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RADGEN: A Radiation Exchange Factor Generator for Rod Bundles

October 1987

**Prepared for the U.S. Department of Energy
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**Pacific Northwest Laboratory
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RADGEN: A RADIATION EXCHANGE FACTOR
GENERATOR FOR ROD BUNDLES

D. R. Rector

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ABSTRACT

The RADGEN computer program has been developed at Pacific Northwest Laboratory (PNL) to generate input required for the thermal radiation models used in the COBRA-SFS (Spent Fuel Storage) computer program. The COBRA-SFS program uses radiation exchange factors to describe the net amount of energy transferred from each surface to every other surface in an enclosure. The RADGEN program generates radiation exchange factors for arrays of rods on a square or triangular pitch as well as open channel geometries. This report describes the input requirements for the RADGEN code, which may be executed in a batch or interactive mode, and outlines the solution procedure used to obtain the exchange factors.

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NOMENCLATURE

Symbols and Notations

- δ - Kronecker delta
- ϵ - surface emissivity
- σ - Stephan-Boltzmann constant (Btu/h-ft² - R⁴)
- A - area (ft²)
- D,d - fuel rod diameter (ft)
- F - blackbody viewfactor
- F - radiation exchange factor
- n - number of surfaces
- PDR - pitch-to-diameter ratio
- Q - total heat transfer rate
- T - temperature (R)
- X - rod-to-wall distance (ft)

Subscripts

- i,j,k - surface indices
- n,m - partial-rod-indices

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1.0 INTRODUCTION

The COBRA-SFS (Spent Fuel Storage) computer program (Rector, Wheeler and Lombardo 1986) was designed to accurately predict flow and temperature distributions in spent nuclear fuel storage systems. The decay heat generated by the spent fuel in a storage system is removed through a combination of conduction, natural convection, and thermal radiation. In many spent fuel storage systems, thermal radiation is a significant (and sometimes the dominant) mode of heat transfer. Therefore, an accurate numerical model of radiation heat transfer within the system is required to adequately predict the temperature field within the storage system.

The COBRA-SFS program uses radiation exchange factors to define the net amount of energy transferred from each surface to every other surface in an enclosure. This report describes the RADGEN computer routine, which has been developed at Pacific Northwest Laboratory (PNL)(a) for the U.S. Department of Energy to generate radiation exchange factors for a wide variety of spent fuel rod geometries.

Section 2.0 of the report describes the mathematical models used to define radiation heat transfer in spent fuel storage systems. The input instructions for the RADGEN computer program are presented in Section 3.0. The parameters used to dimension the code are described in Section 4.0. Section 5.0 describes the verification of the code using calculated and analytical results for each of the geometry types.

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2.0 PROGRAM DESCRIPTION

This section describes the mathematical models for radiation heat transfer in spent fuel storage systems. A description of the types of geometries that can be modeled is provided in Section 2.1. The equations and solution procedure used to calculate the radiation exchange factors are presented in Section 2.2, and a discussion of how to combine exchange factors for surface groups is found in Section 2.3.

2.1 RADIATION SURFACE GEOMETRIES

Geometries modeled using the RADGEN program are divided into three categories: rods on a square pitch, rods on a triangular pitch, and open channels. Rods on a square pitch are typical of a spent fuel assembly from a commercial nuclear power reactor, while geometries with rods on a triangular pitch represent a consolidated spent fuel canister or an assembly from a liquid metal reactor. Open channels are used where there are no rod bundles and no shadowing of other surfaces. The axial length of each enclosure is assumed to be large compared with the transverse lengths so that the geometry can be modeled using a set of two-dimensional viewfactors.

To model an enclosure, the rod surface areas and surrounding shroud must be divided into discrete radiation surfaces. Each surface acts independently in emitting, absorbing, and reflecting radiant energy. The accuracy of the heat transfer model is sensitive to how the surfaces have been divided because it is assumed that reflected energy, regardless of its source, is uniform over the entire surface. For example, when the typical rod shown in Figure 2.1a is modeled using one radiation surface, incoming radiation is uniformly reflected in all directions, which is not a physically representative model. In reality, the incident radiation is reflected from, at most, half of the rod surface, and the reflected intensity is dependent on the angle of incidence. Subdivision of the rod into several surfaces results in a more realistic representation of the distribution of reflected energy. For example, the rod in Figure 2.1b is divided into four independent surfaces.

FIGURE 2.1. Radiation Surface Models for a Typical Spent Fuel Rod

A radiation surface is characterized by blackbody viewfactors that are defined as the fraction of radiation leaving one surface that reaches another surface. Viewfactors are automatically generated in RADGEN using expressions based on nondimensional geometric parameters such as the pitch-to-diameter ratio (PDR). The expressions used in the code for the base viewfactors were developed using the cross-string method (McAdams 1954). An example of how one of these expressions is derived is presented in Appendix A.

For rods on a square pitch, each rod is modeled using four quarter-rod surfaces, and the surface area of the surrounding shroud is also divided into n discrete radiation surfaces, where n is the number of rows plus columns of fuel rods multiplied by four. The radiation surface model used to represent a typical 7 x 7 rod bundle is shown in Figure 2.2. The distribution of quarter-rod viewfactors for a typical originating surface, s , that sees a total of 15 other surfaces, is shown in Figure 2.3. The farthest surface that can directly receive radiation is assumed to be three rows from the originating surface. The analytical expressions used to calculate the blackbody viewfactors between the originating surface and each of the other surfaces are presented in Table 2.1. The calculated viewfactor from the originating surface to the outermost surface, h , includes the viewfactors to all the surfaces beyond surface h . This is done to conserve radiant energy.

TABLE 2.1. Quarter Rod Blackbody Viewfactor Expressions

Blackbody Viewfactor	PDR(a) Range	Expression
F_{s-a}	1.0-1.21	$4/\pi \{ [2PDR^2 - 2PDR + 1]^{0.5} - 2[PDR^2 - PDR]^{0.5} + ATAN2[PDR^2 - PDR]^{0.5} \} - 1.0$
	>1.21	$4/\pi \{ [2PDR^2 - 2PDR + 1]^{0.5} - [2PDR^2 - 2PDR + 0.5]^{0.5} \}$
F_{s-b}	1.0-1.29	$1/\pi \{ [2PDR^2 - PDR]^{0.5} - ATAN[2PDR^2 - PDR]^{0.5} - ATAN[(2PDR-1)/2PDR] - 2[PDR^2 - PDR]^{0.5} + ATAN2[PDR-PDR]^{0.5} - 2[PDR^2 - 1]^{0.5} + 2ATAN[PDR^2 - 1]^{0.5} \} - 0.5 * F_{s-a}$
	>1.29	$1.0 - \pi \{ 2[PDR^2 - PDR]^{0.5} - ATAN2[2PDR^2 - PDR]^{0.5} \}$
F_{s-c}	all	$2/\pi \{ 2[PDR^2 - PDR]^{0.5} - ATAN[2(PDR^2 - PDR)]^{0.5} - 2PDR + 1.0 + \pi/2 \}$
F_{s-d}	all	$2/\pi \{ [PDR^2 - 1]^{0.5} - ATAN[PDR^2 - 1]^{0.5} - 2[PDR^2 - PDR]^{0.5} + ATAN2[PDR^2 - PDR]^{0.5} + PDR - 1.0 \}$
F_{s-e}		Same as F_{s-b}

(a) PDR = pitch-to-diameter ratio

TABLE 2.1. (contd)

Blackbody Viewfactor	PDR(a) Range	Expression
F_{s-f}	all	$\left[\text{MAX}[0., 1/\pi\{2(\text{PDR}-1) - 2[\text{PDR}^2 - \text{PDR}]^{0.5}\right. \\ \left. + \text{ATAN2}[\text{PDR}^2 - \text{PDR}]^{0.5}\} - F_{s-d} - F_{s-e}] \right]$
F_{s-g}	all	$2/\pi \{ (5\text{PDR}^2 - 1)^{0.5} - \text{ATAN}[(5\text{PDR}^2 - 1)^{0.5}] \\ - 2(2\text{PDR}^2 - 1)^{0.5} - \text{ATAN}[(2\text{PDR}^2 - 1)^{0.5}] \\ + (\text{PDR}^2 - 1)^{0.5} - \text{ATAN}[(\text{PDR}^2 - 1)^{0.5}] \\ - \text{ATAN}(0.5) \}$
F_{s-h}	all	$1/2 \{ 1 - F_{s-a} - 2[F_{s-b} + F_{s-c} + F_{s-d} + F_{s-e} \\ + F_{s-f} + F_{s-g}] \}$

(a) PDR = pitch-to-diameter ratio

Similar expressions have been developed to calculate the viewfactors from rod surfaces to the surrounding wall surfaces. The distribution of viewfactors to a receiving wall surface, s , is shown in Figure 2.4. Each wall surface sees 11 quarter-rod surfaces. The analytical expressions used to calculate the viewfactors between surfaces are presented in Table 2.2. The expressions are based on another nondimensional parameter, the rod-wall gap-to-radius ratio (XR).

To reduce the volume required for spent nuclear fuel storage, spent fuel rods are removed from their assembly structure to form a close-packed triangular array in a canister. Typically, the canister has a square cross section of the approximate dimensions of the original fuel assembly. This process is known as rod consolidation.

A nominal consolidated rod geometry is assumed to consist of a square cross-section canister containing rods on alternating long and short rows. The radiation surface model used to represent a consolidated canister containing 33 rods is shown in Figure 2.5. Figure 2.6 shows the viewfactor distribution for each one-sixth rod surface. A total of 17 surfaces are seen by an originating surface. The expressions used to calculate the blackbody viewfactors from the originating surface to each of the other surfaces are presented in Table 2.3. The distribution of viewfactors to a receiving wall surface, s , is shown in Figure 2.7. Each wall surface sees 8 one-sixth rod surfaces. The analytical expressions used to calculate the viewfactors between surfaces are presented in Table 2.4.

After the base viewfactors have been calculated, an array of blackbody viewfactors from every surface i to every surface j in the enclosure F_{ij} is constructed. This array is used in the computation of radiation exchange factors.

FIGURE 2.4. Viewfactor Distribution from Quarter Rods to Wall Surface

TABLE 2.2. Rod-to-Wall Viewfactor Expressions for Rods in Square Arrays

Blackbody Viewfactor	XR(a) (b) Range	Expression
F_{1-s}	all	$\frac{1}{\pi} \{ [PDR^2 + XR^2]^{0.5} + [(XR^2 + 1)^{0.5} - ATAN[(XR + 1)^2 - 1]^{0.5} - [(PDR - 1)^2 + (XR + 1)^2]^{0.5} - XR \} + 0.5$
F_{2-s}	all	$\frac{1}{\pi} \{ (4PDR^2 + XR^2)^{0.5} + [(PDR - 1)^2 + (XR + 1)^2]^{0.5} - [(2PDR - 1)^2 + (XR + 1)^2]^{0.5} - [PDR^2 + XR^2]^{0.5} \}$
F_{3-s}	all	$\frac{1}{\pi} \{ [PDR^2 + (XR + 1)^2 - 1]^{0.5} - ATAN[PDR^2 + (XR + 1)^2 - 1]^{0.5} + XR - [PDR^2 + XR^2]^{0.5} - [(XR + 1)^2 - 1]^{0.5} + ATAN[(XR + 1)^2 - 1]^{0.5} + ATAN[PDR/(XR + 1)] \}$
F_{4-s}	all	$\frac{1}{\pi} \{ [PDR^2 + XR^2]^{0.5} - [PDR^2 + (XR + 1)^2 - 1]^{0.5} + ATAN[PDR^2 + (XR + 1)^2 - 1]^{0.5} - ATAN[PDR/(XR + 1)] \}$

(a) PDR = pitch-to-diameter ratio, $XR = 2X/D$

(b) $C1 = (3PDR - 1)/(PDR^2 - PDR)^{0.5} - 1$, $C2 = (4PDR - 1)/(PDR^2 - PDR)^{0.5} - 1$

TABLE 2.2. (contd)

Blackbody Viewfactor	XR(a)(b) Range	Expression
F_{5-s}	$<C1$	$1/\pi \{ [9PDR^2 + XR^2]^{0.5} + [(2PDR - 1)^2 + (XR + 1)^2]^{0.5} - [PDR^2 + (XR + 1)^2 - 1]^{0.5} + ATAN[PDR^2 + (XR + 1)^2 - 1]^{0.5} - [(2PDR - 1)^2 - 1]^{0.5} + ATAN [(2PDR - 1)^2 - 1]^{0.5} - [4PDR^2 + XR^2]^{0.5} - ATAN[PDR/(XR + 1)] \} - 0.5$
	$>C1$	$1/\pi \{ [9PDR^2 + XR^2]^{0.5} + [(2PDR - 1)^2 + (XR + 1)^2]^{0.5} - [(3PDR - 1)^2 + (XR + 1)^2]^{0.5} - [4PDR^2 + XR^2]^{0.5} \}$
F_{6-s}	$<C1$	$1/\pi \{ [16PDR^2 + XR^2]^{0.5} + [PDR^2 + (XR + 1)^2 - 1]^{0.5} - ATAN[PDR^2 + (XR + 1)^2 - 1]^{0.5} + ATAN[PDR/(XR + 1)] - [9PDR^2 + XR^2]^{0.5} + [4PDR^2 + (XR + 1)^2 - 1]^{0.5} + ATAN[4PDR^2$

(a) PDR = pitch-to-diameter ratio, $XR = 2X/D$

(b) $C1 = (3PDR - 1)/(PDR^2 - PDR)^{0.5} - 1$, $C2 = (4PDR - 1)/(PDR^2 - PDR)^{0.5} - 1$

TABLE 2.2. (contd)

Blackbody Viewfactor	XR(a) (b) Range	Expression
		$+ (XR + 1)^2 - 1]^{0.5} - \text{ATAN}[2\text{PDR}/(XR + 1)]\}$
	$C1 < XR < C2$	$1/\pi \{ [16\text{PDR}^2 + \text{XR}^2]^{0.5} + [(3\text{PDR} - 1)^2$ $+ (XR + 1)^2]^{0.5} - [9\text{PDR}^2 + \text{XR}^2]^{0.5}$ $- [(2\text{PDR} - 1)^2 - 1]^{0.5} - [4\text{PDR}^2 + (XR + 1)^2$ $- 1]^{0.5} + \text{ATAN}[4\text{PDR}^2 + (XR + 1)^2 - 1]^{0.5}$ $+ \text{ATAN}[(2\text{PDR} - 1)^2 - 1]^{0.5}$ $- \text{ATAN}[(2\text{PDR}/(XR + 1))]\} - 0.5$
	$> C2$	$1/\pi \{ [(3\text{PDR} - 1)^2 + (XR + 1)^2]^{0.5} + [16\text{PDR}^2$ $+ \text{XR}^2]^{0.5} - [(4\text{PDR} - 1)^2 + (XR + 1)^2]^{0.5}$ $- [9\text{PDR}^2 + \text{XR}^2]^{0.5} \}$
F_{7-s}	$< C2$	$1/\pi \{ 2\text{PDR} + [4\text{PDR}^2 + (XR + 1)^2 - 1]^{0.5} - \text{ATAN}$

(a) PDR = pitch-to-diameter ratio, $\text{XR} = 2X/D$

(b) $C1 = (3\text{PDR} - 1)/(\text{PDR}^2 - \text{PDR})^{0.5} - 1$, $C2 = (4\text{PDR} - 1)/(\text{PDR}^2 - \text{PDR})^{0.5} - 1$

TABLE 2.2. (contd)

Blackbody Viewfactor	XR(a) (b) Range	Expression
		$[4PDR^2 + (XR + 1)^2 - 1]^{0.5} - [16PDR^2 + XR^2]^{0.5}$ $+ ATAN[2PDR/(XR + 1)]\}$
	$\geq C2$	$1/\pi \{2PDR + [4PDR^2 + (XR + 1)^2]^{0.5} - [(2PDR - 1)^2$ $- 1]^{0.5} + ATAN[2PDR - 1)^2 - 1]^{0.5}$ $- [16PDR^2 + XR^2]^{0.5}\} - 0.5$
F_{8-s}	all	$1/\pi \{[(2PDR - 1)^2 + (XR + 1)^2]^{0.5} - [4PDR^2$ $+ (XR + 1)^2 - 1]^{0.5} + ATAN[4PDR^2 + (XR + 1)^2$ $- 1]^{0.5} + ATAN[2PDR/(XR + 1)]\} - 0.5$
F_{9-s}	all	$1/\pi \{[4PDR^2 + (XR + 1)^2 - 1]^{0.5} - ATAN[4PDR^2$ $+ (XR + 1)^2 - 1]^{0.5} - ATAN[2PDR/(XR + 1)]$ $+ (2PDR^2 - 1)^{0.5} - ATAN(2PDR^2 - 1)^{0.5}$

(a) PDR = pitch-to-diameter ratio, $XR = 2X/D$

(b) $C1 = (3PDR - 1)/(PDR^2 - PDR)^{0.5} - 1$, $C2 = (4PDR - 1)/(PDR^2 - PDR)^{0.5} - 1$

TABLE 2.2. (contd)

Blackbody Viewfactor	XR(a) (b) Range	Expression
		$- 2(\text{PDR}^2 - 1)^{0.5} + 2\text{ATAN}(\text{PDR}^2 - 1)^{0.5}$
		$- [(2\text{PDR} - 1)^2 + (\text{X/R} + 1)^2]^{0.5} + 0.5$
F_{10-s}	all	$F_{s-g} + F_{s-h}^{(c)}$
F_{11-s}	all	F_{s-h}

-
- (a) PDR = pitch-to-diameter ratio, $\text{XR} = 2\text{X/D}$
 (b) $\text{C1} = (3\text{PDR} - 1)/(\text{PDR}^2 - \text{PDR})^{0.5} - 1$, $\text{C2} = (4\text{PDR} - 1)/(\text{PDR}^2 - \text{PDR})^{0.5} - 1$
 (c) F_{s-g} and F_{s-h} are defined in Table 2.1.

FIGURE 2.5. Radiation Surface Model for a Typical Consolidated Rod Canister

FIGURE 2.6. Blackbody Viewfactor Distribution for Each One-Sixth Rod Surface

TABLE 2.3. One-Sixth Rod Blackbody Viewfactor Expressions

Blackbody Viewfactor	PDR(a) Range	Expression
F_{s-a}	1.0-1.08	$3/\pi \{ \pi/6 - PDR + 1 \}$
	1.08	$1/\pi \{ 2[PDR^2 - PDR]^{0.5} - ATAN2[PDR^2 - PDR]^{0.5} 2PDR + 1.5 + \pi/3 \}$
F_{s-b}	1.0-1.50	$1/\pi \{ PDR^2 - 1 \}^{0.5} - ATAN[PDR^2 - 1]^{0.5} - 2[PDR^2 - PDR]^{0.5} + ATAN2[PDR^2 - PDR]^{0.5} + PDR - 1.0 \}$
F_{s-c}	1.0-1.08	$3/2\pi \{ 2[PDR^2 - PDR]^{0.5} - ATAN2[PDR^2 - PDR]^{0.5} - 2[PDR^2 - 1]^{0.5} + 2ATAN[PDR^2 - 1]^{0.5} \}$
	>1.08	$3/2\pi \{ 2PDR - 1.0 - [4PDR^2 - 2PDR]^{0.5} + ATAN[4PDR^2 - 2PDR]^{0.5} + ATAN[\sqrt{3}/4(PDR - 0.25)] - \pi/3 \}$
F_{s-d}	1.0-1.11	0.0
	>1.11	$3/2\pi \{ 2PDR - 1 - 2[PDR^2 - PDR]^{0.5} + ATAN2[PDR^2 - PDR]^{0.5} - 0.5 - F_{s-c} - 0.5F_{s-g} \}$

(a) PDR = pitch-to-diameter ratio

TABLE 2.3. (contd)

Blackbody Viewfactor	PDR(a) Range	Expression
F_{s-e}	1.0-1.11	0.0
	>1.11	$0.5 - 6/\pi \{ [PDR^2 - 1]^{0.5} - ATAN[PDR^2 - 1]^{0.5} - PDR \}$ $+ 3.0 - 0.5F_{s-g} - 2 * F_{s-f}$
F_{s-f}	1.0-1.11	0.0
	>1.11	$3/\pi \{ [PDR^2 - 1]^{0.5} - ATAN[PDR^2 - 1]^{0.5} - PDR \}$ $+ 1.5 - F_{s-a} - F_{s-b} - 2 * F_{s-c}$
F_{s-g}		Same as F_{s-c}
F_{s-h}	1.0-1.11	$6/\pi \{ [3PDR^2 - 3PDR + 1] - 2[PDR^2 - PDR]^{0.5}$ $+ ATAN2[PDR^2 - PDR] - \pi/3 \}$
	>1.11	$6/\pi \{ [PDR^2 - 1]^{0.5} - ATAN[PDR^2 - 1]^{0.5} \}$
F_{s-i}		Same as F_{s-d}

(a) PDR = pitch-to-diameter ratio

FIGURE 2.7. Blackbody Viewfactor Distribution from One-Sixth Rods to Wall Surface

2.2 RADIATION EXCHANGE FACTORS

In COBRA-SFS, the radiation heat transfer between surfaces in an enclosure is modeled using radiation exchange factors where the net rate of radiant energy outflow from surface i to surface j , Q_{ij} , is defined in terms of an exchange factor, F_{ij} , as

$$Q_{ij} = A_i F_{ij} \sigma (T_i^4 - T_j^4) \quad (2.1)$$

The quantity F_{ij} specifies the total amount of radiant energy emitted from surface i that reaches surface j and is absorbed. This includes all the paths by which radiation may reach surface j from surface i ; that is, the direct

TABLE 2.4. Rod-to-Wall Viewfactor Expressions for Rods in Triangular Arrays

Blackbody Viewfactor	XR(a) (b) Range	Expression
F_{1-s}	<C1	$3/2\pi \{ [PDR^2 + (XR + 1)^2 - 1]^{0.5} - ATAN[PDR^2 + (XR + 1)^2 - 1]^{0.5} + ATAN[PDR/(XR + 1)] - [(XR + 1 - 3/2)^2 + (PDR - 0.5)^2]^{0.5} \} + 0.25$
	>C1	$3/2\pi \{ [(XR + 1 - 3/2)^2 + (PDR + 0.5)^2]^{0.5} - [(XR + 1 - 3/2)^2 + (PDR - 0.5)^2]^{0.5} \}$
F_{2-s}	<C2	$3/2\pi \{ [(XR + 1 - 3/2)^2 + (PDR - 0.5)^2]^{0.5} - [(SR + 1)^2 + (PDR - 1)^2]^{0.5} \} + 0.5$
	>C2	$3/2\pi \{ [(XR + 1 - 3/2)^2 + (PDR - 0.5)^2]^{0.5} + [(XR + 1)^2 - 1]^{0.5} - ATAN[(XR + 1)^2 - 1]^{0.5} - [(XR + 1)^2 + (PDR - 1)^2]^{0.5} - [(XR + 1 - 3/2)^2 + 0.25]^{0.5} \} + 0.75$

(a) PDR = pitch-to-diameter ratio, $XR = 2X/D$

(b) $C1 = (PDR + 0.5)/\sqrt{3} + 1 - \sqrt{3}/2$

TABLE 2.4. (contd)

Blackbody Viewfactor	XR(a) (b) Range	Expression
F_{3-s}	All	$3/2\pi \{ [(XR + 1 - 3/2)^2 + 0.25]^{0.5} - [(XR + 1)^2 - 1]^{0.5} + \text{ATAN}[(XR + 1)^2 - 1]^{0.5} \} - 0.25$
F_{4-s}	<C1	$3/2\pi \{ 2\text{PDR} + [(XR + 1 - 3/2)^2 + (\text{PDR} - 0.5)^2]^{0.5} - [(\text{PDR} - 0.5)^2 - 0.25]^{0.5} + \text{ATAN}[(2\text{PDR} - 0.5)^2 - 0.25]^{0.5} + \text{ATAN}[3/2(2\text{PDR} - 0.5)] - [\text{PDR}^2 + (XR + 1)^2 - 1]^{0.5} + \text{ATAN}[\text{PDR}^2 + (XR + 1)^2 - 1]^{0.5} - \text{ATAN}[\text{PDR}/(XR + 1)] \} - 0.75$
	>C1	$3/2\pi \{ 2\text{PDR} + [(XR + 1 - 3/2)^2 + (\text{PDR} - 0.5)^2]^{0.5} - [(\text{PDR} - 0.5)^2 - 0.25]^{0.5} + \text{ATAN}[(2\text{PDR} - 0.5)^2 - 0.25]^{0.5} + \text{ATAN}[3/2(2\text{PDR} - 0.5)] - [(XR + 1 - 3/2)^2 + (\text{PDR} + 0.5)^2]^{0.5} \} - 0.5$

- (a) PDR = pitch-to-diameter ratio, $XR = 2X/D$
(b) $C1 = (\text{PDR} + 0.5)/\sqrt{3} + 1 - \sqrt{3}/2$

TABLE 2.4. (contd)

Blackbody Viewfactor	XR(a) (b) Range	Expression
F_{5-s}	All	$3/2\pi \{ [(XR + 1)^2 + (PDR - 1)^2]^{0.5} + [(2PDR - 0.5)^2 - 0.25]^{0.5} - \text{ATAN}[(2PDR - 0.5)^2 - 0.25]^{0.5} - \text{ATAN}[3/2(2PDR - 0.5)] - [(XR + 1 - 3/2)^2 + (PDR - 0.5)^2]^{0.5} - [(2PDR - 1)^2 - 1]^{0.5} + \text{ATAN}[(2PDR - 1)^2 - 1]^{0.5} \}$
F_{6-s}	All	$3/2\pi \{ [(2PDR - 1)^2 - 1]^{0.5} - \text{ATAN}[(2PDR - 1)^2 - 1]^{0.5} - 2[PDR^2 - 1]^{0.5} + 2\text{ATAN}[PDR^2 - 1]^{0.5} \}$
F_{7-s}	All	$0.5 * F_{s-g} + F_{s-h} \quad (c)$
F_{8-s}	All	F_{s-d}

(a) PDR = pitch-to-diameter ratio, $XR = 2X/D$ (b) $C1 = (PDR + 0.5)/\sqrt{3} + 1 - \sqrt{3}/2$ (c) F_{s-d} , F_{s-g} , and F_{s-h} are defined in Table 2.3.

path, paths by means of one reflection, and paths by multiple reflections. For all black surfaces ($\epsilon = 1.0$), the two viewfactors and exchange factors are identical.

The radiation exchange factors, F_{ij} , are calculated from the geometry of the problem and the emissivities of the participating surfaces using the set of equations (Cox 1977)

$$\sum_{i=1}^n \left(F_{ki} \frac{1-\epsilon_i}{\epsilon_i} - \frac{\delta_{ki}}{\epsilon_i} \right) F_{ij} = F_{kj} \epsilon_j; \quad j = 1, \dots, n; \quad k = 1, \dots, n \quad (2.2)$$

where F_{ki} and F_{kj} are the blackbody view factors, ϵ_i is the emissivity of surface i , δ_{ki} is the Kronecker delta, and n is the total number of surfaces in an enclosure. The following assumptions were made in developing this equation:

- nonparticipating media
- isothermal, gray surfaces
- reflected and emitted radiation diffusely distributed
- uniform radiosity over each defined surface.

When a complete set of blackbody viewfactors and surface emissivities is used with Equation (2.2), a set of n^2 equations results. These equations are solved iteratively using the method of successive over-relaxation. An acceleration factor of 1.1 is used, and the solution is assumed to be converged when the maximum change in any exchange factor from one iteration to the next is less than $1 \times 10^{-6}\%$.

2.3 COMBINING EXCHANGE FACTORS

After the n^2 equation set is solved, the resulting set of quarter-rod gray body exchange factors is combined to obtain full-rod gray body exchange factors. The exchange factors are combined so that the total heat transferred from rod i to rod j , Q_{ij} , is equal to the sum of heat transfer from each quarter rod, n , of rod i to each quarter rod, m , of rod j :

$$Q_{ij} = \sum_{n=1}^4 \sum_{m=1}^4 Q_{nm} \quad (2.3)$$

The heat transferred from one quarter rod to another by radiation is

$$Q_{nm} = A \sigma F_{nm} (T_n^4 - T_m^4) \quad (2.4)$$

where F_{nm} are the quarter rod exchange factors. Assuming that rods i and j are isothermal and of equal diameter, the total heat transfer from rod i to rod j is written as

$$\begin{aligned} Q_{ij} &= \sum_{n=1}^4 \sum_{m=1}^4 \Delta x \frac{\pi d}{4} \sigma F_{nm} (T_i^4 - T_j^4) \\ &= \Delta x \frac{\pi d}{4} \sigma (T_i^4 - T_j^4) \sum_{n=1}^4 \sum_{m=1}^4 F_{nm} \end{aligned} \quad (2.5)$$

Recall that the total heat transfer from rod i to rod j is defined as

$$Q_{ij} = A \sigma F_{ij} (T_i^4 - T_j^4) \quad (2.1)$$

Equating Equations (2.5) and (2.1), the rod-to-rod radiation exchange factor F_{ij} is

$$F_{ij} = \frac{1}{4} \sum_{n=1}^4 \sum_{m=1}^4 F_{nm} \quad (2.6)$$

The final set of exchange factors is written to a file to be used as input to the COBRA-SFS code. This approach creates a model in COBRA-SFS that assumes

an isothermal rod surface temperature while allowing the radiosity to vary around the rod.

The idea of combining surfaces with similar temperatures can be extended to groups of rods or other surfaces. For example, if a rod bundle has a temperature distribution which is symmetric about its diagonal, the full-rod exchange factors for the full assembly may be combined to give a set of exchange factors for the half bundle. This procedure of combining exchange factors is possible when it can be assumed that the temperatures of the surfaces in each group are nearly equal.

3.0 INPUT INSTRUCTIONS

This section provides the input instructions for the RADGEN computer routine. The input is read either interactively or through a batch input file. When input is read interactively, questions are answered directly using a computer terminal. During the interactive session, a batch input file is created that can be used or modified for future runs.

The discussion of input is divided into five sections. The input required to set up the problem is described in Section 3.1. In this section, the type of geometry for the problem is selected. If the geometry involves a rod bundle, the geometry input is described in Section 3.2. If an open channel geometry is specified, the geometry input is described in Section 3.3. The surface emissivity input for the various surfaces is described in Section 3.4. If the exchange factors for the individual surfaces will be combined to simplify the model, the required input is described in Section 3.5.

The general input instruction format describes the format for each section of input for the interactive and batch modes and gives a complete description of the variables used.

Some input lines are repeated, and some groups of lines are repeated in a set sequence. These repetitive patterns are called out in the instructions, both in the format for the line and in the text accompanying the input. In many instances, input will depend on values specified in previous input lines. These variables are noted on the input line, with a reference to the line where the variable was defined. For example, the variable for the type of geometry to be modeled, IGEOM, is read on input line RADGEN.3. In all subsequent instructions that refer to IGEOM, the origin of this variable is directed by specifying the variable as IGEOM[RADGEN.3].

3.1 PROBLEM INITIATION

The input required to set up the problem includes the method of reading input, the mode of operation, the title of the problem, and the type of geometry desired.

The answer to the first interactive question determines if the interactive or batch input file is used. When input is read interactively, a batch input file is created that may be used or modified for future runs. If the batch mode is selected, the input file is read from I/O Unit 5.

The RAOGEN computer program may be operated in two different modes. The primary mode (IMODE=0) generates new radiation exchange factors given geometry and emissivity information. These exchange factors may be combined to give exchange factors from one surface group to another. The base and combined exchange factors are both written to I/O Unit 10.

The majority of the cost of a typical RADGEN run is generating the base exchange factors. If a new set of combined exchange factors is required, IMODE = 1 avoids the need to recalculate the base factors if they have previously been calculated and saved. Therefore, an additional operating mode (IMODE=1) was added that reads base exchange factors from an existing file (on I/O Unit 11) before combining them. If this mode is selected, the input skips to Section 3.3.

Three types of geometries are modeled by the RADGEN code: rods on a square pitch, rods on a triangular pitch, and open channels. Geometries with rods on a square pitch (IGEOM=0) are for unconsolidated spent fuel assemblies. Geometries with rods on a triangular pitch (IGEOM=1) are used for consolidated spent fuel rods in a canister. Open channels geometries (IGEOM=2) are channels that do not contain a rod bundle and are limited to channels with no shadowing, i.e., where the view from each surface to another is not blocked by a third surface.

The interactive and batch formats for the problem initiation input are presented below. In the interactive mode description, sentences presented in all capital letters are the questions asked by the routine. Explanations in lowercase letters enclosed in parentheses define the code variable being requested. The user-supplied answer follows the question mark.

Interactive Format:

INPUT FROM TTY? IF NOT, THEN READ FROM TAPES: (code variable READIN)
(Y/YES,RET/NO)
? y
SPECIFY MOOE OF OPERATION (code variable IMODE)
0 - GENERATE NEW EXCHANGE FACTORS
1 - LUMP EXISTING EXCHANGE FACTORS (TO BE READ FROM TAPE11)
? 0
ENTER TITLE FOR PROBLEM (UP TO 68 CHARACTERS) (code variable TEXT)
? sample problem
TYPE OF GEOMETRY DESIRED (code variable IGEOM)
0 - RODS ON SQUARE PITCH
1 - RODS ON TRIANGULAR PITCH
2 - OPEN CHANNEL
? 0

Batch Format:

RADGEN.1 IMODE
FORMAT(I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	IMODE	Mode of operation: 0 - Generate new exchange factors given geometry and emissivity information 1 - Combine existing exchange factors that are read from I/O Unit 11

***** If IMODE=1, go to RADGEN.12

RADGEN.2 TEXT
FORMAT(16A4)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 64	TEXT	Title for problem identification (first line of the output and TAPE 10 files; maximum of 64 characters)

RADGEN.3 IGEOM
FORMAT(I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	IGEOM	Flag for type of geometry: 0 - rods on square pitch 1 - rods on triangular pitch 2 - open channel, no rods

***** If IGEOM=2, go to RADGEN.7

3.2 ROD BUNDLE GEOMETRY

This section describes the geometry parameters that define a rod bundle, whether the rods are on a square (IGEOM=0) or triangular (IGEOM=1) pitch. This input is not read when an open channel geometry is specified (IGEOM=2).

Rod bundle geometries are divided into two categories: standard and user-specified. Examples of standard geometries for rods on square and triangular pitch are shown in Figures 3.1 and 3.2, respectively. For rods on a square pitch, a standard geometry is defined as a square or rectangular array of rods in a square or rectangular canister. For rods on a triangular pitch, a standard geometry is defined as an array of rods arranged on alternating long and short rows differing in length by one rod, surrounded by a square or rectangular canister.

Any rod geometries that do not conform to the standard geometry definitions given above must be user-specified. Examples of user-specified geometries for rods on square and triangular pitch are shown in Figures 3.3 and 3.4, respectively. In both of these cases, the starting point of the rod rows, the length of the rows, and the shape of the surrounding canister are different from the standard case.

The input in this section is divided into three categories: rod bundle parameters, rod location information, and canister geometry input. Each of these categories is discussed in more detail below.

3.2.1 Rod Bundle Parameters

The basic parameters required to define a rod bundle, whether it is a standard or user-specified geometry, include the pitch-to-diameter ratio, the

FIGURE 3.1. Typical Standard Geometry for Rods on a Square Pitch

FIGURE 3.2. Typical Standard Geometry for Rods on a Triangular Pitch

FIGURE 3.3. User-Specified Geometry for Rods on a Square Pitch

FIGURE 3.4. User-Specified Geometry for Rods on a Triangular Pitch

number of rows of rods, the number of rods in each row (if a standard geometry), and the arrangement of rows (if a standard triangular pitch geometry). If the number of rods in each row is not specified (NCOL=0), then the rod location information is read according to the input described in Section 3.2.2.

The interactive and batch formats for the rod bundle parameters are presented below. The interactive input corresponds to the standard geometry for rods on a triangular pitch shown in Figure 3.2.

Interactive Format:

```

ROD PITCH-TO-DIAMETER RATIO (code variable PDR)
? 1.05
NUMBER OF ROWS OF RODS (code variable NROWS)
? 6
NUMBER OF RODS IN EACH ROW (code variable NCOL)
  (FOR TRIANGULAR ARRAYS IN A SQUARE CANISTER, ENTER THE
   LARGER NUMBER OF RODS PER ROW)
  (IF THE NUMBER OF RODS IS TO BE SPECIFIED FOR EACH ROW, RETURN)
? 6
RODS IN A SQUARE CANISTER ARE ASSUMED TO BE ARRANGED IN ALTERNATING
LONG AND SHORT ROWS
INDICATE WHETHER THE TOP ROW IS LONG OR SHORT (code variable IFIRST)
+1 - LONG ROW
-1 - SHORT ROW
? 1

```

Batch Format:

```

RADGEN.4  PDR, NROWS, NCOL, IFIRST
          FORMAT (F5.3, 3I5)

```

<u>Variable</u>	<u>Description</u>
PDR	Rod pitch-to-diameter ratio
NROWS	Number of rows of rods
NCOL	Number of rods in each row. Leave blank if the number of rods is to be specified for each row.

IFIRST   For standard triangular pitch geometries, indicates whether
                  the top row is long or short
                  +1 - long rows
                  -1 - short rows

***** If NCOL > 0, go to RADGEN.6

3.2.2 Rod Location Information

A user-specified geometry (NCOL[RADGEN.4]=0) requires input that defines the rod locations. If a standard geometry has been specified (NCOL[RADGEN.4]>0), the input skips to Section 3.2.3.

Rod location information is specified in terms of rod rows. Each row is defined by the beginning rod location, JBEG, and the number of rods in that row, NLINE. The beginning location is specified by the number of columns from the leftmost rod. Examples of rods on a square and triangular pitch are shown in Figures 3.3 and 3.4, respectively. In Figure 3.3, the first row begins in column three and has a length of two rods. In Figure 3.4, the first row begins in column three and has a length of three rods.

The interactive and batch formats for the rod location information are presented below. The input used in the interactive format example corresponds to the geometry in Figure 3.3.

Interactive Format:

```
NUMBER OF RODS IN EACH ROW (code variable NCOL)
  (IF THE NUMBER OF RODS IS TO BE SPECIFIED FOR EACH ROW, RETURN)
?
USER SPECIFIED GEOMETRY
FOR EACH ROW, ENTER THE BEGINNING LOCATION AND NUMBER OF RODS
FOR ROW NO. 1 (BEGINNING LOCATION, NUMBER OF RODS)
  (code variables JBEG( 1) and NLINE( 1))
? 3,2
FOR ROW NO. 2 (BEGINNING LOCATION,NUMBER OF RODS)
  (code variables JBEG( 2) and NLINE( 2))
? 2,4
FOR ROW NO. 3 (BEGINNING LOCATION,NUMBER OF RODS)
  (code variables JBEG( 3) and NLINE( 3))
? 1,6
FOR ROW NO. 4 (BEGINNING LOCATION,NUMBER OF RODS)
  (code variables JBEG( 4) and NLINE( 4))
```



```

? 1,6
  FOR ROW NO. 5 (BEGINNING LOCATION,NUMBER OF RODS)
    (code variables JBEG( 5) and NLINE( 5))
? 2,4
  FOR ROW NO. 6 (BEGINNING LOCATION,NUMBER OF RODS)
    (code variables JBEG( 6) and NLINE( 6))
? 3,2

```

Batch Format:

```

RADGEN.5 (JBEG(I), (NLINE(I), I=1,NROWS[RADGEN.4])
          FORMAT (2I5)

```

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	JBEG(I)	Column in which the first rod in row I exists
6 - 10	NLINE(I)	Number of rods in row I

*** RADGEN.5 is read in NROWS [RADGEN.4] times

*** RADGEN.5 is read only if NCOL[RADGEN.4]=0

3.2.3 Canister Geometry Input

This section describes the input that defines the canister geometry for a standard rod bundle geometry (NCOL[RADGEN.4]>0). The rods in a standard geometry are surrounded by a square or rectangular canister. The size of the canister and the location of the rod bundle within the canister are defined by specifying the distance between the edge of the rods and the canister wall on all four sides. This allows the user to model the effect of eccentric bundle placement within the canister. The rod outside diameter is required to specify the distances in terms of rod diameters to calculate the base viewfactors. The interactive and batch formats for the canister geometry input are presented below.

Interactive Format:

```

  ROD OUTSIDE DIAMETER (IN.) (code variable DIA)
? .422
  DIAMETER BETWEEN THE EDGE OF THE RODS AND THE CANISTER WALL (IN.)
    AT THE TOP (code variable XR(1))

```

? .2
 ON THE RIGHT SIDE (code variable XR(2))
 ? .2
 AT THE BOTTOM (code variable XR(3))
 ? .2
 ON THE LEFT SIDE (code variable XR(4))
 ? .2

Batch Format:

RADGEN.6 DIA, (XR(I),I=1,4)
 FORMAT (5F5.3)

Columns	Variable	Description
1 - 5	DIA	Rod outside diameter (in.)
6 - 10 11 - 15 etc.	XR(I)	Distance between the edge of the rods and the canister wall for the top, right, bottom, and left sides, respectively (in.)

*** RADGEN.6 only if NCOL[RADGEN.4]>0

3.3 OPEN CHANNEL GEOMETRY

The input required to define an open channel geometry (IGEOM[RADGEN.3]=2) is described below. An open channel is defined as a channel with uniform cross section that contains no rods. Open channel geometries are limited to channels with no shadowing, i.e., where the view from each surface to another is not blocked by a third surface.

Surfaces around the channel are defined by their startpoints and perimeter length. An example of an open channel geometry is shown in Figure 3.5. The coordinates for the startpoint and the length are read for each surface. The surfaces are read in consecutive order around the channel (in this case from surfaces 1 to 6). The endpoint for the final surface (surface 6) is assumed to be the first startpoint read (point 1). If no length is specified, then it is calculated based on a straight line between the startpoint and endpoint. In the example, the lengths for surfaces 1, 2, 5, and 6 are calculated automatically but the lengths for surfaces 3 and 4 must be input.

FIGURE 3.5. Typical Open Channel Geometry

The interactive and batch formats for the open channel geometry input are presented below. The input used in the interactive format example corresponds to the geometry shown in Figure 3.5.

Interactive Format:

```

NUMBER OF RADIATION SURFACES SURROUNDING THE CHANNEL (code variable NWALL)
? 6
FOR EACH SURFACE, ENTER THE X AND Y COORDINATES FOR THE STARTPOINT
AND THE SURFACE LENGTH (IN.) (ENTER ZERO FOR A STRAIGHT LINE)
- READ IN CONSECUTIVE ORDER AROUND THE CHANNEL
- THE ENDPOINT FOR THE FINAL SURFACE IS ASSUMED TO BE THE FIRST POINT
READ
STARTPOINT COORDINATES AND LENGTH FOR SURFACE NO. 1
(code variables X( 1),Y( 1) and PERIM( 1))
? 0.,0.,0.
STARTPOINT COORDINATES AND LENGTH FOR SURFACE NO. 2
(code variables X( 2),Y( 2) and PERIM( 2))
? 1.,0.,0.
STARTPOINT COORDINATES AND LENGTH FOR SURFACE NO. 3
(code variables X( 3),Y( 3) and PERIM( 3))
? 2.,0.,1.571

```

```

STARTPOINT COORDINATES AND LENGTH FOR SURFACE NO. 4
(code variables X( 4),Y( 4) and PERIM ( 4))
? 1.414,1.414,1.571
STARTPOINT COORDINATES AND LENGTH FOR SURFACE NO. 5
(code variables X( 5),Y( 5) and PERIM( 5))
? 0.,2.,0.
STARTPOINT COORDINATES AND LENGTH FOR SURFACE NO. 6
(code variables X( 6),Y( 6) and PERIM( 6))
? 0.,1.,0.

```

Batch Format:

```

RADGEN.7  NWALL
          FORMAT (I5)

```

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	NWALL	Number of radiation surfaces surrounding the channel
RADGEN.8	(X(I),Y(I),PERIM(I),I=1,NWALL) FORMAT(3F5.3)	

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	X(I)	The x-coordinate of the startpoint for surface I
6 - 10	Y(I)	The y-coordinate of the startpoint for surface I
11 - 15	PERIM(I)	Perimeter length for surface I (in.). If set equal to zero, the length is calculated based on a straight line between endpoints.

*** RADGEN.8 is read in NWALL[RADGEN.7] times

*** RADGEN.7 through 8 are read only if IGEOM[RADGEN.3]=2.

3.4 SURFACE EMISSIVITY

Once the radiation surface geometry has been established, the emissivities for each surface must be specified. These emissivities are assumed to be constant over the surface and independent of temperature. All rod surfaces

are assumed to have the same emissivity. The wall surfaces may have the same emissivity or have different emissivities, which are specified for each surface. This is accomplished by specifying a zero for the base wall emissivity (EMWALL[RADGEN.9]=0) and then specifying the number of wall surfaces. The interactive and batch formats for the surface emissivity input are presented below.

Interactive Format:

```

ROD EMISSIVITY (code variables EMROD)
? .8
WALL EMISSIVITY (ENTER ZERO IF VALUES ARE TO BE READ FOR EACH WALL)
  (code variable EMWALL)
? 0.0
NUMBER OF WALL SURFACES (code variable NWALL)
? 8
EMISSIVITY FOR WALL NO. 1 (code variable EMW( 1))
? 0.2
EMISSIVITY FOR WALL NO. 2 (code variable EMW( 2))
? 0.2
EMISSIVITY FOR WALL NO. 3 (code variable EMW( 3))
? 0.6
EMISSIVITY FOR WALL NO. 4 (code variable EMW( 4))
? 0.6
EMISSIVITY FOR WALL NO. 5 (code variable EMW( 5))
? 0.6
EMISSIVITY FOR WALL NO. 6 (code variable EMW( 6))
? 0.6
EMISSIVITY FOR WALL NO. 7 (code variable EMW( 7))
? 0.2
EMISSIVITY FOR WALL NO. 8 (code variable EMW( 8))
? 0.2

```

Batch Format:

```

RADGEN.9  EMROD,EMWALL
          FORMAT(2F5.3)

```

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	EMROD	Rod emissivity. If zero, no rods in enclosure.
6 - 10	EMWALL	Base wall emissivity. If set equal to zero, emissivities are read for each wall surface.

RADGEN.10   NWALL
                   FORMAT(I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	NWALL	Number of radiation surfaces surrounding the rod bundle

*** RADGEN is read only if IGEOM[RADGEN.3]<2

RADGEN.11   (EMW(I),I=1,NWALL)
                   FORMAT(12F5.3)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	EMW(I)	Emissivity for individual wall
6 - 10 etc.		radiation surface I

*** RADGEN.10 and 11 are read only if EMWALL[RADGEN.9]=0.0.

3.5 EXCHANGE FACTOR LUMPING OPTIONS

In a detailed COBRA-SFS rod bundle model, each fuel rod is treated as an individual radiation surface. In many cases, it is possible to reduce the size of the model by combining or lumping individual surfaces into surface groups. Exchange factors must then be combined to correspond to the surface groups. This lumping can be accomplished by either of two methods--by specifying an automatic exchange factor lumping option or by using the user-specified lumping option.

The automatic lumping options are used when problem symmetry allows exchange factors about the axis of symmetry to be combined or folded. For example, an 8 x 8 rod bundle is shown in Figure 3.6. When there is symmetry about the diagonal, the model may be reduced to a half-bundle model as shown in Figure 3.7. A 15 x 15 rod bundle with one-eighth symmetry may be reduced to the model presented in Figure 3.8. For rods on a triangular pitch, a hexagonal array, such as that shown in Figure 3.9, can be reduced with one-sixth symmetry to the model presented in Figure 3.10.

FIGURE 3.6. Radiation Surface Locations for a Full 8 x 8 Rod Bundle

FIGURE 3.7. Radiation Surface Locations for a Half 8 x 8 Rod Bundle with Symmetry along the Diagonal

FIGURE 3.8. Radiation Surface Locations for a 15 x 15 Rod Bundle with One-Eighth Symmetry

FIGURE 3.9. Radiation Surface Locations for a Hexagonal Rod Bundle

FIGURE 3.10. Radiation Surface Locations for a Hexagonal Bundle with One-Sixth Symmetry

For cases where the automatic lumping options do not apply, the user may specify how the exchange factors should be combined. First, the number of radiation surface groups must be specified. Then, the surfaces or portions of surfaces are listed for each group. For example, a typical 7 x 7 rod bundle can be represented by the model presented in Figure 3.11. Note that an individual radiation surface may belong to more than one surface group. When this occurs, a fraction of the surface is assigned to each group.

FIGURE 3.11. Lumped Model Representing a Typical 7 x 7 Rod Bundle

When user-specified lumping is used, all individual rod and wall radiation surfaces must be assigned to a surface group. The wall surfaces are numbered consecutively after the rod surface numbers. For example, for a bundle with 49 rods, the first wall surface is assigned number 50. The algorithm for lumping radiation exchange factors is described in Section 2.3.

The interactive and batch formats for the exchange factor lumping information are presented below. The input used in the interactive format example corresponds to the model presented in Figure 3.11.

Interactive Format:

```

INDICATE AUTOMATIC EXCHANGE FACTOR LUMPING OPTIONS (code variable ILUMP)
  0 - NO AUTOMATIC LUMPING
  1 - HALF SYMMETRY ALONG DIAGONAL (SQUARE PITCH)
  2 - EIGHTH SYMMETRY (SQUARE PITCH)
  3 - SIXTH SYMMETRY (TRIANGULAR PITCH)
? 0
NUMBER OF GROUPS FOR USER-SPECIFIED LUMPING (code variable NGRP)
  (ENTER ZERO IF LUMPING IS NOT DESIRED)
? 13
NUMBER OF WHOLE SURFACES IN GROUP 1 (code variable NWHOLE)
? 8
LIST THE WHOLE SURFACE NUMBERS
? 2,3,4,5,6,10,11,12
NUMBER OF PARTIAL SURFACES IN GROUP 1 (code variable NPART)
? 7
LIST THE SURFACE NUMBERS AND FRACTION OF SURFACE FOR EACH
? 1,0.5,9,0.5,17,0.375,18,0.5,19,0.375,13,0.5,7,0.5
NUMBER OF WHOLE SURFACES IN GROUP 2 (code variable NWHOLE)
? 8
LIST THE WHOLE SURFACE NUMBERS
? 14,20,21,27,28,34,35,42
NUMBER OF PARTIAL SURFACES IN GROUP 2 (code variable NPART)
? 7
LIST THE SURFACE NUMBERS AND FRACTION OF SURFACE FOR EACH
? 7,0.5,13,0.5,19,0.375,26,0.5,33,0.375,41,0.5,49,0.5
NUMBER OF WHOLE SURFACES IN GROUP 3 (code variable NWHOLE)
? 8
LIST THE WHOLE SURFACE NUMBERS
? 38,39,40,44,45,46,47,48
NUMBER OF PARTIAL SURFACES IN GROUP 3 (code variable NPART)
? 7
LIST THE SURFACE NUMBERS AND FRACTION OF SURFACE FOR EACH
? 43,0.5,37,0.5,31,0.375,32,0.5,33,0.375,41,0.5,49,0.5
NUMBER OF WHOLE SURFACES IN GROUP 4 (code variable NWHOLE)

```

? 8
 LIST THE WHOLE SURFACE NUMBERS
 ? 8,15,16,22,23,29,30,36
 NUMBER OF PARTIAL SURFACES IN GROUP 4 (code variable NPART)
 ? 7
 LIST OF THE SURFACE NUMBERS AND FRACTION OF SURFACE FOR EACH
 ? 1,0.5,9,0.5,17,0.375,24,0.5,24,0.5,31,0.375,37,0.5,43,0.5
 NUMBER OF WHOLE SURFACES IN GROUP 5 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 25
 NUMBER OF PARTIAL SURFACES IN GROUP 5 (code variable NPART)
 ? 8
 LIST THE SURFACE NUMBERS AND FRACTION OF SURFACE FOR EACH
 ? 17,0.25,18,0.5,19,0.25,26,0.5,33,0.25,32,0.5,31,0.25,24,0.5
 NUMBER OF WHOLE SURFACES IN GROUP 6 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 50
 NUMBER OF PARTIAL SURFACES IN GROUP 6 (code variable NPART)
 ? 0
 NUMBER OF WHOLE SURFACES IN GROUP 7 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 51
 NUMBER OF PARTIAL SURFACES IN GROUP 7 (code variable NPART)
 ? 0
 NUMBER OF WHOLE SURFACES IN GROUP 8 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 52
 NUMBER OF PARTIAL SURFACES IN GROUP 8 (code variable NPART)
 ? 0
 NUMBER OF WHOLE SURFACES IN GROUP 9 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 53
 NUMBER OF PARTIAL SURFACES IN GROUP 9 (code variable NPART)
 ? 0
 NUMBER OF WHOLE SURFACES IN GROUP 10 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 54
 NUMBER OF PARTIAL SURFACES IN GROUP 10 (code variable NPART)
 ? 0
 NUMBER OF WHOLE SURFACES IN GROUP 11 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 55

NUMBER OF PARTIAL SURFACES IN GROUP 11 (code variable NPART)
 ? 0
 NUMBER OF WHOLE SURFACES IN GROUP 12 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 56
 NUMBER OF PARTIAL SURFACES IN GROUP 12 (code variable NPART)
 ? 0
 NUMBER OF WHOLE SURFACES IN GROUP 13 (code variable NWHOLE)
 ? 1
 LIST THE WHOLE SURFACE NUMBERS
 ? 57
 NUMBER OF PARTIAL SURFACES IN GROUP 13 (code variable NPART)
 ? 0

Batch Format:

RADGEN.12 ILUMP
 FORMAT(I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	ILUMP	Automatic exchange factor lumping options 0 - no automatic lumping 1 - half symmetry along diagonal (square pitch) 2 - eighth symmetry (square pitch) 3 - sixth symmetry (triangular pitch)

RADGEN.13 NGRP
 FORMAT(I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	NGRP	Number of surface groups to be used for user-specified lumping. Enter zero if user-specified lumping is not desired.

RADGEN.14 I,NTOT
 FORMAT(2I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5	I	Surface group identification number
6 - 10	NTOT	Number of individual radiation surfaces in surface group I
RADGEN.15	(LLOC(J),PHI(J),J=1,NTOT)) FORMAT(6(I5,F5.3))	

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1 - 5 11 - 15 etc.	LLOC(J)	Identification number of individual surface belonging to surface group I
6 - 10 16 - 20 etc.	PHI(J)	Fraction of surface LLOC(J) that belongs to surface group I

4.0 DIMENSION PARAMETERS

The dimensions of the arrays in RADGEN are defined with PARAMETER statements. The required values for the dimensions on the various arrays in the code are problem-dependent, and the user can change the dimensions by changing the PARAMETER statements via UPDATE. There are seven dimension parameters that must be specified by the user (or, the user must verify that the existing value in the PARAMETER statement is adequate for the given problem). These parameters are listed below with their definitions and standard values. Error checks are included in the subroutines that process the input stream and look for dimension errors, but these checks can catch only the errors that the code developers were able to anticipate.

In addition to the user-specified parameters listed below, some parameters are calculated by the code to dimension solution arrays. DO NOT MAKE CHANGES TO CODE-CALCULATED PARAMETERS.

The user-specified dimension parameters for RADGEN are defined as follows:

- NR - Maximum number of rows or columns of rods. (For rods on a triangular pitch, the number of columns includes the staggered rods. For example, the number of columns in the array in Figure 3.2 is 11.)
- NP - Maximum number of rods in an array.
- NW - Maximum number of surrounding wall surfaces. (If the geometry is not user-specified, NW is the sum of the number of rows and columns multiplied by four. For a user-specified geometry, NW is dependent on the options selected.)
- ND - Number of surfaces into which each rod is divided. (For rods on a square pitch, $ND \geq 4$. For rods on a triangular pitch, $ND \geq 6$.)
- NL - Maximum number of surface groups when exchange factors are combined.
- NX - Maximum number of surfaces that each surface sees directly. (If the geometry is not user-specified, $NX \geq 16$ for rods on a square pitch and $NX \geq 18$ for rods on a triangular pitch.)

NF - Maximum number of combined surface groups to which an individual surface can belong.

5.0 CODE VERIFICATION

The RADGEN computer program is capable of generating radiation exchange factors for a wide range of geometries. To verify that the geometries are modeled correctly, code results were compared with both calculated and/or analytical results for each of the geometry types.

5.1 RODS ON A SQUARE PITCH

The methods used to develop the quarter-rod viewfactor expressions were an extension of the work performed by Cox (1977) for whole rods on a square pitch. The arrangements of rods used for whole rod analysis are shown in Figure 5.1. The viewfactor expressions for these rod locations are listed in Table 5.1.

To be correct, the calculated quarter-rod viewfactors must be consistent with the whole rod viewfactors calculated by Cox. The expressions relating the quarter-rod to whole rod viewfactors are

$$F_{S-A} = 1/2 [F_{S-c} + F_{S-d}] \quad (5.1)$$

$$F_{S-B} = 1/4 [F_{S-a} + 2(F_{a-b} + F_{S-e} + F_{S-f} - F_{cor})] \quad (5.2)$$

$$F_{S-C} = 1/4 F_{S-g} \quad (5.3)$$

$$F_{S-D} = 1/4 (F_{S-h} + F_{cor}) \quad (5.4)$$

The term F_{cor} corresponds to the viewfactor from quarter-rod surface s to the gap between rods shown in Figure 5.2. For the whole-rod model, the viewfactor for this gap is included in the viewfactor to the outermost rod, F_{S-d} . For the quarter-rod model, the gap viewfactor is included in the viewfactors to the rod behind the originating surface S , F_{S-B} (which includes F_{S-e} and F_{S-f}). The expression for calculating the value of F_{cor} for all pitch-to-diameter ratios is

FIGURE 5.1. Whole-Rod Locations for Rods on a Square Pitch

$$F_{\text{cor}} = 1/\pi \{ 2[\text{PDR}^2 + (\text{PDR} - 1)^2]^{0.5} - 2[2\text{PDR}^2 - \text{PDR}]^{0.5} \\ + \text{ATAN2}[2\text{PDR}^2 - \text{PDR}]^{0.5} + \text{ATAN} \left(\frac{2\text{PDR}-1}{2\text{PDR}} \right) - \pi/2 \} \quad (5.5)$$

The whole-rod viewfactors that are calculated using Equations (5.1) through (5.4) are compared with the viewfactors calculated from the expressions in Table 5.1. The results of the comparison are presented in Table 5.2. In all cases, the viewfactors compare identically, indicating that the partial rod viewfactors and whole rod viewfactors are consistent with each other.

TABLE 5.1. Blackbody Viewfactor Expressions for Whole Rods on a Square Pitch

Blackbody Viewfactor	PDR(a) Range	Expression
F_{S-A}	all	$\frac{1}{\pi} \{ (PDR^2 - 1)^{0.5} - \text{ATAN}(PDR^2 - 1)^{0.5} - PDR + \pi/2 \}$
F_{S-B}	1.0-1.41	$\frac{1}{\pi} \{ (2PDR^2 - 1)^{0.5} - \text{ATAN}(2PDR^2 - 1)^{0.5} - 2(PDR^2 - 1)^{0.5} + 2\text{ATAN}(PDR^2 - 1)^{0.5} \}$
	>1.41	$\frac{1}{\pi} \{ (2PDR^2 - 1)^{0.5} - \text{ATAN}(2PDR^2 - 1)^{0.5} - \sqrt{2}PDR + \pi/2 \}$
F_{S-C}	1.0-1.41	$\frac{1}{\pi} \{ (5PDR^2 - 1)^{0.5} - \text{ATAN}(5PDR^2 - 1)^{0.5} - 2(2PDR^2 - 1)^{0.5} + 2\text{ATAN}(2PDR^2 - 1)^{0.5} + (PDR^2 - 1)^{0.5} - \text{ATAN}(PDR^2 - 1)^{0.5} - \text{ATAN}(0.5) \}$
	>1.41	$\frac{1}{\pi} \{ (5PDR^2 - 1)^{0.5} - \text{ATAN}(5PDR^2 - 1)^{0.5} - (2PDR^2 - 1)^{0.5} + \text{ATAN}(2PDR^2 - 1)^{0.5} - (PDR^2 - 1)^{0.5} + \text{ATAN}(PDR^2 - 1)^{0.5} - \pi/4 \}$
F_{S-D}	all	$\frac{1.0 - 4(F_{S-A} + F_{S-B}) - 8F_{S-C}}{8}$

(a) PDR = pitch-to-diameter ratio

FIGURE 5.2. Viewfactor Geometry Corresponding to F_{cor}

TABLE 5.2. Whole-Rod Viewfactor Comparison for Rods on a Square Pitch

PDR(a)	Method	FS-A	FS-B	FS-C	FS-D
1.0	Cox	0.18169	0.06831	0	0
	RADGEN	0.18169	0.06831	0	0
1.1	Cox	0.15895	0.08337	0.00350	0.00034
	RADGEN	0.15895	0.08337	0.00350	0.00034
1.2	Cox	0.14274	0.08760	0.00861	0.00122
	RADGEN	0.14274	0.08760	0.00861	0.00122
1.3	Cox	0.12997	0.08659	0.01427	0.00246
	RADGEN	0.12997	0.08659	0.01427	0.00246
1.4	Cox	0.11949	0.08221	0.02018	0.00396
	RADGEN	0.11949	0.08221	0.02018	0.00396

(a) PDR = pitch-to-diameter ratio

Another method used to verify the quarter-rod blackbody viewfactor expressions is to measure the lengths from a scale drawing of the geometry and calculate a set of viewfactors using the cross-string formula. Rather than measure the lengths by hand, a computer program (VIEW) was written to digitize the information from a plotter and calculate the lengths automatically. Program VIEW was written for a Hewlett-Packard Series 85 computer. A listing of this program is presented in Appendix B.

The blackbody viewfactor results from program VIEW are compared with those calculated by RADGEN in Table 5.3 for a pitch-to-diameter ratio of 1.25. The accuracy of the viewfactor calculated by program VIEW depends on the accuracy of the scale drawing of the geometry and the level of detail used in digitizing the lengths, especially for curved surfaces. This is especially true for viewfactors with small values that are based on small differences between large lengths. For this reason, viewfactors F_{s-f} and F_{s-h} are not included in the comparison because of a lack of repeatability in the calculated values.

5.2 RODS ON A TRIANGULAR PITCH

The methods used to develop the one-sixth rod viewfactor expressions were an extension of the work performed by Cox (1977) for whole rods on a triangular pitch. The arrangement of rods used for whole-rod analysis is shown in Figure 5.3. The viewfactor expressions for these rod locations are listed in Table 5.4.

To be correct, the calculated one-sixth rod viewfactors must be consistent with the whole-rod viewfactors calculated by Cox. The expressions relating the one-sixth to whole-rod viewfactors are

$$F_{S-A} = 1/3 [F_{s-a} + F_{s-b} + F_{s-c} + F_{s-f} + F_{s-g}] \quad (5.6)$$

$$F_{S-B}^* = 1/6 [F_{s-h} + 2(F_{s-d} + F_{s-e} + F_{s-i})] \quad (5.7)$$

TABLE 5.3. Comparison of One-Quarter Rod Viewfactors to Program VIEW Results (PDR = 1.25)

<u>Viewfactor</u>	<u>RADGEN</u>	<u>Program VIEW</u>	<u>% Error</u>
F _{S-a}	2.726e-1	2.724e-1	0.0
F _{S-b}	1.889e-2	1.915e-2	1.4
F _{S-c}	2.214e-1	2.229e-1	0.7
F _{S-d}	5.063e-2	4.676e-2	-7.6
F _{S-e}	1.889e-2	1.938e-2	2.6
F _{S-g}	4.558e-2	4.870e-2	6.8

FIGURE 5.3. Whole-Rod Locations for Rods on a Triangular Pitch

TABLE 5.4. Blackbody Viewfactor Expressions for Whole Rods on a Triangular Pitch

Blackbody Viewfactor	PDR(a) Range	Expression
F_{S-A}	1.0-1.15	$1/\pi \{ \pi/6 - (PDR^2 - 1)^{0.5} + ATAN(PDR^2 - 1)^{0.5} \}$
	>1.15	$1/\pi \{ (PDR^2 - 1)^{0.5} - ATAN(PDR^2 - 1)^{0.5} - PDR + \pi/2 \}$
F_{S-B}	1.0-1.15	$1/\pi \{ (PDR^2 - 1)^{0.5} - ATAN(PDR^2 - 1)^{0.5} \}$
	>1.15	$1/\pi \{ (3PDR^2 - 1)^{0.5} - ATAN(3PDR^2 - 1)^{0.5} - 2(PDR^2 - 1)^{0.5} + 2ATAN(PDR^2 - 1)^{0.5} - \pi/6 \}$
F_{S-C}	1.0-1.15	0
	>1.15	$1/2 \pi \{ (7PDR^2 - 1)^{0.5} - ATAN(7PDR^2 - 1)^{0.5} + 2(3PDR^2 - 1)^{0.5} + 2ATAN(3PDR^2 - 1)^{0.5} + (PDR^2 - 1)^{0.5} - ATAN(PDR^2 - 1)^{0.5} - ATAN(\sqrt{3}/5) \}$
F_{S-D}	1.0-1.15	0
	>1.15	$\frac{1 - 6(F_{S-A} + F_{S-B}) - 12F_{S-C}}{12}$

(a) PDR = pitch-to-diameter ratio

where $F_{S-B}^* = F_{S-B} + F_{S-C} + F_{S-D}$

The whole-rod viewfactors F_{S-B} , F_{S-C} , and F_{S-D} have been combined to form the composite viewfactor F_{S-B}^* because there are no one-sixth rod viewfactors that correspond to F_{S-C} and F_{S-D} .

The whole-rod viewfactors calculated using Equations (5.6) and (5.7) were compared with the viewfactors calculated from the expressions in Table 2.2. The results of this comparison are presented in Table 5.5. In all cases, the viewfactors compare favorably, indicating that the partial rod viewfactors and whole-rod viewfactors are consistent with each other.

Another method verifying the one-sixth rod blackbody viewfactor expressions is to compare results with those obtained from program VIEW, which is described in Section 5.1. This comparison is presented in Table 5.6 for a pitch-to-diameter ratio of 1.25. The accuracy of the viewfactors calculated by program VIEW depends on the accuracy of the scale drawing of the geometry and the level of detail used in digitizing the lengths, especially for curved surfaces. This is especially true for viewfactors with small values that are based on small differences between large lengths. For this reason, F_{S-e} and F_{S-f} are not included in the comparison because of a lack of repeatability in the calculated values.

5.3 OPEN CHANNEL GEOMETRIES

The procedure for calculating blackbody viewfactors for an open channel geometry can be verified by comparing the viewfactors calculated by RADGEN with those calculated using documented analytical expressions. Two simple geometries were chosen as comparison cases: a rectangle with a 2:1 aspect ratio, shown in Figure 5.4, and a 30-60-90 triangle, shown in Figure 5.5. The analytical expressions used to calculate the individual viewfactors for these geometries are listed in Table 5.7 (Siegel and Howell 1981).

A comparison of the calculated viewfactors for the 2:1 rectangle geometry is presented in Table 5.8. A similar comparison for the 30-60-90 triangle is

presented in Table 5.9. In all cases, the RADGEN values are identical to those calculated using the analytical expression.

TABLE 5.5. Whole-Rod Viewfactor Comparison for Rods on a Triangular Pitch

<u>PDR</u>	<u>Method</u>	<u>FS-A</u>	<u>FS*B</u>
1.0	Cox	0.16667	0
	RADGEN	0.16667	0
1.1	Cox	0.15758	0.00909
	RADGEN	0.15758	0.00909
1.2	Cox	0.14274	0.02393
	RADGEN	0.14274	0.02393
1.3	Cox	0.12997	0.03670
	RADGEN	0.12997	0.03670

TABLE 5.6. Comparison of One-Sixth Rod Viewfactors to Program VIEW Results (PDR = 1.25)

<u>Viewfactor</u>	<u>RADGEN</u>	<u>Program VIEW</u>	<u>% Error</u>
F _{s-a}	3.096e-1	3.145e-1	+ 1.6
F _{s-b}	7.595e-2	7.619e-2	+ 0.3
F _{s-c}	9.103e-3	8.687e-3	- 4.6
F _{s-d}	1.013e-2	9.049e-3	- 10.7
F _{s-g}	9.103e-3	9.350e-3	+ 2.7
F _{s-h}	1.294e-1	1.266e-1	- 2.2
F _{s-i}	1.013e-2	9.350e-3	- 7.7

FIGURE 5.4. Radiation Surface Model for a 2:1 Rectangle

FIGURE 5.5. Radiation Surface Model for a 30-60-90 Triangle

TABLE 5.7. Blackbody Viewfactor Expressions

Geometry Geometry Description	Figure	Expression
Two infinitely long, directly opposed parallel plates of the same finite width.		$H = \frac{h}{w}$ $F_{1-2} = F_{2-1} = \frac{\sqrt{1 + H^2} - H}{2}$
Two infinitely long plates of unequal widths h and w, having one common edge, and at an angle of 90° to each other.		$H = \frac{h}{w}$ $F_{1-2} = \frac{1}{2} \left(1 + H - \sqrt{1 + H^2} \right)$
Infinitely long enclosure formed by three plane areas.		$F_{1-2} = \frac{A_1 + A_2 - A_3}{2A_1}$

TABLE 5.8. Comparison of Blackbody Viewfactors for a 2:1 Rectangle

<u>Viewfactor</u>	<u>RADGEN Value</u>	<u>Analytical Value</u>
F ₁₋₂	0.381966	0.381966
F ₁₋₃	0.236068	0.236068
F ₂₋₁	0.190983	0.190983
F ₂₋₄	0.618034	0.618034

TABLE 5.9. Comparison of Blackbody Viewfactors for a 30-60-90 Triangle

<u>Viewfactor</u>	<u>RADGEN Value</u>	<u>Analytical Value</u>
F ₁₋₂	0.618034	0.618034
F ₁₋₃	0.381966	0.381966
F ₂₋₁	0.276393	0.276393
F ₂₋₃	0.723607	0.723607
F ₃₋₁	0.190983	0.190983
F ₃₋₂	0.809017	0.809017

6.0 REFERENCES

- Cox, R. L. 1977. Radiation Heat Transfer in Arrays of Parallel Cylinders. ORNL-5239, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- McAdams, W. H. 1954. Heat Transmission. McGraw-Hill, Inc., New York.
- Rector, D. R., C. L. Wheeler and N. J. Lombardo. 1986. COBRA-SFS Spent Fuel Storage Thermal-Hydraulic Analysis Computer Program: Volume I - Mathematical Models and Numerical Methods. PNL-6049 Vol. I, Pacific Northwest Laboratory, Richland, Washington.
- Siegel, R., and J. R. Howell. 1981. Thermal Radiation Heat Transfer. McGraw-Hill, Inc., New York.

APPENDIX A

DERIVATION OF VIEWFACTOR EXPRESSIONS

APPENDIX A

DERIVATION OF VIEWFACTOR EXPRESSIONS

The viewfactor expressions presented in Section 2.0 were derived using the Hottel cross-string method for two-dimensional geometries. For a viewfactor from surface A_1 to surface A_2 , the Hottel method may be expressed as follows:

$$F_{12} = \frac{(\text{sum of crossed strings}) - (\text{sum of uncrossed strings})}{2 \times \text{length of } A_1} \quad (\text{A.1})$$

where the strings connect the endpoints of surfaces A_1 and A_2 . For example, the viewfactor for the geometry shown in Figure A.1 may be calculated as

$$F_{12} = \frac{(ae + dh) - (abcd + efgh)}{2ah} \quad (\text{A.2})$$

Note that when there is another surface blocking the path from one point to another, the string is drawn to minimize the path around the obstacle.

In the RADGEN program, expressions are used to calculate viewfactors between each rod segment surface or wall surface and surrounding surfaces. These expressions are derived in terms of nondimensional parameters such as the pitch-to-diameter ratio (PDR), which describes the distance between adjacent rods, or the wall gap-to-radius ratio (XR), which describes the distance between the rod bundle and surrounding walls. An example of adjacent quarter-rod radiation surfaces is shown in Figure A.2. For this geometry, the viewfactor expression using Hottel's method is

$$F_{12} = \frac{2(bc + ce) - (bf + de)}{2bd} \quad (\text{A.3})$$

FIGURE A.1. Cross-String Method

The lengths are expressed in terms of nondimensional parameters as follows:

$$ab = ac = ad = R; \quad bf = 2(R)(PDR); \quad de = 2[(2)(PDR) - R]$$

$$\begin{aligned} ce &= [(ae)^2 - (ac)^2]^{0.5} = \{[2R(PDR) - R]^2 - R^2\}^{0.5} \\ &= 2R[(PDR)^2 - PDR]^{0.5} \end{aligned}$$

$$\omega = \pi/2 - \text{ATAN } ce/ac = \pi/2 - \text{ATAN } 2[(PDR)^2 - PDR]^{0.5}$$

$$bc = R\omega = R\{\pi/2 - \text{ATAN } 2[(PDR)^2 - PDR]^{0.5}\}$$

Substituting in these terms, the expression becomes

$$\begin{aligned} F_{12} &= 2/\pi \{2(PDR^2 - PDR)^{0.5} - \text{ATAN } [2(PDR^2 - PDR)^{0.5} \\ &\quad - 2PDR + 1 + \pi/2]\} \end{aligned} \quad (A.4)$$

which is the same expression found in Table 2.1.

FIGURE A.2. Geometry for Derivation of F_{12}

APPENDIX B

VIEW CODE LISTING

APPENDIX B

VIEW CODE LISTING

A listing of the computer program VIEW, written for a Hewlett-Packard Series 85 computer, is presented below. This program was used in the verification of the RADGEN program as described in Section 5.0.

```
10 PLOTTER IS 1
20 DIM X(50),Y(50)
30 GCLEAR
40 SCALE 0,20,0,20
50 MOVE 10,3
60 LORG 6
70 LABEL "RADIATING SURFACE"
80 MOVE 5,5
90 LORG 9
100 LABEL "S1"
110 MOVE 5,5
120 DRAW 15,5
130 LORG 3
140 LABEL "S2"
150 MOVE 13,13
160 LORG 1
170 LABEL "S4"
180 MOVE 13,13
190 DRAW 7,16
200 LORG 7
210 LABEL "S3"
220 MOVE 7,16
230 LINETYPE 3,3
240 DRAW 5,5
250 DRAW 13,13
260 DRAW 15,5
270 DRAW 7,16
280 LORG 5
290 MOVE 5.9,10 @ LABEL "L1"
300 MOVE 9,9 @ LABEL "L4"
310 MOVE 14,9 @ LABEL "L2"
320 MOVE 9,13.1 @ LABEL "L3"
330 LORG 4 @ MOVE 10,5 @ LABEL "S"
340 GRAPH
350 COPY
360 CLEAR
370 PLOTTER IS 705
380 GCLEAR
```

```

390 DISP "LOCATE"
400 LOCATE
410 DISP "XMIN,XMAX,YMIN,YMAX"
420 INPUT Z1,Z2,Q1,Q2
430 SCALE Z1,Z2,Q1,Q2
440 S=0
441 M1-1 @ M2=1
450 SETUU
460 DISP "DELTA X ?"
470 INPUT D1
480 DISP "IF YOU WANT TO CALIBRATE THE DISTANCE SCALE. BE SURE TO
      DIGITIZE 3 INTERSECTIONS"
490 DISP "OF WHICH 2 ARE A KNOWN DISTANCE APART."
500 DISP "DO YOU WANT TO INPUT SURFACE INTERSECTIONS? (Y/N)"
510 INPUT RO$
520 IF RO$="Y" THEN 690
530 DISP "HOW MANY INTERSECTIONS"
540 INPUT NO
550 FOR I=1 TO NO
560 DISP "DIGITIZE INTERSECTION",I
570 DIGITIZE X(I),Y(I)
580 NEXT I
590 DISP "DO YOU WANT TO DEFINE TWO LENGTHS BETWEEN THE INTERSECTIONS?
      (Y/N)"
600 INPUT QO$
610 IF QO$="Y" THEN 700
620 DISP "GIVE THE INDEX NUMBERS OF THE TWO INTERSECTIONS AND THE KNOWN
      LENGTH BETWEEN."
630 DISP "USE THE FORM I,J,L WHERE I=INDEX1, J=INDEX2, AND L=LENGTH."
640 INPUT I1,I2,L
641 C1=(X(I1)-X(I2))^2 @ C4=(Y(I1)-Y(I2))^2
642 C5=L^2
650 DISP "GIVE THE INDEX NUMBERS OF THE SECOND TWO INTERSECTIONS AND
      THE KNOWN LENGTH BETWEEN."
660 DISP "USE THE SAME FORM AS ABOVE"
670 INPUT I1,I2,L
680 C3=(X(I1)-X(I2))^2 @ C2=(Y(I1)-Y(I2))^2
683 C6=L^2
685 D=C1*C2-C3*C4
686 M1=(C5*C2-C6*C4)/D
687 M2=(C1*C6-C3*C5)/D
690 REM
700 PRINT " "
710 DISP "NEW SOURCE? (Y/N)"
720 INPUT S1$
730 IF S1$="N" THEN 920
740 IF S=0 THEN 810
750 PRINT "S",S
760 R=S-F2

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770 PRINT "REMAF",R
780 R1=R/S
790 PRINT "FII",R1
800 PRINT @ PRINT @ PRINT @ PRINT
810 S=0
820 F2=0
830 IF R0$="Y" THEN 890
840 DISP "DIGITIZE S1
850 DIGITIZE X1,Y1
860 DISP "DIGITIZE S2"
870 DIGITIZE X2,Y2
880 GOTO 920
890 DISP "INPUT INTERSECTION NUMBER OF S1 AND S2"
900 INPUT I1,I2
910 X1=X(I1) @ X2=X(I2) @ Y1=Y(I1) @ Y2=Y(I2)
920 DISP "HEADING?"
930 INPUT H$ @ PRINT H$
940 IF R0$="7" THEN 1000
950 DISP "DIGITIZE S4"
960 DIGITIZE X4,Y4
970 DISP "DIGITIZE S3"
980 DIGITIZE X3,Y3
990 GOTO 1030
1000 DISP "INPUT INTERSECTION NUMBER OF S3 AND S4"
1010 INPUT I1,I2
1020 X3=X(I1) @ X4=X(I2) @ Y3=Y(I1) @ Y4=Y(I2)
1030 IF S1$="N" THEN 1200
1040 REM DEFINE SOURCE AREA
1050 PLOT X1,Y1
1060 DISP "DEFINE LINE S.(L/I/D)"
1070 INPUT L1$
1080 IF L1$#"L" THEN 1110
1090 S=((X2-X1)^2*M1+(Y2-Y1)^2*M2)^.5
1100 GOTO 1190
1110 IF L1$#"D" THEN 1150
1120 DISP "MANUALLY DEFINE LINE S USING THE FORM 'S =DEFF'..THEN CONTINUE"
1130 PAUSE
1140 GOTO 1190
1150 P1=X1 @ P2=Y1
1160 P3=X2 @ P4=Y2
1170 GOSUB 1340
1180 S=L9
1190 REM DEFINE L1
1200 DISP "DEFINE LINE S1-S3.(L/I/D)"
1210 INPUT L1$
1220 IF L1$#"L" THEN 1250
1230 L5=((X3-X1)^2*M1+(Y3-Y1)^2*M2)^.5
1240 GOTO 1590
1250 IF L1$#"D" THEN 1290

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1260 DISP "MANUALLY DEFINE LINE S 1-S3 USING THE FORM 'L5=DEFF.'. THEN
      CONTINUE
1270 PAUSE
1280 GOTO 1590
1290 P1=X1 @ P2=Y1
1300 P3=X3 @ P4=Y3
1310 GOSUB 1340
1320 L5=L9
1330 GOTO 1590
1340 L9=0
1350 PLOT P1,P2,-2
1360 X0=P1 @ Y=P2
1370 X=P1 @ Y=P2
1380 FOR I=1 TO 1000
1390 IF ABS(X-X0)<.1*D1 THEN 1460
1400 A=(Y-Y0)/(X-X0)
1410 IF ABS(A)>1 THEN 1460
1420 S2=Y+A*D1*SGN(X-X0)
1430 S1=D1*SGN(X-X0)+X
1440 PLOT S1,S2
1450 GOTO 1540
1460 IF ABS(Y-Y0)<.1*D1 THEN 1520
1470 A=(X-X0)/(Y-Y0)
1480 S1=X+A*D1*SGN(Y-Y0)
1490 S2=D1*SGN(Y-Y0)+Y
1500 PLOT S1,S2
1510 GOTO 1540
1520 DISP "SET IT BY HAND"
1530 BEEP @ BEEP
1540 X0=X @ Y0=Y
1550 DIGITIZE X,Y @ PLOT X,Y,-2
1560 L9=L9+((X-X0)^2*M1+(Y-Y0)^2*M2)^.5
1570 IF ((X-P3)^2+(Y-P4)^2)^.5<2^.5*D1/2 THEN RETURN
1580 NEXT I
1590 REM DEFINE L2
1600 DISP "DEFINE LINE S2-S4.(L//I/D)"
1610 INPUT L1$
1620 IF L1$#"L" THEN 1650
1630 L6=((X4-X2)^2*M1+(Y4-Y2)^2*M2)^.5
1640 GOTO 1730
1650 IF L1$#"D" THEN 1690
1660 DISP "MANUALLY DEFINE LINE S2-S4 USING THE FORM L6=OEFF..THEN
      CONTINUE"
1670 PAUSE
1680 GOTO 1730
1690 P1=X2 @ P2=Y2
1700 P3=X4 @ P4=Y4
1710 GOSUB 1340
1720 L6=L9

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1730 REM DEFINE L3
1740 DISP "DEFINE LINE S2-S3.(L/I/D)"
1750 INPUT L1$
1760 IF L1$#"L" THEN 1790
1770 L7=((X3-X2)^2*M1+(Y3-Y2)^2*M2)^.5
1780 GOTO 1870
1790 IF L1$#"L" THEN 1830
1800 DISP "MANUAL DEFINE LINE S2-S3 USING THE FORM "L7=DEFF'..THEN CONTINUE
1810 PAUSE
1820 GOTO 1870
1830 P1=X2 @ P2=Y2
1840 P3=X3 @ P4=Y3
1850 GOSUB 1340
1860 L7=L9
1870 REM DEFINE L4
1880 DISP "DEFINE LINE S1-S4.(L/I/D)"
1890 INPUT L1$
1900 IF L1$#"L" THEN 1930
1910 L8=((X4-X1)^2*M1+(Y4-Y1)^2*M2)^.5
1920 GOTO 2010
1930 IF L1$#"D" THEN 1970
1940 DISP "MANUALLY DEFINE LINE S1-S4 USING THE FORM 'L8=DEFF'. THEN
CONTINUE"
1950 PAUSE
1960 GOTO 2010
1970 P1=X1 @ P2=Y1
1980 P3=X4 @ P4=Y4
1990 GOSUB 1340
2000 L8=L9
2010 PLOT X3,Y3,-2
2020 L1=L5 @ L2=L6 @ L3=L7 @ L4=L8
2030 F=(L4+L3-L1-L2)/2/S
2040 F1=S*F
2050 F2=F2+F1
2060 PRINT "F",F
2070 PRINT "AF",F1
2080 PRINT "SUMAF",F2
2090 PRINT @ PRINT
2100 GOTO 700

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