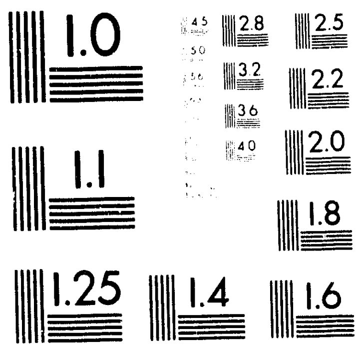
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Minimization of the Effect of Errors in Approximate Radiation View Factors

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Abstract

The maximum temperature of irradiated fuel rods in storage containers was investigated taking credit only for radiation heat transfer. Estimating view factors is often easy but in many references the emphasis is placed on calculating the quadruple integrals exactly. Selecting different view factors in the view factor matrix as independent, yield somewhat different view factor matrices. In this study ten to twenty percent error in view factors produced small errors in the temperature which are well within the uncertainty due to the surface emissivities uncertainty. However, the enclosure and reciprocity principles must be strictly observed or large errors in the temperatures and wall heat flux were observed (up to a factor of 3). More than just being an aid for calculating the dependent view factors, satisfying these principles, particularly reciprocity, is more important than the calculation accuracy of the view factors. Comparison to experiment showed that the result of the radiation calculation was definitely conservative as desired in spite of the approximations to the view factors.

1 Introduction

Radiation view factors are needed in many heat transfer calculations in nuclear applications, including accident analyses and fuel reprocessing. For complicated geometries, the view factors can be quite difficult to compute. Emphasis is often placed on calculating these quadruple integrals exactly rather than ensuring closure of the problem (Fogiel [1]). Many approximations are made in heat transfer problems when thermal radiation transport between opaque surfaces is important. Assumptions of diffuse radiating surfaces, uniform temperatures and radiosities over each surface, non-absorbing intervening gases, and approximate emissivities independent of wave length are usually made. Considering the magnitude of these approximations, view factors need to be calculated only within comparable accuracy.

A method of approximating view factors of complicated geometries from published tables of view factors and other estimates is presented in this paper. Although the view factors are calculated approximately, strict application of the enclosure (sum of the shape factors equal to one) and reciprocity principles are necessary to avoid large errors in the answers. Estimates of the uncertainties in the view factors are used to estimate the error in the temperature and the heat flux calculations. This estimate of the view factors and their uncertainties comprise an alternative calculation method to the exact calculation of view factors.

The problem under consideration is shown in Figure 1. A circular array of irradiated fuel rods are to be stored in a fuel pin can (FPC). The 0.635 cm (0.25) in diameter rods are stored in two rows of 31 rods each as shown in Figure 1. The radius of the centers of the first row of rods is 9.14 cm (3.60 in.), the second is 11.18 cm (4.40 in.), and the inner radius of the FPC is 12.45 cm (4.90 in.) The rods are offset so that they radiate more efficiently

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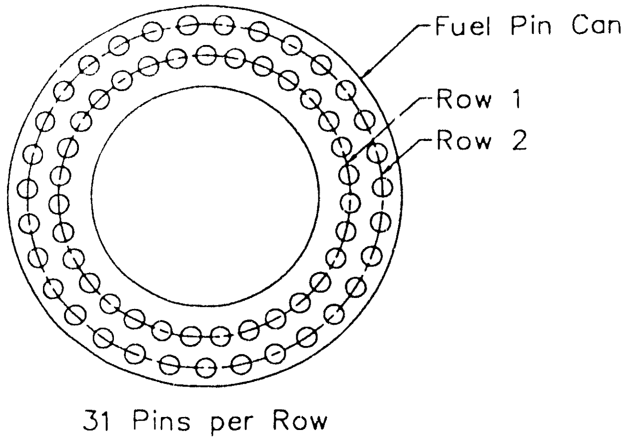

Figure 1: Schematic of Fuel Pin Storage Array.

to the sink temperature of the FPC. At steady state, the energy is transported from the pins by natural convection and radiation to the wall of the FPC. The energy is then conducted into the surrounding medium. The objective of this work is to determine the steady state maximum fuel temperatures and to ascertain that this temperature is low enough to insure a minimal increase in the cumulative damage fraction of the fuel rods. The cumulative damage fraction is to stay below one percent for at least 10 years of storage so that no change in fuel rod geometry will occur.

2 Methodology

The irradiation history of the fuel rods is known so that the decay heat can be calculated at the time the rods are stored in the FPC. The decay heat decreases slowly so that for simplification, it is conservatively assumed the decay heat is constant and the problem becomes one of steady state. The total heat generation in the FPC is obtained by summing the decay heat in each rod. The temperature of the surrounding medium is known and the temperature of the FPC can be obtained by solving a related heat transfer problem. After this temperature is determined, the radiant transfer problem inside the FPC is determined. The problem is made two dimensional by neglecting axial conduction. Convective heat transfer is neglected since a conservative (high) estimate of the temperature is desired.

For the radiation calculation, three surfaces are considered for the geometry of Figure 1: the inner row of rods, the outer row, and the FPC. Each of these surfaces uses the radiative assumptions mentioned above. Sparrow [2] defines the radiosity of surface i, B_i, that is the diffuse radiation energy per unit area leaving surface i, as

$$B_i = \epsilon_i \sigma T_i^4 + (1 - \epsilon_i) \sum_{j=1}^{n} B_j F_{ij} \qquad (1)$$

where

$$\begin{aligned} \epsilon_i &= \textit{emissivity of surface } i. \\ \sigma &= \textit{Stefan Boltzmann constant.} \\ T_i &= \textit{temperature of surface } i. \\ F_{ij} &= \textit{view factor from surface } i \textit{ to } j. \end{aligned}$$

The first term on the right represents the grey body emission and the second represents the incoming radiant energy from all surfaces (including i) reflected back. It is noted that these equations only bring in the actual problem geometry through the view factors. For an N surface heat transfer problem, the relationships in Equation 1 represent N equations and 2N unknowns, the B_i and T_i. The unknown temperatures can be related to the surface heat flux, q_i'', by the relation (Sparrow [2])

$$q_i'' = \frac{\epsilon_i}{1 - \epsilon_i} \left(\sigma T_i^4 - B_i \right) \qquad (2)$$

The relationships in Equation 2 introduce N more equations and N more unknowns, q_i''. There are no geometry properties specified in these equations.

With known view factors, the set of equations are closed by specifying either temperature, heat flux, or a heat balance on each object. In the problem under consideration, the inner row of rods are taken as surface 1, the next row as surface 2, and the FPC as surface 3, so that N=3. The temperature of the FPC is specified from the previously mentioned calculations and the surface heat flux of the inner and outer row of rods is determined by the total heat generation rate of each row divided by the total surface area of the rods.

The solution for this steady state problem proceeds by obtaining a set of N equations with N unknowns in terms of B_i. Equation 1 is used for surfaces in which temperatures are specified. For surfaces where q_i'' is specified, equations 1 and 2 are combined to obtain

$$q_i'' = \sum_{j=1}^{n} (\delta_{ij} - F_{ij}) B_j \quad (3)$$

where δ_{ij} is the kroniker delta. In this problem, equation 3 is used for surfaces 1 and 2 and equation 1 is used for surface 3. After the B_i are obtained, the unknown temperatures and the unknown heat fluxes are solved for from equation 3.

As pointed out, the only place that the actual geometry of the problem is introduced in this closed set of equations is in the view factors. Two rules must be strictly obeyed in the view factor value use. The first states that the total energy leaving a surface must be received by all the surfaces in the enclosure (the enclosure principle), that is,

$$\sum_{j=1}^{n} F_{ij} = 1 \quad (4)$$

The second is the reciprocity rule for shape factors

$$A_i \; F_{ij} = A_j \; F_{ji} \quad (5)$$

The reciprocity relationship is the place where the geometry of the problem is introduced. It specifies the areas of each surface in the enclosure relative to the others. If this relation is not satisfied, the equalities in Equations 1 and 2 are not valid.

View factors are defined in Sparrow [2], and for finite bodies are calculated by a quadruple integral. The general integral is given as

$$F_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos\theta_1 \cos\theta_2 \; dA_2 \; dA_1}{\pi S^2} \quad (6)$$

where

A_1, A_2 = *surface areas for surfaces* 1 *and* 2.
S = *distance between* dA_1 *and* dA_2.
θ_1, θ_2 = *angles between surface normal and* S.

Tables of exact view factors are available in Sparrow [2], Hamilton [3], Siegel [4], and others. Methods for estimating view factors are also mentioned in these references. Emery [5] provides a comparison of methods for computing view factors for complex structures. The method presented here uses approximate values of view factors and the effect of the approximation is assessed by investigating the uncertainty of the view factors on the results.

Calculating view factors exactly for the problem defined here, and many problems, is quite difficult because of the multiple surfaces involved and the many directions that radiation can be exchanged between these surfaces. Consider a single rod in surface 1. It radiates a different amount of energy to half of the rods in surface 1 (symmetry) and the integrals of equation 6 are unique for each of the rods it radiates to. These view factors are then summed to obtain the total view factor of surface 1 to itself.

The view factor from surface 1 to 2 is even more complicated since it involves radiation to some rods in the second row directly (that is outward toward the wall) and other second row rods (radiation inward toward the can center) that goes between the first row rods. The same level of difficulty is associated with each of the other view factors of which there are nine for a three surface system.

3 View Factor Estimation

On one hand, view factors can be very difficult to calculate exactly. On the other hand, they can be estimated quite simply by realizing that they represent the fraction of radiant energy leaving one surface which is incident on another. All nine view factors are estimated in this section, without regard to satisfying the reciprocity or enclosure principles. The purpose of these independent estimates is to allow us to evaluate the importance of these two principles.

The view factor between adjacent rods which is used in the evaluation of several of the F_{ij} is first evaluated. The view factor formula of radiation from cylinder R_1 to cylinder R_2, based on the published table from Sparrow [2] is

$$F_{R_1 R_2} = \frac{1}{\pi}\left(\sqrt{X^2 - 1} - X + \frac{\pi}{2} - cos^{-1}\frac{1}{X}\right) \quad (7)$$

where

X = $D/2r$.
r = *radius of the rods.*
D = *distance between rod centers.*

Note that equation 7 is based upon the whole surface area of the rod and is one half of that in Sparrow [2], which is based upon half the rod area. Since no radiation from the back half of rod 1 reaches rod 2, the view factor must be decreased by 2 if the area is increased by 2. Care must be taken in using published view factors to ensure that they are based on the desired area or a correction must be made to change it to the correct area. If the view factor between rods published in Sparrow were used assuming the wrong area, the view factor would be too large by a factor of two. Often simple checks can be made to ensure the reasonableness of the values. For example, the values given by equation 7 should be very close to that obtained by the approximate expression

$$F_{R_1 R_2} = \frac{1}{\pi}(sin^{-1}\frac{r}{D}) \tag{7a}$$

which is the angle subtended by the two tangents to rod 2 from the center of rod 1 divided by the total angle of the circle; that is, the percentage of the view of rod 1 that is blocked by rod 2. Note, this equation is least accurate for touching rods (8 percent error), most accurate for rods at large distances.

Equation 7 is used to estimate a view factor to two adjacent rods, all the rods have diameters of 0.635 cm (0.25 in.). The view factor for adjacent rod to rod exchange in the inner row with a distance between rod centers of 1.85 cm (0.730 in.). is 0.0551 (note that equation 7a gives 0.0548). The view factor for interchange between adjacent rods in the outer row with a spacing of 2.28 cm (0.896 in.). is 0.045. The spacing between adjacent rods in the inner to outer row is 2.27 cm (0.892 in.) so the view factor is almost the same. An average view factor, FROD = 0.05, is used for interchange between all adjacent rod pairs.

The fraction of energy from a rod, FI, radiated inward is slightly over estimated as

$$FI = \frac{(1 - 2\ FROD)}{2} = 0.45 \tag{8}$$

and the fraction radiated outward toward the can wall, FO, is slightly under estimated as FO = FI.

The view factors for the inner row of rods in Figure 1 (surface 1) can be estimated by considering a single rod since it is representative of the entire row of rods. The fraction of energy surface 1 radiates to itself, F_{11}, is estimated by

$$F_{11} = 2\ FROD + FI \times OP_1 \tag{9}$$

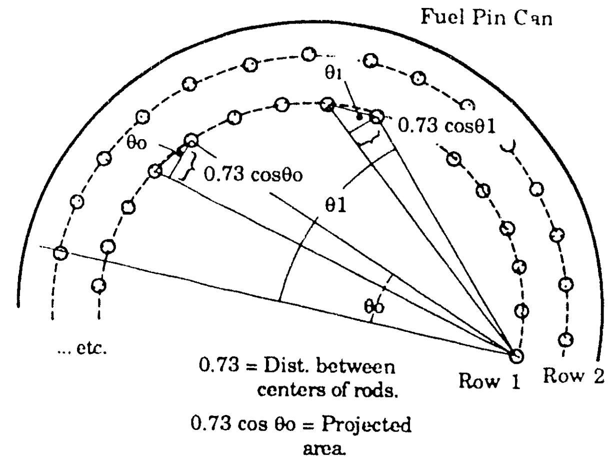

Figure 2: Geometry for Determining Average Opacity OP_1.

The first term represents the fraction of energy from a single rod radiated to its two adjacent rods in row 1. The second is the fraction of energy emitted inward which is incident on the other rods in row 1. The fraction of FI incident on row 1 is represented by the average opacity of the other rods, OP_1, taking into account the spaces between rods. None of the energy fraction radiated outward from these rods, FO, is incident on the other rods in surface 1.

The average opacity is estimated by integrating the opacity seen by a single ray of energy in the direction of the normal of the rod surface from zero to the angle where the ray intersects the adjacent rod. Figure 2 shows the geometry under consideration. At any angle θ, the opacity between any two rod centers is the ratio of the projected rod area, 2 r, to the open projected area, $D cos\ \theta$. This ratio starts from a minimum of 0.343 and increases to 1 at $\theta = 69^o$. The opacity remains at 1 to 82^o, the angle at which the ray intersects the adjacent rod. Thus the average opacity. OP_1 is estimated as

$$OP_1 = \frac{1}{82^o}\left(\int_0^{69^o} \frac{0.635}{1.854\ cos\ \theta} d\theta + 13.0\right) = 0.631 \tag{10}$$

Evaluating equation 9, the total view factor of surface 1 to itself is 0.384.

By a similar argument, the view factor of surface 1 to surface 2, the outer row of rods, is estimated as

$$F_{12} = 2FROD + FROD_{12} + FI(1 - OP_1)OP_2 \quad (11)$$

The first term is the fraction of energy radiated to the two adjacent rods in row 2. The second is an estimate of that radiated outward to the other rods in row 2. The third the fraction radiated back into the inner circle that is transmitted through row 1 and is incident on row 2. The fraction radiated outward to the other rods in row 2 is estimated as $FROD_{12} = 0.1$. The amount radiated to the inner circle that escapes the inner row is $FI(1 - OP_1)$. The fraction of this latter amount that is incident on row 2 is equal to its opacity OP_2.

The opacity of row 2 is estimated as the ratio of the rod diameter to open space between the rods of row 1. Thus $OP_2 = 0.635/(1.854\text{-}0.635) = 0.52$. Substituting into equation 11 yields $F_{12} = 0.286$.

Although the value of F_{13} can be obtained from F_{11} and F_{12} using the enclosure principle, as mentioned previously it will be independently estimated. The fraction of energy which reaches the wall of the can is the remainder of the radiation leaving this rod. This is given by

$$F_{13} = FI(1-OP_1)(1-OP_2)+FO(1-OP_2) \quad (12)$$

The first term represents the energy radiated to the inner circle which is transmitted through row 1 and row 2. The second term represents the energy fraction emitted outward, FO, which is transmitted through the second row of rods. The transmissivity is estimated by $(1-OP_2)$. The resulting value is $F_{13} = 0.296$.

The view factors of row 2 can again be estimated by considering a single rod. The view factor to itself is estimated with the equation

$$F_{22} = 2FROD + FROD_{22} + (FI - FROD_{22}) \times (1 - OP_1)^2 OP_2 \quad (13)$$

where the first term represents the energy fraction incident on the adjacent rods, the second term, $FROD_{22}$, is the energy fraction directly incident on the other row 2 rods, and the third term is an estimate of the energy radiated backward to the inner circle that makes it through row 1 back to row 2. It comprises a part of FI because only radiation emitted back toward the center can reach the inside surfaces of the row 2 rods directly. Engineering judgement is used to estimate $FROD_{22}$ at 0.2 or slightly less than 1/2 of FI. The evaluation of equation 13 yields 0.318.

The view factor to surface 1 is given by

$$F_{21} = (FI - FROD_{22})OP_1 + (FI - FROD_{22})(1 - OP_1)OP_1 \quad (14)$$

where the first term represents the fraction incident on the near row 1 rods and the second term represents the radiation incident on the row 1 rods on the other side. Note that the same opacity is used as derived previously and can be only approximately correct.

The view factor to the can surface is given by

$$F_{23} = FO + (FI - FROD_{22}) \times (1 - OP_1)^2(1 - OP_2) \quad (15)$$

The first term represents that all the radiation in the outward direction is incident on the can. The second term represents the inward radiation which is transmitted through the nearest side of surface 1, through the further side of surface 1, and through the rods of surface 2.

The view factors of the can surface are estimated by considering a representative point on the surface. The fraction of emitted radiation incident on itself is

$$F_{33} = F_{cd} + (1 - F_{cd})(1 - OP_1)^2(1 - OP_2)^2 \quad (16)$$

The first term, F_{cd}, is the fraction of energy directly incident on the wall. The second is the fraction of emitted energy which has been transmitted through row 1 twice and row 2 twice to again reach the wall.

The fraction of emitted energy which directly reaches the wall, as illustrated in Figure 3, is approximated as that energy emitted in the angle 0 to θ_o where $cos\theta_o = r_i/r_o = 11.50/12.45$ so that $\theta_o = 22.6$. In determining the fraction of energy directly transmitted to the wall, since it is almost a flat surface, rather than a circular rod, the cosine of the angle is taken into account so that

$$F_{cd} = \frac{\int_0^{22.6} cos(90 - \theta)d\theta}{\int_0^{90} cos(90 - \theta)d\theta} = 0.0765 \quad (17)$$

Substituting into equation 16 gives 0.105.

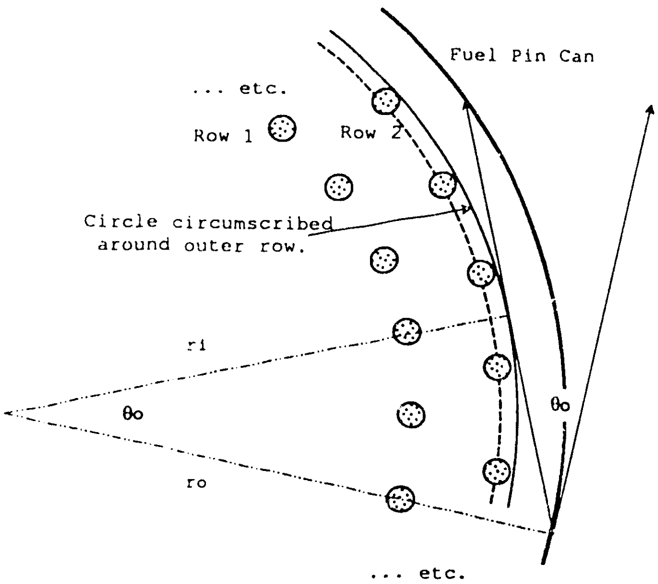

Figure 3: Geometry for Approximating Part of F_{33}.

The fraction of energy emitted by a point on the wall which reaches row 1 is

$$F_{31} = (1 - F_{cd})[(1 - OP_2)OP_1 + (1 - OP_2) \times (1 - OP_1)OP_1] \quad (18)$$

where the first and second terms represent the amount incident on row 1, first on the near side and then the far side. Substituting yields 0.383.

The view factor to the second row is

$$F_{32} = (1 - F_{cd})[OP_2 + (1 - OP_2) \times (1 - OP_1)^2 OP_1] \quad (19)$$

where the first and second terms represent the fraction of energy incident on the near and far side of row 2 respectively. Substituting in values yields 0.512.

4 Numerical Results

In this section, we first look at typical approximations someone could make if they did not realize reciprocity and enclosure ar so important. Then we look at the magnitude of errors acceptable in the view factors with enclosure and reciprocity satisfied.

4.1 Enclosure and Reciprocity Restrictions Neglected

Calculations were performed with the F_{ij} derived in the previous section with the exceptions that the $(1 - F_{cd})$ factor was left out of F_{31} and F_{32}, and, by mistake, $(1 - OP_1)$ was not squared in F_{23}. No attempt was made to satisfy equations 4 and 5. The results are

	$j=1$	$j=2$	$j=3$	$\sum$
F_{1j}	0.384	0.286	0.296	0.966
F_{2j}	0.216	0.318	0.494	1.028
F_{3j}	0.415	0.554	0.105	1.074
$T_j(°C)$	290.0	295.3	240.0	
$q''_j(W/m^2)$	299.6	299.6	−1080.2	

Note that T_3, q''_1, q''_2 are specified. The latter two quantities are the heat flux determined by 62 rods generating a total of 127.05 watts [length 34.3 cm (13.5 in), diameter 0.635 cm (0.25 in)]. This calculation is clearly in error because, 1) the sum of the view factors are not equal to 1 and the reciprocity relationships are not satisfied, 2) the temperature of the outer rods is higher than the inner rods, and 3) the heat flux at the can surface is over a factor of 2 in error. The heat flux should be -473.8 W/m^2 to be in steady state with the heat generated in the rods.

With the term $(1 - F_{cd})$ included back in F_{31} and F_{32} and an inconsistency in the equation for F_{13} removed, the calculations were repeated. Although equation 12 is a valid estimate for F_{13}, to be consistent with the way F_{11} and F_{12} are estimated, the equation for F_{13} should have been

$$F_{13} = FI(1 - OP_1)(1 - OP_2) + (FO - 2FROD - FROD_{12}) \quad (20)$$

The results are

	$j=1$	$j=2$	$j=3$	$\sum$
F_{1j}	0.384	0.286	0.330	1.000
F_{2j}	0.216	0.318	0.494	1.028
F_{3j}	0.383	0.512	0.105	1.000
$T_j(°C)$	291.1	291.3	240.0	
$q''_j(W/m^2)$	299.6	299.6	−882.9	

The sum of the view factors is now equal to 1 for surfaces 1 and 3 although surface 2 is still in error. The reciprocity relationships are not satisfied, the temperature of surface 2 is still slightly greater than surface 1, and the heat flux at the can surface is still in significant error.

Finally, the error was removed from F_{23} by squaring the $(1 - OP_1)$ term in equation 15. Results for this modification are

	$j=1$	$j=2$	$j=3$	$\sum$
F_{1j}	0.384	0.286	0.330	1.000
F_{2j}	0.216	0.318	0.466	1.000
F_{3j}	0.383	0.512	0.105	1.000
$T_j(^oC)$	284.5	281.6	240.0	
$q_j''(W/m^2)$	299.6	299.6	−665.6	

The sum of the view factors for each surface equals 1 in the above calculation. The temperature has been decreased with this correction and surface 2 is less than surface 1. The heat flux at the can surface is still in error. This error is due to the reciprocity rule not being satisfied. Once the reciprocity relation is satisfied, the error in the can heat flux disappears.

4.2 Enclosure and Reciprocity Restrictions Satisfied

Although estimates for all nine view factors were developed, if equations 4 and 5 are to be satisfied, only three of these are independent. The view factor summation equal to 1 for each surface supplies three relations and the reciprocity supplies three more. For an N surface problem, the number of independent view factors is 0.5 N(N-1). Thus, for this problem, only three view factors needed to be estimated. The simplest to determine can always be chosen since the choice of three independent view factors is mathematically equivalent to the choice of any other three. Redundant view factors can be used to check reasonableness.

i) Base Case. In the following, the independent view factors are taken as F_{11}, F_{12}, and F_{23}. Equations 9, 11, and 15 are used respectively. The results with these view factors are given as

	$j=1$	$j=2$	$j=3$	$\sum$
F_{1j}	0.384	0.286	0.330	1.000
F_{2j}	0.286	0.248	0.466	1.000
F_{3j}	0.261	0.369	0.370	1.000
$T_j(^oC)$	279.7	276.9	240.0	
$q_j''(w/m^2)$	299.6	299.6	−473.8	

It is noted that the view factors for surface 3 are significantly different, especially the view factor to itself. The maximum fuel temperature calculated with the above view factors is 279.7 °C. The heat flux at the wall is satisfied exactly as it will be for cases in which all the equations are satisfied.

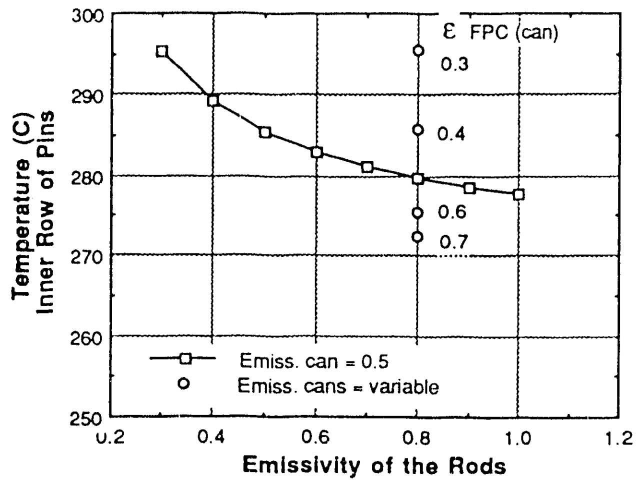

Figure 4: Temperature as a Function of Rod Emissivity and FPC Emissivity.

ii) Emissivity Variation. The emissivities of the surfaces were varied using the above view factors. The resulting temperatures as a function of surface emissivities is shown in Figure 4. The error in the emissivities is estimated to be ±20 percent. Figure 4 shows this corresponds to a temperature range uncertainty $\pm 5^oC$. This difference provides a yard stick for the uncertainty allowed in the view factors.

iii) View Factor Variation. The change of the maximum temperature with each of the independent view factors is shown in Figure 5. An error of ±20 percent in the view factors produces a variation of $\pm 4^oC$, which is less than that caused by the uncertainty of the emissivity. The seven parameters which determine the three independent view factors, F_{11}, F_{12}, and F_{23}, are FO, FI, FROD, FROD12, FROD22, OP1, and OP2. Uncertainties considered in each of these produced much less variation than ± 20 percent.

The value of F_{33} in the above base case is too large and it should be close to the value of 0.105 calculated by equation 17. Decreases in F_{11} and F_{12} and increases to F_{23} cause a decrease in F_{33}. Figure 5 shows these cause a decrease in the maximum temperature as well. Changes in these values to produce an F_{33} closer to 0.105 will also increase F_{13} and F_{23}, which will lower the temperatures of the rods. Leaving F_{33} as is produces a conservative result.

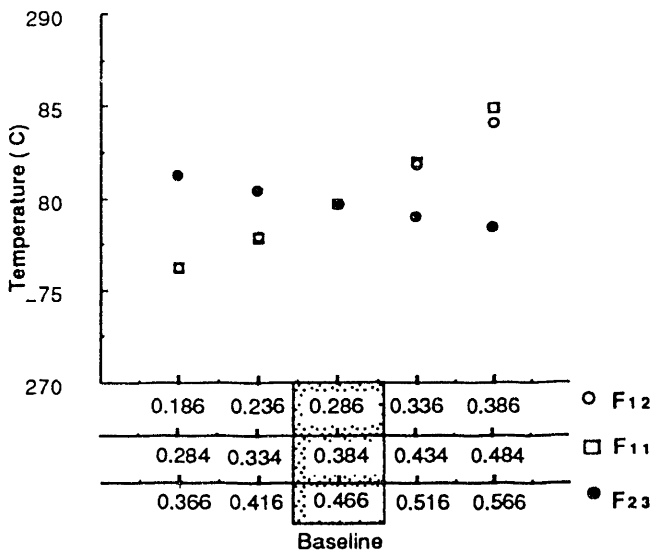

Figure 5: Inner Row Temperature as a Function of View Factor.

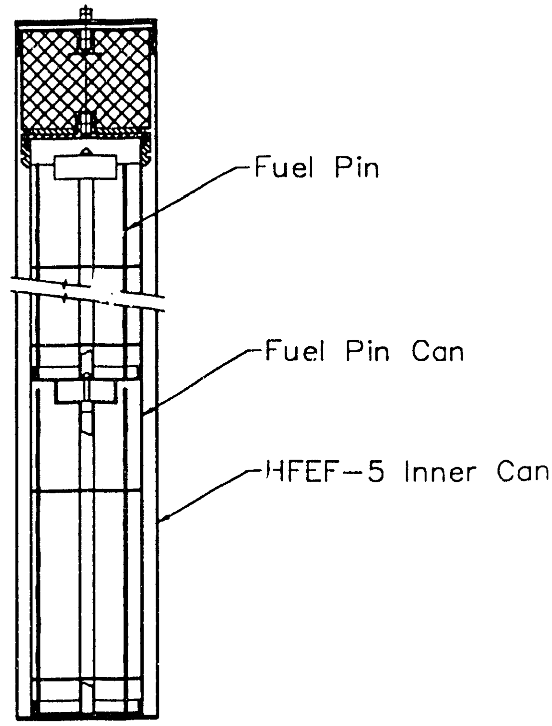

Figure 6: Experimental Apparatus for Fuel Pin Storage.

5 Comparison to Experiment

Safety committee approval for storage of the fuel pins required that a demonstrably conservative method be used to predict the fuel pin temperatures. This calculational technique only takes credit for two dimensional radiation between the rods and FPC walls and neglects all other potential heat transfer paths. The calculations, which used the approximate view factors, were accepted, but the committee required experimental verification. A full-scale experimental apparatus was designed and built to prove the technique was conservative.

The fuel pins and fuel pin can were instrumented with thermocouples. A schematic of the apparatus is shown in Figure 6. The pins were stored in an array as shown in Figure 1. A basket was designed to hold the pins in the array to insure that a criticality safe configuration was maintained. The fuel pins are approximately 76 cm (30 in.) in length, with the fuel element composing approximately 34.3 cm (13.5 in.) of the total length. The remainder of the 76 cm does not contain fuel and is unheated. Two baskets, one on top of the other, are stored within the fuel pin container, which is held within an outer container. The top basket will be referred to as the upper basket, and the bottom basket will be referred to as the lower basket.

Thermocouples were placed on the fuel pins in two axial locations. One thermocouple was placed near the center of the heat generating portion of the element, referred to as the heated region. The other thermocouple was placed near the top of the element, referred to as the cold region. Thermocouples were placed on the fuel pins in the lower and upper baskets. The FPC temperatures were also measured with thermocouples. These thermocouples were placed in contact with the FPC with metal clips. The thermocouples on the metal clips were isolated from the metal clips with fiberglass tape to minimize conduction to the FPC thermocouples.

The calculations discussed in previous sections used a much higher FPC temperature than expected in the experiment. The higher fuel pin can temperatures were the result of conservatisms used in the original determination of the fuel pin can temperature. The computations reported in this section used the measured FPC temperatures as a boundary condition. The total heat generation rate from the two baskets of pins (122) is 275 W.

The measured and predicted fuel pin temperatures are shown below. The measured data includes an estimate of the experimental uncertainty. There are four sets of experimental data, two sets of readings for the upper and lower baskets. The notation "Ht" and "cold" refers the heated and cold regions of the fuel elements. The predictions are for the measurements in the heated region of the lower baskets. The calculations were based on the procedure discussed above.

	Row1	*Row2*	*Fuel Pin Can*
Measured (°C) (*Cold – upper*)	66 ± 4	*na*	57 ± 4
Measured (°C) (*Ht – upper*)	93 ± 4	91 ± 4	64 ± 4
Measured (°C) (*Cold – lower*)	68 ± 4	*na*	61 ± 4
Measured (°C) (*Ht – lower*)	88 ± 4	83 ± 4	56 ± 4
Predicted (°C) (*Radiation only*)	169	163	*given* (56)
Predicted (°C) (*Radiation and Convection*)	118	115	*given* (56)

These analyses were conducted to insure that a maximum fuel pin temperature of $400°C$ would not be exceeded. The results verify that the approximations made in the view factors do not affect the conservatism of the result.

The heat transfer effects that were neglected include 1) free convection heat transfer between the rods and the FPC, 2) three-dimensional radiation effects which allow pins to radiate to much lower temperatures in the regions above and below the hot region, 3) axial conduction within each pin to the lower temperatures of the unheated fuel sections, and 4) conduction from the pin to the storage baskets and storage containers.

To check the importance of the neglected modes of heat transfer, free convection effects were estimated using a reasonable overall heat transfer coefficient of $3W/m^{2o}C$ between the pins and FPC surface, and the surface area of the rods. This brought the maximum fuel rod temperatures down from 169 to $118°C$, which shows the large effect of free convection. Including the other heat transfer mechanisms should bring the temperature down to the experimental data.

6 Conclusions

This paper shows that although view factors can be quite complicated to calculate exactly, they may be adequately estimated in many cases. Even if independent view factors are accurate, large errors will occur in heat transfer calculations if the radiation closure relations are not satisfied exactly in calculating the dependent view factors. Accurate results can be obtained even with 10 to 20 percent error in the view factors if the enclosure and reciprocity conditions are satisfied. Experimental results proved that two dimensional radiation calculations are conservative.

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