UMTRI-96-5

USER'S GUIDE FOR THE UMTRI AIRBAG SKIN BURN MODEL

TECHNICAL REPORT

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Prepared for

Honda Research and Development North America
1990 Harper's Way
Torrance, CA 90501

February 1996

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTRI-96-5		

4. Title and Subtitle	5. Report Date
USER'S GUIDE FOR THE UMTRI AIRBAG SKIN BURN MODEL	February 1996
	6. Performing Organization Code
7. Authors	8. Performing Organization Report No.
Bruce M. Bowman and Matthew P. Reed	UMTRI-96-5
9. Performing Organization Name and Address	10. Work Unit No.
University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, Michigan 48109-2150	
	11. Contract or Grant No.
	304297
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Honda Research and Development North America 1990 Harper's Way Torrance, California 90501	TECHNICAL REPORT
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This manual describes the implementation of a new version of the UMTRI Airbag Skin Burn Model as a FORTRAN computer program. It also describes the use of the model. This model is an analytical formulation and solution of equations that simulate the exposure of bare skin to high-temperature airbag exhaust and the potential of that exposure to produce burn injury. The model can be used for studying the effects of exposure of the skin to both vented airbag exhaust and heat-gun gas jets.

The overall purpose of the model is to aid airbag system designers in the development of inflator/airbag systems that have acceptably low potential for producing second-degree skin burn in the event of direct exposure of the bare skin to vented airbag exhaust. The model calculates, among other things, the time histories of all thermodynamic responses of the airbag system, the time histories of the thermal responses of the skin, including temperature of the skin as a function of depth, and the Henriques burn injury integral, Omega, a measure of the potential for first- and second-degree burn injuries.

This user's manual describes the submodels that comprise the UMTRI Airbag Skin Burn Model, namely, models for: (a) airbag inflation, (b) occupant/airbag interaction, (c) impinging jet heat transfer, (d) heat transfer, and (e) burn injury. User input data requirements are explained, and examples of program outputs are presented and discussed.

17. Key Words	18. Distribution Statement
Airbag, Thermal Burns, Injury Tolerance, Injury Mechanisms, Skin Injury, Restraint Systems, Modeling	Unlimited Distribution

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
None	None	104	

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USER'S GUIDE FOR

THE UMTRI AIRBAG SKIN BURN MODEL

1.0 INTRODUCTION

This manual describes the implementation of the UMTRI Airbag Skin Burn Model as a FORTRAN computer program. It also describes the use of the model. This model is an analytical formulation and solution of equations that simulate the exposure of bare skin to high-temperature airbag exhaust and the potential of that exposure to produce burn injury. The original form of the UMTRI Airbag Skin Burn Model was reported by Reed and Schneider (1994) and Reed, Schneider, and Burney (1994). In the 1994 study the solution equations were partly of closed form and partly a Fourier series approximation. The equations were processed with the *Mathematica* computer program.

In the present study a completely closed-form solution has been used for determination of skin temperature as a function of time at a critical depth, viz., at the basal layer of the epidermis. Other modifications, mostly of minor importance, have been made to the analytical model as well. The FORTRAN program developed in the current study is expected to be much more useful to airbag system designers and skin burn researchers than the *Mathematica* model because of (a) ease of use, (b) ease of porting to any computer system for which a FORTRAN compiler is available, and (c) the addition of many features and capabilities that did not exist in the earlier model.

The model can be used for studying the effects of exposure of the skin to both vented airbag exhaust and heat-gun gas jets.

2.0 PURPOSE AND USES OF THE MODEL

The overall purpose of the model is to aid airbag system designers in the development of inflator/airbag systems that have acceptably low potential for producing second-degree skin burn in the event of direct exposure of the bare skin to vented airbag exhaust. The model can be used to simulate airbag inflation and exhaust or skin exposures from a laboratory heat-gun apparatus used to study skin sensitivity to gas jet exposures. Either nitrogen or air can be used as the inflation gas in any simulation, although normally nitrogen is used for airbag simulations and air is used for heat-gun simulations that are intended to model laboratory heat-gun experiments. The various features of the model allow the user to determine the quantities and responses itemized below.

- the Henriques burn injury integral, Ω, a measure of the potential for first- and second-degree burn injuries
- time histories of all thermodynamic responses of the airbag system
- time histories of the thermal responses of the skin, including temperature of the skin as a function of depth
- effects of inflator design in terms of mass flow rate and pressure in tank tests as functions of time
- airbag exhaust temperature and velocity as functions of time

- effects of fabric stretch
- effects of the nominal airbag volume
- effects of vent diameter and number of vents
- effects of occupant interaction with the airbag
- time histories of the dynamic response of the single-mass occupant model
- exposure duration that will produce first-degree (or second-degree) burn for specified jet velocity and temperature (heat-gun simulation)
- gas jet velocity that will produce first-degree (or second-degree) burn for specified jet temperature and exposure duration (heat-gun simulation)
- gas jet temperature that will produce first-degree (or second-degree) burn for specified jet velocity and exposure duration (heat-gun simulation)
- cell depth for first-degree (or second-degree) burn for specified exposure duration and jet temperature and velocity (heat-gun simulation)

3.0 OVERVIEW OF THE COMPUTER MODEL

The computer model in its current form at UMTRI consists of a single executable program file, called BURN.EXE, for use on IBM-compatible PCs with the DOS operating system. However, executable code can be prepared for essentially any work station or desktop computer using any operating system. It is necessary only to compile the FORTRAN source code, provided in file BURN.FOR, with a FORTRAN 77 or FORTRAN 90 compiler for the system on which BURN is to be used. The Lahey FORTRAN 77, Version 3.00 (16-bit) compiler was used in the current work, but the only compiler-dependent subroutine used was the Lahey routine UNDER0, which sets underflows to zero if they occur. Any compiler likely to be used to compile the UMTRI code will have a library routine of the same function as Lahey's UNDER0.

The BURN program reads one or three input data files, depending on whether the simulation is for a heat-gun "experiment" or for an airbag. Either one, two, three, or four output files are produced for the simulation, whether it is for an airbag or a heat gun, depending on output options selected by the user. The program is interactive only to the extent that the user enters "1" from the keyboard to select an airbag simulation or "2" to select a heat-gun simulation.

The user-provided input data for airbag runs must be in three formatted ASCII (text) files with the specific names AIRBAG, M1TDOT, and PT. Data file AIRBAG contains all system constants and user controls for the simulation. M1TDOT and PT must contain tank test data for the inflator. M1TDOT contains the time history data for mass flow rate in the tank test, i.e., $\dot{m}_{1T}(t)$ (in kg/s). PT contains the time history data for pressure in the tank test, i.e., $P_T(t)$ (in kPa gauge). The only input data needed for a heat-gun simulation are provided by the user in a file with the specific name HEATGUN. Its content is very similar to that of the AIRBAG data file, differing primarily in its lack of airbag system constants.

The output data files that can be produced by airbag and heat-gun runs have the names BURNMODL.OUT, TEMPDIST.OUT, TABLDATA.OUT, and PARSED.OUT.

BURNMODL.OUT is the primary output file. It contains a tabular summary of primary run results, including Ω (the burn injury integral, Omega), gas jet temperature and velocity, exposure duration, average heat flux, etc. This file will always contain, additionally, an echo of the input data set (AIRBAG or HEATGUN) that was used for the simulation, and it can contain, at the user's option, a descriptive summary of the input data, a summary of model constants, and most of the tabular data (including time histories) generated by the simulation. The latter may optionally be written instead to the file TABLDATA.OUT or suppressed. Like BURNMODL.OUT, file TEMPDIST.OUT is produced for every run (except "search" runs). It contains the temperature distribution time history for the skin--i.e., temperature as a function of time and depth. Finally, the file PARSED.OUT may be generated at the user's option. This file contains a "parsed" version of the "Summary of Results" portion of the BURNMODL.OUT output--i.e., lines that include only the numbers and not the descriptive words and units that are present in the primary output in BURNMODL.OUT. The PARSED.OUT file is more easily processed than the BURNMODL.OUT file by postprocessing software that might be written by the user for analysis of the results of batch runs.

The input and output files discussed above are summarized in Table 1. An example of an AIRBAG input data set is shown as Figure 1. All of the input and output files are described more fully in Section 5.0, and listings of example files are included in Appendices B to F. Source code and executable program files, as well as data files, are on an MS DOS distribution diskette, which is described in Appendix A.

Table 1
Input and Output Data Files

Data File Type	File Name	Type of Simulation	Status	Contents
input	AIRBAG	airbag	required	constants/controls
input	M1TDOT	airbag	required	mass flow rate
input	PT	airbag	required	tank test pressure
input	HEATGUN	heat gun	required	constants/controls
output	BURNMODL.OUT	both	always	summary of results[1-6]
output	TEMPDIST.OUT	both	always	skin temp distribution[7]
output	TABLDATA.OUT	both	optional	time histories/other[5]
output	PARSED.OUT	both	optional	numbers-only summary[6]

[1]Also always includes an echo of the input data set.

[2]May optionally include a descriptive summary of input constants.

[3]May optionally include a descriptive summary of model constants.

[4]May optionally include time history outputs and other tabular data.

[5]Tabular data may be written to either BURNMODL.OUT or TABLDATA.OUT.

[6]The "Summary of Results" portion of BURNMODL.OUT can be written in parsed (numbers-only) form to PARSED.OUT.

[7]Fixed depth and time spacings and spans: 0 to 0.000200 m by 0.000001 m spacings and 0 to 500 ms by 10 ms spacings [TEMPDIST.OUT is not written for heat-gun "search" runs.]

```
* Airbag   [8-character data fields]  [ Comment lines begin with ;:*#$@ ]

*line 1: Integration method (1.=R-K) and stepsize (s)
*line 2: Output specifications -- SW1, SW2, KTAB(1-25)  FORMAT(2g8.0, 25I1)
;       Field 1: summary outputs (results and input data summary)
;          =1., summary of results, summary of input data, summary of model consts
;          =2., summary of results, summary of input data
;          =3., summary of results only
;          <0., as above but also print parsed results summary (to separate file)
;       Field 2: tabular output data, including time histories
;          =0., print no tabular data to file
;          =1., print all tabular data to file [KTAB() specifications optional]
;                KTAB(i) for table i: 0 = do not write to file, 1 = write to file,
;                2 = write every 2nd point to file (time histories 7-14,18-25)
;          =2., default (selected) tables to file
;                Table No.  1 2 3 4 5 6 7 8 910111213141516171819202122232425
;                Default    0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 0 0 2 0 0 0 0 0 0
;          <0., as above but write tabular data to different file from summaries
*line 3: Reduced duration (s) for exposure to airbag exhaust if abs() is nonzero
;          =0., use exhaust duration calculated from the airbag thermodynamics
;          >0., reduced duration; ignore the first portion of calc'd exhaust data
;          <0., reduced duration; ignore the last portion of calc'd exhaust data
*line 4: Gas identification:  a) nitrogen or 1.  or  b) air or 2.
*line 5: Ambient temperature (°C)  [include K in field if Kelvin]
*line 6: Initial skin surface temperature (°C)  [include K in field if Kelvin]
*line 7: Tank test volume (m**3)
*line 8: Vent diameter (m) and number of vents
*line 9: Orifice coefficient for vent and fabric area
*line 10: Fabric stretch factor (any value .ge. 0, or -1. for lin. regr. on V20)
;          (e.g., 3.81e-6 m²/(N/m²)/m²)
*line 11: Occupant interaction specifications: 0.=no interaction, 1.=interaction
;           If field 1 is 1., fields 2 through 7 must contain the following data
;           for simulation of a pendulum impact against the airbag.
;           f.2:  moment of inertia about pivot point (kg m**2)
;           f.3:  distance from pivot point to center of airbag contact (m)
;           f.4:  pendulum angular velocity at contact if positive (rad/s);
;                 linear velocity if negative (m/s)
;           f.5:  maximum contact area for pendulum/airbag interaction (m**2)
;           f.6:  airbag deflection over which max contact area is reached (m)
;           f.7:  airbag depth, i.e., deflection for bottoming out (m)
*line 12: Nominal airbag volume (m**3)
*line 13: H/D ratio: H, distance from vent to skin surface; D, jet diameter
*line 14: r/D ratio: r, effective radius of target area; D, jet diameter
*line 15: Multiplicative tuning factor for Phase 1 heat transfer coefficient
*line 16: Effective Qdot for Phase 2 heat transfer (.ge. 0; e.g., 1400 W/m**2)
*line 17: Thermal conductivities of epidermis and dermis (W/m/K) (nonzero)
*line 18: Thermal diffusivities of epidermis and dermis (m**2/s); if a negative
;         value is specified in field 1 (epidermis), fields 3 and 4 must contain
;         nonzero values for density (kg/m**3) and specific heat (J/kg/K);
;         fields 5 and 6 are used similarly for the dermis if field 2 is neg.
*line 19: Critical cell depth (micrometers)
*line 20: Burn integral constants: preexponential factor coefficient and power,
;         and delE/R (activation energy divided by gas constant)

1.      .0005
2.      -1.     1111111111111111112111111
0.
nitrogen
20.85      Blank lines and comment lines beginning with ; : * # $ @ are allowed.
35.85      Comments can also be added after the data fields on any line.
.028317
0.035   2.
0.6
0.
0.      143.1   1.332   4.95    0.15    0.100   0.254
0.06
3.0
1.
.55
1400.
0.20949 0.3791
7.267E-8 1.43E-7
72.
3.1     98.     75000.                  Henriques-Moritz   [44,50] C
```

Figure 1. An Example AIRBAG Input Data Set.

4.0 DESCRIPTION OF THE COMPUTER MODEL

There are six primary components of the analytical model and, accordingly, six corresponding primary modules in the computer model. These are described below in Table 2 and in Sections 4.1 - 4.6.

Table 2
Computer Program Modules

Module Number	Module: function
1	the **airbag inflation model**: determines the duration, temperature, and velocity of the hot gas jet to which the skin is exposed [For heat-gun simulations the user directly specifies constant values for these three quantities.]
2	the **occupant/airbag interaction model**: may be employed optionally together with module 1 in the airbag simulations
3	the **impinging jet heat transfer model**: determines the average heat transfer coefficient during exposure of the gas jet to the skin surface for the values of duration and average temperature and velocity established by module 1 for airbag runs (with or without module 2) and from user specifications for heat-gun runs
4	the **heat transfer model**: for the heat flux for the heat transfer coefficient determined by module 3, determines the subsurface skin temperature distribution for depths through 0.000200 m as a function of time
5	the **burn injury model**: for the temperature vs. time profile determined by module 4 for the critical skin depth (basal epidermal layer; user specified, usually 0.000072 m), calculates the Henriques burn injury integral, Ω, for assessment of the degree of burn injury
6	the **search feature**: determines the duration, temperature, or velocity for a heat-gun jet that will cause either first-degree or second-degree burn, or for specified duration, temperature, and velocity, determines the skin depth at which incipient burn injury occurs

4.1 Airbag inflation model

For simulation of airbag inflation, use was made of a gas dynamics model that was adapted from Wang and Nefske (1988), Wang (1989), and Wang (1991). The adapted model is described by Reed and Schneider (1994) and Reed, Schneider, and Burney (1994). It is a lumped-parameter, isentropic flow model. The Wang model was selected because it provides useful airbag performance predictions that can be verified with laboratory experiments. This model is readily used with the burn injury model.

4.1.1 Inflator data. The airbag inflation model requires specification of data from a tank test of the inflator. The quantities needed are (a) the tank volume, (b) the pressure P_T in the tank as a function of time, and (c) the mass flow rate, i.e., the time rate of change of mass in the tank, $\dot{m}_{1T}$. The tank volume is specified in the AIRBAG data set. The time histories $P_T(t)$ and $\dot{m}_{1T}(t)$ are specified in the PT and M1TDOT data sets. Mass flow rate cannot be measured directly in tank tests; it is normally calculated by inflator manufacturers by using an analytical technique such as that described by Wang (1991) and Reed and Schneider (1994).

4.1.2 Airbag inflation. The airbag inflation process consists of two phases. In the first phase, during which the airbag fills to its nominal volume, the pressure in the airbag is assumed to be atmospheric, and there is no mass flow through the vent ports or fabric. After the airbag fills to its nominal volume, the second phase of airbag dynamics begins, during which the pressure in the airbag is greater than one atmosphere and gas flow through vents and (optionally) fabric occurs. Gas dynamics during exhaust can be affected by optional occupant interaction, which is discussed in Section 4.2. Values for the quantities needed for simulation of airbag gas dynamics are specified in the AIRBAG data set. These quantities, except for ones related to occupant/airbag interaction, are (a) the number of vents and the vent diameter, (b) the orifice coefficient for vents and porous fabric, (c) the fabric stretch factor, and (d) the nominal airbag "full" volume. The inflation gas must be nitrogen (or air).

4.1.3 Method of solution. A fourth-order, fixed-step Runge-Kutta integration algorithm is used for solving the differential equations of airbag gas dynamics. The integration is terminated when the velocity of the exhaust jet reduces to zero. A Lagrange fourth-order numerical differentiation is used to determine the time rate of change of the tank pressure, $\dot{P}_T(t)$, which is needed in the thermodynamics equations.

4.2 Occupant/airbag interaction model

4.2.1 Pendulum model. The equations of airbag gas dynamics in the Wang model include a term for the rate of decrease of airbag volume due to occupant interactions (as a function of time). This term in the equations is set to zero in the UMTRI model if the user does not want to include occupant interaction with the airbag. In lieu of a model features that would fully simulate the interacting geometries of a 2-D or 3-D airbag and an articulated linkage for the occupant, a simpler system that models a pendulum impact with the inflated airbag is used in the UMTRI model. This model mimics pendulum tests used for evaluating steering column performance which use a torso block similar to that described in SAE Recommended Practice J944 (now obsolete). The model assumes that impact of the pendulum with the airbag occurs at just the instant that the airbag becomes full, i.e., at the beginning of exhaust from the airbag. The quantities required for the occupant/airbag interaction model are specified in the AIRBAG data set. They are (a) the moment of inertia of the pendulum about its pivot point, (b) the distance from the pivot point to the center of the area of contact with the airbag, (c) either the initial linear velocity at the contact point or the initial angular velocity of the pendulum, (d) the maximum contact area for the pendulum/airbag interaction, (e) the airbag deflection over which the maximum contact area is reached, and (f) the airbag depth (for bottoming out).

4.2.2 Method of solution. A second-order differential equation describes the motion of the pendulum. This equation is coupled to the gas dynamics equations through the term for rate of change of airbag volume. Therefore, the pendulum equation is integrated simulaneously with the gas thermodynamics equations by the Runge-Kutta algorithm. If the "bottoming-out" depth of the airbag is reached by the pendulum, then an impulse (momentum change) is applied to the equations by calculating and applying the force necessary to stop the pendulum in one time step of the integration. During impact the airbag volume decreases as the pendulum pushes into the airbag (positive volume change rate, by definition). The model allows the airbag volume to increase during rebound of the pendulum provided that the gas volume is less than the "full" volume for the airbag and the pressure of the gas inside the airbag is greater than atmospheric pressure.

4.3 Impinging jet heat transfer model

In order to study the potential for burn injury resulting from exposure of the skin to airbag exhaust from a vent, it is necessary to determine the heat transfer coefficient between the impinging hot gas jet and the skin. The heat transfer coefficient is a measure of the efficiency with which heat is transferred between two media that have different temperatures. For an airbag exhaust jet impinging against a skin surface, the heat transfer coefficient is dependent on many quantities, including the distance of the vent from the skin, the diameter of the vent, the effective radius of the area of skin that is thermally insulted by the impinging jet, the velocity of the jet, and the temperature of the jet. It is also dependent on various temperature-dependent properties of the gas, including its kinematic viscosity, thermal conductivity, and thermal diffusivity.

Relevant quantities specified by the user in the AIRBAG or HEATGUN input data set are (a) vent diameter, (b) H/D, where D is the jet diameter at the vent's distance, H, from the surface, (c) r/D, where r is the effective radius of the area of skin insulted by the jet, and (d) a multiplicative tuning factor for the heat transfer coefficient (empirically determined).

4.3.1 Empirical impinging jet model. Martin (1977) describes an empirical model for heat transfer from a hot gas jet impinging perpendicularly against a flat surface. That model was adopted for use in the UMTRI Airbag Skin Burn Model. Martin's model is described by Reed and Schneider (1994) and Reed, Schneider, and Burney (1994). The model determines the heat transfer coefficient from an empirical relationship between the Reynolds number for the gas jet, the Nusselt number, and the Prandtl number. These quantities, in turn, are calculated from the gas properties mentioned above, which are incorporated in the model from tables in Incropera and DeWitt (1985). Martin makes use of a correction factor for the Nusselt number reported by Schlünder and Gnielinski (1967) as an empirical relationship between H/D and r/D. The result of calculations made with this model is an average value for the heat transfer coefficient, h, over the duration of exposure.

4.3.2 Method of solution. The Martin equations are of closed form except that the gas characteristics are functions of the gas temperature near the jet/surface interface, which is not constant. Therefore, to determine an appropriate average heat transfer coefficient, it is necessary to solve the equations (nonlinear functions of temperature) by iteration. The temperature for which it is appropriate to evaluate the gas characteristics is the film temperature, which is defined to be the average of the surface and free-stream temperatures. While the free-stream temperature is assumed constant for the airbag exhaust (and is, in fact, nearly so), the skin surface temperature (T(x,t) for depth x=0) and, therefore, the film temperature, is not constant. In consequence, it is necessary to determine the skin surface temperature as a function of time for the duration of the exhaust. Thus, this module performs "preprocessor" calculations for h(t) and T(0,t) for module 4 in a time loop that is independent from the module 4 time loop, in which skin temperatures T(x,t) are determined at different depths in the skin, not only at the surface (depth equal to zero). In summary, at each step in a time loop for the duration of the exhaust, the impinging jet model iteratively adjusts the film temperature until convergence is obtained for the solution of nonlinear equations involving the Reynolds number, the Nusselt number, the Prandtl number, and

T(0,t), the skin surface temperature. The quantity of primary interest that is determined in these calculations is h(t), the heat transfer coefficient. The quantity h is found to be nearly constant for typical airbag exhaust exposures. Module 4, the heat transfer model, requires a constant value for h. Therefore, the average value, h_{avg}, determined in the impinging jet model time loop, is used for module 4.

4.4 Heat transfer model

Heat flux between two media at different temperatures is determined simply as the product of the heat transfer coefficient and the difference between the temperatures of the two media. In the case of airbag exhaust against the skin surface, the temperature difference is the free-stream temperature of the gas jet minus the surface temperature of the skin, which changes with time. Many different analytical solutions have been developed for so-called semi-infinite solid heat transfer problems. These solutions are of basically similar form, but they differ in nature and complexity for various initial conditions and boundary conditions. The semi-infinite solid problem is one which assumes infinite extent of a solid in the direction of an inward normal to its surface. As a practical matter, the only problems for which solutions can be obtained analytically are one-dimensional problems. These are ones in which it is assumed that, for the time range of interest, heat flow is unidirectional. The heat transfer model used in the UMTRI Airbag Skin Burn Model is of this sort--i.e., heat flow is assumed to be entirely perpendicular to the surface, and the model therefore determines skin temperature distribution in one dimension only, namely, the depth into the skin, x. This assumption is valid for the reason that the depth into the skin that is of interest, normally about 0.000072 m (i.e., at the basal layer of cells of the epidermis), is much smaller than the diameter of the impinging hot gas jet.

Constants provided by the user in data set AIRBAG or HEATGUN that are used directly in heat transfer model calculations are (a) the ambient temperature, (b) the initial skin temperature (assumed not to be a function of depth), (c) the effective heat flux for Phase 2, (d) the thermal conductivities of the epidermis and dermis, and (e) the thermal diffusivities of the dermis and epidermis.

4.4.1 Temperature distribution in the skin. Two phases of heat transfer in the skin must be considered in order to predict the degree of burn injury that might result from exposure to the hot gas jet. Phase 1 of heat transfer is the period of time during which the skin is exposed to the gas jet. At the end of exposure enough heat has flowed from the skin surface to the basal epidermal layer that first- or second-degree burn may already have occurred. Whether burn has occurred or not, however, after termination of exposure heat accumulated in the outer part of the skin continues to flow inward, increasing the temperature at the critical depth. This phase of heat transfer is called Phase 2.

In order to calculate the burn injury integral, module 5 requires the time history of the temperature at the critical depth. It is the purpose of module 4, the heat transfer model, to calculate that time history. The time history must be determined for Phase 1, during exposure, and for a Phase 2 that has a long enough duration that the value for the burn injury integral, Ω, does not change if longer time lengths are considered. For airbag exhaust exposures studied, a total Phase 1 plus Phase 2 duration of 400 ms is more than ample. Five hundred milliseconds is used in the model.

4.4.2 Method of solution. The solution adopted for Phase 1 is the same as used by Reed and Schneider (1994). It is a closed-form solution given by Incropera and DeWitt (1985). The Incropera-DeWitt solution allows direct evaluation of T(x,t) in terms of the constant values for the initial skin temperature, the impinging gas temperature, the heat transfer coefficient, the thermal conductivity of the skin, and the thermal diffusivity of the skin. The solution includes both an exponential factor and erfc(w) factors, where erfc is the complementary Gaussian error function and w is a function of x and t.

The Phase 2 solution used by Reed and Schneider assumed particular boundary conditions at x=0 and x=L, where L is a sufficiently large depth much greater than the critical depth. The resulting partial differential equation reduces to ordinary differential equations, but these, in turn, do not reduce to a closed-form solution, as is the case for the Incropera-DeWitt solution for Phase 1. The resulting equations were solved by Reed and Schneider by using a Fourier series approximation.

In the current model a closed-form solution for Phase 2 is used. This solution is, again, an approximation. It has been found to give results in good agreement to the Fourier series approximation. This solution was adopted from Carslaw and Jaeger (1959), who consider a problem in which a "phase 1" is for a constant exposure temperature A and a "phase 2" is for a constant exposure temperature B. (The Carslaw-Jaeger phase 1 solution is identical to Incropera and DeWitt's.) Since the Carslaw-Jaeger solution requires use of the same heat transfer coefficient for Phase 1 and Phase 2, the same value was used as for Phase 1 even though a much smaller Phase 2 value is appropriate. A compensating change to B, the Phase 2 exposure temperature, was made from a calculation using the user-specified Phase 2 heat flux (a required input for both the original and current UMTRI models) and the average Phase 2 skin surface temperature.

Thermal conductivity and thermal diffusivity of the solid medium (the skin) are factors in the equations for the temperature distribution. Strictly, the closed-form solution is valid only for values of these quantities that are not dependent on x, i.e., depth. This means using a single value for skin--not different values for the epidermis and dermis. Nonetheless, while it is understood that the closed-form solution is not an exact solution of the boundary value problem if these quantities are not fixed, differences from the true solution should be second-order, and use of different values for the epidermis and dermis is expected to produce first-order improvements in comparison with use of fixed values. The model, therefore, allows use of different values, and transition from epidermis to dermis values is treated in the computer program by ramping from the epidermis value to the dermis value over a four-micrometer ramp centered on the basal layer of the epidermis.

4.5 Burn injury model

Henriques (1947) demonstrated that skin burn injury can be treated as a rate process in which the progression of injury is related both to the temperature and the duration of exposure. This relationship is expressed by the following equation:

$$\Omega = G \int_0^t e^{-\Phi/RT(t)}\, dt$$

where

- Ω is the injury parameter
- R is the universal gas constant (8.31441 J/gm-mol/K)
- T(t) is the temperature at the basal epidermal layer of the skin as a function of time (K)
- G is the preexponential factor, an empirical constant (s^{-1})
- Φ/R is the activation energy factor, an empirical constant (K)
- t is time (s)

Henriques (1947), Henriques and Moritz (1947), Moritz (1947), and Moritz and Henriques (1947) describe experiments with pigs and human volunteers to determine the skin temperatures and exposure durations necessary to produce burns. From this work they determined empirical values for the constants G and Φ/R that yield Ω values that are 1.0 or greater for cases of full epidermal necrosis and less than 1.0 if necrosis of the basal epidermal layer does not occur. Thus, a value of $\Omega = 1.0$ indicates incipient second-degree burn. Henriques (1947) also suggests that a value of $\Omega = 0.53$ can be taken to be the threshold of first-degree burn (erythema with no cell necrosis). The Henriques burn integral is not predictive of any other types of burn injury, although it may be possible to extend its applicability if supportive experimental data are obtained. Without guidance from additional burn injury studies, it is necessary to interpret any value of Ω greater than 1.0 as indicating, simply, a second-degree burn.

Henriques and Moritz' experimental work determined the best-fit values of the constants for the burn integral to be

$$G = 3.1 \times 10^{98}\ s^{-1} \qquad \text{(Henriques-Moritz)}$$
$$\Phi/R = 75000\ K \qquad 44 \le T < 50^\circ\ C$$

for exposure temperatures in the range 44 to 50° C. These constants are called the preexponential factor and the energy activation factor, respectively. Since there are other values of these two constants that are suitable for use in burn prediction, they are not defined as model constants in the BURN program but, rather, must be specified by the user in the input data set AIRBAG or HEATGUN. A critical depth value, i.e., the depth of the basal layer of epidermal cells, is also required in the AIRBAG or HEATGUN data set. A value of 0.000072 m, or sometimes 0.000080 m, is normally used.

There is a thorough discussion of the derivation and use of the burn injury integral in Torvi (1992), Weaver and Stoll (1969), Reed and Schneider (1994), and Reed, Schneider, and Burney (1994).

4.5.1 Injury integral constants.

Torvi (1992) describes three different sets of values for burn integral constants that may be suitable for use in predicting burn in short-duration exposures. These are (a) the original values of Henriques and Moritz and the values determined in later studies by (b) Weaver and Stoll (1969) and (c) Mehta and Wong (1972,1973). The values of the constants for the preexponential factors and the activation energy factors are shown in Table 3.

The work of Henriques and Moritz was for long-duration exposures, mostly in the range of one to ten minutes. Heat was transferred by conduction from a medium of temperature 44 to 50° C and zero velocity relative to the skin surface. Because the exposure durations were long, the skin surface and basal epidermal layer maintained approximately the same temperature as the exposure medium. Since typical airbag exhaust exposure durations are small fractions of a second and produce critical depth temperatures that often exceed 50° C, it is uncertain that the Henriques-Moritz values for the two burn integral constants are the best ones to use in airbag exhaust simulation studies. Torvi (1992), however, has reported using all of the sets of values from Table 3 and calculating similar required exposure times for incipient second-degree burn for heat fluxes that produce burn in 0.22 to 2.78 s.)

Shorter-duration, higher-intensity exposures were considered by Stoll and Greene (1959), Stoll and Chianta (1968), and Weaver and Stoll (1969). From this work Weaver and Stoll determined values for preexponential and activation energy factors that may be more appropriate than the Henriques-Moritz values for use in burn studies related to exposure to airbag exhaust. Even so, exposure durations in this work were in seconds and so would still exceed airbag exhaust exposure times, although heat fluxes were lower. The values of Weaver and Stoll, below, are recommended by both Morse, et al. (1975) and Torvi (1992) for use in prediction of first- and incipient second-degree burns resulting from short exposure durations. The values for $T \geq 50^\circ$ C, in particular, are probably the most appropriate ones to use for airbag simulations.

$$G = 2.185 \times 10^{124}\ s^{-1} \qquad \text{(Weaver-Stoll)}$$
$$\Phi/R = 93534.9\ K \qquad 44 \leq T < 50^\circ\ C$$

$$G = 1.823 \times 10^{51}\ s^{-1} \qquad \text{(Weaver-Stoll)}$$
$$\Phi/R = 39109.8\ K \qquad T \geq 50^\circ\ C$$

Table 3
Burn Integral Constants

Investigators	Preexponential Factor[1,2] coeff	Preexponential Factor[1,2] power	Activation[3] Energy Factor	Conditions[4]
Henriques-Moritz	3.1	98	75000.	44 ≤ T < 50° C
Weaver-Stoll	2.185	124	93534.9	44 ≤ T < 50° C
Weaver-Stoll	1.823	51	39109.8	T ≥ 50° C
Mehta-Wong	1.43	72	55000.	---

[1]The burn integral preexponential factor is coefficient * 10 ^{power}.
[2]G, the preexponential factor (s^{-1})
[3]Φ/R, the activation energy factor (K)
[4]T is the average skin surface temperature, which may be assumed the same as the average temperature of the basal epidermal layer for long exposure times.

4.5.2 Method of solution. The time history of the temperature at the critical depth is determined by the heat transfer model, module 4. The burn injury integral is calculated in a postprocessing operation by integrating the stored values for the temperature. The contributions from Phase 1 (during exposure) and Phase 2 (after exposure) are both calculated, with Ω then being the sum of the two. Typically, the Phase 2 contribution is several times larger than the Phase 1 contribution.

The same Runge-Kutta integration algorithm used for solving the equations of gas thermodynamics is used for calculating the burn injury integral. The procedure is not straightforward, however, because of the numerical size of the factors in the calculation. Power-of-ten exponent sizes are greater and smaller than allowed in FORTRAN. It may be seen from Table 3, for example, that depending on which set of burn integral constants are used, the preexponential factor, G, may be as large as approximately 2×10^{124}. Correspondingly, if a value of, say, 1.0 is to be calculated for Ω, the integral itself will be approximately 0.5×10^{-124} and integrand values will be even smaller. This computation problem is solved by reformulating the equation with exponent biases for both the preexponential factor and the exponential in the integrand. The bias used is $\pm\Phi/RT_{avg}$, where T_{avg} is the average value of T(t) over the range [0,t]. Logarithm function evaluations are used to obtain coefficient and power values for the two factors (G and the integral) in the equation.

4.6 Search feature

4.6.1 Search for critical conditions. It is useful to be able to determine the exposure duration that will produce first-degree (or second-degree) burn for specified jet velocity and temperature and other conditions, including epidermis thickness. The UMTRI Airbag Skin Burn Model includes a "search" feature that will find that particular exposure duration for a heat-gun simulation. Additionally, it can find the gas jet velocity that will produce first-degree (or second-degree) burn for specified jet temperature and exposure duration, and it will similarly find the critical temperature for given duration and velocity values. Also, for given values for duration, temperature, and velocity, the model can find the depth at which basal epidermal cells would have to be for incipient first- or second-degree burn injury to occur.

4.6.2 Heat-gun simulations. The search feature cannot be used in airbag simulations--only heat-gun simulations. In the case of airbag simulations all three gas jet quantities for which a critical value might be sought are completely determined by the gas thermodynamics. In normal (non-search) heat-gun simulations, however, the three quantities are *specified* by the user, and the burn injury integral, Ω, is determined. The search feature allows the user to specify, instead, any two of the three quantities--duration, temperature, and velocity--plus a value for Ω (0.53 or 1.0). It then determines the specific value for the unspecified jet parameter that will satisfy the conditions for the other two and Ω. When values are specified for all three gas jet parameters, the cell depth for the requested burn condition, Ω, can be sought. Even though the three jet parameters are known for airbag runs, the search for critical skin depth is allowed only in heat-gun runs.

Although the search feature is not directly usable in airbag simulations, its use in heat-gun burn studies provides helpful guidance in relation to airbag system design. Additionally, indirect use can be made for airbag simulations by specifying values obtained from an airbag simulation for two of the three jet parameters, duration, temperature, and velocity, plus a value for Ω. The model will determine the value for the unspecified exhaust parameter that would produce the specified Ω.

4.6.3 Method of solution. In a normal heat-gun simulation the duration, temperature, and velocity are inputs to the impinging jet model. After the heat transfer coefficient is calculated, the heat transfer and burn injury models determine, in turn, the temperature distribution in the skin as a function of time and the burn injury parameter (Ω). In a "search-for-critical-condition" simulation, these three submodels are run repeatedly in a loop for different values of the unspecified jet parameter or epidermis thickness until satisfactory convergence to the desired Ω value has been accomplished. An interval-halving method is used, which guarantees fast convergence to the solution.

5.0 HOW TO USE THE MODEL

In Section 3.0, "Overview of the Computer Model," it was explained that the user provides input data in formatted ASCII files of specific names and that simulation results are written to two, three, or four output files, depending on user requests. This section discusses the input data requirements and the model outputs.

The BURN model input and output files are summarized in Table 1, which is repeated below for convenience as Table 4.

Table 4
Input and Output Data Files

Data File Type	File Name	Type of Simulation	Status	Contents
input	AIRBAG	airbag	required	constants/controls
input	M1TDOT	airbag	required	mass flow rate
input	PT	airbag	required	tank test pressure
input	HEATGUN	heat gun	required	constants/controls
output	BURNMODL.OUT	both	always	summary of results[1-6]
output	TEMPDIST.OUT	both	always	skin temp distribution[7]
output	TABLDATA.OUT	both	optional	time histories/other[5]
output	PARSED.OUT	both	optional	numbers-only summary[6]

[1]Also always includes an echo of the input data set.
[2]May optionally include a descriptive summary of input constants.
[3]May optionally include a descriptive summary of model constants.
[4]May optionally include time history outputs and other tabular data.
[5]Tabular data may be written to either BURNMODL.OUT or TABLDATA.OUT.
[6]The "Summary of Results" portion of BURNMODL.OUT can be written in parsed (numbers-only) form to PARSED.OUT.
[7]Fixed depth and time spacings and spans: 0 to 0.000200 m by 0.000001 m spacings and 0 to 500 ms by 10 ms spacings [TEMPDIST.OUT is not written for heat-gun "search" runs.]

5.1 Input data

Different input data files are required depending on whether an airbag simulation or a heat-gun simulation is to be run. The data files must be "flat ASCII" files--that is, text files that do not have embedded control characters, such as would be produced by some word processors. To prepare such data files use any simple text editor or use any word processor that has a flat-ASCII option. Lines in all of the data files can be of any length, but in the files "AIRBAG" and "HEATGUN" the BURN program will ignore line content after the 80th character.

Example input data files and associated run output files are included on the BURN model distribution diskette, which is described in Appendix A.

5.1.1 Airbag simulations. Input data for airbag runs must be in three files with the specific names AIRBAG, M1TDOT, and PT. Data file AIRBAG contains all system constants and user controls for the simulation. Tank test data for the inflator are provided by the user in files M1TDOT and PT. M1TDOT contains the time history data for mass flow rate in the tank test, i.e., $\dot{m}_{1T}(t)$ (in kg/s). PT contains the time history data for pressure in the tank test, i.e., $P_T(t)$ (in kPa gauge).

5.1.1.1 AIRBAG data set. Data for an AIRBAG data set are illustrated in Figure 2. Two things should be noted before a discussion is given of the quantities in the data file. First, each numeric input quantity is assigned a general-format numeric field of eight-character width. That is, the first numeric value on a line should be in columns 1-8, the second should be in columns 9-16, etc. Comma-delimited fields are not allowed. Second, every valid AIRBAG data set has only 20 lines of data used by the program in the simulation. In Figure 2 these 20 lines are:

```
1.      .0005
...
...
3.1     98.     75000.                    Henriques-Moritz    [44,50] C
```

All other lines in the Figure 2 data set are comment lines; they are unnecessary but can often be helpful. The user can remove such lines or include any of his own choosing. Comment lines must begin with one of the following specific characters:

; : * # $ @

Comments may also be added after the used data fields on any line (with or without a preceding special character). Completely blank lines are allowed anywhere in the AIRBAG data set.

```
* Airbag   [8-character data fields]  [ Comment lines begin with ;:*#$@ ]

*line 1: Integration method (1.=R-K) and stepsize (s)
*line 2: Output specifications -- SW1, SW2, KTAB(1-25)  FORMAT(2g8.0, 25I1)
;       Field 1: summary outputs (results and input data summary)
;         =1., summary of results, summary of input data, summary of model consts
;         =2., summary of results, summary of input data
;         =3., summary of results only
;         <0., as above but also print parsed results summary (to separate file)
;       Field 2: tabular output data, including time histories
;         =0., print no tabular data to file
;         =1., print all tabular data to file [KTAB() specifications optional]
;              KTAB(i) for table i: 0 = do not write to file, 1 = write to file,
;              2 = write every 2nd point to file (time histories 7-14,18-25)
;         =2., default (selected) tables to file
;              Table No.  1 2 3 4 5 6 7 8 910111213141516171819202122232425
;              Default    0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 0 0 2 0 0 0 0 0 0
;         <0., as above but write tabular data to different file from summaries
*line 3: Reduced duration (s) for exposure to airbag exhaust if abs() is nonzero
;         =0., use exhaust duration calculated from the airbag thermodynamics
;         >0., reduced duration; ignore the first portion of calc'd exhaust data
;         <0., reduced duration; ignore the last portion of calc'd exhaust data
*line 4: Gas identification:  a) nitrogen or 1.  or  b) air or 2.
*line 5: Ambient temperature (°C)   [include K in field if Kelvin]
*line 6: Initial skin surface temperature (°C)   [include K in field if Kelvin]
*line 7: Tank test volume (m**3)
*line 8: Vent diameter (m) and number of vents
*line 9: Orifice coefficient for vent and fabric area
*line 10: Fabric stretch factor (any value .ge. 0, or -1. for lin. regr. on V20)
;          (e.g., 3.81e-6 m²/(N/m²)/m²)
*line 11: Occupant interaction specifications: 0.=no interaction, 1.=interaction
;            If field 1 is 1., fields 2 through 7 must contain the following data
;            for simulation of a pendulum impact against the airbag.
;            f.2:  moment of inertia about pivot point (kg m**2)
;            f.3:  distance from pivot point to center of airbag contact (m)
;            f.4:  pendulum angular velocity at contact if positive (rad/s);
;                  linear velocity if negative (m/s)
;            f.5:  maximum contact area for pendulum/airbag interaction (m**2)
;            f.6:  airbag deflection over which max contact area is reached (m)
;            f.7:  airbag depth, i.e., deflection for bottoming out (m)
*line 12: Nominal airbag volume (m**3)
*line 13: H/D ratio: H, distance from vent to skin surface; D, jet diameter
*line 14: r/D ratio: r, effective radius of target area; D, jet diameter
*line 15: Multiplicative tuning factor for Phase 1 heat transfer coefficient
*line 16: Effective Qdot for Phase 2 heat transfer (.ge. 0; e.g., 1400 W/m**2)
*line 17: Thermal conductivities of epidermis and dermis (W/m/K) (nonzero)
*line 18: Thermal diffusivities of epidermis and dermis (m**2/s); if a negative
;          value is specified in field 1 (epidermis), fields 3 and 4 must contain
;          nonzero values for density (kg/m**3) and specific heat (J/kg/K);
;          fields 5 and 6 are used similarly for the dermis if field 2 is neg.
*line 19: Critical cell depth (micrometers)
*line 20: Burn integral constants: preexponential factor coefficient and power,
;          and delE/R (activation energy divided by gas constant)

1.      .0005
2.      -1.     1111111111111111112111111
0.
nitrogen
20.85      Blank lines and comment lines beginning with ; : * # $ @ are allowed.
35.85      Comments can also be added after the data fields on any line.
.028317
0.035   2.
0.6
0.
0.      143.1   1.332   4.95    0.15    0.100   0.254
0.06
3.0
1.
.55
1400.
0.20949 0.3791
7.267E-8 1.43E-7
72.
3.1     98.     75000.                  Henriques-Moritz    [44,50] C
```

Figure 2. Illustration of Input Data in AIRBAG Data Set.

The comment lines included in Figure 2 describe the input quantities that comprise the data set, line by line and field by field. Some of these quantities need little explanation beyond the short one given in the comment lines. Additional clarification of most quantities is given below. For dimensional quantities, units are given in parentheses after the name of the quantity.

Line 1

Field 1: Integration method (1.=R-K)

Currently only one numerical integration method is supported--viz., a fourth-order, fixed-stepsize Runge-Kutta algorithm. The user should enter "1." here, but the program will in fact ignore the value entered.

Field 2: Stepsize (s)

The integration stepsize entered should be "0.0005" s, i.e., half a millisecond. Certain arrays in the source code currently are not dimensioned large enough to allow smaller stepsizes. Simulations conducted to date, including a small number with stepsizes of 0.001 s and 0.00025 s, suggest that 0.0005 s should be sufficiently small for both airbag and heat-gun simulations. Although *Mathematica* simulations with the first version of the UMTRI airbag skin burn model were conducted with a one-millisecond step size, the smaller half-millisecond step is recommended.

Line 2

On Line 2 the user specifies the types of outputs desired from the program. There are two basic types of outputs--summary results and tabular data, including time histories. The user has options with regard to each type.

Field 1: Summary outputs (results and input data summary)

Three types of summary output are available in all airbag runs. The first is a summary of simulation results, which is written to the BURNMODL.OUT file following an echo of the input data set. The user does not have an option to suppress the "Summary of Results" output. The second type of summary output is a descriptive version of the input data set, which may be particularly helpful if the AIRBAG data set used does not contain sufficiently descriptive comment lines. The third type of summary output is a description of the "model constants," i.e., constants that are included in the code and over which the user has no control. The universal gas constant is one such constant, for example.

To obtain all three types of summary output the user should enter "1." in field 1. To obtain only the first two (i.e., suppressing the least important of the three, the summary of model constants) enter "2." To obtain only the "Summary of Results" output (the values that summarize the results of the simulation, such as exposure duration, average temperature of the exhaust, the value of the calculated burn injury integral, Ω, etc.) enter "3." A parsed version of the "Summary of Results" output (i.e., with numbers only) can also be obtained if desired by making the entry in this field negative, either "-1.", "-2.", or "-3." If the parsed output is requested, it will be written separately to the file PARSED.OUT. All other summary outputs are written to the file BURNMODL.OUT.

Field 2: Tabular output data, including time histories

Tabular output data can be obtained for any of 25 different quantities. These are listed in Table 5. The value in this field has no bearing on the tabular output for skin temperature as a function of time and depth, which is always written to file TEMPDIST.OUT.

If no tabular outputs are desired, enter "0." in this field. To obtain any or all tables, enter "1." If a default selection of tables (see below) is desired, enter "2." instead. To obtain selected tables (that is, for "1." in this field) the user may specify which tables are desired by entering values 0, 1, or 2 in columns 17-41, the 25 columns immediately after the first two eight-character data fields. An example is illustrated below.

<u>Selecting output tables</u>

```
1.........................25
0000110011110000012111100          (and "1." in field 2)
```

In this example no output for tables 1-4, 7, 8, 13-17, 24, or 25 is desired. This is specified by a "0" in the respective positions. A "1" indicates that the table is desired. The "2" for table 19 (for time histories only) indicates that the values for that table should be written but only for every second integration time step (i.e., the 1st, 3rd, 5th, etc.) A "1" requests that the values be written for all time steps.

<u>Default selection of output tables</u>

The specific selection of output tables indicated below may be obtained by simply entering a "2." in field 2. Tables 5, 6, 9-12, and 19 are written. Only every second time step (viz., one millisecond intervals for the half millisecond stepsize) is written for table 19, the skin temperature at critical depth. That particular time history is always 500 ms in duration.

```
1.........................25
0000110011110000002000000     <—— default selection if "2."
                                   is in field 2
```

<u>Directing tabular output to BURNMODL.OUT or TABLDATA.OUT</u>

Tabular outputs will be written to BURNMODL.OUT, following the summary outputs, unless the value specified for field 2 is negative. To have selected tables written to the file TABLDATA.OUT instead, enter "-1." To write the default selection to file TABLDATA.OUT, enter "-2."

<u>Line 3</u>

Field 1: normally "0."

This field should normally be "0." Zero indicates that the exhaust duration determined from integration of the gas thermodynamics equations should be used for the gas jet exposure to the skin. If a positive number is entered, however, it will be treated as the number of seconds of the first portion of the exhaust data that should be ignored. If a negative number is entered, then the exhaust duration will similarly be reduced except that the last portion of the exhaust time histories will be ignored. The only possibly reasonable use of a nonzero value in this field would be to trim off the "rise-time" portion of the beginning of exhaust, during which exhaust temperature has not yet reached its plateau.

Line 4

Field 1: Gas identification

Enter "1." or "nitrogen" to select nitrogen as the gas to use in the simulation. Enter "2." or "air" for air. Nitrogen should probably always be selected for airbag simulations.

Line 5

Field 1: Ambient temperature (°C) [include K in field if Kelvin]

The ambient temperature is entered here. "Room temperature" is usually used. The value entered will be treated as a Celsius temperature unless a "K" is included in the field, in which case it will be treated as a Kelvin temperature. A "C" may be included, although unnecessary, to indicate a Celsius temperature.

Line 6

Field 1: Initial skin surface temperature (°C) [include K in field if Kelvin]

The initial skin surface temperature, entered here, is used for all skin depths in the current model. As for the value in Line 5, a "K" can be included in the field if it is desired to enter a Kelvin value. Otherwise, the value will be treated as a Celsius temperature.

Line 7

Field 1: Tank test volume (m^3)

The tank volume entered here must be for the specific tank used in the test to obtain the data in files M1TDOT and PT for tank test mass flow rate and pressure.

Line 8

Field 1: Vent diameter (m) (Vents are assumed to be circular.)

Field 2: Number of vents

Line 9

Field 1: Orifice coefficient for vent and fabric area

The effect of gas jet contraction from a vent area A to a vena contracta area B is modeled by using the (effective) exhaust jet diameter $D_{23} = 2\ (\pi\ A_{eff})^{1/2}$ for the effective area $A_{eff} = B = C_{23}\ A$, where $C_{23} = B\ /\ A$ is called the orifice coefficient. Experimentally determined values are normally in the 0.6-0.7 range. Values should probably never be less than 0.6.

The effect of gas loss through porous airbag fabric can perhaps be modeled crudely by assigning an "orifice coefficient" that accounts for porosity effects as well as the vena contracta for exhaust from a vent, but analytical enhancements to the model should be made if serious study of fabric porosity effects is to be done with this model.

Line 10

Field 1: Fabric stretch factor ($m^2/(N/m^2)/m^2$)

The airbag thermodynamics equations include a term for the effect of fabric stretch. An empirical relationship to the nominal airbag volume V_{20} is $Cs = 2.45 \times 10^{-6} + 2.27 \times 10^{-5}\ V_{20}$. A typical experimental value is $3.81 \times 10^{-6}\ m^2/(N/m^2)/m^2$.

Enter "0." to ignore the effects of fabric stretch or enter an appropriate value. To request use of the above linear regression to V_{20}, enter "-1."

Line 11

Field 1: Occupant/airbag interaction option

Occupant/airbag interaction can be modeled, if desired, by specifying data for a pendulum impact against the airbag. (See Section 4.2.) For no occupant/airbag interaction, enter "0." in field 1. To simulate occupant interaction enter "1." and enter appropriate values in fields 2 through 7.

Field 2: Moment of inertia about pivot point ($kg \cdot m^2$)

The moment of inertia of one particular pendulum and torso form that have been used in both steering assembly and airbag impact testing, is 143.1 $kg \cdot m^2$. The distance from the pivot point to the center of contact on the torso form is 1.332 m.

Field 3: Distance from pivot point to center of airbag contact (m)

(See field 2.)

Field 4: Pendulum impact velocity (rad/s or m/s)

If a positive value is entered, it is treated as the initial angular velocity (rad/s) at contact. A negative value indicates a linear velocity (m/s). A typical occupant impact velocity of about 6.6 m/s is obtained by entering 4.95 rad/s as the initial angular velocity if the pendulum length is 1.332 m.

Field 5: Maximum contact area for pendulum/airbag interaction (m^2)

Enter an estimate of the area of contact between the airbag and the occupant (pendulum) at full contact. A value of approximately 0.15 m^2 is normally reasonable.

Field 6: Length of deflection ramp for full contact area (m)

Enter an estimate of the deflection at which full contact, i.e., maximum area, between the occupant and the airbag is reached. A value of approximately 0.1 m is reasonable for many airbag designs.

Field 7: Airbag depth (m)

Specify the deflection of the full airbag at which occupant interaction would "bottom out." A value of approximately 0.25 m is reasonable for many airbag designs.

<u>Line 12</u>

Field 1: Nominal airbag volume (m^3)

The value entered here should be the volume of the fully inflated airbag.

<u>Line 13</u>

Field 1: H/D ratio

The H/D ratio is used for calculating a correction factor for the Nusselt number. Its value should be in the range 1.0 to 12.0. The correction factor does not vary more than about 20 percent over the entire range of allowed H/D and r/D values, so the exact value of H/D is not critical. H is the distance from the vent to the skin surface, and D is the jet diameter at the vena contracta, D_{23}, which is the vent diameter multiplied by the square root of the orifice coefficient, C_{23}. The dependence of the correction factor on H/D and r/D is shown in the table below. (Also see Section 4.3.1 and output table 17.)

Nusselt number correction factor, k(H/D, r/D)

H/D	r/D	k(H/D, r/D)
1.0-6.65	all	1.03
7.5	all	1.0
12.0	0.0	0.775
12.0	1.0	0.775
12.0	2.0	0.80
12.0	3.0	0.81
12.0	5.0	0.86
12.0	7.0	0.90

(linear interpolation for other values of H/D and r/D)

Line 14

Field 1: r/D ratio

The r/D ratio is used with H/D for calculating a correction factor for the Nusselt number, which is directly proportional to the heat transfer coefficient for the jet/skin interface. See the discussion above for line 13. The value of r/D should be in the range 0. to 3. The quantity r is the radius of the area over which the Nusselt number is averaged, which can normally be considered the skin surface area that may be burned. A value of r = 1.0 is probably most appropriate for a wide range of H values. D ($=D_{23}$) is the same diameter described for line 13.

Line 15

Field 1: Multiplicative tuning factor for the heat transfer coefficient

While the skin burn model produces results that are in good qualitative agreement with heat-gun experiment results, direct use of the heat transfer coefficient calculated by the impinging jet heat transfer model causes burns to be predicted for exposure durations that are smaller than found experimentally. For a wide range of experimental conditions, the best corrected simulation results are obtained with the current model by using a multiplicative tuning factor of 0.55 to 0.6.

Line 16

Field 1: Effective heat flux for post-exposure heat transfer (W/m^2)

The heat flux at the skin surface following exposure to the hot gas jet is very small in comparison to the heat flux during exposure because the temperature differential is smaller and also because the heat transfer coefficient is much smaller for quiescent air. Simulation results are not sensitive to the value specified here as long as it is small in comparison with the average heat flux during exposure. A value of zero is reasonable for this field. UMTRI has used a value of 1400 W/m^2 in some simulations.

Line 17

Field 1: Thermal conductivity of the epidermis (W/m/K) (nonzero)

Torvi (1992; pp. 55, 70-77, 93) reports that the range of published values for thermal conductivity of the epidermis is 0.21 to 0.26 W/m/K. In simulations for values within this range he found that results are not sensitive to thermal conductivity for high intensity exposures.

Field 2: Thermal conductivity of the dermis (W/m/K) (nonzero)

Torvi has found published values for the dermis to be in the range 0.37 to 0.52 W/m/K and that simulation results are not sensitive to the value used.

Line 18

Field 1: Thermal diffusivity of the epidermis (m^2/s) (nonzero)

If positive, the value is the thermal diffusivity. If any negative value is entered (e.g., "-1."), then the thermal diffusivity will be calculated from the thermal conductivity and the values in fields 3 and 4. (The thermal diffusivity is equal to the thermal conductivity divided by the product of the density and the specific heat.)

Calculations from published values reported by Torvi (1992; pp. 55, 70-77, 93) show thermal diffusivities of the skin to vary by about 20 percent from their mean. Torvi uses values near the low end of the range. His value for the epidermis is 5.906×10^{-8} m^2/s. UMTRI has used a value 7.267×10^{-8} m^2/s, which is near the high end of the range.

Torvi (pg. 93) finds that the values used for volumetric heat capacities -- or, equivalently, thermal diffusivity -- are important in high-intensity exposures.

Field 2: Thermal diffusivity of the dermis (m^2/s) (nonzero)

If positive, the value is the thermal diffusivity. If any negative value is entered (e.g., "-1."), then the thermal diffusivity will be calculated from the thermal conductivity and the values in fields 5 and 6.

Calculations from published values for the dermis that are reported by Torvi (pp. 55, 76) yield a range of 1.411×10^{-7} to 2.152×10^{-7} m^2/s. Torvi uses 1.353×10^{-7} m^2/s. UMTRI has used 1.43×10^{-7} m^2/s.

Field 3: Density of the epidermis (kg/m^3)

A nonzero value must be entered here for the density of the epidermis only if some negative number was entered in field 1 instead of a value for the thermal diffusivity.

Field 4: Specific heat of the epidermis (J/kg/K)

A nonzero value must be entered here for the specific heat of the epidermis only if some negative number was entered in field 1 instead of a value for the thermal diffusivity.

Field 5: Density of the dermis (kg/m^3)

A nonzero value must be entered here for the density of the dermis only if some negative number was entered in field 2 instead of a value for the thermal diffusivity.

Field 6: Specific heat of the dermis (J/kg/K)

A nonzero value must be entered here for the specific heat of the dermis only if some negative number was entered in field 2 instead of a value for the thermal diffusivity.

Line 19

Field 1: Critical cell depth (micrometers)

Second-degree burn is indicated by full necrosis of the epidermis. Thus, the critical cell depth for incipient second-degree burn is the depth of the basal epidermal layer. Values of 72 to 80 micrometers are reasonable.

Line 20

Field 1: Coefficient for preexponential factor in calculation of burn injury parameter (s^{-1})

The Weaver-Stoll or Henriques-Moritz values are recommended for fields 1, 2, and 3. See Section 4.5 and Table 3.

Field 2: Power (of 10) for preexponential factor in calculation of burn injury parameter

Field 3: Activation energy factor in calculation of burn injury parameter (K)

Table 5
Tables for Optional Output to BURNMODL.OUT or TABLDATA.OUT

Table Number	Description
	All tables may be obtained for airbag simulations. Only tables 1-4 and 15-19 are relevant to heat-gun simulations.
1	**kinematic viscosity** of gas as a function of temperature (nitrogen or air) [m^2/s]
2	**thermal conductivity** of gas as a function of temperature (nitrogen or air) [W/m/K]
3	**Prandtl number** of gas as a function of temperature (nitrogen or air) [·]
4	**ratio of specific heats** of gas, C_p, as a function of temperature (N_2 or air) [·]
5	**inflator mass flow rate,** $\dot{m}_{1T}$, as a function of time [kg/s]
6	**time rate of change of pressure in tank in tank test,** $\dot{P}_T$; function of time [Pa/s]
7	**volume of gas in airbag** as a function of time [m^3]
8	**gas mass in airbag,** m_2, as a function of time [kg]
9	**gas pressure in airbag,** P_2, as a function of time [Pa, absolute]
10	**gas temperature in airbag,** T_2, as a function of time [K]
11	**exhaust velocity** as a function of time [m/s]
12	**exhaust temperature** as a function of time [K]
13	**time integral of** u^n, where n is dependent on r/D; function of time [m^n/s^{n-1}]
14	**time integral of exhaust temperature** as a function of time [K·s]
15	**Martin's coefficient C for circular impinging gas jet** as a function of r/D [·]
16	**Martin's exponent n for circular impinging gas jet** as a function of r/D [·]
17	**Martin/Schlünder-Gnielinski correction factor for Nusselt number** at H/D=12 as function of r/D; approximation from Martin graph [·]
18	**gas-to-skin heat transfer coefficient** as a function of time [$W/m^2/K$]
19	**skin temperature at critical depth** as a function of time [K]
20	**airbag deflection from pendulum contact** as a function of time [m]
21	**airbag deflection velocity from pendulum contact** as a function of time [m/s]
22	**airbag deflection acceleration from pendulum contact**; function of time [m/s^2]
23	**pendulum/airbag force** as a function of time [N]
24	**airbag volume decrease from pendulum contact** as a function of time [m^3]
25	**rate of decrease of airbag volume from pendulum contact**; function of time [m^3/s]

5.1.1.2 M1TDOT and PT data sets. Example data for the M1TDOT and PT data sets are shown in Figures 3 and 4. These data sets contain the tank test data for the inflator to be simulated. M1TDOT and PT are for the mass flow rate and tank pressure, respectively. The first line of each data file is treated as a 32-charactor description of the inflator data. The pair of data sets, M1TDOT and PT, should contain the same 32-character description. A blank card must be included as a header line if a description is not provided. All other lines in each data set contain numeric data. The first value on each line is the time in seconds. The second value is either $\dot{m}_{1T}$ or P_T with units of kg/s or kPa (gauge), respectively. (One Pascal is one N/m^2.) The data points need not be equally spaced in time. The values are read from two general-format numeric fields of eight-character width--that is, the data must be in columns 1-8 and 9-16. Comma-delimited fields are not allowed. Since mass flow rate cannot be measured directly in tank tests, it is normally calculated by inflator manufacturers by using an analytical technique. Wang (1991) and Reed and Schneider (1994) describe the method usually used.

Inflator Capacity: 487 kPa

0	0
0.001	0
0.002	0
0.003	2.079
0.004	1.29
0.005	1.386
0.006	1.462
0.007	1.521
0.008	1.562
0.009	1.58
0.01	1.588
0.011	1.575
0.012	1.539
0.013	1.484
0.014	1.425
0.015	1.361
0.016	1.301
0.017	1.24
0.018	1.19
0.019	1.139
0.02	1.089
0.021	1.04
0.022	0.993
0.023	0.945
0.024	0.9
0.025	0.853
0.026	0.809
0.027	0.787
0.028	0.726
0.029	0.686
0.03	0.648
0.031	0.612
0.032	0.576
0.033	0.543
0.034	0.511
0.035	0.481
....	
....	
0.053	0.059
0.054	0.044
0.055	0.03
0.056	0.017
0.057	0
0.058	0
....	
....	
0.205	0
0.21	0

Figure 3. Example Input Data in M1TDOT Data Set

```
Inflator Capacity: 487 kPa
0        0
0.001    0
0.002    0
0.003    6.23
0.004    10.7
0.005    17.9
0.006    26.9
0.007    37.2
0.008    49.9
0.009    64.7
0.01     81.4
0.011    99.3
0.012    118.1
0.013    137.8
0.014    157.99
0.015    177.9
0.016    197
0.017    216
0.018    234
0.019    251
0.02     266
0.021    280
0.022    294
0.023    308
0.024    322
0.025    336
0.026    348
0.027    371
0.028    381
0.029    391
0.03     400
0.031    408
0.032    415
0.033    422
0.034    429
0.035    434
...........
...........
0.047    479
0.048    481
0.049    483
0.05     484
0.051    486
0.052    487
0.053    487
...........
...........
0.203    487
0.208    487
```

Figure 4. Example Input Data in PT Data Set

5.1.2 Heat-gun simulations. Only one input data file is used in heat-gun simulations. This file must have the name HEATGUN. Its layout is nearly identical to that of the AIRBAG data file. It differs importantly only in (a) not having airbag system constants and (b) requiring specification of exposure duration, temperature, and velocity--quantities that are determined for airbag simulations by the airbag gas thermodynamics. An example HEATGUN data set is illustrated in Figure 5.

5.1.2.1 Search simulations. An option for heat-gun simulations is a search for critical conditions, which is described in Section 4.6. Instead of specifying the (four) values for epidermis thickness and gas jet duration, temperature, and velocity, the user can specify only three and request the model to find the value of the fourth quantity such that either 0.53 or 1.0 will result for Ω, i.e., either first- or second-degree burn. User specifications for the search are entered on data lines 6, 7, 8, and 17 of the HEATGUN data set, as described below in Section 5.1.2.2.

5.1.2.2 HEATGUN data set. Only the differences between the layouts of the HEATGUN and AIRBAG data sets are discussed below. The user is referred to the descriptions in Section 5.1.1.1 for all quantities in the HEATGUN data set that are the same as ones in the AIRBAG data set.

There are 18 data lines in a valid HEATGUN data set.

Line 1 Integration controls -- See Section 5.1.1.1, Line 1.

Line 2 Output controls -- See Section 5.1.1.1, Line 1 (and below).

The only difference from the information for the same data line in an AIRBAG data set is that the default tabular outputs are different. Further, as may be seen from Table 5, only output tables 1-4 and 15-19 are relevant for heat-gun simulations.

```
1  4            15   19
0000            00002          <—— default selection if "2."
                                   is in field 2
```

Line 3 Gas identification -- See Section 5.1.1.1, Line 4.

Line 4 Ambient temperature -- See Section 5.1.1.1, Line 5.

Line 5 Initial skin surface temperature -- See Section 5.1.1.1, Line 6.

Line 6 Duration of exposure to heat-gun jet

Field 1: Duration (s)

A positive value entered here is the duration of exposure to the heat-gun jet. Alternatively, provided that positive values are specified for temperature and velocity on lines 7 and 8 and critical cell depth on line 17, a negative value can be entered in this field to request a search for the particular duration that will yield either a first-degree burn or a second-degree burn. To search for the exposure duration for incipient first-degree burn (Ω = 0.53), enter "-1." To find the exposure duration for incipient second-degree burn (Ω = 1.0), enter "-2."

Line 7 Temperature of heat-gun jet

Field 1: Temperature (°C) [include K in field if Kelvin]

A positive value entered here is the temperature of the heat-gun jet. (As for other temperature values in AIRBAG and HEATGUN, a "K" can be included in the field to indicate a Kelvin value.) Alternatively, provided that values are specified for duration and velocity on lines 6 and 8 and critical cell depth on line 17, a negative value can be entered in this field to request a search for the particular gas temperature that will yield either a first-degree burn or a second-degree burn. To search for the exposure temperature for incipient first-degree burn ($\Omega = 0.53$), enter "-1." To find the exposure temperature for incipient second-degree burn ($\Omega = 1.0$), enter "-2."

Line 8 Velocity of heat-gun jet

Field 1: Velocity (m/s)

A positive value entered here is the velocity of the heat-gun jet. If a negative value not equal to -1. or -2. is entered, the value will be treated as a pitot tube pressure differential in inches of water, from which the velocity will be calculated by the program.

Alternatively, provided that positive values are specified for duration and temperature on lines 6 and 7 and critical cell depth on line 17, a negative entry can be made in this field to request a search for the particular jet velocity that will yield either a first-degree burn or a second-degree burn. To search for the velocity for incipient first-degree burn ($\Omega = 0.53$), enter "-1." To find the velocity for incipient second-degree burn ($\Omega = 1.0$), enter "-2."

Line 9 Port diameter (m) -- See Section 5.1.1.1, Line 8.

Line 10 Orifice coefficient for port -- See Section 5.1.1.1, Line 9.

Line 11 H/D ratio -- See Section 5.1.1.1, Line 13.

Line 12 r/D ratio -- See Section 5.1.1.1, Line 14.

Line 13 Multiplicative tuning factor for the heat transfer coefficient -- See Section 5.1.1.1, Line 15.

Line 14 Effective heat flux for post-exposure heat transfer (W/m^2) -- See Section 5.1.1.1, Line 16.

Line 15 Thermal conductivities of the epidermis and dermis (W/m/K) -- See Section 5.1.1.1, Line 17.

Line 16 Thermal diffusivities of the epidermis and dermis (m^2/s) -- See Section 5.1.1.1, Line 18.

Line 17 Critical cell depth (micrometers) -- See Section 5.1.1.1, Line 19.

Line 18 Burn integral constants -- See Section 5.1.1.1, Line 20.

```
* Heat gun   [8-character data fields]  [ Comment lines begin with ;:*#$@ ]

*line 1: Integration method (1.=R-K) and stepsize (s)
*line 2: Output specifications -- SW1, SW2, KTAB(1-25)  FORMAT(2g8.0, 25I1)
;       Field 1: summary outputs (results and input data summary)
;          =1., summary of results, summary of input data, summary of model consts
;          =2., summary of results, summary of input data
;          =3., summary of results only
;          <0., as above but also print parsed results summary (to separate file)
;       Field 2: tabular output data, including time histories
;          =0., print no tabular data to file
;          =1., print all tabular data to file [KTAB() specifications optional]
;               KTAB(i) for table i: 0 = do not write to file, 1 = write to file,
;               2 = write every 2nd point to file (time histories 7-14,18-25)
;          =2., default (selected) tables to file
;               Table No.  1 2 3 4 5 6 7 8 910111213141516171819202122232425
;               Default    0 0 0 0                           0 0 0 0 2
;          <0., as above but write tabular data to different file from summaries
*line 3: Gas identification:  a) nitrogen or 1.  or  b) air or 2.
*line 4: Ambient temperature (°C)   [include K in field if Kelvin]
*line 5: Initial skin surface temperature (°C)   [include K in field if Kelvin]
*line 6: Duration of exposure to heat gun jet (s)
;           or -1. to search for the exposure duration that results in Ω=0.53
;           or -2. to search for the exposure duration that results in Ω=1
*line 7: Temperature of gas flow from heat gun (°C) [incl. K in field if Kelvin]
;           or -1. to search for the gas jet temperature that results in Ω=0.53
;           or -2. to search for the gas jet temperature that results in Ω=1
*line 8: Velocity of heat gun jet (m/s) or, if negative (and not -1. or -2.),
;           the pitot tube pressure differential in inches of water,
;           or -1. to search for the gas jet velocity that results in Ω=0.53
;           or -2. to search for the gas jet velocity that results in Ω=1
*line 9: Heat-gun port diameter (m)
*line 10: Orifice coefficient for heat-gun port
*line 11: H/D ratio: H, distance from vent to skin surface; D, gas jet diameter
*line 12: r/D ratio: r, effective radius of target area; D, gas jet diameter
*line 13: Multiplicative tuning factor for Phase 1 heat transfer coefficient
*line 14: Effective Qdot for Phase 2 heat transfer (.ge. 0; e.g., 1400 W/m**2)
*line 15: Thermal conductivities of epidermis and dermis (W/m/K) (nonzero)
*line 16: Thermal diffusivities of epidermis and dermis (m**2/s); if a negative
;          value is specified in field 1 (epidermis), fields 3 and 4 must contain
;          nonzero values for density (kg/m**3) and specific heat (J/kg/K);
;          fields 5 and 6 are used similarly for the dermis if field 2 is neg.
*line 17: Critical cell depth (micrometers)
;            or -1. to search for the cell depth for which Ω=0.53
;            or -2. to search for the cell depth for which Ω=1
*line 18: Burn integral constants: preexponential factor coefficient and power,
;          and delE/R (activation energy divided by gas constant)

1.       .0005
-1.      -1.      1111111111111111112111111
air
20.85        Blank lines and comment lines beginning with ; : * # $ @ are allowed.
35.85        Comments can also be added after the data fields on any line.
0.150
450.
66.
0.010
1.
3.0
1.0
.55
1400.
0.20949 0.3791
7.267E-8 1.43E-7
72.
3.1      98.      75000.                      Henriques-Moritz   [44,50] C
*2.185   124.     93534.9                      Weaver-Stoll   [44,50] C
*1.823   51.      39109.8                      Weaver-Stoll    >50 C
*1.43    72.      55000.                       Mehta-Wong       ---
* Comment lines must begin with one of these:  ; : * # $ @
* Comments can be added after data fields on any line (w. or w/o ;:*#$@).
* Completely blank lines are also allowed.
```

Figure 5. Illustration of Input Data in HEATGUN Data Set.

5.2 Running the model

Execution of the BURN program in DOS is very simple. The BURN.EXE file (the executable program) and the required input data sets should be in the same directory. For an airbag simulation the required data sets are AIRBAG, M1TDOT, and PT. For a heat-gun simulation only the HEATGUN data set is needed. In example outputs to the screen shown below, the name of the directory is C:\BAG, but the name of the directory used is not of consequence. To run the program from DOS type in "BURN" or "burn" at the DOS prompt (which is "C:\BAG>" in this instance). The BURN program will respond with the following output to the screen. You are asked to indicate whether you wish to make an airbag simulation or a heat-gun simulation. After you enter "1" or "2", respectively, the simulation will begin.

```
  BURN INJURY MODEL

  1 = airbag
  2 = heat gun

Enter 1 or 2:  _
```

No other keyboard inputs will be required. As the simulation proceeds, the program prints several lines to the screen that inform you of the stage of the calculations. When the calculations have been completed, the program writes a "Summary of Results" to the screen and tells you the names of the input files and output files that were used. The summary of results will always be written to BURNMODL.OUT as well as to the screen.

For a heat-gun run in which the search option was selected for the exposure duration, temperature, or velocity to produce $\Omega = 1.0$ or $\Omega = 0.53$, the results of the search are written to the screen and to BURNMODL.OUT. A summary of results is not written. The user may wish to make a second run in which the "-2." or "-1." entry for duration, temperature, or velocity is replaced by the value determined by the search. (In the case of duration use the value nearest to an integer multiple of the integration time step.)

It is noted here that since run outputs are always written to file BURNMODL.OUT, it should be renamed or copied to a file of a different name before a rerun of the BURN program. This is true, also, of file TEMPDIST.OUT and, if they are requested, files TABLDATA.OUT and PARSED.OUT. This will be discussed further in Section 5.2.3, "Batch runs on MS DOS systems."

5.2.1 <u>Outputs to the screen</u>. Outputs to the screen from three kinds of runs are shown below without further comment. These are for (1) an airbag simulation with occupant/airbag interaction, (2) a standard heat-gun simulation, and (3) a "search-for-duration" heat-gun simulation which determines the duration for $\Omega = 1.0$.

SCREEN OUTPUT FROM AN AIRBAG SIMULATION

```
C:\BAG>burn

BURN INJURY MODEL

  1 = airbag
  2 = heat gun

Enter 1 or 2:  1

Inflator Capacity: 487 kPa
Simulation with occupant interaction

Integrating equations of airbag gas thermodynamics...
Determining skin surface temp T(0,t) and heat transfer coefficient h(t)...
Finding distribution of skin temperatures T(x,t) during exposure to gas jet...
Calculating Phase 1 burn injury criterion function...
Finding distribution of skin temperatures T(x,t) after exposure to gas jet...
Calculating Phase 2 burn injury criterion function...

                          SUMMARY OF RESULTS

        Burn Injury Integral Ω for Critical Depth 72 µm

 Inflator Capacity: 487 kPa              Gas: nitrogen
 Occupant Contact:  yes                  Vent diameter: 35.00 mm

                          During          After
                         Exposure        Exposure          Total

 Time range (ms)          0.0- 81.0     81.0-500.0       0.0-500.0

 Omega (Ω)                  1.1432        15.7483          16.8915

 Gas jet temperature     810.130 °K         ---              ---
   (average)             536.980 °C         ---              ---

 Gas jet velocity (avg)  432.880 m/s        ---              ---

 Average skin surface    358.692 °K     333.474 °K     337.560 °K
   temperature            85.542 °C      60.324 °C      64.410 °C

 Avg heat trans coeff   395.094 W/m²/K  30.888 W/m²/K     ---

 Average heat flux      178.372 kW/m²   -1.400 kW/m²      ---

 Average temperature     323.569 °K     328.511 °K     327.710 °K
   at 72 mm depth         50.419 °C      55.361 °C      54.560 °C

 Maximum temperature     338.975 °K     340.665 °K     340.665 °K
   at 72 mm depth         65.825 °C      67.515 °C      67.515 °C

 Time at maximum temp       81.0 ms        90.0 ms        90.0 ms

Other

  The heat transfer coefficient value for Phase 2 ( 30.888 W/m²/K)
is the *effective* value, which results from the user-specified
Phase 2 heat flux ( -1.400 kW/m²), an estimated (not actual) average
Phase 2 skin surface temperature of 339.326 °K, and an adjusted
(ambient) exposure temperature of 335.782 °K.  (The actual ambient
temperature is 294.000 °K.)

  Airbag inflation time (full bag, beginning of exhaust):  22.5 ms
  Time at end of exhaust: 103.5 ms

Input:   M1TDOT  PT   AIRBAG
Output:  BURNMODL.OUT  TEMPDIST.OUT

End of simulation.

C:\BAG>
```

SCREEN OUTPUT FROM A STANDARD HEAT-GUN SIMULATION

C:\BAG>burn

BURN INJURY MODEL

1 = airbag
2 = heat gun

Enter 1 or 2: 2

Heat gun: 450 °C, 66 m/s, 150 ms

Determining skin surface temp T(0,t) and heat transfer coefficient h(t)...
Finding distribution of skin temperatures T(x,t) during exposure to gas jet...
Calculating Phase 1 burn injury criterion function...
Finding distribution of skin temperatures T(x,t) after exposure to gas jet...
Calculating Phase 2 burn injury criterion function...

SUMMARY OF RESULTS

Burn Injury Integral Ω for Critical Depth 72 μm

Heat gun: 450 °C, 66 m/s, 150 ms Gas: air Port dia: 10.00 mm

	During Exposure	After Exposure	Total
Time range (ms)	0.0-150.0	150.0-500.0	0.0-500.0
Omega (Ω)	0.1327	0.4401	0.5728
Gas jet temperature	723.150 °K 450.000 °C	--- ---	--- ---
Gas jet velocity	66.000 m/s	---	---
Average skin surface temperature	342.800 °K 69.650 °C	329.747 °K 56.598 °C	333.663 °K 60.513 °C
Avg heat trans coeff	234.830 W/m^2/K	39.250 W/m^2/K	---
Average heat flux	89.320 kW/m^2	-1.400 kW/m^2	---
Average temperature at 72 mm depth	322.428 °K 49.278 °C	326.009 °K 52.859 °C	324.935 °K 51.785 °C
Maximum temperature at 72 mm depth	334.368 °K 61.218 °C	334.948 °K 61.798 °C	334.948 °K 61.798 °C
Time at maximum temp	150.0 ms	157.0 ms	157.0 ms

Other

The heat transfer coefficient value for Phase 2 (39.250 W/m^2/K) is the *effective* value, which results from the user-specified Phase 2 heat flux (-1.400 kW/m^2), an estimated (not actual) average Phase 2 skin surface temperature of 329.669 °K, and an adjusted (ambient) exposure temperature of 323.707 °K. (The actual ambient temperature is 294.000 °K.)

Input: HEATGUN
Output: BURNMODL.OUT TEMPDIST.OUT

End of simulation.

C:\BAG>

SCREEN OUTPUT FROM A "SEARCH-FOR-DURATION" HEAT-GUN SIMULATION

```
C:\BAG>burn

BURN INJURY MODEL

  1 = airbag
  2 = heat gun

Enter 1 or 2:  2

Heat gun: 450 °C, 66 m/s, ??? ms
Critical cell depth:  72 µm

Search for exposure duration for Ω = 1.00

 Duration (s)      Omega       Omega - 1.00     Omega(1)       Omega(2)

 0.200000E+00  0.261650E+02  0.251650E+02  0.785459E+01  0.183104E+02
 0.100000E+00  0.574553E-02 -0.994254E+00  0.850791E-03  0.489474E-02
 0.150000E+00  0.572794E+00 -0.427206E+00  0.132714E+00  0.440080E+00
 0.175000E+00  0.417873E+01  0.317873E+01  0.111856E+01  0.306018E+01
 0.162500E+00  0.157951E+01  0.579515E+00  0.395108E+00  0.118441E+01
 0.156500E+00  0.975909E+00 -0.240914E-01  0.235596E+00  0.740313E+00
 0.159500E+00  0.124307E+01  0.243072E+00  0.305555E+00  0.937518E+00
 0.158000E+00  0.110177E+01  0.101766E+00  0.268409E+00  0.833356E+00
 0.157500E+00  0.105818E+01  0.581814E-01  0.257016E+00  0.801166E+00
 0.157000E+00  0.101626E+01  0.162573E-01  0.246080E+00  0.770177E+00

 Duration (s)      Omega       Omega - 1.00     Omega(1)       Omega(2)

Results for Ω nearest to 1.00
 0.157000E+00  0.101626E+01  0.162573E-01  0.246080E+00  0.770177E+00

Results for Ω ≥ 1.00 nearest to 1.00
 0.157000E+00  0.101626E+01  0.162573E-01  0.246080E+00  0.770177E+00

Interpolated results for Ω = 1.00
 0.156799E+00  0.100000E+01  0.000000E+00  0.242144E+00  0.757856E+00

C:\BAG>
```

Note: Omega(1) and Omega(2) are the contributions to Omega from Phase 1 and Phase 2 exposures, respectively.

5.2.2 Outputs to file. All outputs to the screen illustrated above in Section 5.2.1 are written also to file BURNMODL.OUT for both airbag and heat-gun simulations and without respect to the output control specifications made by the user in the AIRBAG or HEATGUN data set. Through those output control specifications, however, as described in Section 5.1.1.1 (data line 2), the user can obtain many additional outputs to file. These have been previously described in Section 3.0, Table 1 (Table 4), and Table 5. They are discussed further in Section 5.3 and illustrated there and in Appendices C through F.

5.2.3 Batch runs on MS DOS systems. Runs of the BURN model can be made interactively as described in Section 5.2 by preparing the required input data set(s), typing in "burn", and entering "1" for an airbag run or "2" for a heat-gun run. If a large number of runs are to be made, however, it may be desirable to run them all in a "batch" rather than one at a time. There are means for doing this with all operating systems. Figure 6 illustrates a batch file (BATCHRUN.BAT) that could be used with the MS DOS operating system for making a set of nine heat-gun simulations.

In this example the nine "HEATGUN" data sets have names such as T450V60.140, where the naming scheme is selected to indicate gas jet temperature (T = 450° C), jet velocity (V = 60 m/s), and exposure duration (140 ms). Since the BURN model requires that the input data set for a heat-gun run have the specific name "HEATGUN", the first step necessary for each simulation in a batch run is to copy the prepared input data set (T450V60.140 for this example) to the file named HEATGUN. If the BURN runs are to be airbag simulations, then the prepared airbag data files would be copied to the file named AIRBAG, and, further, if different inflator data are to be used for the various simulations in the batch, the appropriate files containing mass flow rate and pressure data would have to be copied to the files named M1TDOT and PT.

The second step is to run the BURN program. Note that in a batch run the DOS command for executing the program must be either "BURN < ONE" or "BURN < TWO" rather than simply "BURN". The reason for this is that the program must be told where to look for the "1" or "2" input that would be entered by the user if the run were being made interactively. The symbol "<" here is the DOS redirection symbol, and it tells the program to obtain interactive input data from the file ONE or TWO instead of from the keyboard. Files ONE and TWO are simple text files with single lines that begin with the values "1" and "2", respectively. An input "2" is required for a heat-gun run, as in the Figure 6 example, and "1" is required for an airbag run.

The third step required for each of the simulations is to save the output files since they will be overwritten by successive runs of the BURN program. This can be done with the COPY command, or, if old versions of the output files do not already exist, it can be done with the RENAME command. Any desired file-naming scheme may be used, of course, for the saved output files. There is no need to COPY (or RENAME) files that are not written by the BURN model runs. For example, do not include the COPY for PARSED.OUT unless the output control specifications request that that file be written.

The example file BATCHRUN.BAT listed in Figure 6, as well as files ONE and TWO, are included, together with the source and executable codes and example input and output data files, on the distribution diskette for the UMTRI Airbag Skin Burn Model. (The distribution diskette is described in Appendix A.)

```
@echo  Begin batch run for heat-gun simulations for temperature=450 deg C,
@echo  veloc=60, 70, and 80 m/s, and exposure durations 140, 150, and 160 ms

@rem   This example batch file assumes that nine "HEATGUN" data sets
@rem   T450V60.140 ... T450V80.160 have been prepared and that the file TWO
@rem   is a text file consisting of one line beginning with the value 2.
@rem   For airbag simulations similarly use DOS redirection for a one-line
@rem   file ONE that contains the value 1.

@rem   There is no need to COPY (or RENAME) files that are not written by the
@rem   BURN model runs.  For example, do not include the COPY for PARSED.OUT
@rem   unless the output control specifications request that file to be written.

COPY T450V60.140 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V60.140
COPY TEMPDIST.OUT T450V60.140
COPY TABLDATA.OUT L450V60.140
COPY PARSED.OUT P450V60.140

COPY T450V60.150 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V60.150
COPY TEMPDIST.OUT T450V60.150
COPY TABLDATA.OUT L450V60.150
COPY PARSED.OUT P450V60.150

COPY T450V60.160 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V60.160
COPY TEMPDIST.OUT T450V60.160
COPY TABLDATA.OUT L450V60.160
COPY PARSED.OUT P450V60.160

COPY T450V70.140 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V70.140
COPY TEMPDIST.OUT T450V70.140
COPY TABLDATA.OUT L450V70.140
COPY PARSED.OUT P450V70.140

COPY T450V70.150 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V70.150
COPY TEMPDIST.OUT T450V70.150
COPY TABLDATA.OUT L450V70.150
COPY PARSED.OUT P450V70.150

COPY T450V70.160 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V70.160
COPY TEMPDIST.OUT T450V70.160
COPY TABLDATA.OUT L450V70.160
COPY PARSED.OUT P450V70.160

COPY T450V80.140 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V80.140
COPY TEMPDIST.OUT T450V80.140
COPY TABLDATA.OUT L450V80.140
COPY PARSED.OUT P450V80.140

COPY T450V80.150 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V80.150
COPY TEMPDIST.OUT T450V80.150
COPY TABLDATA.OUT L450V80.150
COPY PARSED.OUT P450V80.150

COPY T450V80.160 HEATGUN
BURN < TWO
COPY BURNMODL.OUT B450V80.160
COPY TEMPDIST.OUT T450V80.160
COPY TABLDATA.OUT L450V80.160
COPY PARSED.OUT P450V80.160

@echo  End of batch run.
```

Figure 6. An Example Batch File BATCHRUN.BAT for Batch Runs in MS DOS.

5.3 Output data

The output data produced by the BURN model are self-explanatory in the context of the analytical model, which this manual does not discuss in any significant amount of detail (but see Section 4). Except for the output file PARSED.OUT, all output files produced by the BURN model contain sufficient description of the data that, given an understanding of the analytical model, there should be no question about the meaning of the numerical outputs. Their proper interpretation with respect to skin burn potential and the implications for airbag system design requires study, of course.

The user is directed to the previously mentioned references by Reed and Schneider (1994) and Reed, Schneider, and Burney (1994) for a full description of the analytical model.

Full descriptions of the output files available from BURN simulations may be found in Sections 3.0 and 5.1.1.1 and Tables 1 and 5. These files are BURNMODL.OUT, TEMPDIST.OUT, TABLDATA.OUT, and PARSED.OUT. Examples of files BURNMODL.OUT and TEMPDIST.OUT are included in Appendices C through F. The example there for BURNMODL.OUT includes all of the tabular time-history data, which can, at the user's option, be written instead to TABLDATA.OUT. Only the file PARSED.OUT has not yet been illustrated.

Section 5.1.1.1 explains how to obtain (optionally) a parsed version of the "Summary of Results" output, which is written to both the screen and the BURNMODL.OUT file for all runs except for heat-gun search runs. The full summary output is illustrated above in Section 5.2.1 for an airbag simulation (see SCREEN OUTPUT FOR AN AIRBAG SIMULATION) and also in Appendix C. The numerical content of the full summary output is written to PARSED.OUT, which is illustrated in Figure 7 for the airbag simulation of Section 5.2.1 and Appendix C. The only nonnumeric data in PARSED.OUT are the title line, the inflator description, the gas identification, and the word "yes" (or "no"), which indicates that the simulation included occupant/airbag interaction (or did not). All numbers may be seen to be identical to the numbers in the same data lines of the full "Summary of Results" output. The purpose of writing a parsed summary of results to file is that such a file is easy to use in postprocessing of the results of batch runs. A postprocessing program written by the user for analysis of simulation results might be run, for example, immediately after each "BURN < TWO" command in the BATCHRUN.BAT file illustrated in Figure 6 or after the last BURN run in the batch file.

```
                       PARSED SUMMARY OF RESULTS
     72.
Inflator Capacity: 487 kPa                   Gas: nitrogen
yes                35.00
       0.0          81.0         81.0       500.0        0.0       500.0
    1.1432     15.7483      16.8915
   810.130
   536.980
   432.880
   358.692     333.474      337.560
    85.542      60.324       64.410
   395.094      30.888
   178.372      -1.400
   323.569     328.511      327.710
    50.419      55.361       54.560
   338.975     340.665      340.665
    65.825      67.515       67.515
      81.0        90.0         90.0
    30.888
    -1.400
   339.326
   335.782
   294.000
      22.5
     103.5
```

Figure 7. Parsed Summary of Results (PARSED.OUT) for an Airbag Simulation

6.0 LIST OF REFERENCES

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APPENDIX A

DISTRIBUTION FILES

```
==============================================================================
                     The UMTRI Airbag Skin Burn Model

This file describes the content of the March 6, 1996, release diskette of the
UMTRI Airbag Skin Burn Model.  For information on how to use the model, refer
to the document USER'S GUIDE FOR THE UMTRI AIRBAG SKIN BURN MODEL, report number
UMTRI-96-5 from the University of Michigan Transportation Research Institute.
------------------------------------------------------------------------------
 File Name     Size    Date     Time    Description
------------------------------------------------------------------------------
READ     ME          03-06-96         this file
BURN     EXE  436262 03-01-96  8:49a  the MS DOS executable program
BURN     FOR  190220 03-01-96  8:49a  the FORTRAN source code
TABLES   DOC    2717 03-06-96 11:20a  description of time history output tables
BATCHRUN BAT    2228 02-27-96  2:57p  example MS DOS file for making batch runs
ONE                3 12-19-95  5:32p  \ needed for making batch runs; input via
TWO                3 12-19-95  5:33p  / DOS redirection: ONE=airbag,TWO=heat gun
M1TDOT   313     926 05-30-95  1:30p  313 kPa; nominal 320 kPa \   example
M1TDOT   349    1189 05-30-95  1:30p  349 kPa; nominal 350 kPa  \  mass flow
M1TDOT   407    1625 05-30-95  1:30p  407 kPa; nominal 420 kPa   ) rate data for
M1TDOT   487    1587 05-30-95  1:30p  487 kPa; nominal 475 kPa  /  different
M1TDOT   499    1491 05-30-95  1:30p  499 kPa; nominal 560 kPa /   inflators
PT       313    1093 05-30-95  1:29p  313 kPa; nominal 320 kPa \
PT       349    1364 05-30-95  1:28p  349 kPa; nominal 350 kPa  \  example tank
PT       407    1364 05-30-95  1:28p  407 kPa; nominal 420 kPa   ) pressure data
PT       487    1145 05-30-95  1:28p  487 kPa; nominal 475 kPa  /  for different
PT       499    1051 05-30-95  1:29p  499 kPa; nominal 560 kPa /   inflators
M1TDOT          1587 05-30-95  1:30p  mass flow rate data used in sims; 487 kPa
PT              1145 05-30-95  1:28p  tank pressure data used in sims; 487 kPa
AIRBAG   B_2    4283 02-05-96  3:57p  AIRBAG input data set for simulation
                                        for a 487 kPa inflator and no occupant
AIRBAG   BO2    4283 02-05-96  3:55p  AIRBAG input data set for simulation
                                        for a 487 kPa inflator and with
                                        occupant/airbag interaction (pendulum)
AIRBAG   BO4    4283 02-01-96  9:53p  same as AIRBAG.BO2 except tabular output
                                        is written to TABLDATA.OUT instead of to
                                        BURNMODL.OUT and PARSED.OUT is requested
HEATGUN  G_2    3809 02-23-96  9:48a  HEATGUN input data set for simulation
                                        for 150 ms exposure duration, 450 deg C,
                                        and 66 m/s gas jet velocity
HEATGUN  G_4    3809 03-01-96 10:08a  same as HEATGUN.G_2 except tabular output
                                        is written to TABLDATA.OUT instead of to
                                        BURNMODL.OUT and PARSED.OUT is requested
HEATGUN  DUR    3807 03-01-96 10:24p  search-for-duration data set; otherwise,
                                        same as HEATGUN.G_4
BURNMODL B_2  116319 03-02-96 12:00a  BURNMODL.OUT from run for AIRBAG.B_2
TEMPDIST B_2   84928 03-02-96 12:00a  TEMPDIST.OUT from run for AIRBAG.B_2
BURNMODL BO2  137945 03-01-96 11:57p  BURNMODL.OUT from run for AIRBAG.BO2
TEMPDIST BO2   84928 03-01-96 11:57p  TEMPDIST.OUT from run for AIRBAG.BO2
TABLDATA BO4  121787 03-02-96 12:09a  TABLDATA.OUT from run for AIRBAG.BO4
PARSED   BO4     619 03-02-96 12:09a  PARSED.OUT from run for AIRBAG.BO4
BURNMODL G_2   42399 03-01-96 11:31p  BURNMODL.OUT from run for HEATGUN.G_2
TEMPDIST G_2   84930 03-01-96 11:31p  TEMPDIST.OUT from run for HEATGUN.G_2
TABLDATA G_4   28145 03-01-96 11:22p  TABLDATA.OUT from run for HEATGUN.G_4
PARSED   G_4     590 03-01-96 11:22p  PARSED.OUT from run for HEATGUN.G_4
BURNMODL DUR    7312 03-01-96 10:25p  search-for-duration output (HEATGUN.DUR)

Output file descriptions
~~~~~~~~~~~~~~~~~~~~~~~~
  BURNMODL.OUT -- echo of input data set, summary of results; also time-history
                    and other tabular data if not written to TABLDATA.OUT
  TEMPDIST.OUT -- skin temperature distribution, T(x,t), x = 0 to 0.000200 m and
                    t = 0 to 500 ms
  TABLDATA.OUT -- time histories and other tabular data (if not in BURNMODL.OUT)
  PARSED.OUT   -- parsed (numbers-only) summary of results (optional output)

==============================================================================
```


```
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==============================================================================
```

APPENDIX B

EXAMPLE INPUT DATA SETS

EXAMPLE 1: Data set AIRBAG for a 0.06 cubic meter airbag with two 35 mm vents and occupant/airbag interaction. Inflator data are read from data sets M1TDOT and PT.

```
* Airbag   [8-character data fields]

*line 1: Integration method (1.=R-K) and stepsize (s)
*line 2: Output specifications -- SW1, SW2, KTAB(1-25)  FORMAT(2g8.0, 25I1)
;       Field 1: summary outputs (results and input data summary)
;         =1., summary of results, summary of input data, summary of model consts
;         =2., summary of results, summary of input data
;         =3., summary of results only
;         <0., as above but also print parsed results summary (to separate file)
;       Field 2: tabular output data, including time histories.
;         =0., print no tabular data to file
;         =1., print all tabular data to file [KTAB() specifications optional]
;              KTAB(i) for table i: 0 = do not write to file, 1 = write to file,
;              2 = write every 2nd point to file (time histories 7-14,18-25)
;         =2., default (selected) tables to file
;              Table No.  1 2 3 4 5 6 7 8 910111213141516171819202122232425
;              Default    0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 0 0 2 0 0 0 0 0 0
;         <0., as above but write tabular data to different file from summaries
*line 3: Reduced duration (s) for exposure to airbag exhaust if abs() is nonzero
;         =0., use exhaust duration calculated from the airbag thermodynamics
;         >0., reduced duration; ignore the first portion of calc'd exhaust data
;         <0., reduced duration; ignore the last portion of calc'd exhaust data
*line 4: Gas identification:  a) nitrogen or 1.  or  b) air or 2.
*line 5: Ambient temperature (°C)  [include K in field if Kelvin]
*line 6: Initial skin surface temperature (°C)  [include K in field if Kelvin]
*line 7: Tank test volume (m**3)
*line 8: Vent diameter (m) and number of vents
*line 9: Orifice coefficient for vent and fabric area
*line 10: Fabric stretch factor (any value .ge. 0, or -1. for lin. regr. on V20)
;          (e.g., 3.81e-6 m²/(N/m²)/m²)
*line 11: Occupant interaction specifications: 0.=no interaction, 1.=interaction
;           If field 1 is 1., fields 2 through 7 must contain the following data
;           for simulation of a pendulum impact against the airbag.
;           f.2:  moment of inertia about pivot point (kg m**2)
;           f.3:  distance from pivot point to center of airbag contact (m)
;           f.4:  pendulum angular velocity at contact if positive (rad/s);
;                 linear velocity if negative (m/s)
;           f.5:  maximum contact area for pendulum/airbag interaction (m**2)
;           f.6:  airbag deflection over which max contact area is reached (m)
;           f.7:  airbag depth, i.e., deflection for bottoming out (m)
*line 12: Nominal airbag volume (m**3)
*line 13: H/D ratio: H, distance from vent to skin surface; D, jet diameter
*line 14: r/D ratio: r, effective radius of target area; D, jet diameter
*line 15: Multiplicative tuning factor for Phase 1 heat transfer coefficient
*line 16: Effective Qdot for Phase 2 heat transfer (.ge. 0; e.g., 1400 W/m**2)
*line 17: Thermal conductivities of epidermis and dermis (W/m/K) (nonzero)
*line 18: Thermal diffusivities of epidermis and dermis (m**2/s); if a negative
;          value is specified in field 1 (epidermis), fields 3 and 4 must contain
;          nonzero values for density (kg/m**3) and specific heat (J/kg/K);
;          fields 5 and 6 are used similarly for the dermis if field 2 is neg.
*line 19: Critical cell depth (micrometers)
*line 20: Burn integral constants: preexponential factor coefficient and power,
;          and delE/R (activation energy divided by gas constant)

1.      .0005
-1.     -1.     1111111111111111112111111
0.
nitrogen
20.85
35.85
.028317
0.035   2.
0.6
0.
1.      143.1   1.332   4.95    0.15    0.100   0.254
```

```
0.06
3.0
1.
.55
1400.
0.20949 0.3791
7.267E-8 1.43E-7
72.
3.1      98.      75000.                      Henriques-Moritz    [44,50] C
*2.185   124.     93534.9                      Weaver-Stoll   [44,50] C
*1.823   51.      39109.8                      Weaver-Stoll    >50 C
*1.43    72.      55000.                       Mehta-Wong       ---
* Comment lines must begin with one of these:  ; : * # $ @
* Comments can be added after data fields on any line (w. or w/o ;:*#$@).
* Completely blank lines are also allowed.
```

EXAMPLE 2: Data set M1TDOT for the mass flow rate for a 487 kPa inflator from a tank test (1 cubic foot tank)

two data fields of width 8 characters

f.1: time (s)
f.2: mass flow rate (kg/s)

```
Inflator Capacity: 487 kPa
0        0
0.001    0
0.002    0
0.003    2.079
0.004    1.29
0.005    1.386
0.006    1.462
0.007    1.521
0.008    1.562
0.009    1.58
0.01     1.588
0.011    1.575
0.012    1.539
0.013    1.484
0.014    1.425
0.015    1.361
0.016    1.301
0.017    1.24
0.018    1.19
0.019    1.139
0.02     1.089
0.021    1.04
0.022    0.993
0.023    0.945
0.024    0.9
0.025    0.853
0.026    0.809
0.027    0.787
0.028    0.726
0.029    0.686
0.03     0.648
0.031    0.612
0.032    0.576
0.033    0.543
0.034    0.511
0.035    0.481
0.036    0.451
0.037    0.422
0.038    0.394
0.039    0.359
0.04     0.343
0.041    0.318
0.042    0.293
0.043    0.288
0.044    0.242
0.045    0.219
0.046    0.185
0.047    0.171
0.048    0.16
0.049    0.13
0.05     0.111
0.051    0.092
0.052    0.075
0.053    0.059
0.054    0.044
0.055    0.03
0.056    0.017
0.057    0
0.058    0
0.059    0
```

0.06	0
0.061	0
0.062	0
0.063	0
0.064	0
0.065	0
0.066	0
0.067	0
0.068	0
0.069	0
0.07	0
0.071	0
0.072	0
0.073	0
0.074	0
0.075	0
0.076	0
0.077	0
0.078	0
0.079	0
0.08	0
0.081	0
0.082	0
0.083	0
0.084	0
0.085	0
0.086	0
0.087	0
0.088	0
0.089	0
0.09	0
0.091	0
0.092	0
0.093	0
0.094	0
0.095	0
0.096	0
0.097	0
0.098	0
0.099	0
0.1	0
0.105	0
0.11	0
0.115	0
0.12	0
0.125	0
0.13	0
0.135	0
0.14	0
0.145	0
0.15	0
0.155	0
0.16	0
0.165	0
0.17	0
0.175	0
0.18	0
0.185	0
0.19	0
0.195	0
0.2	0
0.205	0
0.21	0

EXAMPLE 3: Data set PT for the tank pressure from a 487 kPa inflator in a tank test (1 cubic foot tank)

two data fields of width 8 characters

f.1: time (s)
f.2: pressure (kPa, gauge)

Inflator Capacity: 487 kPa

0	0
0.001	0
0.002	0
0.003	6.23
0.004	10.7
0.005	17.9
0.006	26.9
0.007	37.2
0.008	49.9
0.009	64.7
0.01	81.4
0.011	99.3
0.012	118.1
0.013	137.8
0.014	157.99
0.015	177.9
0.016	197
0.017	216
0.018	234
0.019	251
0.02	266
0.021	280
0.022	294
0.023	308
0.024	322
0.025	336
0.026	348
0.027	371
0.028	381
0.029	391
0.03	400
0.031	408
0.032	415
0.033	422
0.034	429
0.035	434
0.036	440
0.037	446
0.038	450
0.039	454
0.04	458
0.041	463
0.042	466
0.043	470
0.044	472
0.045	475
0.046	478
0.047	479
0.048	481
0.049	483
0.05	484
0.051	486
0.052	487
0.053	487
0.058	487
0.063	487
0.068	487
0.073	487
0.078	487

0.083	487
0.088	487
0.093	487
0.098	487
0.103	487
0.108	487
0.113	487
0.118	487
0.123	487
0.128	487
0.133	487
0.138	487
0.143	487
0.148	487
0.153	487
0.158	487
0.163	487
0.168	487
0.173	487
0.178	487
0.183	487
0.188	487
0.193	487
0.198	487
0.203	487
0.208	487

EXAMPLE 4: Data set HEATGUN for a simulated heat-gun experiment with a 450° C, 66 m/s hot-air jet, and skin exposure duration of 150 ms

```
* Heat gun    [8-character data fields]

*line 1: Integration method (1.=R-K) and stepsize (s)
*line 2: Output specifications -- SW1, SW2, KTAB(1-25)   FORMAT(2g8.0, 25I1)
;       Field 1: summary outputs (results and input data summary)
;         =1., summary of results, summary of input data, summary of model consts
;         =2., summary of results, summary of input data
;         =3., summary of results only
;         <0., as above but also print parsed results summary (to separate file)
;       Field 2: tabular output data, including time histories
;         =0., print no tabular data to file
;         =1., print all tabular data to file [KTAB() specifications optional]
;              KTAB(i) for table i: 0 = do not write to file, 1 = write to file,
;              2 = write every 2nd point to file (time histories 7-14,18-25)
;         =2., default (selected) tables to file
;              Table No.  1 2 3 4 5 6 7 8 910111213141516171819202122232425
;              Default    0 0 0 0                          0 0 0 0 2
;         <0., as above but write tabular data to different file from summaries
*line 3: Gas identification:  a) nitrogen or 1.  or  b) air or 2.
*line 4: Ambient temperature (°C)   [include K in field if Kelvin]
*line 5: Initial skin surface temperature (°C)   [include K in field if Kelvin]
*line 6: Duration of exposure to heat gun jet (s)
;          or -1. to search for the exposure duration that results in Ω=0.53
;          or -2. to search for the exposure duration that results in Ω=1
*line 7: Temperature of gas flow from heat gun (°C)  [incl. K in field if Kelvin]
;          or -1. to search for the gas jet temperature that results in Ω=0.53
;          or -2. to search for the gas jet temperature that results in Ω=1
*line 8: Velocity of heat gun jet (m/s) or, if negative (and not -1. or -2.),
;          the pitot tube pressure differential in inches of water,
;          or -1. to search for the gas jet velocity that results in Ω=0.53
;          or -2. to search for the gas jet velocity that results in Ω=1
*line 9: Heat-gun port diameter (m)
*line 10: Orifice coefficient for heat-gun port
*line 11: H/D ratio: H, distance from vent to skin surface; D, gas jet diameter
*line 12: r/D ratio: r, effective radius of target area; D, gas jet diameter
*line 13: Multiplicative tuning factor for Phase 1 heat transfer coefficient
*line 14: Effective Qdot for Phase 2 heat transfer (.ge. 0; e.g., 1400 W/m**2)
*line 15: Thermal conductivities of epidermis and dermis (W/m/K) (nonzero)
*line 16: Thermal diffusivities of epidermis and dermis (m**2/s); if a negative
;         value is specified in field 1 (epidermis), fields 3 and 4 must contain
;         nonzero values for density (kg/m**3) and specific heat (J/kg/K);
;         fields 5 and 6 are used similarly for the dermis if field 2 is neg.
*line 17: Critical cell depth (micrometers)
;           or -1. to search for the cell depth for which Ω=0.53
;           or -2. to search for the cell depth for which Ω=1
*line 18: Burn integral constants: preexponential factor coefficient and power,
;         and delE/R (activation energy divided by gas constant)

1.      .0005
-1.     -1.     1111111111111111112111111
air
20.85
35.85
0.150
450.
66.
0.010
1.
3.0
1.0
.55
1400.
0.20949 0.3791
7.267E-8 1.43E-7
72.
3.1     98.     75000.                     Henriques-Moritz   [44,50] C
*2.185   124.    93534.9                    Weaver-Stoll   [44,50] C
*1.823   51.     39109.8                    Weaver-Stoll    >50 C
```

```
*1.43    72.    55000.                  Mehta-Wong      ---
* Comment lines must begin with one of these:  ; : * # $ @
* Comments can be added after data fields on any line (w. or w/o ;:*#$@).
* Completely blank lines are also allowed.
```

APPENDIX C

EXAMPLE "BURNMODL.OUT" OUTPUT (airbag)

Airbag simulation with occupant/airbag interaction:
all summary output and all tables

AIRBAG SIMULATION: input data echo and simulation results

(Also see file TEMPDIST.OUT.)

```
* Airbag   [8-character data fields]

*line 1: Integration method (1.=R-K) and stepsize (s)
*line 2: Output specifications -- SW1, SW2, KTAB(1-25)  FORMAT(2g8.0, 25I1)
;       Field 1: summary outputs (results and input data summary)
;         =1., summary of results, summary of input data, summary of model consts
;         =2., summary of results, summary of input data
;         =3., summary of results only
;         <0., as above but also print parsed results summary (to separate file)
;       Field 2: tabular output data, including time histories
;         =0., print no tabular data to file
;         =1., print all tabular data to file [KTAB() specifications optional]
;               KTAB(i) for table i: 0 = do not write to file, 1 = write to file,
;               2 = write every 2nd point to file (time histories 7-14,18-25)
;         =2., default (selected) tables to file
;               Table No.  1 2 3 4 5 6 7 8 910111213141516171819202122232425
;               Default    0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 0 0 2 0 0 0 0 0 0
;         <0., as above but write tabular data to different file from summaries
*line 3: Reduced duration (s) for exposure to airbag exhaust if abs() is nonzero
;         =0., use exhaust duration calculated from the airbag thermodynamics
;         >0., reduced duration; ignore the first portion of calc'd exhaust data
;         <0., reduced duration; ignore the last portion of calc'd exhaust data
*line 4: Gas identification:  a) nitrogen or 1.  or  b) air or 2.
*line 5: Ambient temperature (°C)  [include K in field if Kelvin]
*line 6: Initial skin surface temperature (°C)  [include K in field if Kelvin]
*line 7: Tank test volume (m**3)
*line 8: Vent diameter (m) and number of vents
*line 9: Orifice coefficient for vent and fabric area
*line 10: Fabric stretch factor (any value .ge. 0, or -1. for lin. regr. on V20)
;          (e.g., 3.81e-6 m²/(N/m²)/m²)
*line 11: Occupant interaction specifications: 0.=no interaction, 1.=interaction
;            If field 1 is 1., fields 2 through 7 must contain the following data
;            for simulation of a pendulum impact against the airbag.
;            f.2:  moment of inertia about pivot point (kg m**2)
;            f.3:  distance from pivot point to center of airbag contact (m)
;            f.4:  pendulum angular velocity at contact if positive (rad/s);
;                  linear velocity if negative (m/s)
;            f.5:  maximum contact area for pendulum/airbag interaction (m**2)
;            f.6:  airbag deflection over which max contact area is reached (m)
;            f.7:  airbag depth, i.e., deflection for bottoming out (m)
*line 12: Nominal airbag volume (m**3)
*line 13: H/D ratio: H, distance from vent to skin surface; D, jet diameter
*line 14: r/D ratio: r, effective radius of target area; D, jet diameter
*line 15: Multiplicative tuning factor for Phase 1 heat transfer coefficient
*line 16: Effective Qdot for Phase 2 heat transfer (.ge. 0; e.g., 1400 W/m**2)
*line 17: Thermal conductivities of epidermis and dermis (W/m/K) (nonzero)
*line 18: Thermal diffusivities of epidermis and dermis (m**2/s); if a negative
;          value is specified in field 1 (epidermis), fields 3 and 4 must contain
;          nonzero values for density (kg/m**3) and specific heat (J/kg/K);
;          fields 5 and 6 are used similarly for the dermis if field 2 is neg.
*line 19: Critical cell depth (micrometers)
*line 20: Burn integral constants: preexponential factor coefficient and power,
;          and delE/R (activation energy divided by gas constant)

1.      .0005
1.      1.      1111111111111111112111111
0.
nitrogen
20.85
35.85
.028317
0.035   2.
0.6
0.
1.      143.1   1.332   4.95    0.15    0.100   0.254
0.06
3.0
1.
```

```
.55
1400.
0.20949 0.3791
7.267E-8 1.43E-7
72.
3.1      98.      75000.                          Henriques-Moritz    [44,50] C
*2.185    124.     93534.9                         Weaver-Stoll   [44,50] C
*1.823    51.      39109.8                         Weaver-Stoll    >50 C
*1.43     72.      55000.                          Mehta-Wong         ---
* Comment lines must begin with one of these:  ; : * # $ @
* Comments can be added after data fields on any line (w. or w/o ;:*#$@).
* Completely blank lines are also allowed.
```

Inflator Capacity: 487 kPa
Simulation with occupant interaction
Critical cell depth: 72 μm

SUMMARY OF RESULTS

Burn Injury Integral Ω for Critical Depth 72 μm

Inflator Capacity: 487 kPa
Occupant Contact: yes

Gas: nitrogen
Vent diameter: 35.00 mm

	During Exposure	After Exposure	Total
Time range (ms)	0.0- 81.0	81.0-500.0	0.0-500.0
Omega (Ω)	1.1432	15.7483	16.8915
Gas jet temperature (average)	810.130 °K 536.980 °C	--- ---	--- ---
Gas jet velocity (avg)	432.880 m/s	---	---
Average skin surface temperature	358.692 °K 85.542 °C	333.474 °K 60.324 °C	337.560 °K 64.410 °C
Avg heat trans coeff	395.094 W/m²/K	30.888 W/m²/K	---
Average heat flux	178.372 kW/m²	-1.400 kW/m²	---
Average temperature at 72 mm depth	323.569 °K 50.419 °C	328.511 °K 55.361 °C	327.710 °K 54.560 °C
Maximum temperature at 72 mm depth	338.975 °K 65.825 °C	340.665 °K 67.515 °C	340.665 °K 67.515 °C
Time at maximum temp	81.0 ms	90.0 ms	90.0 ms

Other

The heat transfer coefficient value for Phase 2 (30.888 W/m²/K) is the *effective* value, which results from the user-specified Phase 2 heat flux (-1.400 kW/m²), an estimated (not actual) average Phase 2 skin surface temperature of 339.326 °K, and an adjusted (ambient) exposure temperature of 335.782 °K. (The actual ambient temperature is 294.000 °K.)

Airbag inflation time (full bag, beginning of exhaust): 22.5 ms
Time at end of exhaust: 103.5 ms

SUMMARY OF INPUT DATA

Control specifications

Integration method: Runge-Kutta fixed-step
Integration stepsize: 0.00050 s
End time for integration: 0.2000 s

Output specifications

Summary output plus specified tabular time histories to file
Tables (1-28): 11111 11111 11111 11121 11111 000

Simulation data

Initial conditions
Ambient temperature: 20.85 °C (= 294.00 K)
Initial skin surface temperature: 35.85 °C (= 309.00 K)

Inflator description: Inflator Capacity: 487 kPa
Gas: nitrogen
Tank test volume: 0.028317 m**3 = 1.0000 ft**3
Tank test data files (input)
M1TDOT for mass flow rate vs. time (duration = 0.0570 s)
Mass flow rate: peak value = 2.079 kg/s at 0.0030 s
PT for pressure vs. time (duration = 0.0520 s)
Pressure: maximum value = 487.00 kPa (gauge)

Airbag specifications
Vents: number = 2 diameter = 0.03500 m
total area = 0.001924 m^2 orifice coefficient = 0.600
Nominal airbag volume: 0.0600 m**3
Fabric stretch factor: 0.0 $m^2/(N/m^2)/m^2$ (user-specified)
Occupant interaction: pendulum model
Moment of inertia about pivot: 143.10 kg m^2
Distance, pivot to center of airbag contact: 1.332 m
Angular velocity of pendulum: 4.9500 rad/s (6.5934 m/s)
Maximum pendulum/airbag contact area: 0.150 m^2
Deflection ramp to reach maximum contact area: 0.100 m
Airbag depth for bottoming out: 0.254 m

Specifications for impinging exhaust jet and heat transfer models

The full duration of exhaust from the airbag simulation is used for determining the average exhaust temperature and velocity for exposure.
H/D, nondimensional distance to skin surface: 3.0
(H, vent-to-skin distance; D, diameter of contracted jet)
r/D, nondimensional radius of target area: 1.0
(r, effective radius; D, diameter of contracted jet)
Multiplicative tuning factor for heat transfer coeff: 0.550
Heat transfer rate (flux) from surface after exposure: -1400 W/m^2

Skin properties

Thermal conductivity
Epidermis: 0.20949 W/m/K
Dermis: 0.37910 W/m/K
Thermal diffusivity
Epidermis: 0.7267E-07 m^2/s
Dermis: 0.1430E-06 m^2/s
Critical cell depth (base of the epidermal layer): 72 μm

Burn integral constants

G = 3.100 x 10**(98) 1/s
deltaE/R = 75000.0 K (delE = 623.581 kJ/gm-mol)

Threshold for first-degree burn (epidermal injury)
  $\Omega = 0.53$ (model constant)
Threshold for burn with partial skin loss and injury fully through the epidermis (full epidermal necrosis)
  $\Omega = 1.0$ (model constant)

SUMMARY OF MODEL CONSTANTS

Universal constants

Absolute zero kelvin = 273.15 °C
Universal gas constant = 8.31441 J/gram-mol/K (kJ/kg-mol/K)
= 8314.41 J/kg-mol/K

Molecular weights
- Nitrogen: 28.0134 kg/kg-mol
- Air (average): 28.9660 kg/kg-mol

Gas constants (Runiv/m.w.)
- Nitrogen: 296.80 J/kg-mol/K
- Air: 287.04 J/kg-mol/K

Density of water = 1000 kg/m**3 (assumed incompressible)

Earth constants

One atmosphere pressure = 101325 Pascal [N/m²] = 14.696 lb/in²
Density of air at 1 atm and 700 K = 0.4975 kg/m**3
(used with perfect gas law in calculation of gas density for pitot-tube determination of velocity of jet)
Earth standard gravity = 9.80665 m/s² = 32.174 ft/s²

Gas properties

For nitrogen and air, tabular values as functions of temperature, 200 to 1000 K (from Incropera and DeWitt, Table A.4)
- Kinematic viscosity [m²/s]
- Thermal conductivity [W/m/K]
- Prandtl number
- Specific heat at constant pressure [KJ/kg/K]

Empirical constants

Fabric stretch factor, regression to airbag volume

Cs = 2.45e-6 + 2.27e-5 * Vol [m²/(N/m²)/m²]

For a single round jet and H/D = 3.0 and r/D = 1.0, the relationship between the Nusselt number (Nu), the Prandtl number (Pr), and the Reynolds number (Re):

Nu / Pr**0.42 = k(H/D, r/D) C Re**n,

where C = 0.62330, n = 0.5409

and k(H/D, r/D) is a correction function that has the value 1.0300 for the specified values of H/D and r/D. In general, for H/D = 7.5, the values of C and n for various r/D values are as follows (from Martin, Fig. 9):

r/D	C	n
0.0	1.0918	0.5049
1.0	0.6233	0.5409
2.0	0.3314	0.5815
3.0	0.2254	0.6001

The correction function is as follows (from Martin, Fig. 10):

H/D	r/D	k(H/D, r/D)
1.0-6.65	all	1.03
7.5	all	1.0
12.0	0.0	0.775
12.0	1.0	0.775
12.0	2.0	0.80
12.0	3.0	0.81

12.0	5.0	0.86
12.0	7.0	0.90

with linear interpolation for other values of H/D and r/D.

Model assumptions

The basic model is for a two-phased heat flow in a semi-infinite solid. In phase 1 the surface is exposed to a medium (exhaust) with temperature A, and the heat transfer coefficient is hA. In phase 2 (post-exhaust) the external medium has temperature B, and the heat transfer coefficient is hB. A, B, hA, and hB are constants. The temperature distribution in the solid (skin epidermis and dermis) is determined as a function of time from a generalization of equations due to Carslaw and Jaeger (pg. 74, eqs. 2 and 3).

Burn severity is predicted by calculating the integral injury function described by Henriques. Burn injury is treated as a rate process in which the progression of the injury is related to both the temperature and the duration of the temperature. The burn injury integral, omega (Ω), is defined such that Ω = 1.0 is the threshold for burn with partial skin loss and injury fully through the epidermis (full epidermal necrosis). The threshold for first-degree burn (epidermal injury) is Ω = 0.53.

Other assumptions

Heat transfer coefficient after exposure

= Qdot / (ambient temperature - Tskinsurf,avg)

where Qdot<0 is an input constant, the effective heat transfer rate (flux) from the skin surface after exposure, and Tskinsurf,avg is the average skin surface temperature during exposure.

The average temperature of the external medium after exposure is assumed to be the ambient (room) temperature. (Reasonable alternative estimates that would model the effect of a boundary layer are Tskinsurf,avg, as above, and the average of Tskinsurf,avg and the ambient temperature.)

The pendulum model for occupant interaction assumes that occupant/airbag contact begins at the instant the airbag becomes full (i.e., the beginning of exhaust).

Model constraints

The estimation of time rate of change of airbag volume from occupant interaction assumes that the restraining effect of airbag membrane forces is small compared with the pressure forces.

The heat transfer coefficient value for Phase 2 is the *effective* value, which results from the user-specified Phase 2 heat flux, an estimated (not actual) average Phase 2 skin surface temperature, and an adjusted (ambient) exposure temperature.

Table 1 = VISCOSTY (12 points)
viscosity (nitrogen or air) [m^2/s]

0.200000E+03	0.765000E-05
0.250000E+03	0.114800E-04
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.800000E+03	0.829000E-04
0.900000E+03	0.100300E-03

Table 2 = CONDUCTV (12 points)
conductivity (N2 or air) [W/m/K]

0.200000E+03	0.183000E-01
0.250000E+03	0.222000E-01
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.800000E+03	0.548000E-01
0.900000E+03	0.597000E-01

Table 3 = PRANDTL (12 points)
Prandtl number (N2 or air) [-]

0.200000E+03	0.736000E+00
0.250000E+03	0.727000E+00
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.800000E+03	0.715000E+00
0.900000E+03	0.721000E+00

Table 4 = K-RATIO (13 points)
ratio of specific heats (N2 or air) [-]

0.200000E+03	0.139775E+01
0.250000E+03	0.139828E+01
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.800000E+03	0.132149E+01
0.900000E+03	0.134951E+01
0.200000E+04	0.134951E+01

Table 5 = M1TDOT (124 points)
inflator mass flow rate (1 cu ft tank test) [m1Tdot] [kg/s]

0.000000E+00	0.000000E+00
0.100000E-02	0.000000E+00
0.200000E-02	0.000000E+00
0.300000E-02	0.207900E+01
0.400000E-02	0.129000E+01
0.500000E-02	0.138600E+01
0.600000E-02	0.146200E+01
0.700000E-02	0.152100E+01
0.800000E-02	0.156200E+01
0.900000E-02	0.158000E+01
0.100000E-01	0.158800E+01
0.110000E-01	0.157500E+01
0.120000E-01	0.153900E+01
0.130000E-01	0.148400E+01
0.140000E-01	0.142500E+01
0.150000E-01	0.136100E+01
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.460000E-01	0.185000E+00
0.470000E-01	0.171000E+00
0.480000E-01	0.160000E+00
0.490000E-01	0.130000E+00

```
  0.500000E-01  0.111000E+00
  0.510000E-01  0.920000E-01
  0.520000E-01  0.750000E-01
  0.530000E-01  0.590000E-01
  0.540000E-01  0.440000E-01
  0.550000E-01  0.300000E-01
  0.560000E-01  0.170000E-01
  0.570000E-01  0.000000E+00
  0.580000E-01  0.000000E+00
  0.590000E-01  0.000000E+00
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.210000E+00  0.000000E+00
  0.100000E+01  0.000000E+00


Table  6 = PTDOT        (  86 points)
time rate of change of pressure in tank [PTdot] [Pa/s]

  0.000000E+00  0.563171E+07
  0.100000E-02 -0.222335E+07
  0.200000E-02  0.326167E+07
  0.300000E-02  0.564167E+07
  0.400000E-02  0.553833E+07
  0.500000E-02  0.821917E+07
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.110000E-01  0.183750E+08
  0.120000E-01  0.192842E+08
  0.130000E-01  0.200433E+08
  0.140000E-01  0.201583E+08
  0.150000E-01  0.194900E+08
  0.160000E-01  0.190658E+08
  0.170000E-01  0.185750E+08
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.500000E-01  0.150001E+07
  0.510000E-01  0.166668E+07
  0.520000E-01  0.482132E+06
  0.530000E-01 -0.297685E+06
  0.580000E-01  0.135000E+02
  0.630000E-01  0.142228E+01
  0.680000E-01  0.873927E+01
  0.730000E-01 -0.932869E+01
  0.780000E-01  0.287003E+01
  0.830000E-01 -0.114952E+02
  0.880000E-01 -0.251230E+01
  0.930000E-01  0.873927E+01
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.198000E+00 -0.243575E+00
  0.203000E+00 -0.100000E+01
  0.208000E+00 -0.220000E+02
  0.100000E+01 -0.220000E+02


Table  7 = AIRBGVOL    ( 208 points)
airbag volume (V2) [m**3]

  0.000000E+00  0.000000E+00
  0.500000E-03  0.366422E-03
  0.100000E-02  0.340490E-03
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.210000E-01  0.568911E-01
  0.215000E-01  0.583326E-01
  0.220000E-01  0.597807E-01
  0.225000E-01  0.612334E-01
  0.230000E-01  0.612253E-01
  0.235000E-01  0.612008E-01
  0.240000E-01  0.611601E-01
  0.245000E-01  0.611030E-01
```

0.250000E-01	0.610297E-01
0.255000E-01	0.609401E-01
0.260000E-01	0.608343E-01
0.265000E-01	0.607124E-01
0.270000E-01	0.605743E-01
. . . .	. . . .
. . . .	. . . .
0.660000E-01	0.412314E-01
0.665000E-01	0.412291E-01
0.670000E-01	0.412338E-01
0.675000E-01	0.412454E-01
0.680000E-01	0.412638E-01
0.685000E-01	0.412889E-01
0.690001E-01	0.413207E-01
. . . .	. . . .
. . . .	. . . .
0.102000E+00	0.524224E-01
0.102500E+00	0.526504E-01
0.103000E+00	0.528784E-01
0.103500E+00	0.531064E-01

Table 8 = GASMASS (208 points)
gas mass in airbag (m2) [kg]

0.000000E+00	0.000000E+00
0.500000E-03	0.000000E+00
0.100000E-02	0.000000E+00
0.150000E-02	0.000000E+00
0.200000E-02	0.000000E+00
0.250000E-02	0.259875E-03
0.300000E-02	0.103950E-02
. . . .	. . . .
. . . .	. . . .
0.410000E-01	0.352062E-01
0.415000E-01	0.352202E-01
0.420000E-01	0.352266E-01
0.425000E-01	0.352280E-01
0.430000E-01	0.352269E-01
0.435000E-01	0.352182E-01
0.440000E-01	0.351970E-01
. . . .	. . . .
. . . .	. . . .
0.102000E+00	0.226749E-01
0.102500E+00	0.226596E-01
0.103000E+00	0.226528E-01
0.103500E+00	0.226528E-01

Table 9 = PRESSURE (208 points)
gas pressure in airbag (P2) [Pa = N/m²]

0.000000E+00	0.101325E+06
0.500000E-03	0.101325E+06
. . . .	. . . .
. . . .	. . . .
0.220000E-01	0.101325E+06
0.225000E-01	0.101325E+06
0.230000E-01	0.104484E+06
0.235000E-01	0.107603E+06
0.240000E-01	0.110730E+06
. . . .	. . . .
. . . .	. . . .
0.515000E-01	0.221272E+06
0.520000E-01	0.221683E+06
0.525000E-01	0.221884E+06
0.530000E-01	0.221903E+06
0.535000E-01	0.221809E+06
0.540000E-01	0.221667E+06
0.545000E-01	0.221478E+06
. . . .	. . . .
. . . .	. . . .

0.102000E+00	0.102505E+06
0.102500E+00	0.101827E+06
0.103000E+00	0.101206E+06
0.103500E+00	0.100631E+06

Table 10 = GASTEMP (208 points)
gas temperature in airbag (T2) [K]

0.000000E+00	0.294000E+03
0.500000E-03	0.294000E+03
0.100000E-02	0.294000E+03
0.150000E-02	0.294000E+03
0.200000E-02	0.294000E+03
0.250000E-02	0.109939E+04
0.300000E-02	0.443159E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.500000E-01	0.974817E+03
0.505000E-01	0.975824E+03
0.510000E-01	0.977022E+03
0.515000E-01	0.977932E+03
0.520000E-01	0.978072E+03
0.525000E-01	0.977576E+03
0.530000E-01	0.976579E+03
0.535000E-01	0.975372E+03
0.540000E-01	0.974248E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.103000E+00	0.795974E+03
0.103500E+00	0.794784E+03

Table 11 = EXHVELOC (208 points)
u(exhaust) [m/s]

0.000000E+00	0.000000E+00
0.500000E-03	0.000000E+00
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.220000E-01	0.000000E+00
0.225000E-01	0.000000E+00
0.230000E-01	0.117580E+03
0.235000E-01	0.165392E+03
0.240000E-01	0.202002E+03
0.245000E-01	0.231649E+03
0.250000E-01	0.255702E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.505000E-01	0.575189E+03
0.510000E-01	0.575566E+03
0.515000E-01	0.575853E+03
0.520000E-01	0.575897E+03
0.525000E-01	0.575740E+03
0.530000E-01	0.575427E+03
0.535000E-01	0.575047E+03
0.540000E-01	0.574693E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.100500E+00	0.125724E+03
0.101000E+00	0.110608E+03
0.101500E+00	0.937385E+02
0.102000E+00	0.740203E+02
0.102500E+00	0.483475E+02
0.103000E+00	0.000000E+00
0.103500E+00	0.000000E+00

Table 12 = EXHTEMP (208 points)
Texhaust [K]

0.000000E+00	0.294000E+03

0.500000E-03	0.294000E+03
0.100000E-02	0.294000E+03
0.150000E-02	0.294000E+03
0.200000E-02	0.294000E+03
0.250000E-02	0.109939E+04
0.300000E-02	0.443159E+03
0.350000E-02	0.329420E+03
0.400000E-02	0.309160E+03
0.450000E-02	0.311711E+03
. . . . . .	. . . . . .
. . . .	. . . .
0.505000E-01	0.836954E+03
0.510000E-01	0.837888E+03
0.515000E-01	0.838597E+03
0.520000E-01	0.838706E+03
0.525000E-01	0.838319E+03
0.530000E-01	0.837542E+03
0.545000E-01	0.834913E+03
. . . . . .	. . . . . .
. . . .	. . . .
0.102500E+00	0.796201E+03
0.103000E+00	0.796202E+03
0.103500E+00	0.796202E+03

Table 13 = INTGRUn (208 points)
integral of u**n [(m/s)**n s]

0.000000E+00	0.000000E+00
0.500000E-03	0.000000E+00
0.100000E-02	0.000000E+00
. . . . . .	. . . . . .
. . . .	. . . .
0.260000E-01	0.605008E-01
0.265000E-01	0.718474E-01
0.270000E-01	0.836832E-01
0.275000E-01	0.959309E-01
. . . . . .	. . . . . .
. . . .	. . . .
0.102500E+00	0.215747E+01
0.103000E+00	0.216021E+01
0.103500E+00	0.216021E+01

Table 14 = INTGRTe (208 points)
integral of Texhaust [K s]

0.000000E+00	0.000000E+00
0.500000E-03	0.147000E+00
0.100000E-02	0.294000E+00
0.150000E-02	0.441000E+00
. . . . . .	. . . . . .
. . . .	. . . .
0.685000E-01	0.498442E+02
0.690001E-01	0.502487E+02
0.695001E-01	0.506525E+02
0.700001E-01	0.510555E+02
. . . . . .	. . . . . .
. . . .	. . . .
0.102500E+00	0.769829E+02
0.103000E+00	0.773810E+02
0.103500E+00	0.777791E+02

Table 15 = JET C (4 points)
Martin's coefficient C for circular impinging gas jet [-]

0.000000E+00	0.109180E+01
0.100000E+01	0.623300E+00
0.200000E+01	0.331400E+00
0.300000E+01	0.225400E+00

Table 16 = JET n (4 points)
Martin's exponent n for circular impinging gas jet [-]

0.000000E+00	0.504900E+00
0.100000E+01	0.540900E+00
0.200000E+01	0.581500E+00
0.300000E+01	0.600100E+00

Table 17 = KORR12HD (6 points)
correction factor at H/D = 12 as function of r/D [-]

0.000000E+00	0.775000E+00
0.100000E+01	0.775000E+00
0.200000E+01	0.800000E+00
0.300000E+01	0.810000E+00
0.500000E+01	0.860000E+00
0.700000E+01	0.900000E+00

Table 18 = Hgas (163 points)
gas-to-skin heat transfer coefficient [W/m²/K]

0.000000E+00	0.396895E+03
0.500000E-03	0.396915E+03
0.100000E-02	0.396759E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.385000E-01	0.395017E+03
0.390000E-01	0.395100E+03
0.395000E-01	0.395182E+03
0.400000E-01	0.395264E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.795000E-01	0.393911E+03
0.800000E-01	0.393964E+03
0.805000E-01	0.394017E+03
0.810000E-01	0.394070E+03

Table 19 = Tcritdep (501 points)
skin temperature at critical depth [K]

0.000000E+00	0.309000E+03
0.100000E-02	0.309000E+03
0.200000E-02	0.309002E+03
0.300000E-02	0.309023E+03
0.400000E-02	0.309091E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.870000E-01	0.340520E+03
0.880000E-01	0.340610E+03
0.890000E-01	0.340656E+03
0.900000E-01	0.340665E+03
0.910000E-01	0.340644E+03
0.920000E-01	0.340598E+03
0.930000E-01	0.340531E+03
0.940000E-01	0.340448E+03
0.950000E-01	0.340352E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.202000E+00	0.329997E+03
0.203000E+00	0.329945E+03
0.204000E+00	0.329893E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.304000E+00	0.326414E+03
0.305000E+00	0.326390E+03
0.306000E+00	0.326367E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.410000E+00	0.324595E+03

0.411000E+00	0.324582E+03
0.412000E+00	0.324570E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.497000E+00	0.323721E+03
0.498000E+00	0.323713E+03
0.499000E+00	0.323705E+03
0.500000E+00	0.323697E+03

Table 20 = BAG DEFL (207 points)
airbag deflection from pendulum contact [m]

0.000000E+00	0.000000E+00
0.500000E-03	0.000000E+00
0.100000E-02	0.000000E+00
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.225000E-01	0.000000E+00
0.230000E-01	0.329669E-02
0.235000E-01	0.659333E-02
0.240000E-01	0.988977E-02
0.245000E-01	0.131858E-01
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.655000E-01	0.183282E+00
0.660000E-01	0.183345E+00
0.665000E-01	0.183361E+00
0.670000E-01	0.183330E+00
0.675000E-01	0.183252E+00
0.680000E-01	0.183129E+00
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.101500E+00	0.110258E+00
0.102000E+00	0.108738E+00
0.102500E+00	0.107219E+00
0.103000E+00	0.105699E+00

Table 21 = DEFL VEL (207 points)
airbag deflection velocity from pendulum contact [m/s]

0.000000E+00	0.000000E+00
0.500000E-03	0.000000E+00
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.215000E-01	0.000000E+00
0.220000E-01	0.000000E+00
0.225000E-01	0.659340E+01
0.230000E-01	0.659337E+01
0.235000E-01	0.659314E+01
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.650000E-01	0.270621E+00
0.655000E-01	0.173942E+00
0.660000E-01	0.784639E-01
0.665000E-01	-0.157758E-01
0.670000E-01	-0.108743E+00
0.675000E-01	-0.200406E+00
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.101500E+00	-0.303774E+01
0.102000E+00	-0.303916E+01
0.102500E+00	-0.303994E+01
0.103000E+00	-0.304013E+01

Table 22 = DEFLACCL (207 points)
airbag deflection acceleration from pendulum contact [m/s²]

0.000000E+00	0.000000E+00
0.500000E-03	0.000000E+00

. . . .	. . . .
. . . .	. . . .
0.225000E-01	0.000000E+00
0.230000E-01	-0.193659E+00
0.235000E-01	-0.769862E+00
. . . .	. . . .
. . . .	. . . .
0.515000E-01	-0.223074E+03
0.520000E-01	-0.223839E+03
0.525000E-01	-0.224212E+03
0.530000E-01	-0.224249E+03
0.535000E-01	-0.224073E+03
0.540000E-01	-0.223809E+03
0.545000E-01	-0.223457E+03
. . . .	. . . .
. . . .	. . . .
0.102000E+00	-0.219414E+01
0.102500E+00	-0.933723E+00
0.103000E+00	0.000000E+00

Table 23 = OCCFORCE (207 points)
pendulum/airbag force [N]

0.000000E+00	0.000000E+00
0.500000E-03	0.000000E+00
. . . .	. . . .
. . . .	. . . .
0.220000E-01	0.000000E+00
0.225000E-01	0.000000E+00
0.230000E-01	0.156195E+02
0.235000E-01	0.620932E+02
0.240000E-01	0.139518E+03
. . . .	. . . .
. . . .	. . . .
0.510000E-01	0.178942E+05
0.515000E-01	0.179920E+05
0.520000E-01	0.180537E+05
0.525000E-01	0.180838E+05
0.530000E-01	0.180868E+05
0.535000E-01	0.180726E+05
0.540000E-01	0.180513E+05
0.545000E-01	0.180229E+05
0.550000E-01	0.179873E+05
0.555000E-01	0.179444E+05
0.560000E-01	0.178944E+05
. . . .	. . . .
. . . .	. . . .
0.102000E+00	0.176968E+03
0.102500E+00	0.753094E+02
0.103000E+00	0.000000E+00

Table 24 = DV (207 points)
airbag volume change from pendulum contact [m**3]

0.000000E+00	0.000000E+00
0.500000E-03	0.000000E+00
. . . .	. . . .
. . . .	. . . .
0.220000E-01	0.000000E+00
0.225000E-01	0.000000E+00
0.230000E-01	0.815112E-05
0.235000E-01	0.326040E-04
0.240000E-01	0.733557E-04
. . . .	. . . .
. . . .	. . . .
0.650000E-01	0.199757E-01
0.655000E-01	0.199923E-01
0.660000E-01	0.200018E-01
0.665000E-01	0.200041E-01
0.670000E-01	0.199995E-01

```
  0.675000E-01  0.199878E-01
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.102000E+00  0.881077E-02
  0.102500E+00  0.858280E-02
  0.103000E+00  0.835479E-02

Table 25 = DVdot         ( 207 points)
airbag volume change rate (DVdot) [m**3/s]

  0.000000E+00  0.000000E+00
  0.500000E-03  0.000000E+00
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.225000E-01  0.000000E+00
  0.230000E-01  0.326044E-01
  0.235000E-01  0.652061E-01
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.370000E-01  0.824422E+00
  0.375000E-01  0.840824E+00
  0.380000E-01  0.855745E+00
  0.385000E-01  0.854682E+00
  0.390000E-01  0.843163E+00
  0.395000E-01  0.831354E+00
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.655000E-01  0.260912E-01
  0.660000E-01  0.117696E-01
  0.665000E-01 -0.236637E-02
  0.670000E-01 -0.163115E-01
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.102000E+00 -0.455875E+00
  0.102500E+00 -0.455991E+00
  0.103000E+00 -0.456020E+00


Input:   M1TDOT  PT   AIRBAG
Output:  BURNMODL.OUT  TEMPDIST.OUT

End of simulation.
```

APPENDIX D

EXAMPLE "TEMPDIST.OUT" OUTPUT (airbag)

Airbag simulation with occupant/airbag interaction:
all summary output and all tables

AIRBAG SIMULATION: skin temperature distribution results

(Also see file BURNMODL.OUT.)

Inflator Capacity: 487 kPa
gas: nitrogen

Test specifications:
Duration of exposure = 0.0810 s
Velocity = 432.880 m/s
Free-stream temperature = 536.98 °C
= 810.13 °K
Orifice diameter = 0.03500 m
Estimated effective Phase 2 heat transfer rate = -1400. W/m²

Temperatures, T(x,t)   Columns are for times 0 ms, 10 ms, 20 ms, ... 500 ms.

Depth (m)	0.	10.	20.		80.	90.	100.		500.
0.000000	309.000	336.501	347.200	...	380.974	360.051	353.075	...	326.428
0.000001	309.000	335.617	346.333	...	380.167	360.090	353.104	...	326.410
0.000002	309.000	334.751	345.479	...	379.366	360.116	353.126	...	326.392
0.000003	309.000	333.903	344.636	...	378.570	360.129	353.140	...	326.374
0.000004	309.000	333.073	343.807	...	377.780	360.129	353.147	...	326.356
0.000005	309.000	332.262	342.989	...	376.995	360.116	353.147	...	326.338
0.000006	309.000	331.468	342.184	...	376.216	360.090	353.140	...	326.320
0.000007	309.000	330.693	341.392	...	375.443	360.051	353.125	...	326.301
0.000008	309.000	329.935	340.612	...	374.674	360.000	353.103	...	326.283
0.000009	309.000	329.195	339.844	...	373.912	359.935	353.074	...	326.264
0.000010	309.000	328.474	339.088	...	373.155	359.858	353.038	...	326.245
0.000011	309.000	327.770	338.345	...	372.403	359.768	352.994	...	326.226
0.000012	309.000	327.083	337.614	...	371.657	359.665	352.943	...	326.207
0.000013	309.000	326.415	336.896	...	370.917	359.551	352.885	...	326.188
0.000014	309.000	325.763	336.189	...	370.182	359.424	352.820	...	326.168
0.000015	309.000	325.129	335.495	...	369.453	359.285	352.749	...	326.149
0.000016	309.000	324.512	334.813	...	368.729	359.134	352.670	...	326.129
0.000017	309.000	323.912	334.143	...	368.011	358.972	352.584	...	326.109
0.000018	309.000	323.329	333.486	...	367.298	358.798	352.491	...	326.089
0.000019	309.000	322.763	332.840	...	366.591	358.613	352.392	...	326.069
0.000020	309.000	322.212	332.206	...	365.889	358.417	352.285	...	326.049
0.000021	309.000	321.679	331.584	...	365.193	358.210	352.172	...	326.029
0.000022	309.000	321.161	330.974	...	364.503	357.992	352.053	...	326.008
0.000023	309.000	320.658	330.375	...	363.818	357.764	351.927	...	325.988
0.000024	309.000	320.172	329.789	...	363.139	357.526	351.794	...	325.967
0.000025	309.000	319.701	329.213	...	362.465	357.278	351.656	...	325.946
0.000026	309.000	319.244	328.650	...	361.797	357.021	351.510	...	325.925
0.000027	309.000	318.803	328.097	...	361.134	356.754	351.359	...	325.904
0.000028	309.000	318.376	327.556	...	360.477	356.478	351.202	...	325.883
0.000029	309.000	317.964	327.026	...	359.825	356.194	351.038	...	325.861
0.000030	309.000	317.565	326.508	...	359.179	355.901	350.869	...	325.840
0.000031	309.000	317.181	326.000	...	358.539	355.600	350.694	...	325.818
0.000032	309.000	316.809	325.503	...	357.904	355.291	350.513	...	325.797
0.000033	309.000	316.451	325.017	...	357.274	354.974	350.327	...	325.775
0.000034	309.000	316.106	324.542	...	356.650	354.650	350.135	...	325.753
0.000035	309.000	315.774	324.077	...	356.031	354.319	349.938	...	325.730
0.000036	309.000	315.454	323.623	...	355.418	353.981	349.735	...	325.708
0.000037	309.000	315.146	323.179	...	354.810	353.637	349.527	...	325.686
0.000038	309.000	314.850	322.745	...	354.208	353.287	349.315	...	325.663
0.000039	309.000	314.565	322.322	...	353.611	352.931	349.097	...	325.641
0.000040	309.000	314.292	321.908	...	353.020	352.570	348.875	...	325.618
0.000041	309.000	314.029	321.505	...	352.434	352.203	348.648	...	325.595
0.000042	309.000	313.778	321.111	...	351.853	351.832	348.416	...	325.572
0.000043	309.000	313.536	320.726	...	351.278	351.455	348.180	...	325.548
0.000044	309.000	313.304	320.351	...	350.709	351.075	347.940	...	325.525
0.000045	309.000	313.082	319.985	...	350.144	350.691	347.695	...	325.502
0.000046	309.000	312.870	319.629	...	349.585	350.302	347.447	...	325.478
0.000047	309.000	312.667	319.282	...	349.031	349.911	347.194	...	325.454
0.000048	309.000	312.472	318.943	...	348.483	349.516	346.938	...	325.431
0.000049	309.000	312.286	318.613	...	347.940	349.118	346.678	...	325.407
0.000050	309.000	312.109	318.292	...	347.402	348.718	346.415	...	325.382
0.000051	309.000	311.940	317.980	...	346.870	348.315	346.148	...	325.358
0.000052	309.000	311.778	317.676	...	346.342	347.911	345.878	...	325.334
0.000053	309.000	311.624	317.380	...	345.820	347.504	345.605	...	325.309
0.000054	309.000	311.477	317.092	...	345.303	347.096	345.328	...	325.285
0.000055	309.000	311.337	316.812	...	344.792	346.686	345.049	...	325.260
0.000056	309.000	311.204	316.540	...	344.285	346.276	344.767	...	325.235

0.000057	309.000	311.077	316.275	...	343.784	345.864	344.483	...	325.210
0.000058	309.000	310.957	316.018	...	343.288	345.452	344.196	...	325.185
0.000059	309.000	310.842	315.768	...	342.797	345.040	343.906	...	325.160
0.000060	309.000	310.733	315.526	...	342.311	344.627	343.615	...	325.134
0.000061	309.000	310.630	315.291	...	341.830	344.214	343.321	...	325.109
0.000062	309.000	310.532	315.062	...	341.354	343.801	343.026	...	325.083
0.000063	309.000	310.439	314.841	...	340.884	343.389	342.728	...	325.057
0.000064	309.000	310.352	314.625	...	340.418	342.977	342.429	...	325.031
0.000065	309.000	310.268	314.417	...	339.957	342.566	342.128	...	325.005
0.000066	309.000	310.190	314.215	...	339.501	342.156	341.826	...	324.979
0.000067	309.000	310.115	314.019	...	339.051	341.747	341.522	...	324.953
0.000068	309.000	310.045	313.829	...	338.605	341.340	341.217	...	324.926
0.000069	309.000	309.978	313.646	...	338.164	340.933	340.911	...	324.900
0.000070	309.000	309.915	313.468	...	337.728	340.528	340.604	...	324.873
0.000071	309.000	310.278	314.287	...	338.453	340.848	340.337	...	324.256
0.000072	309.000	310.593	314.880	...	338.648	340.665	339.740	...	323.697
0.000073	309.000	310.857	315.309	...	338.554	340.235	339.016	...	323.193
0.000074	309.000	311.076	315.618	...	338.299	339.687	338.256	...	322.738
0.000075	309.000	310.993	315.456	...	338.004	339.453	338.096	...	322.722
0.000076	309.000	310.912	315.296	...	337.712	339.219	337.936	...	322.705
0.000077	309.000	310.835	315.140	...	337.421	338.985	337.774	...	322.689
0.000078	309.000	310.759	314.986	...	337.133	338.750	337.611	...	322.673
0.000079	309.000	310.687	314.836	...	336.847	338.515	337.447	...	322.656
0.000080	309.000	310.617	314.689	...	336.563	338.279	337.282	...	322.640
0.000081	309.000	310.550	314.545	...	336.281	338.044	337.116	...	322.623
0.000082	309.000	310.485	314.404	...	336.001	337.808	336.949	...	322.606
0.000083	309.000	310.422	314.266	...	335.723	337.572	336.781	...	322.590
0.000084	309.000	310.362	314.130	...	335.447	337.336	336.613	...	322.573
0.000085	309.000	310.303	313.998	...	335.174	337.101	336.443	...	322.556
0.000086	309.000	310.247	313.868	...	334.902	336.865	336.273	...	322.539
0.000087	309.000	310.193	313.741	...	334.633	336.630	336.103	...	322.523
0.000088	309.000	310.141	313.617	...	334.365	336.394	335.931	...	322.506
0.000089	309.000	310.092	313.495	...	334.100	336.159	335.759	...	322.489
0.000090	309.000	310.043	313.376	...	333.837	335.924	335.586	...	322.472
0.000091	309.000	309.997	313.260	...	333.575	335.690	335.413	...	322.455
0.000092	309.000	309.953	313.146	...	333.316	335.456	335.239	...	322.437
0.000093	309.000	309.910	313.035	...	333.059	335.223	335.065	...	322.420
0.000094	309.000	309.869	312.926	...	332.803	334.990	334.890	...	322.403
0.000095	309.000	309.829	312.819	...	332.550	334.757	334.715	...	322.386
0.000096	309.000	309.791	312.715	...	332.299	334.525	334.539	...	322.369
0.000097	309.000	309.755	312.614	...	332.050	334.294	334.363	...	322.351
0.000098	309.000	309.720	312.514	...	331.802	334.064	334.186	...	322.334
0.000099	309.000	309.687	312.417	...	331.557	333.834	334.010	...	322.316
0.000100	309.000	309.655	312.322	...	331.314	333.605	333.833	...	322.299
0.000101	309.000	309.624	312.230	...	331.073	333.376	333.655	...	322.281
0.000102	309.000	309.594	312.139	...	330.833	333.149	333.478	...	322.264
0.000103	309.000	309.566	312.051	...	330.596	332.922	333.300	...	322.246
0.000104	309.000	309.539	311.965	...	330.360	332.697	333.122	...	322.229
0.000105	309.000	309.513	311.880	...	330.126	332.472	332.945	...	322.211
0.000106	309.000	309.488	311.798	...	329.895	332.248	332.766	...	322.193
0.000107	309.000	309.465	311.718	...	329.665	332.025	332.588	...	322.175
0.000108	309.000	309.442	311.640	...	329.437	331.803	332.410	...	322.157
0.000109	309.000	309.420	311.563	...	329.211	331.582	332.232	...	322.140
0.000110	309.000	309.399	311.489	...	328.987	331.363	332.054	...	322.122
0.000111	309.000	309.379	311.416	...	328.765	331.144	331.876	...	322.104
0.000112	309.000	309.360	311.345	...	328.545	330.926	331.698	...	322.086
0.000113	309.000	309.342	311.276	...	328.326	330.710	331.520	...	322.067
0.000114	309.000	309.325	311.209	...	328.110	330.495	331.342	...	322.049
0.000115	309.000	309.308	311.143	...	327.895	330.280	331.165	...	322.031
0.000116	309.000	309.293	311.079	...	327.682	330.068	330.987	...	322.013
0.000117	309.000	309.278	311.017	...	327.471	329.856	330.810	...	321.995
0.000118	309.000	309.263	310.956	...	327.262	329.645	330.633	...	321.976
0.000119	309.000	309.250	310.897	...	327.054	329.436	330.456	...	321.958
0.000120	309.000	309.237	310.839	...	326.849	329.228	330.280	...	321.940
0.000121	309.000	309.224	310.783	...	326.645	329.021	330.104	...	321.921
0.000122	309.000	309.212	310.729	...	326.443	328.816	329.928	...	321.903
0.000123	309.000	309.201	310.675	...	326.243	328.612	329.753	...	321.884
0.000124	309.000	309.190	310.623	...	326.044	328.409	329.578	...	321.866
0.000125	309.000	309.180	310.573	...	325.847	328.207	329.403	...	321.847
0.000126	309.000	309.170	310.524	...	325.653	328.007	329.229	...	321.828
0.000127	309.000	309.161	310.476	...	325.459	327.808	329.055	...	321.810
0.000128	309.000	309.152	310.430	...	325.268	327.611	328.882	...	321.791
0.000129	309.000	309.144	310.385	...	325.078	327.415	328.709	...	321.772
0.000130	309.000	309.136	310.341	...	324.890	327.220	328.537	...	321.753

0.000131	309.000	309.129	310.298	...	324.704	327.027	328.365	...	321.734
0.000132	309.000	309.121	310.256	...	324.519	326.835	328.194	...	321.715
0.000133	309.000	309.115	310.216	...	324.336	326.644	328.023	...	321.697
0.000134	309.000	309.108	310.177	...	324.155	326.455	327.853	...	321.678
0.000135	309.000	309.102	310.139	...	323.975	326.267	327.683	...	321.659
0.000136	309.000	309.096	310.102	...	323.797	326.081	327.514	...	321.639
0.000137	309.000	309.091	310.066	...	323.621	325.896	327.346	...	321.620
0.000138	309.000	309.086	310.031	...	323.446	325.712	327.179	...	321.601
0.000139	309.000	309.081	309.997	...	323.274	325.530	327.012	...	321.582
0.000140	309.000	309.076	309.964	...	323.102	325.349	326.845	...	321.563
0.000141	309.000	309.072	309.932	...	322.932	325.170	326.680	...	321.543
0.000142	309.000	309.067	309.901	...	322.764	324.992	326.515	...	321.524
0.000143	309.000	309.063	309.870	...	322.598	324.815	326.351	...	321.505
0.000144	309.000	309.060	309.841	...	322.433	324.640	326.187	...	321.485
0.000145	309.000	309.056	309.813	...	322.270	324.466	326.025	...	321.466
0.000146	309.000	309.053	309.785	...	322.108	324.294	325.863	...	321.446
0.000147	309.000	309.050	309.758	...	321.948	324.123	325.702	...	321.427
0.000148	309.000	309.047	309.732	...	321.789	323.954	325.541	...	321.407
0.000149	309.000	309.044	309.707	...	321.632	323.786	325.382	...	321.387
0.000150	309.000	309.041	309.683	...	321.476	323.619	325.223	...	321.368
0.000151	309.000	309.039	309.659	...	321.322	323.454	325.065	...	321.348
0.000152	309.000	309.036	309.636	...	321.169	323.290	324.908	...	321.328
0.000153	309.000	309.034	309.614	...	321.018	323.128	324.752	...	321.309
0.000154	309.000	309.032	309.593	...	320.869	322.967	324.597	...	321.289
0.000155	309.000	309.030	309.572	...	320.721	322.807	324.442	...	321.269
0.000156	309.000	309.028	309.552	...	320.574	322.649	324.289	...	321.249
0.000157	309.000	309.026	309.532	...	320.429	322.492	324.136	...	321.229
0.000158	309.000	309.025	309.513	...	320.285	322.336	323.984	...	321.209
0.000159	309.000	309.023	309.495	...	320.143	322.182	323.833	...	321.189
0.000160	309.000	309.022	309.477	...	320.002	322.030	323.683	...	321.169
0.000161	309.000	309.020	309.460	...	319.863	321.878	323.534	...	321.149
0.000162	309.000	309.019	309.443	...	319.725	321.728	323.386	...	321.129
0.000163	309.000	309.018	309.427	...	319.589	321.580	323.238	...	321.109
0.000164	309.000	309.017	309.412	...	319.453	321.432	323.092	...	321.089
0.000165	309.000	309.016	309.397	...	319.320	321.286	322.947	...	321.068
0.000166	309.000	309.014	309.382	...	319.187	321.142	322.802	...	321.048
0.000167	309.000	309.014	309.368	...	319.056	320.999	322.659	...	321.028
0.000168	309.000	309.013	309.354	...	318.927	320.857	322.516	...	321.007
0.000169	309.000	309.012	309.341	...	318.798	320.716	322.374	...	320.987
0.000170	309.000	309.011	309.328	...	318.671	320.577	322.234	...	320.967
0.000171	309.000	309.010	309.316	...	318.546	320.439	322.094	...	320.946
0.000172	309.000	309.010	309.304	...	318.421	320.302	321.955	...	320.926
0.000173	309.000	309.009	309.293	...	318.298	320.167	321.817	...	320.905
0.000174	309.000	309.008	309.282	...	318.177	320.033	321.681	...	320.885
0.000175	309.000	309.008	309.271	...	318.056	319.900	321.545	...	320.864
0.000176	309.000	309.007	309.261	...	317.938	319.768	321.410	...	320.843
0.000177	309.000	309.007	309.251	...	317.820	319.638	321.276	...	320.823
0.000178	309.000	309.006	309.241	...	317.703	319.509	321.143	...	320.802
0.000179	309.000	309.006	309.232	...	317.588	319.381	321.012	...	320.782
0.000180	309.000	309.005	309.223	...	317.474	319.255	320.881	...	320.761
0.000181	309.000	309.005	309.214	...	317.361	319.129	320.751	...	320.740
0.000182	309.000	309.005	309.206	...	317.249	319.005	320.622	...	320.719
0.000183	309.000	309.004	309.198	...	317.139	318.882	320.494	...	320.698
0.000184	309.000	309.004	309.190	...	317.030	318.761	320.367	...	320.677
0.000185	309.000	309.004	309.182	...	316.922	318.640	320.241	...	320.657
0.000186	309.000	309.004	309.175	...	316.815	318.521	320.116	...	320.636
0.000187	309.000	309.003	309.168	...	316.710	318.403	319.992	...	320.615
0.000188	309.000	309.003	309.162	...	316.605	318.286	319.870	...	320.594
0.000189	309.000	309.003	309.155	...	316.502	318.171	319.748	...	320.573
0.000190	309.000	309.003	309.149	...	316.400	318.056	319.627	...	320.551
0.000191	309.000	309.002	309.143	...	316.299	317.943	319.507	...	320.530
0.000192	309.000	309.002	309.137	...	316.199	317.831	319.388	...	320.509
0.000193	309.000	309.002	309.132	...	316.101	317.720	319.270	...	320.488
0.000194	309.000	309.002	309.126	...	316.003	317.610	319.153	...	320.467
0.000195	309.000	309.002	309.121	...	315.907	317.501	319.037	...	320.446
0.000196	309.000	309.002	309.116	...	315.811	317.394	318.922	...	320.424
0.000197	309.000	309.002	309.111	...	315.717	317.287	318.808	...	320.403
0.000198	309.000	309.001	309.107	...	315.624	317.182	318.695	...	320.382
0.000199	309.000	309.001	309.102	...	315.532	317.077	318.583	...	320.361
0.000200	309.000	309.001	309.098	...	315.441	316.974	318.472	...	320.339

APPENDIX E

EXAMPLE "BURNMODL.OUT" OUTPUT (heat gun)

Heat-gun simulation

HEAT GUN SIMULATION: input data echo and simulation results

(Also see file TEMPDIST.OUT.)

```
* Heat gun   [8-character data fields]

*line 1: Integration method (1.=R-K) and stepsize (s)
*line 2: Output specifications -- SW1, SW2, KTAB(1-25)  FORMAT(2g8.0, 25I1)
;       Field 1: summary outputs (results and input data summary)
;         =1., summary of results, summary of input data, summary of model consts
;         =2., summary of results, summary of input data
;         =3., summary of results only
;         <0., as above but also print parsed results summary (to separate file)
;       Field 2: tabular output data, including time histories
;         =0., print no tabular data to file
;         =1., print all tabular data to file [KTAB() specifications optional]
;              KTAB(i) for table i: 0 = do not write to file, 1 = write to file,
;              2 = write every 2nd point to file (time histories 7-14,18-25)
;         =2., default (selected) tables to file
;              Table No.  1 2 3 4 5 6 7 8 910111213141516171819202122232425
;              Default    0 0 0 0                        0 0 0 0 2
;         <0., as above but write tabular data to different file from summaries
*line 3: Gas identification:  a) nitrogen or 1.  or  b) air or 2.
*line 4: Ambient temperature (°C)  [include K in field if Kelvin]
*line 5: Initial skin surface temperature (°C)  [include K in field if Kelvin]
*line 6: Duration of exposure to heat gun jet (s)
;          or -1. to search for the exposure duration that results in Ω=0.53
;          or -2. to search for the exposure duration that results in Ω=1
*line 7: Temperature of gas flow from heat gun (°C) [incl. K in field if Kelvin]
;          or -1. to search for the gas jet temperature that results in Ω=0.53
;          or -2. to search for the gas jet temperature that results in Ω=1
*line 8: Velocity of heat gun jet (m/s) or, if negative (and not -1. or -2.),
;          the pitot tube pressure differential in inches of water,
;          or -1. to search for the gas jet velocity that results in Ω=0.53
;          or -2. to search for the gas jet velocity that results in Ω=1
*line 9: Heat-gun port diameter (m)
*line 10: Orifice coefficient for heat-gun port
*line 11: H/D ratio: H, distance from vent to skin surface; D, gas jet diameter
*line 12: r/D ratio: r, effective radius of target area; D, gas jet diameter
*line 13: Multiplicative tuning factor for Phase 1 heat transfer coefficient
*line 14: Effective Qdot for Phase 2 heat transfer (.ge. 0; e.g., 1400 W/m**2)
*line 15: Thermal conductivities of epidermis and dermis (W/m/K) (nonzero)
*line 16: Thermal diffusivities of epidermis and dermis (m**2/s); if a negative
;          value is specified in field 1 (epidermis), fields 3 and 4 must contain
;          nonzero values for density (kg/m**3) and specific heat (J/kg/K);
;          fields 5 and 6 are used similarly for the dermis if field 2 is neg.
*line 17: Critical cell depth (micrometers)
;           or -1. to search for the cell depth for which Ω=0.53
;           or -2. to search for the cell depth for which Ω=1
*line 18: Burn integral constants: preexponential factor coefficient and power,
;          and delE/R (activation energy divided by gas constant)

1.      .0005
1.      1.      1111111111111111112111111
air
20.85
35.85
0.150
450.
66.
0.010
1.
3.0
1.0
.55
1400.
0.20949 0.3791
7.267E-8 1.43E-7
72.
3.1     98.     75000.                  Henriques-Moritz   [44,50] C
*2.185   124.    93534.9                 Weaver-Stoll  [44,50] C
*1.823   51.     39109.8                 Weaver-Stoll   >50 C
```

```
*1.43     72.      55000.                     Mehta-Wong       ---
* Comment lines must begin with one of these:  ; : * # $ @
* Comments can be added after data fields on any line (w. or w/o ;:*#$@).
* Completely blank lines are also allowed.
```

Heat gun: 450 °C, 66 m/s, 150 ms

SUMMARY OF RESULTS

Burn Injury Integral Ω for Critical Depth 72 μm

Heat gun: 450 °C, 66 m/s, 150 ms   Gas: air   Port dia: 10.00 mm

	During Exposure	After Exposure	Total
Time range (ms)	0.0-150.0	150.0-500.0	0.0-500.0
Omega (Ω)	0.1327	0.4401	0.5728
Gas jet temperature	723.150 °K 450.000 °C	--- ---	--- ---
Gas jet velocity	66.000 m/s	---	---
Average skin surface temperature	342.800 °K 69.650 °C	329.747 °K 56.598 °C	333.663 °K 60.513 °C
Avg heat trans coeff	234.830 W/m²/K	39.250 W/m²/K	---
Average heat flux	89.320 kW/m²	-1.400 kW/m²	---
Average temperature at 72 mm depth	322.428 °K 49.278 °C	326.009 °K 52.859 °C	324.935 °K 51.785 °C
Maximum temperature at 72 mm depth	334.368 °K 61.218 °C	334.948 °K 61.798 °C	334.948 °K 61.798 °C
Time at maximum temp	150.0 ms	157.0 ms	157.0 ms

Other

The heat transfer coefficient value for Phase 2 (39.250 W/m²/K) is the *effective* value, which results from the user-specified Phase 2 heat flux (-1.400 kW/m²), an estimated (not actual) average Phase 2 skin surface temperature of 329.669 °K, and an adjusted (ambient) exposure temperature of 323.707 °K. (The actual ambient temperature is 294.000 °K.)

```
                         SUMMARY OF INPUT DATA

Control specifications

  Integration method: Runge-Kutta fixed-step
  Integration stepsize:  0.00050 s
  End time for integration:  0.1500 s   (the user-specified
    value or, if specified, the duration of exposure)

Output specifications

  Summary output plus specified tabular time histories to file
    Tables (1- 1): 11111 11111 11111 11200 00000 00

Heat gun test specifications

  Gas:  air
  Duration of exposure to heat gun gas jet:  0.1500 s
  Temperature of gas jet:  450.00 °C  (= 723.15 °K)
  Velocity of gas jet:  66.0 m/s
  Heat-gun port:  diameter = 0.01000 m   orifice coefficient = 1.000
  H/D, nondimensional distance to skin surface:  3.0
    (H, vent-to-skin distance; D, diameter of [uncontracted] jet)
  r/D, nondimensional radius of target area:  1.0
    (r, effective radius; D, diameter of [uncontracted] jet)
  Multiplicative tuning factor for heat transfer coeff: 0.550
  Heat transfer rate (flux) from surface after exposure: -1400 W/m²

Skin properties

  Thermal conductivity
    Epidermis: 0.20949 W/m/K
    Dermis:    0.37910 W/m/K
  Thermal diffusivity
    Epidermis: 0.7267E-07 m²/s
    Dermis:    0.1430E-06 m²/s
  Critical cell depth (base of the epidermal layer): 72 μm


Burn integral constants

  G = 3.100 x 10**( 98) 1/s
  deltaE/R = 75000.0 K    (delE = 623.581 kJ/gm-mol)

  Threshold for first-degree burn (epidermal injury)
    Ω = 0.53  (model constant)
  Threshold for burn with partial skin loss and injury
  fully through the epidermis (full epidermal necrosis)
    Ω = 1.0   (model constant)
```

SUMMARY OF MODEL CONSTANTS

Universal constants

Absolute zero kelvin = 273.15 °C
Universal gas constant = 8.31441 J/gram-mol/K (kJ/kg-mol/K)
= 8314.41 J/kg-mol/K

Molecular weights
Nitrogen: 28.0134 kg/kg-mol
Air (average): 28.9660 kg/kg-mol

Gas constants (Runiv/m.w.)
Nitrogen: 296.80 J/kg-mol/K
Air: 287.04 J/kg-mol/K

Density of water = 1000 kg/m**3 (assumed incompressible)

Earth constants

One atmosphere pressure = 101325 Pascal [N/m²] = 14.696 lb/in²
Density of air at 1 atm and 700 K = 0.4975 kg/m**3
(used with perfect gas law in calculation of gas density for pitot-tube determination of velocity of jet)
Earth standard gravity = 9.80665 m/s² = 32.174 ft/s²

Gas properties

For nitrogen and air, tabular values as functions of temperature, 200 to 1000 K (from Incropera and DeWitt, Table A.4)
Kinematic viscosity [m²/s]
Thermal conductivity [W/m/K]
Prandtl number
Specific heat at constant pressure [KJ/kg/K]

Empirical constants

Fabric stretch factor, regression to airbag volume

Cs = 2.45e-6 + 2.27e-5 * Vol [m²/(N/m²)/m²]

For a single round jet and H/D = 3.0 and r/D = 1.0, the relationship between the Nusselt number (Nu), the Prandtl number (Pr), and the Reynolds number (Re):

Nu / Pr**0.42 = k(H/D, r/D) C Re**n,

where C = 0.62330, n = 0.5409

and k(H/D, r/D) is a correction function that has the value 1.0300 for the specified values of H/D and r/D. In general, for H/D = 7.5, the values of C and n for various r/D values are as follows (from Martin, Fig. 9):

r/D	C	n
0.0	1.0918	0.5049
1.0	0.6233	0.5409
2.0	0.3314	0.5815
3.0	0.2254	0.6001

The correction function is as follows (from Martin, Fig. 10):

H/D	r/D	k(H/D, r/D)
1.0-6.65	all	1.03
7.5	all	1.0
12.0	0.0	0.775
12.0	1.0	0.775
12.0	2.0	0.80
12.0	3.0	0.81

12.0	5.0	0.86
12.0	7.0	0.90

with linear interpolation for other values of H/D and r/D.

Model assumptions

The basic model is for a two-phased heat flow in a semi-infinite solid. In phase 1 the surface is exposed to a medium (exhaust) with temperature A, and the heat transfer coefficient is hA. In phase 2 (post-exhaust) the external medium has temperature B, and the heat transfer coefficient is hB. A, B, hA, and hB are constants. The temperature distribution in the solid (skin epidermis and dermis) is determined as a function of time from a generalization of equations due to Carslaw and Jaeger (pg. 74, eqs. 2 and 3).

Burn severity is predicted by calculating the integral injury function described by Henriques. Burn injury is treated as a rate process in which the progression of the injury is related to both the temperature and the duration of the temperature. The burn injury integral, omega (Ω), is defined such that Ω = 1.0 is the threshold for burn with partial skin loss and injury fully through the epidermis (full epidermal necrosis). The threshold for first-degree burn (epidermal injury) is Ω = 0.53.

Other assumptions

Heat transfer coefficient after exposure

= Qdot / (ambient temperature - Tskinsurf,avg)

where Qdot<0 is an input constant, the effective heat transfer rate (flux) from the skin surface after exposure, and Tskinsurf,avg is the average skin surface temperature during exposure.

The average temperature of the external medium after exposure is assumed to be the ambient (room) temperature. (Reasonable alternative estimates that would model the effect of a boundary layer are Tskinsurf,avg, as above, and the average of Tskinsurf,avg and the ambient temperature.)

The pendulum model for occupant interaction assumes that occupant/airbag contact begins at the instant the airbag becomes full (i.e., the beginning of exhaust).

Model constraints

The estimation of time rate of change of airbag volume from occupant interaction assumes that the restraining effect of airbag membrane forces is small compared with the pressure forces.

The heat transfer coefficient value for Phase 2 is the *effective* value, which results from the user-specified Phase 2 heat flux, an estimated (not actual) average Phase 2 skin surface temperature, and an adjusted (ambient) exposure temperature.

Table 1 = VISCOSTY (15 points)
viscosity (nitrogen or air) [m²/s]

0.200000E+03	0.759000E-05
0.250000E+03	0.114400E-04
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.850000E+03	0.938000E-04
0.900000E+03	0.102900E-03

Table 2 = CONDUCTV (15 points)
conductivity (N2 or air) [W/m/K]

0.200000E+03	0.181000E-01
0.250000E+03	0.223000E-01
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.850000E+03	0.596000E-01
0.900000E+03	0.620000E-01

Table 3 = PRANDTL (15 points)
Prandtl number (N2 or air) [-]

0.200000E+03	0.737000E+00
0.250000E+03	0.720000E+00
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.850000E+03	0.716000E+00
0.900000E+03	0.720000E+00

Table 4 = K-RATIO (16 points)
ratio of specific heats (N2 or air) [-]

0.200000E+03	0.139869E+01
0.250000E+03	0.139924E+01
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.850000E+03	0.134879E+01
0.900000E+03	0.134419E+01
0.200000E+04	0.134419E+01

Table 15 = JET C (4 points)
Martin's coefficient C for circular impinging gas jet [-]

0.000000E+00	0.109180E+01
0.100000E+01	0.623300E+00
0.200000E+01	0.331400E+00
0.300000E+01	0.225400E+00

Table 16 = JET n (4 points)
Martin's exponent n for circular impinging gas jet [-]

0.000000E+00	0.504900E+00
0.100000E+01	0.540900E+00
0.200000E+01	0.581500E+00
0.300000E+01	0.600100E+00

Table 17 = KORR12HD (6 points)
correction factor at H/D = 12 as function of r/D [-]

0.000000E+00	0.775000E+00
0.100000E+01	0.775000E+00
0.200000E+01	0.800000E+00
0.300000E+01	0.810000E+00

0.500000E+01	0.860000E+00
0.700000E+01	0.900000E+00

Table 18 = Hgas (301 points)
gas-to-skin heat transfer coefficient [$W/m^2/K$]

0.000000E+00	0.236394E+03
0.500000E-03	0.234662E+03
0.100000E-02	0.234894E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.740000E-01	0.235831E+03
0.745000E-01	0.235851E+03
0.750000E-01	0.235871E+03
0.755000E-01	0.235861E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.148500E+00	0.233366E+03
0.149000E+00	0.233380E+03
0.149500E+00	0.233393E+03
0.150000E+00	0.233406E+03

Table 19 = Tcritdep (501 points)
skin temperature at critical depth [K]

0.000000E+00	0.309000E+03
0.100000E-02	0.309000E+03
0.200000E-02	0.309001E+03
0.300000E-02	0.309011E+03
0.400000E-02	0.309045E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.730000E-01	0.322870E+03
0.740000E-01	0.323047E+03
0.750000E-01	0.323222E+03
0.760000E-01	0.323397E+03
0.770000E-01	0.323571E+03
0.780000E-01	0.323744E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.152000E+00	0.334622E+03
0.153000E+00	0.334739E+03
0.154000E+00	0.334833E+03
0.155000E+00	0.334899E+03
0.156000E+00	0.334937E+03
0.157000E+00	0.334948E+03
0.158000E+00	0.334938E+03
0.159000E+00	0.334909E+03
0.160000E+00	0.334866E+03
0.161000E+00	0.334810E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.236000E+00	0.328572E+03
0.237000E+00	0.328513E+03
0.238000E+00	0.328455E+03
0.239000E+00	0.328397E+03
0.240000E+00	0.328340E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.317000E+00	0.325085E+03
0.318000E+00	0.325054E+03
0.319000E+00	0.325022E+03
0.320000E+00	0.324991E+03
0.321000E+00	0.324960E+03
. . . . . .	. . . . . .
. . . . . .	. . . . . .
0.409000E+00	0.322835E+03
0.410000E+00	0.322816E+03
0.411000E+00	0.322797E+03
0.412000E+00	0.322778E+03

```
  0.413000E+00  0.322760E+03
  . . . . . .   . . . . . .
  . . . . . .   . . . . . .
  0.497000E+00  0.321455E+03
  0.498000E+00  0.321442E+03
  0.499000E+00  0.321429E+03
  0.500000E+00  0.321416E+03


Input:    HEATGUN
Output:   BURNMODL.OUT  TEMPDIST.OUT

End of simulation.
```

APPENDIX F

EXAMPLE "TEMPDIST.OUT" OUTPUT (heat gun)

Heat-gun simulation

HEAT GUN SIMULATION: skin temperature distribution results

(Also see file BURNMODL.OUT.)

Heat gun: 450 °C, 66 m/s, 150 ms
gas: air

Test specifications:
Duration of exposure = 0.1500 s
Velocity = 66.000 m/s
Free-stream temperature = 450.00 °C
= 723.15 °K
Orifice diameter = 0.01000 m
Estimated effective Phase 2 heat transfer rate = -1400. W/m²

Temperatures, T(x,t) Columns are for times 0 ms, 10 ms, 20 ms, ... 500 ms.

Depth (m)	0.	10.	20.		150.	160.	170.		500.
0.000000	309.000	322.752	328.238	...	358.483	346.681	342.797	...	323.259
0.000001	309.000	322.307	327.799	...	358.075	346.703	342.816	...	323.258
0.000002	309.000	321.872	327.365	...	357.669	346.718	342.831	...	323.257
0.000003	309.000	321.447	326.939	...	357.266	346.727	342.842	...	323.256
0.000004	309.000	321.030	326.518	...	356.864	346.728	342.848	...	323.255
0.000005	309.000	320.623	326.104	...	356.465	346.723	342.850	...	323.254
0.000006	309.000	320.225	325.697	...	356.067	346.711	342.849	...	323.252
0.000007	309.000	319.836	325.296	...	355.672	346.692	342.842	...	323.250
0.000008	309.000	319.456	324.901	...	355.278	346.666	342.832	...	323.248
0.000009	309.000	319.085	324.512	...	354.887	346.633	342.817	...	323.246
0.000010	309.000	318.723	324.130	...	354.498	346.594	342.798	...	323.243
0.000011	309.000	318.370	323.754	...	354.111	346.548	342.775	...	323.240
0.000012	309.000	318.026	323.385	...	353.726	346.495	342.748	...	323.237
0.000013	309.000	317.691	323.022	...	353.343	346.436	342.717	...	323.234
0.000014	309.000	317.365	322.665	...	352.962	346.370	342.681	...	323.231
0.000015	309.000	317.048	322.314	...	352.583	346.298	342.642	...	323.227
0.000016	309.000	316.739	321.970	...	352.206	346.220	342.598	...	323.224
0.000017	309.000	316.439	321.631	...	351.831	346.135	342.550	...	323.220
0.000018	309.000	316.147	321.299	...	351.459	346.044	342.499	...	323.215
0.000019	309.000	315.863	320.973	...	351.088	345.947	342.443	...	323.211
0.000020	309.000	315.588	320.653	...	350.720	345.844	342.383	...	323.206
0.000021	309.000	315.321	320.339	...	350.353	345.735	342.320	...	323.202
0.000022	309.000	315.062	320.032	...	349.989	345.621	342.252	...	323.196
0.000023	309.000	314.811	319.730	...	349.627	345.500	342.181	...	323.191
0.000024	309.000	314.568	319.434	...	349.266	345.375	342.106	...	323.186
0.000025	309.000	314.332	319.144	...	348.908	345.243	342.027	...	323.180
0.000026	309.000	314.104	318.860	...	348.552	345.107	341.945	...	323.174
0.000027	309.000	313.884	318.581	...	348.198	344.965	341.858	...	323.168
0.000028	309.000	313.671	318.309	...	347.846	344.818	341.769	...	323.162
0.000029	309.000	313.465	318.042	...	347.496	344.666	341.675	...	323.155
0.000030	309.000	313.266	317.781	...	347.149	344.510	341.578	...	323.148
0.000031	309.000	313.074	317.525	...	346.803	344.349	341.478	...	323.141
0.000032	309.000	312.888	317.275	...	346.459	344.183	341.374	...	323.134
0.000033	309.000	312.710	317.030	...	346.118	344.013	341.267	...	323.127
0.000034	309.000	312.538	316.791	...	345.778	343.838	341.156	...	323.119
0.000035	309.000	312.372	316.557	...	345.441	343.660	341.042	...	323.111
0.000036	309.000	312.212	316.329	...	345.105	343.477	340.926	...	323.103
0.000037	309.000	312.059	316.105	...	344.772	343.291	340.805	...	323.095
0.000038	309.000	311.911	315.887	...	344.441	343.101	340.682	...	323.087
0.000039	309.000	311.769	315.674	...	344.112	342.907	340.556	...	323.078
0.000040	309.000	311.633	315.466	...	343.785	342.710	340.427	...	323.069
0.000041	309.000	311.502	315.263	...	343.459	342.510	340.295	...	323.060
0.000042	309.000	311.376	315.065	...	343.136	342.306	340.160	...	323.051
0.000043	309.000	311.256	314.872	...	342.815	342.100	340.022	...	323.041
0.000044	309.000	311.140	314.684	...	342.496	341.891	339.882	...	323.031
0.000045	309.000	311.030	314.500	...	342.180	341.678	339.739	...	323.021
0.000046	309.000	310.924	314.321	...	341.865	341.464	339.593	...	323.011
0.000047	309.000	310.823	314.146	...	341.552	341.247	339.445	...	323.001
0.000048	309.000	310.726	313.976	...	341.241	341.027	339.295	...	322.990
0.000049	309.000	310.634	313.811	...	340.932	340.806	339.142	...	322.980
0.000050	309.000	310.545	313.650	...	340.626	340.582	338.986	...	322.969
0.000051	309.000	310.461	313.493	...	340.321	340.357	338.829	...	322.958
0.000052	309.000	310.380	313.340	...	340.018	340.129	338.669	...	322.946
0.000053	309.000	310.304	313.192	...	339.718	339.900	338.507	...	322.935
0.000054	309.000	310.231	313.047	...	339.419	339.670	338.344	...	322.923
0.000055	309.000	310.161	312.907	...	339.122	339.438	338.178	...	322.911
0.000056	309.000	310.095	312.770	...	338.828	339.205	338.010	...	322.899

0.000057	309.000	310.032	312.638	...	338.535	338.970	337.841	...	322.886
0.000058	309.000	309.972	312.509	...	338.244	338.735	337.669	...	322.874
0.000059	309.000	309.915	312.384	...	337.956	338.498	337.496	...	322.861
0.000060	309.000	309.861	312.262	...	337.669	338.261	337.321	...	322.848
0.000061	309.000	309.809	312.144	...	337.385	338.023	337.145	...	322.834
0.000062	309.000	309.761	312.030	...	337.102	337.784	336.967	...	322.821
0.000063	309.000	309.715	311.919	...	336.821	337.545	336.788	...	322.807
0.000064	309.000	309.671	311.811	...	336.543	337.306	336.608	...	322.794
0.000065	309.000	309.630	311.707	...	336.266	337.066	336.426	...	322.780
0.000066	309.000	309.590	311.605	...	335.991	336.826	336.243	...	322.765
0.000067	309.000	309.553	311.507	...	335.718	336.585	336.058	...	322.751
0.000068	309.000	309.518	311.412	...	335.447	336.345	335.873	...	322.736
0.000069	309.000	309.485	311.320	...	335.179	336.105	335.687	...	322.721
0.000070	309.000	309.454	311.231	...	334.912	335.864	335.499	...	322.706
0.000071	309.000	309.634	311.639	...	334.760	335.471	334.818	...	322.016
0.000072	309.000	309.790	311.933	...	334.368	334.866	334.019	...	321.416
0.000073	309.000	309.921	312.145	...	333.872	334.189	333.211	...	320.892
0.000074	309.000	310.029	312.298	...	333.339	333.502	332.434	...	320.431
0.000075	309.000	309.988	312.216	...	333.169	333.371	332.340	...	320.423
0.000076	309.000	309.948	312.137	...	333.001	333.240	332.245	...	320.415
0.000077	309.000	309.909	312.059	...	332.833	333.108	332.150	...	320.406
0.000078	309.000	309.872	311.982	...	332.666	332.975	332.054	...	320.398
0.000079	309.000	309.836	311.907	...	332.500	332.842	331.957	...	320.390
0.000080	309.000	309.801	311.834	...	332.334	332.708	331.859	...	320.381
0.000081	309.000	309.768	311.762	...	332.170	332.574	331.761	...	320.373
0.000082	309.000	309.736	311.691	...	332.006	332.440	331.662	...	320.364
0.000083	309.000	309.704	311.622	...	331.843	332.305	331.562	...	320.356
0.000084	309.000	309.675	311.555	...	331.681	332.170	331.462	...	320.347
0.000085	309.000	309.646	311.489	...	331.520	332.035	331.361	...	320.338
0.000086	309.000	309.618	311.424	...	331.359	331.900	331.260	...	320.329
0.000087	309.000	309.591	311.360	...	331.200	331.764	331.158	...	320.320
0.000088	309.000	309.565	311.299	...	331.041	331.628	331.055	...	320.311
0.000089	309.000	309.541	311.238	...	330.883	331.492	330.952	...	320.302
0.000090	309.000	309.517	311.178	...	330.725	331.356	330.849	...	320.293
0.000091	309.000	309.494	311.120	...	330.569	331.220	330.745	...	320.283
0.000092	309.000	309.472	311.064	...	330.413	331.084	330.640	...	320.274
0.000093	309.000	309.451	311.008	...	330.259	330.947	330.535	...	320.264
0.000094	309.000	309.430	310.954	...	330.104	330.811	330.430	...	320.255
0.000095	309.000	309.411	310.901	...	329.951	330.675	330.324	...	320.245
0.000096	309.000	309.392	310.849	...	329.799	330.538	330.218	...	320.236
0.000097	309.000	309.374	310.798	...	329.647	330.402	330.111	...	320.226
0.000098	309.000	309.357	310.749	...	329.496	330.266	330.004	...	320.216
0.000099	309.000	309.340	310.700	...	329.346	330.129	329.897	...	320.206
0.000100	309.000	309.324	310.653	...	329.197	329.993	329.789	...	320.196
0.000101	309.000	309.309	310.607	...	329.048	329.857	329.681	...	320.186
0.000102	309.000	309.294	310.562	...	328.900	329.722	329.573	...	320.176
0.000103	309.000	309.280	310.518	...	328.754	329.586	329.464	...	320.166
0.000104	309.000	309.267	310.475	...	328.607	329.451	329.355	...	320.155
0.000105	309.000	309.254	310.433	...	328.462	329.315	329.246	...	320.145
0.000106	309.000	309.242	310.392	...	328.317	329.180	329.137	...	320.134
0.000107	309.000	309.230	310.352	...	328.174	329.046	329.027	...	320.124
0.000108	309.000	309.219	310.313	...	328.030	328.911	328.917	...	320.113
0.000109	309.000	309.208	310.275	...	327.888	328.777	328.807	...	320.103
0.000110	309.000	309.198	310.238	...	327.747	328.643	328.697	...	320.092
0.000111	309.000	309.188	310.202	...	327.606	328.509	328.587	...	320.081
0.000112	309.000	309.178	310.166	...	327.466	328.376	328.476	...	320.070
0.000113	309.000	309.169	310.132	...	327.327	328.243	328.366	...	320.059
0.000114	309.000	309.161	310.098	...	327.188	328.111	328.255	...	320.048
0.000115	309.000	309.153	310.066	...	327.051	327.978	328.144	...	320.037
0.000116	309.000	309.145	310.034	...	326.914	327.847	328.033	...	320.026
0.000117	309.000	309.137	310.003	...	326.778	327.715	327.923	...	320.014
0.000118	309.000	309.130	309.973	...	326.642	327.584	327.812	...	320.003
0.000119	309.000	309.124	309.943	...	326.508	327.453	327.701	...	319.992
0.000120	309.000	309.117	309.914	...	326.374	327.323	327.590	...	319.980
0.000121	309.000	309.111	309.886	...	326.241	327.194	327.478	...	319.968
0.000122	309.000	309.105	309.859	...	326.108	327.064	327.367	...	319.957
0.000123	309.000	309.099	309.833	...	325.977	326.935	327.257	...	319.945
0.000124	309.000	309.094	309.807	...	325.846	326.807	327.146	...	319.933
0.000125	309.000	309.089	309.782	...	325.716	326.679	327.035	...	319.921
0.000126	309.000	309.084	309.757	...	325.586	326.552	326.924	...	319.909
0.000127	309.000	309.080	309.734	...	325.458	326.425	326.813	...	319.897
0.000128	309.000	309.075	309.711	...	325.330	326.298	326.702	...	319.885
0.000129	309.000	309.071	309.688	...	325.202	326.173	326.591	...	319.873
0.000130	309.000	309.067	309.666	...	325.076	326.047	326.481	...	319.861

0.000131	309.000	309.064	309.645	...	324.950	325.922	326.371	...	319.849
0.000132	309.000	309.060	309.624	...	324.825	325.798	326.260	...	319.836
0.000133	309.000	309.057	309.604	...	324.701	325.674	326.150	...	319.824
0.000134	309.000	309.053	309.585	...	324.578	325.551	326.040	...	319.811
0.000135	309.000	309.050	309.566	...	324.455	325.428	325.930	...	319.799
0.000136	309.000	309.048	309.547	...	324.333	325.306	325.821	...	319.786
0.000137	309.000	309.045	309.529	...	324.211	325.185	325.711	...	319.773
0.000138	309.000	309.042	309.512	...	324.091	325.064	325.602	...	319.761
0.000139	309.000	309.040	309.495	...	323.971	324.943	325.493	...	319.748
0.000140	309.000	309.038	309.479	...	323.852	324.823	325.384	...	319.735
0.000141	309.000	309.035	309.463	...	323.733	324.704	325.275	...	319.722
0.000142	309.000	309.033	309.447	...	323.615	324.585	325.167	...	319.709
0.000143	309.000	309.031	309.432	...	323.498	324.467	325.058	...	319.695
0.000144	309.000	309.030	309.418	...	323.382	324.350	324.951	...	319.682
0.000145	309.000	309.028	309.404	...	323.266	324.233	324.843	...	319.669
0.000146	309.000	309.026	309.390	...	323.151	324.116	324.735	...	319.656
0.000147	309.000	309.025	309.377	...	323.037	324.001	324.628	...	319.642
0.000148	309.000	309.023	309.364	...	322.924	323.886	324.521	...	319.629
0.000149	309.000	309.022	309.351	...	322.811	323.771	324.415	...	319.615
0.000150	309.000	309.020	309.339	...	322.699	323.657	324.308	...	319.602
0.000151	309.000	309.019	309.327	...	322.587	323.544	324.202	...	319.588
0.000152	309.000	309.018	309.316	...	322.476	323.431	324.097	...	319.574
0.000153	309.000	309.017	309.305	...	322.366	323.319	323.991	...	319.560
0.000154	309.000	309.016	309.294	...	322.257	323.207	323.886	...	319.547
0.000155	309.000	309.015	309.284	...	322.148	323.097	323.782	...	319.533
0.000156	309.000	309.014	309.274	...	322.040	322.986	323.677	...	319.519
0.000157	309.000	309.013	309.264	...	321.933	322.877	323.573	...	319.505
0.000158	309.000	309.012	309.255	...	321.826	322.768	323.470	...	319.490
0.000159	309.000	309.011	309.246	...	321.720	322.659	323.366	...	319.476
0.000160	309.000	309.011	309.237	...	321.615	322.551	323.264	...	319.462
0.000161	309.000	309.010	309.228	...	321.510	322.444	323.161	...	319.448
0.000162	309.000	309.009	309.220	...	321.406	322.338	323.059	...	319.433
0.000163	309.000	309.009	309.212	...	321.303	322.232	322.957	...	319.419
0.000164	309.000	309.008	309.204	...	321.200	322.126	322.856	...	319.404
0.000165	309.000	309.008	309.197	...	321.098	322.022	322.755	...	319.390
0.000166	309.000	309.007	309.190	...	320.996	321.917	322.654	...	319.375
0.000167	309.000	309.007	309.183	...	320.896	321.814	322.554	...	319.361
0.000168	309.000	309.006	309.176	...	320.796	321.711	322.454	...	319.346
0.000169	309.000	309.006	309.169	...	320.696	321.609	322.355	...	319.331
0.000170	309.000	309.005	309.163	...	320.597	321.507	322.256	...	319.316
0.000171	309.000	309.005	309.157	...	320.499	321.406	322.157	...	319.301
0.000172	309.000	309.005	309.151	...	320.402	321.305	322.059	...	319.286
0.000173	309.000	309.004	309.145	...	320.305	321.206	321.961	...	319.271
0.000174	309.000	309.004	309.140	...	320.209	321.106	321.864	...	319.256
0.000175	309.000	309.004	309.134	...	320.113	321.008	321.767	...	319.241
0.000176	309.000	309.004	309.129	...	320.018	320.910	321.671	...	319.226
0.000177	309.000	309.003	309.124	...	319.924	320.812	321.575	...	319.210
0.000178	309.000	309.003	309.120	...	319.830	320.715	321.479	...	319.195
0.000179	309.000	309.003	309.115	...	319.737	320.619	321.384	...	319.180
0.000180	309.000	309.003	309.111	...	319.645	320.524	321.290	...	319.164
0.000181	309.000	309.003	309.106	...	319.553	320.429	321.195	...	319.149
0.000182	309.000	309.002	309.102	...	319.462	320.334	321.102	...	319.133
0.000183	309.000	309.002	309.098	...	319.371	320.240	321.008	...	319.118
0.000184	309.000	309.002	309.094	...	319.281	320.147	320.916	...	319.102
0.000185	309.000	309.002	309.091	...	319.192	320.055	320.823	...	319.086
0.000186	309.000	309.002	309.087	...	319.103	319.962	320.731	...	319.070
0.000187	309.000	309.002	309.083	...	319.015	319.871	320.640	...	319.054
0.000188	309.000	309.001	309.080	...	318.927	319.780	320.549	...	319.039
0.000189	309.000	309.001	309.077	...	318.840	319.690	320.459	...	319.023
0.000190	309.000	309.001	309.074	...	318.754	319.600	320.369	...	319.007
0.000191	309.000	309.001	309.071	...	318.668	319.511	320.279	...	318.991
0.000192	309.000	309.001	309.068	...	318.583	319.423	320.190	...	318.974
0.000193	309.000	309.001	309.065	...	318.499	319.335	320.102	...	318.958
0.000194	309.000	309.001	309.063	...	318.415	319.247	320.013	...	318.942
0.000195	309.000	309.001	309.060	...	318.331	319.160	319.926	...	318.926
0.000196	309.000	309.001	309.058	...	318.248	319.074	319.839	...	318.909
0.000197	309.000	309.001	309.055	...	318.166	318.989	319.752	...	318.893
0.000198	309.000	309.001	309.053	...	318.085	318.904	319.666	...	318.877
0.000199	309.000	309.001	309.051	...	318.003	318.819	319.580	...	318.860
0.000200	309.000	309.001	309.049	...	317.923	318.735	319.495	...	318.844