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TECHNICAL REPORT
NATICK/TR-95/012

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THERMAL OPTIMIZATION OF FLAMELESS RATION HEATERS

By
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December 1994

FINAL REPORT
June 1990 - August 1990

Approved for Public Release; Distribution Unlimited

UNITED STATES ARMY
RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1994	Final June 1990 to August 1990

4. TITLE AND SUBTITLE

THERMAL OPTIMIZATION OF FLAMELESS RATION HEATERS

5. FUNDING NUMBERS

Contract No.
DAAL03-86-D-6002

Delivery No.
#1979

6. AUTHOR(S)

Satish G. Kandlikar

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Natick RD&E Center
ATTN: SATNC-WEA
Natick, MA 01760

8. PERFORMING ORGANIZATION REPORT NUMBER

NATICK/TR-95/012

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A thermal simulation program utilizing finite difference technique is developed to analyze the transient heat transfer problem of heating the Meals-Ready-to Eat (MREs) using Flameless Ration Heaters. The simulation program is employed in evaluating the effects of changing various parameters on the thermal performance. It is suggested that the results from the program be checked with experiments conducted under controlled conditions in which the heater heat generation rate and the temperature profile in the food are carefully monitored under different operating conditions.

14. SUBJECT TERMS

THERMAL ANALYSIS
HEAT TRANSFER
FLAMELESS
MRE (MEAL, READY-TO-EAT)
FLAMELESS RATION HEATER (FRH)
COMPUTER PROGRAMS
FLAMELESS BURNERS
HEATING
HOT MEALS
SELF HEATING
RATIONS

15. NUMBER OF PAGES 54

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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PREFACE

The work reported in this report was performed by Satish G. Kandlikar from June 1990 to August 1990, at the US Army Natick RD&E Center (Natick) under a six week Summer Faculty Research and Engineering Program (Contract DAA103-86-d-0001). The work was sponsored by Mr. Il-Young Kim at the Sustainability Directorate (SusD) at Natick.

ACKNOWLEDGMENTS

The author acknowledges the support and facilities provided by Il-Young Kim for conducting the research reported in this report. The guidance and direction provided by Irwin Taub have played a major role in the successful completion of the project, and are gratefully acknowledged. Special thanks are due to Don Pickard for providing the technical information and sharing his experience on the Flameless Ration Heaters. Finally, the author wishes to acknowledge the prompt and expert support provided by Bob Trottier in conducting the experiments.

NOMENCLATURE

A - surface area in contact between the heater and the food pouch

c_p - specific heat , J/kg-K

i - node number

j - i + 1 node number

k - thermal conductivity, W/m-°C

n - time step number

$R_{i,j}$ - thermal resistance between nodes i and j, °C

T - temperature, °C

Δt - time step, sec

w - thickness, m

SUMMARY

A thermal simulation program utilizing finite difference technique was developed to analyze the transient heat transfer problem of heating the Meals-Ready-to-Eat (MRE's) using Flameless Ration Heaters (FRH). The simulation program was employed in evaluating the effect of changing various parameters on the thermal performance. The results indicate that the heating time could be further reduced by increasing the heater area in contact with the food pouch, and by improving the carton insulation. It is suggested that the results for the optimized geometry be checked with experiments conducted under controlled conditions in which the heater heat generation rate and the temperature profile in the food are carefully monitored under different operating conditions. Based on the experience of the theoretical simulation and experimental work, the scope for future work has been outlined.

THERMAL OPTIMIZATION OF FLAMELESS RATION HEATERS

1. INTRODUCTION

The Flameless Ration Heater (FRH) is used by soldiers for heating the Meals-Ready-to-Eat (MRE) packaged in a plastic pouch. The FRH consists of a heating pad which is activated by water to start a controlled oxidation reaction of Magnesium. The specification and composition of heater element is as follows:

Weight:	20 gms.
Size:	11.4 cm x 8.9 cm x 0.3 cm thick (4.5" x 3.5" x 0.12" thick)
Composition:	Mg powder - 40% Fe powder - 10% Salt (NaCl) - 3% Other materials - 47% (Includes binder, wetting agent, fumed silica and other inert materials)

Amount of Water Required to Activate - 56 gms. (2 ozs.)

With the specified amount of water, the FRH generates 123.4 kJ (117 BTU) of thermal energy. The heat released during the reaction is utilized in heating the MRE pouch. The technical characteristics of the heater related to its thermal performance are as follows:

* Flameless Ration Heater should raise the temperature of a 227 gms (8 ozs.) packet of unfrozen Meals-Ready-to-Eat by 44.4 °C (80 °F) in less than 20 minutes (preferably 10 mins or less).

* Flameless Ration Heater should be able to perform as stated above over an ambient temperature range from -32 °C to 43 °C (-25 °F to 110 °F).

The present work is aimed toward simulating the thermal performance of the heating process and evaluating the effect of varying different parameters on the performance.

2. OBJECTIVES OF PRESENT WORK

The objectives of the present work are as follows:

a) Develop a computer program to simulate the thermal performance of the Flameless Ration Heater during the heating process.

b) Conduct experiments to obtain the thermal performance of the heating process under controlled conditions to verify the computer model predictions and identify any significant departures from the assumed system behavior.

c) Identify the system parameters which have the greatest influence on the heat transfer performance of the heater. Conduct a parametric investigation using the simulation program to study the effect of varying these parameters for optimizing the performance of the heating process.

The work undertaken here will be helpful in optimizing the thermal performance of the heater. The understanding of the heating process will be useful in the design of heaters for other applications such as heaters for individual tray packs.

3. THEORETICAL ANALYSIS

3.1 Assumptions

A schematic of the Flameless Ration Heater with a food pouch (Meal-Ready-to-Eat) is shown in Fig. 1a. The transient heat conduction problem is analyzed with the following assumptions:

a) The heat transfer through the food pouch is one-dimensional.

b) The heat generation in the heater starts as a result of a chemical reaction which is initiated after a certain time delay after adding the water to the heater bag. The heater surface temperature is assumed to reach a specified temperature after the reaction is initiated.

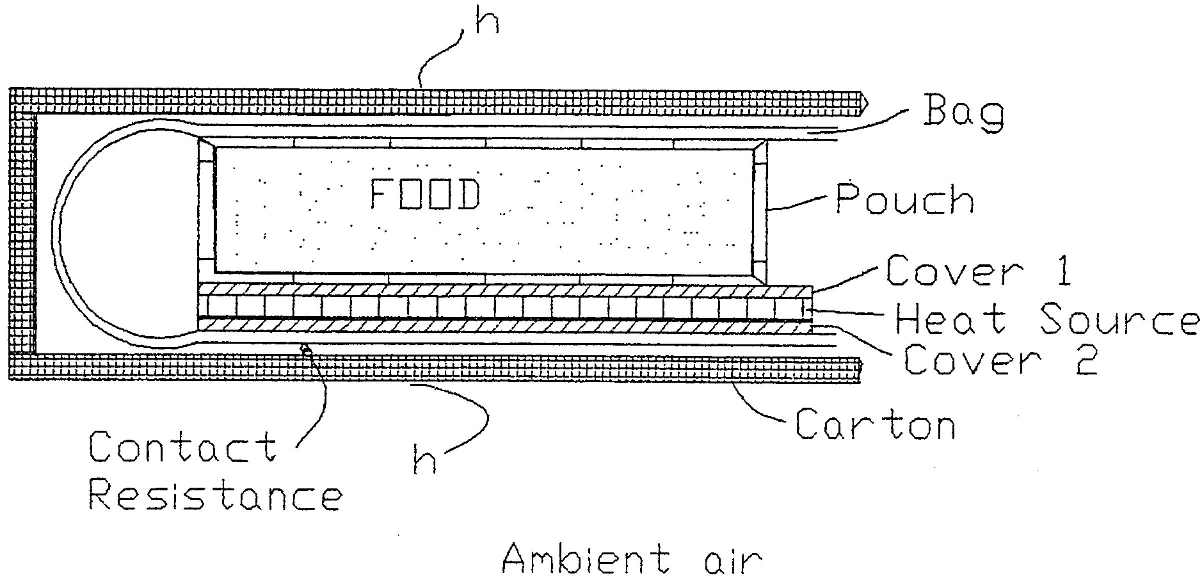
c) The heat generated in the heater is assumed to be conducted away from both sides of the heater.

d) The contact resistances between the food pouch and the heater cover, and between the heater pad and the cover are assumed to be negligible due to the presence of water.

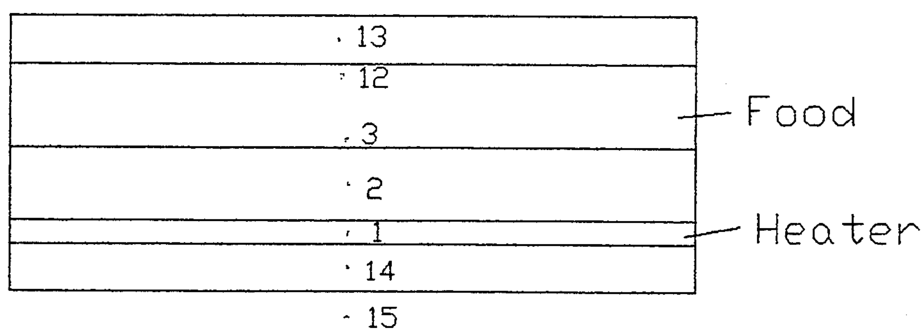
The above assumptions were made on the basis of the information available at the beginning of the project. The validity of these assumptions was checked by conducting experiments discussed in Section 5.

3.2 Finite Difference Formulation

The transient heat conduction problem is solved by a one-dimensional finite difference formulation. The location of the nodes are shown in Fig. 1b. The food pouch was divided into ten nodes, and the thermal resistances between the heater and the pouch,



(a)



(b)

Figure 1. a) Schematic of a Flameless Ration Heater with MRE pouch.

b) Location of nodes in the heater assembly for finite difference analysis

heater and the surroundings and the pouch and the surroundings were lumped into three individual nodes.

The Crank-Nicholson formulation (Burden et al., 1980) is employed to obtain the following finite difference equations.

Internal nodes: i=2-12, time step n to n+1

$$m_i\, c_{p,i}\, (T_i^{n+1} - T_i^n) = \{(1/R_{i,(i-1)})[(T_{i-1}^{n+1} - T_i^{n+1}) + (T_{i-1}^{n} - T_i^n)]/2$$

$$+ (1/R_{i,(i+1)})[(T_{i+1}^{n+1} - T_i^{n+1}) + (T_{i+1}^{n} - T_i^n)]/2\}\ \Delta t \tag{1}$$

Node 13

$$m_{13}\, c_{p,13}\, (T_{13}^{n+1} - T_{13}^n) = \{(1/R_{13,1})[(T_1^{n+1} - T_{13}^{n+1}) + (T_1^{n} - T_{13}^n)]/2$$

$$+ (1/R_{13,15})[(T_{15}^{n+1} - T_{13}^{n+1}) + (T_{15}^{n} - T_{14}^n)]/2\}\ \Delta t \tag{2}$$

Node 14

$$m_{14}\, c_{p,14}\, (T_{14}^{n+1} - T_{14}^n) = \{(1/R_{14,1})[(T_1^{n+1} - T_{14}^{n+1}) + (T_1^{n} - T_{14}^n)]/2$$

$$+ (1/R_{14,15})[(T_{15}^{n+1} - T_{14}^{n+1}) + (T_{15}^{n} - T_{14}^n)]/2\}\ \Delta t \tag{3}$$

where $R_{i,j}$ is the thermal resistance between the nodes i and j and is given by

$$R_{i,j} = w_{ij} / (A_{ij} k_{ij})$$

w_{ij} - distance between nodes i and j
A_{ij} - Surface area for heat transfer between nodes i and j
k_{ij} - Equivalent thermal conductivity between nodes i and j

The above formulation yields equations which are average of the forward and backward difference equations. This Crank-Nicholson formulation provides guaranteed convergence, as well as having faster convergence characteristics.

The temperatures of all nodes are assumed to be at the specified room temperature until the time instant when the reaction starts, and the heater temperature rises to T_1. Equations (1)-(3) are then applied for every time step from that instant on until the end of the heating period.

At every time step n+1, the 14 equations for the 14 nodes have to be solved simultaneously. To enable the computations on Personal Computer, a Gauss-Seidel iterative method is employed for solving the simultaneous equations.

The average food temperature at any time instant is then calculated by finding the average temperature of the heated and the unheated portions of food.

4. COMPUTER PROGRAM

A computer program, PROGRAM HEATR1 is developed to implement the finite difference scheme described in Section 3. The program allows the user to input the information on the food and material properties, initial temperatures, heater temperature, time step, and heat transfer surface area through an input file, INPUT.DAT. The program has the following features:

* Documentation at every major step in the program to facilitate the incorporation of any subsequent changes.

* Nomenclature within the program code for easy reference.

* Structured for future expansion.

A copy of the program and the sample input data file are included in Appendixes A and B, respectively, A sample output file is given in Appendix C. Appendix D contains a user's manual illustrating the use of the computer program.

5. EXPERIMENTAL INVESTIGATION

An experimental investigation is undertaken for the following three reasons:

a) To obtain data for validating the numerical model described in sections 3 and 4.

b) To study the heating process and observe any clues which might be helpful in improving the numerical model.

c) To gain a practical, hands-on experience of the entire heating process to identify any aspects where improvements could be made.

For the experiments, a food pouch (MRE) was selected instead of pouches filled with water since the water pouches do not simulate the actual heating process because of a significant amount of convection occurring in them.

The thermocouples used for the heating process were specially prepared by applying a thin coating of epoxy on the exposed surface near the thermocouple junction. Care was taken as to form only a thin layer so as not to affect the transient response of the thermocouples.

The thermocouples were placed at the following locations:

i) On the two sides of the heater element between the pad and the cover.

ii) Two thermocouples between the heater cover and the food pouch.

iii) Two thermocouples on the opposite side of the food pouch.

iv) One thermocouple inside the food pouch for the specially prepared food pouches.

v) One thermocouple on the outer surface of the carton.

The output from the thermocouples was connected to a data recorder (DATASTRIP III) which was set to scan all the output channels every 20 seconds.

The experimental procedure followed is given in Appendix E.

The time-temperature data obtained by the data recorder is then used for further analysis and comparison with the numerical scheme.

Seven tests were conducted and the results and discussion are presented in the next section.

6. RESULTS AND DISCUSSION

6.1 Sensitivity Analysis

A sensitivity analysis was performed using the numerical model described in Sections 3 and 4. The purpose of the analysis is to identify the major system variables which have the greatest influence on the thermal performance of the heater. The following parameters enter directly in the performance calculations, and are varied over a wide range to study their influence.

i) Thermal resistance of the cover pad on the heater

ii) Thermal resistance of the heat loss paths to the atmosphere

iii) Ambient temperature

iv) Surface area of the food pouch for heat transfer

The effects of varying each of the parameter is evaluated through the thermal simulation program. The base conditions for the simulation program were:

Food material: Chili, 8 ozs.

Thermal properties of food: $k = 0.5381$ W/m-^{o}C,

Water content 65 %

Thermal diffusivity = 1.533×10^{-3}

Ambient temperature and Initial temperature of food:

30 ^{o}C and 5 ^{o}C.

Delay time for starting the reaction after addition of water:

1 minute for $T_{initial} = 30$ ^{o}C

3 minutes for $T_{initial} = 5$ ^{o}C

Heater pad surface temperature after the start of reaction:

95 ^{o}C for $T_{initial} = 30$ ^{o}C

100 ^{o}C for $T_{initial} = 5$ ^{o}C

Surface area for heat transfer:

Heater pad surface area on one side plus 15% of that area to account for diffusion of heat along the length of the food pouch.

Heat transfer coefficient between the carton and surrounding air: 10 W/m^{2}-^{o}C

i) Thermal resistance of the cover pad

The thermal resistance of the cover pad is the only thermal resistance between the heater and the food pouch. When the cover pad is wet, its thermal resistance decreases considerably due to the presence of water. Figure 2 shows the predictions for the average temperature of the food after mixing as a function of time after starting the heating process (assuming the heating process is terminated at that time).

The two curves drawn show the effect of varying the thickness of the heater cover by a factor of 4. Solid curve shows the performance with a pad thickness of 120 microns which is currently employed. Dashed curve represents the performance with a heater pad thickness of 480 microns. The two curves are very close to each other, and it can be concluded that the heater pad thermal resistance has very little influence on the thermal performance. The thickness of the heater pad will be governed by strength and cost considerations.

ii) Thermal resistance of heat loss path to the surroundings

The heat loss to the surroundings occurs by convective heat loss from the carton to the surrounding air by natural convection. The heat loss by this mode was calculated to be a total of 18.2 kJ from both sides of the heater . This compares to approximately 40 kJ of energy needed to heat the food from 30 °C to 70 °C, and a total of approximately 130 kJ released by the heating process over a 20 minute time period. The heat losses increase to 24.4 kJ when the ambient temperature is 5 °C.

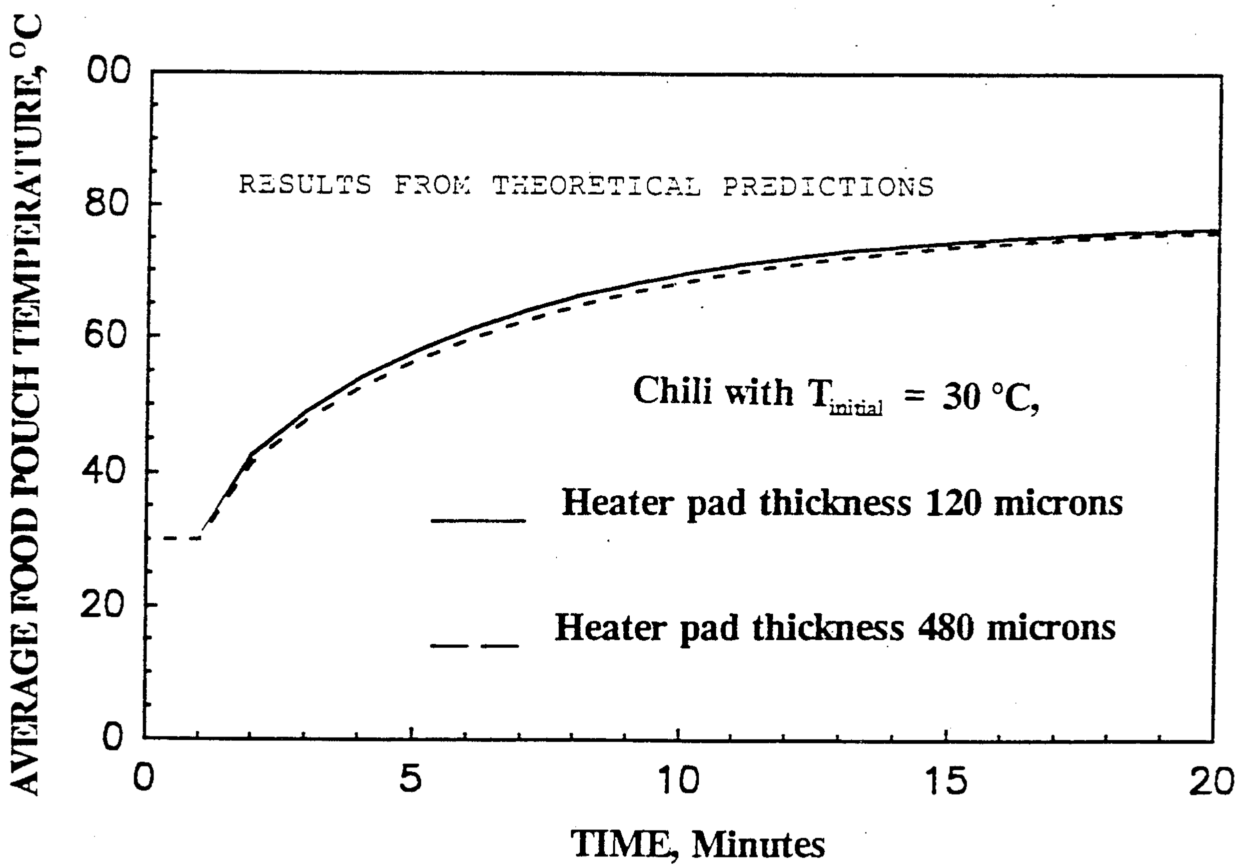


Figure 2. Effect of heater pad thickness on the heating performance

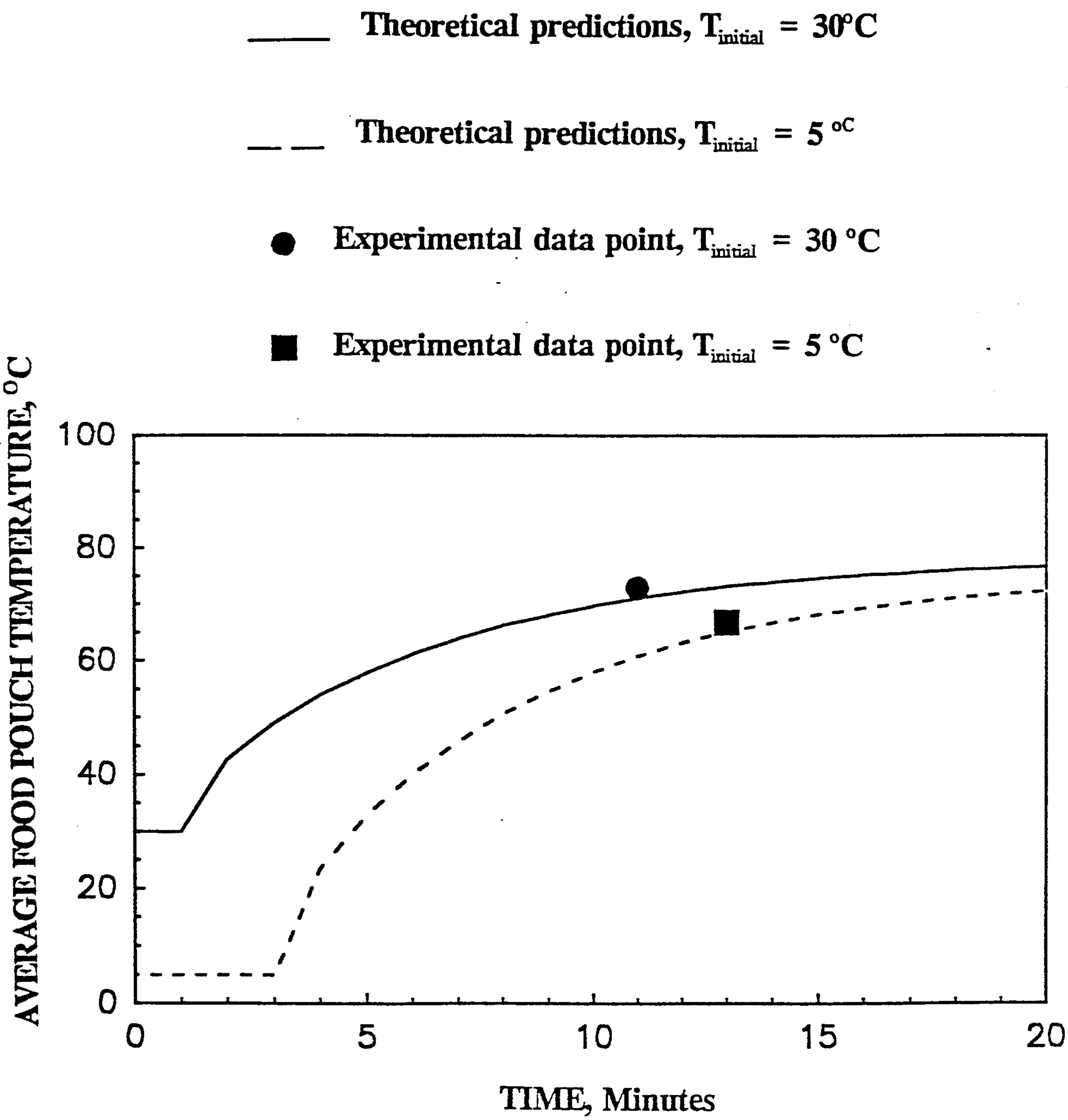


Figure 3. Effect of initial temperature on the thermal performance

There are three resistances in the thermal path for the heat losses to the surroundings. These are a) the thermal resistance of the carton, ($R=1.1x10^{-3}$ $^{O}C/W$), b) the thermal resistance of the polyethylene bag, ($R=7.3x10^{-5}$ $^{O}C/W$) and c) the thermal resistance due to convective heat transfer between the carton and the surrounding air ($R=0.1$ $^{O}C/W$). It is seen that the parameters, which are under the designer's control, such as the thickness of the carton or the thickness of the bag, have very little influence on the performance.

In order to conserve energy so that a smaller heater could be utilized, it is essential to reduce the heat losses significantly. This can be done by insulating the carton. The cost benefit of this effect should be further evaluated in light of the additional weight and volume introduced by increasing the carton insulation. The carton insulation is expected to be a major parameter in the overall system optimization.

iii) Ambient Temperature

The effect of lowering ambient temperature is seen in three different ways. Firstly, the initial temperature of the food and the heater is same as the ambient temperature, and a greater amount of thermal energy will be needed to reach the same final temperature. Secondly, the heat losses from the assembly would increase with a decrease in ambient temperature. Finally, the lower initial temperature would provide a greater temperature difference between the heater and the food since the heater surface temperature is assumed to be close to 100 °C irrespective of the initial temperature. This will make the heating process more efficient, and the thermal energy will be transferred faster into the food pouch. This model assumes that enough thermal energy is released by the heater during the heating process to maintain the increased heat transfer rate while heating the food with a lower initial temperature.

The initial waiting time before the start of the reaction is assumed to be 1 minute for $T_{initial}=30$ ^{O}C, and 3 minutes for $T_{initial}=5$ ^{O}C. Also, the heater surface temperature is assumed to be 95 ^{O}C and 100 ^{O}C respectively for $T_{initial}$ of 30 ^{O}C and 5 ^{O}C respectively.

Figure 3 shows the average temperature of food as a function of different heating periods for two different initial temperatures. At the end of a 10 minute heating period, the average food temperature with $T_{initial} = 30\ ^{o}C$ is 72.8 ^{o}C, while it is 63.1 with $T_{initial} = 5\ ^{o}C$. The corresponding values at the end of 20 minute time period are 80.2 and 73.1, respectively. The temperature rise is thus seen to be faster with a lower initial temperature.

iv) Surface area of the food pouch for heat transfer

The heat transfer rate from the heater to the food pouch is directly proportional to the surface area available for heat transfer. However, since the model is based on a one-dimensional analysis, the heat transfer in the plane of the food pouch near the edges of the heater surface will provide an additional effective area. To account for this area, a factor of 1.15 is employed to represent an effective area for heat transfer. This factor was based on comparison of the theoretical predictions with the experiment. Further discussion on this aspect is presented while discussing the experimental results.

6.2 Experimental Results

The theoretical development presented in Sections 3 and 4 was primarily based on the information available at the time model was developed. The assumptions made in the model therefore need to be verified in order to validate the model and gain an insight into the physics of the heating process.

Two sets of experiments were performed in which the time temperature history and the average bulk temperature at the end of a certain heating time were recorded.

Figure 3 shows the average food temperature as a function of heating time. Solid curve represents the theoretical performance as predicted by the computer program for $T_{initial} = 30\ ^{o}C$. The filled circle represents the experimental data point which was obtained at the end of a 10 minute heating cycle. It can be seen that the experimental point lies close to the theoretical prediction. The dashed curve represents the theoretical

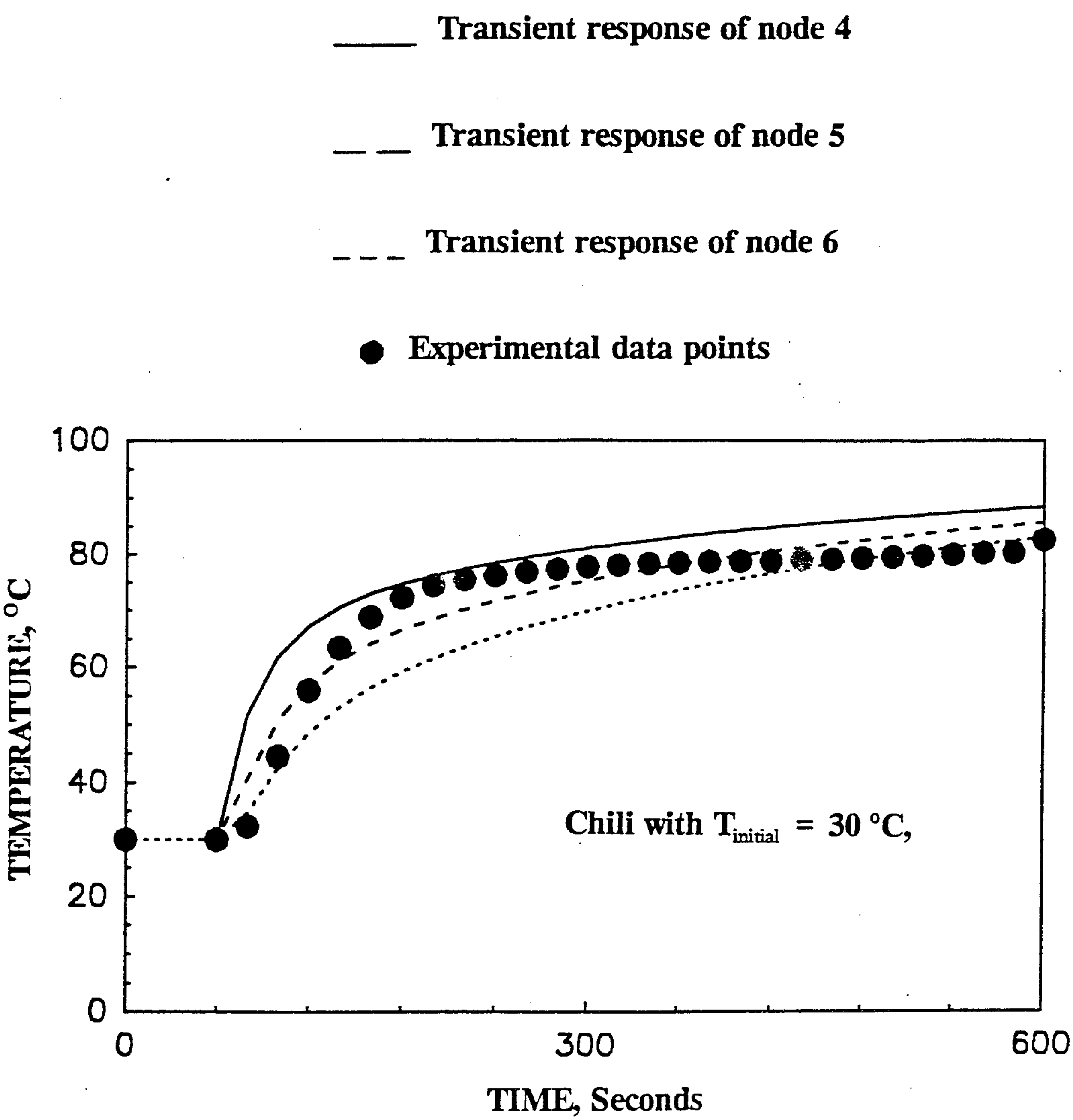


Figure 4. Comparison of transient thermal characteristics of food with theoretical model predictions.

performance for $T_{initial} = 5$ °C. Also shown is an experimental point, filled square, for this case. In case of $T_{initial} = 5$ °C, the model in general tended to predict a lower performance than the experimental values; the main reason being a significant amount of steam generation for the case of $T_{initial}$ = 30 °C, which was not accounted by the model. Further discussion on this aspect is included in Section 6.3.

Figure 4 shows the results of an experiment with the temperature within the food pouch plotted as a function of time. The corresponding plot obtained from the theoretical model is shown in Fig. 4. The agreement between the experiment and theory is reasonable, and further fine-tuning in the thermal model is necessary to improve the agreement. This work could not be undertaken due to a limited time of six weeks available to perform the entire work.

6.3 Observations on the Mechanics of the Heating Process

The following observations were made during the heating process:

i) The heater surface temperature jumped in a very short time from the ambient temperature to about 95-100 °C.

ii) The heater surface temperature after the initiation of reaction was independent of the initial food pouch temperature.

iii) The initiation of the heater reaction was delayed from about 1 minute to approximately 3 minutes when the initial temperature of the food and the water were lowered from 30 °C to 5 °C.

iv) The reaction was initiated and sustained at a higher value of heat generation rate when the $T_{initial}$ was 5 °C, with the heater surface temperature maintained at 100 °C (as against 95 °C for $T_{initial} = 30$ °C). A possible explanation for this may be that with the lower heater temperature, the heater had a longer time to get soaked, and a larger amount of magnesium was able to participate in the reaction.

v) A considerable amount of steam was generated and the heat-transfer process was no longer restricted through the interface between the heater and the food pouch. The steam flowed through the bag and condensed during its passage as it came in contact with the colder parts of the food pouch above the heater. Steam also was seen to condense in the portion of the bag which was wrapped around the food pouch. The heat transfer coefficient with condensing steam being very high, the actual heating process in all experiments was found to be more efficient than the theoretical predictions based on the interface area alone for heat transfer. This fact needs to be further quantified and considered while designing heating systems for other configurations.

7. CONCLUSIONS

A numerical model is developed to predict the transient thermal performance of Flameless Ration Heaters. The model predicts the temperature at various locations in the food as well as the average temperature of the food at the end of a given time period. Experiments were conducted to validate the theoretical model. Good agreement was observed between the theoretical predictions and the experimental values.An additional heat transfer mechanism was observed during the experimentation. When the initial temperature of the heater and the water was lowered to 5°C, the heater reaction was initiated after 3 minutes and a rapid steam generation was observed. This behavior was initiated after 3 minutes and a rapid steam generation was observed. This behavior was not expected on the basis of information available on the heaters. Since the heat transfer mechanism is altered significantly, the simulation model needs to modified further. Additionally, the rate of heat generation in the heater as a function of time needs to be determined accurately.

8. SCOPE FOR FUTURE WORK

The work performed on the simulation and experimentation on the Flameless Ration Heaters provided valuable information in understanding the basic mechanisms of heat transfer involved in heating an MRE. The knowledge gained can be utilized in further refining the model and optimizing its performance. Also, the model provides helpful directions in designing the FRH based systems for heating other configurations such as individual meal trays.

Specifically, the following work may be undertaken in future.

i) The theoretical model developed in the present work could be modified to account for the steam generation and additional heat transfer resulting from the contact of the steam and hydrogen gas with additional surfaces of MRE pouch.

ii) The experience and knowledge gained in this project through the theoretical and experimental work on the Flameless Ration Heaters could be extended to develop efficient heating system design for other configurations including Individual Meal Trays and Tray Packs.

iii) The experimental procedure followed here could be further refined to arrive at a standardized testing procedure for conducting quick and accurate quality control checks on the Flameless Ration Heaters.

This document reports research undertaken at the U.S. Army Natick Research, Development and Engineering Center and has been assigned No. NATICK/TR-95/012 in the series of reports approved for publication.

9. REFERENCES

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APPENDICES

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APPENDIX A

COMPUTER PROGRAM

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      PROGRAM HEATER
C THIS PROGRAM SIMULATES THE PERFORMANCE OF THE MRE HEATER
C THE WORK IS PERFORMED BY DR. SATISH G. KANDLIKAR FOR THE
C US ARMY LABORATORY AT NATICK, MA, DURING SUMMER 1990.
C
C NOMENCLATURE
C
C BH - WIDTH OF THE HEATER, M
C BF - WIDTH OF THE FOOD BLOCK IN THE POUCH, M
C CH - LENGTH OF THE HEATER, M
C CF - LENGTH OF THE FOOD BLOCK IN THE POUCH, M
C CPB - SPECIFIC HEAT OF BAG MATERIAL, J/KG-K
C CPC - SPECIFIC HEAT OF COVER MATERIAL, J/KG-K
C CPF - SPECIFIC HEAT OF FOOD. J/KG-K
C CPH - SPECIFIC HEAT OF HEATER, J/KG-K
C CPP - SPECIFIC HEAT OF POUCH MATERIAL, J/KG-K
C CPW - SPECIFIC HEAT OF WATER, J/KG-K
C
C CP(25) - SPECIFIC HEAT OF MATERIAL AT THE INDIVIDUAL NODES, J/KG-K
C HAMB - HEAT TRANSFER COEFFICIENT ON THE CARTON SURFACES EXPOSED TO
C        AMBIENT AIR, W/M**2-C
C HFG - LATENT HEAT OF STEAM, J/KG
C K(25) - THERMAL CONDUCTIVITY OF MATERIAL AT THE INDIVIDUAL NODES,
C        W/M-C
C KB - THERMAL CONDUCTIVITY OF BAG MATERIAL, W/M-C
C KC - THERMAL CONDUCTIVITY OF COVER MATERIAL, W/M-C
C KF - THERMAL CONDUCTIVITY OF FOOD, W/M-C
C KH - THERMAL CONDUCTIVITY OF HEATER MATERIAL, W/M-C
C KP - THERMAL CONDUCTIVITY OF POUCH MATERIAL, W/M-C
C KPW - THERMAL CONDUCTIVITY OF WATER, W/M-C
C
C MS - AMOUNT OF STEAM GENERATED, KG
C MASS(25) - MASS PER UNIT AREA AT DIFFERENT NODES, KG/M**2
C N - NUMBER OF NODES IN THE FOOD
C QGEN - HEAT GENERATION RATE, W/M**3
C R(25,2) - CONTACT RESISTANCE ON THE TWO SIDES OF A NODE, C/W
C          R(N,1) RESISTANCE BETWEEN THE NODE AND ADJACENT LOWER
C                 NUMBERED NODE
C          R(N,2) CONTACT RESISTANCE BETWEEN THE NODE AND ADJACENT
C                 HIGHER NUMBERED NODE
C RHO(25) - DENSITY OF MATERIAL AT THE INDIVIDUAL NODES, KG/M**3
C RHB - DENSITY OF BAG MATERIAL, KG/M**3
C RHC - DENSITY OF COVER MATERIAL, KG/M**3
C RHH - DENSITY OF HEATER, KG/M**3
C RHP - DENSITY OF POUCH MATERIAL, KG/M**3
C RHF - DENSITY OF FOOD, KG/M**3
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C RHW  - DENSITY   OF  WATER,   KG/M**3
C T(25,600)    - TEMPERATURE    AT  50  NODES   AT  600  TIME   STEPS
C TAMB   - AMBIENT   TEMPERATURE,     C
C TSTART   - TIME   ELAPSED   BEFORE   THE   HEATER   REACTION   IS  INITIATED,    SEC
C TSTEP   - TIME   STEP,   SEC
C W(25)   - WIDTH   OF  INDIVIDUAL   NODES,   M
C WB  - THICKNESS   OF  BAG,   M
C WC  - THICKNESS   OF  COVER,   M
C WH  - THICKNESS   F  HEATER,   M
C WP  - THICKNESS   OF  POUCH,   M
C WF  - THICKNESS   OF  FOOD,   M
C WG  - THICKNESS   OF  WATER   GAP,   M
C
C CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
        REAL  K,  MS,  KC,  KH,  KP,  KF,  KG,  MASS
        CHARACTER*1     RES
        DIMENSION    CP(25),   D(25,2),    K(25),    R(25),    RHO(25),
     1              TOLD(25),    TNEW(25),    TNEWPR(25),     W(25),    MASS(25),
     2  TAVE(30)
        COMMON/PAR/BH,      BF,  CPB,   CPC,   CPH,   CPK,   CPP,   CPF,   CPW,   ERRLMT,
     1  HAMB,   HFG,   KB,   KC,   KH,   KK,   KP,   KF,   KW,   N,   QGEN,
     2  RHB,   RHC,   RHH,   RHK,   RHP,   RHF,   RHW,   TAMB,   TSTEP,   WB,   WC,   WH,
     3  WK,   WP,   WF,   WG,   THEATR,    TIMEMAX,    TSTART
C
C INPUT   THE   VALUES   OF  ALL   GEOMETRICAL    AND   THERMAL    VARIABLES    THROUGH
C AN  INPUT   SUBROUTINE.
C
        CALL   INPUT
C
C ESTIMATE    THICKNESS    AND   AVERAGE    THERMAL    PROPERTIES    OF  EACH   NODE
C
        MASS(1)   = WH*RHH
        CP(1)   = CPH
        R(1)   = 1
C
        MASS(2)   = WC*RHC   + WG*RHW   + WP*RHP
        CP(2)   = (WC*RHC*CPC     + WG*RHW*CPW     + WP*RHP*CPP)/
     1            (WC*RHC    + WG*RHW    + WP*RHP)
        R(2)   = WC/KC   + WG/KW   + WP/KP
        D(2,1)   = TSTEP/(2.0*MASS(2)*CP(2)*(R(2)/2.0))
        D(2,2)   = TSTEP/(2.0*MASS(2)*CP(2)*((R(2)+R(3))/2.0))
C
        DO  100   I=3,2+N
        MASS(I)   = (WF/N)*RHF
        CP(I)   = CPF
```

```
      R(I)   =  (WF/N)/KF
      R(I+1)=R(I)
      D(I,1)   =  TSTEP/(2.0*MASS(I)*CP(I)*(R(I)+R(I-1))/2.0)
      D(I,2)   =  TSTEP/(2.0*MASS(I)*CP(I)*(R(I)+R(I+1))/2.0)
 100  CONTINUE
C
      MASS(N+3)   = WP*RHP   + WG*RHW   + WB*RHB   + WK*RHK
      CP(N+3)   = (WP*RHP*CPP   + WG*RHW*CPW   + WB*RHB*CPB   + WC*RHC*CPC)/
     1          (WP*RHP   + WG*RHW   + WB*RHB   + WK*RHK)
      R(N+3)   = WP/KP   + WG/KW   + WB/KB   +WK/KK
      D(N+3,1)   = TSTEP/(2.0*MASS(N+3)*CP(N+3)*(R(N+3)+R(N+2))/2.0)
      D(N+3,2)   = TSTEP/(2.0*MASS(N+3)*CP(N+3)*(R(N+3)/2.0+
     1 1.0/HAMB))
C
      MASS(N+4)   = WC*RHC   + WG*RHW   + WB*RHB   + WC*RHC
      CP(N+4)   = (WC*RHC*CPC   + WG*RHW*CPW   + WB*RHB*CPB   + WC*RHC*CPC)/
     1           (WC*RHC   + WG*RHW   + WB*RHB   + WC*RHC)
      R(N+4)   = WC/KC   + WG/KW   + WB/KB   + WC/KC
      D(N+4,1)   = TSTEP/(2.0*MASS(N+4)*CP(N+4)*(R(N+4)/2.0))
      D(N+4,2)   = TSTEP/(2.0*MASS(N+4)*CP(N+4)*(R(N+4)/2.0+
     1 1.0/HAMB))
C
C WRITE   TITLE   FOR   THE   TIME   TEMPERATURE   RESULTS
C
      WRITE(6,51)
      WRITE(10,51)
 51   FORMAT(5X,'TIME   IN   SECONDS   AND   TEMPERATURES   AT   14   NODES   ARE   AS   F
     1OLLOWS:')
C
C SUPPLY   INITIAL   VALUES   OF   T   AT   TIME=0   UP   TO   TIME=60   SEC   SINCE
C NO   REACTION   OCCURS   FOR   THE   FIRST   TSTART   SECONDS
C
      TIME=0.0
      DO  200   I=1,N+4
      TOLD(I)   =  TAMB
 200  CONTINUE
      WRITE(10,21)TIME,(TOLD(I),I=1,14)
 21   FORMAT(2X,F5.1,3X,14(F7.3))
      TIME=TSTART
      WRITE(10,21)TIME,(TOLD(I),I=1,14)
      WRITE(6,21)TIME,(TOLD(I),I=1,14)
C
C INCREMENT   THE   TIME   STEP   AND   EVALUATE   ALL   T'S   BY   GAUSS-SIEDEL
C ITERATION   TECHNIQUE   FOR   NEXT   9 MINUTES.
C
      TOLD(1)   =  THEATR
```

```
      NSTEP=(TIMEMAX-TSTART)/TSTEP
C
C SET HEAT LOSSES EQUAL TO ZERO
C
      QLOSS1=0.0
      QLOSS2=0.0
      DO 1000 ISTEP=1,NSTEP
      TIME=TIME+TSTEP
C
C SUPPLY INITIAL GUESSES FOR ALL TEMPERATURES
C
      DO 300 I=1,N+4
      TNEW(I)   = TOLD(I)
 300  CONTINUE
C
C ITERATE FOR A GIVEN TIME STEP
C
      DO 400 ITER=1,100
      DO 700 I=1,N+4
      TNEWPR(I)   = TNEW(I)
 700  CONTINUE
      TNEW(2)=(TOLD(2)+D(2,1)*(TNEW(1)+TOLD(1)-TOLD(2))
     1         +D(2,2)*(TNEW(3)+TOLD(3)-TOLD(2)))/(1.0+D(2,1)+D(2,2))
      DO 500 I=3,N+2
      TNEW(I)=(TOLD(I)+D(I,1)*(TNEW(I-1)+TOLD(I-1)-TOLD(I))
     1         +D(I,2)*(TNEW(I+1)+TOLD(I+1)-TOLD(I)))/
     1          (1.0+D(I,1)+D(I,2))
 500  CONTINUE
      I=N+3
      TNEW(I)=(TOLD(I)+D(I,1)*(TNEW(I-1)+TOLD(I-1)-TOLD(I))
     1         +D(I,2)*(2.0*TAMB-TOLD(I)))/
     1          (1.0+D(I,1)+D(I,2))
      I=N+4
      TNEW(I)=(TOLD(I)+D(I,1)*(TNEW(1)+TOLD(1)-TOLD(I))
     1         +D(I,2)*(2.0*TAMB-TOLD(I)))/
     1          (1.0+D(I,1)+D(I,2))
      ERRMAX=0.0
      DO 600 I=1,N+4
      ERR=ABS(TNEWPR(I)-TNEW(I))
      IF(ERR.GT.ERRMAX)ERRMAX=ERR
 600  CONTINUE
      IF(ERRMAX.LT.ERRLMT)GO      TO 610
 400  CONTINUE
      WRITE(10,22)ISTEP
      WRITE(6,22)ISTEP
 22   FORMAT(//,2X,'ITERATION     NOT CONVERGED    AT ISTEP=',I4,//)
```

```
 610      CONTINUE
          I1  =  TIME/20.0
          I2  =  (TIME-TSTEP)/20.0
          IF(I1.GT.I2)GO      TO  620
          GO  TO  630
 620      CONTINUE
          WRITE(10,21)TIME,(TNEW(I),I=1,14)
          WRITE(6,21)TIME,(TNEW(I),I=1,14)
 630      CONTINUE
C          WRITE(6,21)TIME,(TNEW(I),I=1,14)
C         WRITE(6,25)
C25       FORMAT(2X,'ENTER      N  IF  YOU  WANT  TO  STOP,  ANY  OTHER  KEY  TO  CONTINU
C      1E')
C         READ(5,26)RES
C26       FORMAT(A1)
C         IF(RES.EQ.'N')GO      TO  1010
          I1=TIME/60.0
          I2=(TIME-TSTEP)/60.0
          IF(I1.GT.I2)THEN
              IJ=(TIME/60)
              TAVE(IJ)=0.0
              DO  800  I=3,N+2
              TAVE(IJ)=TAVE(IJ)+TNEW(I)
 800        CONTINUE
              TAVE(IJ)    =  TAVE(IJ)/N
              TAVE(IJ)    =  (TAVE(IJ)*BH     +  TAMB*(BF-BH))/BF
          ENDIF
          DO  900  I=1,N+4
          TOLD(I)=TNEW(I)
 900      CONTINUE
          QLOSS1=QLOSS1+(6.5*3.5*2.54**2/1E4)*HAMB*(TNEW(13)-TAMB)*TSTEP
          QLOSS2=QLOSS2+(6.5*3.5*2.54**2/1E4)*HAMB*(TNEW(14)-TAMB)*TSTEP
 1000     CONTINUE
 1010     CONTINUE
          IJMAX=TIMEMAX/60
          WRITE(6,31)
          WRITE(10,31)
          DO  810  IJ=1,IJMAX
          WRITE(10,32)IJ,TAVE(IJ)
          WRITE(6,32)IJ,TAVE(IJ)
 31       FORMAT(2X,//,'TIME      IN  MINUTES      AVERAGE   FOOD  TEMPERATURE,     C',/)
 32       FORMAT(8X,I2,14X,F6.1)
 810      CONTINUE
          QLOSS1=QLOSS1/1000.0
          QLOSS2=QLOSS2/1000.0
          QLOSS=QLOSS1+QLOSS2
```

```
      WRITE(10,23)QLOSS1,QLOSS2,QLOSS
      WRITE(6,23)QLOSS1,QLOSS2,QLOSS
 23   FORMAT(//,5X,'     HEAT   LOSSES   IN  KILOJOULES    FROM   THE   CARTON    ARE-',/,
     2 15X,'TOP    SIDE',8X,'BOTTOM      SIDE',8X,'TOTAL',/,15X,F10.2,8X,F10.2,
     3 8X,F10.2)
      END
C END  OF  PROGRAM   HEATER
C CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE    INPUT
C
C SUBROUTINE    INPUT   READS   THE   VALUES   OF  GEOMETRICAL    AND   THERMAL
C PARAMETERS    CONTAINED    IN  COMMON/PAR/
C
      REAL  K,  MS,  KB,  KC,  KH,  KK,  KP,  KF,  KW
      COMMON/PAR/BH,      BF,  CPB,  CPC,  CPH,  CPK,  CPP,  CPF,  CPW,  ERRLMT,
     1 HAMB,  HFG,  KB,  KC,  KH,  KK,  KP,  KF,  KW,  N,  QGEN,
     2 RHB,  RHC,  RHH,  RHK,  RHP,  RHF,  RHW,  TAMB,  TSTEP,  WB,  WC,  WH,
     3 WK,  WP,  WF,  WG,  THEATR,  TIMEMAX,  TSTART
      READ(20,*)BH,BF
      READ(20,11)I
 11   FORMAT(I1)
      READ(20,*)     CPB,CPC,CPH,CPK,CPP,CPF,CPW
      READ(20,11)I
      READ(20,*)     ERRLMT,HAMB,HFG
      READ(20,11)I
      READ(20,*)     KB,KC,KH,KK,KP,KF,KW
      READ(20,11)I
      READ(20,12)N
 12   FORMAT(2X,I2)
      READ(20,11)I
      READ(20,*)RHB,RHC,RHH,RHK,RHP,RHF,RHW
      READ(20,11)I
      READ(20,*)TAMB,       TSTEP
      READ(20,11)I
      READ(20,*)WB,      WC,  WH,  WK,  WP,  WF,  WG
      READ(20,11)I
      READ(20,*)THEATR,       TIMEMAX
      READ(20,11)I
      READ(20,*)TSTART
C
C ERROR   MESSAGES
C
C MESSAGE    1,  INPUT   TEMPERATURE    BELOW   0  C
C
 30   CONTINUE
```

```
      IF(TAMB.LE.0.0)THEN
        WRITE(6,31)
31      FORMAT(2X,'FATAL      ERROR   # 10,  INPUT   TEMPERATURE     BELOW   FREEZING
     1TEMPERATURE',/,2X,'PLEASE          ENTER   A  VALUE   ABOVE   0  C  TO  CONTINUE,
     2OR  ENTER   1000   TO  EXIT')
        READ(6,*)TAMB
        IF(TAMB.EQ.1000)      GO  TO  1000
        GO  TO  30
      ENDIF
40    CONTINUE
      IF(TAMB.GE.100.0)THEN
        WRITE(6,41)
41      FORMAT(2X,'FATAL      ERROR   # 20,  INPUT   TEMPERATURE     ABOVE   BOILING   TEM
     1PERATURE',/,2X,'PLEASE          ENTER   A  VALUE   BELOW   100  C  TO  CONTINUE,     OR
     2ENTER   1000   TO  EXIT')
        READ(6,*)TAMB
        IF(TAMB.EQ.1000)      GO  TO  1000
        GO  TO  40
      ENDIF
1000  CONTINUE
      END
C
C END  OF  SUBROUTINE    INPUT
```

APPENDIX B

SAMPLE INPUT DATA FILE

SAMPLE INPUT DATA FILE

```
  0.140               0.178
1 HEATER    LENGTH      FOOD   LENGTH
        2010.0      1340.0      2930.0      1340.0      2010.0      3200.0      4180.0
1       CPB         CPC         CPH         CPK         CPP         CPF         CPW
  0.01          10.0          2.4E6
1 ERRLMT        HAMB          HFG
        0.3       0.5          0.68              0.2            0.3              0.58        0.68
1       K-BAG     K-COVER      K-HEATER          K-CARTON       K-POUCH          K-FOOD      K-WATER
  10
1 NUMBER    OF   NODES   IN   FOOD
     2200.0           930.0         1300.0        160.0           2200.0        900.0          1000.0
1    RH-BAG           RH-COVER      RH-HEATER     RH-CARTON       RH-POUCH      RH-FOOD        RH-WATER
  30.0       1.0
1 TAMB       TSTEP
      0.000022       0.00012       0.002       0.00022       0.00008       0.0125       0.00005
1     W-BAG          W-COVER       W-HEATER    W-CARTON      W-POUCH       W-FOOD       W-WATER     GAP
      95.0           600.0
1     THEATR         MAXIMUM     TIME    IN    SECONDS
    60.0
1   TIME    ELAPSED    BEFORE    THE    HEATER    REACTION    IS   INITIATED,    SECONDS
```

APPENDIX C

SAMPLE OUTPUT FILE

SAMPLE OUTPUT FILE

```
      TIME    IN   SECONDS     AND    TEMPERATURES       AT   14   NODES    ARE    AS   FOLLOWS:
     0.0       30.000    30.000    30.000    30.000    30.000    30.000    30.000    30.000    30.000    30.000
 30.000    30.000    30.000    30.000
    60.0       30.000    30.000    30.000    30.000    30.000    30.000    30.000    30.000    30.000    30.000
 30.000    30.000    30.000    30.000
    80.0       95.000    81.786    68.671    51.835    40.778    34.670    31.790    30.611    30.188    30.052
 30.013    30.004    30.003    94.844
   100.0       95.000    85.365    75.749    61.918    50.757    42.561    37.071    33.705    31.810    30.829
 30.365    30.180    30.159    94.845
   120.0       95.000    87.043    79.098    67.212    56.918    48.553    42.173    37.603    34.530    32.599
 31.492    30.971    30.906    94.845
   140.0       95.000    88.070    81.147    70.587    61.108    53.004    46.404    41.288    37.528    34.934
 33.308    32.486    32.370    94.845
   160.0       95.000    88.782    82.569    72.981    64.192    56.450    49.899    44.589    40.488    37.512
 35.558    34.532    34.371    94.845
   180.0       95.000    89.316    83.636    74.805    66.601    59.237    52.858    47.543    43.317    40.160
 38.031    36.884    36.685    94.845
   200.0       95.000    89.740    84.484    76.271    68.575    61.582    55.431    50.218    45.997    42.787
 40.584    39.374    39.142    94.845
   220.0       95.000    90.093    85.190    77.502    70.256    63.617    57.721    52.668    48.528    45.342
 43.129    41.893    41.631    94.845
   240.0       95.000    90.397    85.797    78.569    71.729    65.429    59.796    54.933    50.916    47.798
 45.612    44.374    44.085    94.845
   260.0       95.000    90.664    86.331    79.514    73.046    67.066    61.695    57.033    53.161    50.137
 48.001    46.775    46.461    94.845
   280.0       95.000    90.905    86.814    80.369    74.244    68.566    63.450    58.994    55.276    52.359
 50.283    49.075    48.739    94.845
   300.0       95.000    91.126    87.256    81.154    75.348    69.955    65.085    60.831    57.270    54.463
 52.453    51.267    50.910    94.845
   320.0       95.000    91.331    87.664    81.882    76.373    71.250    66.615    62.556    59.150    56.454
 54.511    53.348    52.972    94.845
   340.0       95.000    91.521    88.045    82.559    77.330    72.461    68.049    64.179    60.922    58.334
 56.458    55.319    54.925    94.845
   360.0       95.000    91.699    88.400    83.193    78.226    73.597    69.397    65.706    62.592    60.109
 58.298    57.183    56.771    94.845
   380.0       95.000    91.865    88.733    83.787    79.067    74.664    70.664    67.143    64.166    61.784
 60.035    58.943    58.515    94.845
   400.0       95.000    92.022    89.046    84.346    79.857    75.667    71.857    68.497    65.649    63.363
 61.673    60.604    60.161    94.845
   420.0       95.000    92.169    89.340    84.871    80.601    76.612    72.980    69.773    67.048    64.852
 63.219    62.171    61.713    94.845
```

440.0	95.000	92.307	89.617	85.365	81.301	77.501	74.038	70.975	68.366	66.256	64.677	63.649	63.178	94.845
460.0	95.000	92.438	89.877	85.830	81.960	78.339	75.035	72.107	69.609	67.580	66.051	65.042	64.558	94.845
480.0	95.000	92.561	90.123	86.269	82.581	79.128	75.974	73.175	70.780	68.827	67.347	66.356	65.860	94.845
500.0	95.000	92.676	90.354	86.682	83.166	79.872	76.859	74.181	71.884	70.003	68.568	67.594	67.087	94.845
520.0	95.000	92.785	90.572	87.071	83.718	80.573	77.693	75.129	72.924	71.112	69.719	68.761	68.244	94.845
540.0	95.000	92.888	90.777	87.438	84.237	81.233	78.480	76.023	73.905	72.157	70.804	69.862	69.334	94.845
560.0	95.000	92.985	90.971	87.784	84.727	81.856	79.221	76.866	74.829	73.142	71.827	70.899	70.362	94.845
580.0	95.000	93.076	91.153	88.109	85.189	82.443	79.919	77.659	75.700	74.070	72.791	71.877	71.331	94.845
600.0	95.000	93.162	91.325	88.416	85.624	82.996	80.577	78.408	76.521	74.945	73.700	72.798	72.244	94.845

TIME IN MINUTES	AVERAGE FOOD TEMPERATURE, C
1	.0
2	42.7
3	49.1
4	54.0
5	57.9
6	61.2
7	63.9
8	66.2
9	68.1
10	69.7

HEAT LOSSES IN KILOJOULES FROM THE CARTON ARE-

TOP SIDE	BOTTOM SIDE	TOTAL
1.74	5.14	6.88

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APPENDIX D

USER'S GUIDE FOR COMPUTER PROGRAM

USER'S GUIDE FOR COMPUTER PROGRAM

The computer program to simulate the transient thermal performance of the Flameless Ration Heater for heating an MRE pouch is available in an executable file called **HEATER.EXE**. A separate input file called **INPUT.DAT** is required to run the program. Although a user will not need the source code FORTRAN program called **HEATER.FOR**, it is included in the disk provided, and a listing of the program is given in APPENDIX A.

Following steps may be followed to run the program.

Step 1 - Using any ASCII editor, make the necessary changes in the input file INPUT.DAT to incorporate the geometrical conditions, food and material properties and the time duration for the heating process.

Step 2 - Make sure that the files HEATER.EXE and INPUT.DAT are in the same subdirectory or on the same floppy disk. Enter that subdirectory or floppy disk as your screen prompt.

Step 3 - At the screen prompt, enter "HEATER", and press RETURN key.

Step 4 - The computer will ask for the name of UNIT 20. Enter the name of the input file, INPUT.DAT and press ENTER key.

Step 5 - The computer will ask for the name of UNIT 10 which is an output file. Enter any name such as OUTPUT.OUT and press ENTER key.

WARNING: Any existing file with the same name as UNIT 20 name, OUTPUT.DAT in the above example will be erased and overwritten by the output from the program.

Step 6 - The output of the program is in OUTPUT.OUT file which can be printed using the PRINT OUTPUT.DAT command.

Step 7 - You may rerun the program by following steps 1 through 6.

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APPENDIX E

EXPERIMENTAL PROCEDURE

EXPERIMENTAL PROCEDURE

The procedure followed while conducting the experiments is described below.

Preparation

Step 1. Place the food pouch in a refrigerator or at any other place to attain the desired initial temperature. Allow at least an hour in the controlled temperature environment before conducting a test. In case of the tests with the initial temperature as the room temperature, keep the food pouches in a room where there are no significant temperature changes (less than 1 C) for at least one hour prior to conducting experiments.

Step 2. Place a bottle containing clean water in the controlled temperature environment to attain the desired initial temperature.

Step 3. Keep a beaker handy to measure the required amount of water needed to start the chemical reaction in the heater.

Step 4. Start the data acquisition system and make sure that it is functioning properly.

Step 5. Label the thermocouples and connect them in the corresponding slots in the data acquisition system.

Conducting Experiment

Step 4. Weigh the heater pad.
Step 5. Instrument the heater pad with two thermocouples located on each side of

the pad between the pad and the cover, and two thermocouples each on the outer surfaces of the cover.

Step 6. Place the heater pad in the bag with the thermocouple wires coming out along one of the corner edges of the bag. Make sure that the edge coated with adipic acid is toward the bottom of the bag.

Step 7. Note all the thermocouple numbers and their corresponding locations.

Step 8. Take out the food pouch from a refrigerator if it is cooled prior to heating process, or from a place where it is kept to attain a certain initial temperature. Place it immediately in the bag on one side of the heater making sure that the two thermocouples on the outer cover of the heater are firmly in place.

Step 9. Start the data acquisition system.

Step 10. Take out the water bottle from the refrigerator or the controlled temperature enclosure, and measure 2 ozs. in a beaker.

Step 11. Raise the heater pad and the food pouch above the water level markings on the bag and pour 2 ozs. of water in the bag.

Step 12. Fold the bag over and lay it flat on a horizontal surface for about 1 minute while inserting it in a cardboard carton.

Step 13. Raise the bag about 15 degrees and rest it on a support so that the water is contained near the lower end of the bag.

Step 14. Run the test for the desired length of time while recording the thermocouple outputs every 20 seconds.

Step 15. At the end of the desired time period (5, 10 or 15 minutes), carefully remove the food pouch from the carton and the bag and knead it quickly to mix the food so that it attains an average temperature. Record the average temperature by inserting a thermocouple inside the pouch.

Step 16. Stop the data acquisition system, and remove all thermocouple connections from the heater and pouch.

Step 17. Discard the food, heater bag with heater, and carton.