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MELTER: A Model of the Thermal Response of Cargos Transported in the Safe-Secure Trailer Subject to Fire Environments for Risk Assessment Applications

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Abstract

MELTER is an analysis of cargo responses inside a fire-threatened Safe-Secure Trailer (SST) developed for the Defense Program Transportation Risk Assessment (DPTRA). Many simplifying assumptions are required to make the subject problem tractable. **MELTER** incorporates modeling which balances the competing requirements of execution speed, generality, completeness of essential physics, and robustness. Input parameters affecting the analysis include those defining the fire scenario, those defining the cargo loaded in the SST, and those defining properties of the SST. For a specified fire, SST, and cargo geometry **MELTER** predicts the critical fire duration that will lead to a failure. The principal features of the analysis include: a) Geometric considerations to interpret fire-scenario descriptors in terms of a thermal radiation boundary condition, b) a simple model of the SST's wall combining the diffusion model for radiation through optically-thick media with an endothermic reaction front to describe the charring of rigid foam in the SST wall, c) a transient radiation enclosure model, d) a one-dimensional, spherical idealization of the shipped cargos providing modularity so that cargos of interest can be inserted into the model, and e) associated numerical methods to integrate coupled, differential equations and find roots.

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Nomenclature

A	area	m^2
a_w	absorptivity of charred foam in diffusion model	m^{-1}
C	specific heat	$J/kg/K$
d	fire separation distance	m
D	fire diameter	m
F	view factor	Dimensionless
$F_{A_7, f}$	view factor from A_7 to fire	Dimensionless
h	layer thickness	m
	height	m
	convection coefficient	$W/m^2/K$
k	thermal conductivity	$W/m/K$
l_w, l_f	wall and floor foam thicknesses	m
$[P]$	matrix of radiation enclosure properties	Dimensionless
q	heat flux	W/m^2
Q	heat transfer rate	W
R	fire radius	m
T	temperature	K
x	spatial coordinate	m
W, H, L	SST width, height, & length	m
Greek		
α	thermal diffusivity	m^2/s
β	illuminated cargo fraction	Dimensionless
β, θ	angle between surface and ray	Dimensionless
δ_{ij}	Kronecker delta	Dimensionless
$\Delta E_{gassify}$	energy to gassify foam	J/kg
ϵ	emissivity	Dimensionless
η, ω	conduction & radiation connectors	W/K
ϕ, θ	temperature predictions	K
ρ	density	kg/m^3
$\rho C h$	thermal capacitance per area	$J/m^2/K$
σ	Stefan Boltzman constant	$W/m^2/K^4$
τ	transmittance	Dimensionless

subscripts

$1-9$	refer to areas of enclosure problem
f	designates quantity associated with fire
$A_{4..6}$	refers to areas 4 through 6
f	Fire
$A_{7,f}$	from A_7 to fire, for example
	$F_{A_{7,f}}$ = is view factor from A_7 to fire
∞	ambient condition
pw	plywood
s	surface

Fonts

Most of the theory in this document is discussed with the symbols previously listed. The **type-writer** font is used to make reference to variable names as they appear in the computer code implementation of MELTER.

1 Introduction

Sandia National Laboratories (SNL) was the lead agency in conducting a study to assess the risk associated with ground transportation of radioactive defense program materials. A significant part of the risk is associated with a fire environment that might result from a traffic accident. A physical model, which has inherited the name **MELTER**, of the thermal response of cargos inside a Safe Secure Trailer (SST) subjected to a fire environment was developed. This report describes **MELTER**'s underlying theory and information essential to the user of the associated code.

MELTER performs a transient thermal analysis of a SST and its cargo subjected to a fire boundary condition. Three sources of information determine conditions modeled in a given analysis:

1. Properties of the SST.
2. Properties defining the SST's cargo.
3. Scenario-specific parameters defining the fire boundary conditions and the condition of the SST and its cargo.

Properties defining each unique cargo considered in the risk assessment were derived once per cargo. Since there are a number of different cargos, **MELTER** must permit a convenient means of specifying the unique characteristics of each cargo. Once this information is developed it is effectively a data module which, along with characteristics of the SST embodied in the code, defines the system to be subjected to boundary conditions defined by the probabilistic risk assessment (PRA). Selection of scenarios used in the PRA, definition of individual cargo characteristics, and post-processing of **MELTER** results to assess risk are described elsewhere.

MELTER has been developed with an effort to be balanced in the level of detail attempted in the analysis. Descriptions of scenarios (boundary conditions, really), free of delusive detail, are coarse. As such, the modeling of a response to these conditions to extreme detail is not justified. Furthermore, along with detail comes computational intensity. An affordable level of computational intensity has been struck with **MELTER** with most systems being represented by 15-21 degrees of freedom (variables) for most scenarios.

Section 2 includes a discussion of the underlying theory. Subsections cover the treatment of the fire radiation boundary condition, the charring SST wall, the transient thermal radiation enclosure analysis, the representation of cargos, and the numerical methods needed to render solutions. Section 3 presents results that are representative of the thermal response of the SST and its cargo for several scenarios of interest. Section 4 is devoted to describing the inputs needed to utilize **MELTER**. Section 5 assesses **MELTER**'s

performance based on results from its use in the PRA. Section 6 offers conclusions and assesses the strengths and weaknesses of MELTER.

Many simplifying assumptions are made to keep the model tractable including:

- All fires are represented by radiatively black, right circular cylinders. (Further consideration is given fires that are partly under the SST, see Section 2.2.)
- The SST wall response to fire is approximated with a simple, 3-variable model that represents foam decomposition with a planar interface dividing the charred and uncharred foam regions.
- Radiant heat transfer within the enclosure is between, at most, nine uniform surfaces.
- Convection is not considered on the interior or exterior of the SST.
- All cargos are represented by a spherically-symmetric geometry using a very limited number of state variables (temperature nodes) to represent thermal response.
- Except for allowance for a melting exterior, the thermal impedances of materials presumed to decompose within cargos are omitted rather than dealing with the decomposition processes.

Appendices include information too detailed to be included in the body of the report. The analysis leading to parameter selection characterizing the thermal response of the SST wall is documented in appendix A. Appendix B includes an optional output file produced by MELTER. Appendix C includes a listing of the FORTRAN source code for MELTER.

Figure 1: Schematic representation of the most general configuration modeled.

2 MELTER Theory

2.1 Introduction

Figure 1 presents an schematic overview of MELTER's underlying physical model. This figure represents the most complicated circumstance admitted by the model. In this section reference is occasionally made to variables by their names as they are implemented in the code. When these references occur the variable will be typeset in the typewriter font. The salient features of the model include:

1. At the heart of the system is a package whose thermal response is in question. The package's surface is partitioned into two areas designated A_1 and A_2 . A_1 is some fraction of the cargo's total exterior area which is prorated to the fraction

of the SST's exterior receiving direct heating by the fire. Associated with each of these areas are a temperature and surface emissivity. As described later, all cargos are represented by a spherical idealization.

2. The SST also includes *inert* mass which is important because it modifies the thermal response of the sensitive cargo. This inert mass represents various cargo within the interior walls of the SST. Treated as though it is dispersed throughout the volume, it is characterized by its total surface area, its total thermal capacitance, and a *transmittance* (*transm*) characterizing the view across the SST.¹ The surface associated with this mass is designated as A_3 . When the cargo in question consists of many identical copies, all but one threatened item will be lumped into the inert mass.
3. The floor is divided into areas A_4 and A_5 . A_4 trades radiant energy with the rest of the enclosure, but that is its only means of changing temperature. A_4 is regarded as having thermal capacitance in communication with the SST's interior but insulated from the outside. A_5 , on the other hand, is that portion of the floor subjected to a fire boundary condition.
4. The thermally massive interior walls of the SST are subdivided according to their exterior boundary conditions. That part of SST interior not being directly heated by the fire is designated as A_6 . Conservatively, A_6 is assumed to be perfectly insulated on its exterior side.
5. A_7 is that portion of the SST's interior adjacent to an intact wall subjected to a fire boundary condition on its exterior.
6. A_8 is an area for which the armor interior is intact, but the exterior skin and foam insulation have been removed by mechanical damage to the SST and subjected to a fire boundary condition. Compared to A_7 , this section offers less protection from the fire.
7. A_9 represents an opening on the surface of the SST with an open view of a fire.

Various scenarios result in corresponding distributions of $A_{1..9}$. All of $A_{1..3}$ and least one of $A_{5,7..9}$ are present in every scenario. The PRA requires representation of:

- the fire characteristics of diameter, separation distance, and temperature.
- the SST's state of repair represented by various values of A_7 , A_8 , and A_9 .

¹A clean, *unattenuated*, view has a transmittance of 1 while a value of 0 corresponds to complete obstruction.

- as many as four damage states representing the condition of the cargo.

MELTER generates its solution to every combination of several discrete values of each of foregoing variables. From the fire characteristics of diameter, distance, and temperature MELTER develops the quantities represented in Figure 1 to represent the fire boundary condition. The interior surfaces ($A_{1..9}$) exchange energy only by thermal radiation. The *state variables* of the model consist of a temperature for each of the $A_{1..8}$ present, temperatures representing locations in the cargo's interior, *skin* temperatures and char displacements for wall sections adjacent to A_5 and A_7 , and the plywood/foam interface temperature associated with A_5 . MELTER's end product is an estimation of the minimum duration a given fire geometry must have to induce a critical temperature in the cargo.

It is natural to consider this analysis from the fire inwards to the threatened cargo. Logical pieces of the analysis are:

- The *fire boundary condition's* representation.
- The *wall model* which is descriptive of the charring process that occurs in either the floor or the wall.
- The *radiation enclosure* problem associated which heat transfer inside the SST.
- The *cargo model*.
- Numerics associated with solving the model's equations.

Each of the these topics is addressed in the following subsections.

2.2 Fire Boundary Condition

2.2.1 Fire Geometry

MELTER allows fires to be of any displacement, size, or temperature and, in fact, these three variables constitute a complete fire description to MELTER. The complexity of gaseous radiation consideration is avoided by assuming unit emissivity for the fire. Since unit emissivity is a limiting value associated with large fires, the assumption can only be conservative which is consistent with the philosophy used throughout the model.²

²Reference [1] deals with a more detailed treatment of the fire's shape and temperature distribution. While that study produced satisfying results, the spatial integrations through gray gaseous matter of a specified temperature distribution impose too much calculational detail to be included in the present model.

A fire's displacement is the distance between its base's center and a point centered under the SST measured along a line that is a perpendicular bisector of the long side of the SST. Zero displacement corresponds to a fire centered beneath the SST.

A_5 is present in the model only for fires located at least partially beneath the SST. When the fire is not under the SST its geometry is presumed to be that of a right circular cylinder of a height three times the base diameter.³ The method of calculating $A_{1..9}$ and view factors between SST exterior surfaces and the fire are given in the following subsection.

2.2.2 Inferred Parameters

The primary aim of this section is to define the means MELTER uses to infer the more complete fire description from the limited input of separation distance, diameter, and temperature. Specifically, (refer to Figure 1) A_7 , A_5 , and $F_{A_7,f}$ must be systematically inferred from the inputs of fire distance and diameter. $F_{A_5,f}$ is always unity. The specification of A_8 and A_9 are not within the domain of MELTER. They are specified by the PRA analyst. In MELTER, when A_9 and A_8 are greater than zero they reduce A_7 in that order to determine SST exposure through these areas. By reducing A_7 in the order just specified, the most hazardous surface is given preferential access to the fire. For simplicity, the view factors $F_{A_8,f}$ and $F_{A_9,f}$ are taken to be the same as $F_{A_7,f}$.

The calculation of these quantities must consider all combinations of separation distance and fire diameter. For the present discussion let the SST have length, width, and height dimensions of L , W , and H ; and the fire have separation distance, d ; diameter D ; and height, h_f . Reference to Figure 2 will be useful in the following discussion. The following list, ordered by separation distance, summarizes the methods of calculation used:

1. Fire center under SST ($0 < d < W/2$).
 - (a) A_5 is the intersection of the circular fire base area (πR^2) and the projection of the SST's area ($L \times W$) onto the ground. A maximum corresponding to the whole bottom area of the SST is imposed.
 - (b) A_7 is calculated for the specified fire diameter, but the fire location is artificially presumed to be such that the center is immediately under one edge of the SST ($d \sim W/2$). (What actually happens when a fire is under the vehicle is, of course, complicated and dependent on many details left unspecified in the present analysis. Hence, the simplifying assumption.) See the next item for additional detail on this calculation.

³Reference [2] gives information pertinent to the aspect ratio of the fire. The aspect ratio (h_f/D_f) grows slightly with increasing fire size. $h_f/D_f = 3$ gives a conservatively tall fire for larger fires.

z - direction is positive out of page and $z=0$ at ground level

At "A" the view factor to the fire=1 at "B" it's about 0.2

Figure 2: Geometry to define fire boundary conditions.

- (c) $F_{A_7,f}$ is one.
2. Center out from under SST but fire extending under ($W/2 < d < W/2 + R$).
- (a) A_5 is the intersection of the circular fire base area (πR^2) and the projection of the SST's area ($L \times W$) onto the ground. A maximum corresponding to the whole bottom area of the SST is imposed.
 - (b) A_7 is *at least* an area corresponding to the height of the SST times the length of the chord formed by the intersection of the plane of the SST wall and the fire base circle. This area will generally be greater than that, the additional length being calculated in the manner described in the following subsection. If the fire diameter is such that the plane of the far side of the SST also intersects the base circle, that chord length is also considered. A_7 also includes area from the SST's roof in a manner proportional to the area calculated considering the vertical sides. That is, when the foregoing calculation indicates that all of the vertical wall surface is exposed, all of the ceiling area is also exposed. A maximum corresponding to all the vertical surface area of the SST plus the roof area is imposed.
 - (c) $F_{A_7,f}$ is one.
3. Fire clear of SST ($d > W/2 + R$).
- (a) A_5 is zero.
 - (b) A_7 for the vertical surfaces is determined by the somewhat lengthy process described in the following subsection. The SST's roof is prorated as described earlier.
 - (c) $F_{A_7,f}$ is the view factor between a right circular cylinder of the fire's dimensions and an element of area located on a radial from the fire center at a height half way up the side of the SST. This is described further in the following section.

2.2.3 View Factors and Exposed Area

This section describes a calculational procedure for specifying A_7 and $F_{A_7,f}$, when a fire diameter, height, and separation distance are specified. A_7 and $F_{A_7,f}$ are the area of normal construction SST wall exposed to fire and the corresponding view factor to the fire. For computational expedience we are assuming that all fires are centered on a perpendicular bisector of the long side of the SST. The origin of the coordinate system is at the center of the base of the fire. The side of the SST facing the fire is

perpendicular to the x -axis, the length of the SST is aligned with the y -axis, and the z -axis is perpendicular to the ground.

The following assumptions are made:

1. All fires are located along the perpendicular bisector of one side of the SST trailer.
2. All fires are right circular cylinders.
3. All fires are optically thick, so that the SST perceives the right circular cylinder as a solid, blackbody radiator.

In general, the view factors and areas between some plane area in the side of the SST and the fire are related by:

$$A_1 F_{1,2} = A_2 F_{2,1} = \frac{1}{\pi} \int_{A_1} \int_{A_2} \frac{\cos \theta_i \cos \theta_j}{S_{i,j}^2} dA_i dA_j \quad (1)$$

where $S_{i,j}$ is the path length between two area elements A_i and A_j , and θ_i and θ_j are the angles between $S_{i,j}$ and a line normal to A_i or A_j respectively.

Siegel and Howell (Ref. [3]) give a formula for evaluating Eq. (1) when A_2 is an area element that is perpendicular to a line passing through one end of the axis of symmetry of a right circular cylinder. Let us denote that formula as $g(\lambda, \kappa)$ where λ and κ are as defined in Figure 3.

A more general formula may be formed for area elements not perpendicular to the aforementioned line passing through the base midpoint of the cylinder. That is:

$$g^*(\lambda, \kappa^*) = \cos(\beta) g(\lambda, \kappa) \quad (2)$$

where β is the angle between a line normal to the area element and a line passing through the base center of the cylinder and the element. κ^* is based on the distance from the element to the cylinder's centerline. For the coordinate system described earlier, $\kappa^* = 2x/(D \cos \beta)$, where $\beta = \tan^{-1}(y/x)$. Finally, an area element on the side of the SST is not at the same z -coordinate as the fire base. To deal with this, we let the fire be two right circular cylinders, one measuring down from z -location of the area element and one measuring up (this assumes the fire is tall enough so that $h_f > z$, where z corresponds to the area element). Then

$$F_{d1,2} = g^*[2z/D, 2x/(D \cos \beta)] + g^*[2(h_f - z)/D, 2x/(D \cos \beta)] \quad (3)$$

So for a particular d , D , and h_f , Eq. (3) can be integrated over some area in the plane of the SST's side to yield the view factor between the two finite areas. In the analysis of radiation exchange between surfaces, Eq. (1), is based on the idealization that thermal conditions be uniform over A_1 and A_2 . For our analysis assuming constant

Plane element dA_1 to right circular cylinder of finite length l and radius r ; normal to element passes through one end of cylinder and is perpendicular to cylinder axis.

$$\begin{aligned}\lambda &= \frac{l}{r} & \kappa &= \frac{h}{r} \\ X &= (1 + \kappa)^2 + \lambda^2 \\ Y &= (1 - \kappa)^2 + \lambda^2\end{aligned}$$

$$\begin{aligned}g(\lambda, \kappa) = F_{d1-2} = & \frac{1}{\pi \kappa} \tan^{-1} \frac{\lambda}{\sqrt{(\kappa)^2 - 1}} + \\ & \frac{\lambda}{\pi} \left[\frac{X - 2\kappa}{\kappa \sqrt{XY}} \tan^{-1} \sqrt{\frac{X(\kappa - 1)}{Y(\kappa + 1)}} \frac{1}{\kappa} \tan^{-1} \sqrt{\frac{(\kappa - 1)}{(\kappa + 1)}} \right]\end{aligned}$$

Figure 3: View factor formula from Reference [3].

conditions over A_1 (the fire) is reasonable. Uniformity over A_2 , the SST side, is clearly an idealization for convenience. Imagine, for example, the situation depicted in Figure 2. Clearly the conditions are not uniform over A_2 . This subsection deals with defining an appropriate viewfactor and finite area to represent the fire.

We need a means to pick A_7 and $F_{A_7,f}$, the area and view factor of normally constructed wall exposed to the fire. If the circumstance modeled is to include A_8 or A_9 areas they will be deducted from the calculated A_7 . Consider some subarea on the side of the SST that can see both a fire and a cooler surrounding temperature. That area element will be its hottest if it is not losing heat through the wall, but is in radiative equilibrium (we're ignoring convection here). Under those conditions, its equilibrium emissive power, E , is given by:

$$E = E_\infty + F \times (E_f - E_\infty) \quad (4)$$

where F is the local view factor to the fire. For the conditions of Figure 2, the emissive power at $x = d$, $y = 0$, $z = \bar{h}_{sst}$ is equal to that of the fire, where $\bar{h}_{sst}$ is the z -value half way up the SST's wall. At $x = d$, $y = d$, $z = \bar{h}_{sst}$ the view factor is only 0.19 for a tall fire and the corresponding decrease in emissive power can be seen from Eq. (4). Clearly, letting the view factor be 1 and the area, A_7 , the whole side of the SST is too conservative. There is a whole two-dimensional field of $E(x = d, y, z)$ (and corresponding view factor variation) on the side of the SST. The task at hand is to pick single values of A_7 and $F_{A_7,f}$ that realistically approximate the real conditions.

Consider conditions similar to those of Figure 2. If we choose A_7 to be large, then much of it must lie in areas for which the view factor should be comparatively small. On the other hand, if A_7 is chosen to be comparatively small, we might miss significant energy deposition on the side of the SST. Equations (3) and (4) can be used to estimate the emissive power of locations on the heated surface for conditions of radiative equilibrium.⁴ That is:

$$\begin{aligned} E(x = d, y, z) = & E_\infty + (E_f - E_\infty) \times \\ & \{g^*[2z/D, 2x/(D \cos \beta)] \\ & + g^*[2(h_f - z)/D, 2x/(D \cos \beta)]\} \end{aligned} \quad (5)$$

Now we may use the preceding equation to consider how far A_7 should extend. We know that the foam construction of the wall will decompose only very slowly below a temperature of around 585K (Refs. [4,5]). Clearly, energy from the fire that lands on some surface not achieving an important temperature rise is of little consequence.

⁴This leads to a conservatively high estimate in the current case because our surface experiences heat loss through the wall and/or to ambient air.

Since the SST is a lot longer than it is tall, it is sensible to make life still a bit easier by looking at the emissive power on the wall only at one value of z , say $\bar{h}_{sst}$. The following means of setting A_7 is used:

$$E_{max}A_7 = 2 \int_0^{y^*} E(x = d, y, z = \bar{h}_{sst})H dy \quad (6)$$

where H is the vertical length of the SST side. y^* is the lesser of half the SST's length and that value of y for which $E(x = d, y, z = \bar{h}_{sst}) = \sigma T_f^4$ after which E is too low to threaten the wall construction. E_{max} is the value of E at $y = 0$ and the factor of 2 comes from the fact the problem has symmetry about the ($y = 0$)-plane. Notice that the area of integration on the right hand side is greater than A_7 . Recognizing that the background emissive power is negligible compared to that of the fire, the E -distribution (for our adiabatic wall) is the same as the distribution of incident radiant energy. Then Eq. (6)'s right hand side is the summation of all the energy that is deposited on the side of the SST in such concentration as to produce local temperatures that will result in foam decomposition. A_7 is then chosen so that the aforementioned quantity of energy is preserved, but it is all to be delivered at the maximum intensity. This a convenient means of defining the extent of A_7 . Furthermore, it's conservative. For an actual fire of some practical duration and approximating the geometry depicted in Figure 2, the effect of the fire will be most severe along $y = 0$. At some larger value of y there will begin areas which are only partly burnt through. These areas, while absorbing energy from the fire, will not contribute significantly to the overall heat transmission into the SST's interior. This approach takes this same energy and concentrates it to an intensity that is much more effective at burning its way into the SST's interior.

Figure 4 includes plots of A_7 , $F_{A_7,f}$, and A_5 versus separation distance for fire diameters of 1, 2, 4, 8, and 16 meters.

2.3 Charring Foam Wall Model

With reference to Figure 1, the areas A_5 and A_7 correspond to floor and wall area of nominal construction subjected to a fire boundary condition. A simplified model, as described in this section, is utilized to represent the significant impediment to heat transfer represented by the foamed wall/floor construction. The form of the model governing the charring of the foam is identical for the wall and floor locations.

2.3.1 Wall Model

The foamed wall of the SST plays an important role in many potential fire scenarios. Fire tests on SST wall sections directly adjacent to fire have demonstrated:

Figure 4: A_7 , $F_{A_7,f}$, and A_5 versus separation distance for several fire diameters.

1. There is virtually no heat transfer through the wall until the foam is decomposed. Most locations on the wall interior show no response for perhaps 10 minutes after the start of a directly-impinging fire.
2. The behavior of the wall burning process varies from test to test and from location to location on a given test.
3. After the wall's foam is completely charred, the residue is of very low thermal capacitance, but offers a significant impediment to radiation heat transfer through the wall.

As we wish to represent this complicated process with a simple model, it is disconcerting that the composition of the SST wall is not uniform following a fire test. Obviously, the resultant residue of a fire is dependent on many parameters—more than can be realistically included in our modeling effort. Nonetheless, some sort of simplified wall model must be present to give a fair representation of the SST's response under many circumstances. It is not actually the wall's temperature response we are concerned about, but rather the degree to which the wall impedes heat transfer into the SST's interior. In the tests that were conducted (Ref. [6]) conditions were severe enough to guarantee the hasty decomposition of the foam. A matter of considerable concern is the prediction of the wall's behavior when the fire boundary condition is less severe. If the fire is distant enough there exists some point at which the foam in the wall will experience no significant deterioration and there will be effectively no heat transfer through the wall for hours.

It seems apparent that great detail in resolving temperature profiles through the wall is not justified. Moreover, it's not even particularly useful—all we really care about is the response of the SST's interior. In order to eliminate needless number-crunching we seek an approximate model of the wall's behavior which will yield satisfactory results. Figure 5 shows the simplified wall model schematically. In the simplified model the state of the wall is characterized by its two surface temperatures and the position of the decomposition front:

1. The exterior skin's temperature's (T_s) derivative is given by:

$$\frac{\partial}{\partial t} T_s = \frac{1}{(h\rho C)_s} (q_f - q_{rad}) \quad (7)$$

where,

$$q_f = \sigma \epsilon_s \{ F_{A_f, f} (T_f^4 - T_\infty^4) + T_\infty^4 - T_s^4 \} \quad (8)$$

and

$$q_{rad} = \frac{\sigma (T_s^4 - T_{react}^4)}{1 + \frac{3a_{wx}}{4}} \quad (9)$$

a_w is the absorption coefficient for radiation in the charred region, and T_{react} is a constant temperature at which the foam is assumed to gassify.

Equation (9) is the steady heat transfer rate through an optically thick medium between radiatively black plates (Reference [3]). T_{react} (Eq. (9)) is replaced by the temperature of A_7 when $x = l_w$.

2. x is the position of the char front. At the start of the analysis $x = 0$ and during the analysis the velocity of the front is given by:

$$\frac{\partial x}{\partial t} = \frac{q_{rad}}{\rho_w \Delta E_{gassify}} \quad (10)$$

until $x = l_w$ and zero thereafter. To conserve energy, q_{wall} , the energy conducted from the reaction front inwards to the armor, should be deducted from the numerator of Eq. (10). However, due to the simple definition of q_{wall} , the front could not advance all the way to the armor. Consequently, the wall is allowed to “create” this insignificant amount of energy for numerical expedience.

3. The interior wall (T_{A_7}) temperature is found by integrating:

$$\frac{\partial}{\partial t} T_{A_7} = \frac{1}{(h\rho C)_7} (q_{wall} - q_7) \quad (11)$$

4. In Eq. (11), $q_{wall} = q_{rad}$ as predicted by Eq. (9) after $x = l_w$ and $q_{wall} = (T_{react} - T_{A_7})k_w/(l_w - x)$ for $x < l_w$, but not allowing $q_{wall} > q_{rad}$. q_7 is the heat flux into the SST from A_7 as determined by the enclosure analysis defined in a subsequent section (see Eq. (18)). k_w , treated as constant, is the thermal conductivity of the foam before charring.

The parameters a_w , $\Delta E_{gassify}$, and T_{react} have important influences on the wall model's response. A study was conducted to choose these parameters to make the model agree with the best available test data. That study is incorporated as Appendix A.

2.3.2 The Charring Floor Model

This model is associated with A_5 identified earlier in Figure 1. Figure 6 is a schematic of the burning floor model which shows the layer of plywood present in the floor construction. Equations identical to (7-10) are used to characterize the adjacent skin temperature and char displacement. In tests associated with the floor it has been demonstrated that the plywood layer is a significant impediment to heat transfer. As a

Figure 5: Schematic of burning wall model.

Figure 6: Schematic of burning floor model.

result, corresponding to Eq. (11) of the wall model are two equations associated with the floor's plywood and metal temperatures.

$$\frac{\partial}{\partial t} T_{pw} = \frac{1}{(h\rho C/2)_{pw}} (q_{wall} - q_{pw}) \quad (12)$$

$$\frac{\partial}{\partial t} T_{As} = \frac{1}{(h\rho C/2)_{pw} + (h\rho C)_5} (q_{pw} - q_5) \quad (13)$$

In the preceding equations q_{pw} is the conduction heat flux through the plywood given by:

$$q_{pw} = \frac{k_{pw}}{h_{pw}} \times (T_{pw} - T_{As}) \quad (14)$$

In Eq. (12) the term $(h\rho C/2)_{pw}$ is half the thermal capacitance associated with the plywood. The other half is grouped with that associated with the metal of the floor (Eq. (13)). This partitioning of the plywood's thermal capacitance is appropriate since it is much less thermally diffusive than the adjacent metal. Thermal properties of virgin plywood are used throughout the analysis. As with the wall model, q_5 is determined by the enclosure analysis of the following section. q_{wall} is also calculated as described for the wall model.

An analysis similar to that for the charring of the foam might have been incorporated to represent the charring of the plywood. Since we expect the plywood charring to act as a heat sink and the thermal resistance of the plywood to increase as it is charred, the present approach is conservative.

2.4 Enclosure Analysis

Thermal radiation is the dominant mechanism for transport of energy across the SST enclosure. In fact, convection and conduction are not considered. While the armor is a fair thermal conductor, long path lengths associated with energy movement through the SST result in slow conduction responses. Further, the *threatening* fire environments give rise to significantly elevated temperatures at which radiation can be expected to dominate (Ref. [7]).

2.5 Convection

Figure 7 is included to illustrate the relative importance of convection across the enclosure. The physical system considered in Figure 7 is comprised of two parallel planes. The space between the planes is filled with air which is transparent to the thermal radiation but contributes to the total heat flux by convection. The significance of the

convection is estimated by:

$$q_{conv} = h(T)(T_1 - T_2)/2.0 \quad (15)$$

where

$$h(T) = 1.31\{(T_1 - T_2)/2\}^{1/3} \quad (16)$$

Eq. (16) is a simplified expression for h for turbulent natural convection between air and a vertical surface as given by Reference [8]. h is expressed in $W/m^2/K$ and $T_1 - T_2$ in K . The radiation is estimated from:

$$q_{rad} = \sigma \frac{(T_1^4 - T_2^4)}{1/\epsilon_1 + 1/\epsilon_2 - 1} \quad (17)$$

In the present discussion T_1 is simulating one of the directly heated surfaces shown in Figure 1. One surface temperature, T_1 , is varied from 300 to 1500K while the other, T_2 , is held constant at 300K. The total heat flux between the planes and fraction of it due to convection are shown in Figure 7 over the range of T_1 . As T_1 reaches threatening temperatures the total heat transfer is dominated by radiation. The convection estimate assumes the same h at the hot and cold walls so that the air temperature is assumed to be the average of T_1 and T_2 . That is, this simple analysis is making the conservative assumption that the air is always well mixed.

2.6 Radiation

2.6.1 Radiating Enclosure Theory

The thermal radiation model used can be described in terms of a series of discrete surface areas forming an enclosure. This theory, widely used, includes some very limiting assumptions including: emissivity independent of wavelength, uniform properties over each enclosing surface identified, and diffuse emission and reflection. All of these assumptions are frequently made in engineering analyses to arrive at a tractable formulation. The poorest of these assumptions in the current context is undoubtedly the uniform conditions across a given surface. The equations that are used to solve the radiating enclosure problem are linear in the emissive powers of the enclosure surfaces. Their precise form varies in texts on the topic so the approach used in the current investigation is stated briefly here. Given the emissivities and surface temperatures of an N - surface enclosure the heat fluxes can be summarized tersely as:

$$\bar{q} = \{[F] - [I]\}[P]^{-1}\bar{b} \quad (18)$$

In the preceding equation: $[F]$ is the $N \times N$ matrix of the view factors between the surfaces and $[I]$ is the identity matrix. $[P]$ is the square matrix whose elements are,

Total Heat Flux & %-Convected vs. T_1

Radiation/Convection Between Planes

Figure 7: Combined radiation and convection heat flux between planes.

$P_{ij} = \frac{\delta_{ij}}{1-\epsilon_i} - F_{ij}$ when $\epsilon_i < 1$ or $P_{ij} = \delta_{ij}$ for black surfaces.⁵ $b_i = \frac{\epsilon_i}{1-\epsilon_i} E_i$ for $\epsilon_i < 1$ and $b_i = E_i$ for black surfaces. The quantity, $[P]^{-1}\bar{b}$, gives the vector of radiosities.⁶

Equation (18) is a very compact statement of the radiating enclosure analysis. In the current case we follow all the surface temperatures through the simulation and this statement is precisely what is needed to evaluate the q_i of the system which let us evaluate the instantaneous rates of change of surface temperatures. Eqs. (11) and (13) are typical of those that are integrated to track interior surface temperatures. The temperatures of surfaces A_4 and A_6 are modified only by q_4 and q_6 as their backsides are regarded as being perfectly insulated.

2.6.2 View Factor Estimation

In multidimensional analyses, a matter of considerable complexity is the evaluation of the F_{ij} , the view factors, for the enclosure surfaces. When these are derived by direct integration (Eq. (1)) the task gets unwieldy very fast. In the current analysis approximate view factors which obey reciprocity and conservation considerations are developed.

In the present model the location of the surface area associated with *inert cargo*, A_3 , is only vaguely defined. A_3 is dispersed throughout the volume confined by $A_{4..9}$. This feature of MELTER is motivated by the need for the current modeling effort to be flexible enough to accommodate a wide range of payloads. `transm` and `ttrans` are code inputs used to specify average transmittances for enclosure surfaces viewing across the enclosure and for the cargo viewing an enclosure wall. Both of these transmittances have a value between 0 and 1 corresponding, respectively, to unobstructed and totally obstructed *views*. `ttrans=1` has generally been used, which corresponds to the cargo having a clear view of SST interior walls. `transm` is assigned on a cargo by cargo basis. If the cargo fills the SST so that there are few unobstructed views across the SST `transm` tends towards zero. Conversely, if the cargo is best represented as an isolated entity on the SST's centerline it will generally not obstruct radiant exchange across the enclosure and the value of `transm` will tend towards unity. In the limit of `transm=0` none of $A_{4..9}$ can exchange energy directly with each other. In the other extreme, `transm=1` and `ttrans=1`, A_3 can not exchange energy with any other surface in the enclosure. The procedures used are as follows:

1. The surface area of the cargo, a_{cargo} , is partitioned into A_1 and A_2 such that

⁵ $\delta_{ij} = 1$ if $i = j$ and zero otherwise.

⁶The radiosity of a surface, mentioned in any introductory treatment of radiation heat transfer, is the sum of all radiant energy leaving a surface. That is, the reflected and emitted energy. For black surfaces the radiosity and emissive power, E , of the surface are the same. Conversely, for highly reflecting enclosures, surfaces may have a radiosity that is much greater than E .

$A_1/A_2 = \sum A_{5,7..9} / \sum A_{4,6}$. That is, A_1 is to the whole of the cargo's exterior as the area of the directly heated exterior of the SST is to its whole exterior area.

2. The view factors between the six interior surfaces of the SST ($A_{4..9}$) are estimated as though the box is empty.

- (a) A variable A^* is set which is considered to be the largest area a surface can have without seeing itself. A^* is equivalent to a side of the SST.
- (b) $F_{i,j} = A_j / (A_{tot} - A_i)$ and $F_{i,i} = 0$ if $A_i < A^*$ otherwise $F_{i,j} = A_j / (A_{tot} - A^*)$ and $F_{i,i} = (A_i - A^*) / (A_{tot} - A^*)$ where A_{tot} is the whole interior area of the SST.
- (c) The view factors from each area to all others are calculated in ascending order of size. To describe this process let us use subscripts $a..f$ to correspond to the interior surface areas in order of size (a is smallest). Conservation and reciprocity are applied along the way. That is:
 - i. $F_{a,i}$ are calculated for $i = a..e$ and then $F_{a,f} = 1 - \sum_{i=a}^e F_{a,i}$
 - ii. $F_{b,a} = A_a F_{a,b} / A_b$, $F_{b,b..e}$ are found according the rules of 2b. $F_{b,f} = 1 - \sum_{i=a}^e F_{b,i}$
 - iii. $F_{c,a} = A_a F_{a,c} / A_c$, $F_{c,b} = A_b F_{b,c} / A_c$, etc...

The benefit of calculating the view factors for areas in ascending order of size is that reciprocity is always applied so that the area ratio used is less than 1. If the reciprocity rule is applied in the other order between a small surface and a large surface, the impossible circumstance of a view factor exceeding unity can be predicted. After this process is completed, the view factors associated with $A_{a..f}$ are reordered to map onto $A_{4..9}$ as defined in Figure 1. Each of these viewfactors (between interior wall areas) are then *attenuated* by a transmittance specified in code input `transm`. The amounts by which the view factors diminish during this process are recovered later in view factors between these surfaces and A_3 , the inert cargo. In the limit of `transm` approaching zero each of the interior surfaces ($A_{4..9}$) would have a unit view factor to the inert cargo.

3. $F_{i,j}$ for A_1 and A_2 are zero to themselves and each other.

4. A variable `proximity`, input to the code, is used to indicate whether the cargo is isolated on the SST's centerline (`proximity=0`) and away from the walls or is positioned close to the wall (`proximity=1`). The view factors from A_1 to the heated surfaces A_9 , A_8 , A_7 , and A_5 are calculated in that order.

- (a) If `proximity=0` $F_{1,i} = A_i / A_{5,7..9} \times ttrans$.

- (b) If **proximity=1**: $F_{1,9} = \min(A_1, A_9)/A_1 \times \text{ttrans}$; $F_{1,8}$ is the minimum of $\min(A_1, A_8)/A_1 \times \text{ttrans}$ and $1 - F_{1,9}$; $F_{1,7}$ is the minimum of $\min(A_1, A_7)/A_1 \times \text{ttrans}$ and $1 - F_{1,8} - F_{1,9}$; and $F_{1,5}$ is the minimum of $\min(A_1, A_5)/A_1 \times \text{ttrans}$ and $1 - F_{1,7} - F_{1,8} - F_{1,9}$. This approach gives A_1 , and hence the threatened cargo, preferential access to the most severe of $A_{5,7,9}$.

For values of **proximity** between 0 and 1 the preceding rules are mixed in linear proportion.

5. $F_{2,4} = A_4/(A_4 + A_6)$ and $F_{2,6} = A_6/(A_4 + A_6)$.
6. View factors between A_3 and other areas are calculated by conservation and reciprocity. For example, $F_{2,3} = 1 - \sum_{i \neq 3} F_{2,i}$ and $F_{3,2} = F_{2,3}A_2/A_3$.

The preceding steps are completed even when some of $A_{4..9}$ are equal to zero.⁷ Before the radiation matrix equations are conditioned, zero-area A_i 's are removed from consideration.

2.7 Cargo Model

Before MELTER formulates the model for a given scenario the cargo is known to it as a series of spherically concentric shells. The shells have thermal capacitance $(MC_p)_i, i = 1, \text{ncs}$, where ncs is the number of spherical annuli representing the cargo. The radiation enclosure view factor calculations are described in the previous section, but the first part of that analysis divides the whole surface area of the cargo into A_1 and A_2 . The variable **split** (also referred to as β later) is the A_1 's fraction of the whole surface area of the cargo. Figure 8 is a schematic rendering of the cargo as it is modeled. Shown is a model for which $\text{ncs}=5$. The interior annulus is node 1 and the nodes to the left (towards the hot surface) are nodes 2, 4, 6, & 8. The nodes to the right of center are 3, 5, 7, & 9.

To create the parameters supporting the idealized spherical model of the cargo in question the "shortest path" into the critical portion of the device is chosen as the representative series of thermal barriers from the outside to the inside. This introduces immense conservatism for some cases and at least some conservatism for even the most unfavorable conditions. This is because no matter what orientation the package bears to its most intensely heated surface, there will always be greater thermal capacitance than is being represented to "share the load." Geometries and material specifications supporting this activity for specific cargos are described elsewhere.

⁷ $F_{i,j}$ is actually carried along during the estimation process as the quantity $A_i F_{i,j}$ until after the zero-area surfaces have been dismissed avoiding reciprocity and the divide-by-zero error it would create.

Figure 8: Schematic representation of the cargo model for which $ncs=5$.

When the short path is examined its thermal capacitance is concentrated into shells. Concentric shells are "connected" by thermal diffusion and radiative conductors. Thermal diffusion conductors have the value:

$$\eta_i = \frac{4\pi k}{1/r_i - 1/r_{i+1}} \quad (19)$$

Radiative conductors have the value:

$$\omega_i = 4\sigma\pi r_i^2 \left[\frac{1 - \epsilon_i}{\epsilon_i} + \frac{1 - \epsilon_{i+1}}{\epsilon_{i+1}} \frac{r_i^2}{r_{i+1}^2} + 1.0 \right]^{-1} \quad (20)$$

The origins of Eqs. (19) and (20) are explained clearly in Ref. [8]. Their use for a generous number of layers would constitute a rather traditional finite difference model. In the present model the number of concentric shells used is minimized for computational expediency. As a result, the model suggested by Equations (19) and (20) is first used with sufficiently fine discretization to yield reasonable results as the cargo is subjected to reference boundary conditions. The resulting solution is then used as a reference to which a coarser model is fit. In the coarser model the η_i of Eq. (19) are replaced by values that optimize the agreement between the fine and coarse models. This procedure is documented elsewhere.

Given the ω_i and η_i , the heat transfer to a spherical shell sandwiched between two shells for an entire sphere would be:

$$Q_i = (T_{i+1}^4 - T_i^4)\omega_i + (T_{i-1}^4 - T_i^4)\omega_{i-1} + \eta_i(T_{i+1} - T_i) + \eta_{i-1}(T_{i-1} - T_i) \quad (21)$$

The preceding equation is written as if the sphere is strictly the one-dimensional geometry after which the conductors are fashioned. In the present model the situation is complicated by the splitting of the exterior surface of the cargo into A_1 and A_2 . We have a pseudo-spherically-symmetric-1-D analysis. The conductors of Eqs. (19) and (20) are apportioned to the hot and cool sides of the cargo. For example, for the case in which $ncs=5$ the equations that are integrated are:

$$\frac{\partial T_1}{\partial t} = \{\beta[(T_2 - T_1)\eta_1 + (T_2^4 - T_1^4)\omega_1] + (1 - \beta)[(T_3 - T_1)\eta_1 + (T_3^4 - T_1^4)\omega_1]\} / (mC_p)_1 \quad (22)$$

In Eq. (22) β (the same as `split` in the code) represents the fraction of the sphere "belonging" to the hot side of the sphere. mC_p is the thermal capacitance of the entire spherical layer. As an example of an interior node:

$$\frac{\partial T_2}{\partial t} = \{(T_4 - T_2)\eta_2 + (T_4^4 - T_2^4)\omega_2 + (T_1 - T_2)\eta_1 + (T_1^4 - T_2^4)\omega_1\} / (mC_p)_2 \quad (23)$$

Eq. (23) is typical of equations for either the hot or cool sides. The factors β and $(1 - \beta)$ don't appear because they modify the net heat transfer rate and the thermal

capacitance of the node in like proportion (they cancel out). For the exterior node (node 8 for the hot side in this case) the sphere communicates thermally with the enclosure analysis. The resulting equation is:

$$\frac{\partial T_8}{\partial t} = \{ \beta[(T_6 - T_8)\eta_4 + (T_6^4 - T_8^4)\omega_4] + q_1 A_1 \} / (mC_p)_5 / \beta \quad (24)$$

where $q_1 A_1$ comes from the radiating enclosure analysis (See Eq. (18)). In Eqs. (22-24), note that the T_i are described as in Figure 8 so as you proceed radially outward the subscript on ω and η only grows half as fast as that on T (there are two T 's per shell but only one new ω or η).

ω and η , as described in the preceding paragraphs are consistent with finite difference theory and should provide an accurate one-dimensional model if sufficiently many layers are used. In the present model we wish to use a modest number of layers. The result of this coarseness will generally be a model that responds too quickly. However, if the foregoing theory is applied, care must be taken so that the critical temperature to be monitored is not made part of a thick material region. Since each "node" is (spatially) isothermal, not resolving the gradient of temperature through a region can result in its temperature being suppressed.

Variations of Eq. (24) are used to simulate melting of the exterior shell of the cargo on the hot side. Eq. (24) is integrated as it is written while T_8 heats up to `tmelt`. Once T_8 reaches `tmelt`, the meaning of T_8 changes. Eq. (24) continues to be integrated but `tmelt` is substituted for T_8 on the right hand side of the equation. Likewise, the constant temperature `tmelt` is used in the radiation enclosure analysis during this interval. During the melting the variable T_8 actually represents `tmelt` + $\int_0^t q(t^*) / (C_p \rho h) dt^*$ until the integrated heat addition accounts for melting through the thickness. `umelt`, a code input, is the melting material's heat of fusion divided by the its constant value of specific heat. The melting is complete when $T_8 = \text{tmelt} + \text{umelt}$.

After the melting is complete, the temperature of the next spherical shell in is substituted for the temperature of A_1 in the enclosure analysis. The optio-geometric properties of the SST are not recomputed. Instead, the system is allowed to depart slightly from conserving energy. The energy $q_1 A_1$ from the enclosure analysis is reduced by the factor $(r_6/r_8)^2$ as it is applied to the node corresponding to T_6 . Of course, the subscripts ₆ and ₈ used in the preceding sentence are only correct for `ncs=5`. No adjustments are made to ϵ_1 during this process.

To effect damaged cargo, four *damage states*, designated 0 through 3 can be communicated to MELTER (See the input descriptions in Secs. 4.3.1 and 4.3.2.). Damage state 0 corresponds to intact cargo. Damage states 1, 2, & 3 correspond to cargo models with increasingly many layers stripped away. Damage state 3 *always* corresponds to the critical layer being exposed. The number of layers constituting models corresponding to the intermediate damage states are known to MELTER through information it reads

in from *cargo.TAR* (See Section 4.3.2).

2.8 Failure Criteria

One layer of the foregoing cargo model is designated as the *sensitive* layer. The temperature of that layer is monitored to determine if failure has occurred. MELTER accepts as input a user-specified temperature-time curve⁸ which defines the temperature at which the sensitive layer fails as a function of time. Figure 9 shows qualitatively such a temperature-time failure criterion. In MELTER conservatism is introduced in that "time zero" is taken to be the start of the fire. Depending upon the scenario, there may be a very significant delay between the start of the fire and the onset of appreciable heating to the cargo. No credit is taken for that delay which may be considerable for some scenarios. Curves A, B, C, and D represent four different temperature histories that might result at the sensitive layer in order of decreasing scenario severity. Failures associated with Curves A, B, and C are assumed when the curve intersects the failure curve. Curve D suggests no failure. MELTER monitors the response of the sensitive layer and the failure curve. For scenario D MELTER will conclude that no failure occurs at the time designated t_{safe} . The conditions allowing the "safe" conclusion that the curves never will intersect are that fire is extinguished and that $\frac{\partial T_{crit}}{\partial t} < \frac{\partial T_{fc}}{\partial t}$. That is, the time rate of change of the critical layer must be more negative than that corresponding to the failure curve. Note that for Curve C the failure occurs at a time after the maximum value of T_{crit} is realized.

2.9 Numerical Methods

The numerical methods used to render results from the foregoing equations are fairly trivial. Three significant requirements arise:

1. **Integration:** A method of integrating the 1st-order coupled differential equations that have been developed must be incorporated. MELTER was developed using a Runge-Kutta routine (Ref. [9]). Subsequently, *ode* (Ref. [10]), a more sophisticated integrator, has been implemented for greater efficiency.
2. **Matrix Inversion:** The radiation problem requires a matrix to be inverted. That matrix is at most 9×9 in size and is always well-behaved and easily inverted. A simple Gauss-Jordan method with pivoting is employed.
3. **Root-Finding:** When MELTER is to find the minimum fire duration that leads to failure a root-finding method is needed. Bisection is used. Generally speaking,

⁸This curve is defined in a piecewise linear fashion with parameters defined in the input file defining the cargo. See Section 4.3.2.

Figure 9: Temperature-time failure criteria used in MELTER and four hypothetical cargo responses.

bisection is unsophisticated and not famous for speed. However, in the present application it is effective. Bisection requires that upper and lower bounds be known for the search variable. A very good estimate is found for the upper bound by "leaving the fire on" until a failure occurs. Zero fire duration makes a good lower bound which will only ever be approached by halving the uncertainty interval "from the right" so that it is efficiently replaced with a more appropriate lower bound. Finally, the present implementation is efficient because the integration never needs to begin earlier than the current lower bound on the search variable. That is, the state of the system is saved at the time defining the lower end of the uncertainty interval. In subsequent search steps the integration can always be resumed at that point. This aspect of MELTER works very well.

	Parameter	Case I	Case II	Case III	Case IV
Inputs:	Fire Temperature (K)	2133	2133	2133	2133
	Fire Diameter (m)	9.1	9.1	9.1	9.1
	Fire Displacement (m)	0	5.6	5.6	11.7
	Fire Duration (s)	1800	2400	2400.0	2400.0
	$A_8, (m^2)$	0.0	0.9	0.0	0.0
	$A_9, (m^2)$	0.0	0.9	5.6	0.0
Computed Quantities:	$F_{A7,f}$	1.0	1.0	1.0	0.3
	$A_1, (m^2)$	6.2	2.0	2.0	2.5
	$A_3, (m^2)$	200.0	200.0	200.0	200.0
	$A_4, (m^2)$	2.3	20.4	20.4	20.4
	$A_5, (m^2)$	18.1	0.0	0.0	0.0
	$A_6, (m^2)$	19.7	47.7	47.7	42.4
	$A_7, (m^2)$	49.5	19.6	16.9	26.8
Results:	Time to failure, (s)	2230	1630	620	none
	T_{crit} at failure, (K)	519	535	570	

Table 1: Summary of cases considered.

3 Case Studies

As it will be used in the risk assessment, MELTER determines the minimum fire duration which, for other conditions specified, leads to a failure. MELTER also can be operated with a user-specified fire duration. In that case the transient thermal response of the SST is calculated from zero time until a failure occurs or until it can be asserted that no failure will occur. Table 1 summarizes four case studies that are included to demonstrate the qualitative nature of the SST's response for several scenarios of interest. Figure 10 represents the geometry of all four cases as an aid to visualize the relative size of the SST, fire, and separation distance. All of these fires feature a 2100F fire.

3.1 Case I

The first case considered is one for which the fire is centered under the SST and is of sufficient size to engulf most of the SST's exterior. Table 1 gives the quantitative distribution of $A_{1..9}$ associated with the fire. For Case I, the SST is in nominal condition at the start of the fire ($A_8 = A_9 = 0$). Referring to Figure 11, several temperatures of

Figure 10: Schematic representation of geometries for four case studies.

interest and the char displacement (x) in the wall are plotted.

- The analysis stops at 2230s, which is more than 400s after the fire is extinguished. The critical state is reached after the fire's extinction due to the energy that was stored in the SST's walls. The cargo used in this example has a relatively thin outer layer coupled to the next layer in by a radiation gap.
- T_{crit} at failure is 519K.
- The directly heated armor (A_7) and case temperatures outrun the temperature associated with secondary heating (A_6).⁹
- At this high temperature and unit view factor, the foam in the wall chars rapidly, introducing only about a 100 s delay before heat is "felt" on the interior.
- The thin outer skin rapidly moves to a *quasi*-equilibrium temperature very close to the fire's temperature after the start of the fire.

3.2 Case II

In Case II the fire is the same size but it is displaced so that the near edge of the fire just coincides with the fireside edge of the SST. Note in Table 1 how $A_{1..9}$ are redistributed. In this case nearly a square meter ($10ft^2$) of A_8 and A_9 have been specified. A_8 corresponds to damage to the SST which is associated with removal of the exterior skin and foam down to the armor. A_9 corresponds to a complete breach of the SST. A_9 and A_8 are both in line with the fire. Referring to Figure 12:

- For Case II the early SST skin temperature history and char displacement are identical to the first case since the view factor to the fire is still unity and the fire temperature is unchanged.
- The temperature associated with bare armor (A_8) rapidly moves to *quasi*-equilibrium. This temperature is lower than the skin temperature of the previous case because the heat flux through the bare armor is higher than that through the charred wall.
- The cargo case temperature outruns the armor temperature associated with A_7 because of its clean view to the fire through A_9 and to the directly heated armor (A_8).

⁹Referring to the conservative rules that are used for determining view factors, the "sunny" side of the cargo is generally given a clean view of the hot armor.

CASE I RESULTS

Figure 11: Case I results.

- T_{crit} at failure is $535K$. The heating rate for this case is greater than that for the first case and a higher failure temperature is used.

3.3 Case III

The fire geometry for Case III is identical to the previous case. A very significant hole ($5.6m^2$, $50ft^2$) has been opened on the side of the SST. Referring to Figure 13:

- The case temperature climbs very rapidly to its melting point ($933K$) and is flat during the melting process which is not completed at failure.
- The failure time is shortened to $620s$ and a corresponding increase of T_{crit} to $570K$ is observed.

3.4 Case IV

Case IV corresponds to a scenario for which there is no structural damage to the SST and there is considerable separation distance between the fire and the SST. Referring to Table 1 notice that A_7 is larger than for the previous case which may be counter-intuitive to the reader. However, referring to Eq. (6) appreciate that E_{max} is decreased for this case (to about 30% of E_f) so that the energy deposition for this case is appropriately less than that for the previous case. As a result of the separation distance this fire is not particularly threatening. The fire duration is an hour for this case and no failure occurs. Referring to Figure 14:

- The skin temperature again moves quickly to a *quasi*-equilibrium temperature of about $1040K$ which roughly corresponds to an emissive power that is about 30% of that of the fire (see Eq. (4)).
- The charring of the wall takes about $540s$ or about 5 times as long as the previous cases for this reduced heating rate.
- The cargo's case temperature does not lag far behind the temperature associated with A_7 . Due to the modest heating rate, the whole interior of the SST will be comparatively isothermal.
- The analysis stops at around $4300s$ when the temperature of the sensitive layer "turns around." This is about $900s$ after the fire is extinguished.

CASE II RESULTS

Figure 12: Case II results.

CASE III RESULTS

Figure 13: Case III results.

CASE IV RESULTS

Figure 14: Case IV results.

4 MELTER Code Description

4.1 Introduction

This section describes the coding of MELTER, which is written in FORTRAN. As discussed in the first section, information defining an analysis depends on the SST's properties, those of the cargo, and scenario-specific information. Properties of the SST are "hard-wired" in the code, that is, the source code must be edited to modify them. The cargo and scenario properties are communicated to the code through interface files.

A listing of MELTER is included in the Appendix C for reference. The source code for MELTER is about 2500 lines (including ode). Constants defined in the source are all initialized in the BLOCK DATA routine and made available to other subprograms through COMMON statements. MELTER has been operated extensively on SUN SparcStations. After compilation, MELTER is executed as follows:

```
system_prompt: MELTER scenes cargo <carriage return>
```

scenes and *cargo* are command line parameters that identify the files containing scenario and cargo information (See Sections 4.3.1 and 4.3.2).

4.2 Overview of Code Operation

The steps of the analysis, as they unfold during MELTER's operation, are summarized in the following outline:

1. Read input.
 - (a) Read *scenes.BRC* to get scenario-specific parameters.
 - (b) Read *cargo.TAR* to get cargo-specific parameters.
2. For each scenario considered construct the model. Most of MELTER's source code serves the purpose of constructing the equations that make up the model.
 - (a) For a given scenario calculate boundary conditions in terms of exposed area(s) and view factors.
 - (b) Formulate enclosure radiation problem consistent with the scenario and cargo characteristics.
 - i. Estimate all view factors needed for enclosure radiation problem.

- ii. Strip out zero area surfaces.
 - iii. Condition matrix needed for radiation calculations inside SST.
3. Find minimum critical fire duration or whether specified fire duration leads to failure. If minimum critical fire duration is calculated:
 - (a) Solve equations with fire burning continuously until failure occurs and take that value as the high end of the search interval (t_{high}) and $t = 0$ as the low end (t_{low}).
 - (b) Reset the fire duration, $t_{dur} = (t_{high} + t_{low})/2$ and restart the thermal simulation.
 - (c) If failure occurs set $t_{high} = t_{dur}$ otherwise set $t_{low} = t_{dur}$.
 - (d) If $t_{high} - t_{low} > \min(50, 0.01 \times t_{dur})$ go back to (b) otherwise quit.
 4. Write results to *cargo.MEL*.
 5. Repeat steps 2-4 for each scenario presently under consideration.

4.3 Input

Besides physical characteristics of the SST which are hard-wired into MELTER's source code, inputs are needed to describe the cargo and the scenarios for a particular analysis. MELTER reads problem specification parameters from two input files, *cargo.TAR* and *scenes.BRC*. In general, parameters found in *cargo.TAR* are those that define the cargo and characteristics of the way it is loaded. Parameters found in *scenes.BRC* are those that define the scenarios to be considered.

4.3.1 *scenes.BRC*

The PRA is facilitated by discretizing the *parameter space*. That is, discrete values relating to fire size, temperature, and separation; SST damage state reflected through A_8 and A_9 ; and cargo damage conditions reflected through *proximity* and *nstrip* are considered. MELTER incorporates loops which exhaustively test every possible combination of discrete values specified for this purpose. Table 2 includes the lines of source code which result in MELTER's reading of *scenes.BRC*. The variables read are as follows:

nndam number of *ndam(i)-prox(i)* pairs to be read, a maximum of 4 values may be specified.

```

c      open(unit=7,file='branch.dat',status='old')
c      there has to be the same number of proximities and
c      damage states considered (4 maximum)
      read(7,*)nndam,(ndam(i),i=1,nndam)
      read(7,*)      (prox(i),i=1,nndam)
c      there are the same number of adam9 and adam8 values (6 max)
      read(7,*)nadam9,(adam9(i),i=1,nadam9)
      read(7,*)(adam8(i),i=1,nadam9)
c      there may be as many as 10 temperatures
      read(7,*)ntemp,(ftemp(i),i=1,ntemp)
c      there may be as many as 10 diameters
      read(7,*)ndcdia,(dcdia(i),i=1,ndcdia)
c      there may be as many as 7 distances
      read(7,*)ndcdist,(dcdist(i),i=1,ndcdist)
c      tdur0 is zero if the calculation is to yield the minimum critical
c      duration. Otherwise it is the specified fire duration.
      read(7,*)tdur0
      close(7)

```

Table 2: Portion of MELTER that reads *scenes.BRC* to define scenario parameters.

ndam(i) an array of integer values (0-3) assigned to **nstrip** indicating degree of damage to cargo. "0" corresponds to undamaged cargo. "3" corresponds to the most damaged possible state. Associated information in *cargo.TAR* tells MELTER the number of layers to peel off of the spherically-idealized model for each value of **ndam(i)**.

prox(i) (Refer to Section 2.6) an array of values for the variable proximity. These influence the rules used to calculate view factors. For each **ndam(i)** there must be a corresponding value of **prox(i)**.

nadam9 number of **adam9(i)**-**adam8(i)** pairs to be read, a maximum of 6 pairs may be specified.

adam9(i) array of values for the variable A_9 .

adam8(i) array of values for the variable A_8 . There must be one value **adam8(i)** for each **adam9(i)**.

ntemp the number of **ftemp(i)** values to be read up to a maximum of 10.

ftemp(i) an array of values for fire temperature.

ndcdia the number of **dcdia(i)** values to be read up to a maximum of 10.

dcdia(i) an array of fire diameters to be considered.

ndcdist the number of **dcdist(i)** values to be read up to a maximum of 7.

dcdist(i) an array of separation distances to be considered.

tdur0 specified fire duration. If specified greater than zero the analysis indicates whether that duration leads to failure. If **tdur0** is set equal to zero the minimum critical duration will be determined.

4.3.2 *cargo.TAR*

Table 3 includes the FORTRAN source from MELTER that reads information about the cargo being analyzed subject to all of the foregoing scenario parameters.

ncs0 the number of concentric shells used to represent the intact cargo. This is the same as **ncs** for undamaged cargo.

lleft(1) The number of model layers to be included if damage state "1" is being considered (see **ndam(i)** description in previous section).

```

c      open(unit=4,file=fname,status='old')
      open(unit=4,file='targ.dat',status='old')
      read(4,*)ncs0,lleft(1),lleft(2),modelnumber,noutput
      read(4,*)acargo0,cargoeps0,transm,ttrans,a(3),rmcp3
      read(4,*)tmelt,umelt
      read(4,*)ncrit0,ndtim
      do 5 i=1,ndtim
      read(4,*)dtimes(i),dtemps(i)
5 continue
      read(4,*)(ck(i),i=1,ncs0-1)
      read(4,*)(cr(i),i=1,ncs0-1)
      read(4,*)(mcp(i),i=1,ncs0)
      read(4,*)(rcarg(i),i=1,ncs0)
      close(4)

```

Table 3: Code section that reads *cargo.TAR*.

lleft(2) The number of model layers to be included if damage state "2" is being considered (see *ndam(i)* description in previous section).

modelnumber An integer used to communicate whether the exterior surface of the cargo is to be allowed to melt. *modelnumber=1* tells the code that the exterior shell can melt away on the hot side of the cargo.

noutput an integer that is checked to see if the code should generate output. The higher the value, the greater the amount of output generated. Normally, *noutput=0*, in which case the only output of the program is in *cargo.MEL*.

acargo0 The surface area of the outside of the cargo (m^2). When many copies of the same cargo item are loaded, this is the exterior area of a single item. The others should be considered as part of the inert cargo.

cargoeps the emissivity of the cargo exterior.

transm an average transmittance for the whole interior. This value should be indicative of the view across the volume. If the SST's volume is packed tightly with cargo this value approaches zero. If the SST is empty or near empty this value approaches unity.

ttrans the transmittance between the threatened cargo and the hottest wall. Usually, we expect this to be higher than the previous value (*transm*).

a(3) This area (m^2) corresponds to the inert cargo. This constant must be specified as some value larger than zero. At present it has no influence on results.¹⁰

rmcp3 This is the thermal capacitance (J/K) of inert cargo in the SST.

tmelt The melting temperature (K) of the exterior shell of the cargo.

umelt The melting energy of the exterior shell expressed as the latent heat of fusion divided by the constant value of C_p that is used to represent the solid during its sensible heating.

ncrit0 This identifies which concentric shell of the cargo is to be watched for the critical condition. This value must be greater than 1 if a scenario involving damage state 3 is considered.

ndtim This tells how many points are used to describe the failure temperature curve.

dtimes(i) These are **ndtim** values of time which are used to define the failure temperature curve.

dtemps(i) These are **ndtim** values of temperature which are used to define the failure temperature curve.

ck(i) These are conduction-style connectors between concentric shells. **ck(i)** connects mCp_i to mCp_{i+1} . (see Section 2.7)

cr(i) These are radiation-style connectors between concentric shells. **cr(i)** connects mCp_i to mCp_{i+1} . (ω_i/σ , Eq. (20))

mcp(i) These are the thermal capacitances of concentric shells representing the cargo.

rcarg(i) Radii of shells.

Generally *scenes.BRC* contains the scenario-dependent parameters and *cargo.TAR* contains the parameters that describe the package and information about the configuration in which it is shipped in the SST. However, some information must be communicated cooperatively. For example, MELTER allows four levels of cargo damage to be considered which correspond to damage states 0 through 3. These are specified in *scenes.BRC*. However, information to interpret the *meaning* of the damage state must be specified in *cargo.TAR* for each cargo. As indicated earlier the variables **lleft(1)**

¹⁰As MELTER is presently formulated **rmcp3** gives the total thermal capacitance of the inert cargo, and **ttransm** specifies that cargo's transmittance. While **a(3)** is used in the calculations its magnitude has no effect. Its identity is maintained to provide flexibility in any future versions of MELTER that might incorporate additional detail in the treatment of inert cargo.

and `lleft(2)` are the numbers of spherical layers that remain for damage states 1 and 2. Damage state 0 corresponds to undamaged cargo, and damage state 3 corresponds to cargo for which the critical layer (identified through `ncs0`) is the external layer presented to the rest of the enclosure analysis.

4.4 Output

As used in the PRA, MELTER's principal product is the file *cargo.MEL* which it creates. For each scenario analyzed the following values are written to *cargo.MEL*: 1) the minimum critical fire duration, 2) the corresponding quantity of fuel for that scenario which is proportional to fire diameter times duration. and 3-7) the indices of the parameters read from *scenes.BRC* that define the scenario. In the event that no failure can be predicted for any fire duration arbitrarily large (10^7) values are written to the fire duration and fuel quantity fields. The PRA analyst must coordinate the construction of *scenes.BRC* and subsequent use of *cargo.MEL*.¹¹

Table 4 includes the lines from MELTER which produce *cargo.MEL*. `quest1` is a logical variable which is `.true.` if the fire duration has been specified. In that case three values are written to *cargo.MEL*. The first value is a '1.0' or '2.0' indicating, respectively, failure or survival. If a failure has resulted the time of that failure and the fire duration are reported. If the cargo survives the time at which the analysis was halted and the temperature of the critical layer at that point in time are reported.

MELTER also produces files that contain information useful to assess the consistency of its results. *cargo.STA* contains the number of failures and average value of the critical fire duration for each index of each parameter specified in *scenes.BRC*. For example, if the most distant fires specified in *scenes.BRC* never lead to failures, the range of that parameter should be decreased to improve resolution. Cases have been encountered for which the critical fire duration is difficult to determine because failure occurs *much* later than the extinction of the fire. If a really obstinate scenario is encountered MELTER can move on to the next case without successfully resolving the critical fire duration. In those cases MELTER writes to *cargo.XXX* the sequence of `iflag` values that were returned by `ode`, the integrator, during its attempt to solve that problem. There were no such occurrences for 29 of the 33 cargos, two cargos produced a single case in which a solution was not found, and two cargos produced about 5% exceptions, which were invariably associated with distant, small fires. These failures result when difficulty is encountered in integrating the equations. The individual cases were resolved by running these same cargos with a version of MELTER that used a simple finite-difference approach to integrating the equations (which was more robust but slower). MELTER's

¹¹The PRA analysis knows the fire diameter corresponding to each value in *cargo.MEL*. The probability of sufficient fuel existing to reach the critical fire duration is *bottom line* used in determining the probability of fire-induced failures.

output was then repaired with numbers derived with the finite difference version of the code.¹²

If `noutput > 0`, as set in *cargo.TAR*, and the fire duration has been specified MELTER generates an additional file *MELTER.OUT*. This file includes intermediate results calculated such as view factors and the distribution associated with $A_{1..9}$. The *MELTER.OUT* file associated with Case I of the results section is included as Appendix B.

¹²Results for cases solved by both integrators were verified to be in close agreement.

Section that writes *cargo.MEL*:

```
open(unit=8,file='answers.dat',status='unknown')
rewind(8)
.
.
.
if(quest1) then
  if (kaboom) then
c    if question 1 is posed and it fails, '1.0' is written
    write(8,*)'1.0 ',time,tdur
    else
c    if question 1 is posed and it survives, '2.0' is written
    write(8,*)'2.0 ',time,temp(ncrit)
    end if
    else
c    question 2 has been asked
    if (.not.boomonce) then
c    no failure is predicted, write 1e7 to tav and fuel
    write(8,79)idam,iadam,itemp,idia,idist
79 format(1x,'1.0e7 1.0e7',5i3)
    else
c    if question 2 is posed and failure is found within tmax
    tav=(thigh+tlow)/2.0
c    compute the critical quantity of fuel corresponding to tav
    fuel=tav/(40.0*60.0/(3.141592*(dia/0.3048)**2))
    write(8,78)tav,fuel,idam,iadam,itemp,idia,idist
.
.
.
end if
close(1)
```

Table 4: Code section that writes results.

4	3	2	1	0						
	1.0	1.0	1.0	0.0						
6	20.0	5.0	0.0	0.0	0.0	0.0	0.0			
	40.0	40.0	40.0	20.0	5.0	0.0				
9	2300.0	2150.0	2050.0	1950.0	1850.0	1700.0	1500.0	1300.0	1200.0	
9	75.0	45.0	37.5	32.5	27.5	22.5	17.5	12.5	7.5	
7	-1.0	2.5	7.5	15.0	30.0	60.0	80.0			
	0.0									

Table 5: DPTRA.BRC, the *scenes*.BRC file used to defined scenarios considered in results reported in Table 6.

5 MELTER's Performance in PRA

At this writing MELTER has been used on 33 different cargos in combination with a set 13,608 scenarios which span the parameter space of interest. These results have been inspected for consistency and reasonableness. The results produced are consistent within the resolution reasonably expected of the present analysis. As described in Section 4.3.1, *scenes*.BRC defines discrete values for cargo damage, SST damage, fire temperature, fire diameter, and fire displacement. Table 5 includes, DPTRA.BRC, the scenario input that was used to generate results discussed in this section. In DPTRA.BRC the parameters are *nominally* ordered from most to least severe. Each cargo analyzed in concert with DPTRA.BRC resulted in a 13,608-line *cargo*.MEL file. These files have been scanned with a short computer program to observe whether *adjacent* cases exhibit the expected trends. A pair of scenarios sharing all the same parameters except one, that parameter being one increment displaced, are said to be *adjacent*. Over 50,000 such adjacent pairs result for the set of scenarios in question. Each pair is examined and exceptions from what is expected are noted. Depending on the cargo being analyzed, from 0 to 5% of these comparisons yield results departing from the nominal expectation. The sources and expected consequences of these departures are discussed in this section. Table 6 summarizes the results of this scanning activity for the cases that have been analyzed as of this writing. The first three columns of Table 6 correspond to comparisons associated with the distance, diameter, and temperature of the fire; the next two columns deal with the damage condition of the SST and of the cargo; and the last column is the average result for all comparisons. For example, the first column reports the percentage of cases in which an increase in fire distance did not yield the expected increase in critical fire duration. Several types of *apparent* anomalies are produced including:

1. Some adjacent scenarios are virtually equivalent and acceptable numerical uncertainty produces some inconsistency.
2. The cargo in a more damaged SST may require longer fire duration to induce failure than that in a less damaged SST—all other things being equal.
3. Fires of greater diameter produce no failure or less rapid failure when those of lesser diameter have been producing failures.
4. Increasing the damage of the cargo does not always result in a shortening of the failure time.

It should be noted that the results reported in Table 6 are dependent upon the resolution with which the parameter space is discretized. If each parameter were changed only in very significant increments, Table 6 would be a table of 0's. The following sections discuss the apparent inconsistencies that were created using the parameter space defined by DPTRA.BRC given in Table 5.

5.1 Numerical Uncertainty

MELTER hunts for the minimum fire duration that will result in a thermal failure condition. A bisection method is employed to narrow the interval of uncertainty. The accepted interval of uncertainty is the lesser of 1% of the fire duration or 50 seconds. When two scenarios are very close to equivalent but not identical the resulting minimum critical time estimates will be very close to each other and not necessarily ordered as expected. This numerical uncertainty creates many of the discrepancies reported in Table 6 including all of those of the first column.

5.2 Distance

Referring to Table 6, very few inconsistencies are associated with fire separation distance. About 3/4 of those that do occur arise when comparing a SST in an engulfing fire to one with a large fire just against the side of the SST. For cases in which the SST is damaged, the damaged area of the SST is uniformly covered by either of these fires. As a consequence they are virtually equivalent threats to the cargo and, coupled with numerical uncertainty, give rise to an occasional inconsistency. No significant effect on the overall probability of failure can reasonably be associated with these inconsistencies.

5.3 Fire Diameter

A significant source of this type of discrepancy also results from the fact that for some scenarios additional fire diameter really is virtually inconsequential. For fast-

Cargo	dist	dia	temp	sst damage	cargo damage	Average
comp1	0.0	4.3	0.0	4.4	0.0	1.8
comp2	0.0	4.7	0.0	3.0	18.5	4.9
comp3	0.0	3.1	0.0	2.7	0.0	1.2
comp4	0.0	5.0	0.0	10.0	0.0	3.0
comp5	0.5	9.4	0.7	5.5	4.8	4.1
comp6	0.0	5.4	0.1	5.7	0.9	2.4
comp7	0.0	4.8	0.0	10.7	2.8	3.6
comp8	0.0	7.7	0.0	3.2	2.7	2.7
comp9	0.0	5.6	0.1	2.2	0.0	1.6
comp10	0.1	4.8	0.2	7.1	0.0	2.5
comp11	0.1	5.0	0.4	10.6	0.2	3.3
comp12	0.1	5.2	0.3	9.7	0.0	3.1
comp13	0.0	5.2	0.1	9.8	0.6	3.2
comp14	0.0	5.9	0.0	4.4	1.5	2.4
comp16	0.2	5.8	0.2	8.7	0.0	3.0
comp17	0.0	5.1	0.0	5.7	1.2	2.4
north1	0.0	4.8	0.1	14.1	0.5	3.9
north2	0.1	4.1	0.4	14.3	0.4	3.9
north3	0.3	4.6	0.0	14.1	0.4	3.9
north4	0.0	4.7	0.0	8.4	2.7	3.1
north5	0.1	4.9	0.0	8.1	1.0	2.8
north7	0.0	4.5	0.0	12.6	0.5	3.5
north8	0.1	6.2	0.0	8.3	5.3	3.9
north9	0.0	4.5	0.0	12.7	0.5	3.6
west1	0.2	3.7	0.3	3.0	7.3	2.8
west2	1.2	8.1	0.1	8.6	3.4	4.3
west3	1.1	4.5	0.3	19.9	2.1	5.5
west4	0.3	5.3	0.2	6.1	15.4	5.2
west7	0.4	3.9	0.2	10.5	0.3	3.1
west8	0.1	4.4	0.3	13.4	0.6	3.8
west10	0.1	5.5	0.2	6.6	0.9	2.7
west11	2.8	6.7	0.9	18.3	1.1	6.0
west12	0.2	4.6	0.0	17.5	0.2	4.5
average	0.2	5.2	0.2	9.1	2.3	3.4

Table 6: Summary of % of adjacent scenarios not exhibiting expected trend.

failing cases involving a damaged SST, once the fire is big enough to cover A_8 and/or A_9 , additional fire size has little influence. Under these conditions, additional A_7 is of no important consequence. These diameter inconsistencies result from numerical uncertainty. That many of these arise from numerical uncertainty is supported by the fact that comparatively many inconsistencies associated with diameter occur for the largest couple of diameters considered at the engulfing and abutting separations.

Circumstances can arise which MELTER does not resolve correctly. Refer to Figure 15a, and regard the cargo as being isolated in the middle of the SST with an unobstructed view to the heated walls of the SST. A_1 sees both A_7 and A_8 . Consider first a case for which a specified A_8 is just neatly covered by a fire adjacent to the SST. A_8 will be aligned with the fire and there will also be a finite area, A_7 . Referring still to Figure 15a, consider an increase in the fire size while maintaining the same A_8 . The effect is an increase in A_7 . Since A_7 's thermal response lags that of A_8 , A_1 is relieved because the viewfactor-weighted average temperature of the surface seen by A_1 is lower than in the first case.

5.4 SST Damage

5.4.1 Stored Energy Discharge

Nominally, we expect increasing damage to a SST to make it more vulnerable to failure. However, it is physically reasonable that a more damaged SST will have a better chance of survival than a less damaged SST for certain fire and cargo conditions. Suppose a fire of fixed size and duration threatens a damaged SST. If the fire is short and intense it will store a significant amount of energy in the SST before the cargo has an opportunity to respond. After the fire is out a lot of energy has been trapped in the SST's thermal capacitance. For this scenario it is entirely possible that the more damaged SST not lead to failure because of the discharge of that stored energy to the environment before a critical thermal response is induced in the cargo. The physics that are included in MELTER can predict this behavior. This effect accounts for *some* of the SST damage anomalies.

5.4.2 A_8 Nonuniformity

Another source of aberration results from limitations of the enclosure heat transfer analysis. Refer to Figures 15a and 15b which represent two cases having identical A_1 , the "sunny side" area of the cargo by virtue of "seeing" the same total amount of heated armor $A_7 + A_8$. A_7 is the area of nominal wall construction directly heated by the fire. A_8 is the area of wall with the exterior skin and rigid foam removed that is directly heated by the fire. The geometries shown share the feature that the cargo is close to the wall (proximity=1). It seems clear enough that Figure 15b depicts

Fig 15a

Fig 15b

Figure 15: Example of two geometries that illustrate a model limitation.

the more threatening condition and for most fire scenarios MELTER will predict just that. However, for scenarios with a rather severe fire condition, MELTER will generally predict faster ignition for Figure 15a's geometry. The *reason* is that in Figure 15b A_8 views both the exterior of the cargo *and* other thermal capacitance within the SST. In Figure 15a, A_8 tends towards seeing only A_1 . As a result, $T_{A_8}(t)$, the temperature history of A_8 associated with Figure 15b will exhibit a more sluggish response than that associated with Figure 15a. The situation violates the model's idealization that A_8 be spatially isothermal. To remove this discrepancy (perhaps a future version of) MELTER would have to incorporate additional area elements in the radiation enclosure so that a distribution of temperature for A_8 can be resolved. Most of the nonmonotonic results associated with SST damage are due to this effect. Considering all cargos together, nearly 70% of these inconsistencies occur when comparison is made between the SST with $A_8 = 20\text{ft}^2$ and that with $A_8 = 5\text{ft}^2$. Given the uncertainty associated with specifying a distribution of A_8 , MELTER's results are acceptably consistent.

5.5 Cargo Damage

This type of inconsistency is primarily due to numerical uncertainty coupled with conditions for which subsequent damage states are of little consequence. The crude discretization that is used in representing the cargos gives rise to this situation. Often the thermal models representing successive damage states differ by a single spherical annulus. A given single annulus of material within the model is spatially uniform in temperature. As a result the *delay* we expect as thermal energy diffuses through the system is consistently underestimated. In some cases an increment of damage to the cargo will result in eliminating a conduction connector of the type indicated by Eq. (19) and a radiation connector of the type indicated by Eq. (20). The newly exposed exterior surface of the cargo has less surface area than that associated with the next less damaged state. The thermal impedance from the outside of the cargo can actually increase.¹³

¹³This is similar to the counter-intuitive result that the addition of insulation to a simple pipe-insulation-convection system can *increase* the steady heat transfer. See Ref. [8].

6 Concluding Remarks

The MELTER model of the thermal response of cargos transported in a SST subject to fire environments and its implementation in a computer code have been developed. MELTER estimates the minimum fire duration creating a critical condition for a cargo in a SST in a fire. A satisfactory tool to be employed in PRA has been developed. Salient features of MELTER include:

- The existing model accommodates a wide variety of fire scenarios. MELTER incorporates the sampling of the user-specified parameter space.
- Unique *cargo.TAR* files are loaded into the analysis just as unique cargos are loaded into SSTs. Furthermore, the cargo can be rendered more vulnerable by provisions for damage states.
- Means to reflect damage to the SST have been incorporated.
- Qualitatively satisfying results have been obtained. Bigger, hotter, and closer fires lead to shorter failure times as expected (see Section 5.3).
- MELTER is robust. On the order of a million scenarios/cargo combinations have been run.
- Affordable execution times have been achieved.
- A balanced level of modeling detail is maintained.
- Conservative assumptions have been incorporated when necessary.

7 References

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A Parameter Optimization for the Charring Wall Model

This appendix discusses the optimum selection of parameters for the wall model used in MELTER. Figure 16 summarizes data from the 2nd SST Panel Burn Test (Ref. [6]). Shown are the fire temperature at one location and the average armor temperature at each of three different elevations. The block in the upper right hand corner of the plot also shows the thermocouple locations. Clearly, there is vertical stratification in the armor heating. We know that the fire temperatures outside the wall also exhibit this trend and that is the most likely explanation. However, some of this height dependency may also be the result of differences in the condition of the wall resulting from its nonuniform destruction. In any case, we are presently stuck with fitting a one-dimensional model to these results. What is the best temperature history to ask our model to try and duplicate?

Figure 17 shows the average temperatures at the three elevations again along with two methods of averaging those temperatures. The simplest method is the arithmetic average of all nine locations. The other temperature is that which exhibits the same average emissive power as all nine thermocouple locations. That is:

$$\bar{T} = \left(\frac{1}{9} \sum_{i=1}^9 T_i^4 \right)^{1/4} \quad (A1)$$

This yields a higher temperature than simple arithmetic averaging and it is the temperature we should strive to duplicate. This is because it is emissive power rather than temperature that is proportional to the amount of heat we expect to be transferred into the enclosure.

A *univariate* search method (Ref. [11]) was developed to find the optimum set of: T_f , a_w , $\Delta E_{gassify}$, and T_{react} for the wall model described in Section 2.3. The goal of the search is to find values for the parameters that will minimize:

$$H = \sum_i (\phi_i - \theta_i)^2 \quad (A2)$$

where ϕ_i and θ_i represent the data¹⁴ and the prediction using the simple wall model.

Searches like these are often not well-behaved and that was the case for this one. The search for optimum T_f and T_{react} were abandoned. T_f was fixed at 1280K, which is the average of the fire temperature shown in Figure 16. T_{react} was fixed at 585K. The search meanders around in a_w - $\Delta E_{gassify}$ space and fails to expose a sharply defined optimum.

¹⁴The average temperature calculated using Eq. (A1).

SST Panel Test 2 Temperatures

Avg. @ each elevation & Cent. Twr. @ 8'

Figure 16: Temperature histories from 2nd SST wall panel burn test.

SST Panel Test 2 Temperatures

Avg. T & T with avg. E

Figure 17: Temperature averages from 2nd SST wall panel burn test.

Fitting period (s)	a_w (mm^{-1})	$\Delta E_{gassify}$ (J/m^3)
0-2000	0.055	70,400
0-5000	0.051	68,500

Table 7: Results of optimum wall parameter search.

Figure 18 shows the model and data for one of the best fits found when requiring the model to match the first 2000 seconds of the data. Figure 19 shows those same results when the matching period is extended to 5000 seconds, well into the cooling of the wall after the fire dies.¹⁵ The fits of Figs. 18 and 19 are visually pleasing. Finally, Figure 20 shows the 5000 second period using the *optimum* parameters from the 2000 second fitting period. The increased discrepancy following the 2000 second interval is fairly visible. Table 7 summarizes the results of these searches.

It is encouraging that a_w and $\Delta E_{gassify}$ remain in the same neighborhood when optimizing periods of either 2000 or 5000 seconds are chosen. That the optimum is evasive is easily understood in terms of the physics of the problem. The time delay before the armor begins to heat is increased by increasing either of a_w or $\Delta E_{gassify}$. Consequently, this feature of the graph can be matched well with nearly any value we like for one of the parameters, provided we adjust the other. On the other hand, following the charring of the wall the slope of the armor temperature should be almost exclusively dependent upon a_w which should help define a_w fairly well without regard for the other parameter. It is easy to see that T_{react} would not be well-defined for this problem because the emissive power of the wall's skin temperature is much greater than that at the reaction front. As a consequence, it does not matter much what we call T_{react} and including it only muddled the waters. If we had comparable data for conditions that led to T_{skin} approaching T_{react} , T_{react} would become well-defined.

Referring to Table 7, the parameters that result from the longer averaging period are more conservative. That is, lower $\Delta E_{gassify}$ and lower a_w both favor comparatively rapid heat transfer through the wall. In keeping with the policy of conservatism, those parameters have been implemented in MELTER.

¹⁵The cooling of the wall through its insulated backside is also estimated.

Note: the heavier curve is the data and the lighter curve is the model prediction.

Figure 18: Comparison of data and wall model using parameters optimized to the first 2000 seconds of data.

Note: the heavier curve is the data and the lighter curve is the model prediction.

Figure 19: Comparison of data and wall model using parameters optimized to the first 5000 seconds of data.

Note: the heavier curve is the data and the lighter curve is the model prediction.

Figure 20: Comparison of data and wall model through 5000 seconds with parameters optimized to the first 2000 seconds of data.

B MELTER.OUT File for Case I

The view factors used in the enclosure analysis

.0000	.0000	.4000	.0000	.1610	.0000	.4390
.0000	.0000	.2000	.0822	.0000	.7178	.0000
.0123	.0020	.9226	.0014	.0132	.0125	.0359
.0000	.0730	.1270	.0000	.0000	.1808	.6192
.0548	.0000	.1452	.0000	.0000	.2210	.5790
.0000	.0730	.1270	.0207	.2031	.0000	.5762
.0548	.0000	.1452	.0283	.2124	.2299	.3294

The surface emissivities are:

.7000	.7000	.7000	.7000	.7000	.7000	.7000
-------	-------	-------	-------	-------	-------	-------

Melter Run at 13:40 on 6- 7-93

The total number of state variables is	21
The cargos number of concentric shells	6
The cargos number of temperatures	11
The sunny side of the cargo has area	6.172
The dark side of the cargo has area	2.008
Inerts have area	200.000
Floor area not directly exposed	2.259
Floor area directly exposed	18.141
Wall interior not directly exposed	19.738
Normal wall directly exposed	49.462
Armor with foam removed	.000
Hole area	.000
Distance from the fire is	.000
The fire diameter (m) is	9.144
The view of a(7..9) to fire is	1.000
The specified fire duration is	1800.000

Output is ordered:

time, T(1)...T(ncargo), T(A3)...T(A8), Tskin(A7), xchar(A7), Tskin(A5),
xch
ar(A5)

1	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	300	382	0	382	0	300	1800								
21	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	300	1276	51	1276	51	300	1800								
41	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	300	1354	115	1354	115	300	1800								
61	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	300	1372	163	1372	163	300	1800								
81	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	300	1380	202	1380	202	300	1800								
101	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	300	1386	236	1386	236	300	1800								
121	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	300	1389	266	1389	266	300	1800								
141	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	300	1393	294	1393	294	300	1800								
161	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
300	308	1393	305	1393	305	319	1800								

194	300	300	300	300	300	300	300	300	300	300	301	300	300	300	300
300	327	1392	305	1392	305	361	1800								
226	300	300	300	300	300	300	300	300	300	300	304	301	300	300	302
300	346	1392	305	1392	305	399	1800								
290	300	300	300	300	300	300	300	300	300	300	313	304	300	301	308
300	382	1392	305	1392	305	472	1800								
418	300	300	300	300	300	300	300	300	306	301	349	317	301	305	327
302	454	1393	305	1394	305	600	1800								
674	300	300	300	300	300	301	300	352	315	457	370	310	329	391	
315	585	1394	305	1396	305	799	1800								
974	300	303	300	306	301	313	303	476	366	567	451	337	399	499	
353	709	1394	305	1399	305	959	1800								
1157	301	308	302	316	304	329	307	550	415	621	498	365	465	573	
393	765	1395	305	1402	305	1031	1800								
1295	303	315	304	326	307	344	312	591	456	655	532	392	524	627	
431	799	1396	305	1402	305	1075	1800								
1429	307	323	307	338	312	361	320	624	495	684	565	423	583	677	
473	826	1396	305	1403	305	1111	1800								
1558	311	333	312	351	319	378	330	651	532	709	599	458	637	721	
519	849	1396	305	1405	305	1141	1800								
1678	316	343	318	364	327	395	341	674	566	732	630	493	683	756	
564	866	1397	305	1406	305	1165	1800								
1785	321	353	325	377	335	412	354	693	596	751	660	527	720	784	
605	881	1397	305	1407	305	1183	1800								
1800	322	354	326	378	337	414	356	695	600	753	664	532	724	788	
611	883	1397	305	1407	305	1185	1800								
1891	327	364	333	390	346	427	368	700	622	747	678	560	745	803	
642	852	583	305	648	305	1104	1800								
2075	340	382	349	407	366	441	391	688	645	731	696	605	755	805	
685	804	476	305	554	305	980	1800								
2375	362	405	379	428	398	459	426	678	665	722	713	655	745	784	
718	761	439	305	492	305	864	1800								
2675	386	426	408	447	428	476	457	676	674	717	719	684	735	763	
727	738	424	305	457	305	798	1800								
2975	408	445	435	466	454	493	482	675	677	716	719	700	727	745	
727	724	417	305	435	305	755	1800								
3024	412	449	439	469	458	496	486	675	678	716	719	702	726	743	
727	722	416	305	432	305	750	1800								
3067	415	451	442	471	462	498	489	675	678	715	719	703	725	741	
726	721	415	305	430	305	745	1800								
3153	421	457	449	476	469	503	496	675	678	714	718	705	723	737	
726	718	413	305	426	305	737	1800								
3188	424	459	452	479	471	505	498	675	678	714	718	706	722	736	
725	717	413	305	424	305	734	1800								
3258	429	463	457	483	476	508	503	675	678	713	717	707	721	733	
724	715	412	305	421	305	728	1800								
3398	439	472	467	491	486	515	512	675	678	711	716	709	719	728	
722	711	410	305	416	305	717	1800								
3558	449	481	478	499	497	524	521	674	678	711	714	710	716	722	
720	707	408	305	411	305	707	1800								
3559	449	481	478	499	497	524	521	674	677	711	714	710	716	722	
720	707	408	305	411	305	707	1800								
3561	450	482	479	499	497	524	521	674	677	711	714	710	716	722	
720	707	408	305	411	305	707	1800								

3562	450	482	479	499	497	524	521	674	677	711	714	710	716	722
720	707	408	305	411	305	707	1800							
3563	450	482	479	499	497	524	521	674	677	711	714	710	716	722
720	707	408	305	411	305	707	1800							
3564	450	482	479	499	497	524	521	674	677	711	714	710	716	722
720	707	408	305	411	305	707	1800							
3565	450	482	479	499	497	524	522	674	677	711	714	710	716	722
720	707	408	305	411	305	707	1800							
3566	450	482	479	500	497	524	522	673	677	711	714	710	716	722
720	707	408	305	411	305	707	1800							

C Source Code Listing

Following immediately is the main source code for MELTER. Include files
{\tt RADBC.BLK}, {\tt MELT.BLK}, {\tt FOAM.BLK}, {\tt ENCLOSE.BLK},
and {\tt CARGO.BLK} follow.

c	MELTER.FOR	A	1
c		A	2
c	developed by: M. E. Larsen	A	3
c	Transportation Analysis Department 9614	A	4
c	Sandia National Laboratories	A	5
c	(505)844-7275	A	6
c		A	7
c	overview:	A	8
c	This codes estimates the thermal response of SST-shipped cargoes	A	9
c	to a fire environment. The analysis is described in detail in:	A	10
c		A	11
c	Larsen, M. E., "MELTER: A Model of the Thermal Response of	A	12
c	Cargos Transported in the Safe-Secure Trailer Subject to	A	13
c	Fire Environments for Risk Assessment Applications," SAND93-0737	A	14
c		A	15
c	The first ncargo temperatures, temp(1..ncargo) define the	A	16
c	state of the cargo. The last two of those are on cargo exterior.	A	17
c	The enclosure radiation problem involves surfaces A(1) thru A(9)	A	18
c	those areas being:	A	19
c		A	20
c	Radiation Area	A	21
c		A	22
c	Associated State	A	23
c	Variables	A	24
c		A	25
c	A(1): hot side of cargo exterior.....temp(ncargo-1)	A	26
c	A(2): cold side of cargo exterior.....temp(ncargo)	A	27
c	A(3): inert cargo exterior surface.....temp(ncargo+1)	A	28
c	A(4): floor surf not heated from exterior....temp(ncargo+2)	A	29
c	A(5): floor surf heated from exterior.....temp(ncargo+3)	A	30
c	plywood/foam interface.....temp(ncargo+11)	A	31
c	char displacement.....temp(ncargo+10)	A	32
c	exterior skin temperature.....temp(ncargo+9)	A	33
c	A(6): armor not heated from exterior.....temp(ncargo+4)	A	34
c	A(7): armor heated through intact wall.....temp(ncargo+5)	A	35
c	char displacement.....temp(ncargo+8)	A	36
c	exterior skin temperature.....temp(ncargo+7)	A	37
c	A(8): heated armor with foam stripped off....temp(ncargo+6)	A	38
c	A(9): hole in armor.....no temp variable	A	39
c		A	40
c	When modelnumber=1, a melting case, temp(ncargo-1) is temperature	A	41
c	until melting begins, thereafter it is really tmelt +	A	42
c	q"/(rho h Cp) where q" is the integrated heat flux after melting	A	43
c	begins.	A	44
c		A	45
c	the temperature nodes in the "spherized" cargo number up from the	A	46
c	inside with the hot nodes having even numbers and cold the odd	A	47
c	numbers. If nstrip communicated to the code is greater than zero	A	48
c	the outer shell is is dismissed and two corresponding variables	A	
c	are removed from the system.	A	

c		A	49
	external funct	A	50
	character fname*35	A	51
	character*40 bfile,ofile,tfile,afile,sfile,xfile	A	52
	character*24 fdate,starttime,stoptime	A	53
	include 'enclose.blk'	A	54
	include 'radbc.blk'	A	55
	include 'cargo.blk'	A	56
	include 'melt.blk'	A	57
	include 'foam.blk'	A	58
	real terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax,hottemp	A	59
	common /compute/terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax	A	60
	real dtimes,dtemps	A	61
	integer ndtim,ipd,ipdo	A	62
	common /death/dtimes(20),dtemps(20),ndtim	A	63
	integer lleft(2), flags(80)	A	64
	real sstho2,sstw,ssth,sstl	A	65
	common /sstdim/ sstho2,sstw,ssth,sstl	A	66
	real prox(4),adam9(6),adam8(6),ftemp(11),dcdia(10),dcdist(7)	A	67
	real tfd(30),ttl(30), temp(30),dtdt(30)	A	68
	real rtdis(7),rtdia(10),rttem(11),rta(6),rtdam(4)	A	69
	real work(750)	A	70
	real relerr0,abserr0,tpmin,printt,tdur0,carga0,ceps0,dia	A	71
	real dist,dtcritdtl,tmax,tdur,time,thigh,tlow,fireduration	A	72
	real timestep,abserr,relerr,timeold,time2,d2tcritdt,tcrit	A	73
	real tbest,dtboomdt,tav,fuel,tboom	A	74
	integer nndam,i,nadam9,ntemp,ndcdia,ncs0,noutput,ncrit0,icase	A	75
	integer ipre,idam,iadam,itemp,idia,idist,neq,iflag,lode,ll	A	76
	integer ia,ndcdist,iflag0,maxcalls	A	77
	integer ndam(4)	A	78
	integer idiedis(7),idiedia(10),idietem(11),idiea(6),idiedam(4)	A	79
	integer nrdis(7),nrda(10),nrtem(11),nra(6),nrda(4)	A	80
	logical questl, needtlsolution, needfdsolution	A	81
	logical kaboom, timeout, doneheating, stillburning	A	82
	logical boomonce, preempt, passone	A	83
c		A	84
c	set up the data needed for dave's many cases	A	85
	data idiedis,idiedia,idietem,idiea,idiedam/38*0/	A	86
	data nrdis,nrda,nrtem,nra,nrda/38*0/	A	87
	data rtdis,rtdia,rttem,rta,rtdam/38*0.0/	A	88
	data prox,ndam/3*1.0,0.0,3,2,1,0/	A	89
	data adam9/20.0, 5.0, 0.0, 0.0,0.0,0.0/	A	90
	data adam8/40.0,40.0,40.0,20.0,5.0,0.0/	A	91
	data ftemp/3000.0,2600.0,2400.0,2300.0,2200.0,2100.0,2000.0,	A	92
	x1900.0,1800.0,1700.0,1600.0/	A	93
	data dcdia/100.0,50.0,40.0,35.0,30.0,25.0,20.0,15.0,10.0,5.0/	A	94
	data dcdist/-1.0,0.0,5.0,10.0,20.0,40.0,80.0/	A	95
	data tpmin,printt/2*20.0/	A	96
	data relerr0,abserr0/1.0e-4,0.001/	A	97
c	maxcalls is the number of times we'll call ode to get by a	A	98
c	rough spot before punting.	A	99
	data maxcalls/2/	A	100
c	terror is the allowed interval of uncertainty in the	A	101
c	bisection search. It does not make sense for terror to be	A	102

c	less than at least 30 seconds, since it can be costly to close	A 103
c	the uncertainty interval.	A 104
c	The initial temperature of everything is 300K	A 105
c	the maximum time step allowed in the integration	A 106
c		A 107
c	the file fname'.brch' (fname is the first parameter passed	A 108
c	in the command line) defines the branches of the	A 109
c	parameters that will be mixed to create the scenarios	A 110
c	considered. Lengths are in feet and temperatures in F at	A 111
c	this point. Further distance is defined so that zero distance	A 112
c	corresponds to a fire that "nicks" the SST. A negative value	A 113
c	of distance is used to specify a fire centered under the SST.	A 114
c		A 115
	call getarg(1,fname)	A 116
	bfile=fname(: (index(fname,' ')-1))//'.brc'	A 117
	open(unit=7,file=bfile,status='old')	A 118
c	there has to be the same number of proximities and	A 119
c	damage states considered (4 maximum)	A 120
	read(7,*)nndam,(ndam(i),i=1,nndam)	A 121
	read(7,*) (prox(i),i=1,nndam)	A 122
c	there are the same number of adam9 and adam8 values (6 max)	A 123
	read(7,*)nadam9,(adam9(i),i=1,nadam9)	A 124
	read(7,*)(adam8(i),i=1,nadam9)	A 125
c	there may be as many as 10 temperatures	A 126
	read(7,*)ntemp,(ftemp(i),i=1,ntemp)	A 127
c	there may be as many as 10 diameters	A 128
	read(7,*)ndcdia,(dcdia(i),i=1,ndcdia)	A 129
c	there may be as many as 7 distances	A 130
	read(7,*)ndcdist,(dcdist(i),i=1,ndcdist)	A 131
c	tdur0 is zero if the calculation is to yield the minimum critical	A 132
c	duration. Otherwise it is the specified fire duration.	A 133
	read(7,*)tdur0	A 134
	close(7)	A 135
c	get input file name here	A 136
	call getarg(2,fname)	A 137
	xfile=fname(: (index(fname,' ')-1))//'.xxx'	A 138
	tfile=fname(: (index(fname,' ')-1))//'.tar'	A 139
	afile=fname(: (index(fname,' ')-1))//'.mel'	A 140
	ofile=fname(: (index(fname,' ')-1))//'.dat'	A 141
	sfile=fname(: (index(fname,' ')-1))//'.sta'	A 142
	open(unit=4,file=tfile,status='old')	A 143
c	open(unit=4,file='targ.dat',status='old')	A 144
	read(4,*)ncs0,lleft(1),lleft(2),modelnumber,noutput	A 145
	read(4,*)carga0,ceps0,transm,ttrans,a(3),rmcp3	A 146
	read(4,*)tmelt,umelt	A 147
	read(4,*)ncrit0,ndtim	A 148
	do 5 i=1,ndtim	A 149
	read(4,*)dtimes(i),dtemps(i)	A 150
5	continue	A 151
	read(4,*)(ck(i),i=1,ncs0-1)	A 152
	read(4,*)(cr(i),i=1,ncs0-1)	A 153
	read(4,*)(mcp(i),i=1,ncs0)	A 154
	read(4,*)(rcarg(i),i=1,ncs0)	A 155
	close(4)	A 156

open(unit=8,file=afile,status='unknown')	A 157
open(unit=17,file=xfile,status='unknown')	A 158
rewind(8)	A 159
rewind(17)	A 160
icase=0	A 161
ipre=0	A 162
starttime=fdate()	A 163
do 666 idam=1,nndam	A 164
proximity=prox(idam)	A 165
nstrip=ndam(idam)	A 166
do 666 iadam=1,nadam9	A 167
a(8)=adam8(iadam)*0.3048**2	A 168
a(9)=adam9(iadam)*0.3048**2	A 169
do 666 itemp=1,ntemp	A 170
tfire=(ftemp(itemp)+460.0)*5.0/9.0	A 171
do 666 idia=1,ndcdia	A 172
dia=dcdia(idia)*0.3048	A 173
do 666 idist=1,ndcdist	A 174
if (dcdist(idist).lt.0.0)then	A 175
dist=0.0	A 176
else	A 177
dist=(dcdist(idist)+dcdia(idia)/2.0)*0.3048+sstw/2.0	A 178
end if	A 179
dtcritdt1=0.0	A 180
tmax=50000.0	A 181
passone=.true.	A 182
tdur=tdur0	A 183
icase=icase+1	A 184
c print *, icase, idam, iadam, itemp, idia, idist	A 185
nrdis(idist)=nrdis(idist)+1	A 186
nrdis(idia)=nrdis(idia)+1	A 187
nrtem(itemp)=nrtem(itemp)+1	A 188
nra(iadam)=nra(iadam)+1	A 189
nrdam(idam)=nrdam(idam)+1	A 190
if (noutput.gt.0) then	A 191
print *, 'dist', dist, 'dia', dia, 'tfire', tfire, 'a(9)', a(9)	A 192
print *, 'a(8)', a(8), 'nstrip', nstrip, 'proximity', proximity	A 193
print *, 'case ', icase, ' running'	A 194
end if	A 195
c for the present let the floor fire temp = tfire	A 196
c The variables read from buffer1 are:	A 197
c	A 198
c a(8)-a(9): areas of scraped, and removed surface (m ²)	A 199
c dist: separation distance of the fire	A 200
c dia: diameter of the fire	A 201
c tdur: duration of fire (calculated if tdur.le.0)	A 202
c that is, question 2 is imposed if tdur.le.0 else question 1	A 203
c tfire: fire temperature (K)	A 204
c tmax: maximum amount of time allowed for failure (s)	A 205
c modelnumber: selects model options as follows:	A 206
c 0 full onion, no melting	A 207
c 1 full onion, skin melts	A 208
c	A 209
c read(1,*)nstrip,proximity,a(9),a(8),tfire,dia,dist,tdur,tmax	A 210

c		A 211
c	The variables read from target.dat are:	A 212
c		A 213
c	ncs0: number of concentric shells representing cargo when	A 214
c	undamaged	A 215
c	nstrip: number of layers stripped off	A 216
c	noutput: parameter determining how much output program generates	A 217
c	acargo: exterior surface area of target (m ²)	A 218
c	cargoeps: emissivity of target surface	A 219
c	transm: transmissivity of view across SST	A 220
c	ttrans: transmissivity of view from target to hot wall	A 221
c	proximity: (0-1) gives proximity of target to wall, 1 is	A 222
c	next to wall	A 223
c	a(3): surface area of inerts (make arbitrarily large) (m ²)	A 224
c	rmcp3: thermal capacitance of inert cargo (J/K)	A 225
c	ncrit: number of shell to be watched for critical condition	A 226
c	tcritical: critical temperature (K)	A 227
c	ck(i): conduction connector between mcp(i) & mcp(i+1) (W/K)	A 228
c	cr(i): radiation connector between mcp(i) and mcp(i+1) (W/E)	A 229
c	(E being emissive power)	A 230
c	mcp(i): thermal capacitance of ith shell (J/K)	A 231
c	rcarg(i): radii of mcp(i)	A 232
c	tmelt: melting temperature of mcp(ncs0) (K)	A 233
c	umelt: (latent heat of fusion)/Cp (K)	A 234
c		A 235
c	makemod develops the necessary radiation matrix and sets other	A 236
c	constants used in subroutine funct to evaluate the time	A 237
c	rate of change of temperatures	A 238
c		A 239
	tfiref=tfire	A 240
	canmelt=.false.	A 241
c	if there is any stripping going on the outer layer can not	A 242
c	melt even if modelnumber=1	A 243
	if (nstrip.gt.2)then	A 244
	ncs=ncrit0	A 245
	else if (nstrip.gt.0)then	A 246
	ncs=lleft(nstrip)	A 247
	else	A 248
	ncs=ncs0	A 249
	end if	A 250
	canmelt=((modelnumber.eq.1).and.(ncs.eq.ncs0))	A 251
c	ok to melt	A 252
	if (noutput.gt.0) then	A 253
	open(unit=11,file=ofile,status='unknown')	A 254
	rewind(11)	A 255
	end if	A 256
	quest1=(tdur.gt.0.0)	A 257
	call makemod(neq,dist,dia,preempt,noutput,ncs0,ncrit0,ceps0,	A 258
	lcarga0)	A 259
	if (preempt) then	A 260
	kaboom=.false.	A 261
	boomonce=.false.	A 262
	timeout=.true.	A 263
	time=0.0	A 264

temp(ncrit)=tinf	A 265
thigh=0.0	A 266
tlow=0.0	A 267
ipre=ipre+1	A 268
goto 200	A 269
end if	A 270
c write out problem description	A 271
if(noutput.gt.0) then	A 272
write(11,777)starttime	A 273
777 format(' Melter Run at ',a24,///)	A 274
write(11,778)'The total number of state variables is',neq	A 275
write(11,778)'The cargos number of concentric shells',ncs	A 276
write(11,778)'The cargos number of temperatures',ncargo	A 277
write(11,779)'The sunny side of the cargo has area',a(1)	A 278
write(11,779)'The dark side of the cargo has area',a(2)	A 279
write(11,779)'Inerts have area',a(3)	A 280
write(11,779)'Floor area not directly exposed',a(4)	A 281
write(11,779)'Floor area directly exposed',a(5)	A 282
write(11,779)'Wall interior not directly exposed',a(6)	A 283
write(11,779)'Normal wall directly exposed',a(7)	A 284
write(11,779)'Armor with foam removed',a(8)	A 285
write(11,779)'Hole area',a(9)	A 286
write(11,779)'Distance from the fire is',dist	A 287
write(11,779)'The fire diameter (m) is',dia	A 288
write(11,779)'The view of a(7..9) to fire is',f7f	A 289
if (quest1) then	A 290
write(11,779) 'The specified fire duration is',tdur	A 291
else	A 292
write(11,779)'The fire duration will be calculated'	A 293
end if	A 294
write(11,*)' Output is ordered: '	A 295
write(11,*)' time, T(1)...T(ncargo), T(A3)...T(A8), Tskin(A7),	A 296
1xchar(A7), Tskin(A5), xchar(A5)'	A 297
778 format(a40,i12)	A 298
779 format(a40,f12.3)	A 299
780 format(a78)	A 300
end if	A 301
do 20 i=1 , neq	A 302
20 temp(i)=tinf	A 303
c if a(7) >0 then temp(char7id) is char displacement in wall	A 304
if (ahere(7)) temp(char7id)=0.0	A 305
c if a(5) >0 then temp(char5id) is char displacement in floor	A 306
if (ahere(5)) then	A 307
temp(char5id)=0.0	A 308
temp(plyid)=tinf	A 309
end if	A 310
time=0.	A 311
stillburning=.true.	A 312
doneheating=.false.	A 313
kaboom=.false.	A 314
boomonce=.false.	A 315
needtlsolution=.true.	A 316
needfdsolution=.true.	A 317
c set initial interval of uncertainty for minimum fire duration	A 318

	ipdo=-1	A 319
	tlow=0.0	A 320
	thigh=40.0*15000.0*60.0/(3.141592*(dia/0.3048)**2)	A 321
	if (thigh.gt.tmax/1.1)tmax=thigh*1.1	A 322
c	maximum possible fire duration in seconds	A 323
c	starting point for the bisection method loop	A 324
84	continue	A 325
	printt=tlow	A 326
	stillburning=.true.	A 327
	doneheating=.false.	A 328
	kaboom=.false.	A 329
	efire=sigma*tfire**4	A 330
	efiref=sigma*tfiref**4	A 331
	ehole=einf*(1.0-f9f)+f9f*efire	A 332
	if(quest1) then	A 333
	fireduration=tdur	A 334
	else	A 335
c	bisect the region of uncertainty	A 336
	if (passone) then	A 337
	fireduration=thigh	A 338
	else	A 339
	fireduration=(thigh+tlow)/2.0	A 340
	end if	A 341
	end if	A 342
c	starting point for integration (commences at tlow)	A 343
c	always start slow	A 344
	timestep=minstep	A 345
	abserr=abserr0	A 346
	relerr=relerr0	A 347
	iflag=1	A 348
92	continue	A 349
	timeold=time	A 350
	time2=time+timestep	A 351
	if ((time2.gt.tlow).and.(time.lt.tlow)) then	A 352
c	force the end of an integration step to land on	A 353
	time2=tlow	A 354
	iflag0=-1	A 355
	else if ((time2.gt.fireduration).and.(time.lt.fireduration))then	A 356
c	force the end of an integration step to land on fireduration	A 357
c	the exact moment the fire goes out	A 358
	time2=fireduration	A 359
	iflag0=-1	A 360
	else if ((time2.gt.thigh).and.(time.lt.thigh))then	A 361
c	force the end of an integration step to land on thigh	A 362
	time2=thigh	A 363
	iflag0=-1	A 364
	else	A 365
	iflag0=1	A 366
	end if	A 367
	if (time.ge.tlow) then	A 368
	if (needtlsolution) then	A 369
	needtlsolution=.false.	A 370
c	save state at tlow in case that is the point at which we commence	A 371
	do 40 i=1 , neq	A 372

40	t1(i)=temp(i)	A 373
	end if	A 374
	end if	A 375
	if ((needfdsolution).and.(time.ge.fireduration)) then	A 376
	needfdsolution=.false.	A 377
c	save state at the end of fire in case that is where we pick	A 378
c	up on the next bisection iteration	A 379
	do 30 i=1 , neq	A 380
30	tfd(i)=temp(i)	A 381
	end if	A 382
	lode=0	A 383
47	continue	A 384
c		A 385
	if (iflag0.lt.0)then	A 386
	if ((iflag.eq.1).or.(iflag.eq.2))iflag=iflag*iflag0	A 387
	end if	A 388
	lode=lode+1	A 389
	if (noutput.gt.3)then	A 390
	ipd=int(100.0*time/tmax)	A 391
	if (ipd.gt.ipdo) then	A 392
	ipdo=ipd	A 393
	print *,'time is',time,' ',ipd,'per cent of tmax'	A 394
	write(17,*)'ipd = ',ipd	A 395
	end if	A 396
	end if	A 397
	call ode(funcnt,neq,temp,time,time2,relerr,abserr,iflag,work)	A 398
	if(iabs(iflag).gt.2)then	A 399
c	abserr=abserr0	A 400
c	relerr=relerr0	A 401
	flags(lode)=iflag	A 402
	if (iabs(iflag).gt.5)then	A 403
	print *,'iflag=',iflag,' idam,iadam,itemp,idia,idist',	A 404
	lidam,iadam,itemp,idia,idist	A 405
	stop	A 406
	end if	A 407
	if (lode.lt.maxcalls)then	A 408
	goto 47	A 409
	else	A 410
c	write off this case, assume failure, record flags array	A 411
c	and move on	A 412
	write(17,81)(flags(11),11=1,maxcalls),idam,iadam,itemp,idia,idist	A 413
	boomonce=.true.	A 414
c	set thigh and tlow to zero, zero time will be written as	A 415
c	the critical time	A 416
	thigh=0.0	A 417
	tlow=0.0	A 418
	goto 200	A 419
81	format(1x,90i1)	A 420
	end if	A 421
	end if	A 422
c		A 423
	call funcnt(time,temp,dttdt)	A 424
c		A 425
c	estimate the 2nd derivative of the critical temperature	A 426

c		A 427
	d2tcritdt=(dtdt(ncrit)-dtcritdt1)/(time-timeold)	A 428
	dtcritdt1=dtdt(ncrit)	A 429
	tcrit=tboom(time)	A 430
c		A 431
c	new timestep management as of 5/28/93	A 432
c		A 433
c	timestep managed as follows:	A 434
c		A 435
c	while fire is on	A 436
c	timestep=amax1(minstep,terrel*amin1(fireduration,time)/2.0)	A 437
c	after fire is out timestep=maxstep	A 438
c	note that prior to ode call assurances are made to adjust timestep	A 439
c	so that an integration step ends on tlow and/or on fireduration.	A 440
	if (stillburning) then	A 441
	if (time.ge.fireduration) then	A 442
c	extinguish fire	A 443
	ehole=einf	A 444
	efire=einf	A 445
	efiref=einf	A 446
	stillburning=.false.	A 447
	end if	A 448
	timestep=amax1(minstep,terrel*amin1(fireduration,time)/20.0)	A 449
c	the previous line apparently allows huge steps capping timestep	A 450
	if (timestep.gt.maxstep) timestep=maxstep	A 451
	else	A 452
	timestep=maxstep	A 453
	end if	A 454
	timeout=(time.gt.tmax)	A 455
	if (timeout.and.stillburning) goto 200	A 456
	kaboom=(temp(ncrit).gt.tboom(time))	A 457
	boomonce=(kaboom.or.boomonce)	A 458
	if (time.gt.fireduration) then	A 459
c	"doneheating" is true if the fire is out and Tcrit declines	A 460
c	faster than tboom	A 461
	dtboomdt=tboom(time+1.0)-tcrit	A 462
	doneheating=(dtdt(ncrit).lt.dtboomdt)	A 463
c	by this point the 2nd derivative of tcrit should be negative	A 464
c	for the rest of the solution. If it is, and at our current	A 465
c	rate of temperature climb we won't make it to failure, we can	A 466
c	bail out.	A 467
	if((d2tcritdt.lt.0.0).and.(time.gt.3.0*fireduration))then	A 468
	tbest=(tboom(tmax)-temp(ncrit))/dtdt(ncrit)	A 469
	doneheating=(tbest.gt.(tmax-time))	A 470
	end if	A 471
c		A 472
c	at this point the fire is out. if no temperature in the system	A 473
c	exceeds tboom(tmax) there is no possibility of making it	A 474
c	to failure	A 475
	hottemp=0.0	A 476
	do 71 i=1,neg	A 477
	hottemp=amax1(temp(i),hottemp)	A 478
71	continue	A 479
	if(hottemp.lt.tboom(tmax))doneheating=.true.	A 480

	end if	A 481
	if ((noutput.gt.1).or.((noutput.gt.0).and.quest1))then	A 482
	if (time.gt.printt) then	A 483
	printt=printt+tpmin	A 484
	write(11,77)int(time),int(fireduration),(int(temp(i)),i=1,neq)	A 485
c	if(ipd.gt.700)write(11,72)(dtdt(i)),i=1,neq)	A 486
	end if	A 487
	end if	A 488
	72 format(x,25e7.1)	A 489
	77 format(i6,i7,25i5)	A 490
	if (.not.(timeout.or.kaboom.or.doneheating)) goto 92	A 491
	if (quest1) goto 200	A 492
	if (timeout.or.doneheating) then	A 493
c	the fire was either too short to realize a kaboom or too	A 494
c	short to do so within tmax time	A 495
	if (passone) goto 200	A 496
	tlow=fireduration	A 497
c	we'll probably loop back, but we can start where the fire	A 498
c	went out	A 499
	do 50 i=1 , neq	A 500
	50 temp(i)=tfd(i)	A 501
	end if	A 502
	if (kaboom) then	A 503
c	since it failed, fireduration was long enough	A 504
	thigh=fireduration	A 505
c	if we are here because we failed before the fire was out, we	A 506
c	can safely limit the interval to the current time	A 507
	if (fireduration.gt.time) thigh=time	A 508
c	we'll probably loop back, but we can start at the left	A 509
c	edge of our interval of uncertainty	A 510
	do 60 i=1 , neq	A 511
	60 temp(i)=ttl(i)	A 512
	end if	A 513
	time=tlow	A 514
c	wake up the sentinels responsible for saving solutions	A 515
	needt1solution=.true.	A 516
	needfdsolution=.true.	A 517
	if (noutput.gt.0) then	A 518
	write(11,77)int(time),(int(temp(i)),i=1,neq)	A 519
	print *, int(time),(int(temp(i)),i=1,neq)	A 520
	end if	A 521
	if (noutput.gt.0) print *, 'tlow and thigh are ', tlow, thigh	A 522
	passone=.false.	A 523
	if ((thigh-tlow).gt.	A 524
	lamin1(terrel*amin1(fireduration,time),terrmax)) goto 84	A 525
	200 continue	A 526
	if(quest1) then	A 527
	if (kaboom) then	A 528
c	if question 1 is posed and it fails, '1.0' is written	A 529
	write(8,*)'1.0 ',time,tdur	A 530
	else	A 531
c	if question 1 is posed and it survives, '2.0' is written	A 532
	write(8,*)'2.0 ',time,temp(ncrit)	A 533
	end if	A 534

	else	A 535
c	question 2 has been asked	A 536
	if (.not.boomonce) then	A 537
c	if question 2 is posed and no failure is found within tmax, '2.0'	A 538
c	write(8,*)'2.0 ',tmax,temp(ncrit)	A 539
	write(8,79)idam,iadam,itemp,idia,idist	A 540
79	format(1x,'1.0e7 1.0e7',5i3)	A 541
	if(lode.gt.1) then	A 542
	write(17,82) lode,relerr,abserr,idam,iadam,itemp,idia,idist	A 543
	end if	A 544
	else	A 545
c	if question 2 is posed and failure is found within tmax, '1.0'	A 546
c	thigh and tlow bound the minimum fire duration leading to failure	A 547
c	write(8,*)'1.0 ',thigh,tlow	A 548
	tav=(thigh+tlow)/2.0	A 549
c	compute the critical quantity of fuel corresponding to tav	A 550
	fuel=tav/(40.0*60.0/(3.141592*(dia/0.3048)**2))	A 551
	write(8,78)tav,fuel,idam,iadam,itemp,idia,idist	A 552
78	format(1x,2f10.1,5i3)	A 553
	if(lode.gt.1) then	A 554
	write(17,82) lode,relerr,abserr,idam,iadam,itemp,idia,idist	A 555
	end if	A 556
82	format(1x,i2,2e12.4,5i3)	A 557
	idiedis(idist)=idiedis(idist)+1	A 558
	idiedia(idia)=idiedia(idia)+1	A 559
	idietem(itemp)=idietem(itemp)+1	A 560
	idiea(iadam)=idiea(iadam)+1	A 561
	idiedam(idam)=idiedam(idam)+1	A 562
	rtdis(idist)=rtdis(idist)+tav	A 563
	rt dia(idia)=rt dia(idia)+tav	A 564
	rttem(itemp)=rttem(itemp)+tav	A 565
	rta(iadam)=rta(iadam)+tav	A 566
	rt dam(idam)=rt dam(idam)+tav	A 567
	end if	A 568
	end if	A 569
	if (noutput.gt.0) close(11)	A 570
	call flush(8)	A 571
	call flush(17)	A 572
666	continue	A 573
	stoptime=fdate()	A 574
c	write(8,*)' this run begun at ', starttime,' ended ',stoptime	A 575
	write(17,*)' this run begun at ', starttime,' ended ',stoptime	A 576
	close(8)	A 577
	close(17)	A 578
	open(unit=8,file=sfile,status='unknown')	A 579
	rewind(8)	A 580
	write(8,*)' this run begun at ', starttime,' ended ',stoptime	A 581
	write(8,*)'dist deaths',(idiedis(idist),idist=1,ndcdist)	A 582
	write(8,*)'dist trials',(nrdis(idist),idist=1,ndcdist)	A 583
	write(8,*)'dist av tim',((rtdis(idist)/nrdis(idist)),	A 584
	ldist=1,ndcdist)	A 585
	write(8,*)'dia deaths',(idiedia(idia),idia=1,ndcdia)	A 586
	write(8,*)'dia trials',(nr dia(idia),idia=1,ndcdia)	A 587
	write(8,*)'dia av tim',((rt dia(idia)/nr dia(idia)),idia=1,ndcdia)	A 588

	write(8,*)'temp deaths',(idietem(itemp),itemp=1,ntemp)	A 589
	write(8,*)'temp trials',(nrtem(itemp),itemp=1,ntemp)	A 590
	write(8,*)'temp av tim',((rttem(itemp)/nrtem(itemp)),	A 591
	litemp=1,ntemp)	A 592
	write(8,*)'a deaths ',(idiea(ia),ia=1,nadam9)	A 593
	write(8,*)'a trials ',(nra(ia),ia=1,nadam9)	A 594
	write(8,*)'a av tim ',((rta(ia)/nra(ia)),ia=1,nadam9)	A 595
	write(8,*)'dam deaths',(idiedam(idam),idam=1,nndam)	A 596
	write(8,*)'dam trials',(nrdam(idam),idam=1,nndam)	A 597
	write(8,*)'dam av tim',((rtdam(idam)/nrdam(idam)),idam=1,nndam)	A 598
	write(8,*)ipre,' cases of ',icase,' cases were preempted'	A 599
	close(8)	A 600
	close(17)	A 601
	stop	A 602
	end	A 603
c		B 1
c		B 2
	real function tboom(time)	B 3
	real dtimes,dtemps,time	B 4
	integer ndtim,i	B 5
	common /death/dtimes(20),dtemps(20),ndtim	B 6
	do 10 i=2,ndtim	B 7
	if(time.lt.dtimes(i))then	B 8
	tboom=dtemps(i-1)+(time-dtimes(i-1))/(dtimes(i)-dtimes(i-1))*	B 9
	1(dtemps(i)-dtemps(i-1))	B 10
	return	B 11
c	we've looked far enough	B 12
	end if	B 13
10	continue	B 14
c	must be past right end of data	B 15
	tboom=dtemps(ndtim)	B 16
	return	B 17
	end	B 18
	subroutine makemod(neq,dist,dfire,preempt,noutput,ncs0,ncrit0,	C 1
	lceps0,carga0)	C 2
	include 'enclose.blk'	C 3
	include 'radbc.blk'	C 4
	include 'cargo.blk'	C 5
	include 'melt.blk'	C 6
	include 'foam.blk'	C 7
	real sstho2,sstw,ssth,sstl	C 8
	common /sstdim/ sstho2,sstw,ssth,sstl	C 9
	real terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax	C 10
	common /compute/terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax	C 11
	real x1(9),x2(9),dist,dfire,ahot,ainterior,carga0,ceps0	C 12
	real ss(9,9),f(9,9),astar	C 13
	integer imap(9),i,ncs0,ncrit0,j,k,noutput,neq	C 14
	logical preempt, inverterror	C 15
	efire=sigma*tfire**4	C 16
	einf=sigma*tfinf**4	C 17
	ereactw=sigma*treactw**4	C 18
	ereactf=sigma*treactf**4	C 19
	emelt=sigma*tmelt**4	C 20
	tmelted=tmelt+umelt	C 21

	melting=.false.	C	22
	melted=.false.	C	23
	cool=.true.	C	24
	call bc(dist,dfire,treactw,a(5),a(7))	C	25
	f5f=1.0	C	26
	f8f=f7f	C	27
	f9f=f7f	C	28
c	a(9) and a(8) snitch from a(7) in that order	C	29
	if (a(9).gt.0.0) a(7)=amax1(0.0,a(7)-a(9))	C	30
	if (a(8).gt.0.0) a(7)=amax1(0.0,a(7)-a(8))	C	31
c	a(7) may have vanished, re-assert flag	C	32
c	add up the area that is heated	C	33
	a(4)=sst1*sstw-a(5)	C	34
	a(6)=sst1*sstw+ssth*2.0*(sstw+sst1)-a(7)-a(8)-a(9)	C	35
	ahot=a(5)	C	36
	do 10 i=7, 9	C	37
	ahot=ahot + a(i)	C	38
10	continue	C	39
	ainterior=0.0	C	40
	do 20 i=4 , 9	C	41
	ainterior=ainterior + a(i)	C	42
20	continue	C	43
	acargo=carga0	C	44
	cargoeps=ceps0	C	45
c	write(2,*)' acargo ',acargo,' ainterior ',ainterior, 'ahot ',ahot	C	46
	split=ahot/ainterior	C	47
	arat=(rcarg(ncs-1)/rcarg(ncs))**2	C	48
	if (ncs.lt.ncs0)then	C	49
	acargo=carga0*(rcarg(ncs)/rcarg(ncs0))**2	C	50
	cargoeps=1.0	C	51
c	the exterior of what is left is radiatively black if	C	52
c	stripping happened.	C	53
	end if	C	54
	if (ncrit0.gt.1) then	C	55
	ncrit=2*(ncrit0-1)	C	56
	else	C	57
	ncrit=ncrit0	C	58
	end if	C	59
	ncargo=2*ncs-1	C	60
	a(1)=split*acargo	C	61
c	write(2,*)'a(1) just after it was set ',a(1)	C	62
	a(2)=acargo-a(1)	C	63
	preempt=(ahot.le.0.0)	C	64
	if (preempt)return	C	65
	do 30 i=1, 9	C	66
	ahere(i)=(a(i).gt.0.0)	C	67
30	continue	C	68
c	astar is the largest a surface on the sst's interior can be	C	69
c	with a zero self view factor	C	70
	astar=ssth*sst1	C	71
	rch(3)=rmcp3/a(3)	C	72
c	write(2,*)'rmcp3, a(3), rch(3)',rmcp3,a(3),rch(3)	C	73
	eps(1)=cargoeps	C	74
	eps(2)=cargoeps	C	75

c	write(2,*)'just before call getvs'	C	76
	call getvs(a,astar,ss)	C	77
c	write(2,*) ' just after call getvs'	C	78
c	write(2,*) ss	C	79
	nsurfrad=0	C	80
	do 40 i=1, 9	C	81
	do 40 j=1, 9	C	82
	f(i,j)=0.0	C	83
40	continue	C	84
	do 50 i=1 , 9	C	85
	if (ahere(i)) then	C	86
	nsurfrad=nsurfrad+1	C	87
	arad(nsurfrad)=a(i)	C	88
	epsrad(nsurfrad)=eps(i)	C	89
	imap(nsurfrad)=i	C	90
	end if	C	91
50	continue	C	92
	do 60 i=1 , nsurfrad	C	93
	do 60 j=1 , nsurfrad	C	94
60	f(i,j)=ss(imap(i),imap(j))	C	95
	do 70 i=1 , nsurfrad	C	96
	do 70 j=1 , nsurfrad	C	97
70	f(i,j)=f(i,j)/arad(i)	C	98
	do 80 i=1 , nsurfrad	C	99
	do 80 j=1 , nsurfrad	C	100
	if (epsrad(i).lt.1.0) then	C	101
	if (j.eq.i) then	C	102
	ss(i,j)=1.0/(1.0-epsrad(i))-f(i,j)	C	103
	else	C	104
	ss(i,j)=-f(i,j)	C	105
	end if	C	106
	else	C	107
	if (j.eq.i) then	C	108
	ss(i,j)=1.0	C	109
	else	C	110
	ss(i,j)=0.0	C	111
	end if	C	112
	end if	C	113
80	continue	C	114
	call gaussj(ss,x1,x2,nsurfrad,inverterror)	C	115
	if (inverterror) print *,'hold everything, problems inverting '	C	116
c	write(2,*)' ss after call to gauss'	C	117
	do 91 i=1,nsurfrad	C	118
c	write(2,*) (ss(i,j),j=1,nsurfrad)	C	119
91	continue	C	120
	f (noutput.gt.0)then	C	121
	write(11,*)'The view factors used in the enclosure analysis'	C	122
	do 200 i=1,nsurfrad	C	123
	write(11,77)(f(i,j),j=1,nsurfrad)	C	124
200	continue	C	125
	write(11,*)' The surface emissivities are: '	C	126
	write(11,77)(epsrad(j),j=1,nsurfrad)	C	127
	end if	C	128
77	format(1x,8f9.4)	C	129

do 100 i=1 , nsurfrad	C 130
100 f(i,i)=f(i,i)-1.0	C 131
do 110 i=1 , nsurfrad	C 132
do 110 j=1 , nsurfrad	C 133
hh(i,j)=0.0	C 134
do 130 k=1 , nsurfrad	C 135
130 hh(i,j)=hh(i,j)+f(i,k)*ss(k,j)	C 136
110 continue	C 137
j=0	C 138
c establish indices between integrated variable and numbered	C 139
c surfaces and between radiation enclosure model and numbered	C 140
c surfaces. the array aid holds the equation number corresponding	C 141
c to any numbered surface. the array qid holds the radiation	C 142
c enclosure surface id corresponding to any such surface. isurf	C 143
c holds the equation number corresponding to a radiation enclosure	C 144
c surface.	C 145
c	C 146
c aid(i) is the statevariable number of surface i, i being 1-9	C 147
c invariant qid(i) is the radiation enclosure surface number of	C 148
c invariant i 1-9 isurf(j) is the state variable belonging to	C 149
c enclosure anal. surf j	C 150
c	C 151
do 140 i=1 , 9	C 152
if (ahere(i)) then	C 153
j=j+1	C 154
aid(i)=j+ncargo-2	C 155
qid(i)=j	C 156
isurf(j)=aid(i)	C 157
end if	C 158
140 continue	C 159
c at this point j is the number of surfaces on the radiation	C 160
c enclosure	C 161
if (ahere(9)) j=j-1	C 162
c surface 9 does not generate a state variable	C 163
j=j+ncargo-2	C 164
c now j is the number of state variables, not counting wall models	C 165
if (ahere(7)) then	C 166
skin7id=j+1	C 167
char7id=skin7id+1	C 168
j=j+2	C 169
end if	C 170
if (ahere(5)) then	C 171
skin5id=j+1	C 172
char5id=skin5id+1	C 173
plyid=char5id+1	C 174
j=j+3	C 175
end if	C 176
neq=j	C 177
end	C 178
subroutine funct(time,temp,dttd)	D 1
include 'enclose.blk'	D 2
include 'radbc.blk'	D 3
include 'cargo.blk'	D 4
include 'melt.blk'	D 5

	include 'foam.blk'	D	6
	real terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax	D	7
	common /compute/terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax	D	8
	real temp(30),dtdt(30)	D	9
	real edp(30),q(9),b(9),erad(9),qshellh(10),qshellc(10)	D	10
	real tsmear,eskin,qfire,qgrad,qply,ePLY,qwall,time	D	11
	integer i,j	D	12
	data tsmear/100.0/	D	13
c	determine the state of the target case.	D	14
	if (cannmelt) then	D	15
c	if the case can melt we need to determine its state	D	16
	if (temp(ncargo-1).lt.tmelt)then	D	17
	cool=.true.	D	18
	melting=.false.	D	19
	melted=.false.	D	20
	else if (temp(ncargo-1).lt.tmelted) then	D	21
	melting=.true.	D	22
	melted=.false.	D	23
	cool=.false.	D	24
	else	D	25
	melted=.true.	D	26
	melting=.false.	D	27
	cool=.false.	D	28
	end if	D	29
	end if	D	30
	do 150 i=2 , nsurfrad-1	D	31
150	erad(i)=sigma*temp(isurf(i))**4	D	32
	if (cool) then	D	33
	erad(1)=sigma*temp(isurf(1))**4	D	34
	else if (melting) then	D	35
	erad(1)=emelt	D	36
	else	D	37
	erad(1)=sigma*temp(Ncargo-3)**4	D	38
	end if	D	39
	if (ahere(9)) then	D	40
	erad(nsurfrad)=ehole	D	41
	else	D	42
	erad(nsurfrad)=sigma*temp(isurf(nsurfrad))**4	D	43
	end if	D	44
	do 160 i=1 , ncargo	D	45
160	edp(i)=sigma*temp(i)**4	D	46
	if (melting) edp(ncargo-1)=emelt	D	47
c	write(2,*)'edp ',edp	D	48
c	the following 2 statements limit this routine to ncs.ge.2	D	49
	qshellh(1)=split*(ck(1)*(temp(2)-temp(1))+	D	50
	1cr(1)*(edp(2)-edp(1)))	D	51
	qshellc(1)=(1.0-split)*(ck(1)*(temp(3)-temp(1))+	D	52
	1cr(1)*(edp(3)-edp(1)))	D	53
c	the following if statement added 4/2/0/93	D	54
	if(ncs.gt.2)then	D	55
	do 164 i=2,ncs-2	D	56
	qshellh(i)=split*(ck(i)*(temp(2*i)-temp(2*(i-1)))	D	57
	1+cr(i)*(edp(2*i)-edp(2*(i-1))))	D	58
	qshellc(i)=(1.0-split)*(ck(i)*(temp(2*i+1)-	D	59

	1temp(2*i-1))+cr(i)*(edp(2*i+1)-edp(2*i-1)))	D 60
164	continue	D 61
	i=ncs-1	D 62
	if ((.not.canmelt).or.cool) then	D 63
	qshellh(i)=split*(ck(i)*(temp(2*i)-temp(2*(i-1))))	D 64
	1+cr(i)*(edp(2*i)-edp(2*(i-1))))	D 65
	else if(melting) then	D 66
	qshellh(i)=split*(ck(i)*(tmelt-temp(2*(i-1))))	D 67
	1+cr(i)*(edp(2*i)-edp(2*(i-1))))	D 68
	else	D 69
	qshellh(i)=0.0	D 70
	end if	D 71
	qshellc(i)=(1.0-split)*(ck(i)*(temp(2*i+1)-	D 72
	1temp(2*i-1))+cr(i)*(edp(2*i+1)-edp(2*i-1)))	D 73
	end if	D 74
	do 170 i=1 , nsurfrad	D 75
	if (epsrad(i).lt.1.0) then	D 76
	b(i)=epsrad(i)*erad(i)/(1.0-epsrad(i))	D 77
	else	D 78
	b(i)=erad(i)	D 79
	end if	D 80
170	continue	D 81
	do 180 j=1 , nsurfrad	D 82
	q(j)=0.0	D 83
	do 190 i=1 , nsurfrad	D 84
190	q(j)=q(j)+hh(j,i)*b(i)	D 85
180	continue	D 86
c	the following executable line limits this routine to ncs.ge.2	D 87
	dttd(1)=(qshellh(1)+qshellc(1))/mcp(1)	D 88
	if (ncs.gt.3) then	D 89
c	if ncs greater than 3 these nodes are set in this manner	J 90
c	whether or not the exterior is melted	D 91
	do 182 i=1,ncs-3	D 92
	dttd(i*2)=(qshellh(i+1)-qshellh(i))/mcp(i+1)/split	D 93
	dttd(i*2+1)=(qshellc(i+1)-qshellc(i))/mcp(i+1)/(1.0-split)	D 94
182	continue	D 95
	end if	D 96
c	the derivative of the backside node:	D 97
	dttd(ncargo)=(arad(2)*q(2)-qshellc(ncs-1))/mcp(ncs)/(1.0-split)	D 98
c	if ncs>2 the derivative one layer back is (otherwise dttd(1)):	D 99
	if (ncs.gt.2) dttd(ncargo-2)=(qshellc(ncs-1)-qshellc(ncs-2))/	D 100
	1mcp(ncs-1)/(1.0-split)	D 101
	i=ncs-2	D 102
	if ((.not.canmelt).or.(.not.melted)) then	D 103
	if(i.gt.0)dttd(i*2)=(qshellh(i+1)-qshellh(i))/mcp(i+1)/split	D 104
	dttd(ncargo-1)=(arad(1)*q(1)-qshellh(ncs-1))/mcp(ncs)/split	D 105
	else	D 106
c	this block should not be a problem with i=0 because no melting	D 107
c	model should have ncs<3	D 108
	dttd(ncargo-1)=0.0	D 109
	dttd(i*2)=(arad(1)*q(1)*arat-qshellh(i))/mcp(i+1)/split	D 110
	end if	D 111
c	the following do loop finds the contribution from enclosure	D 112
c	radiation heat transfer. each contribution from the exterior	D 113

c	will be added later.	D 114
	if (ahere(3)) dtdt(aid(3))=q(qid(3))/rch(3)	D 115
	if (ahere(4)) dtdt(aid(4))=q(qid(4))/rch(4)	D 116
	if (ahere(6)) dtdt(aid(6))=q(qid(6))/rch(6)	D 117
	if (ahere(5)) then	D 118
c	modified to include plywood for christmas	D 119
c	this is the heated part of the floor	D 120
	eskin=sigma*temp(skin5id)**4	D 121
c	write(2,*)'skin5id is 'skin5id	D 122
	qfire=epso5*(f5f*efiref+(1.0-f5f)*einf-eskin)	D 123
	if (temp(char5id).lt.1floor) then	D 124
	if (temp(skin5id).gt.treactf) then	D 125
	grad=(eskin-ereactf)/(1.0+aaafloor*0.75*temp(char5id))	D 126
	else	D 127
	grad=0.0	D 128
	end if	D 129
	dtdt(char5id)=grad/heatreqf	D 130
	qpily=(treactf-temp(plyid))/(1floor-temp(char5id))	D 131
1*kvirg	qpily=amin1(qpily,grad)	D 132
	else	D 133
	dtdt(char5id)=0.0	D 134
	epily=sigma*temp(plyid)**4	D 135
	qpily=(eskin-epily)/(1.0+aaafloor*0.75*1floor)	D 136
	grad=qpily	D 137
	end if	D 138
	qwall=(temp(plyid)-temp(aid(5)))/reply	D 139
	dtdt(aid(5))=(qwall+q(qid(5)))/rch(5)	D 140
	dtdt(skin5id)=(qfire-grad)/rchskinf	D 141
	dtdt(plyid)=(qpily-qwall)/rchply	D 142
	end if	D 143
	if (ahere(7)) then	D 144
	eskin=sigma*temp(skin7id)**4	D 145
c	write(2,*)'skin7id is 'skin7id	D 146
	qfire=epso7*(f7f*efire+(1.0-f7f)*einf-eskin)	D 147
	if (temp(char7id).lt.1wall) then	D 148
	if (temp(skin7id).gt.treactw) then	D 149
	grad=(eskin-ereactw)/(1.0+aaawall*0.75*temp(char7id))	D 150
	else	D 151
	grad=0.0	D 152
	end if	D 153
	dtdt(char7id)=grad/heatreqw	D 154
	qwall=(treactw-temp(aid(7)))/(1wall-temp(char7id))*kvirg	D 155
	qwall=amin1(qwall,grad)	D 156
	else	D 157
	dtdt(char7id)=0.0	D 158
	qwall=(eskin-erad(qid(7)))/(1.0+aaawall*0.75*1wall)	D 159
	grad=qwall	D 160
	end if	D 161
	dtdt(aid(7))=(qwall+q(qid(7)))/rch(7)	D 162
	dtdt(skin7id)=(qfire-grad)/rchskinw	D 163
	end if	D 164
	if (ahere(8)) then	D 165
	qfire=epso8*(f8f*efire+(1.0-f8f)*einf-erad(qid(8)))	D 166
		D 167

dtdt(aid(8))=(qfire+q(qid(8)))/rch(8)	D 168
end if	D 169
return	D 170
end	D 171
subroutine getvs(a,astar,f)	E 1
c this procedure calculates all the needed view factors. it starts	E 2
c by solving a full 9 by 9 matrix of views. then for cases not	E 3
c involving some of the model areas, rows and columns will be	E 4
c eliminated.	E 5
c	E 6
include 'radbc.blk'	E 7
include 'cargo.blk'	E 8
include 'melt.blk'	E 9
real a(9),f(9,9),ax(9),tsum(9),astar,seered	E 10
integer i,j	E 11
do 10 i=1 , 9	E 12
do 10 j=1 , 9	E 13
10 f(i,j)=0.0	E 14
do 20 i=1 ,6	E 15
20 ax(i)=a(i+3)	E 16
c	E 17
c get6v estimates viewfactors between the surfaces that make	E 18
c up the interior wall area of the SST. The view factors that	E 19
c will be returned in f are not yet attenuated by "transm"	E 20
c	E 21
call get6v(ax,astar,f)	E 22
c unattenuated views between enclosure walls are now in the upper	E 23
c left corner of the f-matrix. move to lower right corner.	E 24
do 30 i=9,4,-1	E 25
do 30 j=9,4,-1	E 26
30 f(i,j)=f(i-3,j-3)	E 27
c a(1) and (2) can't see themselves or each other	E 28
do 40 i=1 ,2	E 29
do 40 j=1 , 2	E 30
40 f(i,j)=0.0	E 31
c	E 32
do 50 i=4, 6	E 33
50 f(1,i)=0.0	E 34
f(1,9)=seered(9)	E 35
f(1,8)=amin1(ttrans*(a(1)-f(1,9)),seered(8))	E 36
f(1,7)=amin1(ttrans*(a(1)-f(1,9)-f(1,8)),seered(7))	E 37
f(1,5)=amin1(ttrans*(a(1)-f(1,9)-f(1,8)-f(1,7)),seered(5))	E 38
do 60 i=7, 9	E 39
60 f(2,i)=0.0	E 40
f(2,5)=0.0	E 41
f(2,4)=transm*a(2)*a(4)/(a(4)+a(6))	E 42
f(2,6)=transm*a(2)*a(6)/(a(4)+a(6))	E 43
c at this point all the viewfactors except those involving a(3), the	E 44
c distributed area, exist. one additional problem is that the	E 45
c interchange between enclosure areas no longer conserves energy	E 46
c because viewing area has been added to the low number surfaces.	E 47
c the strategy will be to "snitch" area from the lower right 5x5	E 48
c matrix to account for the attenuation. some of this will be	E 49
c relegated to interchange between a(1..2) and a(4..9). the rest	E 50

c	will be sucked up by the term f(i,3).	E	51
	do 70 i= 4, 9	E	52
	do 80 j= 4, 9	E	53
c	write(2,*)'i ',i,' j ',j,' f(i,j) ',f(i,j), ' transm ',transm	E	54
80	f(i,j)=f(i,j)*transm	E	55
	do 81 j= 1 , 2	E	56
81	f(i,j)=f(j,i)	E	57
70	continue	E	58
	do 90 j=1, 2	E	59
	f(j,3)=a(j)	E	60
	do 100 i=1, 9	E	61
	if (i.ne.3) f(j,3)=f(j,3)-f(j,i)	E	62
100	continue	E	63
90	continue	E	64
c	restore reciprocity	E	65
	do 110 i=1, 3	E	66
	do 110 j=3, 9	E	67
110	f(j,i)=f(i,j)	E	68
	do 120 j=4, 9	E	69
	f(j,3)=a(j)	E	70
	do 120 i=1, 9	E	71
	if (i.ne.3) f(j,3)=f(j,3)-f(j,i)	E	72
120	continue	E	73
	do 140 j=4 , 9	E	74
140	f(3,j)=f(j,3)	E	75
	f(3,3)=a(3)	E	76
	do 150 i=1 , 9	E	77
	if (i.ne.3) f(3,3)=f(3,3)-f(3,i)	E	78
150	continue	E	79
c	at this writing, 8/14/91, this routine seems to work acceptably	E	80
c	for all reasonable inputs. two defects that are probably not	E	81
c	worth eliminating are recognized. first, viewing area connecting	E	82
c	a[1] and a[2] to surfaces of the sst interior a[4..8) are snitched	E	83
c	from the views of a[3) to these surfaces.	E	84
c	if the "transmittance=1.0" then the views between a[3) and these	E	85
c	surfaces are zero so that this snitching results in f[i,3)	E	86
c	(i in 4..8) being negative since f[i,3) is calculated	E	87
c	from conservation.	E	88
	do 121 i=1,9	E	89
	tsum(i)=0.0	E	90
	do 122 j=1,9	E	91
	tsum(i)=tsum(i)+f(i,j)	E	92
122	continue	E	93
121	continue	E	94
	return	E	95
	end	E	96
	subroutine swap(a, b)	F	1
	real a,b,hold	F	2
	hold = a	F	3
	a = b	F	4
	b = hold	F	5
	return	F	6
	end	F	7
	subroutine gaussj(b,y,coef,ncol,ierr)	G	1

real w(9,9), coef(9), b(9,9), y(9)	G	2
real determ,big,pivot,t	G	3
integer index(9,3)	G	4
integer nv,n,ncol,i,j,k,irow,icol,1,11	G	5
logical ierr	G	6
ierr = .false.	G	7
nv = 1	G	8
c * single constant vec,xxr *)	G	9
n = ncol	G	10
do 10 i=1,n	G	11
w(i, 1) = y(i)	G	12
c (* copy constant vec,xxr *)	G	13
index(i, 3) = 0	G	14
10 continue	G	15
determ = 1.0	G	16
do 20 i=1,n	G	17
c (* search dox largest element *)	G	18
big = 0.0	G	19
do 30 j = 1,n	G	20
if (index(j, 3).ne.1) then	G	21
do 40 k = 1,n	G	22
if (index(k, 3).gt.1) then	G	23
print*, ' error: matrix singular'	G	24
ierr = .true.	G	25
goto 98	G	26
c (* abort *)	G	27
end if	G	28
if (index(k, 3).lt.1) then	G	29
if (abs(b(j, k)).gt.big) then	G	30
irow = j	G	31
icol = k	G	32
big = abs(b(j, k))	G	33
end if	G	34
end if	G	35
40 continue	G	36
end if	G	37
30 continue	G	38
index(icol, 3) = index(icol, 3) + 1	G	39
index(i, 1) = irow	G	40
index(i, 2) = icol	G	41
c (* interchange rows ,xx put pivot on diagonal *)	G	42
if (irow.ne.icol) then	G	43
determ = - determ	G	44
do 41 l = 1, n	G	45
41 call swap(b(irow, l), b(icol, l))	G	46
if (nv.gt.0) then	G	47
do 42 l = 1, nv	G	48
42 call swap(w(irow, l), w(icol, l))	G	49
end if	G	50
end if	G	51
c (* if irow <> icol *)	G	52
c (* divide pivot row by pivot column *)	G	53
pivot = b(icol, icol)	G	54
determ = determ * pivot	G	55

b(icol, icol) = 1.0	G	56
do 43 l = 1, n	G	57
43 b(icol, l) = b(icol, l) / pivot	G	58
if (nv.gt.0) then	G	59
do 44 l = 1, nv	G	60
44 w(icol, l) = w(icol, l) / pivot	G	61
end if	G	62
c (* reduce nonpivot rows *)	G	63
do 50 l1 = 1, n	G	64
if (l1.ne.icol) then	G	65
t = b(l1, icol)	G	66
b(l1, icol) = 0.0	G	67
do 51 l=1,n	G	68
51 b(l1, l) = b(l1, l) - b(icol, l) * t	G	69
if (nv.gt.0) then	G	70
do 52 l = 1, nv	G	71
52 w(l1, l) = w(l1, l) - w(icol, l) * t	G	72
end if	G	73
end if	G	74
c (* if l1 <> icol *)	G	75
50 continue	G	76
20 continue	G	77
98 continue	G	78
if (ierr) goto 99	G	79
c (* interchange columns *)	G	80
do 60 i = 1, n	G	81
l = n - i + 1	G	82
if (index(l, 1).ne.index(l, 2)) then	G	83
irow = index(l, 1)	G	84
icol = index(l, 2)	G	85
do 61 k=1,n	G	86
61 call swap(b(k, irow), b(k, icol))	G	87
end if	G	88
60 continue	G	89
do 70 k = 1, n	G	90
if (index(k, 3).ne.1) then	G	91
print*, ' error: matrix singular'	G	92
ierr = .true.	G	93
goto 99	G	94
c (* abort *)	G	95
end if	G	96
70 continue	G	97
do 80 i = 1, n	G	98
80 coef(i) = w(i, 1)	G	99
99 continue	G	100
return	G	101
end	G	102
c(* subroutine gaussj *)	H	1
subroutine get6v(ax,astar,ssx)	H	2
c this procedure estimates viewareas between six surfaces forming	H	3
c an enclosure. all that is known going in are the six surface	H	4
c areas and astar. astar is the largest value an area can have w/o	H	5
c beginning to see itself. the resulting estimates obey reciprocity	H	6
c and conservation requirements. a key to always returning	H	7

c	plausible viewareas is that the area array is sorted and the	H	8
c	smallest areas are treated first. Also, f(5,6)=f(6,5)=0.0.	H	9
	real ss(9,9), ssx(9,9), ax(9), axx(9)	H	10
	real awhole, seeme, astar, seeyou, sssum	H	11
	integer iloc(9), i, j	H	12
	do 10 i=1, 6	H	13
c	write(2,*)'in loop ', i	H	14
	iloc(i)=i	H	15
	axx(i)=ax(i)	H	16
10	continue	H	17
c	write(2,*)'just before call sorta'	H	18
	call sorta(iloc, axx, 6)	H	19
c	write(2,*)' just after call sorta'	H	20
	awhole=0.0	H	21
	do 20 i=1, 6	H	22
20	awhole=awhole+axx(i)	H	23
	do 30 i=1, 6	H	24
	do 40 j=i, 5	H	25
	if (i.eq.j) then	H	26
	ss(i,j)=seeme(axx(i), astar, awhole)	H	27
	else	H	28
	ss(i,j)=seeyou(axx(i), astar, axx(j), awhole)	H	29
c	surfaces 4 and 5 are both floor, they can't see each other	H	30
	if((iloc(i)+iloc(j)).eq.3) ss(i,j)=0.0	H	31
	end if	H	32
40	continue	H	33
	if (i.gt.1) then	H	34
c	invoke reciprocity	H	35
	do 50 j=1, i-1	H	36
50	ss(i,j)=ss(j,i)	H	37
	end if	H	38
	sssum=0.0	H	39
c	use conservation to compute each surface's view to the largest	H	40
c	surface	H	41
	do 60 j=1, 5	H	42
60	sssum=sssum+ss(i,j)	H	43
	ss(i,6)=axx(i)-sssum	H	44
30	continue	H	45
c	place results in the array in the "unsorted" order	H	46
	do 70 i=1, 6	H	47
	do 70 j=1, 6	H	48
70	ssx(iloc(i), iloc(j))=ss(i,j)	H	49
c	write(2,*)'ssx just before leaving get6v'	H	50
c	write(2,*)ssx	H	51
	return	H	52
	end	H	53
	real function seeme(al, astar, awhole)	I	1
	real al, astar, awhole	I	2
	if (al.lt.astar) then	I	3
	seeme=0.0	I	4
	else	I	5
	seeme=al*astar/(awhole-astar)	I	6
	end if	I	7
	return	I	8

end	I	9
subroutine sorta(iloc, a, n)	J	1
real a(9),temp,tempi	J	2
integer iloc(9),i,n	J	3
logical sorted	J	4
sorted=.false.	J	5
c write(2,*)'just inside sorta'	J	6
do 10 i=1 , n	J	7
10 iloc(i)=i	J	8
642 continue	J	9
sorted=.true.	J	10
do 20 i=1 , n-1	J	11
if (a(i+1).lt.a(i)) then	J	12
temp=a(i+1)	J	13
a(i+1)=a(i)	J	14
a(i)=temp	J	15
tempi=iloc(i+1)	J	16
iloc(i+1)=iloc(i)	J	17
iloc(i)=tempi	J	18
sorted=.false.	J	19
end if	J	20
20 continue	J	21
c write(2,*)' caught in end do of sorta'	J	22
if (.not. sorted) goto 642	J	23
return	J	24
end	J	25
real function seered(hotsurf)	K	1
include 'enclose.blk'	K	2
include 'cargo.blk'	K	3
real seeredclose,seeredfar	K	4
integer hotsurf	K	5
c this function gives the view area of a(1) to a hot surface	K	6
c write(2,*)' hotsurf ',hotsurf,' a(1) at start of seered',a(1)	K	7
seeredfar=a(1)*a(hotsurf)/(a(5)+a(7)+a(8)+a(9))*ttrans	K	8
seeredclose=amin1(a(1),a(hotsurf))	K	9
c write(2,*)'a(1)',a(1),' a(hotsurf)',a(hotsurf)	K	10
seered=proximity*seeredclose+(1.0-proximity)*seeredfar	K	11
return	K	12
end	K	13
real function seeyou(a1,astar,a2,awhole)	L	1
real a1,a2,awhole,astar	L	2
if (a1.lt.astar) then	L	3
seeyou=a1*a2/(awhole-a1)	L	4
else	L	5
seeyou=astar*a2/(awhole-astar)	L	6
end if	L	7
return	L	8
end	L	9
c This subroutine provides the parameters to characterize	M	1
c the fire boundary condition.	M	2
c	M	3
c Inputs are:	M	4
c	M	5
c dist: This distance from the fire centerline to SST centerline	M	6

c	dfire: The fire diameter	M	7
c	tfire: The fire temperature	M	8
c	tdamage: The minimum temperature to damage foam	M	9
c		M	10
c	Returned are:	M	11
c		M	12
c	Afloor: The area of the floor that is being directly heated	M	13
c	A7: The area of the SST walls being directly heated	M	14
c	F7f: The viewfactor between A7 and the Fire	M	15
c		M	16
	subroutine bc(dist,dfire,tdamage,afloor,a7)	M	17
	include 'radbc.blk'	M	18
	real afmax,areamax,atoprat,fmin,tdamage,dist,afloor,dfire,h	M	19
	real asector, a7, alpha	M	20
	real ssth2,sstw,ssth,sstl	M	21
	common /sstdim/ ssth2,sstw,ssth,sstl	M	22
c	atoprat prorates the roof to the sides as A7 is calculated	M	23
c	all A7 calculations are based on the vertical side only	M	24
	afmax=sstl*sstw	M	25
c	the maximum nonfloor area is:	M	26
	areamax=(2.0*ssth*(sstl+sstw)+afmax)*0.99	M	27
	atoprat=areamax/(areamax-afmax)	M	28
	fmin=(tdamage**4-tinf**4)/(tfire**4-tinf**4)	M	29
	if(dist.le.sstw/2.0)then	M	30
c		M	31
	afloor=3.141592/4.0*dfire*dfire	M	32
c	if a sector sticks out the near side remove it	M	33
	h=dfire/2.0+dist-sstw/2.0	M	34
	if(h.gt.0.0)afloor=afloor-asector(h,dfire)	M	35
c	if a sector sticks out the far side remove it	M	36
	h=dfire/2.0-dist-sstw/2.0	M	37
	if(h.gt.0.0) afloor=afloor-asector(h,dfire)	M	38
c	use for A7 the same area we would calculate if the fire	M	39
c	were centered at the edge of the sst	M	40
	call nearfire(dfire,0.01,fmin,A7)	M	41
	if (dfire.gt.2.0*sstw)then	M	42
c	the fire is big enough to work both sides of the sst	M	43
	alpha=acos(2.0*sstw/dfire)	M	44
c	add area on distant side	M	45
	a7=a7+sin(alpha)*dfire*ssth	M	46
	end if	M	47
	F7f=1.0	M	48
	else if (dist.lt.(sstw/2.0+dfire/2.0)) then	M	49
c		M	50
c	the center of this fire is not under the sst but some of the fire	M	51
c	fire extend to underneath.	M	52
c		M	53
	if(dist.gt.(dfire/2.0-sstw/2.0)) then	M	54
c	fire is under sst but does not extend beyond the opposite side	M	55
	h=dfire/2.0-dist+sstw/2.0	M	56
	afloor=asector(h,dfire)	M	57
	call nearfire(dfire,dist-sstw/2.0,fmin,A7)	M	58
	else	M	59
c	does extend beyond far side	M	60

2 of 2

	h=dfire/2.0-dist+sstw/2.0	M	61
	afloor=asector(h,dfire)	M	62
	h=dfire/2.0-dist-sstw/2.0	M	63
	afloor=afloor-asector(h,dfire)	M	64
	alpha=acos(1.0-2.0*h/dfire)	M	65
c	get nearside a7 by calling near fire	M	66
	call nearfire(dfire,dist-sstw/2.0,fmin,A7)	M	67
c	add area on distant side	M	68
	a7=a7+sin(alpha)*dfire*ssth	M	69
	f7f=1.0	M	70
	end if	M	71
	else	M	72
c	fire is completely removed from sst	M	73
	afloor=0.0	M	74
	call farfire(dfire,dist-sstw/2.0,fmin,a7)	M	75
	end if	M	76
	a7=a7*atopratt	M	77
	if (a7.gt.areamax)a7=areamax	M	78
	if (afloor.gt.afmax)afloor=afmax	M	79
	return	M	80
	end	M	81
	subroutine nearfire(diafire,dist,fmin,a7)	N	1
c		N	2
c	This routine is called if the fire does touches the SST	N	3
	include 'radbc.blk'	N	4
	real ssth02,sstw,ssth,sstl	N	5
	common /sstdim/ ssth02,sstw,ssth,sstl	N	6
	real hfire,diafire,dhf,dist,a7,ecum,dwsst,x,flocal,v2fire	N	7
	real fmin,hw	N	8
	integer i	N	9
c	calculate the half width of the wall portion touching the fire	N	10
	f7f=1.0	N	11
	hfire=3.0*diafire	N	12
	dhf=sqrt(diafire**2/4.0-dist**2)	N	13
c		N	14
	if (dhf.gt.sstl/2.0)then	N	15
c	the fire covers the side of the sst	N	16
	a7=sstl*ssth	N	17
	return	N	18
	end if	N	19
c		N	20
	ecum=dhf*efire	N	21
	dwsst=(sstl/2.0-dhf)/40.0	N	22
	x=dhf	N	23
c		N	24
c	if the following do loop goes to its upper limit the integration	N	25
c	is along the whole side of the sst. if the fire conditions are	N	26
c	such that fmin occurs somewhere along that length, the upper	N	27
c	limit of integration stops there.	N	28
c		N	29
	do 10 i=1,40	N	30
	x=dwsst+x	N	31
	flocal=v2fire(dist,(i-1)*dwsst+dhf,ssth02,diafire,hfire)	N	32
	ecum=dwsst*(einf+flocal*(efire-einf))+ecum	N	33

	if(flocal.lt.fmin) goto 20	N	34
10	continue	N	35
20	continue	N	36
	hw=ecum/efire	N	37
	a7=hw*ssth*2.0	N	38
	return	N	39
	end	N	40
	subroutine farfire(diafire,dist,fmin,a7)	O	1
c		O	2
c	This routine is called if the fire does not touch the SST	O	3
	include 'radbc.blk'	O	4
	real ssth02,sstw,ssth,sst1	O	5
	common /sstdim/ ssth02,sstw,ssth,sst1	O	6
	real hfire,diafire,fmax,v2fire,dist,fmin,a7,ecum,x,dwsst,flocal	O	7
	real hw	O	8
	integer i	O	9
	hfire=3.0*diafire	O	10
	fmax=v2fire(dist,0.0,ssth02,diafire,hfire)	O	11
	if (fmax.lt.fmin) then	O	12
c	if this block is executed the fire is non-threatening	O	13
	a7=0.0	O	14
	f7f=fmax	O	15
	return	O	16
	end if	O	17
c	if we execute past this point	O	18
c	v2fire(dist,y,ssth02,diafire,hfire)>fmin	O	19
c	for some, perhaps all, values of y in [0..sst1/2.0]. The question,	O	20
c	now, is what value of y represents the limit of significant area.	O	21
c		O	22
	ecum=0.0	O	23
	dwsst=sst1/2.0/40.0	O	24
	x=0.0	O	25
c		O	26
c	if the following do loop goes to its upper limit the integration	O	27
c	is along the whole side of the sst. if the fire conditions are	O	28
c	such that fmin occurs somewhere along that length, the upper	O	29
c	limit of integration stops there.	O	30
c		O	31
	do 10 i=1,40	O	32
	x=dwsst+x	O	33
	flocal=v2fire(dist,(i-1)*dwsst,ssth02,diafire,hfire)	O	34
	ecum=dwsst*(einf+flocal*(efire-einf))+ecum	O	35
	if (flocal.lt.fmin) goto 20	O	36
10	continue	O	37
20	continue	O	38
	hw=ecum/(einf+fmax*(efire-einf))	O	39
	a7=hw*ssth*2.0	O	40
	f7f=fmax	O	41
	return	O	42
	end	O	43
c		P	1
	real function V2fire(x,y,z,d,h)	P	2
c	This function calculates the view factor from an area element to	P	3
c	a right circular cylinder. It utilizes Formula 24 from the back	P	4

c	of Siegel and Howell's book to construct the result. The area	P	5
c	element is always in the y-z plane a distance x from the center of	P	6
c	the fire of diameter d and height h. So $x \geq d/2$ is required. The	P	7
c	origin of the coordinate system is at the center of the base of	P	8
c	the cylinder.	P	9
	real lb,lt,x,y,theta,ht,d,h,z,eq24	P	10
	theta=atan(y/x)	P	11
	HT=2.0*x/D/cos(theta)	P	12
	LT=(h-z)*2.0/D	P	13
	LB=z*2.0/D	P	14
	V2fire=cos(theta)*(Eq24(LT,HT)+Eq24(LB,HT))	P	15
	return	P	16
	end	P	17
	real function Eq24(L,H)	Q	1
c	This function is Eq. 24 from Siegel and Howell's Appendix	Q	2
	real l,pi,h,x,y,t1,t2,t3	Q	3
	data pi/3.141592/	Q	4
	if (h.lt.1.001) then	Q	5
	Eq24=0.5	Q	6
	return	Q	7
	end if	Q	8
	x=(1.0+h)**2+1**2	Q	9
	y=(1.0-h)**2+1**2	Q	10
	t1=atan(sqrt((h-1.0)/(h+1.0)))/h	Q	11
	t2=atan(sqrt((h-1.0)/(h+1.0)*x/y))/h*(x-2.0*h)/sqrt(x*y)	Q	12
	t3=atan(L/sqrt(h**2-1.0))/pi/h	Q	13
	Eq24=t3+1/pi*(t2-t1)	Q	14
	return	Q	15
	end	Q	16
	real function asector(h,d)	R	1
	real alpha,h,d	R	2
c	alpha is the subtended angle	R	3
	alpha=2.0*acos(1.0-2.0*h/d)	R	4
	asector=d**2/8.0*(alpha-sin(alpha))	R	5
	return	R	6
	end	R	7

ODE-source code omitted as it is widely distributed and documented elsewhere (Reference [10], for example).

block data	X	1
real terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax	X	2
common /compute/terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax	X	3
include 'enclose.blk'	X	4
include 'radbc.blk'	X	5
include 'cargo.blk'	X	6
include 'foam.blk'	X	7
real ssth02,sstw,ssth,sst1	X	8
common /sstdim/ ssth02,sstw,ssth,sst1	X	9
data ssth02,sstw,ssth,sst1/2.0,2.0,2.0,10.2/	X	10
data firerate,sigma/1.0e4,5.67e-8/	X	11
data terrel,terrmax,emax,hmin,h,maxstep,minstep,waymax	X	12
1/0.01,50.0,0.003,0.02,2.0,50.0,1.0,1500.0/	X	13
data lwall,lfloor,kvirg,heatreqw,heatreqf,aawall,aafloor,	X	14

	ltreactw,treactf	X	15
	2/305.0,305.0,20.18,12440.0,12440.0,0.052,0.052,585.0,585.0/	X	16
	data eps/8*0.7,1.0/	X	17
c	28400 is the armor's rho*cp*thickness product	X	18
	data rch/3*1.0,15000.0,27500.0,3*28400.0/	X	19
	data rchskinw,rchskinf/2*2525.0/	X	20
c	the steady state resistance of virgin plywood is used	X	21
c	along with it's thermal capacitance, 1/2" thickness	X	22
	data rchply,reply/12500.0,0.06/	X	23
	data epso5,epso7,epso8,tinf/3*0.9,300.0/	X	24
	end	X	25

```

c   CARGO.BLK, declarations of variables associated with cargo
c   parameters
c
c   real proximity,ck,cr,mcp,rcarg,acargo,cargoeps,transm,ttrans,split
c   integer nstrip,ncs,modelnumber,ncargo,ncrit
c   common /cargo/proximity,ck(10),cr(10),mcp(10),rcarg(10),acargo,
c   1cargoeps,transm,ttrans,split,nstrip,ncs,modelnumber,ncargo,ncrit
c
c   ENCLOSE.BLK, declarations of variables associated with
c   enclosure parameters.
c
c   real a,arad,hh,eps,epsrad,rmcp3,rch,rchskinf,rchskinw,rchply,reply
c   integer isurf,aid,qid,nsurfrad,skin7id,plyid,skin5id,char7id,
c   1char5id
c   logical ahere
c   common /enclose/a(9),arad(9),hh(9,9),eps(9),epsrad(9),
c   1rmcp3,rch(8),rchskinf,rchskinw,rchply,reply,isurf(30),aid(30),
c   2qid(30),nsurfrad,skin7id,plyid,skin5id,char7id,char5id,ahere(9)
c
c   FOAM.BLK, declarations of variables associated with foam wall
c   parameters
c
c   real lwall,lfloor,kvirg,heatreqw,heatreqf,aawall
c   real aafloor,treactw,treactf,ereactf,ereactw
c   common /foam/lwall,lfloor,kvirg,heatreqw,heatreqf,aawall,
c   1aafloor,treactw,treactf,ereactf,ereactw
c
c   MELT.BLK, declarations of variables associated with the melting
c   of the outside shell of the cargo
c
c   real emelt,umelt,tmelt,tmelted,arat
c   logical melting,melted,cool,canmelt
c   common /melt/emelt,umelt,tmelt,tmelted,arat,melting,melted,cool,
c   1canmelt
c
c   RADBC.BLK, declarations of variables associated with
c   representing the radiation boundary condition
c
c   real epso5,epso7,epso8,tfire,tfiref,tinf,efire,efiref,
c   1einf,f5f,f7f,f8f,f9f,firerate,sigma,ehol :
c   common /radbc/epso5,epso7,epso8,tfire,tfiref,tinf,efire,efiref,
c   1einf,f5f,f7f,f8f,f9f,firerate,sigma,ehole

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