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VOLUME 5

SYNTHESIS OF CALCULATIONAL METHODS FOR THE DESIGN AND ANALYSIS OF RADIATION SHIELDS FOR NUCLEAR ROCKET SYSTEMS

TIC-TOC-TOE

A FORTRAN PROGRAM FOR THE TEMPERATURE IN THE COOLANT TANK AND OTHER CALCULATIONS AND FOR THE THERMAL NEUTRON ORIGINATING ENERGY

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ABSTRACT

This report is Volume 5 of nine volumes of the final report on "Synthesis of Calculational Methods for the Design and Analysis of Radiation Shields for Nuclear Rocket Systems". Presented in this volume is a description of the TIC-TOC-TOE program for the Temperature In the Coolant Tank and Other Calculations and for the Thermal neutron Originating Energy.

The TIC-TOC-TOE program, which is written in FORTRAN IV language, performs rapid calculations of heating rate distributions in on-axis liquid hydrogen propellant tanks. Neutron and photon sources from the reactor are expressed as multigroup, angular equivalent point sources. The propellant tank geometry is described by a series of axisymmetric truncated cones and/or cylinders. Basic heating rate data are interpolated from curve-fits of M. O. Burrell's Monte Carlo data which are built into the program.

Quantities calculated by the TIC-TOC-TOE program for specified points in the tank include:

1) gamma ray heating by energy group,
2) neutron kinetic heating by fast energy group,
3) capture gamma ray heating due to neutron captures in liquid hydrogen, and
4) capture gamma ray heating due to neutron captures in tank wall.

These same quantities are also obtained for points at the corners of the volume elements employed in performing volume integrations over the tank. Quantities obtained from the volume integration include:

1) total gamma and neutron heating rate as a function of propellant height,
2) radial and volume averaged heating rates as a function of propellant height,
3) radial averaged temperature rise as a function of time for a no-mix fluid model, and
4) temperature rise as a function of time for a complete mix fluid model.

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1.0 INTRODUCTION

The TIC-TOC-TOE program is written in FORTRAN IV for the IBM 7094 and CDC 6600 computers. This program utilizes curve-fit Monte Carlo heating rate data(1) generated by M. O. Burrell of the Marshall Space Flight Center (MSFC), to obtain heating rates in an on-axis liquid hydrogen propellant tank whose geometry is described by a series of truncated cones and cylinders. The radiation source is expressed as an equivalent point angular dependent source for three pre-selected gamma ray energy groups, and five pre-selected neutron energy groups (three fast, one epithermal and one thermal).

TIC-TOC-TOE is an integral part of the "early" design method provided for the Marshall Space Flight Center under this contract. A simplified schematic diagram of the "early" design method is shown in Figure 1 and is described in detail in Volume 1. The starting point for the method is the POINT program (Volume 2) which prepares cross section and other basic data for use in the transport programs. In the "early" design method (Figure 1), the TAPAT program system (Volume 3) computes one dimensional neutron and photon fluxes in the reactor geometry. From these fluxes, neutron and photon sources and distributions are obtained and are used as input to the KAP-V program. The KAP-V program (Volume 4) provides gamma ray and fast neutron radiation levels at locations external to the reactor. Radiation levels from the KAP-V program at a specific radial distance from the center of the reactor can then be employed in the TIC-TOC-TOE program (Volume 5) for calculating radiation quantities of interest in an on-axis liquid hydrogen propellant tank.

Quantities calculated by the TIC-TOC-TOE program for specified points in the tank include:

1) gamma ray heating by energy group,
2) neutron kinetic heating by fast energy group,
3) capture gamma ray heating due to neutron captures in the liquid hydrogen, and
4) capture gamma ray heating due to neutron captures in the tank wall.

These quantities are also obtained for points at the corners of the volume elements employed in performing volume integrations over the tank. Quantities obtained from the volume integration include:

1) total gamma and neutron heating rate as a function of propellant height,
2) radial and volume averaged heating rates as a function of propellant height,
3) radial averaged temperature rise as a function of time for a no-mix* fluid model, and
4) temperature rise as a function of time for a complete mix* fluid model.

Typical computer runs on the IBM 7094 require approximately 10 milliseconds per point if the capture gamma ray heating (from both the wall and propellant) is not computed. If these capture gamma ray heating rate components are calculated, a volume integration over the entire tank is performed for each point and the computer time per point becomes proportional to the number of points used in this numerical volume integration.

Section 2.0 of this report presents the equations involved in this program. The program logic is discussed in Section 3.0. Detailed input instructions are given in Section 4.0. Section 5.0 contains a sample problem and a description of the output format. The program listing is given in an appendix.

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* In a no-mix fluid model, the heat deposited in the liquid hydrogen is assumed to remain in the same area until that incremental volume of coolant is pumped out of the tank. In a complete mix fluid model, the total heat deposited is assumed to be instantaneously mixed throughout the tank.

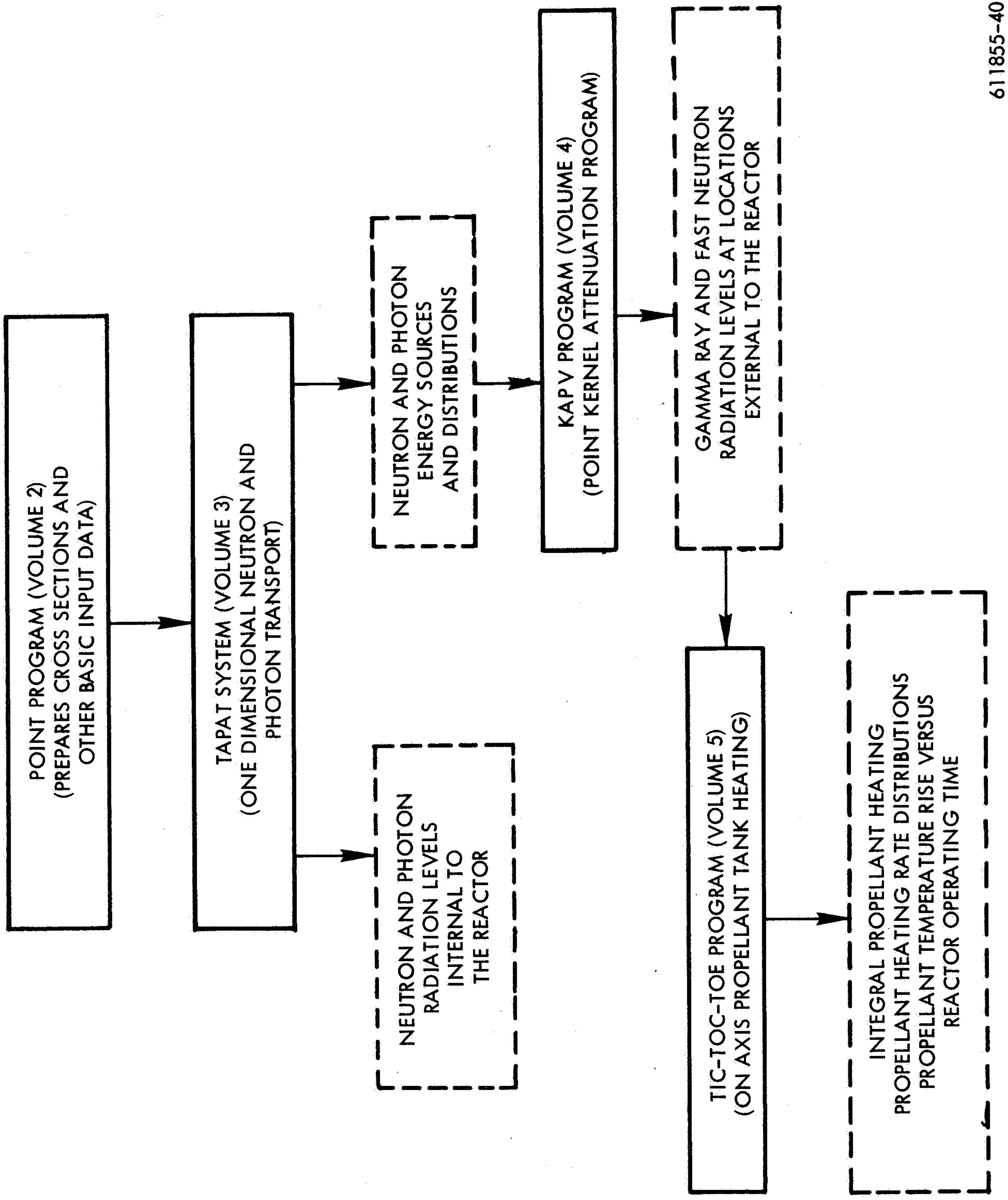

Figure 1. Schematic Diagram of the "Early" Design Method

SECTION
2.0 PROGRAM DESCRIPTION

This section describes the seven essential parts of the TIC-TOC-TOE programs which are:

1) The Monte Carlo data built into the program
2) The point angular source
3) The propellant tank geometry
4) Gamma ray and neutron kinetic heating calculations
5) Capture gamma ray heating calculations
6) Total heating rate calculations
7) Temperature rise calculations.

2.1 BASIC DATA

The basic data used in this program are based on the Monte Carlo calculations of M. O. Burrell reported in Reference 1. These data include propellant heating rates and thermal neutron capture rates as a function of depth, z', and radius, r, in a flat bottomed cylindrical tank for unit monoenergetic sources. All of these data have been empirically fitted, as a function of the two spatial parameters r and z', in the general form:

$$F(r,z') = \sum_{k=0}^{1} A_k(r) \exp\left[-B_k(r) \min(z_o, z') + C_k(r) \max(0, z'-z_o)\right] \qquad (2.1)$$

where:

z_o = a constant depth into the tank defining a breakpoint in the empirical fit of the z dependence.

$$A_k(r) = \sum_{l=0}^{2} a_{l,k} r^l \; ; \; a_{l,k} \; , l = 0, 1, 2 \text{ are constants} \qquad (2.2)$$

$$B_k(r) = \sum_{l=0}^{2} b_{l,k} r^l \quad ; \quad b_{l,k} \quad , l = 0, 1, 2 \text{ are constants} \tag{2.3}$$

$$C_k(r) = \sum_{l=0}^{2} c_{l,k} r^l \quad ; \quad c_{l,k} \quad , l = 0, 1, 2 \text{ are constants} \tag{2.4}$$

r = the radial distance from the tank centerline.

z' = the distance into the tank parallel to the centerline.

$\min(z_o, z')$ = the smaller of the numbers z_o and z'

$\max(0, z_o - z')$ = the larger of the numbers 0.0 and $z_o - z'$

The functions curve fit using Eq. 2.1 are:

$\dot{h}_1(r,z')$, the volumetric energy deposition from 6 Mev Gamma Rays

$\dot{h}_2(r,z')$, the volumetric energy deposition from 3 Mev Gamma Rays

$\dot{h}_3(r,z')$, the volumetric energy deposition from 1 Mev Gamma Ray

$\dot{h}_4(r,z')$, the volumetric energy deposition from 7 Mev Neutrons

$\dot{h}_5(r,z')$, the volumetric energy deposition from 3 Mev Neutrons

$\dot{h}_6(r,z')$, the volumetric energy deposition from 1 Mev Neutrons

$\dot{g}_1(r,z')$, the volumetric capture rate from 7 Mev Neutrons

$\dot{g}_2(r,z')$, the volumetric capture rate from 3 Mev Neutrons

$\dot{g}_3(r,z')$, the volumetric capture rate from 1 Mev Neutron

$\dot{g}_4(r,z')$, the volumetric capture rate from 0.1 Mev Neutrons

$\dot{g}_5(r,z')$, the volumetric capture rate from 2 ev Neutrons

A comparison between the empirical fit and the Monte Carlo energy deposition and capture rate data is given in Reference 2. In general, accuracy within 5 percent of the "smoothed" Monte Carlo data is obtained.

The above functions are extrapolated from the conditions used in the original Monte Carlo study. In particular, this data is extrapolated to account for:

1) different tank bottom shape (flat in the Monte Carlo calculations), and
2) different source to propellant tank separation distance (11.25 feet in the Monte Carlo calculations).

The extrapolation techniques are discussed in connection with equations presented later.

2.2 POINT ANGULAR SOURCES

The point sources required for TIC-TOC-TOE are determined from flux calculations performed at a fixed radial distance, R (in feet), from the center of the reactor sources (usually assumed to be the core geometric center). These fluxes are assumed to be azimuthally symmetric and are supplied for a series of energy groups as a tabulated function of the polar angle, θ, measured from the center-line axis of the reactor-propellant tank configuration:

θ_i = the ith polar angle (degrees)
$\phi_{j,i}$ = the flux in the jth energy group at the ith polar angle (particles/cm^2/sec)

These data define the equivalent point source, $S_j(\mu)$ for each group j, where μ is the cosine of the polar angle, θ. The angular dependence is then obtained by a linear interpolation in μ:

$$S_j(\mu) = \frac{(\mu - \mu_{i+1})\, S_{j,i} + (\mu_i - \mu)\, S_{j,i+1}}{\mu_i - \mu_{i+1}} \qquad (2.5)$$

for $\mu_i \geq \mu > \mu_{i+1}$

where

$\mu_i = \cos\theta_i \qquad i = 1, 2, '''$ (2.6)

$S_{j,i} = 4\pi(30.48R)^2 \phi_{j,i} \qquad i = 1, 2, '''; \; j = 1, 2, ''', 8$ (2.7)

R = the reference radius at which the fluxes are given (feet)

The source group structure is fixed by the Monte Carlo energy deposition and capture distribution data with the notation:

Group 1	6 Mev gamma rays
Group 2	3 Mev gamma rays
Group 3	1 Mev gamma rays
Grpup 4	7 Mev neutrons
Group 5	3 Mev neutrons
Group 6	1 Mev neutrons
Group 7	0.1 Mev neutrons
Group 8	thermal neutrons

2.3 PROPELLANT TANK GEOMETRY

The propellant tank geometry as shown in Figure 2 is described by a series of truncated cones and/or cylinders with center lines on the z-axis of the coordinate system. The i th section of the tank is the volume bounded by:

$z = z_i$, the z - plane at the bottom of the section,

$z = z_{i+1}$, the z - plane at the top of the section, and

$R_{max}(z) = a_i + b_i z$, the equation of the cone or cylinder at the side of the section. (2.8)

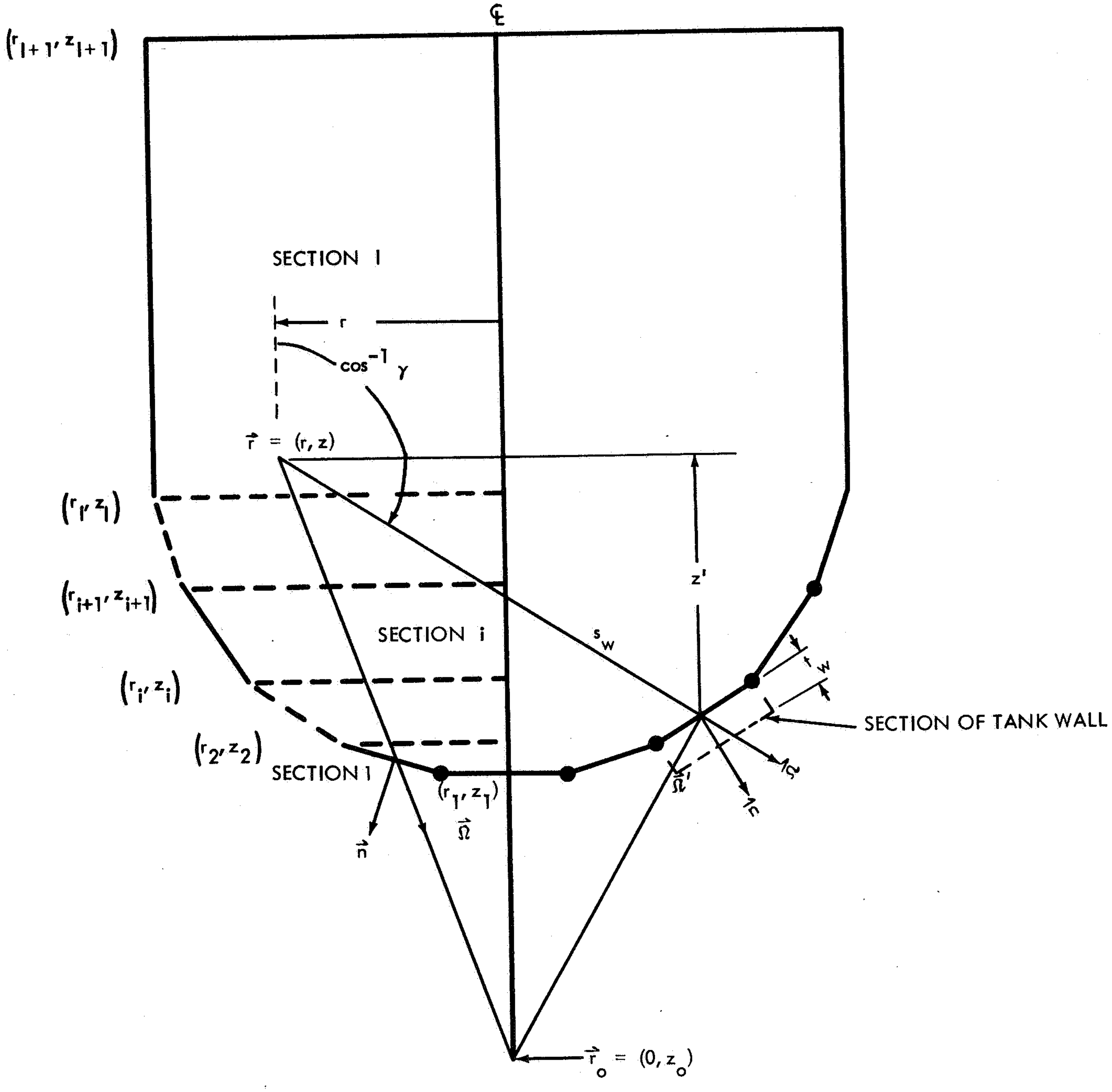

Figure 2. Propellant Tank Geometry

The constants a_i and b_i determine the equation of the line between the points (r_i, z_i) and (r_{i+1}, z_{i+1})

$$b_i = \frac{r_{i+1} - r_i}{z_{i+1} - z_i} \qquad (b_i = 0 \text{ for cylindrical tank sections})$$

$$a_i = r_i - b_i z_i \qquad (a_i = r_i = r_{i+1} \text{ for cylindrical tank sections})$$

The complete tank geometry is specified by a tabulation of the points (r_i, z_i), $i = 1, 2, \ldots, I+1$ where I is the total number of volume sections required to describe the shape of the tank.

The tank wall is assumed to have a constant thickness, t_w, over the outer boundary of the tank; its finite thickness is not treated explicitly in the geometric calculations. Instead, the tank wall effect is approximated using the outward unit vector, $\vec{n}$, normal to the tank surface as described below.

All distance calculations required by the TIC-TOC-TOE program are performed by the function subprogram PATH. The geometric calculations generally involve a point $\vec{r}$ in the tank and a unit direction vector $\vec{\Omega}$ from this point where:

$$\vec{r} = x\vec{i} + y\vec{j} + z\vec{k}$$

$$\vec{\Omega} = \alpha\vec{i} + \beta\vec{j} + \gamma\vec{k} \tag{2.9}$$

$\vec{i}$, $\vec{j}$, $\vec{k}$ are unit vectors parallel to the coordinate system axis.

x, y, z are rectangular coordinates

α, β, γ are direction cosines with respect to the x, y, and z axes, respectively.

The distance s_w from $\vec{r}$ along $\vec{\Omega}$ to the surface of the tank is computed as:

$$
\begin{aligned}
s_w &= \min \left\{ \frac{z_{I+1} - z}{\gamma} \;, s_i \,, \; s_{i+1} \ldots, s_I \right\} \quad \text{if} \quad \gamma > 0 \\
s_w &= \min \left\{ \frac{z_1 - z}{\gamma} \;, s_1 \,, s_2 \,, \ldots, s_i \right\} \quad \text{if } \gamma < 0
\end{aligned}
\tag{2.10}
$$

where

$z_{i+1} \geq z \geq z_i$, i.e. the point $\vec{r}$ is in the i th section of the tank,

$(z_{I+1} - z)/\gamma$ is the distance to the top of the tank from $\vec{r}$ along $\vec{\Omega}$

$(z_1 - z)/\gamma$ is the distance to the bottom of the tank from $\vec{r}$ along $\vec{\Omega}$

s_i is the smaller of the positive distances (if any) to the i th conical or cylindrical boundary of the tank.

The distances s_i, $i = 1, 2, \ldots, I$, are computed, as required, from equation 2.8 by noting that for points on the boundary:

$$
R_{max}(z + \gamma s_i) = a_i + b_i (z + \gamma s_i) = \left[(x + \alpha s_i)^2 + (y + \beta s_i)^2 \right]^{1/2}
\tag{2.11}
$$

An expansion gives:

$$
\left[\alpha^2 + \beta^2 - \gamma^2 b_i^2 \right] s_i^2 + 2 \left[\alpha x + \beta y - \gamma b_i (a_i + b_i z) \right] s_i
$$

$$
+ x^2 + y^2 - (a_i + b_i z)^2 = 0
$$

or:

$$
s_i = \frac{-B \pm \sqrt{B^2 - AC}}{A}
\tag{2.12}
$$

where

$$\left.\begin{aligned} A &= \alpha^2 + \beta^2 - \gamma^2 b_i^2 \\ B &= \alpha\, x + \beta y - \gamma b_i (a_i + b_i z) \\ C &= x^2 + y^2 - (a_i + b_i z)^2 \end{aligned}\right\} \qquad (2.13)$$

The cosine of the angle between $\vec{\Omega}$ and the outward normal $\vec{n}$ at the tank surface is given by

$$\mu_w = |\gamma| \quad \text{if the top or bottom of the tank yields the minimum distance } s_w. \qquad (2.14a)$$

$$\mu_w = \left|\vec{\Omega} \cdot \vec{n}_i\right| \quad \text{if the } i\ \underline{th} \text{ conical or cylindrical boundary yields the minimum distance } s_w. \qquad (2.14b)$$

In the latter case the normal vector is computed as:

$$\vec{n}_i = \frac{C_1 \vec{i} + C_2 \vec{j} + C_3 \vec{k}}{\left[C_1^2 + C_2^2 + C_3^2\right]^{1/2}} \qquad (2.15)$$

where

$$\left.\begin{aligned} C_1 &= x + \alpha s_i \\ C_2 &= y + \beta s_i \\ C_3 &= -b_i \left[a_i + b_i (z + \gamma s_i)\right] \end{aligned}\right\} \qquad (2.16)$$

2.4 DIRECT GAMMA RAY AND FAST NEUTRON HEATING

The heating rate from direct gamma rays and fast neutrons at a specified point $\vec{r}$, at a radius r and height z, is determined by an extrapolation of the curve-fit Monte Carlo data. For the j th group, this extrapolation is:

$$\dot{H}_i(r, z) = S_i(\mu)\,\dot{h}_i(r, z')\,\frac{s_o^2}{s_t^2}\,\exp\left[-\,\Sigma_i^w\,\Delta s_w\right] \tag{2.17}$$

where

s_o^2 = $11.25^2 + r^2$, the square of the distance to the volume element in the original Monte Carlo calculation (2.18)

$\dot{h}_i(r,z')$ = the heating rate from the j th energy group

$\vec{r}_o$ = the angular point source position

s_t = the total distance from the source point to the point in the tank

s_t = $\left|\vec{r}_o - \vec{r}\right|$ (2.19)

$\vec{\Omega}$ = the unit direction vector from $\vec{r}$ to $\vec{r}_o$

$\vec{\Omega}$ = $(\vec{r}_o - \vec{r})/s_t$ (2.20)

μ = $-\vec{k}\cdot\vec{\Omega} = |\gamma|$ (2.21)

s_w = the distance from the point $\vec{r}$ to the tank wall along the direction $\vec{\Omega}$

z' = μs_w, the axial penetration distance into the tank. (2.22)

Σ_i^w = the total attenuation cross section of the tank wall for particles in the j th group.

Δs_w = the distance in the tank wall, approximated by

Δs_w = $t_w/\vec{\Omega}\cdot\vec{n}$ (2.23)

2.5 CAPTURE GAMMA RAY HEATING

The energy deposition due to the liquid hydrogen capture gammas at a point $\vec{r}$ in the tank is computed by a volume integration over these capture sources. This volume integration is performed by subroutine TOE using spherical coordinates with the coordinate system centered at the point $\vec{r}$. The equation used for the propellant capture gamma ray heating is:

$$\dot{H}_p (r,z) = \mu_p^a E_p^\gamma C \int_{-1}^{1} \int_{0}^{2\pi} \int_{0}^{s_w} \frac{S_p(\vec{r}')}{4\pi s^2} \exp\left[-\mu_p^t s\right] B_p(\mu_p^t s)\, s^2 ds\, \theta\, d\mu \qquad (2.24)$$

where

$\dot{H}_p(r,z)$ = the propellant capture gamma heating rate at $\vec{r}$, i.e. at r, and z,

μ_p^a = the energy absorption coefficient,

E_p^γ = the capture gamma ray energy (2.23 Mev),

C = a units conversion factor,

μ = the cosine of the polar angle,

θ = the azimuthal angle,

s = the distance from $\vec{r}$ along $\vec{\Omega}$

$\vec{\Omega}$ = $\vec{i}\sqrt{1-\mu^2}\,\cos\theta + \vec{j}\sqrt{1-\mu^2}\,\sin\theta + \vec{k}\,\mu$

$\vec{r}'$ = $\vec{r} + s\,\vec{\Omega}$, the capture gamma ray source point, (2.25)

μ_p^t = the mass attenuation coefficient,

$B_p(\mu_p^t s)$ = a polynomial buildup factor, and

$S_p(\vec{r}\,')$ = the volumetric capture gamma ray source strength at the source point.

The capture gamma ray source strength is determined from the curve fit Monte Carlo data as:

$$S_p(\vec{r}\,') = \sum_{i=4}^{8} \frac{(11.25 + z')^2 + r^2}{\left|\vec{r}\,' - \vec{r}_o\right|^2} \; g_{i-3}(r\,,\, z')\; S_i\,(\mu')\exp\left[-\Sigma_i^w \Delta s_w\right] \quad (2.26)$$

The same procedures used in this source strength calculation are used in defining the point wise heating rates from direct gamma rays and fast neutrons, i.e. eq. 2.17.

2.5.1 Wall Capture Gamma Ray Heating

The energy deposition from capture gamma rays produced in the tank wall is computed concurrent with the calculation of the liquid hydrogen capture gamma component. A single capture gamma ray energy is allowed and the energy deposition is computed at points in the propellant tank as:

$$\dot{H}_w(r,z) = \mu_w^a \, E_w^{\gamma} C \underbrace{\int_{-1}^{1} \int_{0}^{2\pi}}_{\vec{\Omega}'\cdot\vec{n} > 0} \int_{s_w}^{s_w + \Delta s_w} \frac{S_w(\vec{r}\,')}{4\pi} \; \frac{\exp\left[-\mu_w^t s\right]}{s^2} \; B_w\,(\mu_w^t s)\, s^2 \, ds\, d\theta\, d\mu \quad (2.27a)$$

where

C is a units conversion factor

μ_w^a is the energy absorption coefficient of liquid hydrogen for the wall capture gammas

E_w^γ is the energy (Mev) of the wall capture gammas

μ_w^t is the mass attenuation coefficient of the liquid hydrogen for the wall capture gammas

$B_w(\mu_w^t s)$ is a polynomial buildup factor for the wall capture gammas in liquid hydrogen

Δs_w is the slant thickness of the wall as seen by the point, $\vec{r}$

$S_w(\vec{r}\,')$ is the volumetric source strength of capture gammas in the tank wall

$\vec{\Omega}'$ is the unit direction vector from the capture point to the angular point source

Note: this integration is limited to portions of the tank wall which can "see" the equivalent angular point source.

The attenuation of these capture gamma rays by the tank wall is neglected so that the integration reduces to

$$\dot{H}_w(r,z) = C\,\mu_w^a\,E_w^\gamma \underset{\vec{\Omega}'\cdot\vec{n}>0}{\int_{-1}^{1}\int_{0}^{2\pi}} \left\{ \int_{s_w}^{s_w+\Delta s_w} S_w(\vec{r}\,')\, ds \right\} \frac{\exp\left[-\mu_w^t\, s\right]}{4\pi}\, B_w(\mu_w^t s)\, d\theta\, d\mu \qquad (2.27b)$$

The capture gamma source is obtained from the neutron fluxes at the tank wall as:

$$s_w(\vec{r}\,') = \sum_{i=4}^{8} \Sigma_i^c \frac{S_i(\mu')}{4\pi t^2} \exp\left[-\Sigma_i^t \Delta s_w'\right] \tag{2.28}$$

where

Σ_i^c is the neutron capture cross section for source group i

t is the distance from the angular point sources to the tank wall

Δs_w is the distance into the tank wall of the capture source point measured along the line from the angular point source to the capture point.

From Figure 2, the distance Δs_w is given by

$$t_w - \vec{n}\cdot\vec{\Omega}\,(s - s_w) = \vec{n}\cdot\vec{\Omega}\,'\Delta s_w'$$

or

$$\Delta s_w' = \frac{t_w - \vec{n}\cdot\vec{\Omega}\,(s - s_w)}{\vec{n}\cdot\vec{\Omega}\,'}$$

Since the attenuation of the wall capture gammas by the tank wall is neglected, the source term in eq. 2.27b is obtained analytically:

$$\int_{s_w}^{s_w+\Delta s_w} S_w(\vec{r}\,')\,ds = \sum_{i=4}^{8} \frac{\Sigma_i^c}{4\pi t^2} S_i(\mu')$$

$$\int_{s_w}^{s_w+\Delta s_w} \exp\left[-\Sigma_i^t\left(\frac{t_w - \vec{n}\cdot\vec{\Omega}\,(s - s_w)}{\vec{n}\cdot\vec{\Omega}\,'}\right)\right] ds$$

$$= \sum_{i=4}^{8} \frac{\Sigma_i^c}{\Sigma_i^t} \; \frac{S_i\,(\mu')}{4\pi t^2} \left(1 - \exp\left[-\Sigma_i^t \; t_w/\vec{n}\cdot\vec{\Omega}'\right]\right) \frac{\vec{n}\cdot\vec{\Omega}'}{\vec{n}\cdot\vec{\Omega}} \qquad (2.29)$$

Substitution into eq. 2.27b yields the final equation evaluated in subroutine TOE:

$$\dot{H}_w\;(r,\; z) = C\mu_w^a \;\; E_w^\gamma \underset{\vec{\Omega}'\cdot\;\vec{n}>0}{\int_{-1}^{1}\int_{0}^{2\pi}} \left\{ \sum_{i=4}^{8} \frac{\Sigma_i^c}{\Sigma_i^t} \; S_i\;(\mu') \left(1 - \exp\left[-\Sigma_i^t \; t_w/\vec{n}\cdot\vec{\Omega}'\right]\right)\right\},$$

$$\times \frac{1}{4\pi t^2} \; \frac{\vec{n}\cdot\vec{\Omega}'}{\vec{n}\cdot\vec{\Omega}} \; \frac{\exp\left[-\mu_w^t s\right]}{4\pi} \; B_w\left(\mu_w^t s\right) d\theta d\mu \qquad (2.30)$$

2.6 Average Energy Deposition

The total heating rate at a point is given by a summation over the various heating rate components.

$$\dot{H}\;(r,\; z) \;=\; \sum_{i=1}^{6} \dot{H}_i\,(r,\; z) \;+\; \dot{H}_p\,(r,\; z) + \dot{H}_w\,(r,\; z) \qquad (2.31)$$

The total energy deposited in the tank per unit time is then obtained by an integration over the tank volume. The energy deposition rate for propellant levels up to z is denoted by $\dot{H}\,(z)$ and is given by

$$\dot{H}\;(z) = \int_{z_1}^{z} 2\pi \int_{0}^{R_{max}\,(z'')} \dot{H}\;(r'',\; z'')\;\; d\left(\frac{r''^2}{2}\right)\; dz'' \qquad (2.32)$$

where r" is the variable radius and z" is the variable axial coordinate. The volume averaged heating rate for the propellant below z is simply:

$$\dot{H}_v(z) = \frac{1}{V(z)} \dot{H}(z) \tag{2.33}$$

where

$$V(z) = 2\pi \int R^2_{max}(z'')\, dz'' \tag{2.34}$$

The radial averaged heating rate at the propellant height z is given by:

$$\dot{H}_A(z) = \frac{2\pi}{A(z)} \int_0^{R_{max}(z)} \dot{H}(r'', z)\, d\left(\frac{r''^2}{2}\right) \tag{2.35}$$

where $A(z) = \pi R^2_{max}(z)$ (2.36)

2.7 Propellant Temperature Rise

Neglecting the fact that heating rates are perturbed by the total amount of propellant in the tank, the temperature rise can be computed as a function of the time, , after which the tank starts to empty.

No Mix Model

The radial averaged temperature rise of propellant, initially at a height z at time $\tau = 0$, can be determined by integrating the heating rate over the time required to reach the tank outlet. Assuming no mixing of the propellant, then:

$$\Delta T(z) = \frac{1}{C_p} \int_0^{\tau(z)} \dot{H}_A\left[z''(\tau')\right] d\tau' \tag{2.37}$$

where C_p is the specific heat.

But $\frac{dz''}{d\tau'} = \dot{V}/A(z'')$ where $\dot{V}$ is the volumetric flow rate so that

$$\Delta T\,(z) = \frac{1}{C_p}\int_0^z \dot{H}_A\,(z''\,(\tau'))\frac{d\tau'}{dz''}dz'' = \frac{1}{C_p\dot{V}}\int_0^z A(z'')\,\dot{H}_A\,(z'')\,dz'' \qquad (2.38)$$

$$= \dot{H}\,(z)/C_p\dot{V} \qquad (2.39)$$

where τ is given by

$$\tau = V(z)/\dot{V} \qquad (2.40)$$

Complete Mix Model

The temperature rise under the assumption of a complete and instantaneous mix of the energy deposited in the tank can be determined by solving a differential equation

$$\frac{dH(z)}{d\tau} = \dot{H}\,(z) - \dot{V}\;H(z)/V(z) \qquad (2.41)$$

where H(z) is the total energy contained in the tank when the propellant level has dropped to a height z. The time at this condition is

$$\tau = \frac{V_o - V(z)}{V} \qquad (2.42)$$

or alternatively

$$V(z) = V_o - \dot{V}\tau$$

where V_o is the total tank volume.

Solution of eq. 2.41 yields the temperature rise when the propellant has dropped to the height z:

$$\Delta T\,(z) = \frac{1}{C_p\dot{V}}\int_z^{z_{l+1}} \dot{H}_v\,(z'')\,A\,(z'')\,dz'' \qquad (2.43)$$

with the corresponding time

$$\tau\,(z) = \frac{1}{\dot{V}}\int_z^{z_{l+1}} A\,(z'')\,dz'' = \frac{V_o - V(z)}{\dot{V}} \qquad (2.44)$$

SECTION
3.0 PROGRAM LOGIC

The TIC-TOC-TOE program accepts all input data before proceeding to the calculation of propellant heating rates. Detailed input instructions are given in Section 4.0. Some of the input data are altered as they are input. In particular, the point angular source is defined from input fluxes tabulated at discrete polar angles.

3.1 POINT CALCULATIONS

Heating rate calculations are first performed for discrete points in the tank as specified in the input. The point heating calculations are performed in subroutine POINT. This subroutine is also utilized in the volume integrations, discussed in Section 3.2, where the discrete points are specified by the numerical integration procedures.

3.1.1 Direct Heating

The POINT subroutine computes the direction and total distance from the point in the tank to the source point. The distance in the propellant and the normal derivative at the surface are then computed by the function subprogram PATH. Next, the angular point source is interpolated to obtain the groupwise source for the direction from the source point to the point in the tank. The axial penetration, z', is computed and the heating rate obtained for each group by eq. 2.1 using the function subprogram CURVE to evaluate eq. 2.2, 2.3, and 2.4.

3.1.2 Capture Heating

The option indicator for capture gamma ray calculations is checked. If requested, these capture calculations are performed by subroutine TOE.

The TOE subroutine performs an integration over the tank volume to obtain capture gamma ray heating rates. The volume integration is performed in a spherical coordinate system centered at the point in the tank as indicated in eq. 2.24 and 2.27.

The first procedure in this volume integration is to define a discrete direction through the tank based on the discrete directions obtained from the solid angle portion of the integration. The distance to the tank surface and the outward normal are then computed for this direction by PATH. The volume integration then involves a spatial integration along the path to the wall. Each of the discrete points generated along the path by the numerical spatial integration is a point source of hydrogen capture gammas. The source strength at each of these point sources is obtained from equation 2.1 using subroutine GAMMAS in conjunction with the function subprogram CURVE.

After evaluating the point sources along the line to tank wall, the tank wall capture gamma heating contribution is obtained using eq. 2.30

3.2 VOLUME CALCULATIONS

The volume integration option is checked after all point calculations have been performed. If requested, this integration is performed in a cylindrical coordinate system.

The outermost integration involves the integration along the length of the tank. The inner integration is an area integration. Discrete points are generated for the area integration and the pointwise heating rates are obtained by subroutine POINT.

The radial averaged heating rate, eq. 2.35, is obtained from the inner area integration and volume averaged heating rates are obtained from eq. 2.33 by the integration of the area averages over the axial distance.

The no-mix temperature rise is computed during the volume integration using eq. 2.39. Appropriate quantities are saved for the complete mix temperature rise, eq. 2.43 after the volume integration is completed.

SECTION 4.0 INPUT DATA INSTRUCTIONS

The TIC-TOC-TOE program utilizes standard FORTRAN input statements. A variety of formats are used. Each format utilizes various combinations of the following data fields:

1) hollerith information: A4 field (4 columns)
2) integer data: I3 field (3 columns)
3) floating point data: E9.0 field (9 columns)

NOTE: For floating point data entered without a decimal point, the decimal point is assumed to be to the right of the data field.

In preparing data, it should be remembered that all blanks in integer or floating point fields are interpreted as zeros. Therefore, all integers (including exponents of floating point numbers) must be right adjusted.

Each physical data card is written on the output file as soon as it is read from the input file. The resulting printout includes the information in card columns (cc) 73 through 80 of the data cards. Since TIC-TOC-TOE does not print details of problem data except for the input cards, prolific use of card labeling is desirable. A note of warning: in obtaining the card identification from cc 73-80, all unused data fields in cc 1-72 are interpreted as data and these unused fields should be blank or contain valid data punches.

CARD A, First title card for labeling the printout

NOTE: This card is always required

COLUMN	FORMAT	SYMBOL	DEFINITION
1-80	20A4	---	Any desired information for problem identification--this will appear on the first line of each output page.

CARD B, Second title card for labeling the printout

NOTE: This card is always required

COLUMN	FORMAT	SYMBOL	DEFINITION
1-80	20A4	---	Any desired information for problem identification. This will appear on the second line of each output page.

CARD 0, Input controls for data cards

NOTE: This card is always required

COLUMN	FORMAT	SYMBOL	DEFINITION
1-3	I3	IN1	Input control for Card 1, comments. IN1 ≤ 0, do not input Card 1. IN1 > 0, input Card 1.
4-6	I3	IN2	Input control for Card 2, limits and options. IN2 ≤ 0, do not input Card 2. IN2 > 0, input Card 2.
7-9	I3	IN3	Input control for Card 3, point source location. IN3 ≤ 0, do not input Card 3. IN3 > 0, input Card 3.
10-12	I3	IN4	Input control for Card 4, polar angles for fluxes. IN4 ≤ 0, omit Card 4. IN4 > 0, input Card 4.
13-15	I3	IN5	Input control for Card 5, polar fluxes. IN5 ≤ 0, omit Card 5. IN5 > 0, input Card 5.
16-18	I3	IN6	Input control for Card 6, flux scaling factors. IN6 ≤ 0, omit Card 6. IN6 > 0, input Card 6.
19-21	I3	IN7	Input control for Card 7, tank wall cross section. IN7 ≤ 0, omit Card 7. IN7 > 0, input Card 7.
22-24	I3	IN8	Input control for Card 8, tank wall source. IN8 ≤ 0, omit Card 8. IN8 > 0, input Card 8.
25-27	I3	IN9	Input control for Card 9, cubic buildup. IN9 ≤ 0, omit Card 9. IN9 > 0, input Card 9.
28-30	I3	IN10	Input control for Card 10, tank geometry. IN10 ≤ 0, omit Card 10. IN10 > 0, input Card 10.
31-33	I3	IN11	Input control for Card 11, point detectors. IN11 ≤ 0, omit Card 11. IN11 > 0, input Card 11.

CARD 0, Input controls for data cards (continued)

COLUMN	FORMAT	SYMBOL	DEFINITION
34-72	13I3	---	These columns are not used and should be left blank.
73-80	2A4	---	Any desired information for card identification.

CARD 1, Comments

NOTES:
a) omit this card if IN1 ≤ 0
b) supply IN1 physical cards if IN1 > 0.

COLUMN	FORMAT	SYMBOL	DEFINITION
1-72	18A4	---	Any information for description of problem.
73-80	2A4	---	Any information for card identification.

CARD 2, Limits and options.

NOTES:
a) omit this card if IN2 ≤ 0.
b) supply this card if IN2 > 0.

COLUMN	FORMAT	SYMBOL	DEFINITION
1-3	I3	NAMAX	Number of angles used to tabulate fluxes defining point angular sources 2 ≤ NAMAX ≤ 25.
4-6	I3	NRMAX	Number of conical and cylindrical sections of the tank 1 ≤ NRMAX ≤ 24.
7-9	I3	NTOE	Capture gamma ray calculation option. NTOE = 0, do not calculate. NTOE = 1, calculate.
10-12	I3	NPOINT	Number of discrete points in the tank--described on Card 11. 0 ≤ NPOINT ≤ 100.
13-15	I3	NVOLYM	Volume integration option to obtain heating distributions, total heating and temperature rise. NVOLYM = 0, do not integrate. NVOLYM = 1, integrate.

CARD 2, continued

COLUMN	FORMAT	SYMBOL	DEFINITION
16-18	I3	NIZMAX	Number of intervals in the axial integration to obtain heating distributions.
19-21	I3	NIRMAX	Number of intervals in the radial integration to obtain heating distributions.
22-24	I3	NITMAX	Number of intervals in the azimuthal integration to obtain heating distributions. Use NITMAX = 1.
25-27	I3	IPMAX	Number of intervals in the polar integration to obtain capture gamma ray heating (discrete points on Card 11 have their own limit).
28-30	I3	ITMAX	Number of intervals in the azimuthal integration to obtain capture gamma ray heating.
31-33	I3	ISMAX	Number of intervals in the distance integration to obtain capture gamma ray heating.
34-72	13I3	---	These columns are not used and should be left blank.
73-80	2A4	---	Any information for card identification.

CARD 3, Point source location and other parameters.

NOTES: a) omit this card if IN3 $\leq$ 0.
b) supply this card if IN3 > 0.

COLUMN	FORMAT	SYMBOL	DEFINITION
1-9	E9.0	XS(1)	X-coordinate of the source point (ft). use XS(1) = 0.0.
10-18	E9.0	XS(2)	Y-coordinate of the source point (ft). use XS(2) = 0.0.
19-27	E9.0	XS(3)	Z-coördinate of the source point (ft).
28-36	E9.0	RADIUS	Distance from source point for which polar fluxes are tabulated (ft).
37-45	E9.0	WALL	Tank wall thickness (ft).
46-54	E9.0	ADUM1	Volumetric flow rate (ft^3/sec)

CARD 3, continued

COLUMN	FORMAT	SYMBOL	DEFINITION
55-63	E9.0	ADUM2	Specific heat of propellant (watt sec·cm^{-3}·degree^{-1})
64-72	E9.0	---	These columns are not used and should be left blank.
73-80	2A4	---	Any information for card identification.

CARD 4, Polar angles at which polar fluxes are tabulated

NOTES:
a) omit this card if IN3 $\leq$ 0.
b) supply this card if IN3 $>$ 0.

COLUMN	FORMAT	SYMBOL	DEFINITION
1-72	8E9.0	CSA(1)	First polar angle at which fluxes are tabulated. CSA(1) = 0.0.
		CSA(2)	Second polar angle at which fluxes are tabulated. CSA(2) > CSA (1)
		• • •	• • •
		CSA(NAMAX)	Last polar angle at which fluxes are tabulated.
73-80	2A4	---	Any information for card identification.

CARD 5, Fluxes at discrete polar angles

NOTES:
a) omit these cards if IN5 $\leq$ 0.
b) supply these cards if IN5 $>$ 0, one for each polar angle and in the order of the increasing polar angles (NAMAX physical cards).

COLUMN	FORMAT	SYMBOL	DEFINITION
1-72	8E9.0	FLUX(1,I)	6 Mev photon flux at polar angle CSA(I) (photons/cm^{2}sec).
		FLUX(2,I)	3 Mev photon flux at polar angle CSA(I) (photons/cm^2 sec).
		FLUX(3,I)	1 Mev photon flux at polar angle CSA(I) (photons/cm^{2}sec).

CARD 5, continued

COLUMN	FORMAT	SYMBOL	DEFINITION
		FLUX(4,I)	7 Mev neutron flux at polar angle CSA(I) $(\frac{\text{neutrons}}{\text{cm}^2\ \text{sec}})$
		FLUX(5,I)	3 Mev neutron flux at polar angle CSA(I) (neutrons/cm^2 - sec)
		FLUX(6,I)	1 Mev neutron flux at polar angle CSA(I) (neutrons/cm^2 - sec)
		FLUX(7,I)	0.1 Mev neutron flux at polar angle CSA(I) (neutrons/cm^2 - sec)
		FLUX(8,I)	thermal neutron flux at polar angle CSA(I) (neutrons/cm^2 - sec)
73-80	2A4	---	Any information for card identification.

CARD 6, Flux scaling factors.

NOTES:
a) omit this card if IN6 $\leq$ 0.
b) supply this card if IN6 $>$ 0.
c) all numbers on this card are used and should be non-zero.

COLUMN	FORMAT	SYMBOL	DEFINITION
1-72	8E9.0	FAC(1)	Multiplicative scaling factor for group 1 input fluxes (6 Mev gammas) if they were not in the right units.
		FAC(2)	Multiplicative scaling factor for group 2 input fluxes (3 Mev gammas) in case they were not in the right units.
		• • •	
		FAC(8)	Multiplicative scaling factor for group 8 input fluxes (thermal neutrons) in case they were not in the right units.
73-80	2A4	---	Any information for card identification.

CARD 7, Tank wall cross sections

NOTES: a) omit this card if IN7 ≤ 0.
b) supply this card if IN7 > 0

COLUMN	FORMAT	SYMBOL	DEFINITION
1-72	8E9.0	SGT(1)	Attenuation coefficient of tank wall for group 1 sources (cm^{-1})
		SGT(2)	Attenuation coefficient of tank wall for group 2 sources (cm^{-1})
		• • •	
		SGT(8)	Attenuation coefficient of tank wall for group 8 sources (cm^{-1})
73-80	2A4	---	any information for card identification

CARD 8, Tank wall capture gamma source

NOTES: a) omit this card if IN8 ≤ 0
b) supply this card if IN8 > 0

COLUMN	FORMAT	SYMBOL	DEFINITION
1-72	8E9.0	ENG	Tank wall capture gamma ray energy (Mev)
		ACF	Attenuation coefficient of liquid hydrogen for tank wall capture gamma (cm^{-1})
		EAC	Energy absorption coefficient of liquid hydrogen for tank wall capture gamma (cm^{-1})
		FRA(1)	Fraction of 7 Mev neutrons removed by tank wall that are captured in wall
		FRA(2)	Fraction of 3 Mev neutrons removed by tank wall that are captured in the wall
		• • •	

CARD 8 (Continued)

COLUMN	FORMAT	SYMBOL	DEFINITION
		FRA(5)	Fraction of thermal neutrons removed by tank wall that are captured in the wall
73-80	2A4	---	Any information for card identification

CARD 9, Tank wall capture gamma buildup factor

NOTES: a) omit this card if IN9 ≤ 0

b) supply this card if IN9 > 0

COLUMN	FORMAT	SYMBOL	DEFINITION
1-36	4E9.0	BUF(1)	Constant term in cubic build representation
		BUF(2)	Coefficient of linear term in buildup
		BUF(3)	Coefficient of squared term in buildup
		BUF(4)	Coefficient of cubed term in buildup
37-72	4E9.0	---	These columns are not used and should be left blank
73-80	2A4	---	Any information for card identification

CARD 10, Tank geometry description

NOTES: a) omit this card if IN10 ≤ 0

b) supply this card (s) if IN10 > 0

COLUMN	FORMAT	SYMBOL	DEFINITION
1-72	8E9.0	ARE(1)	Radius of bottom of first tank section (ft)
		ZEE(1)	Height of bottom of first tank section (ft)
		ARE(2)	Radius of top of first tank section (ft) (= radius of bottom of second tank section)
		ZEE(2)	Height of top of first tank section (ft) (= height of bottom of second tank section)
		⋮	

CARD 10 (Continued)

COLUMN	FORMAT	SYMBOL	DEFINITION
		ARE(NRMAX + 1)	Radius of top of last tank section (ft)
		ZEE(NRMAX + 1)	Height of top of last tank section (ft)
73-80	2A4	----	Any information for card identification

CARD 11, Detector point parameters

NOTES: a) omit this card if IN11 ≤ 0

b) supply this card for IN11 points if IN11 > 0

COLUMN	FORMAT	SYMBOL	DEFINITION
1-3	I3	I	Index of point being described
4-6	I3	INT(1, I)	Intervals in polar integration for capture gammas
7-9	I3	INT(2, I)	Intervals in azimuthal integration for capture gammas
10-12	I3	INT(3, I)	Intervals in distance integration for capture gammas
13-18	---	---	These columns are not used
19-27	E9.0	XD(1, I)	x coordinate of point (ft)
28-36	E9.0	XD(2, I)	y coordinate of point (ft)
37-45	E9.0	XD(3, I)	z coordinate of point (ft)
54-72	3E9.0	----	These columns are not used
73-80	2A4		Any information for card identification

NOTE: Use either x = 0.0 and y = radius
or x = radius and y = 0.0

SECTION
5.0 SAMPLE PROBLEM

This sample problem is one of several calculations performed in the checkout of the TIC-TOC-TOE program. This particular problem does not employ all of the options coded in the program.

5.1 PROBLEM DESCRIPTION

This problem employed the propellant tank model described in Volume 1 of this report. The equivalent angular point sources were defined from fluxes obtained from the KAP-V point kernel program described in Volume 4.

The data cards for this problem are not shown since the data on the cards appear in the printout shown in Table 1. The first page of the printout, labeled CASE 1, PAGE 1 in the upper right hand corner, contains the input data. The first two lines of the printout contain the descriptive information as supplied on data cards A and B.

The remainder of the lines on this first printout page correspond to data cards 0 through 11. The printout contains the data in the same form as it was entered -- with one exception; the card identification in card columns 73-80 appears on the left side of the printout and is followed by three periods. Note: some of the data cards did not contain identification punches.

Two major characteristics of this problem are noted: (1) the neutron sources are input as zeros, and (2) the tank wall was not treated.

5.2 CALCULATED RESULTS

Discrete Points

The remainder of the Table 1 contains selected pages of the printout of the computed heating rates. The page identified as CASE 1, PAGE 2 contains pointwise heating rates for the individual points defined via card type 11. The columns on this printout page contain the point number, the point coordinates (radius and height) and the heating rates in watts/cm^3

TABLE 1

TIC-TOC-TOE SAMPLE PROGRAM

```
TIC-TOC FOR NR-1 MSFC TANK 15 FEET SEPARATION  CASE 1                        **TICTOC AND TOE**CASE     1
GAMMA ONLY--GAMMA FROM KAP 10 FEET CORE + SEC                                *ASTRONUCLEAR LAB*PAGE     1

0      ...    0    1    1    1    1    1    1    1    1    1   10   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0
2      ...    7    7    0   10    1  100   33    0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0
3      ...  0.           0.           0.           1.0000E+01   0.           6.7200E+01   1.0700E+04   -0.
4      ...  0.           1.0000E+01   2.0000E+01   3.0000E+01   4.0000E+01   5.0000E+01   6.0000E+01
5 1    ...  9.4000E+11   3.5000E+12   4.5000E+12   0.           0.           0.           0.           0.
5 2    ...  9.4000E+11   3.3000E+12   4.3000E+12   0.           0.           0.           0.           0.
5 3    ...  9.1000E+11   3.0000E+12   3.9000E+12   0.           0.           0.           0.           0.
5 4    ...  1.3000E+12   3.4000E+12   4.7000E+12   0.           0.           0.           0.           0.
5 5    ...  1.9000E+12   6.3000E+12   9.8000E+12   0.           0.           0.           0.           0.
5 6    ...  2.5000E+12   1.2000E+13   2.6000E+13   0.           0.           0.           0.           0.
5 7    ...  3.0000E+12   1.7000E+13   4.8000E+13   0.           0.           0.           0.           0.
6      ...  1.0000E+00   1.0000E+00   1.0000E+00   1.0000E+00   1.0000E+00   1.0000E+00   1.0000E+00   1.0000E+00
7      ... -0.          -0.          -0.          -0.          -0.          -0.          -0.          -0.
8      ... -0.          -0.          -0.          -0.          -0.          -0.          -0.          -0.
9      ... -0.          -0.          -0.          -0.
10     ...  1.0000E+00   1.5000E+01   4.0000E+00   1.5800E+01   6.5000E+00   1.7000E+01   8.2000E+00   1.8500E+01
10     ...  1.3000E+01   2.3100E+01   1.5000E+01   2.6000E+01   1.6000E+01   3.0000E+01   1.6000E+01   6.0000E+01
11 1   ...    1   -0   -0   -0         0.           0.           1.5100E+01  -0.          -0.          -0.
11 2   ...    2   -0   -0   -0         0.           0.           1.5500E+01  -0.          -0.          -0.
11 3   ...    3   -0   -0   -0         0.           0.           1.6000E+01  -0.          -0.          -0.
11 4   ...    4   -0   -0   -0         0.           0.           1.8000E+01  -0.          -0.          -0.
11 5   ...    5   -0   -0   -0         0.           0.           2.0000E+01  -0.          -0.          -0.
11 6   ...    6   -0   -0   -0         0.           0.           2.6500E+01  -0.          -0.          -0.
11 7   ...    7   -0   -0   -0         0.           0.           3.1500E+01  -0.          -0.          -0.
11 8   ...    8   -0   -0   -0         7.2000E+00   0.           1.7500E+01  -0.          -0.          -0.
11 9   ...    9   -0   -0   -0         1.2400E+01   0.           2.2400E+01  -0.          -0.          -0.
11 10  ...   10   -0   -0   -0         1.6000E+01   0.           3.0000E+01  -0.          -0.          -0.
```

```
TIC-TOC FOR NR-1 MSFC TANK 15 FEET SEPARATION  CASE 1                                  **TICTOC AND TOE**CASE    1
GAMMA ONLY--GAMMA FROM KAP 10 FEET CORE + SEC                                          *ASTRONUCLEAR LAB*PAGE    2

POINT      RADIUS     HEIGHT  6 MEV G  3 MEV G  1 MEV G  7 MEV N  3 MEV N  1 MEV N HYDROGEN     WALL      TOTAL
INDEX      (FEET)     (FEET)  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC    WATT/CC
    1      0.0000    15.1000 7.37E-04 1.75E-03 1.34E-03 0.       0.       0.       0.       0.        3.83E-03
    2      0.0000    15.5000 7.00E-04 1.66E-03 1.23E-03 0.       0.       0.       0.       0.        3.59E-03
    3      0.0000    16.0000 6.55E-04 1.55E-03 1.11E-03 0.       0.       0.       0.       0.        3.32E-03
    4      0.0000    18.0000 4.99E-04 1.17E-03 7.20E-04 0.       0.       0.       0.       0.        2.39E-03
    5      0.0000    20.0000 3.76E-04 8.65E-04 4.60E-04 0.       0.       0.       0.       0.        1.70E-03
    6      0.0000    26.5000 1.49E-04 3.09E-04 1.01E-04 0.       0.       0.       0.       0.        5.59E-04
    7      0.0000    31.5000 7.60E-05 1.35E-04 3.05E-05 0.       0.       0.       0.       0.        2.42E-04
    8      7.2000    17.5000 4.90E-04 1.12E-03 7.81E-04 0.       0.       0.       0.       0.        2.39E-03
    9     12.4000    22.4000 3.81E-04 7.43E-04 4.92E-04 0.       0.       0.       0.       0.        1.62E-03
   10     16.0000    30.0000 1.12E-04 1.43E-04 4.58E-05 0.       0.       0.       0.       0.        3.01E-04
```

```
TIC-TOC FOR NR-1 MSFC TANK 15 FEET SEPARATION  CASE 1                              **TICTOC AND TOE**CASE     1
GAMMA ONLY--GAMMA FROM KAP 10 FEET CORE + SEC                                      *ASTRONUCLEAR LAB*PAGE     3

POINT      RADIUS      HEIGHT  6 MEV G  3 MEV G  1 MEV G  7 MEV N  3 MEV N  1 MEV N HYDROGEN     WALL      TOTAL
INDEX      (FEET)      (FEET)  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC    WATT/CC
    1      0.0000     15.0000 7.46E-04 1.77E-03 1.37E-03 0.       0.       0.       0.       0.        3.89E-03
    2      0.1768     15.0000 7.41E-04 1.77E-03 1.36E-03 0.       0.       0.       0.       0.        3.87E-03
    3      0.2501     15.0000 7.38E-04 1.77E-03 1.36E-03 0.       0.       0.       0.       0.        3.86E-03
    4      0.3063     15.0000 7.37E-04 1.76E-03 1.35E-03 0.       0.       0.       0.       0.        3.85E-03
    5      0.3537     15.0000 7.35E-04 1.76E-03 1.35E-03 0.       0.       0.       0.       0.        3.85E-03
    6      0.3954     15.0000 7.34E-04 1.76E-03 1.35E-03 0.       0.       0.       0.       0.        3.84E-03
    7      0.4332     15.0000 7.33E-04 1.76E-03 1.35E-03 0.       0.       0.       0.       0.        3.84E-03
    8      0.4679     15.0000 7.32E-04 1.76E-03 1.34E-03 0.       0.       0.       0.       0.        3.83E-03
    9      0.5002     15.0000 7.31E-04 1.76E-03 1.34E-03 0.       0.       0.       0.       0.        3.83E-03
   10      0.5305     15.0000 7.30E-04 1.75E-03 1.34E-03 0.       0.       0.       0.       0.        3.83E-03
   11      0.5592     15.0000 7.29E-04 1.75E-03 1.34E-03 0.       0.       0.       0.       0.        3.82E-03
   12      0.5865     15.0000 7.28E-04 1.75E-03 1.34E-03 0.       0.       0.       0.       0.        3.82E-03
   13      0.6126     15.0000 7.28E-04 1.75E-03 1.34E-03 0.       0.       0.       0.       0.        3.82E-03
   14      0.6376     15.0000 7.27E-04 1.75E-03 1.34E-03 0.       0.       0.       0.       0.        3.81E-03
   15      0.6617     15.0000 7.26E-04 1.75E-03 1.33E-03 0.       0.       0.       0.       0.        3.81E-03
   16      0.6849     15.0000 7.26E-04 1.75E-03 1.33E-03 0.       0.       0.       0.       0.        3.81E-03
   17      0.7074     15.0000 7.25E-04 1.75E-03 1.33E-03 0.       0.       0.       0.       0.        3.80E-03
   18      0.7291     15.0000 7.24E-04 1.75E-03 1.33E-03 0.       0.       0.       0.       0.        3.80E-03
   19      0.7503     15.0000 7.24E-04 1.75E-03 1.33E-03 0.       0.       0.       0.       0.        3.80E-03
   20      0.7708     15.0000 7.23E-04 1.74E-03 1.33E-03 0.       0.       0.       0.       0.        3.80E-03
   21      0.7909     15.0000 7.23E-04 1.74E-03 1.33E-03 0.       0.       0.       0.       0.        3.79E-03
   22      0.8104     15.0000 7.22E-04 1.74E-03 1.33E-03 0.       0.       0.       0.       0.        3.79E-03
   23      0.8295     15.0000 7.22E-04 1.74E-03 1.33E-03 0.       0.       0.       0.       0.        3.79E-03
   24      0.8481     15.0000 7.21E-04 1.74E-03 1.32E-03 0.       0.       0.       0.       0.        3.79E-03
   25      0.8664     15.0000 7.21E-04 1.74E-03 1.32E-03 0.       0.       0.       0.       0.        3.78E-03
   26      0.8842     15.0000 7.20E-04 1.74E-03 1.32E-03 0.       0.       0.       0.       0.        3.78E-03
   27      0.9017     15.0000 7.20E-04 1.74E-03 1.32E-03 0.       0.       0.       0.       0.        3.78E-03
   28      0.9189     15.0000 7.19E-04 1.74E-03 1.32E-03 0.       0.       0.       0.       0.        3.78E-03
   29      0.9358     15.0000 7.19E-04 1.74E-03 1.32E-03 0.       0.       0.       0.       0.        3.77E-03
   30      0.9523     15.0000 7.18E-04 1.74E-03 1.32E-03 0.       0.       0.       0.       0.        3.77E-03
   31      0.9686     15.0000 7.18E-04 1.73E-03 1.32E-03 0.       0.       0.       0.       0.        3.77E-03
   32      0.9846     15.0000 7.17E-04 1.73E-03 1.32E-03 0.       0.       0.       0.       0.        3.77E-03
   33      1.0004     15.0000 7.17E-04 1.73E-03 1.32E-03 0.       0.       0.       0.       0.        3.77E-03
RADIAL AVERAGES       15.0000 7.26E-04 1.75E-03 1.33E-03 0.       0.       0.       0.       0.        3.81E-03
VOLUME AVERAGES       15.0000 7.26E-04 1.75E-03 1.33E-03 0.       0.       0.       0.       0.        3.81E-03
RADIAL AVERAGED NO-MIX TEMPERATURE RISE TO OUTLET AND CORRESPONDING TIME................ 0.        0.
   34      0.0000     15.4500 7.04E-04 1.67E-03 1.25E-03 0.       0.       0.       0.       0.        3.62E-03
```

```
TIC-TOC FOR NR-1 MSFC TANK 15 FEET SEPARATION  CASE 1                                   **TICTOC AND TOE**CASE     1
GAMMA ONLY--GAMMA FROM KAP 10 FEET CORE + SEC                                           *ASTRONUCLEAR LAB*PAGE   101

POINT      RADIUS    HEIGHT  6 MEV G  3 MEV G  1 MEV G  7 MEV N  3 MEV N  1 MEV N HYDROGEN     WALL    TOTAL
INDEX      (FEET)    (FEET)  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC  WATT/CC
 3327     14.4222   60.0000 2.26E-06 4.93E-07 1.09E-08 0.       0.       0.       0.       0.       2.76E-06
 3328     14.6969   60.0000 2.22E-06 4.76E-07 1.04E-08 0.       0.       0.       0.       0.       2.70E-06
 3329     14.9666   60.0000 2.18E-06 4.60E-07 1.00E-08 0.       0.       0.       0.       0.       2.65E-06
 3330     15.2315   60.0000 2.14E-06 4.44E-07 9.57E-09 0.       0.       0.       0.       0.       2.59E-06
 3331     15.4919   60.0000 2.10E-06 4.29E-07 9.18E-09 0.       0.       0.       0.       0.       2.54E-06
 3332     15.7480   60.0000 2.06E-06 4.14E-07 8.79E-09 0.       0.       0.       0.       0.       2.49E-06
 3333     16.0000   60.0000 2.03E-06 3.98E-07 8.39E-09 0.       0.       0.       0.       0.       2.44E-06
RADIAL AVERAGES     60.0000 2.86E-06 6.69E-07 1.58E-08 0.       0.       0.       0.       0.       3.55E-06
VOLUME AVERAGES     60.0000 6.11E-05 1.12E-04 4.85E-05 0.       0.       0.       0.       0.       2.21E-04
RADIAL AVERAGED NO-MIX TEMPERATURE RISE TO OUTLET AND CORRESPONDING TIME.................. 2.70E-01 4.61E+02
TOTALS (WATTS)............. 5.36E+04 9.78E+04 4.25E+04 0.       0.       0.       0.       0.       1.94E+05
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 0.       0.
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 1.05E-03 5.39E+00
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 5.30E-03 1.08E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 7.45E-03 1.62E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 1.18E-02 2.15E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 1.40E-02 2.69E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 1.85E-02 3.23E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 2.07E-02 3.77E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 2.53E-02 4.31E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 2.76E-02 4.85E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 3.23E-02 5.39E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 3.47E-02 5.92E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 3.95E-02 6.46E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 4.19E-02 7.00E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 4.69E-02 7.54E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 4.94E-02 8.08E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 5.44E-02 8.62E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 5.70E-02 9.16E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 6.22E-02 9.69E+01
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 6.49E-02 1.02E+02
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 7.03E-02 1.08E+02
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 7.30E-02 1.13E+02
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 7.85E-02 1.18E+02
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 8.13E-02 1.24E+02
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 8.70E-02 1.29E+02
COMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME...................................... 8.99E-02 1.35E+02
```

for the 3 gamma ray groups, the 3 fast neutron groups (zero for this problem), the propellant capture gammas, and the tank wall capture gammas, respectively. The last column is the total heating rate.

Volume Integration

The next part of the printout contains quantities obtained from the volume integration. The page identified by CASE 1, PAGE 3 contains the first part of the results of this integration. The major portion of this pase is the pointwise heating rate as obtained during the area integration over the bottom of the tank. These results are read in the same manner as the preceding page for points entered via Card type 11.

The three lines following the discrete points 1 through 33 contain the area averaged heating rates (watts/cm^3) at the tank bottom, the volume averaged heating rates (watts/cm^3) for all the propellant below the indicated height of 15 feet, and the radial averaged temperature rise and corresponding time (seconds) assuming no mixing of the propellant.

The printout for the volume integration proceeds in this manner for each z-plane generated during the volume integration. The page labeled CASE 1, PAGE 101 contains the final points generated in the area integration at the upper propellant level. After the usual summaries of radial and volume averaged heating rates and of no mix temperature rise, there is a summary of the total heating rate (watts) by energy group obtained from the volume integration.

After the summary line containing volume integrated heating rates, the complete mix temperature rise and time (seconds), respectively, are printed for each of the axial positions generated during the volume integration. The remainder of the printout for this problem consisted of similar complete-mix temperature rise results.

6.0 REFERENCES

1. M. O. Burrell, "Nuclear Radiation Transfer and Heat Deposition Rates in Liquid Hydrogen", NASA-TND-1115, August 1962.
2. H. C. Woodsum, P. C. Heiser, "Tank Heating Codes, TIC-TOC and TOE for the IBM-7090 Computer", WANL-TNR-083, January 1963.
3. "IBM 7090/7094 Programming Systems FORTRAN IV Language", C23-6274-1, May 1963.

APPENDIX A

LISTING OF PROGRAM

```
$IBFTC TICTAC  M94/2,XR7
CTICTOC*(T)EMPERATURE (I)N (C)OOLANT (T)ANK AND (O)THER (C)ALCULATIONS
      DATA PI/3.1415927/
      COMMON/INPUTS/IN1   ,IN2   ,IN3   ,IN4   ,IN5   ,IN6   ,IN7   ,
     1              IN8   ,IN9   ,IN10  ,IN11  ,IN12  ,IN13  ,IN14  ,
     2              IN15  ,IN16  ,IN17  ,IN18  ,IN19  ,IN20  ,IN21  ,
     3              IN22  ,IN23  ,IN24
      COMMON/TAPEID/M1    ,M2
      COMMON/CASEID/KASE  ,NPAGE ,LINES ,LINEX ,TITLEA(20)   ,TITLEB(20)
      COMMON/LIMITS/NAMAX ,NRMAX ,NTOE  ,NPOINT,NVOLYM,NIZMAX,NIRMAX,
     1              NITMAX,IPMAX ,ITMAX ,ISMAX ,LIM(13)
      COMMON/SOURCE/XS(3) ,RADIUS,WALL  ,ADUM1 ,ADUM2 ,ADUM3 ,CSA(25),
     1              FLUX(8,25)
      COMMON/REGION/ARE(25)      ,ZEE(25)
      DIMENSION INT(3,100),XD(3,100),ALP(3,100)
      DIMENSION X(3),C(3),FAC(8),ADM(18),H(2),OUT(9),HEAT(9)
      EQUIVALENCE (X(1),X1),(X(2),X2),(X(3),X3),(C(1),C1),(C(2),C2)
     1,(C(3),C3)
      COMMON/WALLAL/SGT(8),EWG,ACF,EAC,FRA(5),BUF(4)
      DIMENSION HRAD(9),VOL(1000),TIME(1000),DEP(1000)
      SIMSON(I,J) = FLOAT(4 - 2*(I - 2*(I/2)) - 1/I - I/J)
      M1 = 5
      M2 = 6
      KASE = 0
      LINEX = 40
      DO 5 I=1,10
    5 XYZ = (1.0E-30)**2
   10 READ(M1,1000)TITLEA,TITLEB
      KASE = KASE + 1
      NPAGE = 0
      LINES = LINEX + 1
      CALL READI(24,IN1)
      IF(IN1.LE.0)GO TO 30
      DO 20 I=1,IN1
   20 CALL READA(18,ADM)
   30 IF(IN2.GT.0)CALL READI(24,NAMAX)
      IF(IN3.GT.0)CALL READE(8,XS)
      IF(IN4.LE.0)GO TO 50
      CALL READE(NAMAX,CSA)
      DO 40 I=1,NAMAX
   40 CSA(I) = COS(CSA(I)*PI/180.0)
   50 IF(IN5.LE.0)GO TO 7C
      FST = 4.0*PI*(2.54*12.0*RADIUS)**2
      DO 60 I=1,NAMAX
      CALL READE(8,FLUX(1,I))
      DO 60 J=1,8
   60 FLUX(J,I) = FST*FLUX(J,I)
```

```
   70 IF(IN6.LE.0)GO TO 90                                                  048
      CALL READE(8,FAC)                                                     049
      DO 80 I=1,NAMAX                                                       050
      DO 80 J=1,8                                                           051
   80 FLUX(J,I) = FAC(J)*FLUX(J,I)                                          052
   90 IF(IN7.GT.0)CALL READE(8,SGT)                                         053
      IF(IN8.GT.0)CALL READE(8,EWG)                                         054
      IF(IN9.GT.0)CALL READE(4,BUF)                                         055
      IF(IN10.GT.0) CALL READEE(NRMAX+1,ARE,ZEE)                            056
      IF(IN11.LE.0) GO TO 110                                               057
      DO 100 N=1,IN11                                                       058
      READ(M1,1010)I,(INT(J,I),J=1,3),(XD(J,I),J= 1,3),(ALP(J,I),J=1,3),H   059
      IF(LABEL(1).GE.0)WRITE(M2,2000)H,I,(INT(J,I),J=1,3),(XD(J,I),J=1,3    060
     1),(ALP(J,I),J=1,3)                                                    061
  100 CONTINUE                                                              062
 1000 FORMAT(20A4)                                                          063
 1010 FORMAT(4I3,6X,6E9.0,2A4)                                              064
 2000 FORMAT(1X,2A4,3(1H.),4I4,8X,1P6E12.4)                                 065
  110 IF(NPOINT.LE.0)GO TO 130                                              066
      LINES = LINEX + 1                                                     067
C POINT DETECTORS                                                           068
      DO 120 I=1,NPOINT                                                     069
  120 CALL POINT(INT(1,I),ALP(1,I),XD(1,I),OUT,I)                           070
  130 IF(NVOLYM.EQ.0)GO TO 10                                               071
      LINES = LINEX + 1                                                     072
      N = 0                                                                 073
C VOLUME INTEGRATION                                                        074
      NIZMOD = MAX0(3,2*(NIZMAX/2)+1)                                       075
      NIRMOD = MAX0(3,2*(NIRMAX/2)+1)                                       076
      NITMOD = MAX0(1,2*(NITMAX/2)+1)                                       077
      DZ = (ZEE(NRMAX+1) - ZEE(1))/FLOAT(NIZMOD - 1)                        078
      DT = PI/FLOAT(MAX0(1,NITMOD-1))                                       079
      X3 = ZEE(1) - DZ                                                      080
      DO 140 J=1,9                                                          081
  140 HEAT(J) = 0.0                                                         082
      RSQUAP = 0.0                                                          083
      VOLTOT = 0.0                                                          084
      DO 160 III=1,NIZMOD                                                   085
      X3 = X3 + DZ                                                          086
      DO 145 J=1,9                                                          087
  145 HRAD(J) = 0.0                                                         088
      SRZ = SIMSON(III,NIZMOD)*DZ*30.48/3.0                                 089
      X1 = 0.0                                                              090
      X2 = 0.0                                                              091
      C1 = 1.0                                                              092
      C2 = 0.0                                                              093
      C3 = 0.0                                                              094
```

```
      RSQUAR = PATH(X,C)**2
      DRS = RSQUAR/FLOAT(NIRMOD - 1)
      RSQ = -DRS
      DO 150 JJJ=1,NIRMOD
      RSQ = RSQ + DRS
      R = SQRT(AMAX1(0.0,RSQ))
      SRR = SIMSON(JJJ,NIRMOD)*DRS*30.48**2/6.0
      THE = -DT
      DO 150 KKK=1,NITMOD
      THE = THE + DT
      X1 = R*COS(THE)
      X2 = R*SIN(THE)
      SRT = 2.0*PI
      IF(NITMOD.GT.1) SRT = SIMSON(KKK,NITMOD)*DT/1.5
      N = N + 1
      CALL POINT(IPMAX,ADUM1,X,OUT,N)
      SRA = SRT*SRR
      SRB = SRA*SRZ
      DO 150 J=1,9
      HRAD(J) = HRAD(J) + SRA*OUT(J)
  150 HEAT(J) = HEAT(J) + SRB*OUT(J)
      AREA = PI*RSQUAR*30.48**2
      DO 155 J=1,9
  155 HRAD(J) = HRAD(J)/AREA
      IF(LABEL(1).GE.0) WRITE(M2,2010)X3 ,HRAD
 2010 FORMAT(1X,16HRADIAL AVERAGES ,0PF10.4,1P9E9.2)
      VOLUME = PI*DZ*(RSQUAR + SQRT(RSQUAR*RSQUAP ) + RSQUAP)*30.48**3/3.
      RSQUAP = RSQUAR
      IF(III.EQ.1) VOLUME = 0.0
      VOLTOT = VOLTOT + VOLUME
      FST = DZ*30.48*AREA/3.0
      IF(III.GT.1) FST = VOLTOT
      DO 156 J=1,9
  156 HRAD(J) = HEAT(J)/FST
      IF(LABEL(1).GE.0) WRITE(M2,2020) X3 ,HRAD
 2020 FORMAT(1X,16HVOLUME AVERAGES ,0PF10.4,1P9E9.2)
      TIME(III) = VOLTOT/(ADUM1*30.48**3)
      TEMP = HEAT(9)/(ADUM1*ADUM2)
      IF(III.EQ.1) TEMP = 0.0
      IF(LABEL(1).GE.0) WRITE(M2,2030)TEMP,TIME(III)
 2030 FORMAT(1X,72HRADIAL AVERAGED NO-MIX TEMPERATURE RISE TO OUTLET AND
     1 CORRESPONDING TIME,17(1H.),1P2E9.2)
      DEP(III) = HRAD(9)*AREA  *SRZ
      IF(III.GT.1) DEP(III) = DEP(III) + DEP(III - 1)
  160 CONTINUE
      CALL OUTPUT(0,0.,0.,0.,HEAT)
      J = NIZMOD + 1
```

```
      DO 170 I=1,NIZMOD
      J = J - 1
      DELT = TIME(NIZMOD) - TIME(J)
      TEMP = (DEP(NIZMOD) - DEP(J))/(ADUM1*ADUM2)
      IF(LABEL(1).GE.0) WRITE (M2,2050)TEMP,DELT
 2050 FORMAT(1X,53HCOMPLETE MIX TEMPERATURE RISE AND CORRESPONDING TIME,
     136(1H.),1P2E9.2)
  170 CONTINUE
      GO TO 10
      END
$IBFTC XPOINT  M94/2,XR7
CPOINT VALUES OF HEATING
      SUBROUTINE POINT(INT,ALP,X,OUT,N)
      COMMON/RRRRRR/RADMAX
      COMMON/WALLAL/SGT(8),EWG,ACF,EAC,FRA(5),BUF(4)
      COMMON/TAPEID/M1     ,M2
      COMMON/CASEID/KASE   ,NPAGE ,LINES ,LINEX ,TITLEA(20)   ,TITLEB(20)
      COMMON/LIMITS/NAMAX ,NRMAX ,NTOE   ,NPOINT,NVOLYM,NIZMAX,NIRMAX,
     1              NITMAX,IPMAX ,ITMAX ,ISMAX ,LIM(13)
      COMMON/SOURCE/XS(3) ,RADIUS,WALL  ,ADUM1 ,ADUM2 ,ADUM3 ,CSA(25),
     1              FLUX(8,25)
      EQUIVALENCE (WALL,TWALL)
      COMMON/REGION/ARE(25)       ,ZEE(25)
      COMMON/ROTATE/THETAZ
      DIMENSION FLX(6),OUT(9),X(3),C(3)
      EQUIVALENCE (C(3),C3)
      DIMENSION AAA(72),AA(12,6)
      EQUIVALENCE (AA,AAA)
      DATA AAA                                                         /
     10.0       ,-0.0844  ,1.7      ,0.0      ,0.0      ,0.1828    ,
     20.000391  ,0.004375 ,0.18     ,3.555E-5 ,0.001592 ,0.0714    ,
     1-0.0017   ,-0.02    ,1.2      ,0.0      ,0.0      ,0.1755    ,
     20.0       ,0.0      ,0.0      ,0.0      ,0.0      ,0.0       ,
     1-0.0005   ,-0.025   ,0.72     ,0.0      ,0.0      ,0.25      ,
     20.0       ,0.0      ,0.0      ,0.0      ,0.0      ,0.0       ,
     10.0       ,-5.7     ,88.0     ,0.00434  ,-0.0411  ,1.547     ,
     20.05      ,3.95     ,-58.0    ,0.0089   ,-0.02    ,2.725     ,
     1-0.25     ,-0.15    ,66.0     ,0.0044   ,0.022    ,2.55      ,
     20.21      ,-0.25    ,-42.     ,0.0085   ,-0.0285  ,3.91      ,
     1-0.275    ,-0.1     ,66.0     ,0.003    ,0.125    ,5.18      ,
     20.26      ,-0.3     ,-52.0    ,0.0054   ,0.148    ,7.23      /
      COMMON/NORMAL/DSN
      DO 115 J=1,9
  115 OUT(J) = 0.0
      STD = VECTOR(X,XS,C)
      STW = PATH(X,C)
      R = 0.0
```

```
      DO 130 J=1,2                                                          189
  130 R = R + X(J)**2                                                       190
      R = SQRT(R)                                                           191
      THE = 0.0                                                             192
      IF(R.GT.0.0) THE = ATAN2(X(2),X(1))                                   193
      THETAZ = THE                                                          194
      PSI = -C3                                                             195
      Z = PSI*STW                                                           196
      FST =((Z + 11.25)**2 + R**2)/STD**2                                   197
      Q = R                                                                 198
      DO 140 J=2,NAMAX                                                      200
      IF(PSI.GE.CSA(J))GO TO 150                                            201
  140 CONTINUE                                                              202
      J = NAMAX                                                             203
  150 K = J - 1                                                             204
      FST = FST/(CSA(K) - CSA(J))                                           205
      AST = FST*(PSI - CSA(J))                                              206
      BST = FST*(CSA(K) - PSI)                                              207
      TTW = 30.48*TWALL/DSN                                                 208
      DO 160 L=1,6                                                          209
  160 OUT(L)=6.43E-22*CURVE(R,Z,AA(1,L),0.0)                                210
     1                                 *(AST*FLUX(L,K)+BST*FLUX(L,J))       211
     1*EXP(-TTW*SGT(L))                                                     212
      IF(NTOE.GT.0) CALL TOE(INT,ALP,X,OUT(7))                              213
      CALL OUTPUT(N,Q,THE,X(3),OUT)                                         214
  180 CONTINUE                                                              215
      RETURN                                                                216
      END                                                                   217
$IBFTC TOEHOE  M94/2,XR7                                                    218
CTOE   *CAPTURE GAMMA RAY HEATING                                           219
      SUBROUTINE TOE(INP,ALP,XX,OUT)                                        220
      COMMON/ROTATE/THETAZ                                                  221
      COMMON/LIMITS/NAMAX,LIM(23)                                           222
      COMMON/SOURCE/XS(3),RZERO,ADUMMY(4),CSA(25),FLUX(8,25)                223
      EQUIVALENCE (ADUMMY(1),TWALL)                                         224
      DIMENSION INP(3),ALP(3),XX(3),HDOT(5),INT(3),ALF(3),XD(3),UZERO(3)    225
     1,DEL(3),C(3),XMIN(3),XMAX(3),X(3),CP(3),CAP(5)                        226
      DATA XMIN/-1.0,0.0,0.0/,XMAX/1.0,3.141593,1.0/                        227
      EQUIVALENCE (INT(1),INTU),(INT(2),INTV),(INT(3),INTW)                 228
      COMMON/NORMAL/DSN                                                     229
      COMMON/WALLAL/SGT(8),EWG,ACF,EAC,FRA(5),BUF(4)                        230
      SIMSON(I,J) = FLOAT(4 - 2*(I - 2*(I/2)) - 1/I - I/J)/3.0              231
      DIMENSION OUT(2)                                                      232
      COMMON/RRRRRR/RACMAX                                                  233
      DO 10 I=1,3                                                           234
      ALF(I) = ALP(I)                                                       235
      XD(I) = XX(I)                                                         236
```

```
      INT(I) = INP(I) + 1
      UZERO(I) = XMIN(I)
   10 DEL(I) = (XMAX(I) - XMIN(I))/FLOAT(INT(I) - 1)
      FLXUVW = 0.0
      CAPUVW = 0.0
      DO 250 NNN=1,INTU
      U = UZERO(1) + FLOAT(NNN-1)*DEL(1)
      C(3) = U
      SNP = SQRT(1.0 - C(3)**2)
      FLXVW = 0.0
      CAPVW = 0.0
      DO 200 MMM=1,INTV
      V = UZERO(2) + FLOAT(MMM-1)*DEL(2)
      THE = V + THETAZ
      C(1) = SNP*COS(THE)
      C(2) = SNP*SIN(THE)
      XMAX(3) = PATH(XD,C)
      DSNW = DSN
      DEL(3) = (XMAX(3) - XMIN(3))/FLOAT(INT(3) - 1)
      FLXW = 0.0
      DO 150 LLL=1,INTW
      W = UZERO(3) + FLOAT(LLL -1)*DEL(3)
      S = W
      IF(LLL.GT.1.OR.(MMM+ NNN).LE.2) GO TO 30
      CAPT = FLUXZ
      GO TO 100
   30 STS = 0.0
      DO 40 I=1,3
      X(I) = XD(I) + C(I)*S
      CP(I) = XS(I) - X(I)
   40 STS = STS + CP(I)**2
      STM = SQRT(STS)
      DO 50 I=1,3
   50 CP(I) = CP(I)/STM
      STB = PATH(X,CP)
      RSQ = X(1)**2 + X(2)**2
      RAD = SQRT(RSQ)
      ZPR = -STB*CP(3)
      CALL GAMMAS(RAD,ZPR,CAP)
      PSI = -CP(3)
      DO 60 I=2,NAMAX
      IF(PSI  .GT.CSA(I))GO TO 70
   60 CONTINUE
      I = NAMAX
   70 AST =(PSI - CSA(I))/(CSA(I-1) - CSA(I))
      BST =(CSA(I-1) - PSI)/(CSA(I-1) - CSA(I))
      TTW = 30.48*TWALL/DSN
```

```
      CAPW = 0.0
      CAPT = 0.0
      DO 80 J=1,5
      ATN = EXP(-TTW*SGT(J+3))
      FLX = ATN*(AST*FLUX(J+3,I-1) + BST*FLUX(J+3,I))
      CAPT = CAPT + FLX*CAP(J)
   80 CAPW = CAPW + FLX*(1./ATN-1.)*FRA(J)
C CAPTURES IN TANK
      CAPT=CAPT*5.46E-15*(1.+S*(.13636+S*5.33E-4) )*EXP(-.1771*S)
     1          *(RSQ+(ZPR+11.25)**2)/STS
C
      IF(LLL.EQ.1) FLUXZ = CAPT
  100 FLXW = FLXW + CAPT *DEL(3)*SIMSON(LLL,INTW)
  140 CAPZ = 0.0
      IF(LLL.LT.INTW) GO TO 150
      IF(STB.GT.0.01) GO TO 150
      IF(DSNW.LT.0.01) GO TO 150
C CAPTURES IN WALL, BUILDUP AND ATTENUATION
      BUP = BUF(4)
      XMP = S*ACF*30.48
      DO 141 I=1,3
      J = 4 - I
  141 BUP = XMP*BUP + BUF(J)
      CAPZ=CAPW*2.17E-18*EWG*EAC*BUP*EXP(-XMP)*DSN/(DSNW*STS)
C
  150 CONTINUE
      SRC = DEL(2)*SIMSON(MMM,INTV)
      FLXVW = FLXVW + SRC*FLXW
      CAPVW = CAPVW + SRC*CAPZ
  190 VP = V
  200 CONTINUE
      IF(FLXVW.EQ.0.0) GO TO 999
      SRC = DEL(1)*SIMSON(NNN,INTU)
      FLXUVW = FLXUVW + SRC*FLXVW
      CAPUVW = CAPUVW + SRC*CAPVW
  240 UP = U
  250 CONTINUE
  999 OUT(1) = FLXUVW
      OUT(2) = CAPUVW
      RETURN
      END
$IBFTC CAPGAM  M94/2,XR7
CGAMMAS*CAPTURE GAMMA SOURCES
      SUBROUTINE GAMMAS(R,Z,S)
      DIMENSION S(5),AAA(60),AA(12,5),BBB(6),BB(3,2)     ,CUT(5)
      EQUIVALENCE (AA,AAA),(BB,BBB)
      DATA CUT,BBB,AAA                                               /
```

```
     11.0E+30   ,1.0       ,0.833     ,1.0E+30   ,1.0E+30              ,        331
     20.0       ,0.032     ,2.47      ,0.0088    ,0.048     ,8.34      ,        332
     10.0       ,-0.058    ,1.14      ,0.0       ,0.036     ,1.42      ,        333
     20.0       ,0.057     ,-1.11     ,0.0       ,0.046     ,1.82      ,        334
     10.0       ,-0.041    ,0.9       ,0.001368  ,0.0382    ,2.107     ,        335
     20.0       ,0.039     ,-0.85     ,-0.000295 ,0.0683    ,3.547     ,        336
     10.0       ,-0.115    ,2.27      ,0.0       ,0.134     ,3.44      ,        337
     20.0       ,0.113     ,-2.22     ,0.0       ,0.196     ,4.8       ,        338
     10.00498   ,-0.245    ,3.12      ,0.0       ,0.0       ,7.67      ,        339
     2-0.00448  ,0.22      ,-2.83     ,0.0       ,0.0       ,12.38     ,        340
     10.0183    ,-0.683    ,10.0      ,0.0573    ,-0.233    ,22.2      ,        341
     2-0.0153   ,0.483     ,-6.5      ,0.108     ,-0.5      ,30.6      /        342
      DO 10 I=1,5                                                               343
      FST = 0.0                                                                 344
      IF(((I-2)*(I-3)).NE.0) GO TO 10                                           345
      ZP = CUT(I) - Z                                                           346
      IF(ZP.GE.0.0) GO TO 10                                                    347
      DO 20 J=1,3                                                               348
   20 FST = R*FST + BB(J,I-1)                                                   349
   10 S(I) = 1.0E-7*CURVE(R,AMIN1(CUT(I),Z),AA(1,I),ZP*FST)                     350
      RETURN                                                                    351
      END                                                                       352
$IBFTC ONTPUT  M94/2,XR7                                                        353
COUTPUT*PRINTOUT OF PCINT HEATING RATES*T.M.JORDAN*WANL*DECEMBER 1966***        354
      SUBROUTINE OUTPUT(N,ARE,THE,ZEE,DOT)                                      355
      COMMON/TAPEID/M1    ,M2                                                   356
      DIMENSION DOT(9)                                                          357
      THET = THE                                                                358
      DOT(9) = 0.0                                                              359
      DO 10 J=1,8                                                               360
      DOT(J) = AMAX1(0.0,DOT(J))
   10 DOT(9) = DOT(9) + DOT(J)                                                  361
      IF(LABEL(1).GT.0) WRITE(M2,2000)                                          362
      IF(N.EQ.0) GO TO 20                                                       363
      WRITE(M2,2010)N,ARE,ZEE,DOT                                               364
      GO TO 40                                                                  365
   20 WRITE(M2,2020)DOT                                                         366
   40 RETURN                                                                    367
 2000 FORMAT(1X,107HPOINT     RADIUS    HEIGHT  6 MEV G  3 MEV G  1 MEV         369
     1G  7 MEV N  3 MEV N  1 MEV N HYDROGEN     WALL    TOTAL/1X,6HINDEX        370
     2 ,2(10H    (FEET)),9(9H  WATT/CC))                                        371
 2010 FORMAT(I6,0PF11.4,F10.4,1P9E9.2)                                          372
 2020 FORMAT(1X,14HTOTALS (WATTS),12(1H.),1P9E9.2)                              373
      END                                                                       374
$IBFTC TRACE   M94/2,XR7                                                        375
CPATH  * PATH LENGTH IN TANK                                                    376
      FUNCTION PATH(XP,CP)                                                      377
```

```
      COMMON/LIMITS/NAMAX,NRMAX,NPOINT,LIM(21)
      COMMON/REGION/ARE(25),ZEE(25)
      DIMENSION XP(3),CP(3),X(3),C(3)
      COMMON/RRRRRR/RADMAX
      DIMENSION XN(3),CN(3)
      COMMON/NORMAL/DSN
      DSN = ABS(CP(3))
      DO 10 I=1,3
      X(I) = XP(I)
   10 C(I) = CP(I)
      X(3) = AMAX1(ZEE(1)+0.0001,X(3))
      X(3) = AMIN1(ZEE(NRMAX+1)-0.0001,X(3))
      DO 20 I=1,NRMAX
      IF(ZEE(I+1).GT.X(3))GO TO 30
   20 CONTINUE
      I = NRMAX
   30 RADMAX = ARE(I) + (X(3) - ZEE(I))*(ARE(I+1)-ARE(I))/(ZEE(I+1) -
     1ZEE(I))
      IF(C(3)) 40,50,60
   40 MIN = 1
      MAX = I
      STM = (ZEE(1) - X(3))/C(3)
      GO TO 70
   50 MIN = I
      MAX = I
      STM = 1.0E+30
      GO TO 70
   60 MIN = I
      MAX = NRMAX
      STM = (ZEE(NRMAX+1) - X(3))/C(3)
   70 RADACT = SQRT(X(1)**2 + X(2)**2)
      IF(RADACT.LT.RADMAX) GO TO 79
      FST =(RADMAX - 0.0001)/RADACT
      DO 75 I=1,2
   75 X(I) = X(I)*FST
   79 DO 110 I = MIN,MAX
      AA = (ARE(I+1) - ARE(I))/(ZEE(I+1) - ZEE(I))
      BB = ARE(I) - AA*ZEE(I)
      Z = AA*X(3) + BB
      ZC = AA*C(3)
      AQ = C(1)**2 + C(2)**2 - ZC**2
      BQ = Z*ZC - X(1)*C(1) - X(2)*C(2)
      CQ = X(1)**2 + X(2)**2 - Z**2
      IF(AQ.NE.0.0)GO TO 80
      IF(BQ.EQ.0.0)GO TO 110
      SP = 2.0*CQ/BQ
      GO TO 90
```

```
   80 BQ = BQ/AQ
      CQ = BQ**2 - CQ/AQ
      IF(CQ.LE.0.0)GO TO 110
      CQ = SQRT(CQ)
      SP = BQ - CQ
      IF(SP.GT.0.0)GO TO 100
      SP = BQ + CQ
   90 IF(SP.LT.0.0)GO TO 110
  100 IF(SP.GT.STM) GO TO 110
      DO 101 J=1,3
      XN(J) = X(J) + SP*C(J)
  101 CN(J) = XN(J)
      CN(3) = - AA*(AA*XN(3) + BB)
      FST = 0.0
      GST = 0.0
      DO 102 J=1,3
      FST = FST + C(J)*CN(J)
  102 GST = GST + CN(J)**2
      IF(FST.LE.0.0) GO TO 110
      JJ = J
      STM = SP
      DSN = FST/SQRT(GST)
  110 CONTINUE
      PATH = STM
      RETURN
      END
$IBFTC LABLE    M94/2,XR7
CLABEL *OUTPUT PAGE HEADINGS FOR PROGRAM FASTER*T.M.JORDAN*WANL*OCT.1966
      FUNCTION LABEL(LINE)
      COMMON/TAPEID/M1    ,M2
      COMMON/CASEID/KASE  ,NPAGE ,LINES ,LINEX ,TITLEA(20)   ,TITLEB(20)
      L = IABS(LINE)
      IF(LINE.LE.0)GO TO 10
      LINES = LINES + L
      LABEL = 0
      IF(LINES.LE.LINEX)GO TO 20
   10 LINES = L + 3
      NPAGE = NPAGE + 1
      LABEL = 1
      WRITE(M2,2000)TITLEA,KASE,TITLEB,NPAGE
 2000 FORMAT(1H1,20A4,22H**TICTOC AND TOE**CASE,I5/1X,20A4,22H*ASTRONUCL
     1EAR LAB*PAGE,I5/1X,1H )
   20 RETURN
      END
$IBFTC VECTR    M94/2,XR7
CVECTOR *UNIT VECTOR
      FUNCTION VECTOR(X,Y,C)
```

```
      DIMENSION X(3),Y(3),C(3)
      FST = 0.0
      DO 10 I=1,3
      C(I) = Y(I) - X(I)
   10 FST = FST + C(I)**2
      FST = SQRT(FST)
      DO 20 I=1,3
   20 C(I) = C(I)/FST
      VECTOR = FST
      RETURN
      END
$IBFTC IREAD    M94/2,XR7
CREADI *INTEGER INPUT, 24I3 FORMAT
      SUBROUTINE READI(MAX,IDM)
      COMMON/TAPEID/M1     ,M2
      DIMENSION IDM(10000),H(2)
      DO 30 I=1,MAX,24
      MOD = I + 23
      IF(MOD.GT.MAX)GO TO 10
      READ(M1,1000)(IDM(J),J=I,MOD),H
      GO TO 20
   10 JMX = MOD - MAX
      MOD = MAX
      READ(M1,1000)(IDM(J),J=I,MOD),(K,J=1,JMX),H
   20 IF(LABEL(1).GE.0)WRITE(M2,2000)H,(IDM(J),J=I,MOD)
   30 CONTINUE
 1000 FORMAT(24I3,2A4)
 2000 FORMAT(1X,2A4,3H...,24I4)
      RETURN
      END
$IBFTC EREAD    M94/2,XR7
CREADE *FLOATING INPUT, 8E9.0 FORMAT
      SUBROUTINE READE(MAX,ADM)
      COMMON/TAPEID/M1     ,M2
      DIMENSION ADM(10000),H(2)
      DO 30 I=1,MAX,8
      MOD = I + 7
      IF(MOD.GT.MAX)GO TO 10
      READ(M1,1000)(ADM(J),J=I,MOD),H
      GO TO 20
   10 JMX = MOD - MAX
      MOD = MAX
      READ(M1,1000)(ADM(J),J=I,MOD),(X,J=1,JMX),H
   20 IF(LABEL(1).GE.0)WRITE(M2,2000)H,(ADM(J),J=I,MOD)
   30 CONTINUE
 1000 FORMAT(8E9.0,2A4)
 2000 FORMAT(1X,2A4,3H...,1P8E12.4)
```

```
      RETURN
      END
$IBFTC AREAD   M94/2,XR7
CREADA *HOLLERITH INPUT, 18A4 FORMAT
      SUBROUTINE READA(MAX,ADM)
      COMMON/TAPEID/M1    ,M2
      DIMENSION ADM(10000),H(2)
      DO 30 I=1,MAX,18
      MOD = I + 17
      IF(MOD.GT.MAX)GO TO 10
      READ(M1,1000)(ADM(J),J=I,MOD),H
      GO TO 20
   10 JMX = MOD - MAX
      MOD = MAX
      READ(M1,1000)(ADM(J),J=I,MOD),(X,J=1,JMX),H
   20 IF(LABEL(1).GE.0)WRITE(M2,2000)H,(ADM(J),J=I,MOD)
   30 CONTINUE
 1000 FORMAT(20A4)
 2000 FORMAT(1X,2A4,27(1H.),18A4)
      RETURN
      END
$IBFTC EEREAD  M94/2,XR7
CREADEE*ALTERNATING FLOATING INPUT, 8E9.0 FORMAT
      SUBROUTINE READEE(MAX,ADM,BDM)
      DIMENSION ADM(10000),BDM(10000),CDM(2,4)
      K= 0
      DO 10 I=1,MAX,4
      MOD = MIN0(4,MAX-K)
      CALL READE(2*MOD,CDM)
      DO 10 J=1,MOD
      K = K + 1
      ADM(K) = CDM(1,J)
   10 BDM(K) = CDM(2,J)
      RETURN
      END
$IBFTC CURVFT  M94/2,XR7
CCURVE FIT EVALUATION FOR TIC TOC AND TOE
      FUNCTION CURVE(R,Z,A,ARG)
      DATA KOUNT/0/
      DIMENSION A(3,2,2),RAD(2)
      EQUIVALENCE (RAD(1),GST),(RAD(2),HST)
      FST = 0.0
      DO 20 I=1,2
      DO 10 J=1,2
      RAD(J) = 0.0
      DO 10 K=1,3
   10 RAD(J) = R*RAD(J) + A(K,J,I)
```

```
      X = ARG - Z*HST
      IF(X.LT.-200.0) X = -200.0
      IF(X.LE.100.C) GC TC 2C
      KOUNT = KCUNT + 1
      IF(KOUNT.GT.100) GO TC 2C
      IF(LABEL(3).GE.0) WRITE(6,2000)R,Z,ARG,GST,HST,X,A
 2000 FORMAT(1X,1P6E14.6)
   20 FST = FST + GST*EXP(X)
      CURVE = FST
      RETURN
      END
```