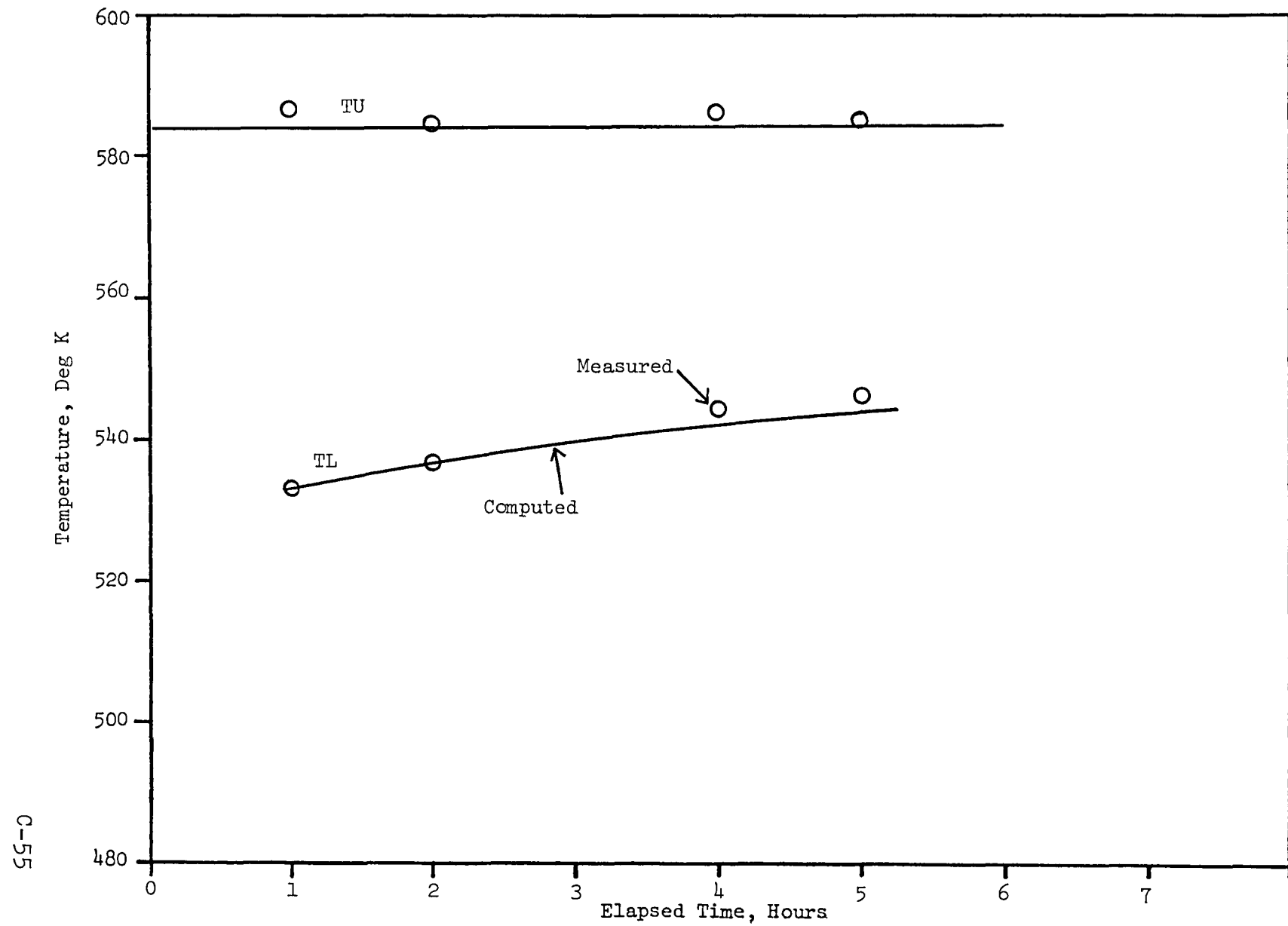
Figure C-53.   T-66 outlet temperature, charge test 015 (1.0 gpm).
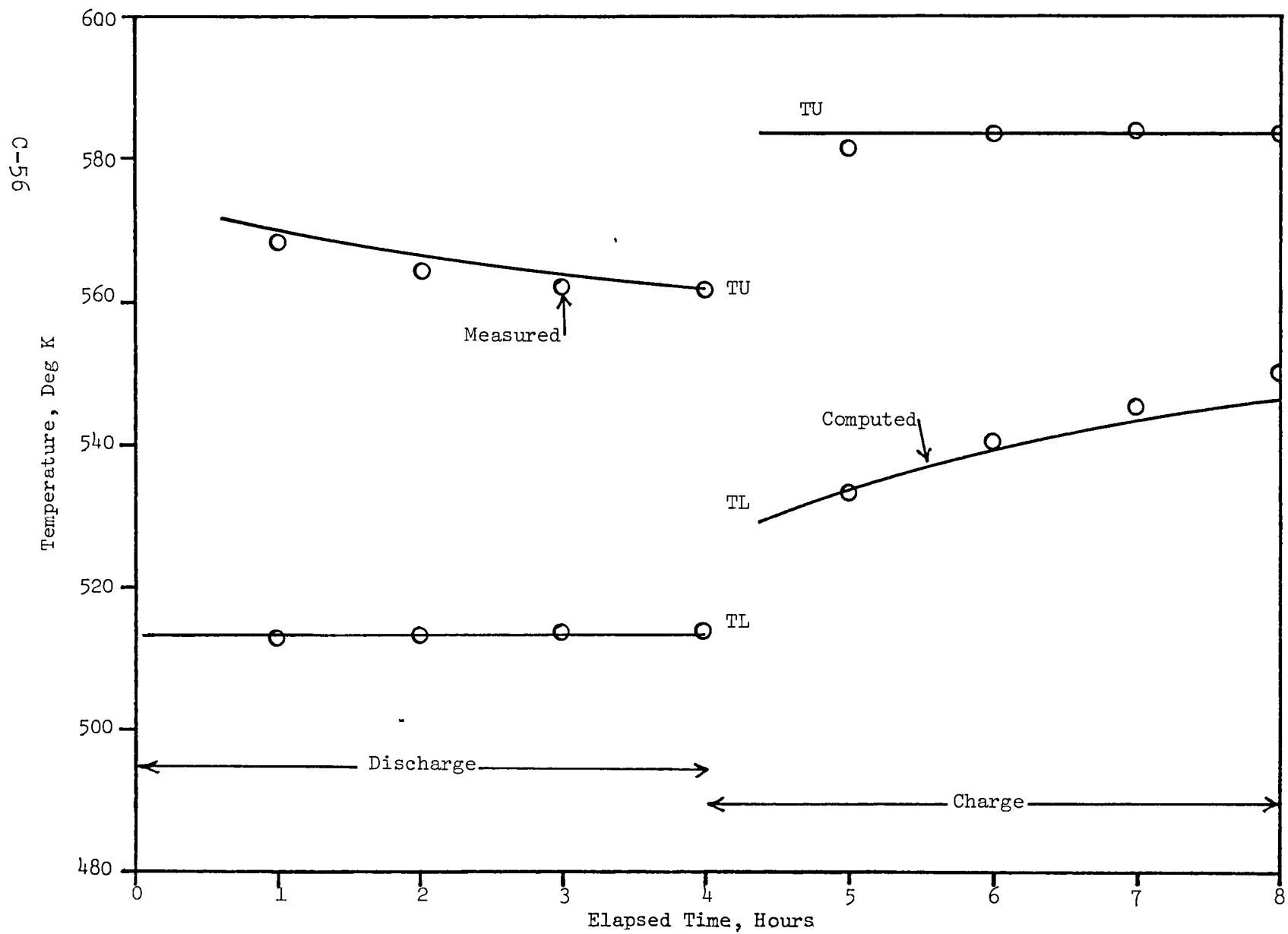
Figure C-54. T-66 outlet temperature, cyclic test 018 (2.0 gpm), first cycle.
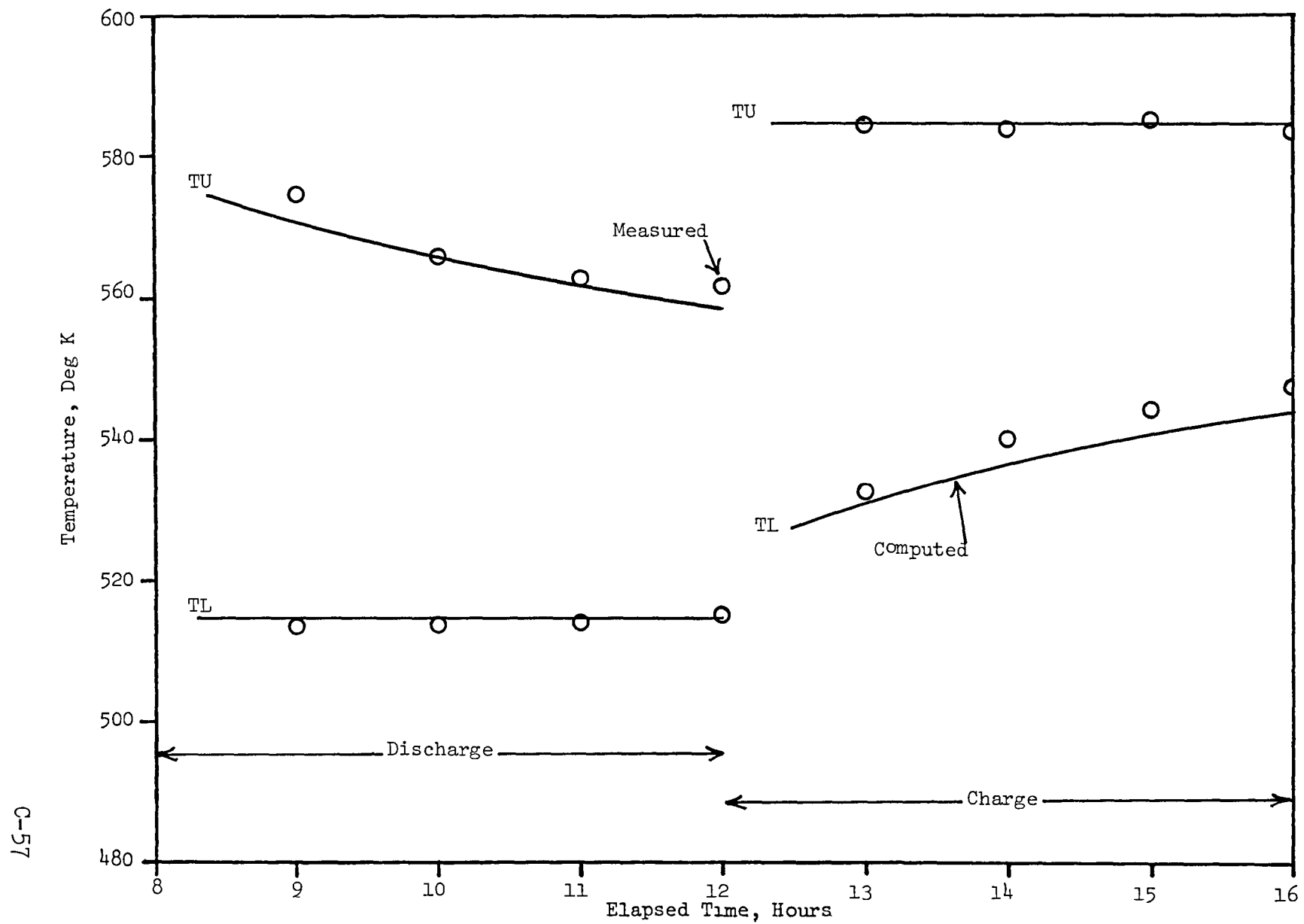
Figure C-55. T-66 outlet temperature, cyclic test 018 (2.0 gpm), second cycle.
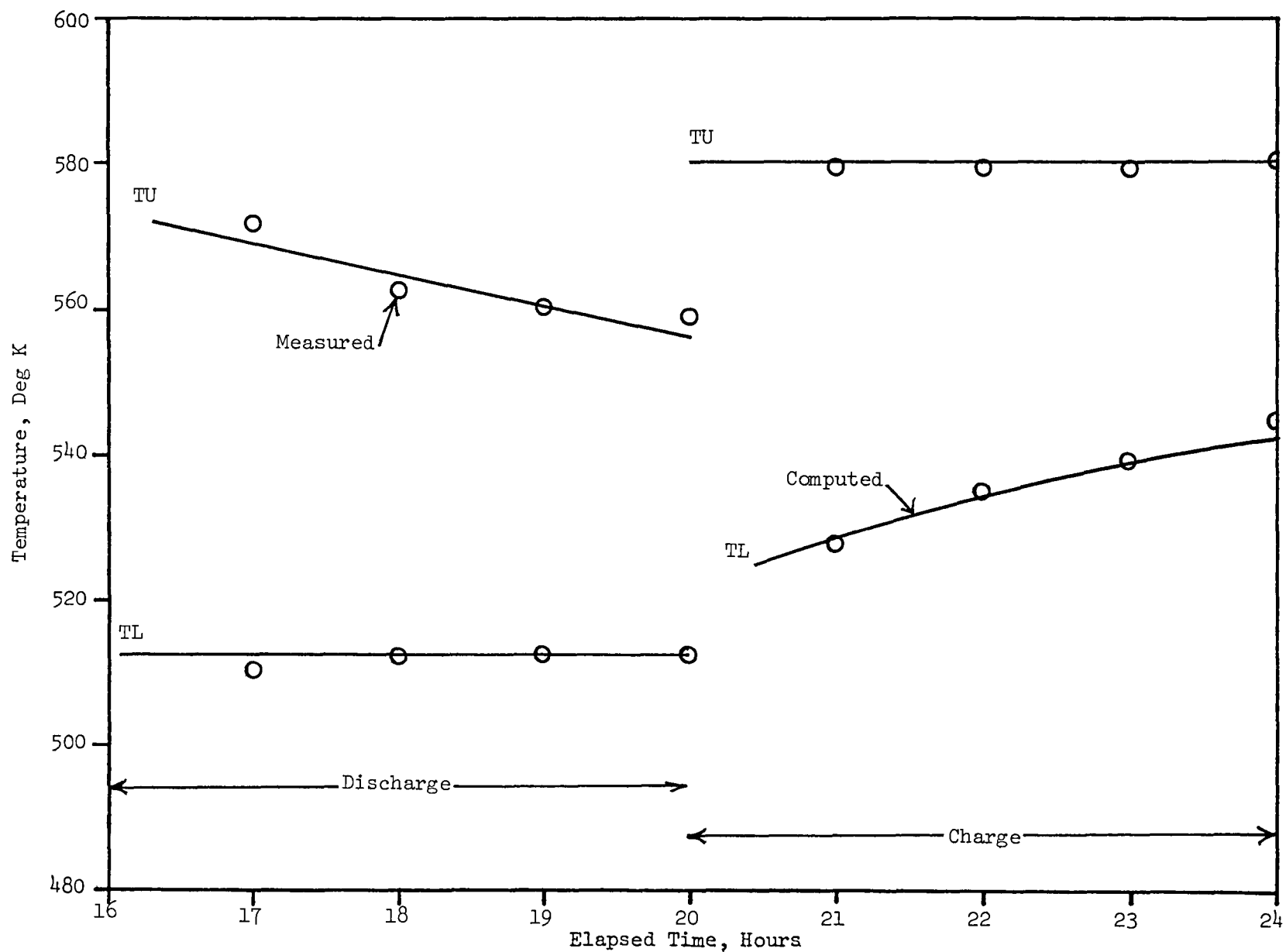
Figure C-56.   T-66 outlet temperature, cyclic test 018 (2.0 gpm), third cycle.
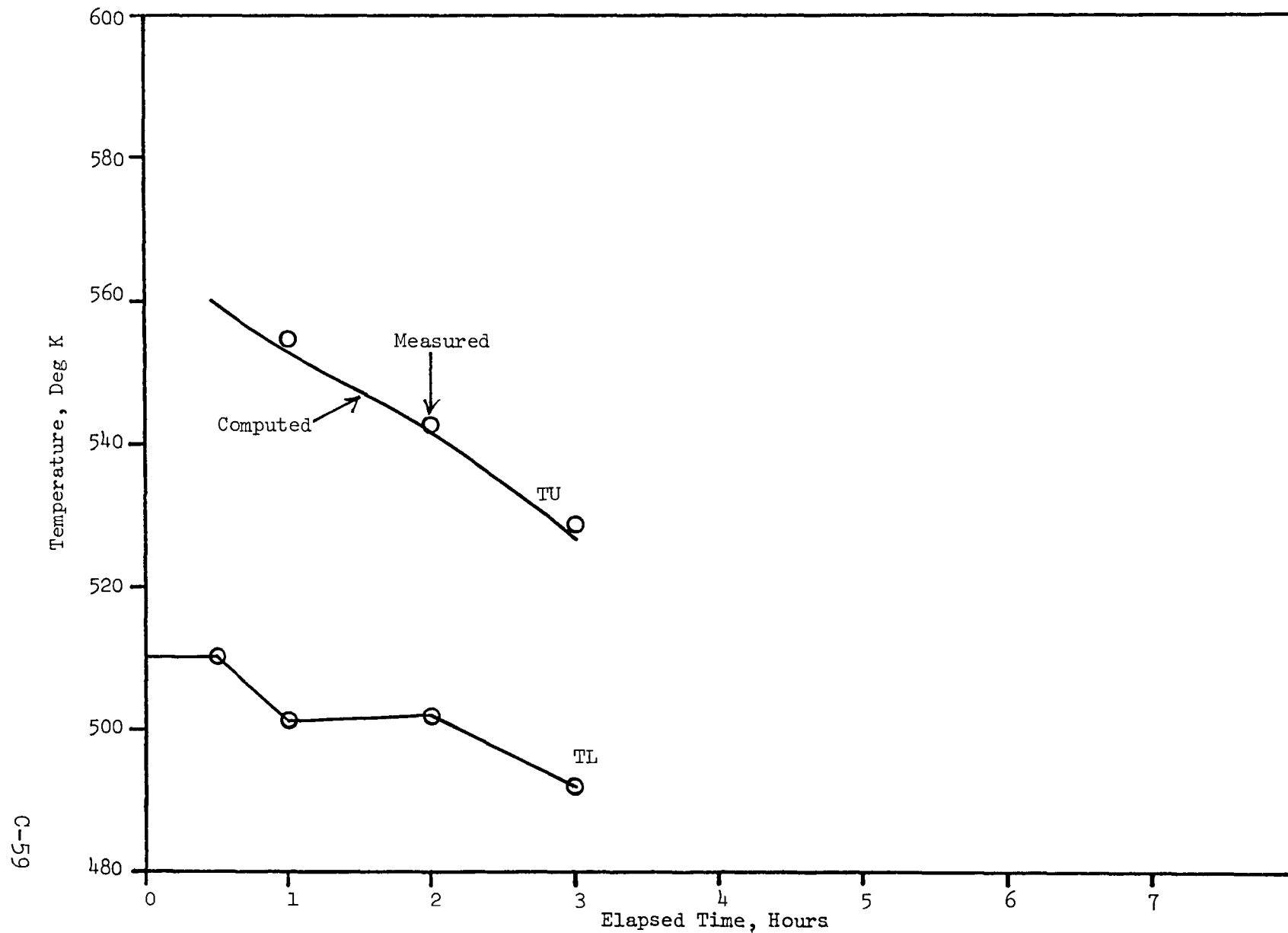
Figure C-57. T-66 outlet temperature, discharge test 019 (6.6. gpm)

Figure C-58. T-66 outlet temperature solar cycle test 023, first cycle.
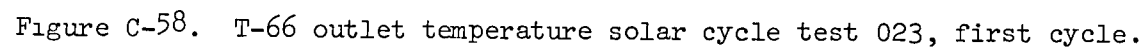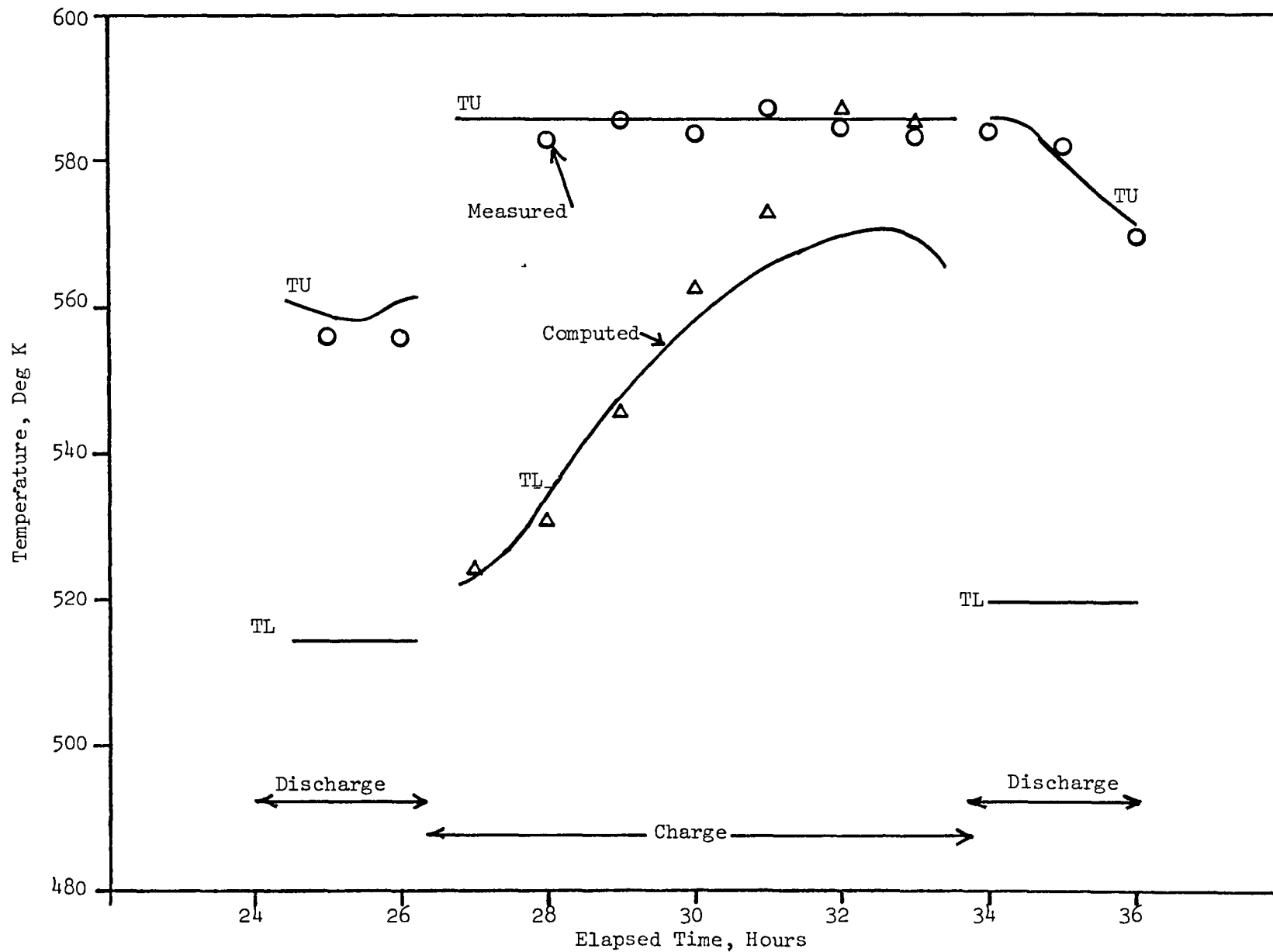
Figure C-59. T-66 outlet temperature solar cycle test 023, second cycle.
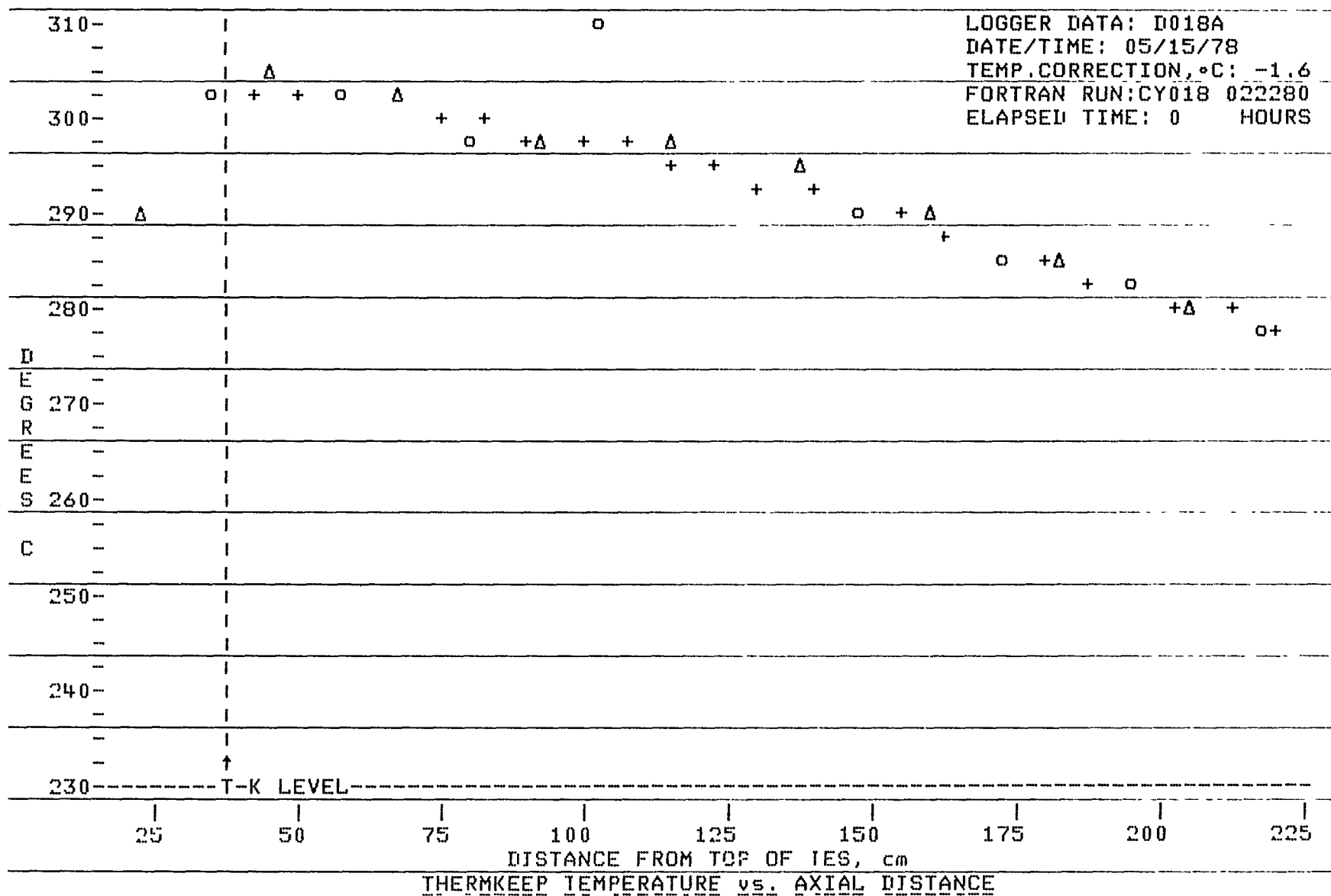
Figure C-60. Thermkeep temperature profile, cyclic test 018 (2.0 gpm), starting profile.

LOGGER DATA: D018A
DATE/TIME: 05/15/78
TEMP.CORRECTION,°C: -2.7
FORTRAN RUN:CY018 022280
ELAPSED TIME: 4   HOURS

310-

300-

290-

280-

D
E
G 270-
R
E
E
S 260-

C

250-

240-

230----------------T-K LEVEL----------------

25   50   75   100   125   150   175   200   225

DISTANCE FROM TOP OF TES, cm

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
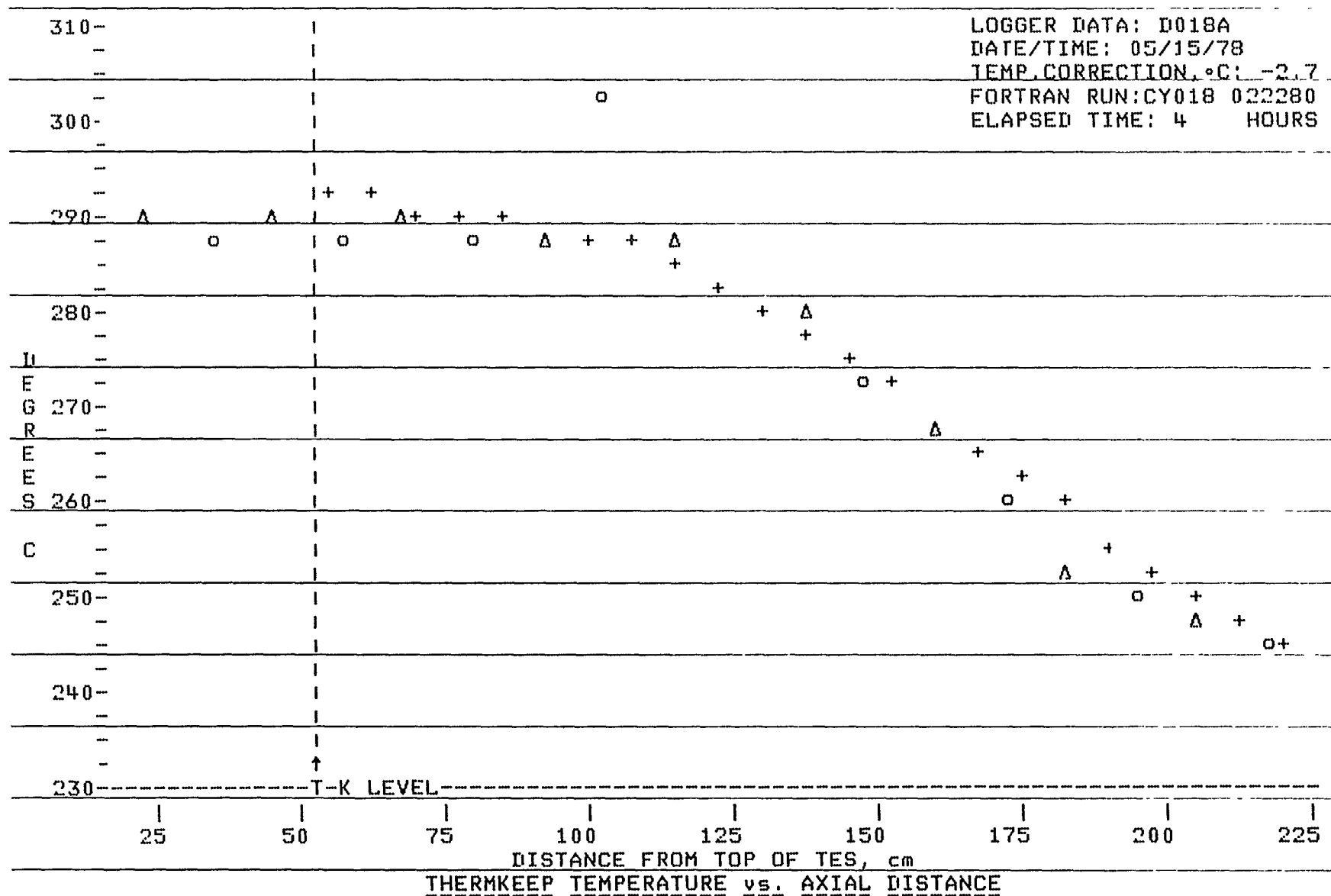
Figure C-61. Thermkeep temperature profile, cyclic test 018 (2.0 gpm), at end of first discharge phase.
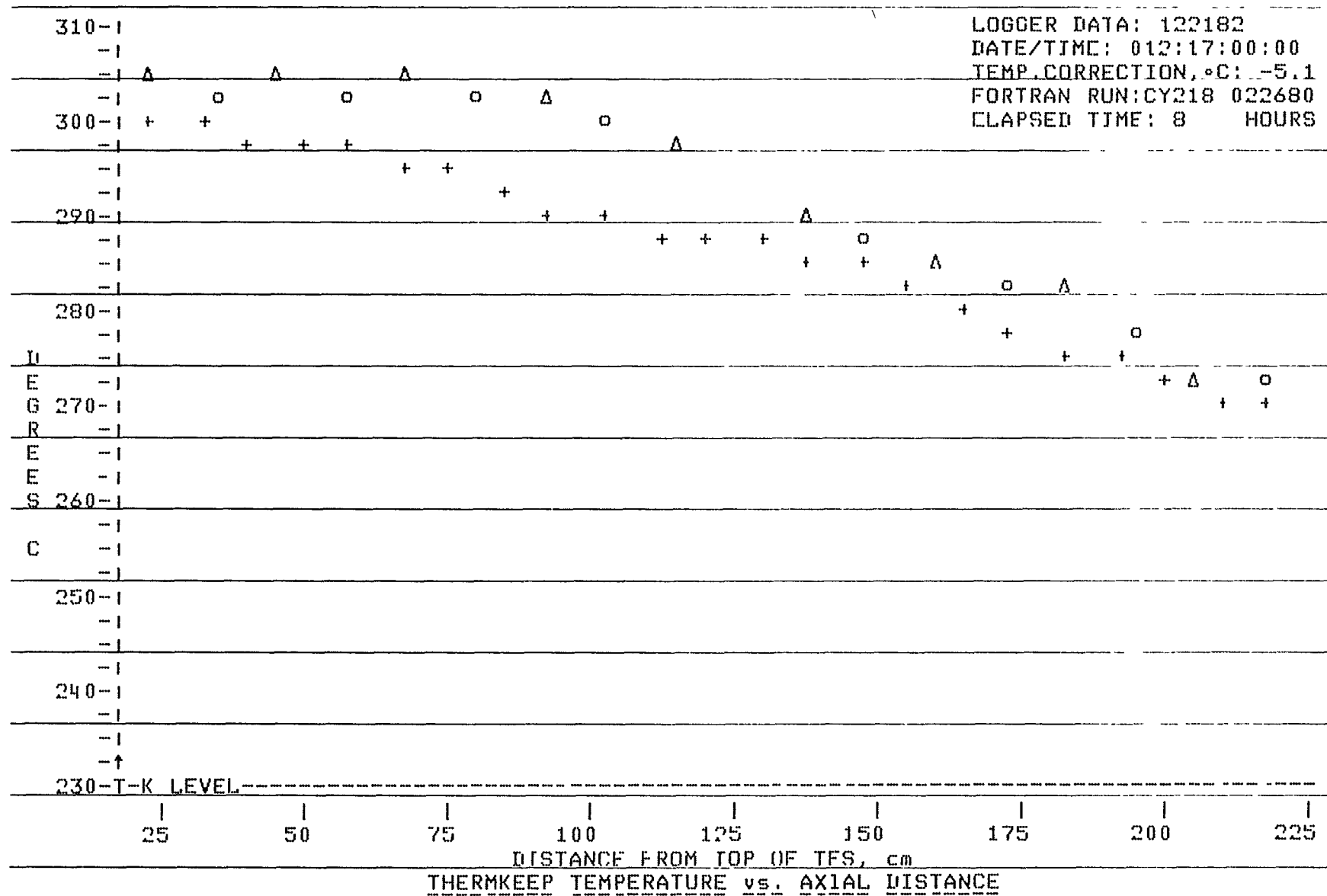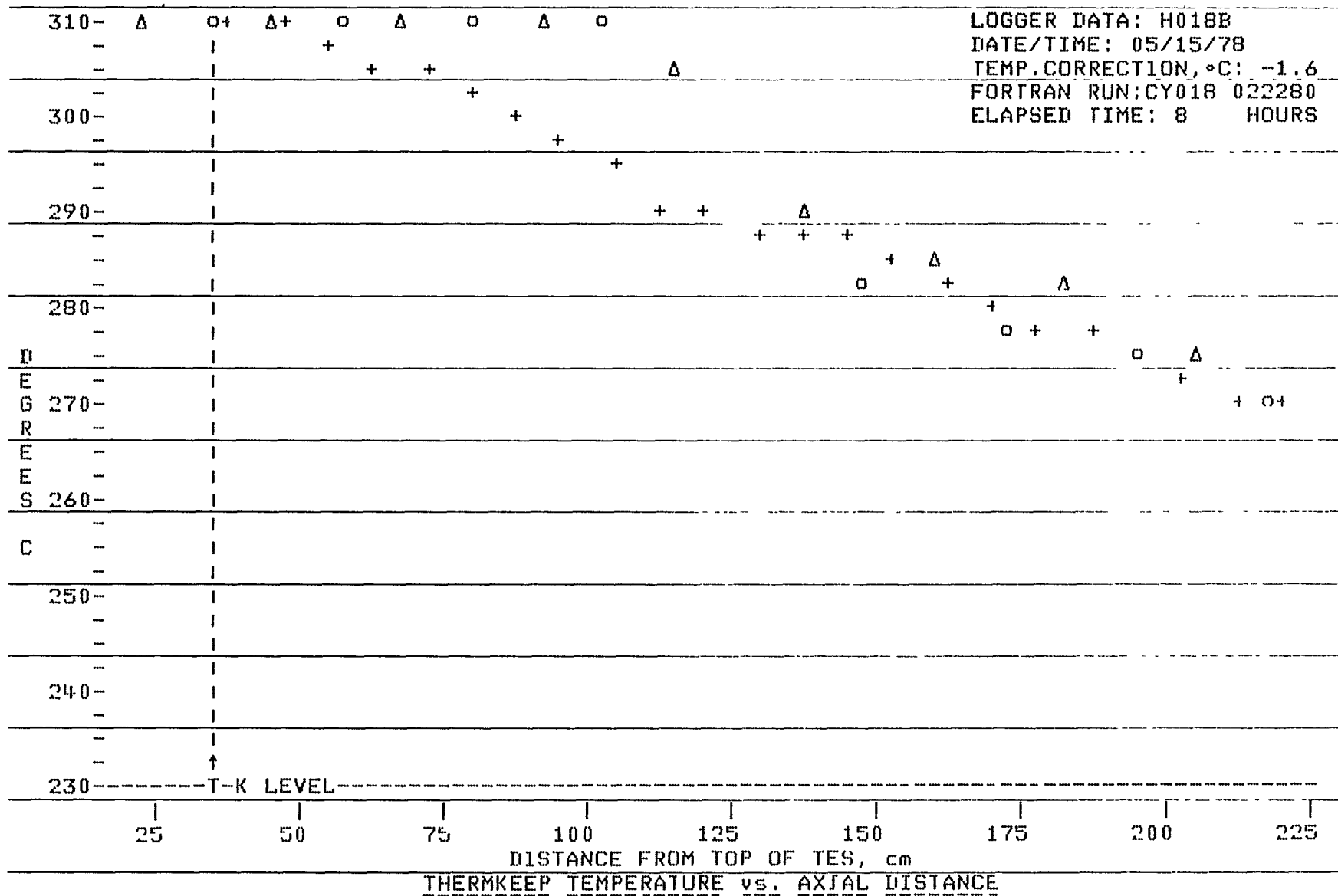
Figure C-62. Thermkeep temperature profile, cyclic test 018 (2.0 gpm), at end of first charge phase.
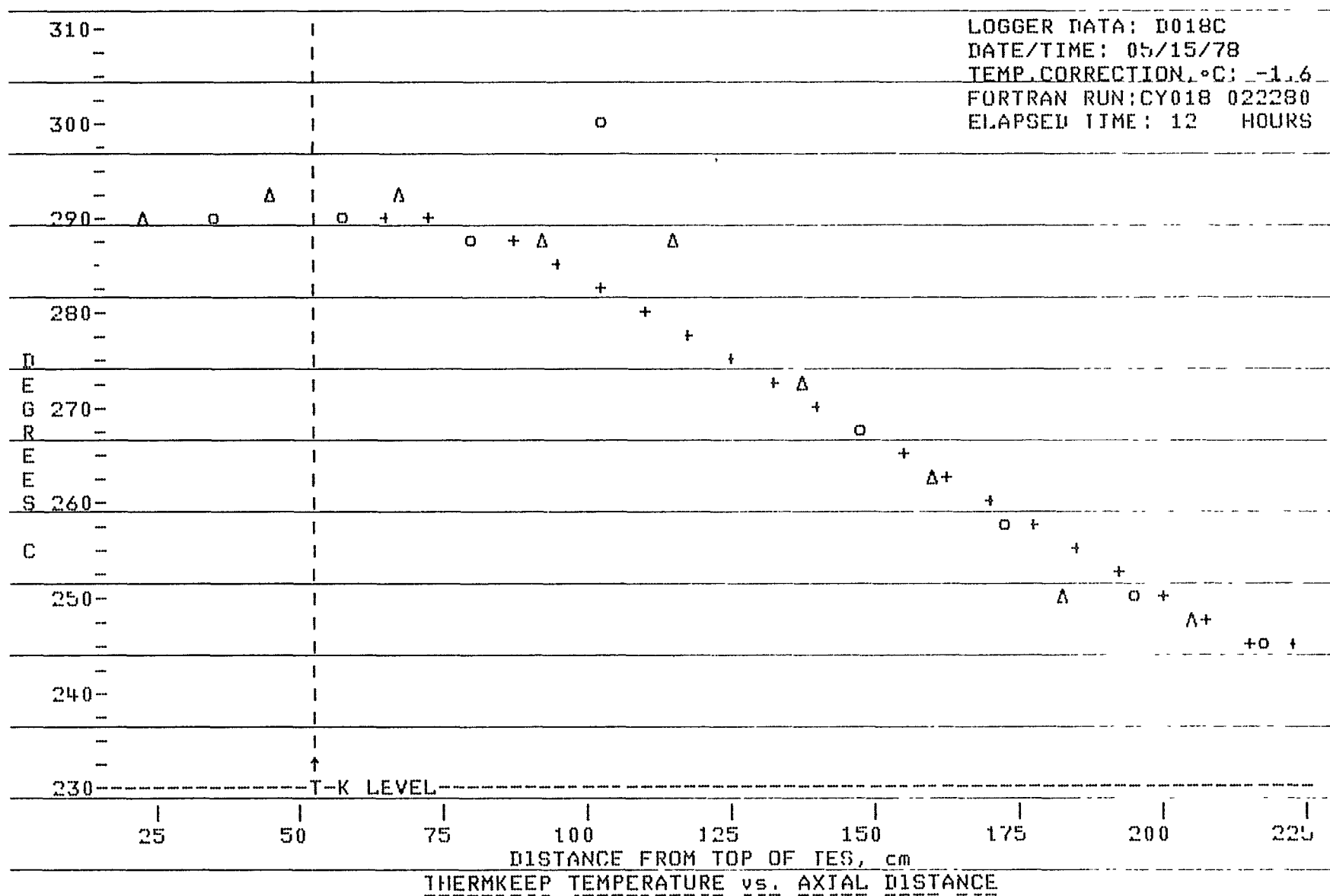
Figure C-63. Thermkeep temperature profile, cyclic test 018 (2.0 gpm), at end of second discharge phase.
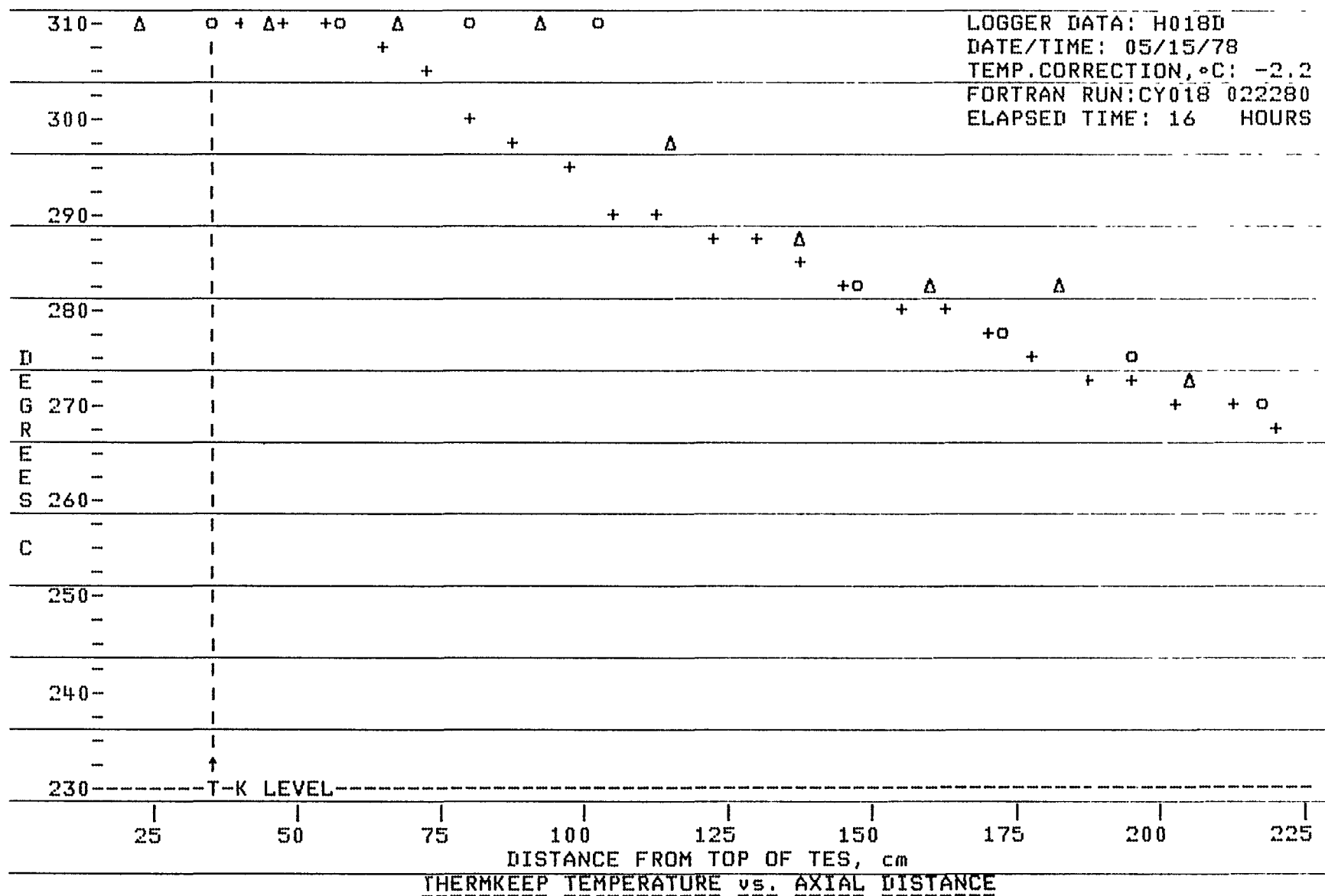
Figure C-64. Thermkeep temperature profile, cyclic test 018 (2.0 gpm), at end of second charge phase.

LOGGER DATA: D018E
DATE/TIME: 05/16/78
TEMP.CORRECTION,°C: -2.7
FORTRAN RUN:CY018 022280
ELAPSED TIME: 20 HOURS

310—

300—

D
E
G 270—
R
E
E
S 260—

C

250—

240 -

230————————————————T-K LEVEL————————————————

290—

280—

DISTANCE FROM TOP OF TES, cm

25   50   75   100   125   150   175   200   225

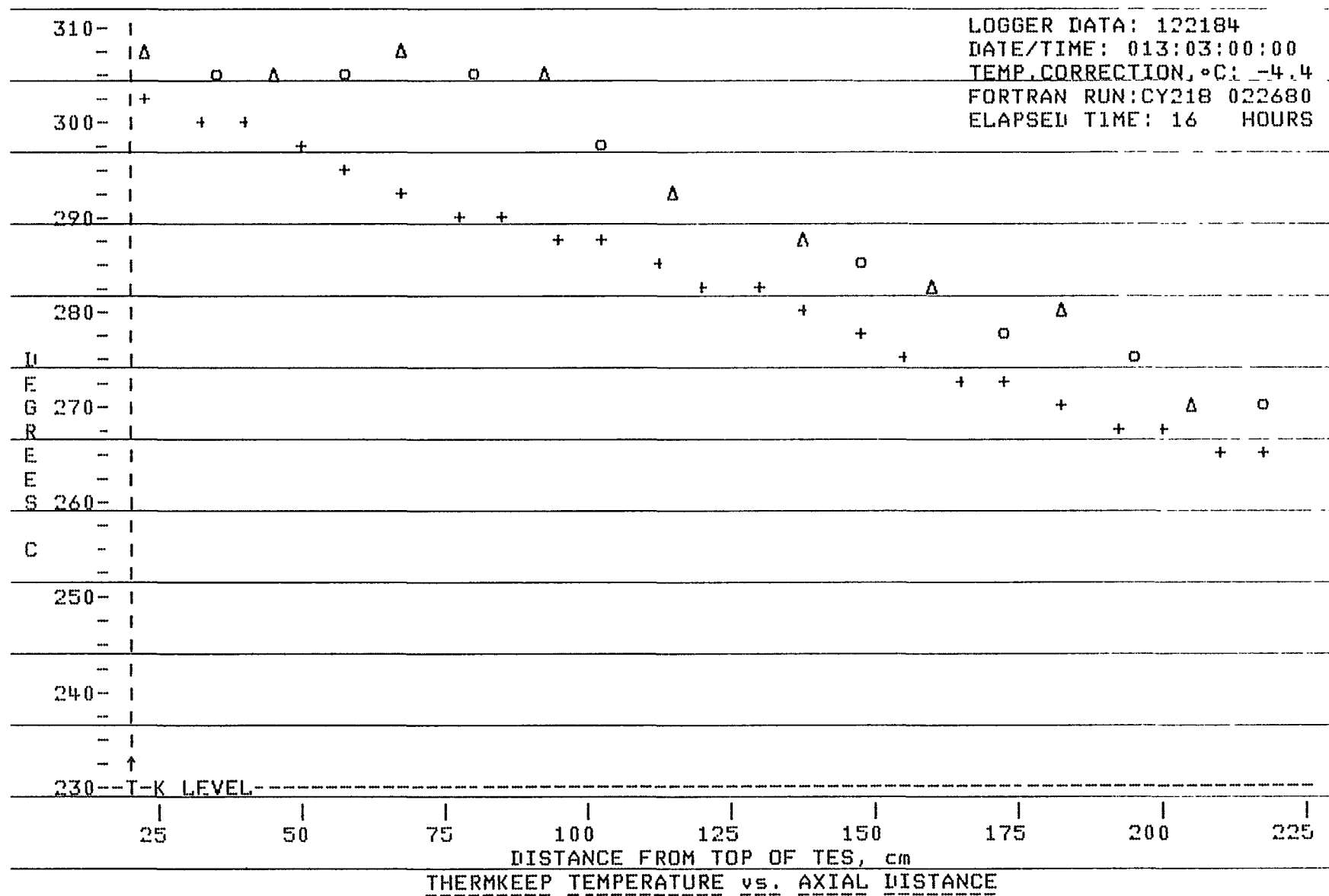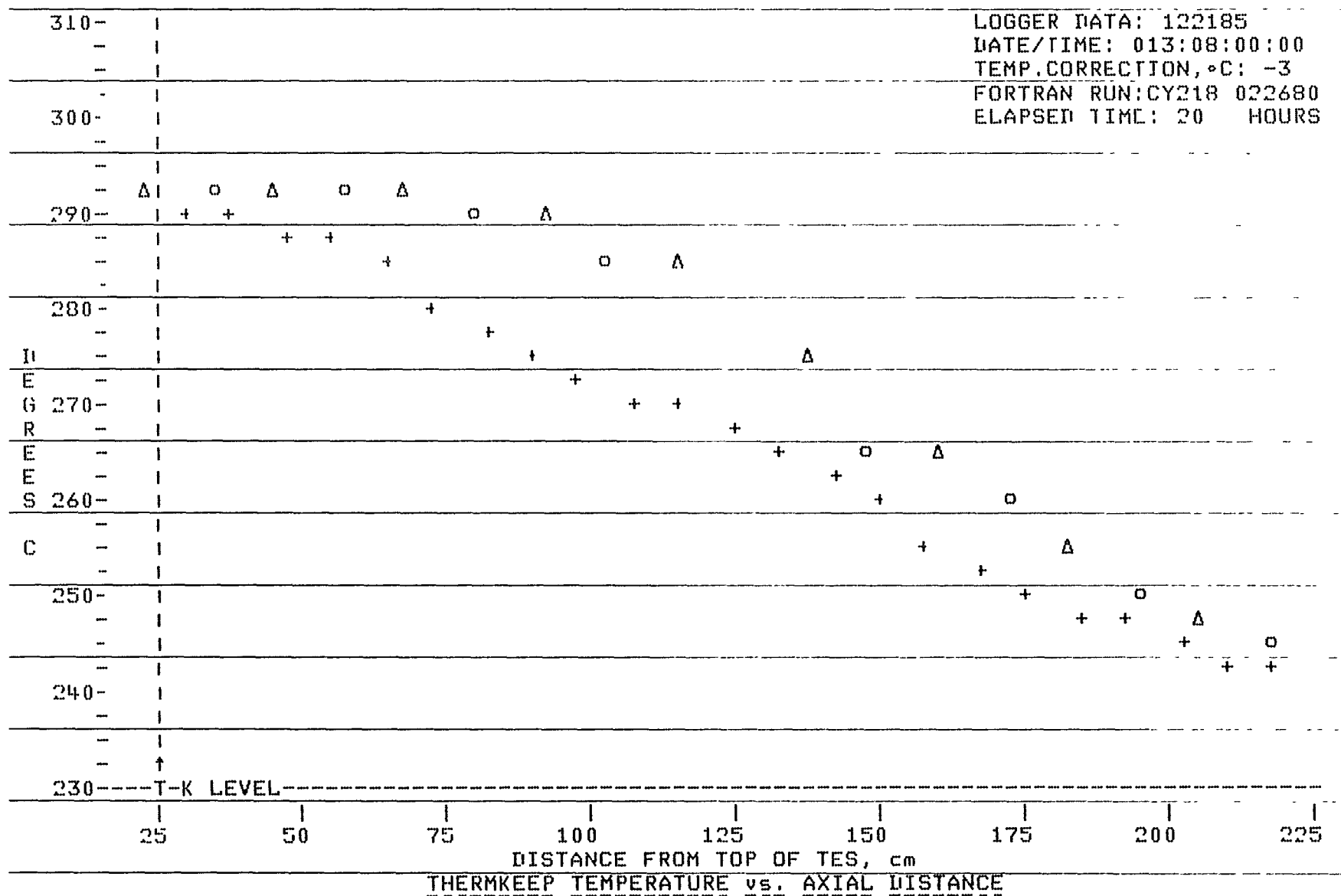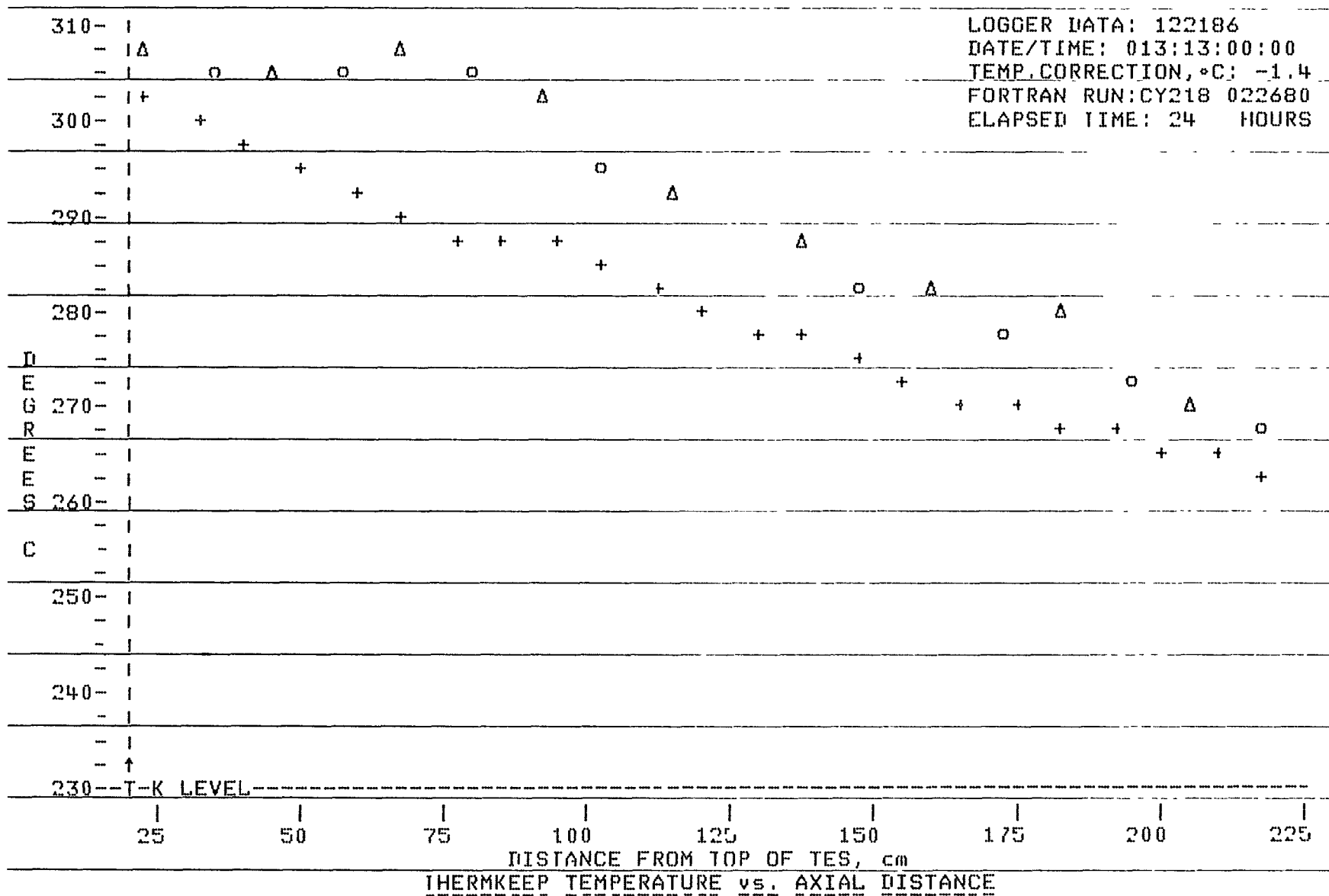THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
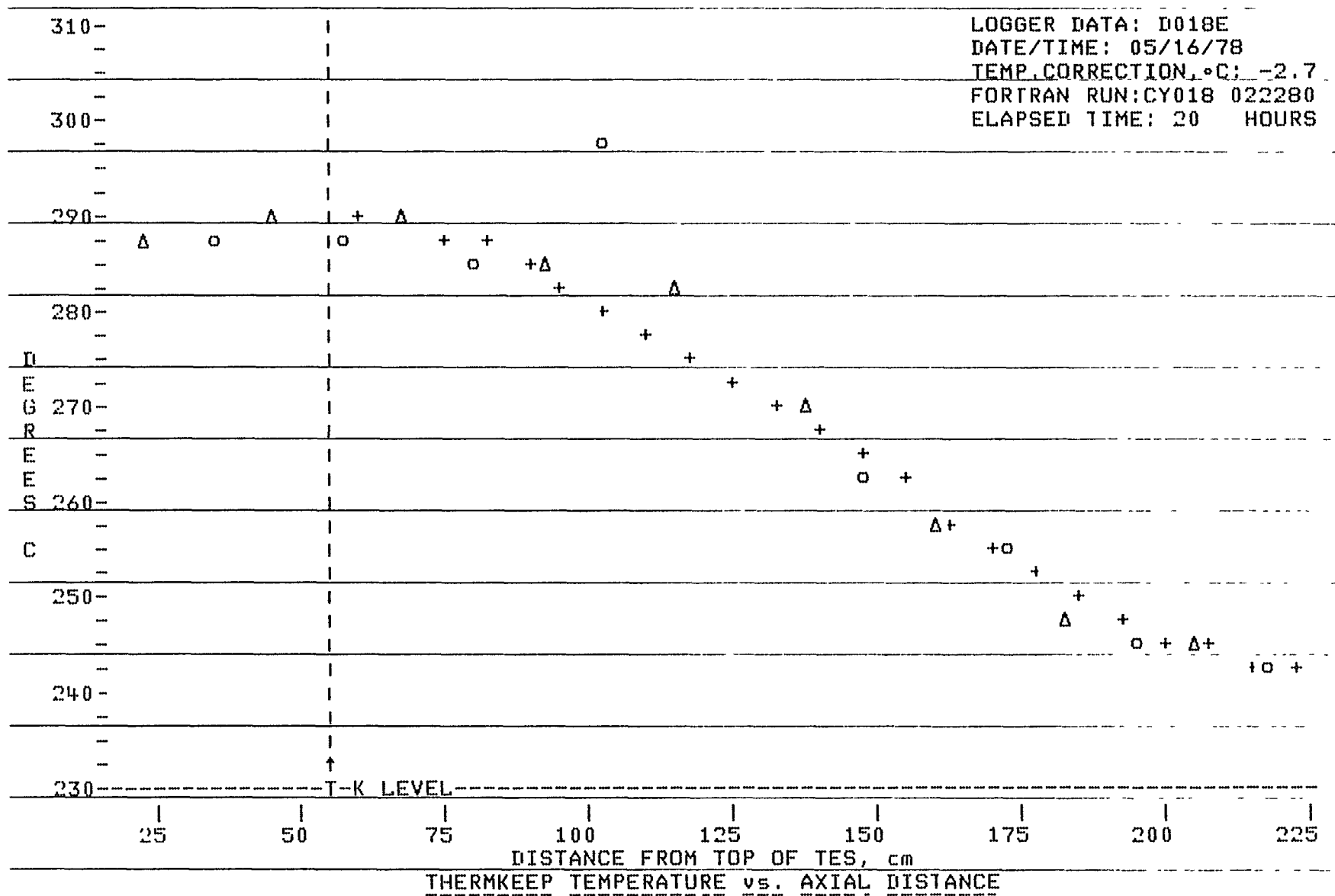
Figure C-65. Thermkeep temperature profile, cyclic test 018 (2.0) gpm), at end of third discharge phase.
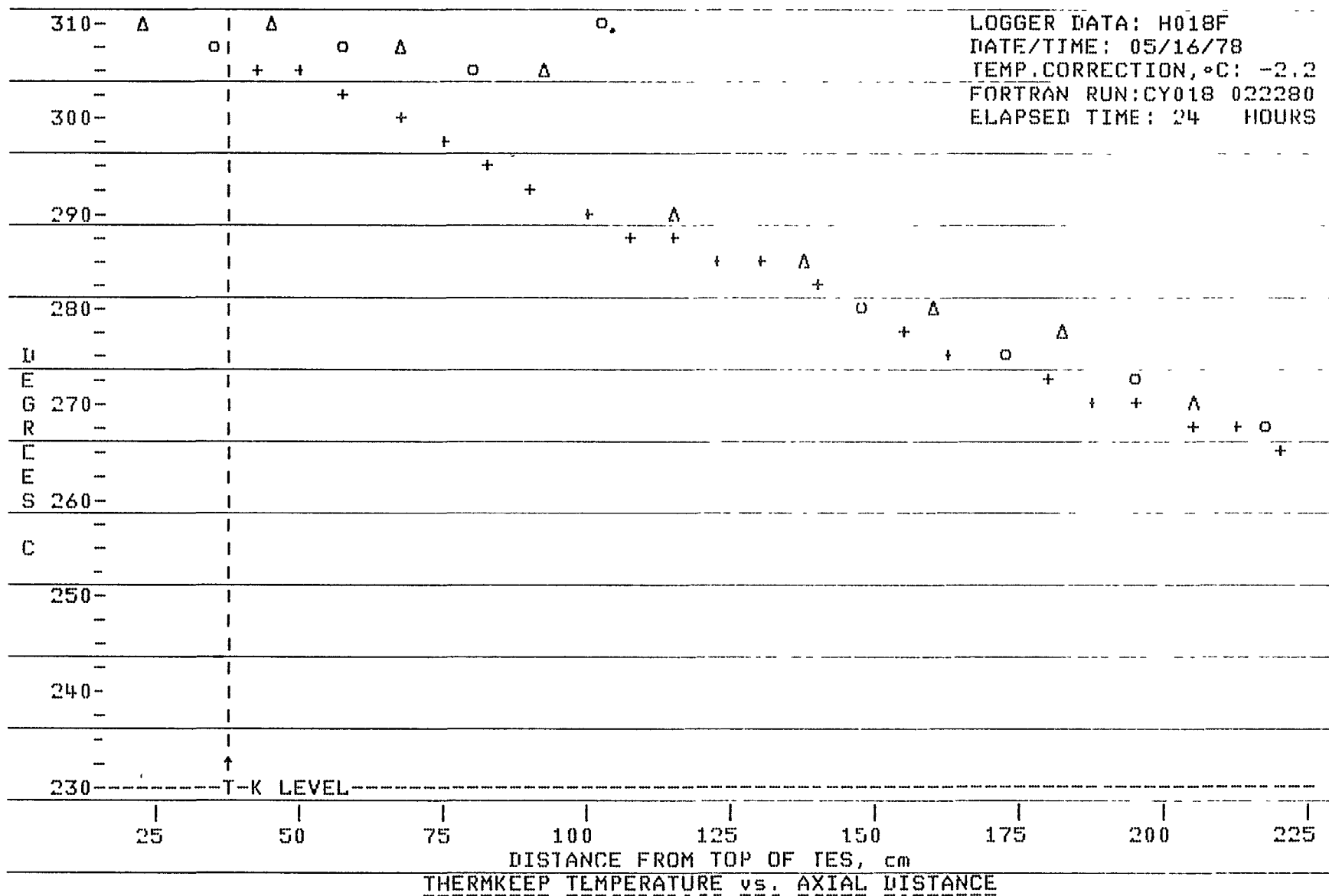
Figure C-66. Thermkeep temperature profile, cyclic test 018 (2.0 gpm), at end of third charge phase.

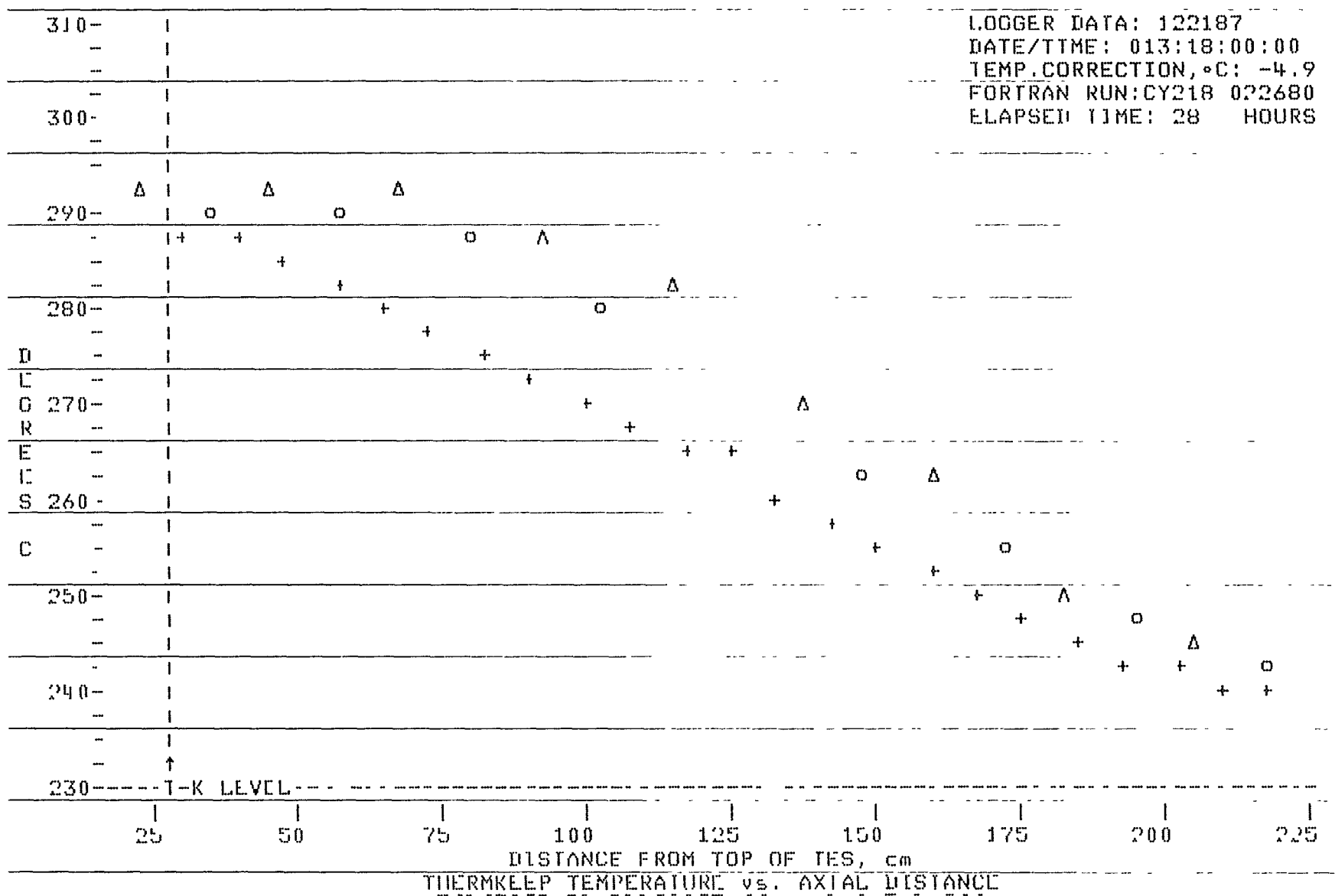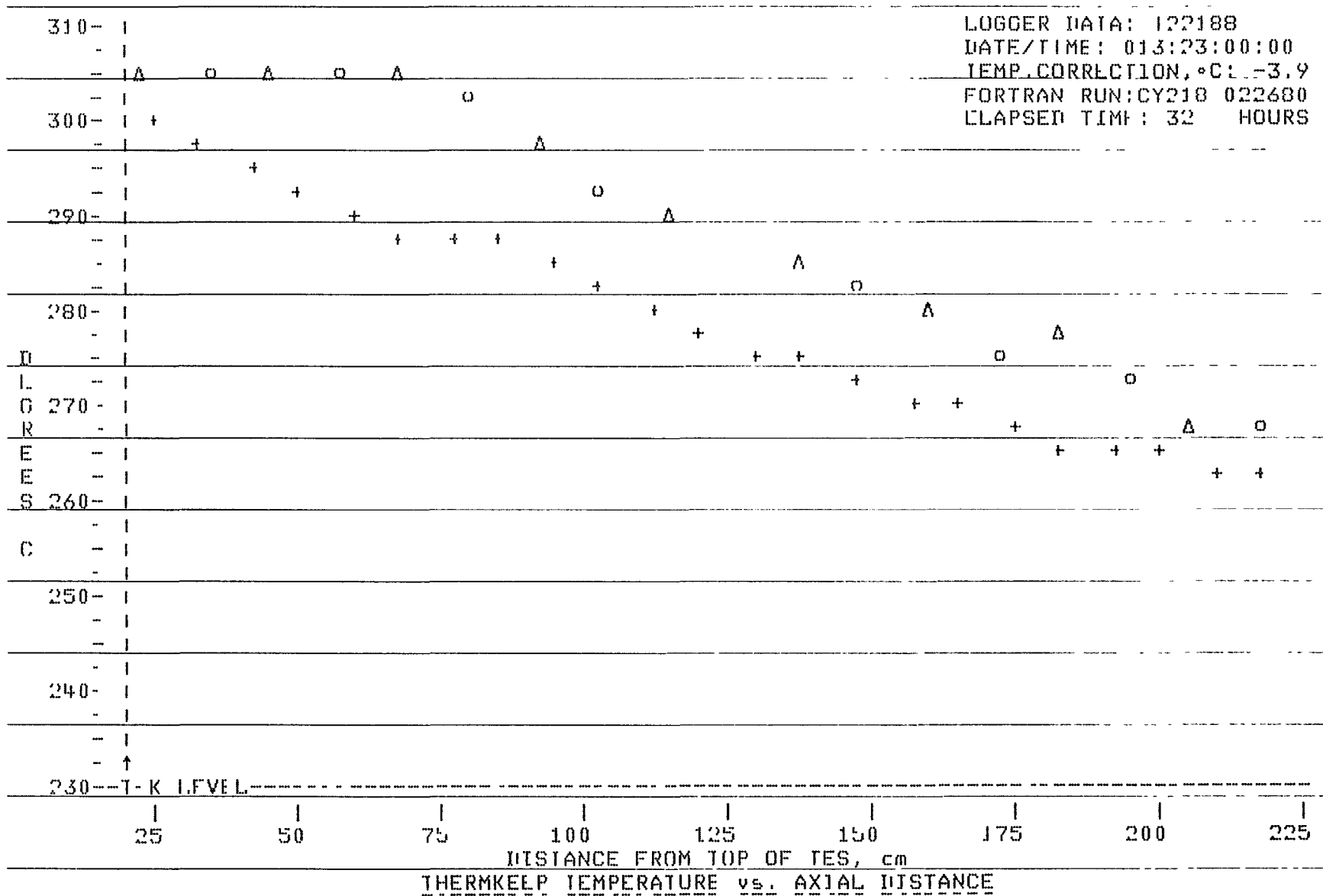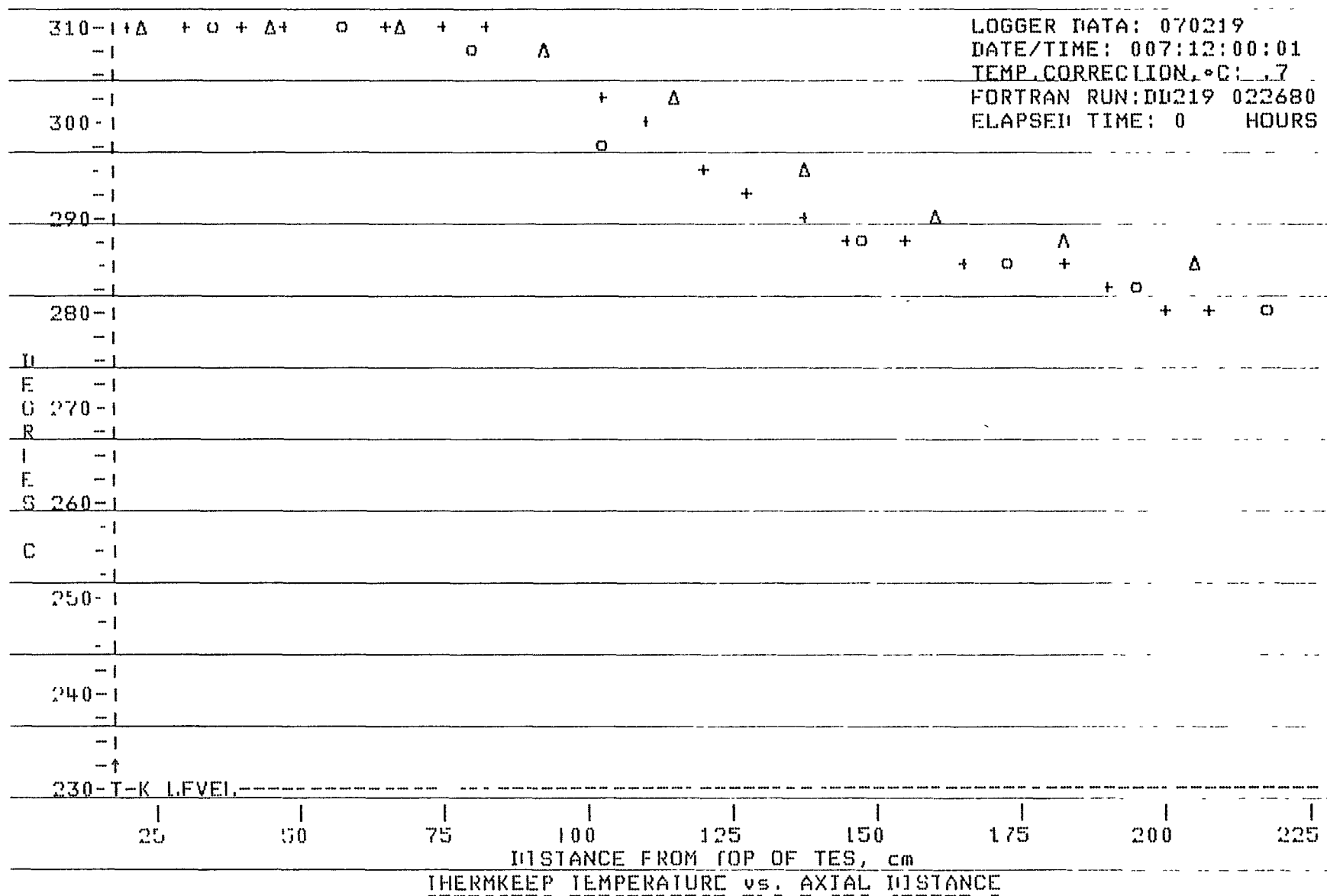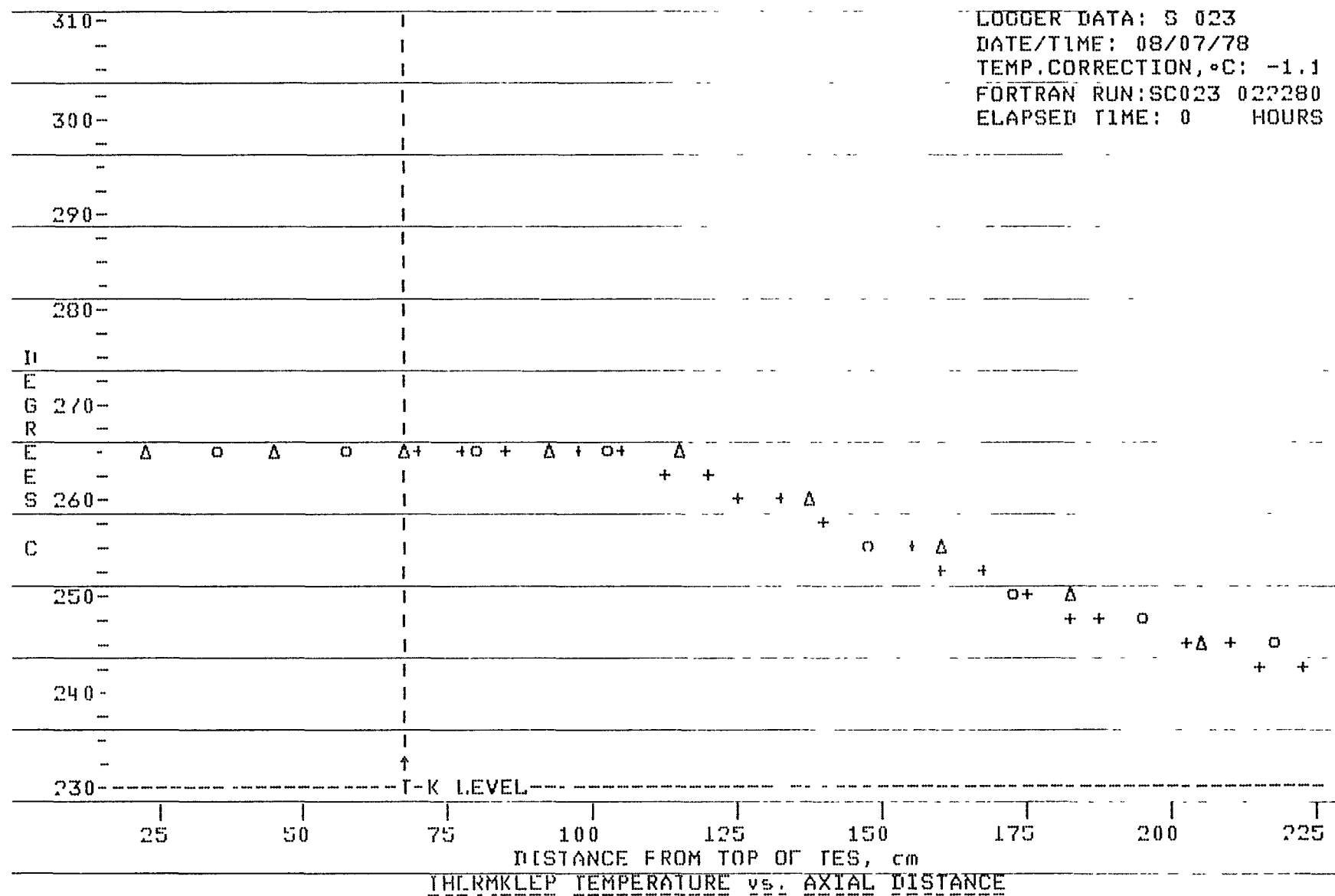Figure C-67. Thermkeep temperature profile, solar cycle test 023, starting profile, cycle 1.
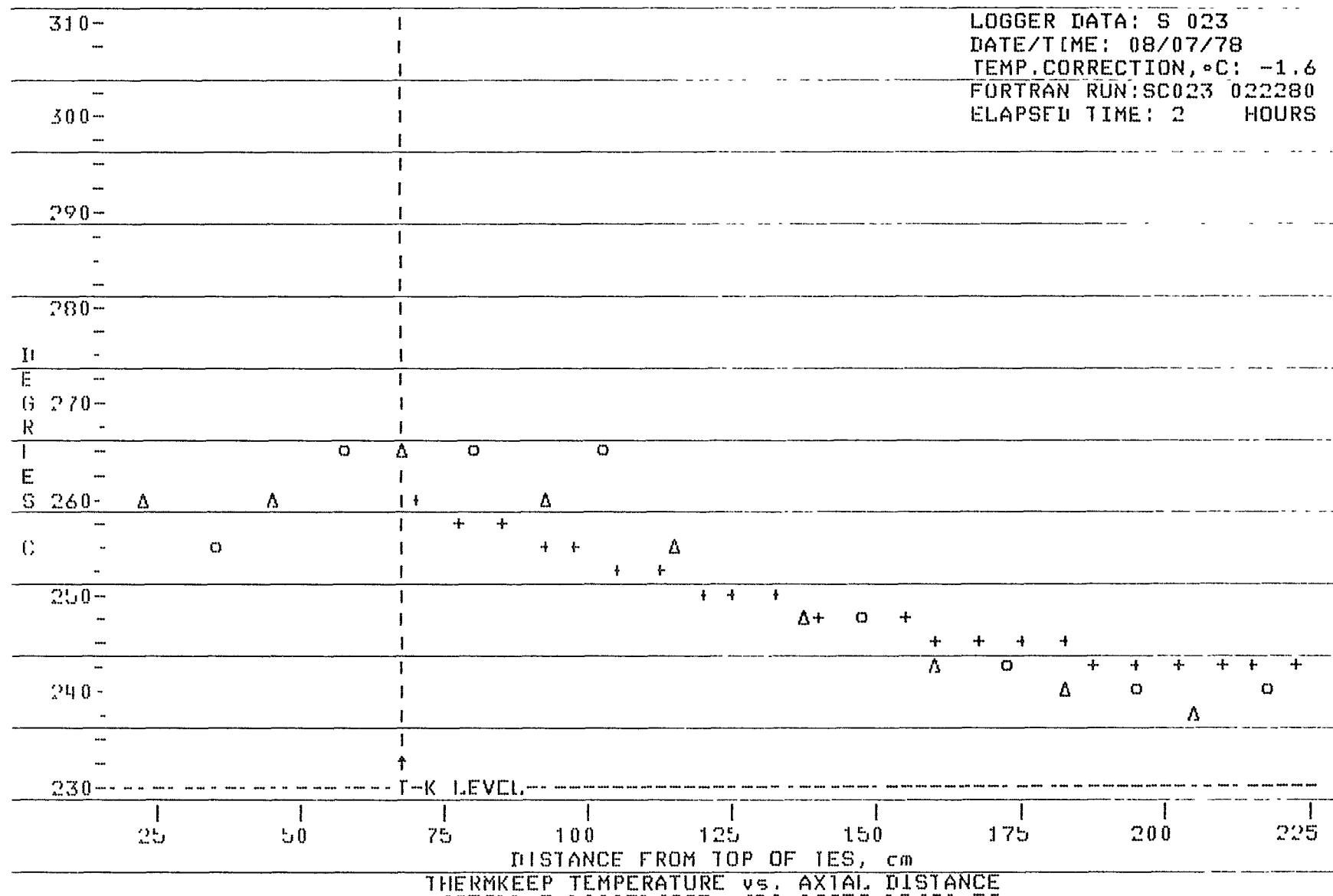
Figure C-68. Thermkeep temperature profile, solar cycle test 023, at end of phase 1 discharge, cycle 1.

LOGGER DATA: S 023
DATE/TIME: 08/07/80
TEMP. CORRECTION, °C: -.5
FORTRAN RUN: SC023 022280
ELAPSED TIME: 10   HOURS

```
310-   I        o         o         o
  -    |o   Λ        Λ         Λ
  -  Λ | +   +   +        Λ
  -    |          +    +            Λ
300    |              +
  -    |                +    +
  -    |                  o         o
  -    |                     +        Λ
290-   Λ|                  +  +           o    Λ
  -    |                        +  +  +   +        o    Λ
  -    |                                    +  +          o
  -    |                                       +  +
280-   |                                             +      +
  -    |
D -    |
E -    |
G 270- |
R -    |
E -    |
E -    |
S 260- |
  -    |
C -    |
  -    |
250-   |
  -    |
  -    |
  -    |
240    |
  -    |
  -    ↑
  -    |
230------- T-K LEVEL.--------------------------------
       |      |      |      |      |      |      |      |      |
      25     50     75    100    125    150    175    200    225
              DISTANCE FROM TOP OF TFS, cm
          THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
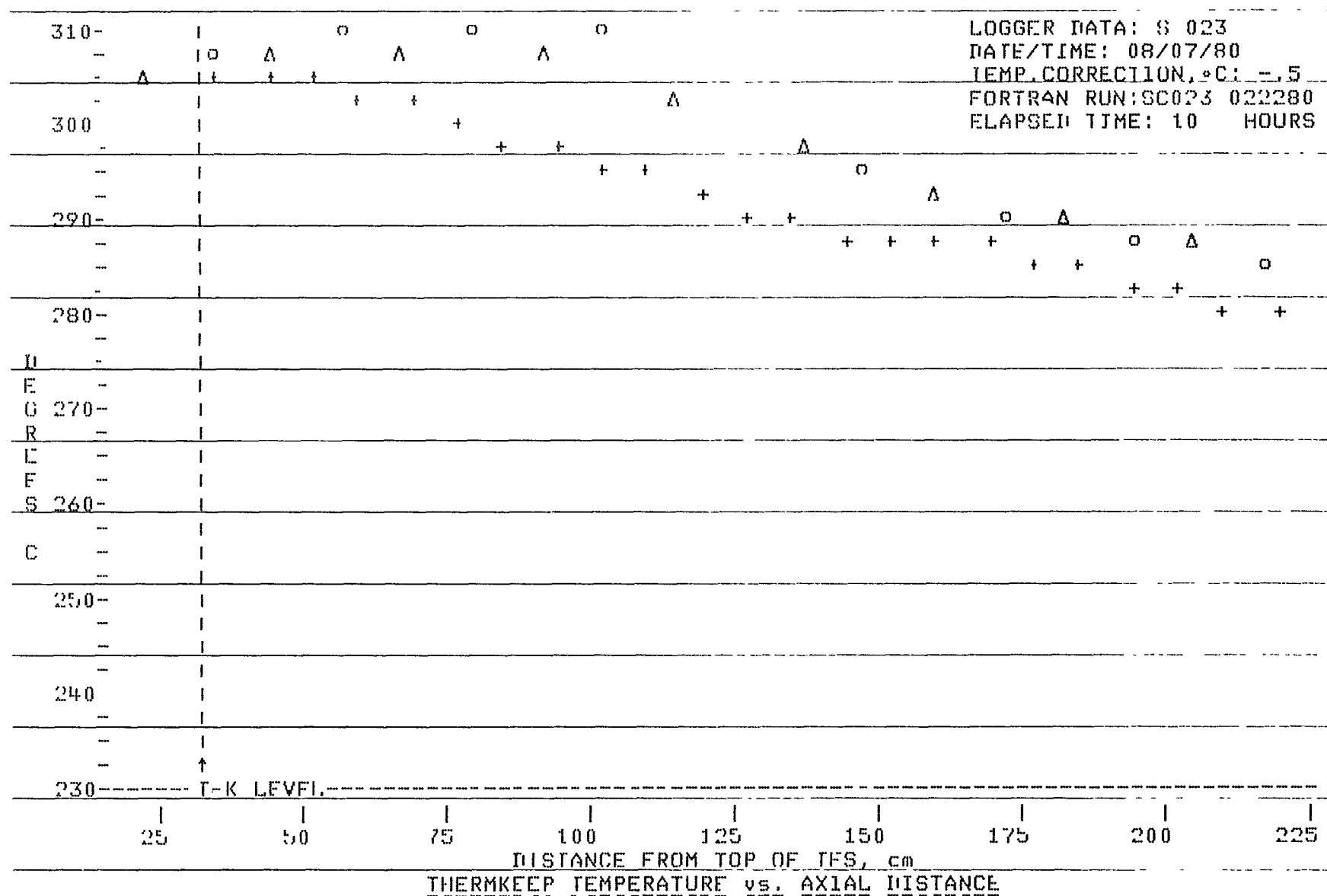
Figure C-69.   Thermkeep temperature profile, solar cycle test 023, at end of cycle 1 charge.

```
310-              |
  --              |
  --              |                 ------------------    --     ---------
  --              |
300-              |
  --      Δ    O  | Δ+
  --              |        +    +   Δ+
  --              |        O           +    +  Δ      O          Δ
290-              |                  O      +   O   +
  --              |                          +    +         Δ
  --              |                             +        O
  --              |                               +        Δ
280-              |                                  +         O
  --              |                                   +    +
D --              |                                      +   Δ       Δ
E --              |                                         +
G 270-            |                                          + O+
R --              |                                              +
E --              |                                                 +
E --              |                                                    +
S 260-            |
  --              |                                                       O
C --              |
  --              |
250-              |
  --              |
  --              |
240-              |
  --              |
  --              ↑
230------------T-K LEVEL----------------------------------------------------
        |      |      |      |      |      |      |      |      |
       25     50     75    100    125    150    175    200    225
              DISTANCE FROM TOP OF TES, cm
              THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

LOGGER DATA: S 023
DATE/TIME: 08/07/78
TEMP.CORRECTION,°C: -.5
FORTRAN RUN:SC023 022280
ELAPSED TIME: 12   HOURS
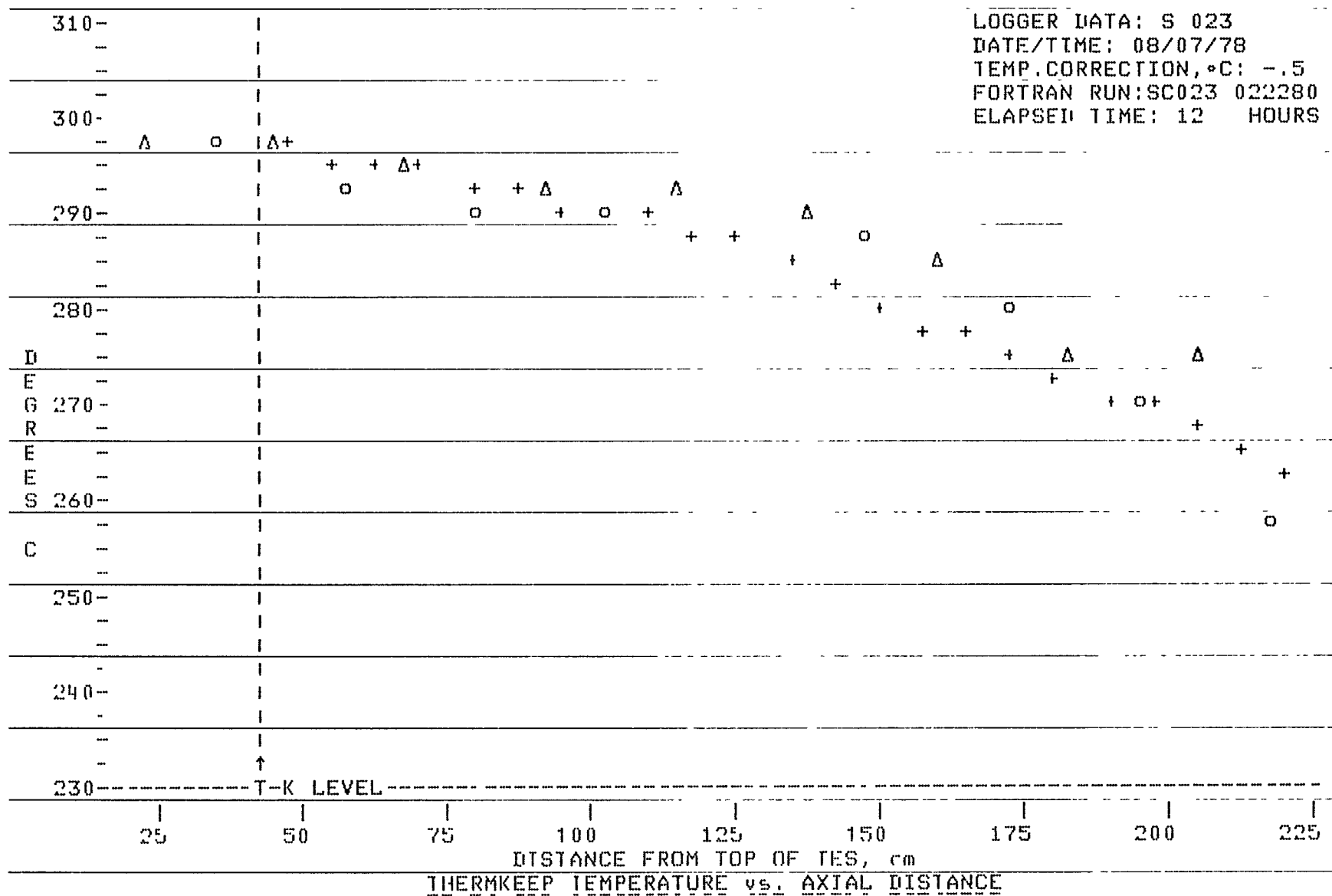
Figure C-70. Thermkeep temperature profile, solar cycle test 023, at end of phase 2 discharge, cycle 1.

LOGGER DATA: S 023
DATE/TIME: 08/08/78
TEMP.CORRECTION,°C: 0
FORTRAN RUN:SC023 022280
ELAPSED TIME: 24 HOURS

310 —
300 —
290 —
280 —
D E G R E E S   C 270
260 —
250 —
240 —
230 — — — — — — — — — T-K LEVEL — — — — — — — — — — — — — — — — —

25   50   75   100   125   150   175   200   225

DISTANCE FROM TOP OF IES, cm

THERMKEEP TEMPERATURE vs. AXIAL DISTANCE

Figure C-71.   Thermkeep temperature profile, solar cycle test 023, starting profile, cycle 2.

```
310-                    |        LOGGER DATA: S 023
   -                    |        DATE/TIME: 08/08/78
                        |        TEMP.CORRECTION,°C: -.5
   -                    |        FORTRAN RUN:SC023 022280
300-                    |        ELAPSED TIME: 26   HOURS
   -                    |
   -                    |
290-  Δ    O    Δ   | O   +Δ +
   -                    |          O   +  Δ+   O
   -                    |                 +       Δ
   -                    |                  +
280-                    |                   +
   -                    |                      +     Δ
D  -                    |                       +
E  -                    |                          +  O
G 270-                  |                            +
R  -                    |                           Λ+
E  -                    |                               +
E  -                    |                                +
S 260-                  |                            O      +
   -                    |                               Δ    +
C  -                    |
   -                    |                                        +
250-                    |                                     O   + +
   -                    |                                        Δ      +
   -                    |                                             O
   -                    |
240-                    |
   -                    |
   -                    ↑
230----------------T-K LEVEL----------------------------------
      |      |       |       |       |       |       |       |
     25     50      75     100     125     150     175     200    225
                    DISTANCE FROM TOP OF TES, cm
              THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```

Figure C-72. Thermkeep temperature profile, solar cycle test 023, at end of phase 1 discharge, cycle 2.

```
310-   Δ I +   O +    Δ     +O + Δ +   O     +Δ + O+     Δ    +     + Δ+   O+
  -    I                                                               +Δ
  -    I                                                                 + O
  -    I                                                                   +
300-   I                                                             Δ+     O
  -    I                                                                +    +
  -    I                                                                    Δ +    O
  -    I                                                                          +
290-   I
  -    I
  -    I                                        LOGGER DATA: S 023
  -    I                                        DATE/TIME: 08/08/78
280-   I                                        TEMP.CORRECTION,°C: 0
  -    I                                        FORTRAN RUN:SC023 022280
D -    I                                        ELAPSED TIME: 34   HOURS
E -    I
G 270- I
R -    I
E -    I
E -    I
S 260- I
  -    I
C -    I
  -    I
250-   I
  -    I
  -    I
  -    I
240-   I
  -    I
  -    ↑
  -   ↑
230----T-K LEVEL----------------------------------------------------------
       I      I      I      I      I      I      I      I      I
      25     50     75    100    125    150    175    200    225
                    DISTANCE FROM TOP OF TES, cm
              THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
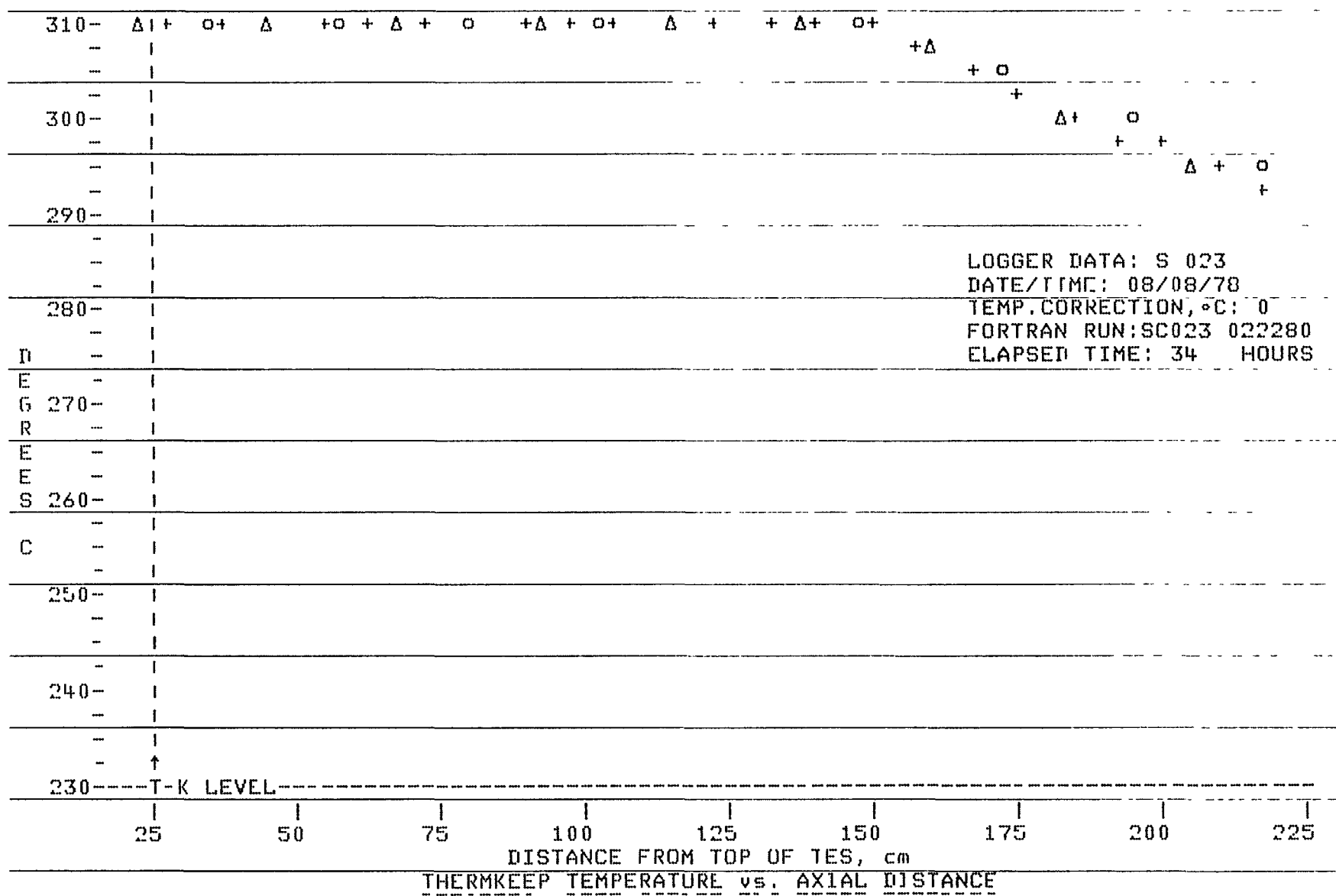
Figure C-73. Thermkeep temperature profile, solar cycle test 023, at end of cycle 2 charge.

LOGGER DATA: S 023
DATE/TIME: 08/08/78
TEMP.CORRECTION, °C: 0
FORTRAN RUN: SC023 022280
ELAPSED TIME: 36 HOURS
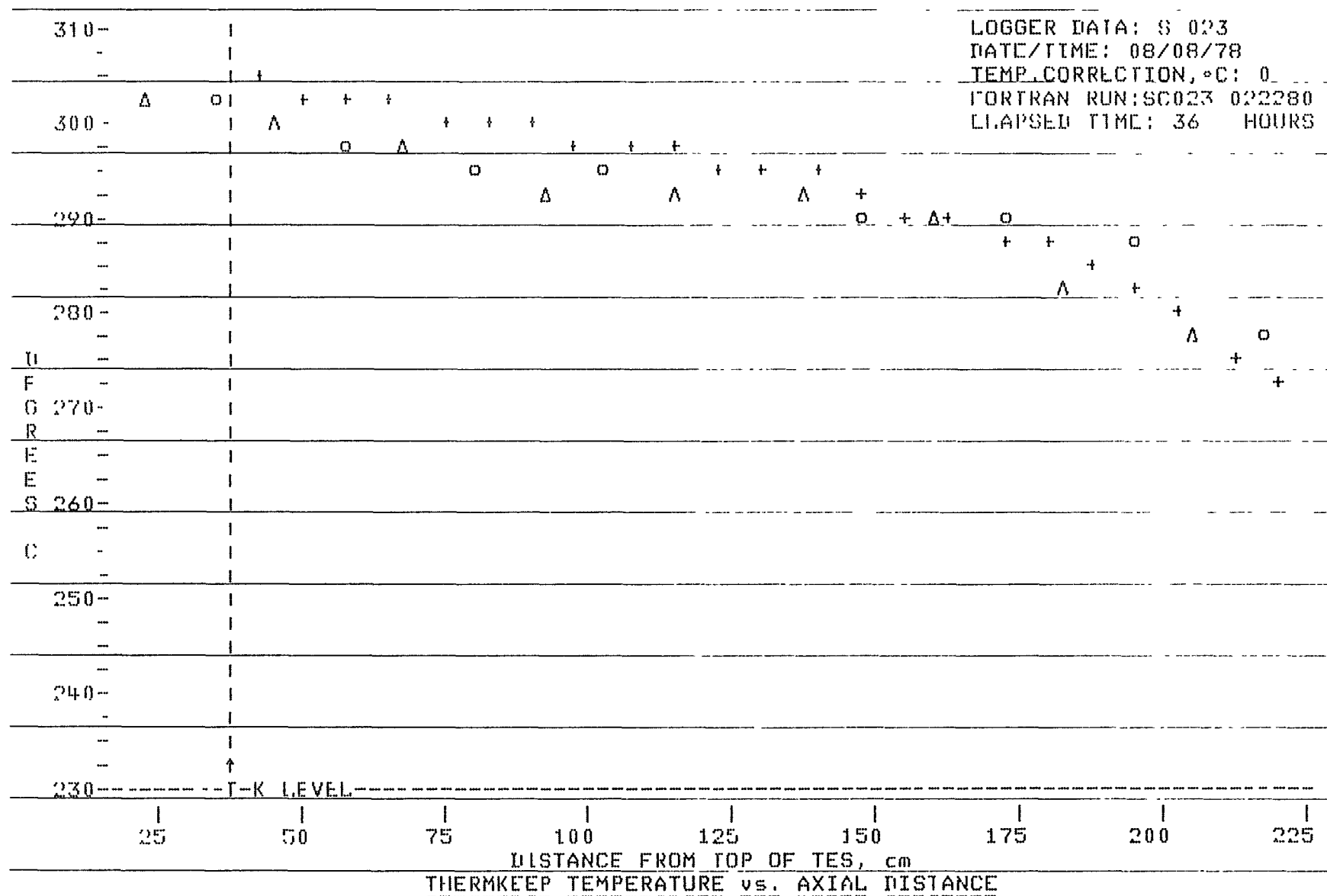
Figure C-74. Thermkeep temperature profile, solar cycle test 023, at end of phase 2 discharge, cycle 2.

```
320-        |
   -        |        o          o          o                    Λ          FIXED DATA: S 023
   -     []  o  []       []          []          []  _ _ .        o  .  Λ  .TEMP.CORRECTION,°C:  0   DATE/TIME: 08/08/78
   -        |                                                                ELAPSED TIME, HRS:32.
310-        |
   -        |                                                    o
   -        |                                                              Λ
300-        |
   -        |                              []                    o          Λ
   -        |                                                              o
290-        |                              []
   -        |                                   []          []
D  -        |
E  -        |
G 280-      |
R  -        |
E  -        |
E  -        |
S 270-      |
   -        |
C  -        |
   -        |
260-        |
   -        |
   -        |
250-        |
   -        |
   -        ↑
240--------T-K LEVEL------------------------------------------------
         |        |        |        |        |        |        |        |        |
        25       50       75      100      125      150      175      200      225
                              DISTANCE FROM TOP OF IES, cm
                         THERMKEEP TEMPERATURE vs. AXIAL DISTANCE
```
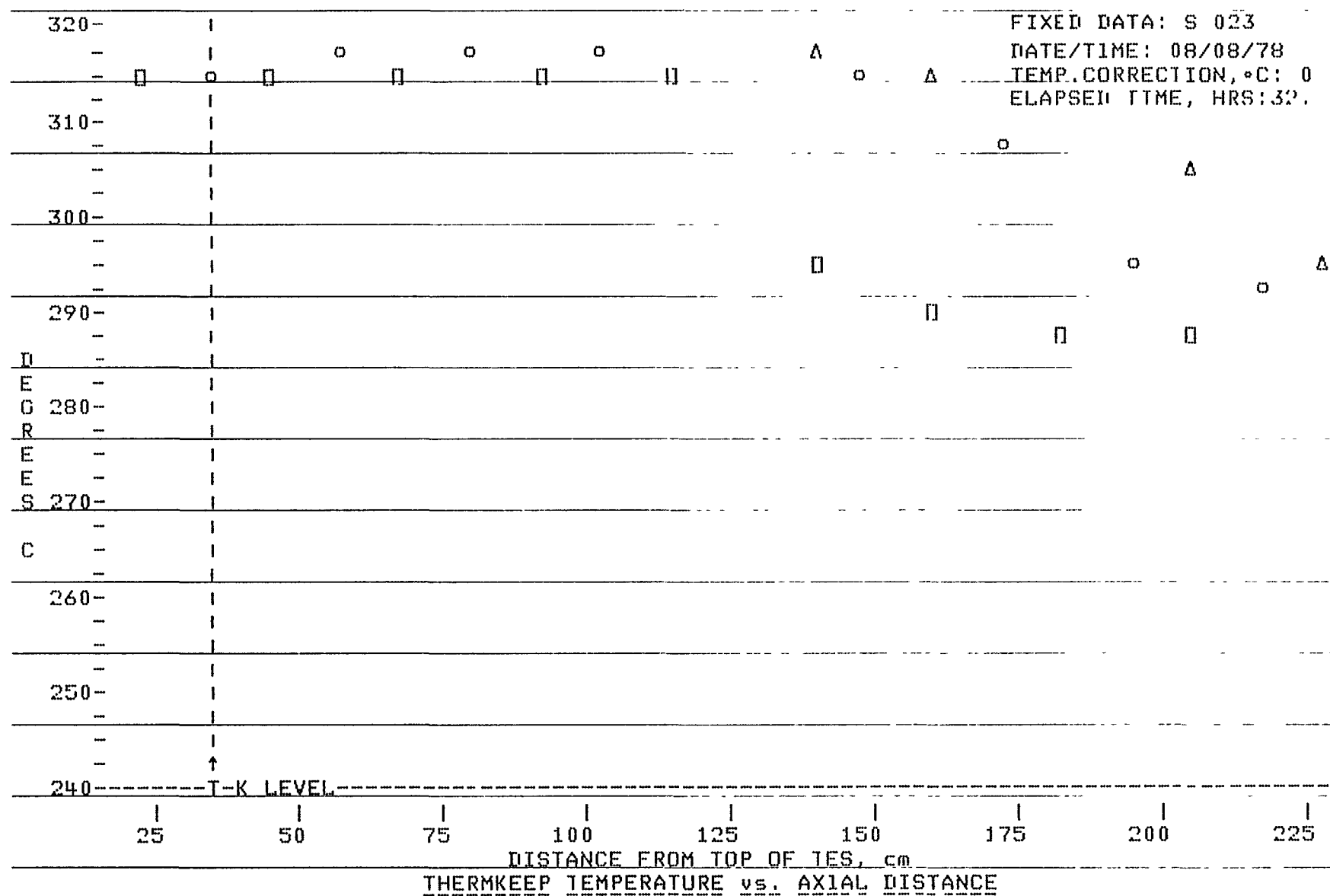
Figure C-75.   Thermkeep temperature profile, solar cycle test 023, at 32 hours.

A P P E N D I X   D

USE OF COMPUTER PROGRAM

Input Data

In order to run a test case with the FORTRAN program,
data must be entered into the DATA section in the proper
format. Each piece of data which is read by the program
is then identified and printed in the output section of
every run to provide easy checking of all parameters.
There are three main groups of data:

1. Main Program Data

A table of solar collector output vs. time,
fluid characteristics, and program control data
(Fig. D-1). These are self-explanatory except
for the following:

ALLOWABLE POWER FLUID OUTLET TEMP is an arbi-
trary temperature, lower than the desired out-
let temperature, used to calculate the amount
of auxiliary heating necessary if the design
criteria were relaxed to this point.

STABILIZATION PERCENTAGE is the percentage dif-
ference between storage input and output over
a complete cycle which must be achieved before
the program will stop. At this point the unit
is assumed to be repeating itself each day.

NUMBER OF DAILY CYCLES is the maximum number of
cycles the program will be allowed to run.

2. Element Analysis Subroutine Data (Fig. D-1)

Definitions:

AEL: The total area in m^2 of inside surface
        of the transfer fluid heat exchanger
        in contact with storage medium.

AEP: The total area in m^2 of inside surface of the power fluid heat exchanger in contact with storage medium.

ADL: The total area in m^2 of common direct contact between the power fluid and transfer fluid heat exchangers.

DEFF: The effective diameter in meters of one double tube of heat exchanger upon which storage medium solidifies (the diameter of a circle whose perimeter is that of a cross section of a touching power fluid and transfer fluid tube).

XLEFF: The effective length in meters of one tube of heat exchanger.

XNT: The number of heat exchanger tubes.

RHOM: The density in kg/m^3 of storage material.

HTCS: The heat transfer coefficient of sub-cooled power fluid in $kW/m^2\text{-}^\circ K$.

HTCV: The heat transfer coefficient of power fluid vapor in $kW/m^2\text{-}^\circ K$.

3. Thermkeep Properties Subroutine Data (Fig. D-1)

In addition to the DATA section, two functions are modified directly for each run: HL(wL) and HT(X). HL(wL) computes the heat transfer coefficient of the transfer fluid as a function of flow rate in $kJ/sec\text{-}m^2\text{-}^\circ K$. For this function the tube size, the fluid properties and a helix diameter must be known. HT(X) computes the heat transfer coefficient of vaporizing power fluid as a function of quality in $kJ/sec\text{-}m^2\text{-}^\circ K$.

DUAL HEAT EXCHANGER - HEAT OF FUSION THERMAL STORAGE ANALYSIS
TABLE OF SOLAR COLLECTOR OUTPUT VS. TIME

RATE IN KW	TIME IN SECONDS
0.0	0.0
0.0	8800.0
250.0000	13800.0
323.0000	15600.0
368.0000	16600.0
432.0000	18900.0
448.0000	19900.0
471.0000	21600.0
480.0000	22600.0
498.0000	25100.0
500.0000	25900.0
493.0000	27800.0
470.0000	30300.0
442.0000	32700.0
362.0000	35600.0
250.0000	39000.0
0.0	43200.0

MAIN PROGRAM DATA

TRANSFER FLUID SPECIFIC HEAT, KJ/KG/K	2.5280
TRANSFER FLUID INLET TEMPERATURE, K	584.00
POWER FLUID SP.HT.-LIQUID, KJ/KG/K	2.260000
POWER FLUID HEAT/VAP, KJ/KG	217.238998
POWER FLUID SP.HT.-VAPOR, KJ/KG/K	1.957000
POWER FLUID SATURATION TEMPERATURE, K	530.00
POWER FLUID INLET TEMPERATURE, K	473.00
DESIRED POWER FLUID OUTLET TEMP., K	584.00
ALLOWABLE POWER FLUID OUTLET TEMP.,K	580.00
POWER FLUID FLOW RATE, KG/SEC	0.55342
INSOLATION STARTING TIME, SEC	8800.00
BEGIN NET CHARGE, SEC	13800.00
END NET CHARGE, SEC	39000.00
THERMKEEP SPECIFIC HEAT, KJ/KG/K	2.5000
NUMBER OF ELEMENTS FOR ANALYSIS	10.
AMOUNT OF STORAGE MATERIAL, KG	10000.00
MINIMUM TIME INCREMENT, SEC	15.00
MAXIMUM TIME INCREMENT, SEC	100.00
MAXIMUM TRANSFER FLUID FLOW, KG/SEC	5.0000
STABILIZATION PERCENTAGE	3.00
NUMBER OF DAILY CYCLES	6

AEP=	49.5493	AEL=	49.5493	APL=	6.1935
DEFF=	0.013009	XLEFF=	18.628	XNT=	150.000
RHOM=	1802.080	HTCS=	0.396740	HTCV=	0.976010

TABLE OF TEMPERATURE, ENTHALPY, AND SOLID FRACTION   OF THERMKEEP

T(I)	H(I)	Z(I)
373.00	-13.50000	1.000000
505.60	259.64990	1.000000
528.00	337.36011	1.000000
530.00	344.30005	0.760000
535.00	361.64990	0.736200
541.63	409.86011	0.670000
544.89	433.60010	0.615000
549.17	464.69995	0.590000
557.86	529.00000	0.400000
560.00	543.57007	0.388700
563.00	600.25000	0.347500
573.00	672.50000	0.295000
583.00	711.00000	0.0
643.00	836.50010	0.0

Figure D-1. Dual heat exchanger program input data.

Input Data Selection

Much of the input data does not change from run to run. The insolation table, Thermkeep properties, and all the main program data remain constant except for the Number of Elements for analysis (normally 10 for general use, and 25 for more accurate final designs) and the amount of storage material. The insolation table is a copy of the "Albuquerque Winter Mean Solar Day" modified to 12 hours by omitting a turbine overnight idle period. The Thermkeep properties are "Table 10" for Thermkeep determined by the work described in Part II. The remaining data applies to toluene as the power fluid and the system characteristics as required by this contract. The maximum and minimum time increments were determined by trial and error during the early stages of program development.

The element analysis data were chosen with the help of a desk top computer. First, desired heat exchanger sizes, areas, and tube diameters are arbitrarily selected. Then the number and length of the tubes are varied until a combination is found which produces about a 10 psi drop in the transfer fluid exchanger and a reasonable drop (20-30 psi) in the power fluid exchanger. Then an amount of storage material is arbitrarily selected. If the height-to-diameter ratio is specified (normally 1.0), this produces a helix diameter of the tubing. From the known mass flow of power fluid and heat exchanger geometry, the heat transfer coefficients of the power fluid are now calculated.

The effective diameter is calculated by using the diameter of a tube whose perimeter is the same as the sum of the two fluid tubes' perimeters minus the section which they have in common. This report uses all equally-sized tubes for both power and transfer fluids and the common area was 11%, or 40° of arc on each tube in direct contact (Figure D-2). A small addition to the perimeter was made for weld fillet between the tubes.

Function HL(wL) receives the transfer fluid flow rate from other parts of the program and returns a heat transfer coefficient. This function is modified for each run because it uses the tube inside diameter and helix diameter which change with each case. The helix diameter is calculated as the diameter of one heat exchanger coil such that one-half of the storage material is enclosed by the coils and one-half lies outside them.

D-4
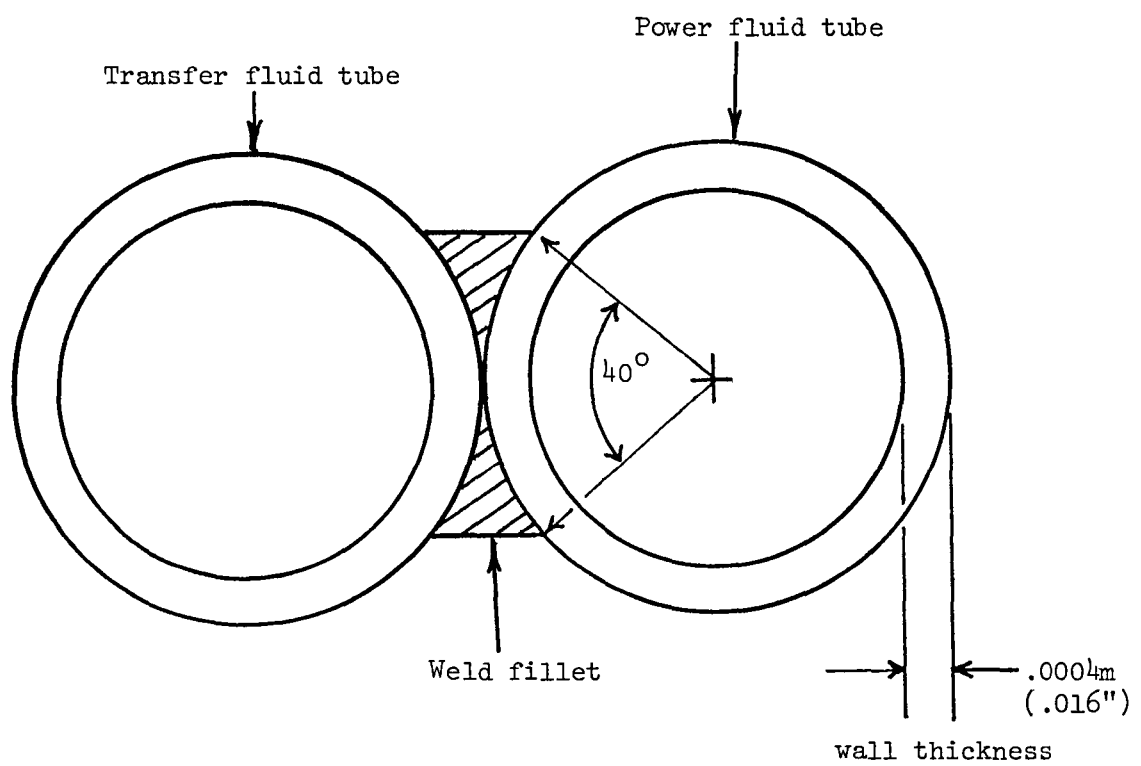
Figure D-2. Typical dual heat exchanger tubing.

From the heat exchanger geometry and transfer fluid properties, the following coefficients are determined:

CRE: A multiplier of the mass flow rate which will give the Reynolds number

$$CRE = d_t/(\text{fluid area x fluid viscosity})$$

where d_t is the tube inside diameter.

RECRIT: The critical Reynolds number

$$RECRIT = 2100 \left[1 + 12 \, (d + d_h)^{0.5} \right]$$

where d_h is the helix diameter.

CHTC: A heat transfer coefficient factor:

$$CHTC = (.022 \times C_f \times Pr^{.4})/d_t$$

where C_f is the fluid thermal conductivity.

QX: A dimensionless factor used in the calculation of the effect of the helix diameter on heat transfer in laminar flow:

$$QX = \left[\left(\frac{d_t}{d_h} \right)^2 \, Pr \right]^{\frac{1}{4}}$$

HTCI: The heat transfer coefficient for turbulent flow:

$$HTCI = CHTC \times Re^{.8}$$

Function HT(X) receives the power fluid quality and returns a heat transfer coefficient. The relationship for toluene is roughly a sigmoidal shaped curve, of which a linear approximation is a good average. Therefore, during this contract we used

$$HT(X) = X \times (HTCV - HTCS) + HTCS$$

Output Data

For each case run, a back-up calculation print-out was made. An example is shown in Figure D-3. Cost calculations are based on the actual cost of a prototype storage unit, and integrate manufacturing and material costs both on a surface area and weight basis. The only difference from case to case is in the tube material cost, where there is a lower cost by weight as tubing gets larger.

A dollar amount for each category is then printed out, along with a unit total cost. As a point of interest, the percentage of total cost of the heat exchanger, insulation, cover, tank and storage material are also listed.

Next, the geometry and weight input data are tabulated, and the resulting dimensions and weights are listed (Figure D-4).

Finally, the heat exchanger dimensions are calculated and listed along with Reynolds numbers, heat transfer coefficients, and pressure drops. These outputs allow us to check total surface area and to vary the number, length, and diameter of tubes in order to produce desired pressure drops. With toluene, we always found that it was in laminar flow in the liquid region, turbulent flow in the vapor region, and the vast majority of pressure drop was due to the vaporization acceleration. Also calculated were the power fluid pressure drop assuming that it was liquid through the entire tube, and vapor pressure drop assuming it was vapor for 90% of the tube -- both of these cases were assumed extremes.

COST CALCULATION INPUT DATA

SHROUD MATERIAL COST, $/KG.	.509
SHROUD SIDE FABRICATION COST, $/SQ.M.	10.14
SHROUD SIDE FABRICATION COST, $/KG.	1.038
SHROUD TOP FABRICATION COST, $/SQ.M.	77.35
SHROUD TOP FABRICATION COST, $/KG.	7.92
SHROUD BOTTOM FABRICATION COST, $/SQ.M.	99.84
SHROUD BOTTOM FABRICATION COST, $/KG.	7.67
SHROUD TOP THICKNESS, M.	1.524E-3
SHROUD SIDE THICKNESS, M.	1.2192E-3
SHROUD BOTTOM THICKNESS, M.	3.4036E-3
VESSEL WALL MATERIAL COST, $/KG.	.4718
VESSEL END MATERIAL COST, $/KG.	.4806
VESSEL FABRICATION COST, $/CU.M.	615.47
VESSEL FABRICATION COST, $/KG.	2.447
TUBE MATERIAL COST COEFFICIENT	.028
TUBE MATERIAL COST, $/KG.	3.9091
TUBE FABRICATION COST, $/KG.	11.9
TUBE FABRICATION COST, $/SQ.M.	964.3398
STORAGE MATERIAL COST, $/KG.	.441
INSULATION COST, $/KG.	.2864

COST CALCULATION OUTPUT DATA

TUBE MATERIAL COST, $	1479.
TOTAL TUBE COST, $	14431.
STORAGE MATERIAL COST, $	4410.
INSULATION COST, $	873.
SHROUD SIDE MATERIAL COST, $	156.
SHROUD SIDE TOTAL COST, $	808.
SHROUD BOTTOM MATERIAL COST, $	108.
SHROUD BOTTOM TOTAL COST, $	541.
SHROUD TOP MATERIAL COST, $	48.
SHROUD TOP TOTAL COST, $	293.
SHROUD TOTAL MATERIAL COST, $	312.
SHROUD TOTAL COST, $	1142.
VESSEL MATERIAL COST, $	1113.
VESSEL TOTAL COST, $	2835.
TOTAL MATERIALS COST FOR TES, $	8186.
TOTAL FABRICATION COST FOR TES, $	15405.
TES TOTAL COST, $	23591.

% OF TOTAL COST	
HEAT EXCHANGER	61
INSULATION	4
SHROUD	5
VESSEL	12
THERMKTEP	19

Figure D-3.   Cost calculations print-out example.

GEOMETRY AND WEIGHT INPUT DATA

TRANSFER TUBE O.D., M.	7.1628E-3
TRANSFER TUBE I.D., M.	6.35E-3
POWER TUBE O.D., M.	7.1628E-3
POWER TUBE I.D., M.	6.35E-3
TUBE LENGTH, M.	18.628
NO. OF TUBES	150
INSULATION THICKNESS, M.	.6096
VESSEL WALL THICKNESS, M.	.0127
VESSEL END THICKNESS, M.	.0254
THERMKLIP DENSITY, KG/CU.M.	1802.08
STEEL DENSITY, KG/CU.M.	7847
FLUID DENSITY, KG/CU.M.	824
INSULATION DENSITY, KG/CU.M.	160.19
ASPECT RATIO, HGT/DIA.	1
AMT. OF STORAGE MATERIAL, KG.	10000

GEOMETRY AND WEIGHT OUTPUT DATA

SHROUD DIAMETER, M.	3.1764
VESSEL DIAMETER, M.	1.9318
TUBE HELIX DIAMETER, M.	.1115
VESSEL HEIGHT, M.	1.9318
VESSEL WEIGHT, KG.	2336.6505
WEIGHT OF TUBES, KG.	378.2771
INSULATION WEIGHT, KG.	3044.4217
SYSTEM HEIGHT, M.	3.2018
SYSTEM WEIGHT, KG.	16371.4152

POWER TUBE ID "	.25
HELIX DIAMETER "	4.391
NUMBER OF TUBES	150
TUBE LENGTH, FT	61.1155

TUBE INSIDE AREA, ft2	600.
TUBE INSIDE AREA, m2	56.
LIQUID Re	608.
VAPOR Re	56894.
CRITICAL Re	8113.

HTCL Btu/hr ft2 °F	69.89579
HTCL kW/m2 °K	.39674

HTCV Btu/hr ft2 °F	171.94957
HTCV kW/m2 °K	.97601

ΔP Acceleration PSI	18.3
ΔP liquid whole tube PSI	.48
ΔP vapor ,90% tube PSI	1.24
ΔP T 66 whole tube PSI	9.62

Figure D-4. Output data print-out example.

The FORTRAN program prints out all the input data as previously mentioned. Then the unit starting conditions are calculated and listed -- the starting temperature, starting solid fraction, and total unit energy. The charging fluid flow rate and both fluid outlet temperatures are printed each half-hour of elapsed time.

A map of the unit showing the temperatures of storage medium and both fluids, along with fluid quality and solid fraction of the medium in each element or "slab" is printed out at two points in each daily cycle -- at the beginning of net charge when the unit is at its lowest state of charge, and at the end of charge when the unit is at its highest state of charge. Also the total unit energy at these times is printed out, and the difference between them, once the unit is stabilized, is equal to the amount of energy actually output from storage, and does not include the heat transferred directly from the transfer to the power fluid.

At the end of a daily cycle, a summary of the energies transferred is printed:

> The LOST COLLECTOR HEAT is the amount of heat available but unused because of maximum flow conditions.

> The STORAGE OUTPUT is the total amount of energy which came out of the unit in the power fluid stream.

> The STORAGE INPUT is the amount of energy which entered the unit in the transfer fluid stream.

> The AUXILIARY INPUT is the amount of heat required to raise the power fluid outlet temperature to the Desired Outlet Temperature.

> The DEFICIT REQUIREMENT is the amount of heat required to raise the power fluid outlet temperature to the Allowable Outlet Temperature.

> The EXCESS HEATING is the amount of heat which exited the unit above the desired outlet temperature.

The BOILER REQUIREMENT is the total daily
boiler consumption.

Also listed are the total collector output, the elapsed
time, the number of time steps used during this cycle,
and the cycle ending total energy.

At this point, a new cycle is begun; or, if the unit
has stabilized, the program stops.

COMPUTER CODE

```
C     MAIN PROGRAM TES341
      COMMON TPOUT,TLOUT,TPIN,TLIN,TSAT,GT,CL,CS,CV,CT,XNE,ASTOR,XOUT,TA
     *FFR,T5,T6,NC
      DIMENSION QL(25),TIME(25)
100   FORMAT(I2)
101   FORMAT(F10.4,F10.1)
102   FORMAT(F10.4,3F10.6,F10.2)
103   FORMAT(4F10.2)
104   FORMAT(F10.5,2F10.2,F10.4,F10.0,I3,F10.2)
105   FORMAT(2F10.2,F10.4)
106   FORMAT(2F10.2)
201   FORMAT(25X,F10.4,9X,F10.1)
202   FORMAT(5X,' TRANSFER FLUID SPECIFIC HEAT, KJ/KG/K ',F10.4)
203   FORMAT(5X,' POWER FLUID SP.HT.-LIQUID, KJ/KG/K    ',F10.6)
204   FORMAT(5X,' POWER FLUID HEAT/VAP, KJ/KG           ',F10.6)
205   FORMAT(5X,' POWER FLUID SP.HT.-VAPOR, KJ/KG/K     ',F10.6)
206   FORMAT(5X,' POWER FLUID SATURATION TEMPERATURE, K ',F10.2)
207   FORMAT(5X,' TRANSFER FLUID INLET TEMPERATURE, K   ',F10.2)
209   FORMAT(5X,' DESIRED POWER FLUID OUTLET TEMP., K   ',F10.2)
208   FORMAT(5X,' POWER FLUID INLET TEMPERATURE, K      ',F10.2)
210   FORMAT(5X,' POWER FLUID FLOW RATE, KG/SEC         ',F10.5)
211   FORMAT(5X,' INSOLATION STARTING TIME, SEC         ',F10.2)
330   FORMAT(5X,' BEGIN NET CHARGE, SEC                 ',F10.2)
331   FORMAT(5X,' END NET CHARGE, SEC                   ',F10.2)
212   FORMAT(5X,' AMOUNT OF STORAGE MATERIAL, KG        ',F10.2)
213   FORMAT(5X,' THERMKEFF SPECIFIC HEAT, KJ/KG/K      ',F10.4)
214   FORMAT(5X,' NUMBER OF ELEMENTS FOR ANALYSIS       ',F10.0)
215   FORMAT(5X,' NUMBER OF DAILY CYCLES                ',7X,I3,///)
219   FORMAT(5X,' STABILIZATION PERCENTAGE              ',F10.2)
301   FORMAT(15X,' TABLE OF SOLAR COLLECTOR OUTPUT VS. TIME ')
302   FORMAT(24X,' RATE IN KW ',9X,' TIME IN SECONDS ')
314   FORMAT(1H1,8X,' MAIN PROGRAM DATA',//)
317   FORMAT(1H1,5X,' DUAL HEAT EXCHANGER - HEAT OF FUSION THERMAL STORA
     *GE ANALYSIS ')
216   FORMAT(5X,' MAXIMUM TIME INCREMENT, SEC           ',F10.2)
217   FORMAT(5X,' MINIMUM TIME INCREMENT, SEC           ',F10.2)
218   FORMAT(5X,' MAXIMUM TRANSFER FLUID FLOW, KG/SEC   ',F10.4)
320   FORMAT(///,20X,' CYCLE DATA',//)
321   FORMAT(10X,' ELAPSED TIME, HR              ',F10.1)
323   FORMAT(10X,' LOST COLLECTOR HEAT, KJ       ',E15.7)
324   FORMAT(10X,' COLLECTOR OUTPUT, KJ          ',E15.7)
325   FORMAT(10X,' STORAGE OUTPUT,KJ             ',E15.7)
326   FORMAT(10X,' STORAGE INPUT, KJ             ',E15.7)
327   FORMAT(10X,' AUXILIARY INPUT, KJ           ',E15.7)
328   FORMAT(10X,' EXCESS HEATING, KJ            ',E15.7)
329   FORMAT(10X,' BOILER REQUIREMENT, KW        ',E15.7)
335   FORMAT(10X,' NUMBER OF TIME INCREMENTS ',I10)
338   FORMAT(10X,' DEFICIT REQUIREMENT, KJ       ',E15.7)
339   FORMAT(5X,' ALLOWABLE POWER FLUID OUTLET TEMP.,K  ',F10.2)
340   FORMAT(F10.4)
      WRITE(6,317)
      WRITE(6,301)
      WRITE(6,302)
      READ(5,100) K5
      DO 10 I=1,K5
      READ(5,101) QL(I),TIME(I)
10    WRITE(6,201) QL(I),TIME(I)
      TD=TIME(K5)
      READ(5,102) CL,CS,GT,CV,TSAT
      READ(5,103) TLIN,TPIN,TPDES,TALWPL
      READ(5,105) DTMAX,DTMIN,WMAX
      READ(5,106) T5,T6
      WRITE(6,314)
```

```
      READ(5,104) WF,T1,ASTOR,CTK,XNF,ND,PCT
      WRITE(6,202) CL
      WRITE(6,207) TLIN
      WRITE(6,203) CS
      WRITE(6,204) QT
      WRITE(6,205) CV
      WRITE(6,206) TSAT
      WRITE(6,208) TPIN
      WRITE(6,209) TPDES
      WRITE(6,339) TALWPL
      WRITE(6,210) WP
      WRITE(6,211) T1
      WRITE(6,330) TS
      WRITE(6,331) TC
      WRITE(6,213) CTK
      WRITE(6,214) XNF
      WRITE(6,212) ASTOR
      WRITE(6,217) DTMIN
      WRITE(6,216) DTMAX
      WRITE(6,218) WMAX
      WRITE(6,219) PCT
      WRITE(6,215) ND
      ET=0.
      QPOWER=WP*(CS*(TSAT-TPIN)+QT+CV*(TPDES-TSAT))
      J6=1
      K1=1
360   NDT=0
      KC=1
      ZL=0.06*ASTOR*CTK/(XNF*CL)
      ZPS=0.06*ASTOR*CTK/(XNF*CS)
      ZPV=0.06*ASTOR*CTK/(XNF*CV)
      IF(ZPS.GE.ZPV) GO TO 11
      ZP=ZPV
      GO TO 12
11    ZP=ZPS
12    QLOSS=C.
      QCHG=0.
      QEXTRA=0.
      QSOLAR=0.
      QBURN=0.
      QDISCH=0.
      WL=0.
      L=0
      NDT=0
      K7=1
      K2=1
      DTIME=ZP/WP
      DT=DTIME
      ET=ET+DTIME/3600.
50    L=L+1
      NDT=NDT+1
      CALL FLANAL(WL,WP,DTIME,K1,K7,J6,T1,TD,K2)
      L=0
51    IF(TPOUT.LE.TSAT) GO TO 52
      QODIS=WP*DTIME*(CV*(TPOUT-TSAT)+QT+CS*(TSAT-TPIN))
      GO TO 60
52    IF(TPOUT.LT.TSAT) GO TO 53
      QODIS=WP*DTIME*(XOUT*QT+CS*(TSAT-TPIN))
      GO TO 60
53    QODIS=WP*DTIME*CS*(TPOUT-TPIN)
60    QDISCH=QDISCH+QODIS
      IF(TPOUT.GT.TPDIS) GO TO 61
      QBURN=QBURN+QPOWER*DTIME-QODIS
```

```
      IF(TPOUT.CE.TALWEL) GO TO 62
      GDEFCT=QDEFCT+(TALWEL-TPOUT)*WF*CV*DTIME
      GO TO 62
   61 GEXTRA=GEXTRA+DCDIS-GPOWER*DTIME
   62 IF(K7.EQ.1) GO TO 70
      DGCHG=WL*CL*(TLIN-TLOUT)*DTIME
      GCHG=GCHG+DQCHG
      GSOLAR=QSOLAR+GC*DTIME
      GLOSS=GLOSS+GC*DTIME-DGCHG
   70 IF(CT.GE.T1) GO TO 80
      DTIME=ZP/WP
      IF(DTIME.LT.DTMIN) DTIME=DTMIN
      IF(DTIME.LE.DTMAX) GC TO 71
      DTIME=DTMAX
   71 CT=CT+DTIME
      IF(CT.LE.T1) GO TO 75
      DTIME=DTIME-(CT-T1)
      CT=T1
      K2=2
   75 ET=ET+DTIME/3600.
      K7=1
      GO TO 50
   80 IF(CT.GE.TD) GO TO 20
      IF(K7.EQ.1) GC TO 400
      DO 2 I=2,K5
      IF(CT.GE.TIME(I)) GO TO 2
      GC=QL(I-1)+(GL(I)-GL(I-1))*(CT-TIME(I-1))/(TIME(I)-TIME(I-1))
      GO TO 85
    2 CONTINUE
   85 DTIMP=ZP/WP
      IF(K7.EQ.2) WL=GC/(CL*(TLIN-TAPPR))
      IF(K7.EQ.3) WL=GC/(CL*(TLIN-TLOUT))
      K7=3
      IF(WL.LE.WMAX) GO TO 87
      WL=WMAX
   87 DTIML=ZL/WL
      IF(DTIML.LT.DTIMP) GO TO 90
      DTIME=DTIMP
      GO TO 88
   90 DTIME=DTIML
      GO TO 88
  400 CT=T1+DTMAX
      ET=ET+DTMAX/3600.
      DTIME=DTMAX
      K7=2
      GO TO 50
   88 IF(DTIME.LT.DTMIN) DTIME=DTMIN
      IF(DTIME.LE.DTMAX) GO TO 91
      DTIME=DTMAX
   91 IF(CT.GE.T5) GO TO 92
      CT=CT+DTIME
      IF(CT.LE.T5) GO TO 410
      DTIME=DTIME-(CT-T5)
      CT=T5
  410 ET=ET+DTIME/3600.
      GO TO 50
   92 IF(CT.GE.T6) GO TO 93
      CT=CT+DTIME
      IF(CT.LE.T6) GO TO 420
      DTIME=DTIME-(CT-T6)
      CT=T6
  420 ET=ET+DTIME/3600.
      GO TO 50
```

```
 93 IF(CT.GE.TD) GO TO 20
    CT=CT+DTIME
    IF(CT.LE.TD) GO TO 430
    DTIME=DTIME-(CT-TD)
    CT=TD
430 ET=ET+DTIME/3600.
    GO TO 50
 20 WRITE(6,320)
    WRITE(6,321) ET
    WRITE(6,323) QLOSS
    WRITE(6,324) QSOLAR
    WRITE(6,325) QDISCH
    WRITE(6,326) QCHG
    WRITE(6,327) QBURN
    WRITE(6,338) QDEFCT
    WRITE(6,328) CEXTRA
    WRITE(6,329) QPOWER
    WRITE(6,335) NDT
    NC=NC+1
    IF(NC.GT.ND) GO TO 99
    L=0
    PCDIFF=ABS(100.-100.*QCHG/QDISCH)
    IF(PCDIFF.LE.PCT) GO TO 99
    GO TO 12
 99 READ(5,340) ASTOR
    IF(ASTOR.EQ.1) GO TO 750
    J6=2
    GO TO 360
350 STOP
    END
```
C
C
C
```
    ---
    ---
    ---
    SUBROUTINE ELANAL(WL,WP,DTIME,K1,K7,J6,T1,TD,K2)
    COMMON TPCUT,TLOUT,TPIN,TLIN,TSAT,QT,CL,CS,CV,CT,XNE,ASTOR,XOUT,TA
   *PPR,T5,T6,NC
    COMMON/PROPTK/FLH,CPST,STMM,STNE
    COMMON/CALCAB/UAEC,UAHC,UAHF,CH,CC,A1,A2,A3,B1,B2,B3,CZ
    COMMON/DIATRI/AI(50),BI(50),CI(50),FI(50),XI(50),CY
    COMMON/TMP/ALFA(50),BETA(50),GAMMA(50)
    DIMENSION ENER(26),RSOLL(26),TF(26),XP(26),QC(26)
    DIMENSION TL(26),T(26),Z(26)
    DIMENSION TEL(25),OLDGEC(25)
101 FORMAT(3F10.4)
102 FORMAT(5F10.0)
103 FORMAT(F10.2,I1,F10.2)
106 FORMAT(12X,' SUBROUTINE ELANAL DATA',/)
188 FORMAT(1H1,///,' STARTING ELEMENT TEMP., K       ',F10.2)
189 FORMAT(' STARTING SOLID FRACTION        ',F10.2)
195 FORMAT(' STARTING TOTAL ENERGY, KJ      ',E15.7,///)
240 FORMAT(10X,F10.1,10X,F10.1,10X,F10.5,10X,F10.2,10X,F10.2)
258 FORMAT(T16,'ET',T32,'CHARGE TIME',T52,'T-66 FLOW',T71,'TOLUENE OUT
   C',T92,'T-66 OUT',/)
400 FORMAT(' (I)      T(I)          Z(I)          TL(I)          TP(I)          X
   *P(I) ',//)
488 FORMAT(1X,I3,1X,F9.2,3X,F9.2,3X,F9.2,3X,F9.2,3X,F9.2)
489 FORMAT(1X,I3,25X,F9.2,3X,F9.2,3X,F9.2)
490 FORMAT(1X,I3,1X,F9.2,3X,F9.2,15X,F9.2,3X,F9.2)
491 FORMAT(1X,I3,37X,F9.2,3X,F9.2)
492 FORMAT(1X,' TOTAL SYSTEM ENERGY, KJ    ',E15.7,///)
500 FORMAT('    POWER FLUID QUALITY CHECK 500 - NFI=',I2,'  NEF=',I2)
501 FORMAT('    POWER FLUID QUALITY CHECK - 501')
510 FORMAT(///,' POWER FLUID VAPORIZED IN ONE ELEMENT - NO.510')
```

```
518 FCRMAT(2I5,2E10.4)
519 FCRMAT(///,' HEATING FLUID GETTING HOTTER AS IT GOES THROUGH UNIT'
    *)
520 FCRMAT(///,' POWER FLUID GETTING COOLER AS IT GOES THROUGH UNIT')
551 FCRMAT(' INTERMEDIATE MAP AT TIME TD=',F4.1,'HRS.',//)
555 FCRMAT(' INTERMEDIATE MAP AT TIME T5=',F4.1,'HRS.',//)
556 FCRMAT(' INTERMEDIATE MAP AT TIME T6=',F4.1,'HRS.',//)
702 FCRMAT(/,' CYCLE ENDING TOTAL ENERGY, KJ ',E15.7)
    CY=CT
    CZ=CT
    CC TO(1,2),K1
  1 IF(J6.EQ.2) GO TO 380
    NF=XNE
    TL(NE+1)=TLIN
    KC=1
    EI(1)=-1.
    AI(2)=0.
    CI(2)=-1.
    CHGTM=C.
    CTI=0.
    HRT5=T5/3600.
    HRT6=T6/3600.
    READ(5,101) AEP,AEL,APL
    READ(5,102) DEFF,XLEFF,XNT,HTCS,HTCV
    READ(5,103) RHOM,K8,TINIT
    WRITE(6,600) AEP,AEL,APL
600 FORMAT('    AEP= ',F10.4,'    AEL= ',F10.4,'    APL= ',F10.4)
    WRITE(6,601) DEFF,XLEFF,XNT
601 FORMAT('   DIFF= ',F10.6,'    XLEFF= ',F10.3,'    XNT= ',F10.3)
    WRITE(6,602) RHOM,HTCS,HTCV
602 FORMAT('   RHOM= ',F10.3,'    HTCS=',F10.6,'    HTCV=',F10.6)
380 AEPE=AEP/XNE
    AELE=AEL/XNE
    APLE=APL/XNE
    AFFE=AEPE+APLE
    XLE=XLEFF/XNE
    FLM=ASTOR/XNE
    CRKTL=6.283*XLE*XNT
    CPST=1.
    STMM=C.
    STME=0.
    E=0.
    CALL TKPROP(TINIT,ENEL,FRAC,1,1,2,J6)
    WRITE(6,188) TINIT
    WRITE(6,189) FRAC
    DO 5 I=1,NE
    ENER(I)=ENEL
    T(I)=TINIT
    E=E+ENER(I)
    Z(I)=FRAC
  5 CONTINUE
    K1=2
    WRITE(6,195) E
    WRITE(6,288)
    NEI=NE+1
    NEF=NE+1
  2 HTCL=HL(WL)
    UAHE=HTCL*AELE
    CH=WL*CL
    IF(K6.EQ.2) GO TO 15
    CCS=WP*CS
    CCV=WP*CV
    IF(K8.EQ.1) K6=2
```

```
   15 IF(WL.EQ.0.) GO TO 72
      CUAHCS=APLE/(1./HTCS+1./HTCL)
      CUAHCV=APLE/(1./HTCV+1./HTCL)
   72 DO 3 I=1,NE
      IF(Z(I).EQ.0.) GO TO 4
      VSTK=Z(I)*ELM/(RHOM*XNT)
      DSTK=SQRT(1.273*VSTK/XLE+DEFF**2)
      RSOLL(I)=ALOG(DSTK/DEFF)/(THCS(T(I))*CRKTL)
      GO TO 3
    4 RSOLL(I)=0.
    3 CONTINUE
      GO TO(10,10,11),K7
C     ---
C     POWER FLUID ONLY
C     ---
   10 TF(1)=TFIN
      M4=0
      DO 20 J=1,NE
      XF(J+1)=0.
      IF(TP(J).GE.TSAT) GO TO 21
      RES=RSOLL(J)+1./(HTCS*APFE)
      XNTU=1./(RES*WP*CS)
      IF(XNTU.GE.11.5) EFF=.99999
      IF(XNTU.GE.11.5) GO TO 22
      EFF=1.-EXP(-XNTU)
   22 TP(J+1)=TP(J)+EFF*(T(J)-TP(J))
      IF(TP(J+1).LT.TSAT) GO TO 19
      ETSAT=(TSAT-TP(J))/(T(J)-TP(J))
      YNTU=XNTU+ALOG(1.-ETSAT)
      FTP=YNTU/XNTU
      RESTP=(RSOLL(J)+1./(HT(XP(J))*APFE))/FTP
      NTI=J
      FXI=1.-(YNTU/XNTU)
      GTP=(T(J)-TSAT)/RESTP
      XP(J+1)=QTP/(WP*QT)
      IF(XP(J+1).LT.1.) GO TO 18
      GTP=WP*QT
      ZNTU=YNTU*(1.-1./XP(J+1))
      FSUP=ZNTU/XNTU
      RESSUP=(RSOLL(J)+1./(HTCV*APFE))/FSUP
      ZNTU=1./(RESSUP*WP*CV)
      IF(ZNTU.GE.11.5) FFF=.99999
      IF(ZNTU.GE.11.5) GO TO 23
      EFF=1.-EXP(-ZNTU)
   23 TF(J+1)=TSAT+FFF*(T(J)-TSAT)
      XF(J+1)=1.
      GP=QTP+WP*(CV*(TP(J+1)-TSAT)+CS*(TSAT-TP(J)))
      FXF=1.-FSUP
      NFF=J
      GO TO 35
   18 GP=GTP+CCS*(TSAT-TP(J))
      TF(J+1)=TSAT
      GO TO 35
   19 QP=CCS*(TF(J+1)-TP(J))
      GO TO 35
   21 IF(TP(J).GT.TSAT) GO TO 25
      RES=RSOLL(J)+1./(HT(XP(J))*APFE)
      GP=(T(J)-TSAT)/RES
      XP(J+1)=GP/(WP*GT)+XP(J)
      IF(XP(J+1).LE.1.) TP(J+1)=TSAT
      IF(XP(J+1).LE.1.) GO TO 35
      QTART=(1.-XP(J))*WP*GT
      FXF=QTART/QP
```

```
      RESSUP=(RSOLL(J)+1./(HTCV*APFE))/(1.-FXF)
      NEF=J
      XNTUSP=1./(RESSUP*WP*CV)
      IF(XNTUSP.GE.100.) EFF=1.
      IF(XNTUSP.GE.100.) GO TO 26
      EFF=1.-EXP(-XNTUSP)
   26 TP(J+1)=TSAT+EFF*(T(J)-TSAT)
      XF(J+1)=1.
      QP=QPART+WP*CV*(TP(J+1)-TSAT)
      GO TO 35
   25 RES=RSOLL(J)+1./(HTCV*APFE)
      XNTU=1./(RES*CCV)
      IF(XNTU.GE.100.) EFF=1.
      IF(XNTU.GE.100.) GO TO 28
      EFF=1.-EXP(-XNTU)
   28 TP(J+1)=TP(J)+EFF*(T(J)-TP(J))
      QP=CCV*(TP(J+1)-TP(J))
      XF(J+1)=1.
   35 ENER(J)=ENER(J)-QP*DTIME
      CALL TKPROP(T(J),ENER(J),Z(J),1,2,2,J6)
   20 CONTINUE
      FXF=1.-FXF
      GO TO 230
   11 IF(NEI.NE.(NE+1).OR.NEF.NE.(NE+1)) GO TO 12
      WRITE(6,500) NEI,NEF
      STOP
C     ---
C
C                                         REGION I
C     ---
C            NEF IS TOP ELEMENT
   12 CONTINUE
  880 IF(NEF.NE.NE) GO TO 56
      UAEC=FXF/(RSOLL(NE)+1./(HTCV*AEPE))
      UAHC=FXF*CUAHCV
      UAHE=FXF*UAHE
      CC=CCV
      CALL ABCALC(NE)
      TLF=A1*T(NE)+A2*TSAT+A3*TLIN
      TP(NE+1)=B1*T(NE)+B2*TSAT+B3*TLIN
      QCFXF=WP*CV*(TP(NE+1)-TSAT)
      GO TO 55
C     ---
C
C            NEF IS NEXT-TO-TOP ELEMENT
   56 IF(NEF.NE.(NE-1)) GO TO 58
      UAHE=FXF*UAHE
      UAHC=FXF*CUAHCV
      UAEC=FXF/(RSOLL(NE-1)+1./(HTCV*AEPE))
      CC=CCV
      CALL ABCALC(NE-1)
      CI(1)=A3
      FI(1)=-A1*T(NE-1)-A2*TSAT
      CI(2)=B3
      FI(2)=-B1*T(NE-1)-B2*TSAT
      UAHE=HTCL*AELE
      UAHC=CUAHCV
      UAEC=1./(RSOLL(NE)+1./(HTCV*AEFE))
      CALL ABCALC(NE)
      AI(3)=-1.
      BI(3)=A2
      CI(3)=0.
      FI(3)=-A1*T(NE)-A3*TLIN
      AI(4)=B2
      FI(4)=-1.
```

```
      FI(4)=-B1*T(NE)-F3*TLIN
      CALL TRIDIA(4)
      TLF=XI(1)
      TL(NE)=XI(2)
      TF(NE)=XI(3)
      TF(NE+1)=XI(4)
      CCFXF=WP*CV*(TP(NE)-TSAT)
      CC(NE)=WP*CV*(TP(NE+1)-TP(NE))
      GO TO 55
C     ---
C              REGION 1 IS 3 OR MORE ELEMENTS
   58 UAHC=RXF*CUAHCV
      UAHE=RXF*HTCL*AELF
      UAEC=RXF/(RSOLL(NEF)+1./(HTCV*AEPE))
      CC=CCV
      CALL ABCALC(NEF)
      CI(1)=A3
      FI(1)=-A1*T(NEF)-A2*TSAT
      FI(2)=E3
      FI(2)=-B1*T(NEF)-B2*TSAT
      UAHC=CUAHCV
      UAHE=HTCL*AELF
      L1=NEF+1
      L2=NE-1
      J=1
      DO 50 I=L1,L2
      UAEC=1./(RSOLL(I)+1./(HTCV*AEPE))
      CALL ABCALC(I)
      J=J+1
      AI(2*J-1)=-1.
      EI(2*J-1)=A2
      CI(2*J-1)=A3
      FI(2*J-1)=-A1*T(I)
      AI(2*J)=B2
      BI(2*J)=B3
      CI(2*J)=-1.
   50 FI(2*J)=-E1*T(I)
      UAEC=1./(RSOLL(NE)+1./(HTCV*AEFE))
      CALL ABCALC(NE)
      J=J+1
      AI(2*J-1)=-1.
      BI(2*J-1)=A2
      CI(2*J-1)=0.
      FI(2*J-1)=-A1*T(NE)-A3*TLIN
      AI(2*J)=B2
      BI(2*J)=-1.
      FI(2*J)=-B1*T(NE)-B3*TLIN
      N=2*(NE-NEF+1)
      CALL TRIDIA(N)
      TLF=XI(1)
      TL(NEF+1)=XI(2)
      J=1
      TF(NEF)=TSAT
      L1=NEF+1
      L2=NE-1
      DO 51 I=L1,L2
      J=J+1
      TF(I)=XI(2*J-1)
      CC(I-1)=WP*CV*(TP(I)-TF(I-1))
      TL(I+1)=XI(2*J)
   51 CONTINUE
      TF(NE)=XI(N-1)
      TF(NE+1)=XI(N)
```

D-20

```
      QC(NE-1)=WP*CV*(TP(NE)-TP(NE-1))
      CC(NE)=WF*CV*(TP(NF+1)-TP(NE))
      QCRXF=QC(NEF)
C     ---
C                                          REGION II
C
C     ---
                SECTICN FXF
   5E IF(RXF.EQ.1) GO TO 59
      FXF=1.-RXF
      CUAHCT=APLE/(1./HT(XP(NEF))+1./HTCL)
      UAHCF=FXF*CUAHCT
      UAHEF=FXF*HTCL*AELE
      UAECF=FXF/(RSOLL(NEF)+1./(HT(XP(NEF))*AEPE))
      CALL VAP(UAECF,UAHCF,UAHEF,CH,TSAT,T(NEF),TLF,QHE,QEC,QHC,TL(NEF))
      OLDQEC(NEF)=QEC
      CC(NEF)=QHC+QEC+QCRXF
      XF(NEF)=1.-(QHC+QEC)/(WP*QT)
      IF(XP(NEF).GE.0.) GO TO 59
C     ---
C
C                               NEF IS NET GOING DOWN
      K=C
      XI1=0.
      XI2=1.
      XF1=XP(NEF)
      XF2=1.
   75 K=K+1
      IF(K.EQ.3) GO TO 78
      XI3=XI1-XP1*(XI2-XI1)/(XP2-XP1)
      FXI=(1.-XI3)*FXF
      UAHCI=RXI*CUAHCT
      UAHEI=RXI*HTCL*AELE
      UAECI=RXI/(RSOLL(NLF)+1./(HT(XF(NEF))*AEPE))
      CALL VAP(UAECI,UAHCI,UAHEI,CH,TSAT,T(NEF),TLF,QHE,QEC,QHC,TLI)
      OLDQEC(NEF)=QEC
      QCRXI=QEC+QHC+QCRXF
      XPXI3=1.-(QEC+QHC)/(WP*QT)
      IF(XPXI3) 76,78,77
   7C XF1=XPXI3
      XI1=XI3
      GC TO 75
   77 XP2=XFXI3
      XI2=XI3
      GC TO 75
   78 FXI=XI3*FXF
      NEI=NEF
      I=NEF
      GC TO 79
C     ---
C             REGICN II MIDDLE ELEMENTS
   59 IF(NEF.EQ.1) GO TO 270
      I=NEF
      UAHC2=CUAHCT
      UAHE2=HTCL*AELE
   60 I=I-1
      UAEC2=1./(RSOLL(I)+1./(HT(XP(I))*AEPE))
      CALL VAP(UAEC2,UAHC2,UAHE2,CH,TSAT,T(I),TL(I+1),QHE,QEC,QHC,TL(I))
      OLDQEC(I)=QEC
      OC(I)=QHC+QEC
      XP(I)=XP(I+1)-(QHC+QEC)/(WP*QT)
      TF(I)=TSAT
      IF(XP(I).GT.XP(I+1)) GC TO 81
      IF(I.EQ.1.AND.XF(I).GE.0.) GO TO 81
```

```
      IF(XP(I).GT.0.) GO TC 60
C     ---
C               REGICN II, IN NEI, FIND RXI
      K=C
      XI1=0.
      XI2=1.
      XP1=XF(I)
      XP2=XF(I+1)
   70 K=K+1
      IF(K.EQ.3) GC TO 80
      XI3=XI1-XP1*(XI2-XI1)/(XP2-XP1)
      RXI=1.-XI3
      UAHCI=RXI*CUAHCT
      UAHEI=RXI*HTCL*AELL
      UAECI=RXI/(RSCLL(I)+1./(HT(XP(I))*AEPE))
      CALL VAP(UAECI,UAHCI,UAHEI,CH,TSAT,T(I),TL(I+1),QHE,QEC,QHC,TLI)
      CLDQEC(NEI)=CEC
      GCRXI=GEC+QHC
      XPXI3=XP(I+1)-(GEC+QHC)/(WP*QT)
      IF(XPXI3) 71,80,73
   71 XF1=XPXI3
      XI1=XI3
      GL TO 70
   73 XF2=XFXI3
      XI2=XI3
      GO TO 70
   80 FXI=XI3
      NEI=I
      GC TO 79
C     ---
C
C     ---
C                  SFT CONDITION M1
   81 L3=I+1
      M1=1
      FXI=1.
      CLDQEC(NEI)=C.
      GCFXI=0.
      TLI=TL(I+1)
      NEI=I
      XF(I)=0.
      GO TO 79
C     ---
C                  SFT CONDITION M3
  270 I=1
      TLI=TLF
      M3=1
      GCFXI=QCRXF
      FXI=1.-RXF
      NEI=NFF
C     ---
C
C     ---
C                                        FCGION  III
C     ---
C               REGICN III IS ONF ELEMENT
   79 IF(I.NE.1) GO TC 90
      UAHC=FXI*CUAHCS
      UAHE=FXI*HTCL*AELF
      UAEC=FXI/(RSCLL(1)+1./(HTCS*AEFE))
      CC=CCS
      CALL ABCALC(1)
      TL(1)=A1*T(1)+A2*TPIN+A3*TLI
      TTRIAL=B1*T(1)+P2*TPIN+B3*TLI
      OC(1)=WF*CS*(TTRIAL-TPIN)+QCRXI
```

```
      IF(M1.EG.1) TP(2)=TTRIAL
      TF(1)=TPIN
      GC TO 15C
C     ---
C               REGICN III IS TWO ELEMENTS
   9C IF(I.NE.2) GC TO 100
      UAHC=CUAHCS
      UAHE=HTCL*AELE
      UAEC=1./(RSOLL(1)+1./(HTCS*AEPE))
      CC=CCS
      CALL AFCALC(1)
      CI(1)=A3
      FI(1)=-A1*T(1)-A2*TPIN
      EI(2)=B3
      FI(2)=-B1*T(1)-E2*TPIN
      UAHC=FXI*CUAHCS
      UAHE=FXI*HTCL*AELE
      UAEC=FXI/(RSOLL(2)+1./(HTCS*AEFE))
      CALL AFCALC(2)
      AI(3)=-1.
      PI(3)=A2
      CI(3)=C.
      FI(3)=-A1*T(2)-A3*TLI
      AI(4)=B2
      II(4)=-1.
      FI(4)=-B1*T(2)-B3*TLI
      CALL TRIDIA(4)
      TL(1)=XI(1)
      TL(2)=XI(2)
      TF(2)=XI(3)
      TTRIAL=XI(4)
      IF(M1.EQ.1) TP(3)=TTRIAL
      GC(1)=WP*CS*(TP(2)-TPIN)
      GC(2)=WP*CS*(TTRIAL-TP(2))+GCFXI
      GO TO 15C
C     ---
C               REGICN III IS THREE OR MORE ELEMENTS
  10C UAHC=CUAHCS
      UAHE=HTCL*AELE
      UAEC=1./(RSOLL(1)+1./(HTCS*AEPE))
      CC=CCS
      CALL AFCALC(1)
      CI(1)=A3
      FI(1)=-A1*T(1)-A2*TPIN
      EI(2)=E3
      FI(2)=-B1*T(1)-F2*TPIN
      L2=NEI-1
      DC 110 I=2,L2
      UAEC=1./(RSOLL(I)+1./(HTCS*AEPE))
      CALL AFCALC(I)
      AI(2*I-1)=-1.
      FI(2*I-1)=A2
      CI(2*I-1)=A3
      FI(2*I-1)=-A1*T(I)
      AI(2*I)=B2
      EI(2*I)=B3
      CI(2*I)=-1.
  110 FI(2*I)=-F1*T(I)
      UAHC=FXI*CUAHCS
      UAHE=FXI*HTCL*AFLF
      UAEC=FXI/(RSOLL(NEI)+1./(HTCS*AEPE))
      CALL AFCALC(NEI)
      AI(2*NEI-1)=-1.
```

```
      LI(2*NEI-1)=A2
      CI(2*NEI-1)=C.
      FI(2*NEI-1)=-A1*T(NEI)-A3*TLI
      AI(2*NEI)=B2
      CI(2*NEI)=-1.
      FI(2*NEI)=-B1*T(NEI)-B3*TLI
      CALL TRIDIA(NEI*2)
      TL(1)=XI(1)
      TL(2)=XI(2)
      L2=NEI-1
      DO 120 I=2,L2
      TF(I)=XI(2*I-1)
      GC(I-1)=WP*CS*(TP(I)-TF(I-1))
  120 TL(I+1)=XI(2*I)
      TF(NEI)=XI(2*NEI-1)
      TTRIAL=XI(2*NEI)
      IF(M1.EQ.1) TP(NEI+1)=TTRIAL
      GC(NEI-1)=WP*CS*(TP(NEI)-TP(NEI-1))
      GC(NEI)=WP*CS*(TTRIAL-TP(NEI))+GCRXI
C     ---
C     ---
  150 CONTINUE                                    REGION III - COMING UP
C
C     ---
      M1=C
      NEITMP=NEI
      NEFTMP=NEF
      IF(NEI.EQ.1) GO TO 172
      L2=NEI-1
      DO 160 I=1,L2
      DQE=(TL(I+1)-TL(I))*WL*CL-(TP(I+1)-TP(I))*WP*CS
      XP(I)=0.
      FNER(I)=ENER(I)+DQE*DTIME
      CALL TKPROP(T(I),FNER(I),Z(I),2,2,2,J6)
      IF(TP(I+1).GT.TSAT) GO TO 165
  160 CONTINUE
      GO TO 172
C     ---
C                         TSAT OCCURS BEFORE NEI
  165 XP(I+1)=CS*(TP(I+1)-TSAT)/QT
      IF(XP(I+1).GT.1.) GO TO 167
      TP(I+1)=TSAT
      NEITMP=I
      GO TO 190
C     ---
C                VAPORIZATION OCCURS IN ONE ELEMENT
  167 NEFTMP=I
      NEITMP=I
      RXF=CV*(TP(I+1)-TSAT)/(CS*(TP(I+1)-TP(I)))
      TF(I+1)=(CS*(TP(I+1)-TSAT)-QT)/CV+TSAT
      XP(I+1)=1.
      GO TO 210
C     ---
C                ELEMENT NEI
  172 I=NEITMP
      XP(NEITMP+1)=(GC(NEITMP)-WP*CS*(TSAT-TP(NEITMP)))/(WP*QT)
      IF(XP(NEITMP+1).LT.0) GO TO 174
      IF(XP(NEITMP+1).GT.1.) GO TO 176
      TP(NEITMP+1)=TSAT
      DQE=WL*CL*(TL(I+1)-TL(I))-GC(I)
      FNER(I)=ENER(I)+DQE*DTIME
      CALL TKPROP(T(I),FNER(I),Z(I),2,2,2,J6)
      GO TO 190
```

D-24

```
C         ---
C                              IN NLI, TSAT DID NOT OCCUR
  174 XF(I+1)=0.
      TP(I+1)=TP(I)+QC(NEITMP)/(WP*CS)
      NEITMP=NEITMP+1
      DGE=WL*CL*(TL(I+1)-TL(I))-QC(I)
      ENER(I)=ENER(I)+DQE*DTIME
      CALL TKPREP(T(I),ENER(I),Z(I),2,2,2,JC)
      GC TO 172
C         ---
C                              IN NEI, TRANSITION IN ONE ELEMENT
  176 TP(NEITMP+1)=(QC(NEITMP)-(TSAT-TP(NEITMP))*WP*CS-WP*QT)/(WP*CV)+TS
     1AT
      NEFTMP=NEITMP
      IF(NEFTMP.EQ.NEI) GC TO 301
  350 IF(NEFTMP.EQ.NEF) GO TO 303
      RXF=WP*CV*(TP(NEITMP+1)-TSAT)/QC(NEITMP)
      DGE=(TL(I+1)-TL(I))*WL*CL-QC(NEI)
      ENER(I)=ENER(I)+DQE*DTIME
      CALL TKPREP(T(I),ENER(I),Z(I),2,2,2,JC)
      GC TO 210
C         ---
C                              NEFTMP IS NLI
  301 IF(NEFTMP.EQ.NEF) GO TO 302
  351 QA=QC(NEI)-QCRXI
      XPA=XP(NEFTMP+1)-QCRXI/(WP*QT)
      IF(XPA-1.) 310,311,312
C         ---
C                              XPA EQUALS ONE
  311 RXF=1.-FXI
      TP(NEFTMP+1)=TSAT+QCRXI/CCV
      GO TO 305
C         ---
C                              XPA IS LESS THAN ONE
  310 QD=(XP(NEFTMP+1)-1.)*WP*QT
      RXF=QD/QCRXI*(1.-FXI)
      TP(NEFTMP+1)=TSAT+QD/CCV
      CC TO 305
C         ---
C                              XPA IS GREATER THAN ONE
  312 QD=(XPA-1.)*WP*QT
      RXF=QD/QA*FXI+1.-FXI
      QSUPHT=QD+QCRXI
      TP(NEFTMP+1)=TSAT+QSUPHT/CCV
      CC TO 305
C         ---
C                              NEFTMP IS NEI & NEF
  302 IF(M3.EQ.1) GO TO 303
      GF=QT*WP
      QA=QC(NEFTMP)-GF-QCRXF
      XPF=XF(NEFTMP+1)-QCRXF/(WP*QT)
      IF(XPF-1.) 304,305,306
C         ---
C                              XPF LESS THAN ONE
  304 QSUPHT=(XP(NEFTMP+1)-1.)*QT*WP
      FXF=RXF*QSUPHT/CCPXF
      TP(NEFTMP+1)=TSAT+QSUPHT/CCV
      GC TO 305
C         ---
C                              XPF GREATER THAN ONE
  306 XPA=XP(NEFTMP+1)-QCRXI/(WP*QT)
      IF(XPA-1.) 307,308,309
C         ---
```

```
C                              XPA IS ONE
   308 FXF=1.-FXI
       QSUPHT=QB+QCRXF
       TP(NEFTMP+1)=TSAT+QSUPHT/CCV
       GO TO 305
C      ---
C                              XPA IS LESS THAN ONE
   307 QD=(XPB-1.)*WP*QT
       FXF=RXF+(QD/QD)*(1.-RXF-FXI)
       QSUPHT=QD+QCRXF
       TP(NEFTMP+1)=TSAT+QSUPHT/CCV
C      ---
C                              XPB IS ONE
   305 DGE=(TL(NEFTMP+1)-TL(NEFTMP))*WL*CL-QC(NEFTMP)
       ENER(NEFTMP)=ENER(NEFTMP)+DQE*DTIME
       CALL TKPROP(T(NEFTMP),ENER(NEFTMP),Z(NEFTMP),2,2,2,J6)
       XP(I+1)=1.
       GO TO 210
C      ---
C                              XPA IS GREATER THAN ONE
   309 QD=(XFA-1.)*WP*QT
       RXF=1.-(1.-QD/QA)*FXI
       QSUPHT=QD+QB+QCRXF
       TP(NEFTMP+1)=TSAT+QSUPHT/CCV
       GO TO 305
C      ---
C                              NEFTMP=NEF, NOT NEI
   303 QA=QC(NEF)-QCRXF
       XFA=XF(NEFTMP+1)-QCRXF/(WP*QT)
       IF(XPA-1.) 320,305,322
C      ---
C                              XPA IS LESS THAN 1
   320 QSUPHT=(XP(NEFTMP+1)-1.)*WP*QT
       FXF=RXF*QSUPHT/QCRXF
       TP(NEFTMP+1)=TSAT+QSUPHT/CCV
       GO TO 305
C      ---
C                              XPA IS GREATER THAN 1
   322 QD=(XFA-1.)*QT*WP
       FXF=FXF+FXF*QD/QA
       QSUPHT=QD+QCRXF
       TP(NEFTMP+1)=TSAT+QSUPHT/CCV
       GO TO 305
C      ---
C                                             REGION II, COMING UP
C      ---
   190 I=I+1
       IF(I.NE.NE+1) GO TO 191
       WRITE(6,501)
       STOP
   191 XF(I+1)=XF(I)+QC(I)/(WP*QT)
       DGE=(TL(I+1)-TL(I))*WL*CL-QC(I)
       IF(XP(I+1).GT.1.) GO TO 200
       ENER(I)=ENER(I)+DGE*DTIME
       CALL TKPROP(T(I),ENER(I),Z(I),2,2,2,J6)
       GO TO 190
C      ---
C                              IN ELEMENT NEF
   200 NEFTMP=I
       TP(I+1)=(QC(I)-WP*QT*(1.-XP(I)))/(WP*CV)+TSAT
       IF(NEFTMP.EQ.NEI) GO TO 301
   302 IF(NEFTMP.EQ.NEF) GO TO 303
       XF(I+1)=1.
```

D-26

```
          ENER(I)=ENER(I)+DQE*DTIME
          CALL  TKPROP(T(I),ENER(I),Z(I),2,2,2,J6)
          RXF=1.-WP*QT*(1.-XP(1))/QC(I)
C         ---
C                                                    REGION 1. COMING UP
C         ---
  210 CONTINUE
  881 L1=NEFTMP+1
          SUM=0.
          DO 155 I=NEI,NEF
          IF((TEL(I)-TSAT).LT.1E-10) GO TO 155
          SUM=SUM+(1.-(T(I)-TSAT)/(TEL(I)-TSAT))*OLDQEC(I)
  155 CONTINUE
          QANT=(OLDQEC(NEF)*(T(I)-TSAT)/(TEL(I)-TSAT))/FXF
          DRXF=-SUM/QANT
          RXF=RXF+DRXF
  668 IF(RXF.LE.0.) NEFTMP=NEFTMP+1
          IF(RXF.LE.0.) RXF=RXF+1.
          IF(RXF.LE.0.) GO TO 668
  669 IF(RXF.GT.1.) NEFTMP=NEFTMP-1
          IF(RXF.GT.1.) RXF=RXF-1.
          IF(RXF.GT.1.) GO TO 669
          IF(RXF.LT..5E-1) RXF=.5E-1
          IF(L1.GT.NE) GO TO 229
          DO 220 I=L1,NE
          DQE=WL*CL*(TL(I+1)-TL(I))-QC(I)
          ENER(I)=ENER(I)+DQE*DTIME
          CALL  TKPROP(T(I),ENER(I),Z(I),2,2,2,J6)
  220 CONTINUE
C         ---
  229 CONTINUE
          NEI=NEITMP
          NEF=NEFTMP
  230 TPOUT=TP(NE+1)
          DO 154 K=1,NE
  154 TEL(K)=T(K)
          TLOUT=TL(1)
          M3=0
          XOUT=XF(NE+1)
          ET=CT/3600.
          IF(CT.EQ.T5) GO TO 255
          IF(CT.EQ.T6) GO TO 256
          IF(CT.EQ.TD) GO TO 700
          CT1=CT1+DTIME
          IF(CT.GE.T5.AND.CT.LE.T6) CHGTM=(CT-T5)/3600.
          IF(CT1.LT.1793.) GO TO 257
          WRITE(6,240) ET,CHGTM,WL,TPOUT,TLOUT
          CT1=0.
  257 RETURN
  255 WRITE(6,555) HRT5
          GO TO 260
  256 WRITE(6,556) HRT6
          CHGTM=(T6-T5)/3600.
  260 E=0.
          WRITE(6,400)
          DO 252 I=1,NE
          IF(XP(I).LT.0.) XP(I)=0.
          WRITE(6,408) I,T(I),Z(I),TL(I),TP(I),XP(I)
  252 E=E+ENER(I)
          J=NE+1
          WRITE(6,408) J,TL(J),TP(J),XF(J)
          WRITE(6,492) E
          WRITE(6,258)
```

D-27

```
      WRITE(6,240) LT,CHGTM,WL,TPOUT,TLOUT
      CHGTM=0.
      CTI=0.
      TAPPR=T(1)
      RETURN
  700 E=0.
      DO 701 I=1,NE
  701 E=E+ENER(I)
      WRITE(6,702) E
      CTI=0.
      RETURN
      END
C     ---
C     ---
C     ---
      SUBROUTINE ABCALC(I)
      COMMON/CALCAB/UAEC,UAHC,UAHE,CH,CC,A1,A2,A3,B1,B2,B3,CZ
C     THIS SUBROUTINE PROVIDES COEFFICIENTS FOR THE SIMULTANEOUS LINEAR
C     EQUATIONS WHICH SOLVE THE THREE-WAY ANALYSIS.
      ALFA1=(UAHE+UAHC)/CH-(UAHC+UAEC)/CC
      ALFA2=(UAHC**2-(UAHC+UAHE)*(UAEC+UAHC))/(CH*CC)
      TEST=ALFA1**2-4*ALFA2
      POWER1=(-ALFA1+SQRT(TEST))/2.
      POWER2=(-ALFA1-SQRT(TEST))/2.
      Z1=POWER1*CH/UAHC+1.+UAHE/UAHC
      Z2=POWER2*CH/UAHC+1.+UAHE/UAHC
      IF(POWER1.LT.-145.) POWER1=-145.
      IF(POWER2.LT.-145.) POWER2=-145.
      EPWR1=EXP(POWER1)
      EPWR2=EXP(POWER2)
      EDIFF=EPWR1-EPWR2
      X=ABS(POWER1)
      Y=ABS(POWER2)
      IF(X.GT.1.E-2.AND.Y.GT.1.E-2) GO TO 4
      EDIFF=POWER1+POWER1**2/2.+POWER1**3/6.
      EDIFF=EDIFF-POWER2-POWER2**2/2.-POWER2**3/6.
    4 B=Z1*EPWR1-Z2*EPWR2
      A1=1.+(EPWR1*EPWR2*(Z2-Z1)-EDIFF)/B
      A2=EDIFF/B
      A3=EPWR1*EPWR2*(Z1-Z2)/B
      B1=1.-(Z1-Z2+EDIFF*Z1*Z2)/B
      B2=(Z1-Z2)/B
      B3=Z1*Z2*EDIFF/B
      RETURN
      END
C     ---
C     ---
C     ---
      SUBROUTINE VAP(UAEC,UAHC,UAHE,CH,TSAT,TE,TL1,QHE,QEC,QHC,TL2)
      POWER=(UAHE+UAHC)/CH
      IF(POWER.GT.145.) POWER=145.
      EPWR=EXP(-POWER)
      CONST1=(UAHE*TE+UAHC*TSAT)/(UAHE+UAHC)
      CONST2=CH*(TL1-CONST1)/(UAHE+UAHC)
      QHE=UAHE*(CONST2*(1.-EPWR)+CONST1-TE)
      QHC=UAHC*(CONST2*(1.-EPWR)+CONST1-TSAT)
      QEC=UAEC*(TE-TSAT)
      TL2=(TL1-CONST1)*EPWR+CONST1
      RETURN
      END
C     ---
C     ---
C     ---
```

```
      SUBROUTINE TRIDIA(N)
      COMMON/DIATRI/AI(50),BI(50),CI(50),FI(50),XI(50),CY
      COMMON/TMP/ALFA(50),BETA(50),GAMMA(50)
      IF(BI(1).EQ.0.) GO TO 100
      BETA(1)=BI(1)
      GAMMA(1)=CI(1)/BETA(1)
      NM1=N-1
      DO 10 I=1,NM1
      IF(BETA(I).EQ.0.) GO TO 101
      GAMMA(I)=CI(I)/BETA(I)
      IP1=I+1
   10 BETA(IP1)=BI(IP1)-AI(IP1)*GAMMA(I)
      ALFA(1)=FI(1)/BETA(1)
      DO 30 I=2,N
   30 ALFA(I)=(FI(I)-AI(I)*ALFA(I-1))/BETA(I)
      XI(N)=ALFA(N)
      DO 40 I=1,NM1
      J=N-I
   40 XI(J)=ALFA(J)-GAMMA(J)*XI(J+1)
      RETURN
  100 WRITE(6,600)
  600 FORMAT('BI(1)=0 IN TRIDIA')
      STOP
  101 WRITE(6,601) I
  601 FORMAT(' BETA(I) IN TRIDIA=0 FOR I=',I2)
      STOP
      END
C     ---
C     ---
C     ---
      SUBROUTINE TKPROP(TEMP,ENTH,FRAC,M,K2,N,J6)
C     THIS SUBROUTINE ESTABLISHES TABLES OF ELEMENT ENTHALPY VS. THE
C     FRACTION OF SOLID THERMKEEP AND TEMPERATURE
      COMMON/PROPTK/ELM,CPST,STMM,STME
      DIMENSION EM(18),FE(18),T(18),H(18),Z(18)
  200 FORMAT(I2)
  201 FORMAT(F10.2,F12.5,F10.6)
  202 FORMAT(/,5X,' TABLE OF TEMPERATURE,ENTHALPY, AND SOLID FRACTION
     COF THERMKEEP',/)
  203 FORMAT(10X,' T(I)',10X,' H(I)',10X,'    Z(I)',/)
  204 FORMAT(6X,F10.2,5X,F12.5,5X,F10.6)
  205 FORMAT(5X,' ENERGY BEYOND TABLE LIMITS FOR ENTH=',E10.4)
      IF(N.EQ.1) GO TO 300
      GO TO(1,2),K2
    1 IF(J6.EQ.2) GO TO 101
      WRITE(6,202)
      READ(5,200) K4
      WRITE(6,203)
  101 J4=K4-1
      J3=1
      DO 11 I=1,K4
      IF(J6.EQ.2) GO TO 102
      READ(5,201) T(I),H(I),Z(I)
  102 CONTINUE
      IF(K2.EQ.2) GO TO 2
      IF(J3.EQ.2) GO TO 10
      IF(T(I).LT.TEMP) GO TO 10
      ENTH=ELM*(H(I-1)+(TEMP-T(I-1))*(H(I)-H(I-1))/(T(I)-T(I-1)))
      FRAC=Z(I)+(T(I)-TEMP)*(Z(I-1)-Z(I))/(T(I)-T(I-1))
      J3=2
   10 EM(I)=ELM*H(I)+STMM*CPST*T(I)
      FE(I)=ELM*H(I)+STME*CPST*T(I)
      IF(J6.EQ.2) GO TO 11
```

```
      WRITE(6,204) T(I),H(I),Z(I)
   11 CONTINUE
      RETURN
    2 CC TO(3,4),M
    3 IF(ENTH.GT.EM(K4).OR.ENTH.LT.EM(1)) GO TO 250
      DC 5 I=1,J4
      IF(ENTH.GT.EM(I+1)) GO TO 5
      TEMP=T(I)+(T(I+1)-T(I))*(ENTH-EM(I))/(EM(I+1)-EM(I))
      FRAC=Z(I)+(Z(I+1)-Z(I))*(ENTH-EM(I))/(EM(I+1)-EM(I))
      RETURN
    5 CONTINUE
      GO TO 250
    4 IF(ENTH.GT.EE(K4).OR.ENTH.LT.EE(1)) GO TO 250
      DC 6 I=1,J4
      IF(ENTH.GT.EE(I+1)) GO TO 6
      TEMP=T(I)+(T(I+1)-T(I))*(ENTH-EE(I))/(EE(I+1)-EE(I))
      FRAC=Z(I)+(Z(I+1)-Z(I))*(ENTH-EE(I))/(EE(I+1)-EE(I))
      RETURN
    6 CONTINUE
      GO TO 303
  300 DC 302 I=1,K4
      IF(T(I).LT.TEMP) GO TO 302
      FRAC=Z(I)+(T(I)-TEMP)*(Z(I-1)-Z(I))/(T(I)-T(I-1))
      IF(M.EQ.2) GO TO 311
      ENTH=EM(I-1)+(EM(I)-EM(I-1))*(TEMP-T(I-1))/(T(I)-T(I-1))
      GO TO 301
  311 ENTH=EE(I-1)+(EE(I)-EE(I-1))*(TEMP-T(I-1))/(T(I)-T(I-1))
  301 CONTINUE
      RETURN
  302 CONTINUE
  303 CONTINUE
  250 WRITE(6,205) ENTH
      STOP
      END
C     ---
C     ---
C     ---
      FUNCTION THCS(T)
C     THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY OF SOLID THERMKEEP
C     AT 25CF. IT IS NOW A DUMMY FUNCTION WITH A CONSTANT VALUE
C     IN KJ/M-SEC-K
      THCS=1.0800E-3
      RETURN
      END
C     ---
C     ---
C     ---
      FUNCTION HL(WL)
C     THIS FUNCTION COMPUTES THE HEAT TRANSFER COEFFICIENT OF THE
C     HEATING FLUID AS A FUNCTION OF FLOW RATE IN KJ/SEC/M2/K
      CRE=2368.9764
      RECRIT=7724.
      CHTC=9.9139E-4
      QX=.8803
      RE=WL*CRE
      IF(RE.LT.RECRIT) GO TO 451
      HTCI=CHTC*RE**0.8
      GO TO 453
  451 HTCI=.0609
      ZNU=0.181*QX*(1.-0.839/QX+35.4/QX**2-207./QX**3+419./QX**4)
      HTCI=ZNU*HTCI
  453 HL=HTCI
      RETURN
```

```
      END
C     ---
C     ---
C     ---
      FUNCTION HT(X)
C          THIS FUNCTION COMPUTES THE HEAT TRANSFER COEFFICIENT OF
C          VAPORIZING POWER FLUID AS A FUNCTION OF QUALITY
      HT=X*.50107+.37884
      RETURN
      END
```

LIST OF SYMBOLS FOR MAIN PROGRAM

I,L	Integer loop counters
CL	Specific heat of transfer fluid, kJ/kg-$^{\circ}$K
CS	Specific heat of subcooled power fluid, kJ/kg-$^{\circ}$K
CT	Cycle time, seconds
CV	Specific heat of vaporized power fluid, kJ/kg-$^{\circ}$K
ET	Total elapsed time, hours
J6	Indicator 1 = first time through 2 = a new Thermkeep mass has been entered
K5	The number of entries in the table of solar collector output vs. time

K7	Indicator 1 = single fluid flow
	          2 = transition between single and two-fluid flow
	          3 = two fluid flow

NC	Number of daily cycles run
ND	Maximum number of daily cycles desired
QC	Rate of solar collector output, kW
QL(I)	Rate of solar collector output at time I, kW
QT	Heat of vaporization of power fluid, kJ/kg
TD	End of the daily cycle, secs
T1	Start of the daily cycle, secs
T5	Beginning of net charge, secs
T6	End of net charge, secs
WL	Transfer fluid flow rate, kg/sec
WP	Power fluid flow rate, kg/sec
ZL,ZP,ZPS, ZPV	Coefficients used to determine time step
QCHG	Heat rate storage, kJ
TIME(I)	Time which matches QL(I)

TLIN	Transfer fluid inlet temperature, $^\circ K$
TPIN	Power fluid inlet temperature, $^\circ K$
TSAT	Power fluid saturation temperature, $^\circ K$
WMAX	Maximum transfer fluid flow rate, kg/sec
XOUT	Power fluid outlet quality
ASTOR	Amount of storage medium, kg
DQCHG	Increment of storage input, kJ
DQDIS	Increment of storage output, kJ
DTIME	Time step, secs
DTIML, DTIMP	Temporary time step calculations
DTMAX, DTMIN	Maximum and minimum time steps, secs
QBURN	Auxiliary heat required to maintain the desired outlet temperature, kJ
QLOSS	Solar collector heat unable to be used, kJ
TAPPR	Transfer fluid outlet temperature approximation at beginning of two-fluid flow, $^\circ K$
TLOUT	Transfer fluid outlet temperature, $^\circ K$
TPDES	Desired power fluid outlet temperature, $^\circ K$
TPOUT	Power fluid outlet temperature, $^\circ K$
PCDIFF	Percent different between storage heat in and heat out
QDEFCT	Heat required to raise the power fluid outlet temperature to the minimum allowable temperature, $^\circ K$
QDISCH	Storage output, kJ
QEXTRA	Heat from power fluid exiting above the desired outlet temperature, kJ
QPOWER	Boiler requirement, kJ
QSOLAR	Solar collector output, kJ
TALWBL	Minimum allowable outlet temperature, $^\circ K$

LIST OF SYMBOLS FOR SUBROUTINE ELANAL

E	The unit total energy content, kJ
I,J,K	Integer loop counters
T(I)	The temperature of the Ith element, $^{\circ}K$
Z(I)	The solid fraction of element I
AI,BI,CI	Coefficients of unknowns in diagonals A, B, C used in subroutine TRIDIA
FI(I)	The coefficient of the result of equation I used in subroutine TRIDIA
A1,A2,A3, B1,B2,B3	Coefficients of unknowns used to calculate AI, BI, and CI
CC	Product of the power fluid flow and specific heat
CH	Product of the transfer fluid flow and specific heat
CL	Transfer fluid specific heat, $kJ/kg-^{\circ}K$
CS	Specific heat of subcooled power fluid, $kJ/kg-^{\circ}K$
CT	Cycle time, secs.
CV	Specific heat of power fluid vapor, $kJ/kg-^{\circ}K$
ET	Elapsed time, hours
HL(WL)	Function which returns the transfer fluid heat transfer coefficient as a function of flow rate
HT(X)	Function which returns the power fluid heat transfer coefficient as a function of quality
J6	Indicator 1 = first time through program 2 = restart cycle with a new storage mass
K1-K8	Integer loop counters
L1,L2	Integer loop counters
M1	Condition indicator: 1 = transfer fluid was calculated to increase going through an element

M3	Condition indicator: 1 = vaporization occurs completely in bottom element
ND	Number of daily cycle in progress
NE,XNE	Number of elements used in numerical analysis
QA	Rate of heat flux into the power fluid stream in an element above the previous time step's point of total vaporization, kW
QB	Rate of heat flux into the power fluid stream in an element below the previous time step's point of incipient vaporization, kW
QD	Rate of heat flux into the power fluid stream in an element in the previous time step's transition region, kW
QP	Heat transferred to the power fluid in a whole element in the 2-phase region, kJ
QT	The heat of vaporization of the power fluid, kJ/kg
TD	The cycle ending point, secs
TL(I)	Temperature of the transfer fluid at the lower boundary of element I, $^{\circ}K$
TP(I)	Temperature of the power fluid at the lower boundary of element I, $^{\circ}K$
T5	Beginning of net charge, secs
T6	End of net charge, secs
WL	Transfer fluid flow rate, kg/sec
WP	Power fluid flow rate, kg/sec
XI(I)	The solution to the Ith equation in TRIDIA, $^{\circ}K$
XP(I)	The quality of power fluid at the lower boundary of element I
AEL	The total contact surface between the transfer fluid and the storage medium, m^2
AEP	The total contact surface area between the power fluid and the storage medium, m^2

APL	The total contact surface area between the power fluid and transfer fluid, m^2
CCS	Product of the power fluid flow rate and subcooled specific heat
CCV	Product of the power fluid flow rate and superheated vapor specific heat
CT1	Half-hour timer for display purposes, secs
DQE	The rate of energy change of an element during a time step
EFF	Heat exchange effectiveness
ELM	The storage medium mass in one numerical element, kg
FTP	The fraction of an element in which the power fluid is in 2-phase flow
FXF	The fraction of element NEF which contains less than quality 1.0 fluid
FXI	The subcooled fraction of the element NEI
NEF	The element in which the power fluid reaches quality 1.0
NEI	The element in which the power fluid begins to vaporize
QEC	The heat rate from storage medium into the power fluid stream
QHC	The heat rate from the transfer fluid into the power fluid stream
QHE	The heat rate from the transfer fluid into the storage medium
QTP	Heat transferred to the power fluid in the two-phase region of an element, kJ
RES	Resistance to heat transfer into the power fluid
RXF	The fraction of element NEF in which the power fluid has greater than 1.0 quality
RXI	The fraction of element NEI in which the power fluid has greater than 0 quality
SUM	Anticipated heat to be transferred to the superheated power fluid, kJ
TEL(I)	An element temperature from the previous time step

TLF	The temperature of the transfer fluid at point RXF, ^{O}K
TLI	The temperature of the transfer fluid at point FXI, ^{O}K
VAP	The vaporization subroutine
XI1,XI2,XI3	Temporary points used in an iterative search for the point at which vaporization ends
XLE	The length of a tube in an element
XNE	The number of elements used for analysis
XNT	The number of tubes in each heat exchanger
XPA	The calculated power fluid quality leaving an element which contained the end of transition the previous time step
XPB	The calculated power fluid quality leaving an element which completely contained transition the previous time step
XP1,XP2	Temporary qualities used in an iterative search for the point at which vaporization ends
AELE	Contact surface area between storage medium and transfer fluid in one element, m^2
AEPE	Contact surface area between storage medium and power fluid in one element, m^2
APFE	Inside surface area of the power fluid tube in one element, m^2
APLE	Contact surface area between transfer fluid and power fluid in one element, m^2
CPST	The specific heat of steel, $kJ/kg-^{O}K$
DEFF	The effective diameter of dual heat exchanger tube
DRXF	The calculated change in RXF
DSTK	The diameter of solid Thermkeep buildup on a tube, m
ENEL	The energy content of one element returned by subroutine TKPROP, kJ
ENER(I)	The energy of the Ith element, kJ

FRAC	The solid fraction of an element returned by subroutine TKPROP
FSUP	The fraction of an element which contains superheated power fluid
HRT5	Elapsed time at time T5, hrs
HRT6	Elapsed time at time T6, hrs
HTCL	Transfer fluid heat transfer coefficient, kW/m^2-^oK
HTCS	Heat transfer coefficient of subcooled power fluid, kW/m^2-^oK
HTCV	Heat transfer coefficient of power fluid vapor, kW/m^2-^oK
QANT	Heat into the power fluid anticipated for section FXF, kJ
RHOM	Storage medium density, kg/m^3
STME	Steel mass in an end element, kg
STMM	Steel mass in a middle element, kg
THCS	Thermal conductivity of solid storage material, $kJ/m-^oK$
TL1N	Inlet temperature of transfer fluid, ^oK
TPIN	Inlet temperature of power fluid, ^oK
TSAT	Power fluid saturation temperature, ^oK
UAEC	Conduction coefficient of storage medium to power fluid, $kW/^oK$
UAHC	Conduction coefficient of transfer fluid to power fluid, $kW/^oK$
UAHE	Conduction coefficient of transfer fluid to storage medium, $kW/^oK$
VSTK	The volume of solid storage material in one element, m^3
XNTU	Number of heat transfer units in an element
XOUT	The power fluid outlet quality
YNTU	Number of heat transfer units in the two-phase section of an element
ZNTU	Number of heat transfer units in the superheated section of an element.

ASTOR	Amount of storage material, kg
CHGTM	Elapsed time from beginning of net charge, hrs.
CRKTL	Intermediate variable = 2π x XLE x XNT used in calculating solid layer resistance
DTIME	Length of time step, secs
ETSAT	Intermediate variable used to calculate YNTU
QCRXF	Heat into the power fluid in section RXF, kJ
QCRXI	Heat into the power fluid in section RXI, kJ
QPART	Heat into the power fluid in the two-phase section of an element
RESTP	Resistance to heat transfer into the power fluid in the two-phase region
RSOLL(I)	The solid layer resistance in element I
TINIT	Unit starting temperature, ^{O}K
TLOUT	Transfer fluid outlet temperature, ^{O}K
TPOUT	Power fluid outlet temperature, ^{O}K
UAECF	Conduction coefficient of storage medium to power fluid in section FXF, $kW/^{O}F$
UAECI	Conduction coefficient of storage medium to power fluid in section RXI, $kW/^{O}K$
UAEC2	Conduction coefficient of storage medium to power fluid in a purely transition element, $kW/^{O}K$
UAHCF	Conduction coefficient of transfer fluid to power fluid in section FXF, $kW/^{O}K$
UAHCI	Conduction coefficient of transfer fluid to power fluid in section RXI, $kW/^{O}K$
UAHC2	Conduction coefficient of transfer fluid to power fluid in a purely transition element, $kW/^{O}K$
UAHEF	Conduction coefficient of transfer fluid to storage medium in section FXF, $kW/^{O}K$

UAHEI	Conduction coefficient of transfer fluid to storage medium in section RXI, $kW/^{\circ}K$
UAHE2	Conduction coefficient of transfer fluid to storage medium in a purely transition element
XLEFF	Tube length, m
XPXI3	Intermediate variable used in an iterative search for the vaporization ending point
CUAHCS CUAHCT CUAHCV	Conduction coefficient of transfer fluid to power fluid in partial elements for subcooled, transition, and vapor phases, $kW/^{\circ}K$
NEFTMP	Element where end of transition is temporarily located
NEITMP	Element where the beginning of transition is temporarily located
OLDQEC(I)	Heat transferred from storage to power fluid in the Ith element during the previous time step
QSUPHT	Heat into the power fluid in the vapor region of an element
RESSUP	Resistance to heat transfer into the power fluid in the superheated region
TTRIAL	A calculated power fluid temperature at the beginning of two-phase flow, $^{\circ}K$
XNTUSP	Number of heat transfer units in the superheated fraction of an element

A P P E N D I X   E

SINGLE HEAT EXCHANGER COMPUTER CODE

```
C         MAIN PROGRAM TESPR
          COMMON CPF,TU,TL,XNE,PMAX,PDMAX,WPUMP,WPEAK,TF(51),CT,ASTOR,EN3,WC
         &OLL
          DIMENSION QOUT(25),TIM(25)
  300 FORMAT(I3,6F10.1)
  301 FORMAT(19X,' TABLE OF SOLAR COLLECTOR OUTPUT VS. TIME ')
  302 FORMAT(24X,' RATE IN KW ',9X,' TIME IN SECONDS ')
  303 FORMAT(F10.4,F10.1)
  304 FORMAT(2F10.4,2F10.1,F10.0,F10.2,F10.3)
  305 FORMAT(5X,' FLUID SPECIFIC HEAT, KJ/KG/K ',F10.4)
  306 FORMAT(5X,' THERMKEEP SPFC HEAT, KJ/KG/K ',F10.4)
  307 FORMAT(5X,' TURBINE INLET TEMP., K        ',F10.1)
  308 FORMAT(5X,' TURBINE OUTLET TEMP., K       ',F10.1)
  309 FORMAT(5X,' NO. OF ELEMENTS FOR ANALYSIS ',F10.0)
  310 FORMAT(5X,' AMT. OF STORAGE MATL., KG     ',F10.2)
  311 FORMAT(5X,' MAX. PUMP FLOW, KG/SEC.       ',F10.3)
  312 FORMAT(5X,' MAX. TIME INCREMENT, SEC.     ',F10.2)
  313 FORMAT(5X,' BOILER DEMAND, KW             ',F10.3)
  314 FORMAT(1H1,8X,' MAIN PROGRAM DATA',//)
  315 FORMAT(25X,F10.4,9X,F10.1)
  316 FORMAT(5X,' NO. OF DAILY CYCLES           ',7X,I3,///)
  317 FORMAT(1H1,5X,' HEAT OF FUSION THERMAL STORAGE ANALYSIS',///)
  320 FORMAT(////,20X,' CYCLE DATA',//)
  321 FORMAT(10X,' ELAPSED TIME, HR             ',F10.1)
  322 FORMAT(10X,' CYCLE TIME, SEC              ',F10.2)
  323 FORMAT(10X,' LOST COLLECTOR HEAT, KJ      ',E15.7)
  324 FORMAT(10X,' COLLECTOR OUTPUT, KJ         ',E15.7)
  325 FORMAT(10X,' STORAGE OUTPUT, KJ           ',E15.7)
  326 FORMAT(10X,' STORAGE INPUT, KJ            ',E15.7)
  327 FORMAT(10X,' AUXILIARY INPUT, KJ          ',E15.7)
  328 FORMAT(10X,' BOILER REQUIREMENT, KJ       ',E15.7)
  329 FORMAT(10X,' PEAK STORAGE FLOW, KG/S      ',E10.4)
  330 FORMAT(10X,' PEAK PRESS DROP, KCF/SM      ',E10.4)
  334 FORMAT(10X,' PEAK PRESS DROP, PSI         ',E10.4)
  331 FORMAT(10X,' PEAK PUMP POWER, KW          ',E10.4)
  332 FORMAT(10X,' TOTAL PUMP WORK, KW-HR       ',E10.4)
  333 FORMAT(3F10.2,F10.3,I3)
  335 FORMAT(10X,' NUMBER OF TIME INCREMENTS',I10,///)
  336 FORMAT(5X,' MIN. TIME INCREMENT, SEC.     ',F10.2)
  337 FORMAT(5X,' IDLE TIME INCREMENT, SEC.     ',F10.2)
  338 FORMAT(10X,' DEFICIT REQUIREMENT, KJ      ',E10.4,12X,' CYCLE TIME
         &FLOW        TF(1)       TF(NE+1)     TF(1)-F     TF(NE+1)-F ')
  340 FORMAT(F10.0)
      READ(5,300) KS,T1,T2,T3,T4,T5,T6
      READ(5,304) CFF,CTK,TU,TL,XNE,ASTOR,WMAX
      READ(5,333) DTMAX,DTMIN,DTIDLE,GE,ND
      J6=1
  360 CONTINUE
      IF(J6.EQ.2) GO TO 370
      WRITE(6,317)
      WRITE(6,301)
      WRITE(6,302)
      DO 1 I=1,KS
      READ(5,303) QOUT(I),TIM(I)
    1 WRITE(6,315) QOUT(I),TIM(I)
  370 WRITE(6,314)
```

```
      WRITE(6,305) CPF
      WRITE(6,306) CTK
      WRITE(6,307) TU
      WRITE(6,308) TL
      WRITE(6,309) XNE
      WRITE(6,310) ASTOR
      WRITE(6,311) WMAX
      WRITE(6,312) DTMAX
      WRITE(6,336) DTMIN
      WRITE(6,337) DTIDLE
      WRITE(6,313) QB
      WRITE(6,316) NC
      K1=1
      DHMAX=CPF*(TU-TL)
      WMIN=QB/DHMAX
      ET=0.
      QDEFCT=0.
      QBOIL=QB*(T2+TC-T3)
      WPEAK=0.
      PMAX=0.
      WPUMP=0.
      PCMAX=0.
      NDT=0
      NC=1
C     INITIALIZATION OF DAILY CYCLE
C     K7: 1=NO FLOW, 2=CHARGING, 3=DISCHARGING
   40 DT=DTMAX
      ET=ET+DTMAX/3600.
      K7=1
      QLOSS=0.
      QSOLAR=QB*DTMAX
      QDISCH=0.
      QCHG=0.
      QBURN=0.
      WF=0.
      DTIME=DTMAX
      QC=QB
      L=0
   50 L=L+1
      NDT=NDT+1
      CALL ELANAL(WF,T1,T2,T3,T4,T5,T6,K7,DTIME,K1,JC)
      IF(L.NE.10) GO TO 51
      TEML=1.8*TF(1)-459.67
      TEMU=1.8*TF(NE+1)-459.67
      L=0
   51 Z=.06*ASTOR*CTK/(XNE*CPF)
      IF(K7.EQ.1) GO TO 60
      IF(K7.EQ.3) GO TO 55
      QLOSS=QLOSS+(QC-QB-WF*CPF*(TU-TF(1)))*DTIME
      QSOLAR=QSOLAR+QC*DTIME
      QCHG=QCHG+WF*CPF*(TU-TF(1))*DTIME
      GO TO 70
   55 NE=XNE
      QBURN=QBURN+WF*CPF*(TU-TF(NE+1))*DTIME
      IF(TF(NE+1).LT.580.) QDEFCT=QDEFCT+WF*CPF*(580.-TF(NE+1))*DTIME
      QDISCH=QDISCH+WF*CPF*(TF(NE+1)-TL)*DTIME
   60 QSOLAR=QSOLAR+QC*DTIME
   70 DO 2 I=2,K5
```

E-4

```
      IF(CT.GE.TIM(I)) GO TC 2
      QC=QOUT(I-1)+(QOUT(I)-QOUT(I-1))*(CT-TIM(I-1))/(TIM(I)-TIM(I-1))
      GC TO 80
    2 CONTINUE
C     INADEQUATE COLLECTOR OUTPUT AT END OF DAY. EVENING
   80 IF(CT.GE.T1) GO TO 90
      WCOLL=QC/DHMAX
      WF=WMIN-WCOLL
      K7=3
      DTIME=Z/WF
      IF(DTIME.LT.DTMIN) DTIME=DTMIN
      IF(DTIME.LE.DTMAX) GO TO 81
      DTIME=DTMAX
   81 CT=CT+DTIME
      IF(CT.LE.T1) CO TO 82
      DTIME=DTIME-(CT-T1)
      CT=T1
   82 ET=ET+DTIME/3600.
      GO TO 50
C     NO HEATING AVAILABLE FROM COLLECTORS
   90 IF(CT.GE.T2) CC TO 100
      WF=WMIN
      WCOLL=0.
      K7=3
      DTIME=Z/WF
      IF(DTIME.LT.DTMIN) DTIME=DTMIN
      IF(DTIME.LE.DTMAX) GO TO 91
      DTIME=DTMAX
   91 CT=CT+DTIME
      IF(CT.LE.T2) GO TO 92
      DTIME=DTIME-(CT-T2)
      CT=T2
   92 ET=ET+DTIME/3600.
      GC TO 50
C     OVERNIGHT IDLE
  100 IF(CT.GE.T3) GO TO 110
      WF=0
      K7=1
      DTIME=DTIDLE
      CT=CT+DTIME
      IF(CT.LE.T3) GO TC 102
      DTIME=DTIME-(CT-T3)
      CT=T3
  102 ET=ET+DTIME/3600.
      GC TO 50
C     NO HEATING AVAILABLE FROM COLLECTORS AFTER OVERNIGHT IDLE
  110 IF(CT.GE.T4) CO TO 120
      WF=WMIN
      K7=3
      DTIME=Z/WF
      IF(DTIME.LT.DTMIN) DTIME=DTMIN
      IF(DTIME.LE.DTMAX) GC TO 111
      DTIME=DTMAX
  111 CT=CT+DTIME
      IF(CT.LE.T4) GO TO 112
      DTIME=DTIME-(CT-T4)
      CT=T4
  112 ET=ET+DTIME/3600.
```

```
          GC TO 50
C         INADEQUATE COLLECTOR OUTPUT AT BEGINNING OF DAY. MORNING
   120    IF(CT.GE.T5) GO TO 130
          WCOLL=QC/DHMAX
          WF=WMIN-WCOLL
          K7=3
          DTIME=Z/WF
          IF(DTIME.LT.DTMIN) DTIME=DTMIN
          IF(DTIME.LE.DTMAX) GC TO 121
          DTIME=DTMAX
   121    CT=CT+DTIME
          IF(CT.LE.T5) GO TO 122
          DTIME=DTIME-(CT-T5)
          CT=T5
   122    ET=ET+DTIME/3600.
          GC TO 50
C         EXCESS SOLAR HEATING AVAILABLE FOR STORAGE
   130    IF(CT.GE.T6) GO TO 140
          IF(CT.GT.T5) CO TO 131
          WF=0
          K7=1
          DTIME=DTMAX
          GC TO 132
   131    WF=(QC-QB)/(CFF*(TU-TF(1)))
          WCOLL=WF+WMIN
          IF(WCOLL.GT.WMAX) WF=WMAX-WMIN
          IF(WCOLL.GT.WMAX) WCOLL=WMAX
          K7=2
          DTIME=Z/WF
          IF(DTIME.LT.DTMIN) DTIME=DTMIN
          IF(DTIME.LE.DTMAX) GC TO 132
          DTIME=DTMAX
   132    CT=CT+DTIME
          IF(CT.LE.T6) CO TO 133
          DTIME=DTIME-(CT-T6)
          CT=T6
   133    ET=ET+DTIME/3600.
          GO TO 50
C         CUMULATIVE INFORMATION AND MAIN PROGRAM END
   140    WRITE(6,320)
          WRITE(6,321) ET
          WRITE(6,323) QLOSS
          WRITE(6,324) QSOLAR
          WRITE(6,325) QDISCH
          WRITE(6,326) QCHG
          WRITE(6,327) QEURN
          WRITE(6,338) QDEFCT
          WRITE(6,328) QBOIL
          WRITE(6,329) WPEAK
          WRITE(6,330) PDMAX
          PSIMAX=PDMAX*.001422
          WRITE(6,334) PSIMAX
          WRITE(6,331) FMAX
          WRITE(6,332) WPUMP
          WRITE(6,335) NDT
          NC=NC+1
          QDIFF1=0.9*ENR
          QDIFF2=QCHG-QDISCH
```

```
      IF(QDIFF2.GE.QDIFF1) GO TO 99
      IF(NC.GT.ND) GO TO 99
      QLOSS=0.
      QSOLAR=0.
      QDISCH=0.
      QCHG=0.
      QBURN=0.
      QDEFCT=0.
      WPEAK=0.
      PLMAX=0.
      PMAX=0.
      WPUMP=0.
      NDT=0
      GO TO 40
   99 READ(5,340) ASTOR
      IF(ASTOR.EQ.1.) GO TO 350
      J6=2
      GO TO 360
  350 STOP
      END
```

```
      SUBROUTINE ELANAL(WF,T1,T2,T3,T4,T5,T6,K7,DTIME,K1,J6)
C     THIS SUBROUTINE PERFCRMS THE HEAT TRANSFER CCMPUTATIONS ON THE
C     ELEMENTS
      DIMENSION ENER(51),Z(51),T(51),RMA(51)
      CCMMON CPF,TU,TL,XNE,PMAX,PDMAX,WPUMP,WPEAK,TF(51),CT,ASTOR,EN3,WC
     LOLL
      CCMMON/PROPTK/ELM,CPST,STMM,STME
      IF(J6.EQ.2) GC TO 360
      GC TO(1,2),K1
C     FIRST TIME THROUGH - INITIALIZE AND READ DATA
    1 NE=XNE
      CT1=0.
      READ(5,101) DC,DI,XLT,XNT,TINS,CDO,DIO
      READ(5,102) TEND,TSHELL,DHEL
      READ(5,103) RHOST,RHCF,RHOM,RHOINS
      READ(5,104) THCINS,THCST,THCF,PRF,VISCF,CPST
      READ(5,105) TAMB,TSHR,TINIT
      READ(5,700) PMATS,PFSSA,PFSSW,PFSTA,PFSTW,PFSBA,FFSEW
      READ(5,701) GATOPS,GASIDE,GABOTS,PMVW,PMVE,FFVV,FFVW
      READ(5,702) CFMTW,PFTW,PFTA,PTK,PINS,ASPECT
  360 CCNTINUE
      IF(K1.EQ.2) GC TO 2
C     GEOMETRICAL CALCULATIONS
      VTUBES=.7854*XLT*XNT*CO**2
      VOLTK=ASTOR/RHOM
      VTOT=VOLTK+VTUBES
C     ATTEMPT SPECIFIED ASPECT RATIO
      JE=1
      DSHELL=(VTOT*1.27324/ASPECT)**(1./3.)
      HSHELL=DSHELL*ASPECT
      IF(HSHELL.LE.XLT) GO TO 3
      HSHELL=XLT
      DSHELL=2.*SQRT(VTOT/(3.1416*HSHELL))
      JE=2
    3 DSHR=DSHELL+2.*TINS+2.*TSHELL
C     WEIGHT CALCULATIONS
      HGTTOT=HSHELL+2.*TINS+2.*TEND
      WTENDS=1.5708*TEND*RHOST*DSHELL**2
      WTSHEL=3.1416*DSHELL*TSHELL*HSHELL*RHOST
      WTVESS=WTSHEL+WTENDS
      WTTUBE=.7854*(DO**2-DI**2)*RHOST*XLT*XNT
      WTINS=RHOINS*(.7854*(DSHR**2-(DSHELL+2.*TEND)**2)*HSHELL+1.5708*TI
     *NS*DSHR**2)
C     CCST CALCULATIONS USING SIX-TENTHS FACTOR
      ATUBES=3.1416*XLT*XNT*DC
      PMTW=CPMTW/DC
      CMTUBE=WTTUBE*PMTW
      CCTUBE=CMTUBE+23.6163*PFTW*(WTTUBE/47.2326)**.6+1.007*PFTA*(ATUBES
     */2.1343)**.6
      COSTOR=ASTOR*FTK
      CCINS=WTINS*PINS
      ASIDES=3.1416*DSHR*HGTTOT
      WTSIDE=ASIDES*GASIDE*RHOST
      CMSIDE=WTSIDE*PMATS
      CCSIDE=CMSIDE+23.92*FFSSW*(WTSIDE/47.84)**.6+2.5*FFSSA*(ASIDES/5.)
     ***.6
```

```
      ABOTS=.7854*DSHR**2.
      WTBOTS=ABOTS*CABOTS*RHOST
      CMBOTS=WTBOTS*PMATS
      COBOTS=CMBOTS+8.17*FFSBW*(WTBOTS/16.34)**.6+.30595*FFSBA*(ABOTS/.6
     *119)**.6
      ATOPS=ABOTS
      WTTOPS=ATOPS*GATOPS*RHOST
      CMTOPS=WTTOPS*PMATS
      COTOPS=CMTOPS+3.66*FFSTW*(WTTOPS/7.32)**.6+.30595*FFSTA*(ATOPS/.01
     *19)**.6
      CMSHRD=CMSIDE+CMBOTS+CMTOPS
      COSHRD=COSIDE+COBOTS+COTOPS
      CMVESS=WTSHEL*PMVW+WTENDS*PMVE
      COVESS=CMVESS+90.5*FFVW*(WTVESS/181.)**.6+.284*FFVV*(VTOT/.568)**.
     *6
      CMTOT=CMTUBE+CMSHRD+CMVESS+COINS+COSTOR
      COTOT=COTUBE+COSHRD+COVESS+COINS+COSTOR
      COFTES=COTOT-CMTOT
      WTSHRD=WTSIDE+WTTOPS+WTBOTS
      WTTOT=WTVESS+WTTUBE+WTINS+ASTOR+WTSHRD
C     RESISTANCE CALCULATIONS - LATERAL
      FLAREA=0.7854*XNT*DI**2
      RECRIT=2100.*(1.+12.*(DI/CHEL)**0.5)
      CRE=DI/(FLAREA*VISCF)
      CHTC=0.022*THCF*(PRF**.4)/DI
      ATUBEI=3.1416*XNT*DI*XLT/XNE
      CRKTL=6.283*XLT*XNT/XNE
      RINSL=ALOG(DSHR/DSHELL)*XNE/(6.283*THCINS*HSHELL)
C     RESISTANCE CALCULATIONS - AXIAL
      RTUBEA=XLT/(.7854*THCST*XNT*XNE*(DO**2-DI**2))
      RSHELA=HSHELL/(3.1416*XNE*THCST*TSHELL*DSHELL)
      CRKMA=HSHELL/(.7854*XNE*(DSHELL**2-XNT*DO**2))
C     RESISTANCE CALCULATIONS - END
      RTUBEE=TINS/(.7854*THCST*(DOO**2-DIO**2))
      RINSE=TINS/(.7854*THCINS*(DSHR**2-XNT*DO**2))
      RAXE=1./(1./RTUBEE+1./RINSE)
C     MASS CALCULATIONS
      ELM=ASTOR/XNE
      STMM=3.1416*RHOST*(DSHELL*TSHELL*HSHELL+XLT*XNT*((DO**2-DI**2)/4.)/
     1XNE
      STME=STMM+.7854*RHOST*TEND*(DSHELL**2-XNT*DI**2)
  101 FORMAT(2F10.8,F10.2,F10.0,3F10.5)
  102 FORMAT(3F10.6)
  103 FORMAT(4F10.2)
  104 FORMAT(3F10.9,F10.5,F10.9,F10.5)
  105 FORMAT(3F10.2)
  106 FORMAT(///,12X,' SUBROUTINE FLANAL DATA',/)
  107 FORMAT(5X,' SHROUD DIAMETER, M.        ',F10.4)
  108 FORMAT(5X,' VESSEL DIAMETER, M.        ',F10.4)
  109 FORMAT(5X,' TUBE O.D., M.              ',F10.6)
  110 FORMAT(5X,' TUBE I.D., M.              ',F10.6)
  111 FORMAT(5X,' VESSEL HEIGHT, M.          ',F10.4)
  112 FORMAT(5X,' TUBE LENGTH, M.            ',F10.2)
  113 FORMAT(5X,' NO. OF TUBES               ',F10.0)
  114 FORMAT(5X,' INSULATION THICKNESS, M. ',F10.5)
  115 FORMAT(5X,' VESSEL WALL THICKNESS, M.',F10.6)
  116 FORMAT(5X,' VESSEL END THICKNESS, M. ',F10.6)
  117 FORMAT(5X,' THERMKEEP DENS., KG/CU.M.',F10.2)
```

```
118 FCRMAT(5X,' STEEL DENSITY, KG/CU.M.   ',F10.2)
119 FLRMAT(5X,' FLUID DENSITY, KG/CU.M.   ',F10.2)
120 FCRMAT(5X,' TH. COND. INSUL., KW/M-K  ',F10.8)
121 FCRMAT(5X,' TH. COND. STEEL, KW/M-K   ',F10.8)
122 FCRMAT(5X,' TH. COND. FLUID, KW/M-K   ',F10.8)
123 FCRMAT(5X,' FLUID PRANDTL NUMBER      ',F10.5)
124 FCRMAT(5X,' FLUID VISCOSITY, KG/M-SEC',F10.5)
125 FCRMAT(5X,' AMBIENT TEMP., K          ',F10.2)
126 FCRMAT(5X,' SHROUD TEMP..K            ',F10.2)
120 FORMAT(5X,' INITIAL TEMP., K          ',F10.2)
127 FCRMAT(5X,' STEEL SP. HT., KJ/KG-K    ',F10.5)
128 FCRMAT(10X,' ASPECT RATIO NOT MET FCR TUBE LENGTH OF ',F10.2)
132 FCRMAT(5X,' INSUL. DENSITY, KG/CU.M. ',F10.2)
133 FCRMAT(5X,' SYSTEM HEIGHT, M.         ',F10.4)
134 FCRMAT(5X,' SYSTEM WEIGHT, KG.        ',F10.1)
135 FCRMAT(5X,' VESSEL WEIGHT, KG.        ',F10.1)
136 FCRMAT(5X,' WEIGHT OF TUBES, KG.      ',F10.1)
137 FCRMAT(5X,' INSULATION WEIGHT, KG.    ',F10.1)
138 FCRMAT(5X,' OUTLET O.D., M.           ',F10.5)
139 FCRMAT(5X,' OUTLET I.D., M.           ',F10.5)
179 FCRMAT(1H1,' BEGINNING OF DAILY CYCLE',//)
181 FORMAT(' INTERMEDIATE MAP AT CT=T1=',F10.1,' SECS',//)
182 FORMAT(' INTERMEDIATE MAP AT CT=T2=',F10.1,' SECS',//)
183 FORMAT(' INTERMEDIATE MAP AT CT=T3=',F10.1,' SECS',//)
184 FORMAT(' INTERMEDIATE MAP AT CT=T4=',F10.1,' SECS',//)
185 FCRMAT(' INTERMEDIATE MAP AT CT=T5=',F10.1,' SECS',//)
186 FCRMAT(' END-OF-CYCLE SYSTEM MAP AT CT=T6=',F10.1,' SECS',//)
187 FORMAT(' (I)     T(I)          Z(I)          TF(I)          T(I)-F ',//)
188 FCRMAT(1X,I3,1X,F9.2,3X,F9.2,3X,F9.2,3X,F9.2)
189 FCRMAT(1X,I3,1X,F9.2,3X,F9.2)
191 FCRMAT(1X,' TOTAL SYSTEM ENERGY, KJ   ',E15.7,///)
192 FCRMAT(1X,I3,25X,F9.2)
194 FCRMAT(1H1,' STARTING TOTAL ENERGY THIS CYCLE, KJ.   ',E10.5,///)
240 FCRMAT(10X,F10.2,10X,F10.1,10X,F10.5,10X,F10.2,10X,F10.5,10X,F10.2
   ()
250 FCRMAT(T15,'ET',T25,'CHARGE TIME',T45,'STORAGE FLOW',T65,'T-66 OUT
   C',T85,'COLLECTOR FLOW',T105,'RETURN COMBINED TEMP.',/)
601 FCRMAT(/,5X,I1,5X,F10.2,5X,F10.2,5X,E12.4,5X,E12.4,5X,E12.4,5X,I2)
700 FCRMAT(7F10.4)
701 FCRMAT(3F10.7,4F10.4)
702 FCRMAT(6F10.4)
750 FCRMAT(1H1,30X,' COST CALCULATION INPUT DATA',//)
751 FCRMAT(30X,' SHROUD MATERIAL COST, $/KG.             ',F10.4)
752 FCRMAT(30X,' SHROUD SIDE FABRICATION COST, $/SQ.M.   ',F10.4)
753 FCRMAT(30X,' SHROUD SIDE FABRICATION COST, $/KG.     ',F10.4)
754 FCRMAT(30X,' SHROUD TOP FABRICATION COST, $/SQ.M.    ',F10.4)
755 FCRMAT(30X,' SHROUD TOP FABRICATION COST, $/KG.      ',F10.4)
756 FCRMAT(30X,' SHROUD BOTTOM FABRICATION COST, $/SQ.M. ',F10.4)
757 FORMAT(30X,' SHROUD BOTTOM FABRICATION COST, $/KG.   ',F10.4)
758 FCRMAT(30X,' SHROUD TOP THICKNESS, M.                ',F10.7)
759 FORMAT(30X,' SHROUD SIDE THICKNESS, M.               ',F10.7)
760 FCRMAT(30X,' SHROUD BOTTOM THICKNESS, M.             ',F10.7)
761 FCRMAT(30X,' VESSEL WALL MATERIAL COST, $/KG.        ',F10.4)
762 FCRMAT(30X,' VESSEL END MATERIAL COST, $/KG.         ',F10.4)
763 FCRMAT(30X,' VESSEL FABRICATION COST, $/CU.M.        ',F10.4)
764 FCRMAT(30X,' VESSEL FABRICATION COST, $/KG.          ',F10.4)
765 FCRMAT(30X,' TUBE MATERIAL COST, $/KG.               ',F10.4)
766 FCRMAT(30X,' TUBE FABRICATION COST, $/KG.            ',F10.4)
```

E-10

```
767 FORMAT(30X,' TUBE FABRICATION COST, $/SQ.M.            ',F10.4)
768 FORMAT(30X,' STORAGE MATERIAL COST, $/KG.              ',F10.4)
769 FORMAT(30X,' INSULATION COST, $/KG.                    ',F10.4)
770 FORMAT(5X,' ASPECT RATIO, HGT/DIA.       ',F10.4)
771 FORMAT(/,30X,' COST CALCULATION OUTPUT DATA',/)
772 FORMAT(30X,' TUBE MATERIAL COST, $               ',F12.2)
773 FORMAT(30X,' TOTAL TUBE COST, $                  ',F12.2)
774 FORMAT(30X,' STORAGE MATERIAL COST, $            ',F12.2)
775 FORMAT(30X,' INSULATION COST, $                  ',F12.2)
776 FORMAT(30X,' SHROUD SIDE MATERIAL COST, $        ',F12.2)
777 FORMAT(30X,' SHROUD SIDE TOTAL COST, $           ',F12.2)
778 FORMAT(30X,' SHROUD BOTTOM MATERIAL COST, $      ',F12.2)
779 FORMAT(30X,' SHROUD BOTTOM TOTAL COST, $         ',F12.2)
780 FORMAT(30X,' SHROUD TOP MATERIAL COST, $         ',F12.2)
781 FORMAT(30X,' SHROUD TOP TOTAL COST, $            ',F12.2)
782 FORMAT(30X,' SHROUD TOTAL MATERIAL COST, $       ',F12.2)
783 FORMAT(30X,' SHROUD TOTAL COST, $                ',F12.2)
784 FORMAT(30X,' VESSEL MATERIAL COST, $             ',F12.2)
785 FORMAT(30X,' TOTAL MATERIALS COST FOR TES, $     ',F12.2)
786 FORMAT(30X,' TOTAL FABRICATION COST FOR TES, $   ',F12.2)
787 FORMAT(30X,' TES TOTAL COST, $                   ',F12.2)
788 FORMAT(30X,' VESSEL TOTAL COST, $                ',F12.2)
789 FORMAT(/,30X,' FABRICATION COSTS ARE SCALED FROM NOI I TES',/)
790 FORMAT(30X,' TUBE MATERIAL COST COEFFICIENT            ',F10.4)
791 FORMAT(5X,' HELIX DIAMETER, M.          ',F10.6)
    WRITE(6,106)
    WRITE(6,107) DSHR
    WRITE(6,108) DSHELL
    WRITE(6,111) HSHELL
    WRITE(6,109) DO
    WRITE(6,110) DI
    WRITE(6,112) XLT
    WRITE(6,113) XNT
    WRITE(6,791) DHEL
    WRITE(6,114) TINS
    WRITE(6,138) DOD
    WRITE(6,139) DID
    WRITE(6,115) TSHELL
    WRITE(6,116) TEND
    WRITE(6,117) RHOM
    WRITE(6,118) RHOST
    WRITE(6,119) RHOF
    WRITE(6,132) RHOINS
    WRITE(6,120) THCINS
    WRITE(6,121) THCST
    WRITE(6,122) THCF
    WRITE(6,123) FRF
    WRITE(6,124) VISCF
    WRITE(6,125) TAMB
    WRITE(6,129) TSHR
    WRITE(6,126) TINIT
    WRITE(6,127) CPST
    WRITE(6,135) WTVESS
    WRITE(6,136) WTTUBE
    WRITE(6,137) WTINS
    WRITE(6,133) HGTTOT
    WRITE(6,134) WTTOT
    WRITE(6,770) ASPECT
```

```
      IF(J5.EG.1) GC TO 4
      WRITE(6.128) XLT
    4 WRITE(6.750)
      WRITE(6.751) FMATS
      WRITE(6.752) FFSSA
      WRITE(6.753) FFSSW
      WRITE(6.754) FFSTA
      WRITE(6.755) FFSTW
      WRITE(6.756) FFSBA
      WRITE(6.757) FFSBW
      WRITE(6.758) GATOPS
      WRITE(6.759) CASIDE
      WRITE(6.760) GABOTS
      WRITE(6.761) FMVW
      WRITE(6.762) FMVE
      WRITE(6.763) FFVV
      WRITE(6.764) FFVW
      WRITE(6.790) CPMTW
      WRITE(6.765) FMTW
      WRITE(6.766) FFTW
      WRITE(6.767) FFTA
      WRITE(6.768) FTK
      WRITE(6.769) FINS
      WRITE(6.789)
      WRITE(6.771)
      WRITE(6.772) CMTUBE
      WRITE(6.773) COTUBE
      WRITE(6.774) COSTOR
      WRITE(6.775) CDINS
      WRITE(6.776) CMSIDE
      WRITE(6.777) COSIDE
      WRITE(6.778) CMBOTS
      WRITE(6.779) COBOTS
      WRITE(6.780) CMTOPS
      WRITE(6.781) COTOPS
      WRITE(6.782) CMSHRD
      WRITE(6.783) COSHRD
      WRITE(6.784) CMVESS
      WRITE(6.786) COVESS
      WRITE(6.785) CMTOT
      WRITE(6.786) COFTES
      WRITE(6.787) COTOT
C     INITIALIZE TABLE OF ELEMENT ENERGIES AT TINIT
      CALL TKPROP(TINIT,ENEL,FRAC.1.1,J6)
      E=0.
      DC 5 I=1,NE
    6 T(I)=TINIT
      Z(I)=FRAC
      E=E+ENER(I)
    5 CONTINUE
      WRITE(6.194) E
      KI=2
C     DECIDE FLOW OR NO-FLOW
    2 IF(K7.NE.1) GC TO 15
      QFL=0
      GC TO 20
C     CALCULATE INSIDE HEAT TRANSFER COEFFICIENT AND RESISTANCE
   15 RE=WF*CRE
```

```
  450 IF (RE.LT.RECRIT) GO TO 451
  452 HTCI=CHTC*RE**0.8
      GO TO 453
  451 HTCI=3.66*THCF/DI
      REMOD=RE*(DI/CHEL )**0.5
      QX=((REMOD**2)*PRF)**0.25
      ZNU=0.181*QX*(1.-0.839/QX+35.4/QX**2-207./QX**3+419/QX**4)
      HTCI=ZNU*HTCI
  453 RFLI=1./(HTCI*ATUBEI)
C     COMPUTATION OF PUMP REQUIREMENT FOR PUMP EFF=1.0
      PD=.102*FF(RE)*XLT*(WF/FLAREA)**2./(2.*DI*RHOF)
      IF (PD.GT.PDMAX) PDMAX=PD
      POWER=WF*PD/(102.*RHOF)
      IF (POWER.GT.PMAX) PMAX=POWER
      WORK=POWER*DTIME/3600.
      WPUMP=WPUMP+WORK
      IF (WF.GT.WPEAK) WPEAK=WF
   20 CONTINUE
   65 IF (K7.EQ.2) GO TO 130
C     ENERGY CALCULATIONS - COOLING OR NO FLOW
      TF(1)=TL
      DO 50 I=1.NE
      IF (K7.EQ.1) GO TO 21
      IF (Z(I).EQ.0.) RSOLL=0
      IF (Z(I).EQ.0.) GO TO 66
      VSTK=Z(I)*ELM/(RHOM*XNT)
      DSTK=SQRT(1.273*VSTK*XNE/XLT+DO**2)
      RSOLL=ALOG(DSTK/DO)/((THCS(T(I))*CRKTL)
   66 RTOT=RFLI+RTUBEL+RSOLL
      XNTU=1./(RTOT*WF*CPF )
      IF (XNTU.GT.100.) EFF=1.
      IF (XNTU.GT.100.) GO TO 140
      EFF=1.-EXP(-XNTU)
  140 TF(I+1)=TF(I)+EFF*(T(I)-TF(I))
      QFL=WF*CPF*(TF(I)-TF(I+1))
C     DECIDE TOP(71), BOTTOM(72), OR MIDDLE
   21 CONTINUE
      QTOT=QFL
      ENER(I)=ENER(I)+QTOT*DTIME
      CALL TKPROP(T(I),ENER(I),Z(I),1,2,J6)
      GO TO 50
C     BOTTOM ELEMENT CALCULATIONS
   71 RAXLW=1./(2./RTUBEA+2./RSHELA+2./RMA(I))+RAXE
      RAXUP=1./(1./RTUBEA+1./RSHELA+1./((RMA(I)+RMA(I+1))/2.))
      QAXLW=(TAMB-T(I))/RAXLW
      QAXUP=(T(I+1)-T(I))/RAXUP
      QTOT=QAXLW+QAXUP+QFL+QINS
      ENER(I)=ENER(I)+QTOT*DTIME
      CALL TKPROP(T(I),ENER(I),Z(I),2,2,J6)
      QAXLW=-QAXUP
      GO TO 50
C     TOP ELEMENT CALCULATIONS
   72 RAXUP=1./(2./RTUBEA+2./RSHELA+2./RMA(I))+RAXE
      QAXUP=(TAMB-T(I))/RAXUP
      QTOT=QAXLW+QAXUP+QINS+QFL
      ENER(I)=ENER(I)+QTOT*DTIME
      CALL TKPROP(T(I),ENER(I),Z(I),2,2,J6)
   50 CONTINUE
```

```
      GC TO 193
C     ENERGY CALCULATIONS - HEATING
 130  TF(NE+1)=TU
      DO 150 I=1,NE
      J=NE-I+1
      IF(Z(J).EQ.0.) RSOLL=0
      IF(Z(J).EQ.0.) GO TO 170
      VSTK=Z(J)*ELM/(RHOM*XNT)
      DSTK=SQRT(1.273*VSTK*XNE/XLT+DO**2)
      RSOLL=ALOG(DSTK/DO)/(THCS(T(J))*CRKTL)
 170  RTOT=RFLI+RTUBEL+RSOLL
      XNTU=1./(RTOT*WF*CPF)
      IF(XNTU.GT.100.) EFF=1.
      IF(XNTU.GT.100.) GO TO 141
      EFF=1.-EXP(-XNTU)
 141  TF(J)=TF(J+1)+EFF*(T(J)-TF(J+1))
      QFL=WF*CPF*(TF(J+1)-TF(J))
      QTOT=QFL
      ENER(J)=ENER(J)+QTOT*DTIME
      CALL TKPROP(T(J),ENER(J),Z(J),1,2,J6)
      GC TO 150
C     TOP ELEMENT CALCULATIONS
 171  RAXUP=1./(2./RTUBEA+2./RSHELA+2./RMA(J))+RAXE
      RAXLW=1./(1./RTUBEA+1./RSHELA+1./((RMA(J)+RMA(J-1))/2.))
      QAXUP=(TAMB-T(J))/RAXUP
      QAXLW=(T(J-1)-T(J))/RAXLW
      QTOT=QAXUP+QAXLW+QINS+QFL
      ENER(J)=ENER(J)+QTOT*DTIME
      CALL TKPROP(T(J),ENER(J),Z(J),2,2,J6)
      QAXUP=-QAXLW
      GC TO 150
C     BOTTOM ELEMENT CALCULATIONS
 172  RAXLW=1./(2./RTUBEA+2./RSHELA+2./RMA(J))+RAXE
      QAXLW=(TAMB-T(J))/RAXLW
      QTOT=QAXLW+QAXUP+QINS+QFL
      ENER(J)=ENER(J)+QTOT*DTIME
      CALL TKPROP(T(J),ENER(J),Z(J),2,2,J6)
 150  CONTINUE
 193  IF(CT.EQ.T5) GO TO 165
      IF(CT.EG.T6) GO TO 166
      CT1=CT1+DTIME
      IF(CT.GE.T5.AND.CT.LE.T6) CHGTM=(CT-T5)/3600.
      IF(CT1.LT.1800.) GO TO 257
      COMT=(WF*TF(NE+1)+WCOLL*TL)/(WF+WCOLL)
      WRITE(6,240) ET,CHGTM,WF,TF(NE+1),WCOLL,COMT
      CT1=0.
 257  RETURN
 165  WRITE(6,185) T5
      CT1=0.
      GO TO 190
 166  WRITE(6,186) T6
      CHGTM=(T6-T5)/3600.
 190  E=0.
      WRITE(6,187)
      IF(K7.EG.1) GO TO 168
      DO 167 I=1,NE
      TEMPEL=1.8*T(I)-459.67
      WRITE(6,188) I,T(I),Z(I),TF(I),TEMPEL
```

E-14

```
167 E=E+ENER(I)
    LOWEND=NE+1
    WRITE(6,192) LOWEND,TF(NE+1)
    GO TO 180
168 DO 169 I=1,NE
    WRITE(6,189) I,T(I),Z(I)
169 E=E+ENER(I)
180 WRITE(6,191) E
    WRITE(6,240) ET,CHGTM,WF,TF(NE+1),WCOLL,CGMT
    CHGTM=0.
198 RETURN
    END
```

```
      SLBROUTINE TKFROP(TEMF,ENTH,FRAC,M,K2,J6)
C     THIS SUBROUTINE ESTABLISHES TABLES OF ELEMENT ENTHALPY VS. THE
C     FRACTION OF SOLID THERMKEEP AND TEMPERATURE
      COMMON/PROPTK/ELM,CPST,STMM,STME
      DIMENSION EM(14),EE(14),T(14),H(14),Z(14)
  200 FORMAT(I2)
  201 FCRMAT(F10.2,F12.5,F10.6)
  202 FORMAT(1H1,5X,' TABLE OF TEMPERATURE, ENTHALPY, AND SOLID FRACTION
     * OF THERMKEEP',//)
  203 FORMAT(10X,' T(I)',10X,' H(I)',10X,'   Z(I)',/)
  204 FCRMAT(6X,F10.2,5X,F12.5,5X,F10.6)
  205 FORMAT(5X,' ENERGY BEYOND TABLE LIMITS FOR ENTH=',E10.4)
      GO TO(1,2),K2
    1 IF(J6.EQ.2) GO TO 101
      WRITE(6,202)
      READ(5,200) K4
      WRITE(6,203)
  101 J4=K4-1
      J3=1
      DO 11 I=1,K4
      IF(J6.EQ.2) GO TO 102
      READ(5,201) T(I),H(I),Z(I)
  102 CONTINUE
      IF(K2.EQ.2) GO TO 2
      IF(J3.EQ.2) GO TO 10
      IF(T(I).LT.TEMP) GO TO 10
      ENTH=ELM*(H(I-1)+(TEMP-T(I-1))*(H(I)-H(I-1))/(T(I)-T(I-1)))
      FRAC=Z(I)+(TEMP-T(I-1))*(Z(I)-Z(I-1))/(T(I)-T(I-1))
      J3=2
   10 EM(I)=ELM*H(I)+STMM*CPST*T(I)
      EE(I)=ELM*H(I)+STME*CPST*T(I)
      IF(J6.EQ.2) GO TO 11
      WRITE(6,204) T(I),H(I),Z(I)
   11 CONTINUE
      RETURN
    2 GO TO(3,4),M
    3 IF(ENTH.GT.EM(K4).OR.ENTH.LT.EM(1)) GO TO 250
      DO 5 I=1,J4
      IF(ENTH.GT.EM(I+1)) GO TO 5
      TEMP=T(I)+(T(I+1)-T(I))*(ENTH-EM(I))/(EM(I+1)-EM(I))
      FRAC=Z(I)+(Z(I+1)-Z(I))*(ENTH-EM(I))/(EM(I+1)-EM(I))
      RETURN
    5 CONTINUE
      GO TO 250
    4 IF(ENTH.GT.EE(K4).OR.ENTH.LT.EE(1)) GO TO 250
      DO 6 I=1,J4
      IF(ENTH.GT.EE(I+1)) GO TO 6
      TEMP=T(I)+(T(I+1)-T(I))*(ENTH-EE(I))/(EE(I+1)-EE(I))
      FRAC=Z(I)+(Z(I+1)-Z(I))*(ENTH-EE(I))/(EE(I+1)-EE(I))
      RETURN
    6 CONTINUE
  250 WRITE(6,205) ENTH
      RETURN
      END
```

E-16

```
      FUNCTION THCS(T)
C     THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY OF SOLID THERMKEEP
C     AT 250F. IT IS NOW A DUMMY FUNCTION WITH A CONSTANT VALUE
C     IN KJ/M-SEC-K
      THCS=1.0800E-3
      RETURN
      END
```

```
      FUNCTION THCL(T)
C     THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY OF LIQUID THRMKEEP
C     AT 750F. IT IS NOW A DUMMY FUNCTION WITH A CONSTANT VALUE
C     IN KJ/M-SEC-K
      THCL=1.0207E-3
      RETURN
      END
```

```
      FUNCTION FF(R)
C     THIS FUNCTION COMPUTES THE CIRCULAR TUBE FRICTION FACTOR FOR
C     ROUGHNESS RATIO OF .00012
      IF(R.GT.2000.) GO TO 1
      FF=64./R
      RETURN
    1 IF(R.GT.500000.) GO TO 2
      FF=.3387*R**(-.2549)
      RETURN
    2 FF=0.0124
      RETURN
      END
```

A P P E N D I X   F

REFERENCES

1. Perdue, Donald G. and Larry H. Gordon,
   "Engineering Evaluation of a Sodium Hydroxide
   Thermal Energy Storage Module," DOE/NASA/1034-80/7,
   NASA TM-81417, February 1980.

2. Mellor, Comprehensive Treatise on Inorganic and
   Theoretical Chemistry, Vol. II, Sup. II, Page 1250.

3. Private communication from T. D. Harrison,
   Sandia Laboratories, Albuquerque, N.M.

4. Harrison, Thomas D. and William H. McCulloch,
   "Midtemperature Solar Systems Test Facility (MSSTF)
   System Test Results, Winter Season," presented at
   ISES Congress, Atlanta, GA, May 1979.

5. Cohen, Barry M., Richard E. Rice, and Peter E. Rowny,
   "Development of a Phase-Change Thermal Storage System
   Using Modified Anhydrous Sodium Hydroxide for Solar
   Electric Power Generation," DOE/NASA/0615-79/1, NASA
   CR-159465, December 1978.

1 Report No NASA CR-165206	2 Government Accession No	3 Recipient's Catalog No
4 Title and Subtitle EXTENDED DEVELOPMENT OF A SODIUM HYDROXIDE THERMAL ENERGY STORAGE MODULE		5 Report Date September 1980
		6 Performing Organization Code 776-71-43
7 Author(s) Richard E Rice, Peter E. Rowny, and Barry M. Cohen (consultant)		8 Performing Organization Report No
		10 Work Unit No
9 Performing Organization Name and Address Comstock & Wescott, Inc. 765 Concord Avenue Cambridge, MA 02238		
		11 Contract or Grant No DEN 3-138
		13 Type of Report and Period Covered Contractor Report
12 Sponsoring Agency Name and Address U.S. Department of Energy Division of Energy Storage Systems Washington, D.C. 20545		
		14 Sponsoring Agency Code Report No. DOE/NASA/0138-1

15 Supplementary Notes
Final Report. Prepared under Interagency Agreement De-AI01-77ET26945, formerly EC-77-A-31-1034 Project Manager, L. H. Gordon, Wind and Stationary Power Division, NASA Lewis Research Center, Cleveland, Ohio 44135.

16 Abstract
The program completed the development of a sodium hydroxide (Thermkeep) thermal energy storage module for use in solar electric power generation. Design, fabrication and testing of this single heat exchanger module were reported under Contract NAS3-20615 in NASA Report CR-159465. This follow-on activity completed the post-test analysis of the thermal storage module and the verification of the module performance (experimental/analytical) using an alternate heat transfer fluid, Caloria HT-43. Using the previous results, a design analysis of an advanced heat exchange concept was made. A computer model and a reference design for a dual heat exchanger system (storage working fluid/power cycle working fluid) within the storage module were completed. This advanced system was estimated to have a capital cost of approximately one half of the previously developed single heat exchange concept.

17 Key Words (Suggested by Author(s)) Thermal storage Energy storage Sodium hydroxide Phase change	18 Distribution Statement Unclassified – unlimited STAR Category 44 DOE Category UC-94a		
19 Security Classif (of this report) Unclassified	20 Security Classif (of this page) Unclassified	21 No of Pages	22 Price*

End of Document