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ABSTRACT

Radiation heat transfer in an array of fixed discrete surfaces is an important problem that is particularly difficult to analyze because of the nonhomogeneous and anisotropic optical properties involved. This article presents an efficient Monte Carlo method for evaluating radiation heat transfer in arrays of fixed discrete surfaces. This Monte Carlo model has been optimized to take advantage of the regular arrangement of surfaces often encountered in these arrays. Monte Carlo model predictions have been compared with analytical and experimental results.

INTRODUCTION

In a recent review article, Howell indicates that radiative heat transfer in a fixed array of surfaces, where the surfaces have a fixed orientation, is a significant problem that is not being widely addressed (Howell 1988). In most problems involving radiative heat transfer in participating medium, optical properties such as extinction coefficient and anisotropic scattering are treated as being independent of incident angle. As Howell observes, when the orientation of the absorbing array is fixed, the scattering phase function depends on the angle of incidence as well as the angle of reflection. This increases the complexity of the problem. Howell observes that methods for treating this situation are not available.

The research documented in this article developed an analytical approach that models the absorbing array as discrete surfaces and uses a Monte Carlo

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model to evaluate the radiation heat transfer in the array. Monte Carlo modeling is a statistical method of analyzing a problem as a series of probabilistic and deterministic events. Model development is one component of an analytical and experimental investigation of radiation heat transfer in arrays of fixed discrete absorbing surfaces. The Monte Carlo approach was optimized for this application and takes advantage of the regular geometry often encountered in arrays of fixed discrete absorbers. The model includes an innovative method of determining photon trajectories, substantially improving the computational efficiency of modeling a large number of surfaces. The Monte Carlo model is fully capable of evaluating arrays nonhomogeneous extinction coefficients, anisotropic scattering, various surface properties, and large numbers of surfaces.

BACKGROUND

Arrays of fixed discrete absorbing surfaces are encountered in a number of important applications. Development of a volumetric air heating receiver (VAHR) is a current research focus in solar thermal power generation. The VAHR uses an array of discrete and fixed absorbing surfaces to absorb concentrated solar energy and to heat incoming ambient air by convection from the absorbing array (Drost and Eyler 1981; Drost et al. 1985). A VAHR absorbing array consists of fixed discrete surfaces with dimensions much larger than the wavelength of the incident radiation. The surfaces can be specular and an individual component of the array can have rectangular, circular, or triangular cross-sections. This results in an array with strongly anisotropic optical properties (assuming that the array was being modeled as a participating media) and a high degree of symmetry.

The least complicated approach to evaluating the radiative heat transfer in the absorbing array of a VAHR consists of dividing the array into zones with composite optical properties and then using analytical techniques developed by Viskanta for radiation heat transfer in multiple transparent plates (Viskanta 1978; Drost and Eyler 1981). Drost used a Monte Carlo technique optimized for an array of symmetric discrete absorbers to evaluate the radiative heat transfer in a VAHR (Drost 1985; Drost et al. 1985; Drost and Welty 1985). Skocypec et al. (1988) evaluated radiation heat transfer in an array of randomly oriented but fixed cylindrical discrete absorbing surfaces by modeling the array as a participating medium and then using a two-flux model to predict the radiative heat transfer.

Radiative heat transfer is an important heat transfer mechanism in fibrous insulation. Fibrous insulation can be modeled as discrete fibers with a fixed orientation. Normally the fibers have a small diameter and can be modeled as Mie scatterers. The fibers are often assumed to being randomly oriented and scattering can be independent (fiber spacing is sufficiently large to prevent interactions between fibers) or dependent (scattering from a fiber is influenced by adjacent fibers).

The usual analytical approach is to model the array as a participating media and then use any of the numerous methods available for evaluating radiation heat transfer in a participating medium. Lee has used a number of techniques to evaluate radiation heat transfer in a fibrous medium composed of microscopic fibers with regular and random orientation (Lee 1985, 1986, 1988). Tong and Tien (1983) also analytically investigated radiation heat transfer in fibrous insulation while Tong et al. (1983) conducted an experimental study of the same phenomena. The related problem of radiation heat transfer in a packed bed has been extensively investigated and recent research has been reviewed by Tien (1988).

A more recent application of arrays of discrete fixed surfaces involved radiative heat transfer in ceramic fabrics. Ceramic fabrics may have a number of important applications as space power systems. The ceramic fabrics are made from yarn that is, in turn, fabricated from small ceramic fibers. If individual ceramic fibers are evaluated, Mie scattering is encountered. When yarn is evaluated, the dimensions are sufficiently large that photon/surface interactions can be modeled using geometric optics. The fibers can have many cross-sectional shapes and can have a wide range of surface coatings, including metal coating. The fibers are typically formed into yarns of various dimensions and the yarns can be woven into fabrics with various yarn spacings and weave patterns.

The applications described above demonstrate the range of characteristics encountered in arrays of fixed discrete surfaces. The extinction coefficient (modeling the array as a participating medium) is always nonhomogeneous but the nonhomogeneity can range from very strong nonhomogeneous effects in arrays of fin-shaped elements to fairly weak nonhomogeneity in arrays of cylindrical-shaped surfaces. The surface dimensions can be large relative to the wavelength of the incident radiation or have dimensions of the same magnitude as the incident radiation's wavelength. Surfaces can be specular reflectors, diffuse reflectors, or semi-transparent. Finally, scattering is always anisotropic, but can be either dependent or independent.

The characteristics of fixed discrete absorbers presents an extremely challenging problem for the analyst. In general, two approaches have been used. The most widely applied approach is to model the array as a participating medium and then use any of a number of analytical approaches to obtain a solution. This approach has difficulty addressing nonhomogeneous optical properties, particularly the nonhomogeneous extinction coefficient and the assumption that an array of large surfaces (relative to the wavelength of the incident radiation) can be modeled as a participating medium. The second approach is to model the individual surfaces and use techniques developed for macroscopic radiation heat transfer to obtain a solution. The large number of surfaces involved make this approach very challenging.

PROBLEM DESCRIPTION

The objective of this research was to develop and conduct a preliminary validation of a Monte Carlo model capable of efficiently analyzing the radiation heat transfer in an array of fixed discrete surfaces. Ultimately the model will be used to support an experimental investigation of this phenomena.

A typical experimental array is shown in Figure 1. Monochromatic collimated radiation impinges an array of isothermal fixed discrete surfaces at a variable incident angle. The array is enclosed in either specular or black boundaries. To evaluate radiation heat transfer in the array, the analytical model must be able to predict the monochromatic radiation flux throughout the array. Radiation heat transfer between isothermal array elements was not included in the analyses.

MONTE CARLO MODEL

The strong anisotropic scattering and directional dependence of optical properties typically encountered in arrays of fixed discrete absorbers presents a extremely challenging problem for analytical methods that model the array as a participating medium. Consequently, it was decided to model the array as discrete surfaces and to evaluate radiative interactions by using geometric optics.

Monte Carlo modeling has been widely applied and the method is well documented (Siegel and Howell 1972; Haji-Sheikh 1988, Burns and Pryor 1989; Maltby and Burns 1991). This section presents a brief overview of the Monte Carlo method followed by a more detailed discussion of the specific features of this application.

In radiation heat transfer applications, energy emitted from a surface is simulated by a large number of photons. The photons are followed as they proceed from one interaction to another with the results of each event being recorded. This is continued until the photon either leaves the array or is absorbed on a surface. A sufficiently large number of photons must be considered to ensure that variations in the results caused by random events are small. The results can be used to determine the fraction of the emitted energy that has been absorbed on each surface or has left the array.

The major challenges in a Monte Carlo model involve calculating photon trajectories and surface interactions. Determination of photon trajectories is particularly important because this calculation typically consumes 80% of the computer time used in a simulation (Maltby and Burns 1991). Methods for modeling the interactions of a photon with a surface are described by several authors (Siegel and Howell 1972; Yang 1981; Haji-Sheikh 1988; Burns and Pryor 1989; Maltby and Burns 1991).

SURFACE INTERACTION MODEL

When a photon strikes a surface, the incident angle and wavelength should be known. If surface properties such as absorption and secularity are known as a function of incident angle and wavelength, the relevant optical properties can be calculated. If the photon is totally or partially absorbed, the energy reduction caused by the interaction is added to the total energy absorbed for that surface. When a photon is not totally absorbed, a reflection angle must be selected. For a diffusely reflecting surface, the angle is selected to ensure that there is an equal probability for reflection in any direction. If the reflection is specular, the angle of reflection equals the angle of incidence.

It has been shown by previous investigators that direction-dependent properties can have a significant impact on radiation heat transfer (Toor 1967; Toor and Viskanta 1968). The sample problem is particularly sensitive to direction-dependent properties because many of the interactions take place at large incident angles. If the assumption of diffuse reflection in the diffuse-gray model is relaxed, it is necessary to provide information on the incident angle dependence of emissivity, reflectivity, absorptivity, and specularity. For model verification, surface properties were taken from Modest (1978) for metallic specular surfaces such as silver-teflon. The surface properties were assumed to be independent of wavelength. Incident angle dependence was modeled by using the correlation presented in Equation (1) for short wavelengths ($0.1\ \mu m < \lambda < 2.5\ \mu m$).

$$\epsilon'_{\lambda} = \alpha'_{\lambda} = \epsilon'_{\lambda,n}\left[1 - \left(\frac{2\beta}{\pi}\right)^{8}\right] + (\epsilon'_{\lambda,mxs} - \epsilon'_{\lambda,n})\ \exp\left[-\left(\frac{30\beta}{\pi} - 7\right)^{2}\right] \tag{1}$$

A second correlation, given by Equation (2), was used for infrared wavelengths ($\lambda > 2.5\ \mu m$).

$$\epsilon'_{\lambda} = \alpha'_{\lambda} = \epsilon'_{\lambda,n}\left[1 - \left(\frac{2\beta}{\pi}\right)^{10}\right] + (\epsilon'_{\lambda,mxs} - \epsilon'_{\lambda,n})\left(\frac{2\beta}{\pi}\right)^{2}\left[1 - \left(\frac{2\beta}{\pi}\right)^{2}\right] \tag{2}$$

PHOTON TRANSPORT MODEL

Photon trajectory calculations involve determining which surface interacts with a photon and where on that surface the interaction occurs. When complex geometries are considered (Corlett 1966; Modest 1978; Burns and Pryor 1989; Maltby and Burns 1991), the conventional method consists of describing each surface mathematically and determining which surface first intercepts the vector that describes the path of the photon. When a large number of surfaces are involved, the computational resources required to determine the impact location becomes substantial.

The regular spacing of the elements in the sample array (Figure 1) and their arrangement into rows suggests that a more efficient method of determining impact location can be used. This approach consists of dividing the receiver into computational cells, where the cells are arranged so that absorbing surfaces are located on cell boundaries. This simplifies identification of the impact location because, of the four surfaces in a two-dimensional cell, one is the emitting surface and the emitted photon must strike one of the remaining three cell boundaries.

The cell boundaries and the definition of zones for the sample problem are shown in Figure 2. The array is divided into zones where one zone corresponds to one row of elements. Each zone is divided into cells where the cell boundary is either the edge of an array element or the centerline of a wedge-shaped fin. Zone geometric characteristics that affect photon transport include variables such as element spacing, wedge angle, and offset. These are shown in Figure 2.

The Monte Carlo analysis of absorbed incident radiation distribution requires emission of a large number of photons with an incident angle into the external zone of the array. Photons interact with the surfaces in the array until they are absorbed or leave the array. If the photon is transmitted through the first zone, it enters a cell in an adjacent zone and the process is repeated until the photon is absorbed or leaves the array. Therefore, the interaction of the photon and with the array involves two calculations: the determination of the result of the interaction between the photon and a cell and the cell-to-cell transport of photons that have exited one cell and are entering another. Details of the photon-transport model are presented in Drost (1985) and Drost et al. (1985).

PHOTON-CELL INTERACTION ALGORITHM

Whenever a photon enters a cell, the location of the entry, the entry angle, and the current energy level are known. With the identification of the entry point, two angles are calculated: Beta_r and Beta_l. As shown in Figure 3, the photon strikes the right cell wall if the entry angle is less than Beta_r. If the photon entry angle is less than Beta_l but greater than Beta_r, the photon exits the cell through the opposing cell surface. Finally, if the entry angle exceeds Beta_l, the photon strikes the left wall. A similar method was employed by Howell and Bannerot (1974) in their evaluation of surface geometries for improved solar collectors.

Once the impacted surface has been identified, the location of the impact is determined by geometry. The energy of the photon is reduced by an amount equal to the product of its current energy level and the surface emissivity. The energy given up by the photon is absorbed by the impacted surface. If the photon energy has dropped below a minimum amount, the photon history is terminated. Otherwise, the photon is reflected.

At this point, the process is repeated with the impacted surface becoming the emitting surface, and Beta_r and Beta_l are recalculated based on the new impact location. The angle of reflection is determined by the optical properties of the surface. With the new emission location and angle selected, the procedure is repeated. This continues until the photon exits the cell or its energy drops below a minimum level.

The algorithm for analyzing a single cell is applicable to a wide variety of cell shapes, but the method used in this analysis was limited to 1) cells with straight cell boundaries, 2) left and right cell boundary wedge angles that are equal to each other and greater than 0.0, and 3) two-dimensional cells.

CELL-TO-CELL TRANSPORT ALGORITHM

If a photon history is not terminated in a cell, the photon will enter an adjacent cell (assuming that the photon has not exited the complete array). The photon-cell interaction procedure determines the exiting surface, location, and angle. The information is passed to the cell-to-cell transport algorithm where it is used to calculate the inlet location and angle for the next cell entered by the photon.

The location where an incoming photon enters a cell is calculated from the exiting location of the adjacent donor cell. The total distance from the exiting location to a datum (usually one of the array boundaries) is calculated. This is used along with the receiving cell dimensions to determine the inlet location. The inlet angle can be calculated directly from the outlet angle from the donor cell. If the algorithm indicated that the photon strikes a pin tip, then the photon energy is reduced by an amount equal to the product of the current photon energy and the surface emissivity. If the current energy of the photon is still above the minimum level, it will be reflected back into the donor cell. The entering location of the photon will be the same as the previous exiting location, but the inlet angle of the photon entering the original donor cell will depend on the optical properties of the pin tip.

EXCHANGE FACTOR ALGORITHM

While the research reported in this paper has focused on determining the absorption of incident radiation in an array of isothermal fixed discrete surfaces, the Monte Carlo model can also be used to calculate exchange factors between zones. Details of the exchange factor calculations are presented in Drost (1985) and Drost et al. (1985).

SAMPLE SIZE CONSIDERATIONS

The uncertainty in the results of a Monte Carlo simulation depends on the number of photons simulated. As the number of simulated photons increases, the uncertainty decreases, but the cost of computational resources demands a compromise between statistical uncertainty and the number of photons included in a simulation.

Most variance reduction techniques developed for photon and neutron transport problems were not relevant to this problem and were not used, but survival biasing was included. In this case, the photon energy was incrementally reduced rather than having the photon either terminated or unaffected by an interaction. Survival biasing was found to be beneficial because this technique allowed more information to be obtained from one photon.

Typical simulations used batch sizes of 10,000 photons with 20 batches being simulated. This resulted in standard deviations typically less than 1% of the mean values. A simulation of a test array will usually require approximately 15 min. of computer time on a Sun SPARC II work station.

COMPARISON WITH OTHER PHOTON TRANSPORT SCHEMES

The photon transport scheme summarized in this paper and more fully documented in Drost (1985) and Drost et al. (1985) can be compared to other photon transport schemes. Maltby and Burns (1991) provide an excellent description of the conventional photon transport scheme. This approach consists of describing each surface mathematically and determining which surface first intercepts the vector that describes the path of the photon. The conventional scheme requires that all surfaces involved in the problem be checked for a possible intercept. When a large number of surfaces are involved, the computational resources required to determine the impact location becomes substantial.

The cell-to-cell transport scheme simplifies identification of photon surface interactions, while limiting the number of candidate surfaces that need to be checked. When a photon enters a cell, the photon can only strike one of three surfaces and identification of that surface is easily accomplished by a comparison of the photon's entering angle with B_l and B_r. This approach does require cell-to-cell transport of photons but cell-to-cell transport is not computationally demanding.

Maltby and Burns (1991) describes an alternative approach, the Margolies grid shading photon transport scheme. This algorithm involves dividing the volume of interest into regular grid cells. Photon trajectories are traced through the cells. Within a specific cell, a search for valid intersections is performed using only the surfaces within that cell. For complex geometries, Maltby and Burns reports a significant reduction in execution time (typically 3 to 4 times).

The cell-to-cell transport scheme presented in this paper uses a grid scheme that places solid surfaces along cell boundaries and uses irregular cell sizes. The first feature allows the use of a simple comparison of the photon incoming angle with B_l and B_r to determine the surface being struck by the photon avoiding the use of a distance shading algorithm. The second feature allows the selection of cell sizes to minimize the number of cells traversed by a photon. While the cell-to-cell transport scheme has been limited to two-dimensional applications with complex but regular geometries, the scheme can be generalized to three dimensions and irregular geometries.

We have not conducted a comparison of the these two photon transport schemes. It is suggested as a topic for future research.

MODEL VALIDATION

To develop confidence in the Monte Carlo model and the resulting computer code, a variety of tests were conducted to verify the results. The verification of a Monte Carlo model is complicated because of the variation in results caused by the probabilistic nature of the technique. Therefore, three approaches were pursued: comparison of Monte Carlo model predicted results with manual ray tracing, analytical results, and experimental results.

The first method compared the predicted locations of photon/surface interactions and incident angles with manual calculations and graphic ray tracing. In all cases, the predicted results agreed with the manual calculations.

The second approach compared predicted results with analytical results for an enclosure with diffuse-gray surfaces. The enclosure is shown in Figure 3. In the diffuse-gray case, the analytical results are approximate because the diffuse-gray model assumes uniform incident flux on every surface. This is a poor assumption for the case being simulated. To improve the accuracy of the analytical results, each surface was divided into four increments, each assumed to be isothermal and subject to uniform flux. These results are presented in Table 1 and show excellent agreement between the Monte Carlo model and analytical results. In all cases, the difference between the two sets of results was within the standard deviation of the Monte Carlo results.

TABLE 1. Comparison of Diffuse-Gray Surface Analysis

	Diffuse-Gray Surfaces		
	% of Energy Leaving Surface		
Heat Transfer Path	Analytical	Computer Results	Computed Results Standard Deviation
1-2	41.39	41.36	0.94
1-3	48.97	48.86	0.97
1-4	9.64	9.78	0.50

The final method of validation compared the Monte Carlo model predictions to experimental results. A literature review did not identify previously developed experimental results for radiation heat transfer in an array of discrete fixed absorbers useful for model validation. Some preliminary experimental investigations were conducted as a proof-of-concept for development of a volumetric solar central receiver (Drost et al. 1985) and these were used for comparison.

The experimental investigation consisted of constructing a two-row array of wedge-shaped fins with secularly reflecting surfaces. A planar laser was directed into the array and the fraction of incident radiation transmitted through the first row and through the first and second rows was measured as a function of incident angle. The experimental facility was intended to be a proof-of-concept rather than for model verification. Because of this, precise measurements of array dimensions and some surface properties were not made. Consequently, the experimental results must be used with care; however, the results do allow a comparison with model results.

The results for transmission of incident radiation through the first row are presented in Figure 5. The Monte Carlo model was used to simulate the same situation, assuming a constant emissivity independent of incident angle or wavelength and that all photons were emitted into the array with the specified incident angle. The results show that the Monte Carlo model duplicated the general trend of decreasing transmittance with increasing angle of incidence. As the angle of incidence increases, the Monte Carlo model tends to underestimate the transmittance. As the incident angle increases, it is more likely that a photon with experience multiple specular reflections. In this situation, any inaccuracy in element spacing and dimensions or surface properties will have an increasingly large impact on the transmittance. Other investigators have recognized this situation as being particularly challenging for Monte Carlo modeling (Howell and Bannerot 1974). Given the uncertainties in the experimental apparatus, the comparison is acceptable but a more carefully controlled experimental verification is required.

The transmittance for the combined first and second rows as a function of incident angle is presented in Figure 6. As with the single row results, the Monte Carlo model tends to underestimate the transmittance while

duplicating the general trend of decreasing transmittance with increasing angle of incidence.

CONCLUSIONS

Radiation heat transfer in arrays of fixed discrete surfaces is a poorly understood phenomena encountered in important engineering applications. The most common approach to evaluating this phenomena involves modeling the array as a participating media but the validity of the assumption that an array of discrete surfaces can be modeled as a participating medium has not been investigated. As part of a larger study to investigate radiation heat transfer in arrays of discrete surfaces, a Monte Carlo model using cell-to-cell photon transport has been developed. Cell-to-cell photon transport is a computationally efficient scheme for evaluating radiation heat transfer in arrays of fixed discrete surfaces. The resulting computer code has been validated with preliminary experimental results. Future research will involve using the Monte Carlo code for carefully controlled experimental validation, followed by parametric investigations of the impact of array characteristics on the accuracy of modeling an array of fixed discrete surfaces and a participating medium.

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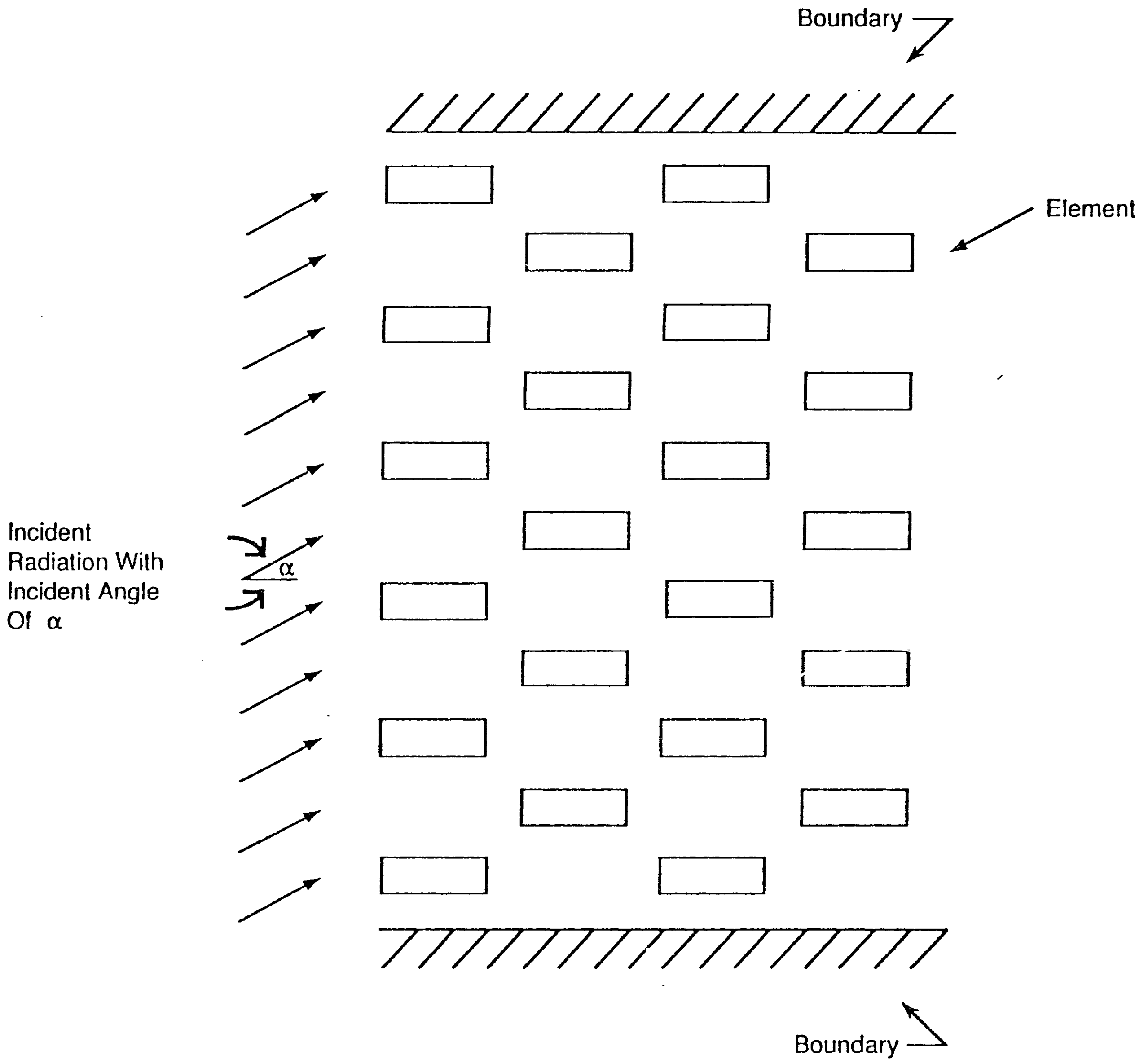


FIGURE 1.

R9111102.1

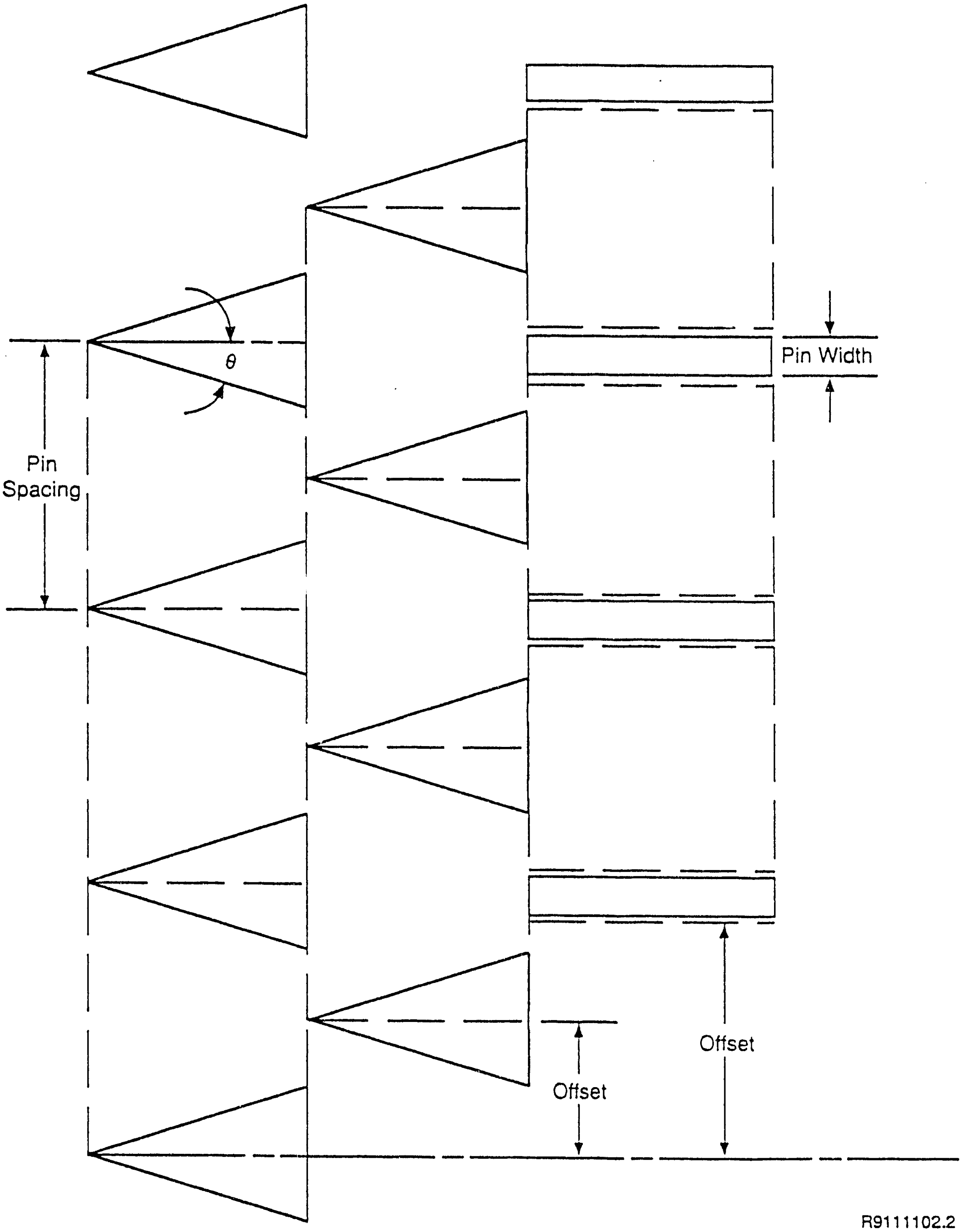


FIGURE 2.

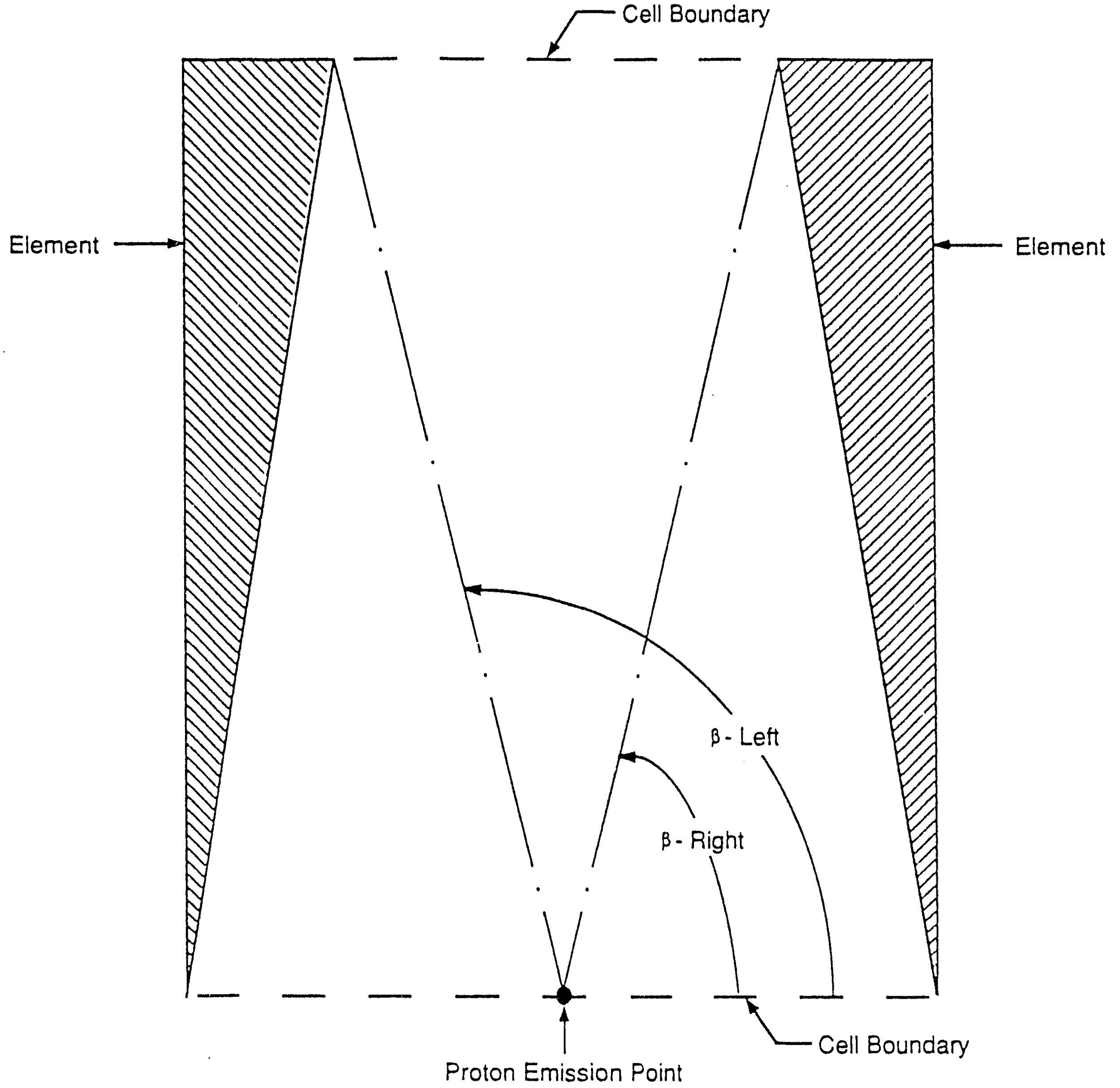
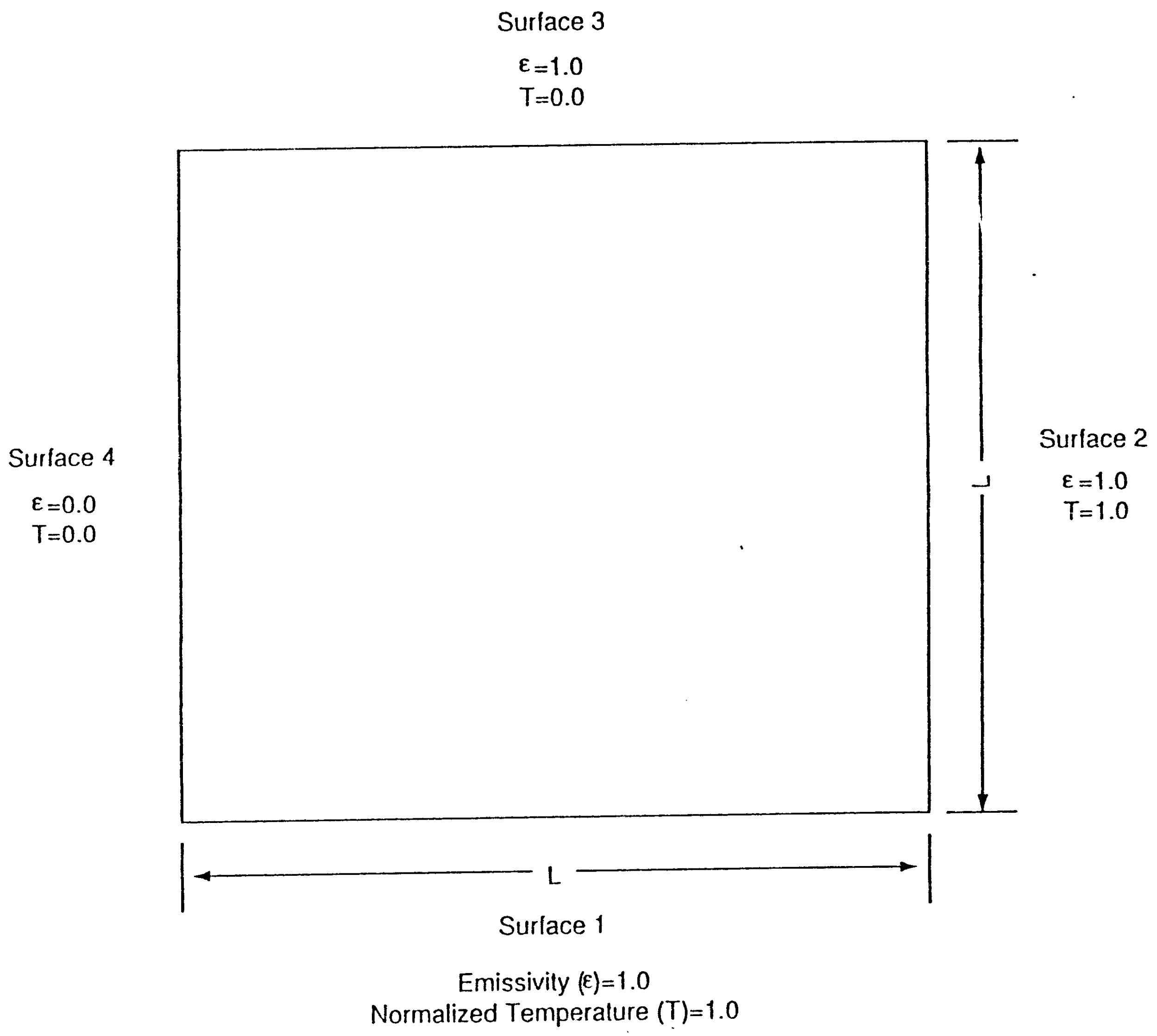

Cell Boundary
Element
Element
β - Left
β - Right
Cell Boundary
Proton Emission Point
R9111102.3

FIGURE 3.



R9111102.4

FIGURE 4.

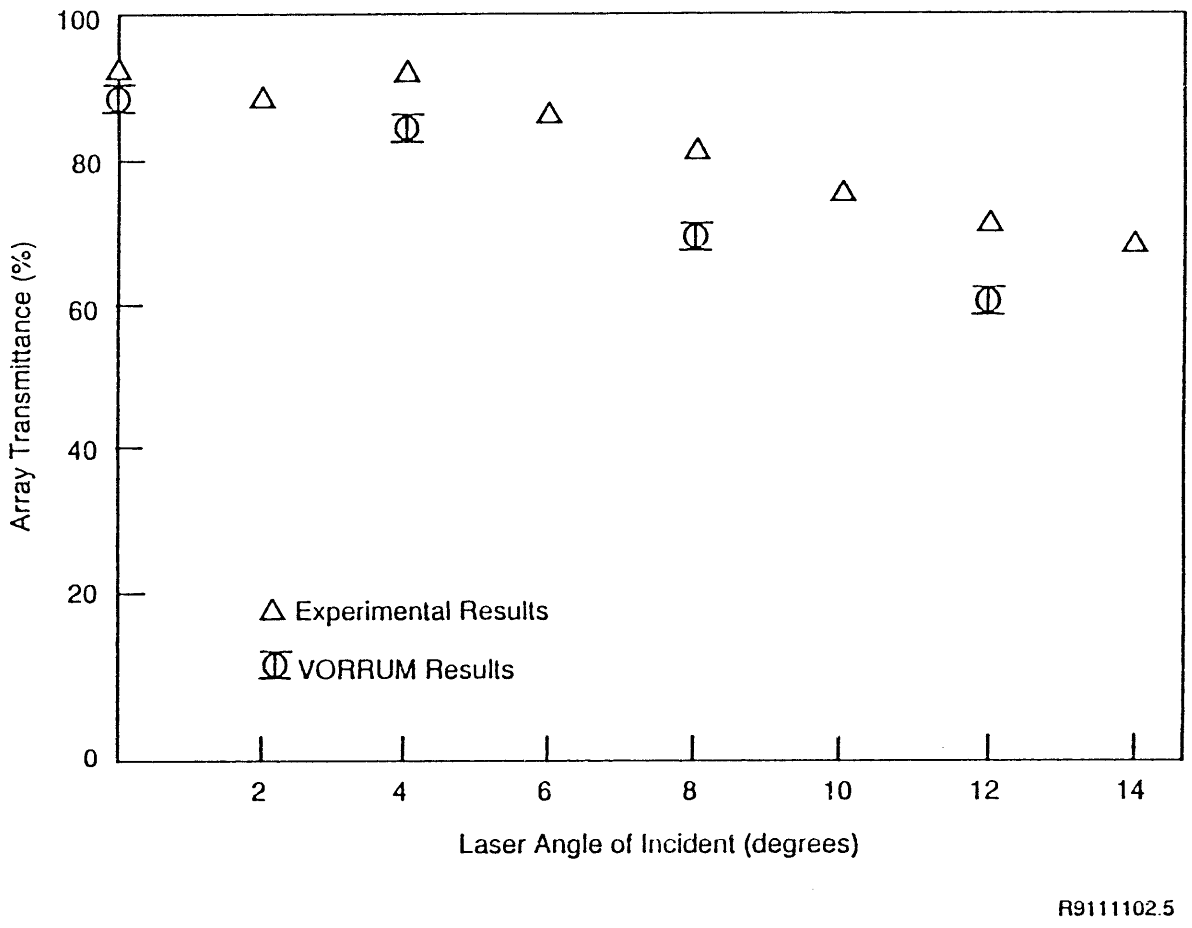
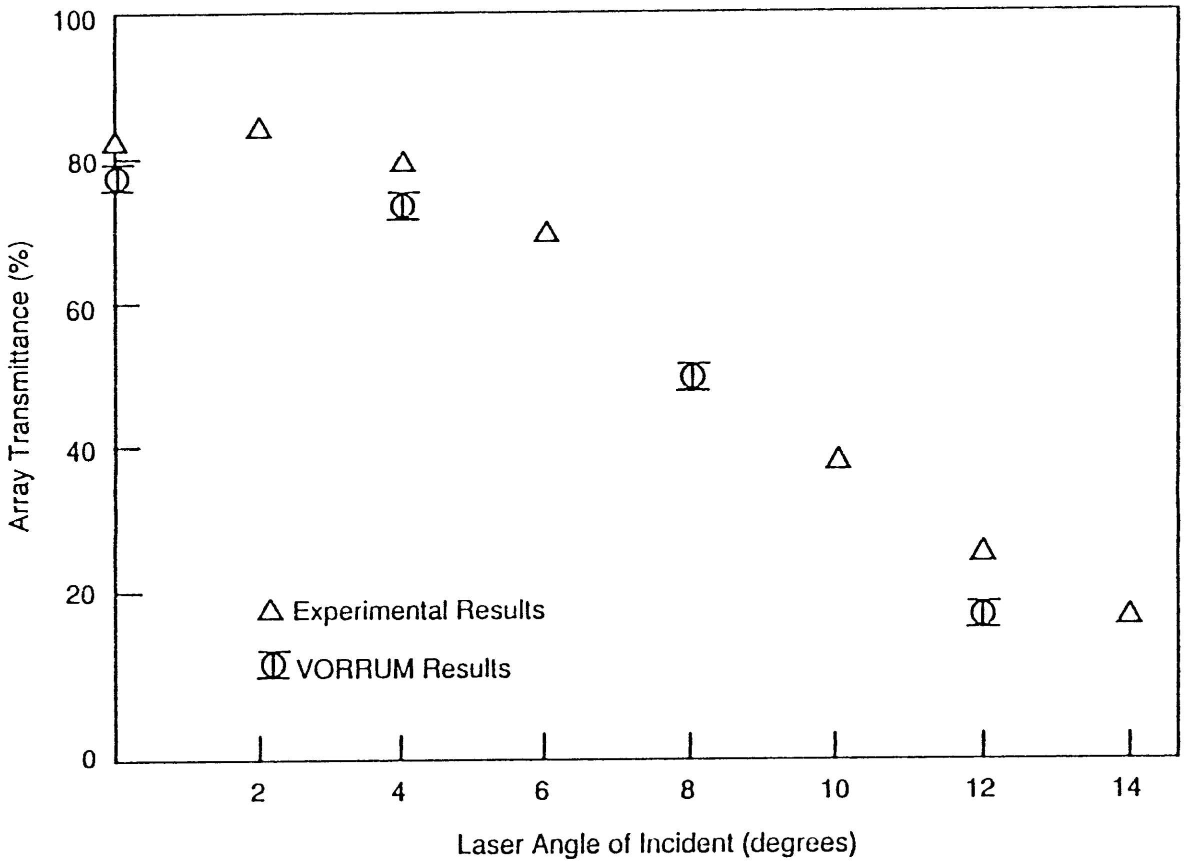

100
80
60
40
20
0
Array Transmittance (%)
2
4
6
8
10
12
14
Laser Angle of Incident (degrees)
△ Experimental Results
Φ VORRUM Results
R9111102.5

FIGURE 5.



R9111102.6

FIGURE 6.

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