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STATUS OF NEUTRON TRANSPORT IN THE ATMOSPHERE

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Abstract

Attempts have been made since the mid 1940's at determining the radiation fields from nuclear weapons. Earlier attempts were experimental in nature with the efforts in the first few years being mostly calculational. A review of the progress that has been made in the past few years, the information that is currently available, and approaches to solving the problem of determining the detailed radiation field description is given.

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There have been several investigators who have recently been seeking to understand and improve neutron cross sections for oxygen and nitrogen and to evaluate radiation transport techniques.[1-3] These cross sections are important because of the need to determine the full radiation field description for a neutron source in the atmosphere. In considering the status of neutron transport in the atmosphere, three areas will be reviewed: (1) the progress that has been made in the past few years in determining the radiation fields in the atmosphere, (2) the information that is currently available, and (3) approaches to solving the general problem of cross-section uncertainty and the need for knowing the detailed radiation field description everywhere.

Progress. There have been serious attempts at determining the radiation fields from weapons since the mid 1940s. Since cross sections and analytical tools were not available to any significant degree before the late 1950s and early 1960s, the early attempts at defining radiation fields were experimental in nature and were associated with weapons tests.[4] The complexity of such experiments prevents the determination of a detailed description of the radiation fields. In the early 1960s, attempts in calculating the radiation field suffered from lack of both the existence and communication of cross-section information in the scientific community and from the lack of transport codes -- Monte Carlo and the moments method were the only radiation transport tools available with anisotropic scattering. The calculated results that existed in 1961 are given in a review article by Wells.[5]

In 1965 the state-of-the-art of radiation transport in infinite homogeneous air was such that there was doubt as to the validity of transport code results -- the cross-section input was known to be important, but the extent of the importance was not fully realized. A summary of results[6] of $4\pi R^2$ neutron dose versus range for a fission source in infinite air is shown in Fig. 1. The cause of these disagreements could not be attributed to codes alone since the same techniques had been used by several investigators. By looking only at the dose, one cannot easily determine what might have caused the differences. Obviously, some problem could result from different flux-to-dose conversion factors and this does cause some of the differences. The energy spectra at a given range, however, helps to pinpoint the cause (see Fig. 2). The differences could be traced, at least in part, to differences in cross sections used. This is even more evident when one considers results for a 14-MeV neutron source (see Fig. 3). Sensitivity calculations were made with the inelastic scattering treated in varying degrees of approximation and indicated that the existing results could be bracketed by varying the inelastic treatment. The heavy lines in Fig. 3 are the result of treating inelastic scattering as elastic scattering or absorption. This indicates that the cross-section input could easily cause the disagreements noted earlier.

In early 1967, calculations were made with the ANISN discrete ordinates code and the 05R Monte Carlo code with the cross-section input based on the same point cross-section data. If the same cross-section information were used, the detailed results of transport calculations using few-group (22) and only P_3 expansion of the angle of scattering in discrete ordinates codes would agree with results of Monte Carlo calculations using point cross sections ($\approx$ 1000 points) and P_8 expansion of the angle of scattering. The excellent agreement in these results[7] again indicated

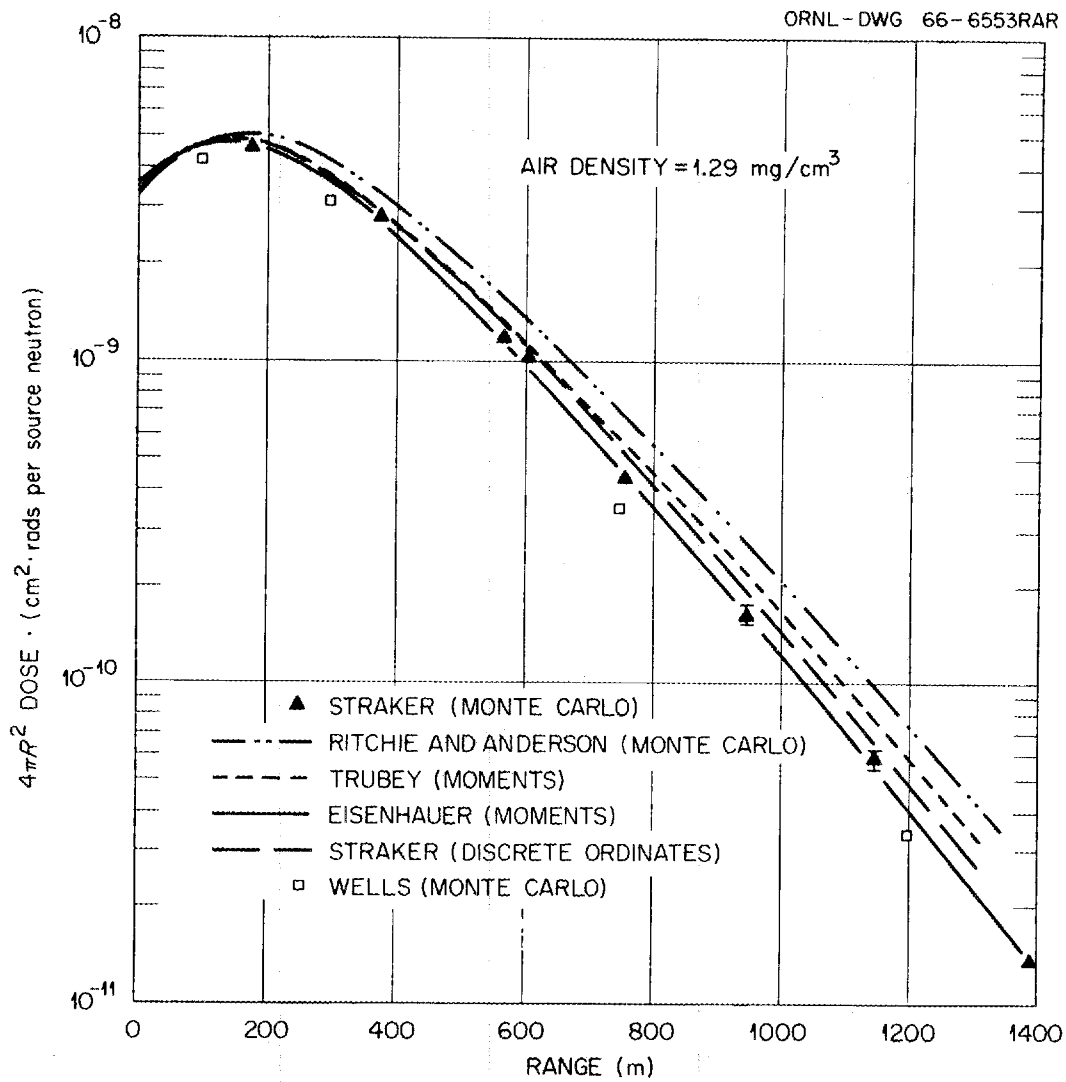

Fig. 1. $4\pi R^2$ Dose Versus Range for a Point Fission Source in Infinite Homogeneous Air.

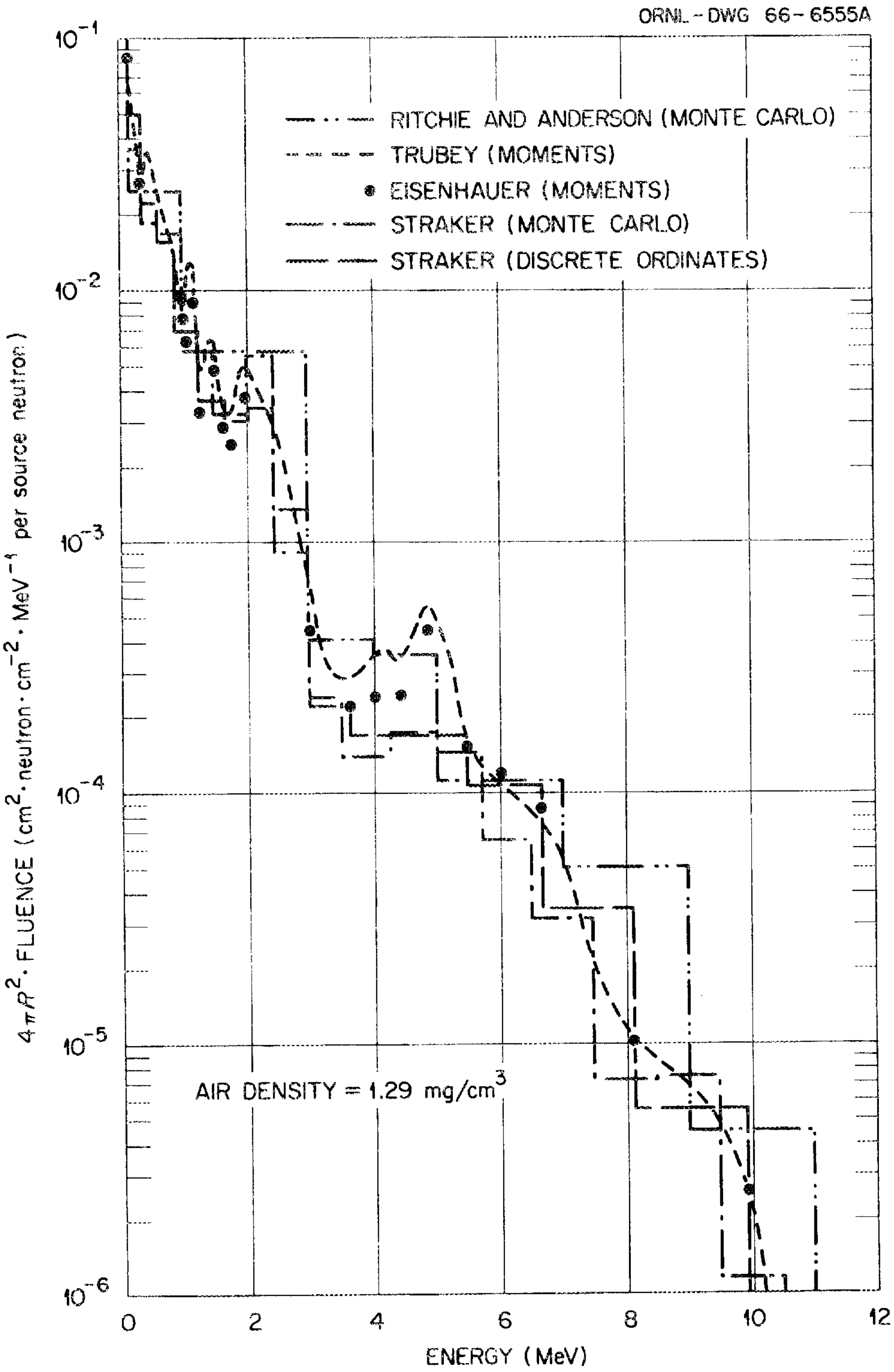

Fig. 2. Neutron Spectrum in Infinite Homogeneous Air at a Range of 1150 Meters from a Point Fission Source.

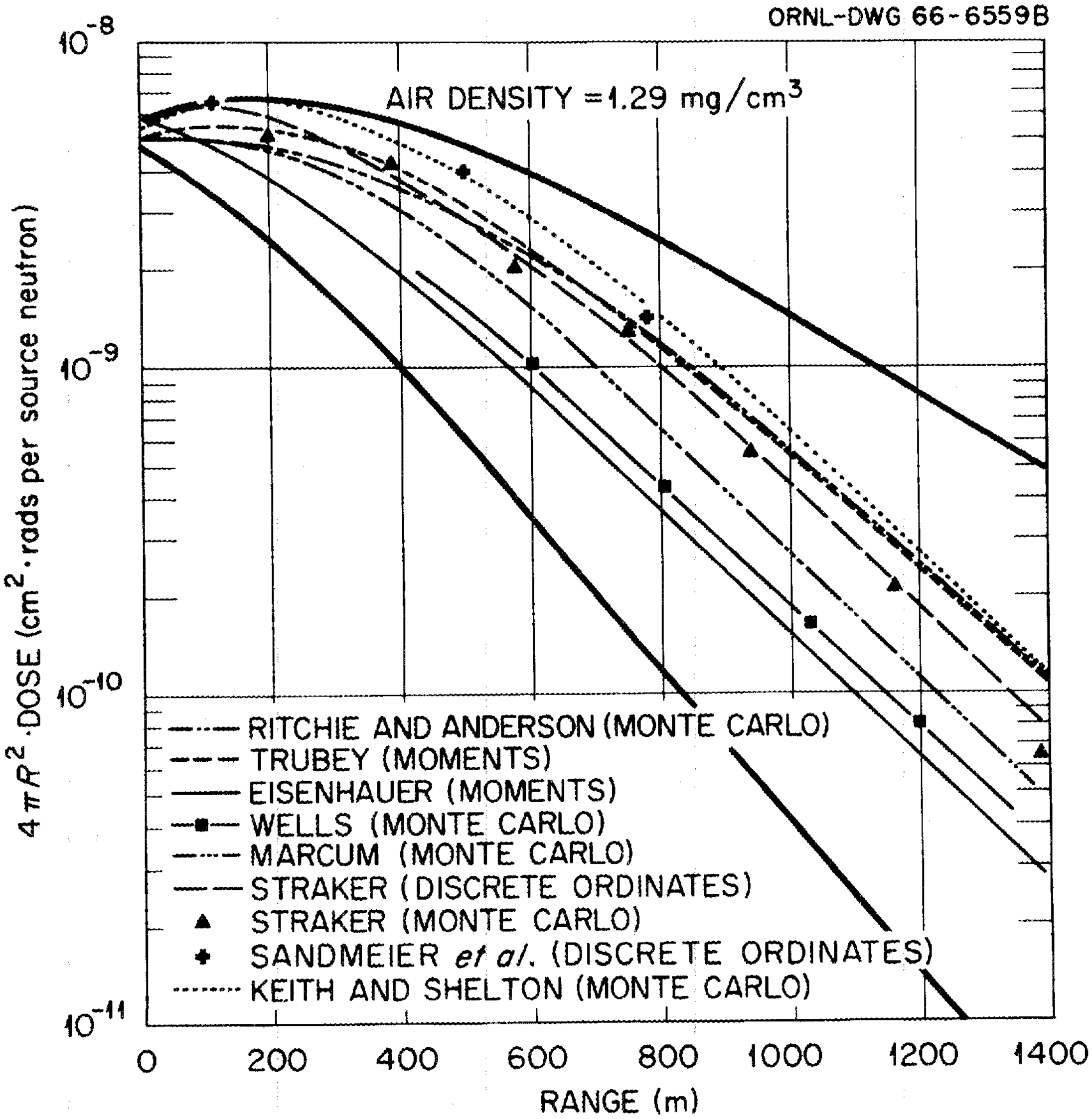

Fig. 3. $4\pi R^2$ Dose Versus Range for a Point 14-MeV Source in Infinite Homogeneous Air.

that the codes were not basically in error. This same conclusion for the calculation of dose in lithium hydride had been reached a few months earlier using the same codes.[8] Figure 4 illustrates the type of comparison that was obtained. The results are for the fluence in the 8.18- to 12.2-MeV energy group versus range due to a point 12.2- to 15-MeV neutron source in infinite air.

After validating the transport techniques, the remaining problem was to validate the cross-section input. Accurate, unclassified, experimental data for neutron transport in infinite homogeneous air are not available. Experimental results from weapons tests indicate that calculational results were not wrong by factors greater than 2-5 in integral quantities, and in some cases better agreement was obtained. Steady-state experimental results from Operation BREN for high source and detector heights permit some conclusions to be drawn by correcting for the ground effect. For the free-field dose, comparisons of calculational and experimental results indicate that calculations of dose are not off by more than a factor of 2.

Comparisons of measured and calculated results[9] for Operation HENRE also indicate disagreements less than a factor of 2 and as low as 1.3 in some regions. Thus, it is concluded that the free-field dose can be calculated to within an uncertainty of 20-100% for ranges of approximately a mile and probably to 2-3 miles with errors less than a factor of 3.

For the design of shielded structures or systems, more information than the free-field dose is obviously required - the energy spectra of neutrons and secondary gamma rays are required, sometimes on a time-dependent basis. The state-of-the-art of calculations for these detailed

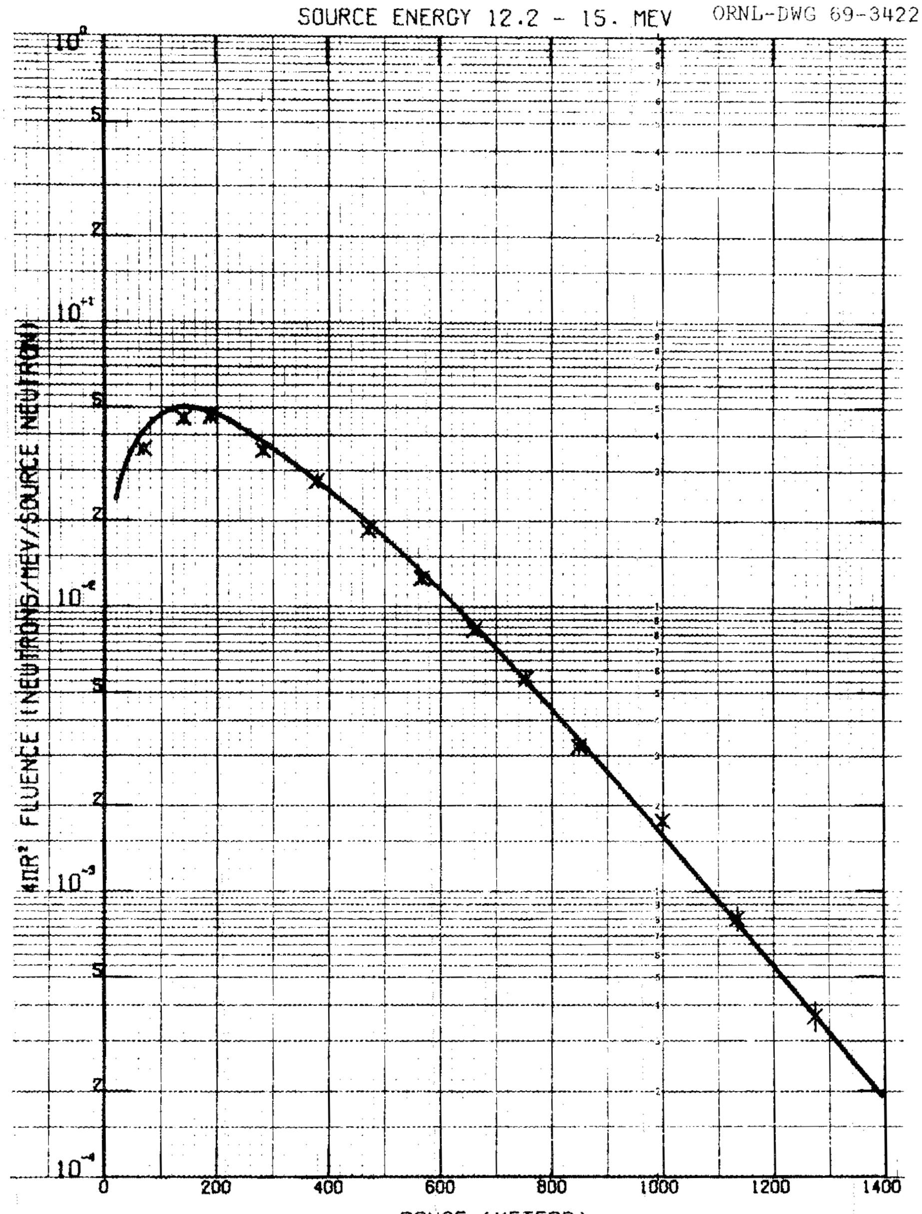

Fig. 4. $4\pi R^2$ Fluence in the 8.18- to 10-MeV Energy Interval Versus Range for a Point Isotropic 12.2- to 15-MeV Source in Infinite Homogeneous Air.

results has been illustrated previously[9] if the cross sections are correct. There have been several attempts[1-3] at proving the cross sections by comparison of calculations with differential results from experiments in idealized geometries. Because of the complexity of such experiments, they can perhaps only be performed under laboratory conditions, but results from field measurements are needed to check the more integral quantities which are most pertinent in real life. It has been shown[10] that the steady-state integrated multicollision dose inside concrete structures does not depend strongly on the radiation spectrum incident outside within some limited variations. However, for the determination of rate effects such as time-dependent secondary gamma-ray dose or for the determination of the total energy deposited, the importance of knowing the detailed energy spectra has not been adequately determined. The safe approach is to attempt to provide accurate spectra; thus, one strives to find the "best" cross-section set available.

To illustrate the "state-of-the-art" results obtained in the past two years for transport of 14-MeV neutrons in infinite air are shown in Fig. 5. Results are converging with time, but apparently fairly slowly. A factor of 4 spread in results at 1000 meters in Fig. 3 is only a factor of 1.6 now. This illustrates that any experimental data for air transport in order to be useful in deciding which calculations are correct must be accurate to ±20% or better on an absolute basis. Examples of the progress that has been made in improving the results for transport in air have been based on results for infinite homogeneous air because this is the simplest radiation transport case. However, there are at least three areas of radiation transport in the atmosphere that must be

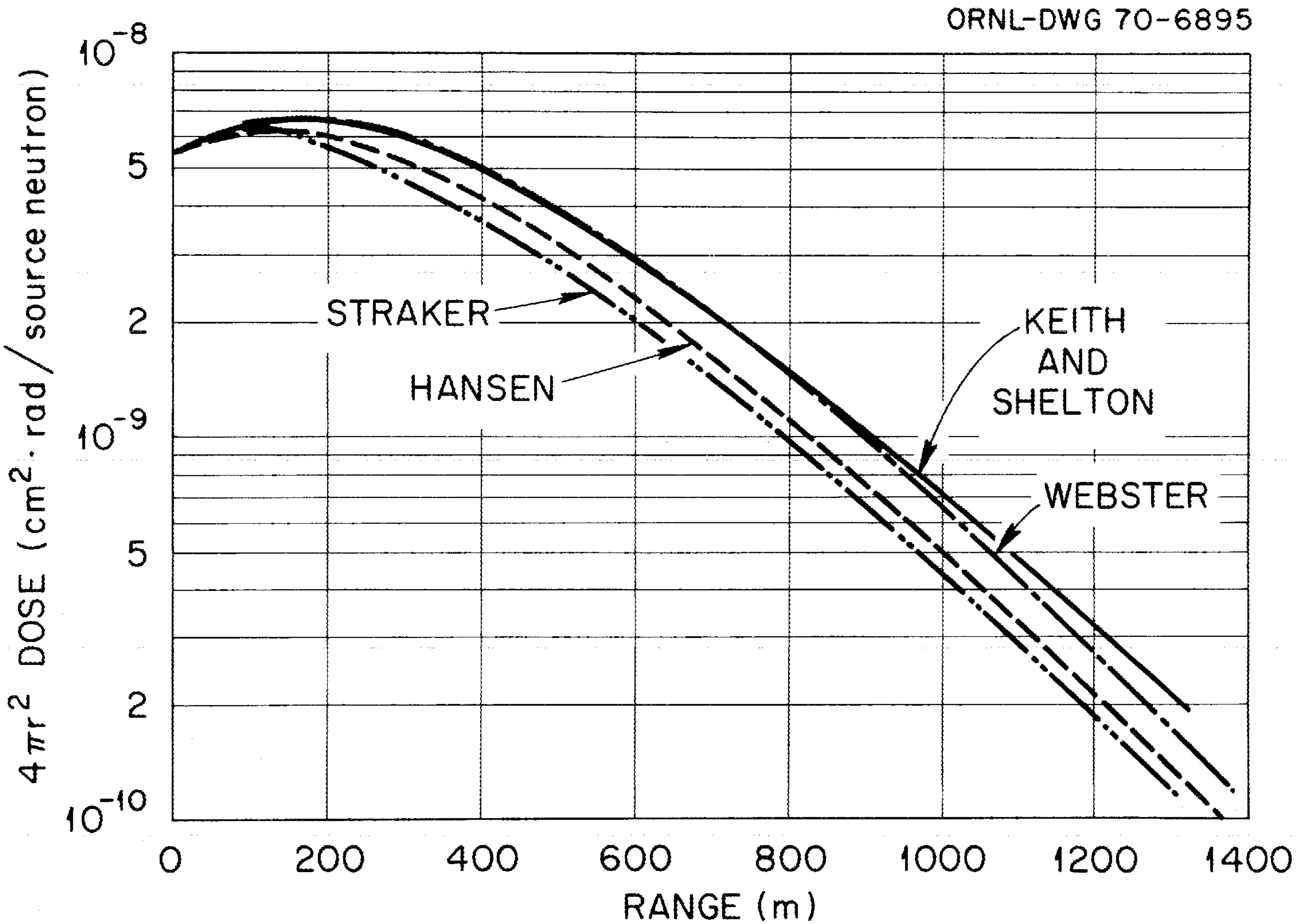

Fig. 5. $4\pi R^2$ Dose Versus Range for a Point 14-MeV Source in Infinite Homogeneous Air.

considered. These are (1) exponential air, i.e., sources at heights greater than ≈ 30,000 ft, (2) infinite homogeneous air, i.e., sources between ≈ 2,000 and 30,000 ft, and (3) air-ground, i.e., sources or detectors at altitudes less than ≈ 2,000 ft. A further subdivision of some of these areas could be made. For example, the exponential air problem could be further divided to separate the exoatmosphere source where the curvature of the atmosphere must be considered, and the infinite air and air-over-ground problem could be subdivided to separate out problems where the shock wave should be considered. These subdivisions have been omitted here.

Information Currently Available. It is rather obvious, but it must be emphasized -- the results included in the following tables are the ones of which the author is aware and include, with a few exceptions, only those that have appeared in the unclassified literature. There is, undoubtedly, a larger number of unpublished results, and results for specific applications, but these are not included.

A compilation[11] of transport codes which can be, or have been, used for air transport indicated that some 20 codes have been used to generate air transport data. With such a large number of codes one might expect an abundance of published and unpublished air transport results.

A. Exponential Air

Only Monte Carlo codes have been used to determine radiation fields taking into account the nonuniformity of the atmosphere. The importance of the air density variation, of course, changes gradually with altitude, but effects of the order of 20-50% become noticeable (outside statistics of the Monte Carlo results) for altitudes greater than about 30,000 ft.

At lower altitudes the infinite air results may be used with ρR scaling, thereby taking into account the actual amount of air between source and detector to account for density variations. The results for sources at high altitudes are given in Table I. Listed are the approximate number of report pages to aid one in estimating the amount of data available. There is probably ten times this amount of information available in classified reports, internal memos, and computer outputs.

B. Infinite Homogeneous Air. Because the radiation transport is simpler in infinite air (one-dimensional) and because results for infinite air can be used to approximate, in some sense, radiation fields for source heights both higher and lower than those mentioned previously, there has been a large number of calculations for this case. Table II gives a summary of those calculations. It will be some time before the "right" set of results (i.e., "right" cross section) can be pinpointed, and thus there will undoubtedly be many more calculations made. Various recommendations such as taking the most conservative (highest intensity) results or the results based on the most reliable cross sections, etc., have been made -- but it apparently is left as an exercise for the reader to determine which set is "best."

C. Air/Ground. Because the air/ground calculation is two-dimensional, it has only been in the last three years that codes other than Monte Carlo have been used.* For this two-dimensional geometry there is also good agreement[9] for results obtained by discrete ordinates and Monte Carlo when the same cross sections are used, and, therefore, as in the infinite air case, the problem reduces to a determination of the "right" cross section. Since the neutron transport is dominated by the air,

*The development of the two-dimensional discrete ordinates code DOT by F. R. Mynatt has provided an efficient means of determining detailed energy angular distributions for the air over ground case.

Table I. List of Calculations for Exponential Air

Investigator	Date	Method	Source Energy	Source Height	Pages	Results*	Code
Marcum[12]	1963	Monte Carlo	14 MeV	100,000 200,000	40	$\phi(r,E)$	RAND
Marcum[13]	1965	Monte Carlo	14 MeV Fission	33,000 158,000	24	$S_g(r,t)$	RAND
George and Lavagnino[14-16]	1966	Monte Carlo	17 Mono. Energies	30,000 50,000 80,000	788	$\phi(r,E,t)$	AUGEAS
Shelton and Keith[17]	1968	Monte Carlo	8 Energy Intervals	110,000 85,000	131	$\phi(r,E,\Omega)$	NHAT
Celnik[18]	1969	Monte Carlo	7 Energy Intervals	65,000 to 250,000	3	$\phi(r,E,t)$	UNC-SAM2

*ϕ denotes fluence, S denotes source term, g denotes secondary gamma ray, D denotes dose.

the same comments regarding cross sections made for the infinite air case hold. There have been several calculations for the air/ground case as shown in Table III. Disagreements in results for the air/ground case are essentially the same as for the infinite air case. All of these calculations were made for flat ground with no features in the terrain; but only for very severe undulations in the terrains would there be significant effects in the total dose. (For time dependence there would be a reduction in the peak rates if the source or detector and its immediate area were shadowed by a hill.) References for experimental data from Operations BREN[19-21] and HENRE[22-28] are given for completeness.

Approach to General Problem. From the previous tables, it can be seen that there are some 3,285 pages of published information on air transport. One may ask what can be done with it.

In many cases the results exist in graphical form. This is a very helpful aid in determining trends, approximate intensities, etc. But in many cases one wants to consider a different source spectrum than that for which the published data are available or wants to perform some other calculation with a given energy-angular distribution as a source. Many times the desired information may be obtained from the published tables. Other times, there is not enough detail or the exact information desired is not published. There are at least two approaches in solving the problem of "different source." One is very direct -- repeat the calculations with the real source. For some cases this is indeed the best way. For instance, if energy angular distributions are required for steady-state, infinite air, then it is easier to calculate results for a given source spectrum than it is to edit and combine results from

Table II. List of Calculations for Infinite Air

Investigator	Date	Method	Source Energy	Pages	Results*	Code
Holland and Richards[29]	1955	Moments	Monoenergetic	113	$\phi(r,E)$	
Mehl[30]	1958	Monte Carlo	8 Energies	135	$\phi(r,E,\Omega)$	
Wells[31] [32]	1960	Monte Carlo	Fission 8 Energies	276	$\phi(r,E,\Omega)$	K-74
Spielberg[33]	1961	Moments	Fission	33	$\phi(r,E)$	RENUPAK
Kinney[34]	1962	Monte Carlo	6 Energies	17	$\phi(r,E)$	05R
Ritchie and Anderson[35,36]	1962	Monte Carlo	14 Energies	9	$\phi(r,E)$ $D(r,\Omega)$	
Marcum[37]	1963	Monte Carlo	14 MeV	40	$\phi(r,E)$	
Eisenhauer	1965	Moments	Fission 14 MeV	N.P.	$\phi(r,E)$	
Johnson[38]	1965	Monte Carlo	14 MeV Fission 5 Energies	41	$\phi(r,E,\Omega)$	K-74
Sandmeier[39]	1965	Discrete Ordinates	12-14 MeV	69	$\phi(r,E)$	DTF-IV
Straker[6]	1965	Monte Carlo	Fission 14 MeV	7	$\phi(r,E)$ $D(r)$	05R

Table II (continued)

Investigator	Date	Method	Source Energy	Pages	Results*	Code
Straker[6]	1965	Discrete Ordinates	Fission 14 MeV	7	D(r) $\phi(r,E)$	ANISN
Trubey	1965	Moments	14 MeV Fission	N.P.	$\phi(r,E)$ D(r)	RENUPAK
Karcher[40]	1966	Monte Carlo	Spectrum	44	$\phi(r,E)$ $\phi(r,\Omega)$	05R
DeVries[41]	1967	Monte Carlo	14 MeV	75	$\phi(r,E,\Omega)$ $\phi_g(r,E,\Omega)$	COHORT
Yampolskii[42]	1967	Monte Carlo	9 Energies	10	$\phi(r,E)$	
Keith and Shelton[43]	1968	Monte Carlo	14 MeV	15	D(r)	NHAT
Keith and Shelton[44]	1968	Monte Carlo	12 Energies	155	$\phi(r,E)$ $\phi(r,t)$	NHAT
Webster[45]	1969	Monte Carlo	12 Energies	67	$\phi(r,E)$	SORS
Straker and Gritzner[46]	1969	Discrete Ordinates	8 Energies Fission	410	$\phi(r,E,\Omega)$ $\phi_g(r,E,\Omega)$	ANISN
Hansen, et al.[1]	1970	Monte Carlo	14 MeV	50	$\phi(r,E)$ D(r)	SORS

*ϕ denotes fluence, g denotes secondary gamma ray, D denotes dose.

Table III. List of Calculations for Air/Ground

Investigator	Date	Method	Source Energy	Source Height	Pages	Results*	Code
Biggers, Brown, Kohr[47]	1960	Monte Carlo	12 Energies Weapons Leakage	300 ft	173	$\phi(r,E,t)^{\dagger}$	NHM
Marcum[48]	1960	Monte Carlo	3, 14 MeV	300 ft	55	$\phi(r,E)$	RAND
Kinney[34]	1962	Monte Carlo	6 Energies	0	17	$\phi(r,E)$	05R
Ritchie, Anderson[35,36]	1962	Monte Carlo	14 Energies	300 ft 650 ft	18	$\phi(r,E)$ $D(r,\Omega)$	NHM
Marcum[12]	1963	Monte Carlo	14 MeV	0, 750, 3,000	40	$\phi(r,E)$ $D(r)$	CAPS
DeVries[41]	1967	Monte Carlo	14 MeV	116 ft	75	$\phi(r,E,\Omega)$ $\phi_g(r,E,\Omega)$	COHORT
Straker and Mynatt[49]	1967	Discrete Ordinates	Fission	300 ft	19	$\phi(r,E)$ $D(r)$	DOT
Straker[50]	1968	Monte Carlo	9 Energy Bands	50 ft	250	$\phi(r,E,\Omega,t)$ $D(r,t)$ $\phi_g(r,E,\Omega,t)$ $D_g(r,t)$	06R
Straker[50]	1968	Discrete Ordinates	9 Energy Bands	50 ft	250	$\phi(r,E,\Omega)$ $D(r,\Omega)$ $\phi_g(r,E,\Omega)$ $D_g(r,E,\Omega)$	DOT

*ϕ denotes fluence, g denotes secondary gamma ray, D denotes dose.

†Shock wave included.

previous calculations. If the calculations are "difficult" or "costly" another approach is to approximate the source spectrum by combining results for 14-MeV, fission, and energy band sources. Sometimes one hesitates in making this "approximation," but many times such fears have been demonstrated to be unfounded when differences between the approximated spectrum and the desired one are relatively small. The importance of the source spectrum can be easily determined by comparing published results for different source energy bands. The importance of calling a 10-MeV neutron 6 MeV can be ascertained (see Fig. 6). In approximating a source spectrum, one may consider it to be composed of fission and 14-MeV components, or a modified typical spectrum, or compounded from energy band spectra. To aid in solving this type of problem, detailed energy, angle, space, and time-dependent results[50] for the air/ground case are available on tape with edit and folding codes so that the problem of combining source spectra for the air/ground case is minimized. Similar data at other source heights may be obtained from the 50-ft source height data since the effect of source height on energy and time distributions is small,[9] the effect on intensity can reasonably be approximated by French's first-last collision model,[51] and the effect on angular distributions may be determined by rotation of coordinates to angles from source-receiver axis. This requires some data handling, but it is perhaps easier than redoing the complete calculation.

Sensitivity calculations can also be used to determine the importance of some effects. For example, the effect of the ground composition on the neutron dose due to a fission source was determined[49] by varying the ground compositions. The conclusion was that for reasonable

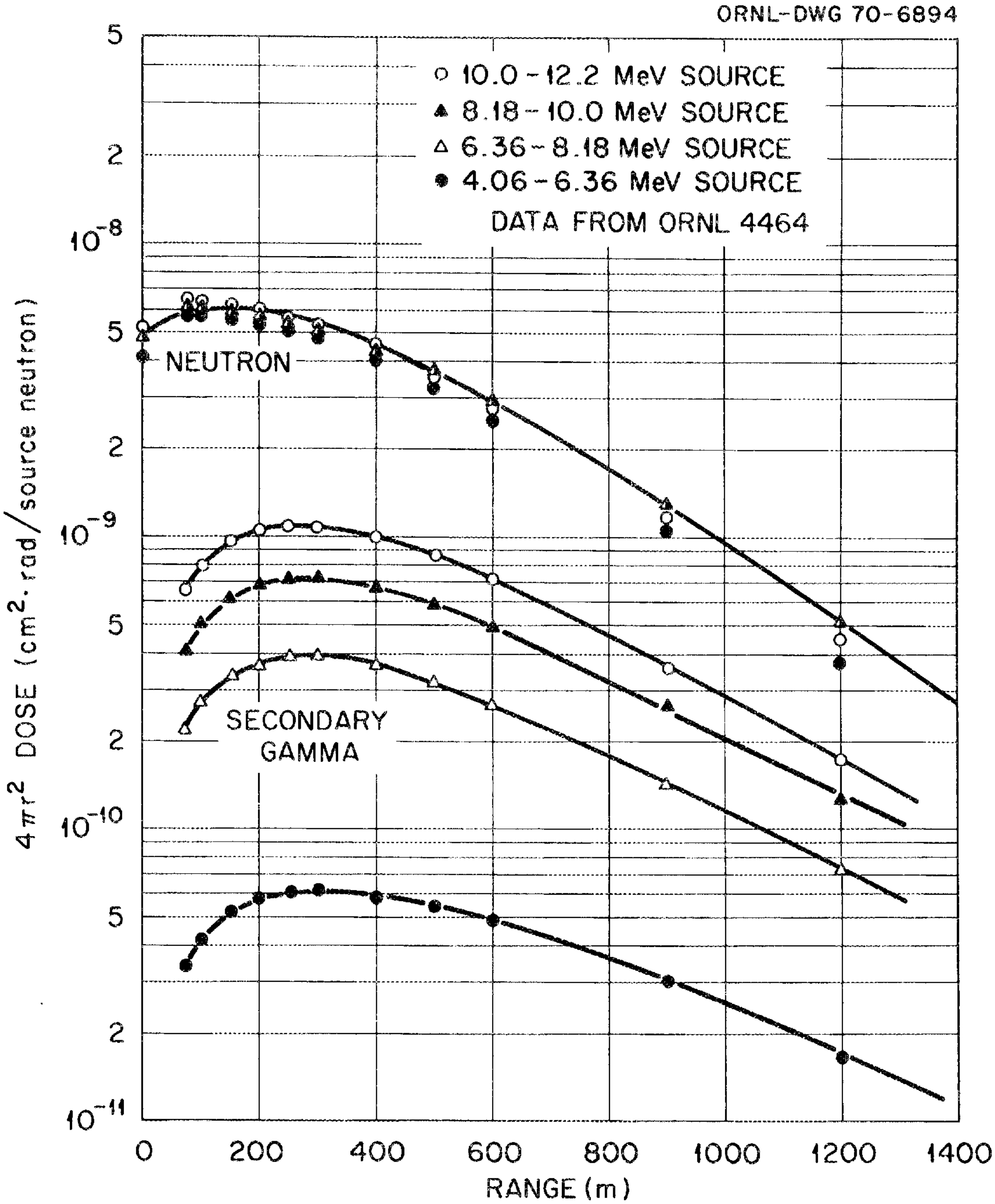

Fig. 6. $4\pi R^2$ Dose Versus Range in Infinite Homogeneous Air.

variations the ground composition has little effect on the dose or even on the spectrum (if the thermal neutron fluence is not included). Also, sensitivity of secondary gamma-ray dose to various ground cross sections indicates[9] that for a 12.2- to 15-MeV source the gamma rays born in the ground contribute little to the gamma dose at the interface, and for a fission source the thermal captures in the ground are important (>20%) for ranges less than 1,000 meters. Thus, if $(n,x\gamma)$ cross sections for fast neutrons for elements in the ground are changed considerably, the gamma-ray dose at the interface will not be affected significantly for a 12.2- to 15-MeV source. Other sensitivity calculations of this type have been, and should be, performed instead of more production calculations of air transport results.

With the fast computers and the abundance of neutron and gamma-ray transport codes today, it is frequently decided that new calculations should be performed instead of trying to use the results of others. This appears ridiculous, but in the past couple of years the trend has not changed and probably won't. Thus, for the person charged with compiling air transport results, it appears that he has a lifetime job.

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