Final Report

GENERAL ANALYSIS OF RADIOLOGICAL RECOVERY CAPABILITIES

Prepared for:

OFFICE OF CIVIL DEFENSE
OFFICE OF THE SECRETARY OF THE ARMY
WASHINGTON, D.C. 20310

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I INTRODUCTION

This report summarizes the results of previous investigations on RADEF planning and on radiological target analysis procedures for decontamination scheduling. Procedures were developed for evaluating the residual numbers for shelter and operating locations before, during, and after decontamination so that exposure doses could be calculated.[1,2,3] The correlation of the computational results with shelter protection and decontamination capability data provided a means of deriving decontamination assignments and operational schedules that could be carried out within prescribed exposure dose limits.

In the previous investigations, various specific target analysis and decontamination problems were treated and, of the many problems that were recognized and identified, several were selected as being important and in need of further consideration. These included: (1) the extension of dose estimating techniques to a wide variety of postattack operational situations; (2) methods for estimating the optimum time to carry out radiological recovery actions; and (3) the derivation of relationships between target area size and decontamination organizational requirements. This report discusses the radiological recovery aspects of these problems and the derived methods and analytical expressions appropriate to their solution.

Procedures were developed for estimating decontamination start times with minimum total exposure to groups of people in both decontamination and facility operations. Methods for estimating exposure doses to decontamination crews and facility operator crews were revised to simplify the evaluation of the effect of previous and concurrent decontamination operations on the effective residual number for a prescribed postattack routine. A method was devised for relating the size of decontamination organizations to the dimensions of the area to be decontaminated and the surviving population in urban areas.

The final problem explored was the effect of increased size (and number) of decontamination crews on the decontamination completion time.

II DECONTAMINATION START TIME

One major objective of decontamination planning and scheduling is to prepare the means to recover the use of facilities when they are needed in the postattack period. In addition, it is desirable that the recovery be planned for achievement with the least expenditure of exposure dose, materials, and use of manpower. With respect to postattack situations and needs, a facility may be usable or operative before, during, or immediately after a decontamination operation; it may not be operative until repairs are made, or it may be operable without repairs or decontamination when inputs and people are available. If facility operation requires both decontamination and repairs, a greater decontamination lead time generally would be needed for a given operation start time than for a facility that does not require repair work.

In general, the radiological recovery of a given facility requires consideration of manpower utilization for either sequential or simultaneous decontamination and facility operations. Where the recovery of industrial output is to be achieved, the planning and scheduling of such operations must include consideration of all facilities in the production network, so that the allocation of manpower, equipment, and supplies becomes more complicated. In addition, postattack countermeasures other than decontamination will require an appropriate share of the resources. Thus decontamination operations, as a single countermeasure, should be planned on the basis of a minimum expenditure of exposure dose, effort, supplies, and equipment. In addition, the benefits of decontamination should accrue with respect to other countermeasure operations as well as to facility operation. For these reasons, plans and schedules for the decontamination operation need to be designed so that the initial decontamination efforts will decrease the exposure dose for later operations (rather than the reverse).

Exposure Dose and Recovery Effort

The accumulation of exposure dose over a given time period for an individual or groups of individuals may be represented in general by

$$D_{ij} = RN_{ij} \int_{t_{is}}^{t_{is} + \Delta t_{ij}} I_j \, dt \qquad (1)$$

or

$$D_{ij} = RN_{ij} \int_{t_{if} - \Delta t_{ij}}^{t_{if}} I_j \, dt \qquad (2)$$

where the subscript i represents an individual or a group of individuals (each of which has the same exposure); the subscript j represents a location at which the exposure for the ith group starts at the time t_{is} after attack and ends at the time t_{if} after attack; t is the time after attack; Δt_{ij} is the time period that the ith group remains at the jth location; I_j is the exposure rate at time, t, after attack at location j (referred to an extended real plane); and RN_{ij} is the residual number for the ith group at location j.

If the value of the limiting exposure dose, D^*, is selected so that it represents a threshold for radiation sickness (i.e., all groups i with an exposure dose of D^* or less can perform work without medical treatment), then the sequential exposure dose for the maximum available work force is given by

$$D^* = \sum_{j=1}^{J} D_{ij} \qquad (3)$$

or

$$D^* = \sum_{j=1}^{J} RN_{ij} \int_{t_{is}}^{t_{is} + \Delta t_{ij}} I_j \, dt \qquad (4)$$

Since the first increment of exposure would normally be accrued in shelter, the allowed (or maximum) exposure dose during the recovery period (or longer) for the case where the people are all in shelter before fallout arrives is given by

$$\Delta D_i^* = D^* - D_{ii} \tag{5}$$

where

$$D_{ii} = RN_{ii} \int_{t_{ia}}^{t_{ia} + \Delta t_{ii}} I_i \, dt \tag{6}$$

and where RN_{ii} is the shelter residual number; t_{ia} is the time of fallout arrival; and Δt_{ii} is the required shelter stay period. In Equations (5) and (6), the ith group is referred to the shelter location for identification so that, subsequently, the initial shelter exposures and associated groups can be treated interchangeably.

With Equations (5) and (6), the form of Equations (3) or (4) becomes

$$\Delta D_i^* = \sum_{j=1}^{J} RN_{ij} \int_{t_{is}}^{t_{is} + \Delta t_{ij}} I_j \, dt \quad , \qquad t_{is} \geq t_{ia} + \Delta t_{ii} \tag{7}$$

or

$$\Delta D_i^* = \sum_{j=1}^{J} RN_{ij} \int_{t_{if} - \Delta t_{ij}}^{t_{if}} I_j \, dt \quad , \qquad t_{if} - \Delta t_{ij} \geq t_{ia} + \Delta t_{ii} \tag{8}$$

For a given set of values of ΔD_i^* as constraints on Equations (7) and (8), there exists a finite set of limiting values of the parameters RN_{ij}, I_j, t_{is}, and t_{if} or Δt_{ij}.

The ΔD_i^* of Equations (7) and (8) will consist of dose allocations among the j exposure locations and consecutive Δt_{ij} intervals at each location; if the allocation for each location and time interval is designated as ΔD_{ij}^*, the latter are constrained, as in Equations (7) and (8), by the sum

$$\Delta D_i^* = \sum_{j=1}^{J} \Delta D_{ij}^* \tag{9}$$

and ΔD_{ij}^* is equal to one of the respective j terms on the right side of Equations (7) or (8). If the integrals of Equations (7) and (8) are evaluated in terms of a dose rate multiplier, designated as φ_{ij} (where φ_{ij} is the same as DRM of previous reports), then the integrals can be written as

$$\Delta\varphi_{ij} \, I_j^o = \int_{t_{is}}^{t_{is} + \Delta t_{ij}} I_j \, dt \tag{10}$$

where t_{is} is an arbitrary time after a detonation or time after attack and I_j^o is the value of I_j at a reference time (usually one hour after attack); the values of φ_{ij} and $\Delta\varphi_{ij}$ depend on the selected reference time for I_j^o.

If the Δt_{ij} values are rather short and t_{is} is large, then the integrals of Equations (7) and (8) may be estimated from

$$\bar{I}_j \, \Delta t_{ij} = \int_{t_{is}}^{t_{is} + \Delta t_{ij}} I_j \, dt \tag{11}$$

Conservative estimates of the time interval allocations can generally be made by assuming that I_j varies as $I_j^o \, t^{-1}$ (where I_j^o is the value of I_j at t = one hour after detonation); using this variation of I_j with t, the integrals of Equations (7) and (8) become

$$I_j^o \, \ell n \, \frac{(t_{is} + \Delta t_{ij})}{t_{is}} = \int_{t_{is}}^{t_{is} + \Delta t_{ij}} I_j \, dt \tag{12}$$

and

$$I_j^o \, \ell n \, \frac{t_{if}}{(t_{if} - \Delta t_{ij})} = \int_{t_{if} - \Delta t_{ij}}^{t_{if}} I_j \, dt \tag{13}$$

The values of ΔD_{ij}^* for the representations of Equations (10) through (13) are, respectively:

$$\Delta D_{ij}^* = RN_{ij} \, \Delta\varphi_{ij} \, I_j^o \tag{14}$$

$$\Delta D_{ij}^* = RN_{ij} \, \Delta t_{ij} \, \bar{I}_j \tag{15}$$

$$\Delta D_{ij}^* = RN_{ij} \, I_j^o \, \ell n \left[(t_{is} + \Delta t_{ij})/t_{is} \right] \tag{16}$$

and

$$\Delta D_{ij}^* = RN_{ij} \, I_j^o \, \ell n \left[t_{if}/(t_{if} - \Delta t_{ij}) \right] \tag{17}$$

If m_i is designated as the number of workers in shelter i (i.e., of the initial ith group) and n is the number of shelters having positive values of ΔD_i^* (i.e., if ΔD_i^* is zero or negative, the group is not counted as contributing to the work force), then the maximum work that can be obtained from the group up to time, t, after attack is given by

$$E(max) = \bar{\tau} \sum_{i=1}^{n} (t - t_{ix}) \, m_i \quad \text{man-days} \tag{18}$$

where t_{ix} is the shelter exit time, equal to $t_{ia} + \Delta t_{ii}$, and $\bar{\tau}$ is the average fraction of time or of each day over which all the workers could perform useful work (e.g., for an 8-hour work day, $\bar{\tau}$ is 1/3).

If α_{ij} is the fraction of the ith group that work at location j either to contribute work as part of a decontamination crew or, because of their skills, to work at a facility operation, then the distribution of the workers to a location for a given task over the time period Δt_{ij} or on a continuing basis may be represented through the work requirements given by

$$E_j(\text{dec}) = \sum_{i=1}^{n} \alpha_{ij}\, m_i\, \tau_{ij}\, \Delta t_{ij} \qquad \text{man-days} \tag{19}$$

for short-term tasks, such as decontamination, or by

$$E_j(\text{fo}) = \sum_{i=1}^{n} \alpha_{ij}\, m_i\, \tau_{ij}\, (t-t_{is}) \qquad \text{man-days} \tag{20}$$

for long-term tasks or facility operation. In Equations 19 and 20, τ_{ij} is the fraction of the time or of the day that group i (or fraction thereof) works at location j. Thus for each group, the sum of τ_{ij} over the locations must be equal to unity; hence

$$1 = \sum_{j=1}^{J} \tau_{ij} \tag{21}$$

The actual working time at location j for all i groups, ΔT_j, is defined by

$$\Delta T_j = \tau_j\, \Delta t_j \tag{22}$$

where Δt_j is the total of the time periods assigned for work at location j and τ_j is the average fraction of time that all workers spend on the job. Then,

$$\Delta T_j = \sum_{i=1}^{n} \tau_{ij}\, \Delta t_{ij} \tag{23}$$

When ΔT_j is the time required to do a short-term task at location j and it is performed by a single group of people, then the subscript i can be dropped and Equation (23) reduces to Equation (22).

If all the values for E_j(dec) and E_j(fo) are known, then the total required effort may be estimated from

$$E_T = \sum_{j=1}^{J} \left[E_j(\text{dec}) + E_j(\text{fo}) \right] \tag{24}$$

The constraint on the manpower for E_T is that at all times, t,

$$E_T \leq E\ (\text{max}) \tag{25}$$

For most short term tasks and facility operations, full utilization of the manpower will not be realized until full crews or the major portion of the crews are present for work. Under these conditions, Δt_{ij} becomes Δt_j and t_{is} becomes t_{js} in Equations (15) through (17) and in Equations (19) and (20); the latter two can then be written as

$$E_j(\text{dec}) = \tau_j \Delta t_j \sum_{i=1}^{n} \alpha_{ij}\ m_i \tag{26}$$

or

$$E_j(\text{dec}) = \tau_j \Delta t_j m_j \tag{27}$$

and

$$E_j(\text{fo}) = \tau_j (t - t_{js}) \sum_{i=1}^{n} \alpha_{ij}\ m_i \tag{28}$$

or

$$E_j(\text{fo}) = \tau_j (t - t_{js})\ m_j \tag{29}$$

where

$$m_j = \sum_{i=1}^{n} \alpha_{ij}\ m_i \tag{30}$$

Since $E_j(dec)$, $E_j(fo)$ or $dE_j(fo)/dt$, and m_j for specified tasks and facility operations are usually known, the manpower requirements and time limitations may be evaluated through substitution of Equations (26) through (29) in Equations (14) through (17), as applicable. The explicit forms are:

$$\Delta D^*_{ij} = \frac{RN_{ij}\, E_j(dec)\, \bar{I}_j}{\tau_j m_j} \qquad (31)$$

or

$$\Delta D^*_{ij} = RN_{ij}\, I^o_j\, \ln\left[\frac{t_{js} + E_j(dec)/\tau_j m_j}{t_{js}}\right] \qquad (32)$$

where t_{js} is the starting time for the recovery task; if the ΔD^*_{ij} are allocated among the tasks or the j locations for each group of people, then t_{js} is given by

$$t_{js} = \frac{E_j(dec)}{\tau_j m_j \left[e^{(\Delta D^*_{ij}/RN_{ij} I^o_j)} - 1\right]} \qquad (33)$$

for short-time tasks, and for continuous facility operation after t_{js}.

A series of starting times were calculated from Equation (33) for various assumed values of ΔD^*_{ij} and Δt_{ij}. These were then compared with t_{js} values determined from Equation (14), where the latter provides the best estimates currently available. The results from a typical example are shown in Table 1 for the case where ΔD^*_{ij} = 100r and $E_j(dec)/\tau_j m_j$ = 10 days. Residual number RN_{ij} was assigned a value of 1.0 for all the examples tried. It is readily apparent from the entries in the table that Equation (33) gives starting times 5 to 8 times larger (later) than those derived from Equation (14). Obviously, such ultraconservative t_{js} values are not suitable for planning and scheduling recovery operations.

Table 1

STARTING TIME COMPARISONS*

I_j^o (r/hr)	Eq.(33)	Eq.(14)	Eq.(36)
1,000	95	19	21
2,000	196	40	42
5,000	500	108	95
10,000	1,000	180	175
20,000	2,000	260	320

* t_{js} in days.

More reasonable estimates of t_{js} can be made from Douglass'[4] first approximation of the $t^{-1.2}$ relationship where the integral of Equation (7) is represented by

$$I_j^o \Delta t_{ij} \left(t_{js} + \frac{\Delta t_{ij}}{2}\right)^{-1.2} = \int_{t_{js}}^{t_{js}+\Delta t_{ij}} I_j \, dt \qquad (34)$$

The expression for allowable dose becomes

$$\Delta D^*_{ij} = RN_{ij} \, I_j^o \, \Delta t_{ij} \left(t_{js} + \frac{\Delta t_{ij}}{2}\right)^{-1.2} \qquad (35)$$

from which the starting time in hours is

$$t_{js} = \left(\frac{RN_{ij} \, I_j^o}{\Delta D^*_{ij}} \Delta t_{ij}\right)^{0.833} - 1/2 \, \Delta t_{ij} \qquad (36)$$

where $\Delta t_{ij} \simeq \Delta t_j = \frac{E_j(dec)}{T_j \, m_j}$ from Equations (19) and (27).

Using Equation (36) and the ΔD_{ij}^{*} and Δt_{j} inputs cited earlier, additional values of t_{js} were obtained and entered in Table 1 for ready comparison with the previous results. It is evident that for this typical case, Equation (36) agrees closely with Equation (14), the reference expression, except for the highest I_{j}^{o}.

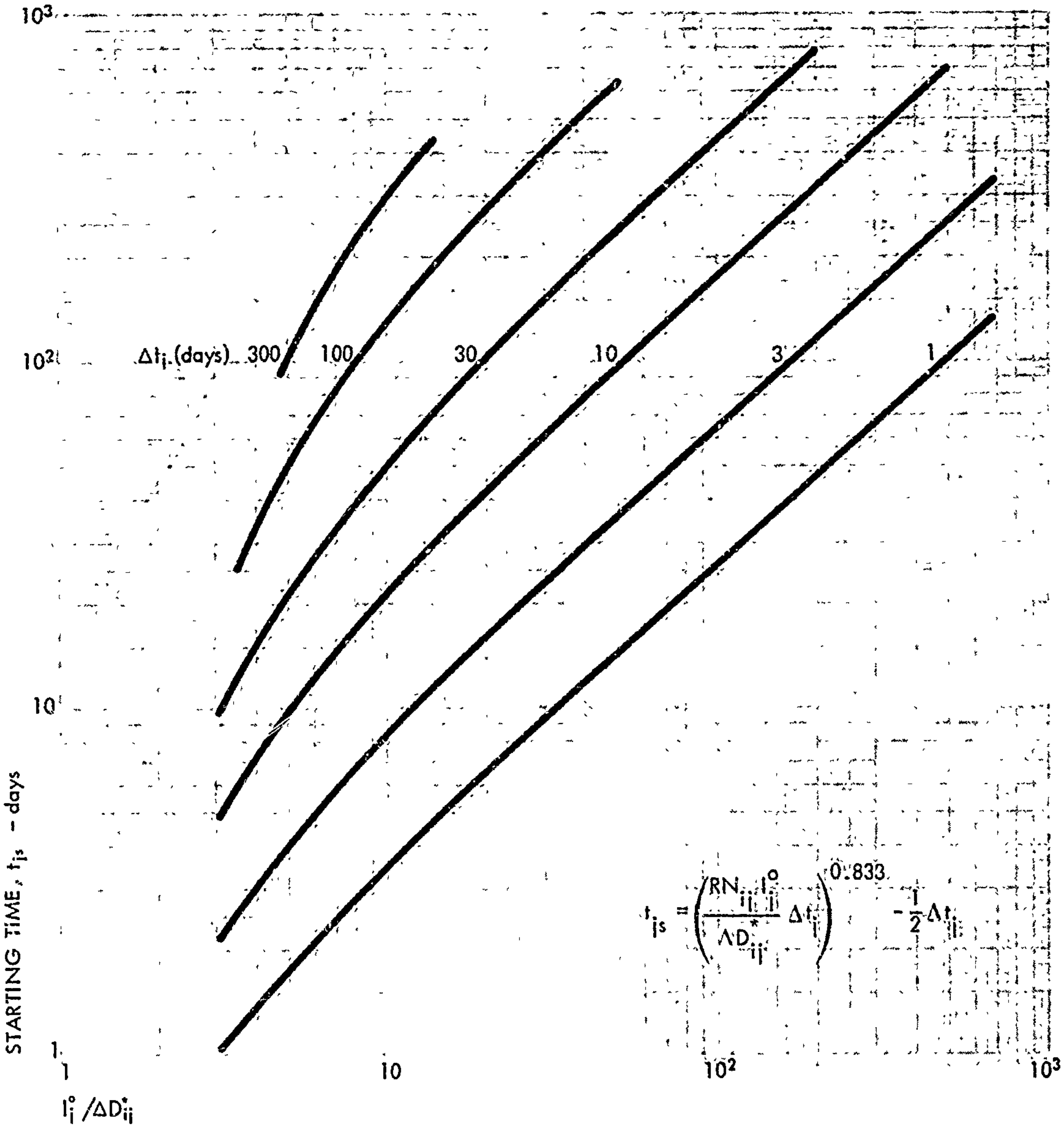
Equations (35) and (36) are especially applicable to the shorter term tasks. They may be used for moderately long term tasks (> 1 month) if the ratio of Δt_{j} to t_{js} is generally less than 3. Under these conditions, the equations usually provide conservative estimates for either dose or starting time. When the sum of Δt_{j} and t_{js} approaches two years, starting time estimates will tend to be over conservative.

Equation (36) was used to construct the family of curves shown in Figure 1. The curves reveal how starting time t_{js} increases with respect to the standard exposure rate I_{j}^{o} for selected values of task interval Δt_{j}.

The restrictions on manpower allocations at location j at any time are given by

Figure 1

RECOVERY STARTING TIMES VS STANDARD EXPOSURE RATE FOR SELECTED EXPOSURE PERIODS, $RN_{ij} = 1.0$



$$N_o = \sum_{i=1}^{n} m_i \tag{37}$$

or

$$N_o = \sum_{j=1}^{J} \sum_{i=1}^{n} \alpha_{ij} m_i \tag{38}$$

where

$$1 = \sum_{j=1}^{J} \alpha_{ij} \tag{39}$$

If the time periods, Δt_j, or the work rates, $E_j(\text{dec})/\Delta t_j$, are known, then the total manpower requirements for both short term and long term tasks at a given time may be estimated from

$$N = \sum_{j=1}^{J} (1/\tau_j) \left[dE_j(\text{fo})/dt + E_j(\text{dec})/\Delta t_j \right] \tag{40}$$

in which the maximum number for allocation is at $N = N_o$

The postattack situation variables that must be known before manpower allocation can be made include the n shelters, the m_i workers/shelter, the RN_{ii} shelter residual numbers, the I_j^o standard intensity values for the j locations. The operational parameters that are needed include the effective RN_{ij} residual numbers, the α_{ij} group dispersion or skill distribution coefficients, the τ_{ij} or τ_j effective working time factors, the $dE_j(\text{fo})/dt$ and $E_j(\text{dec})/\Delta t_j$ manpower requirements for both long term facility operations and short term tasks for all j locations of interest (these define the m_j), and D^*, the limiting exposure dose.

Although the above equations, as written, specify parameter values for the conditions under which each person of all groups i (or at least those of one group) receive the maximum allowed exposure dose, D^*, more conditions should be found where this is not the case; thus for t_{is} or t_{js} values greater than the minimum value (for given values of RN_{ij} and I_j^o), the exposure dose, D_{ij}, within two years after the attack would be less than ΔD_{ij}^*, and the total of these could be less than ΔD_i^*. And where this is the case, consideration could be given to manpower allocations that result in more equal exposure doses to all persons or to those that would minimize the (average) exposure dose of the N_o workers where the latter is represented by

$$\bar{D} = (1/N_o) \sum_{j=1}^{J} \sum_{i-1}^{n} \alpha_{ij} m_j D_{ij} \qquad (41)$$

From the point of view of recovery objectives, it would appear that emphasis should be given on manpower allocations that minimize the t_{js} for long term operations, maximize the number of workers on the long term tasks, minimize the number of workers on the short term tasks, or minimize the time spent on short term tasks. (Actually, if the last three were accomplished, the t_{js} would be minimized.) In general, allocations that emphasize early recovery of facilities would tend to maximize the exposure dose allocations and would be in opposition to minimizing $\bar{D}$ of Equation (41).

Contribution Factors, Residual Numbers, and Decontamination Effectiveness

The relationships among decontamination effectiveness, effort, surfaces, decontamination methods, radiation intensities, and surface density of fallout particles are discussed below. In general, the gamma radiation at a point in location j is the sum of the radiations from fallout particles lying on exposed surfaces within 200 to 300 feet from the point. If the whole area on which the contributing sources are deposited is sectioned according to type of surface and geometrical configuration with respect to the point of interest and each section is designated by the letter k, then S_{jk} is the area of the kth surface at location j whose sources contribute to the gamma radiation at the point j. If the radiation rate at point j contributed by the sources on surface k is designated as I_{jk}, then the radiation rate at point j is given by

$$I_j = \sum_{k=1}^{x} I_{jk} \tag{42}$$

where x is the total number of contributing surfaces. If n_j is designated as the average number of radioactive atoms per unit area that would have been deposited on an ideal smooth plane over the area of the k surfaces (and are present at time, t, after attack) and K_j is defined as the ratio of the exposure rate at 3 feet from the plane to the number of atoms per unit area (at time, t), then the infinite smooth plane exposure rate at a height of 3 feet is given by

$$I_j(\infty) = K_j n_j \tag{43}$$

If variation in the surface density of the fallout particles among the k surfaces is considered, then the average value of n_j is given by

$$n_j = (1/S_j) \sum_{k=1}^{x} S_{jk} n_{jk} \tag{44}$$

where n_{jk} is the average surface density of the radioactive atoms on the kth surface at location j, and S_j is the sum of the S_{jk} over k. Although an $I_{jk}(\infty)$ value could be computed from $K_j n_{jk}$ for each S_{jk} area, the average value of $I_j(\infty)$ from Equations (43) and (44) would generally be representative of $I_j(\infty)$. Where fallout models are used, $I_j(\infty)$ is estimated directly as the reference point.

The relative exposure rate contribution factor of the sources on surface k to the exposure rate at point j is defined by

$$C^{o}_{jk} = I_{jk}/I_{jk}(\infty) \qquad (45)$$

or

$$C^{o}_{jk} = I_{jk}/I_{j}(\infty) \qquad (46)$$

where C^{o}_{jk} is actually the fraction of the infinite smooth plane exposure rate (at 3 feet) at point j that is contributed by the sources on surface k. The average shielding residual number, relative to the infinite smooth plane exposure rate, is defined by

$$\overline{RN}_{j}(\infty) = I_{j}/I_{j}(\infty) \qquad (47)$$

or

$$\overline{RN}_{j}(\infty) = \sum_{k=1}^{x} C^{o}_{jk} \qquad (48)$$

If $F_{j\ell k}$ is designated as the fraction of n_{jk} (or n_{j}) that remains after decontamination of the surface area k by method ℓ (subscript ℓ indicates surface type and method combination), then the remaining surface density of the radiation sources, $n'_{jk\ell}$, after application of the method, is

$$n'_{jk\ell} = F_{j\ell k}\, n_{jk} \qquad (49)$$

and the exposure rate contributions after decontamination are

$$I'_{jk\ell}(\infty) = F_{j\ell k}\, I_{jk}(\infty) \qquad (50)$$

$$I'_{jk\ell} = F_{j\ell k}\, I_{jk} \qquad (51)$$

and

$$I'_{jk\ell} = F_{j\ell k}\, C^{o}_{jk}\, I_{j}(\infty) \qquad (52)$$

The decontamination residual number for the location j (i.e., for those of group i at location j) is defined by

$$RN_{ij}(\mathrm{dec}) = (1/I_j) \sum_{k=1}^{x} I'_{jk\ell} \qquad (53)$$

and substitution of Equations (47) or (48) and (52) in Equation (53) gives

$$RN_{ij}(\mathrm{dec}) = \left[1/\overline{RN}_j(\infty)\right] \sum_{k=1}^{x} F_{j\ell k}\, C^{o}_{jk} \qquad (54)$$

or

$$RN_{ij}(\mathrm{dec}) = \sum_{k=1}^{x} F_{j\ell k}\, C^{o}_{jk} \Big/ \sum_{k=1}^{x} C^{o}_{jk} \qquad (55)$$

Thus, the post decontamination residual number relative to the infinite smooth plane exposure dose rate [or other reference used in the calculation of $I_j(\infty)$] is

$$RN_{ij} = RN_{ij}(\mathrm{dec})\, \overline{RN}_j(\infty) \qquad (56)$$

or

$$RN_{ij} = \sum_{k=1}^{x} F_{j\ell k}\, C^{o}_{jk} \qquad (57)$$

The value of the fraction of the fallout particles not removed from a surface such as a roof or paved street depends on the amount of particles per unit area, on the level of work applied in the removal, and on the removal method. In most cases, work is applied incrementally in proportion to the number of passes that are made over a given area. Although fractional passes over the area are possible, the area would normally be divided so that the section designated by k was treated one or more times by a given method; in addition, fractional passes could be made to clean up spills and portions of a surface that were more difficult to clean than the remainder of the area.

The effort and time relationships given in Equation (58) to (63) below will result when the following designations are used: $p_{\ell k}$ is the number of decontamination passes over the kth surface by method ℓ; $\epsilon_{jk\ell}$ is the equipment-hours per pass over the kth surface of area S_{jk} (i.e., S_{jk} is the area to be covered per pass); $r_{\ell k}$ is the rate of area coverage in square feet per equipment-hour; $e_{jk\ell}$ is the specific effort applied in equipment-hours per square foot; $n_{\ell k}$ is the number of equipment units that operate simultaneously on the kth surface; and σ_ℓ as the number of men used per equipment unit.

$$\epsilon_{jk\ell} = e_{jk\ell}\, S_{jk} \qquad \text{equipment-hours/pass} \qquad (58)$$

$$\epsilon_{jk\ell} = S_{jk}/r_{\ell k} \qquad \text{equipment-hours/pass} \qquad (59)$$

$$E'_{jk\ell} = \epsilon_{jk\ell}\, p_{\ell k} \qquad \text{equipment-hours} \qquad (60)$$

$$E_{jk\ell} = \sigma_\ell\, E'_{jk\ell} \qquad \text{man-hours} \qquad (61)$$

$$\Delta t'_{jk\ell} = E'_{jk\ell}/n_{\ell k} \qquad \text{hours} \qquad (62)$$

and

$$m_{\ell k} = n_{\ell k}\, \sigma_\ell \qquad \text{men} \qquad (63)$$

Also, for all methods and surfaces at location j,

$$E'_{jk} = \sum_{\ell=1}^{L} \epsilon_{jk\ell}\, p_{\ell k} \qquad \text{equipment-hours} \qquad (64)$$

$$E'_{j} = \sum_{k=1}^{x} E'_{jk} \qquad \text{equipment-hours} \qquad (65)$$

$$\Delta t'_{j\ell} = \sum_{k=1}^{x} E'_{jk\ell}/n_{\ell k} \qquad \text{hours} \qquad (66)$$

where $\Delta t'_{j\ell}$ is the operating time of method ℓ at location j. If $\Delta t^{o}_{jk\ell}$ is designated as the combined set-up and delay times in applying method ℓ to the surface k, then the total decontamination time at location j of method ℓ, $\Delta t(\text{dec})_{j\ell}$, is

$$\Delta t(\text{dec})_{j\ell} = \sum_{k=1}^{x} (\Delta t'_{jk\ell} + \Delta t^{o}_{jk\ell}) \quad \text{hours} \tag{67}$$

The quantities that are known or that may be set by the characteristics of the surfaces, operational requirements or limitations, and equipment designs include S_{jk}, $p_{\ell k}$, $r_{\ell k}$, and $n_{\ell k}$. These variables control the $\Delta t'_{jk\ell}$ of Equation (67); substitution gives

$$\Delta t(\text{dec})_{j\ell} = \sum_{k=1}^{x} \left[p_{\ell k} \, S_{jk} \big/ n_{\ell k} \, r_{\ell k} + \Delta t^{o}_{jk\ell} \right] \tag{68}$$

Since $n_{\ell k}$ is the number of equipment units that are operating simultaneously on the kth surface, the total manpower required and the overall duration of the operation will depend on how the manpower is allocated and how the operation is scheduled. If each of the k surfaces decontaminated by method ℓ is treated serially (using a given number of equipment units), then the manpower for application of the method at location j is represented by

$$m_{j\ell} = m_{\ell k} \tag{69}$$

or

$$m_{j\ell} = n_{\ell k} \, \sigma_{\ell} \tag{70}$$

For all the methods at location j, the total (minimum) manpower requirement would be given by

$$m_{j} = \sum_{\ell=1}^{L} n_{\ell k} \, \sigma_{\ell} \tag{71}$$

In general, the total manpower requirements are given by

$$m_j = \sum_{k=1}^{x} \sum_{\ell=1}^{L} n_{\ell k}\, \sigma_\ell \qquad (72)$$

where the maximum requirement is determined by the number of available equipment units.

Essentially all decontamination methods, especially the mechanized methods, consume input products such as fuel for bulldozers, sweepers, and trucks, and water for firehosing. If the average consumption rate of product m for all the equipment with a given method is designated as $c^o_{m\ell}$ (in gallons or pounds per equipment-hour), then the total requirement of the consumable product m at location j is given by

$$c_{jm} = \sum_{\ell=1}^{L} \sum_{k=1}^{x} c^o_{m\ell}\, n_{\ell k}\, \Delta t'_{jk\ell} \qquad (73)$$

Three general types of relationships have been reported[1] between the fraction of fallout remaining after decontamination and the effort or work applied in the removal of the fallout particles; these relationships are termed decontamination efficiency functions. The equations, where the work is related to the number of passes, $p_{\ell k}$, over the kth surface, are:

$$F_{j\ell k} = F^*_{j\ell k} + (1 - F^*_{j\ell k})\, e^{-K_{\ell k} p_{\ell k}} \qquad (74)$$

for methods such as mechanized sweeping of paved areas, and firehosing of roofs and paved areas with standard nozzles,

$$F_{j\ell k} = F^*_{j\ell k} + (1 - F^*_{j\ell k})\, e^{-3K^o_{\ell k}\, p_{\ell k}^{1/3}} \qquad (75)$$

for methods such as mechanized flushing of paved areas and firehosing of these areas with nozzles giving a flat spray pattern, and

$$F_{j\ell k} = e^{-K_{\ell k}\, n_{\ell k}} \qquad (76)$$

for surface removal methods such as grading, scraping, and bulldozing of unpaved areas where $K_{\ell k}$ and $3K^{o}_{\ell k}$ are the decontamination efficiency coefficients. The $F^{*}_{j\ell k}$ in Equations (74) and (75) represents the fraction of the deposited fallout (or of the exposure rate at the start of decontamination) that would not be removed from the surface after a very large number of passes had been made; this non-removal fraction depends on the surface density of the particles on the kth surface at the jth location and is estimated from

$$F^{*}_{j\ell k} = (R'_{\ell k}/Y_{jk})\left[1 - e^{-\alpha_{\ell k}\, Y_{jk}}\right] \qquad (77)$$

for methods such as mechanized sweeping and low-pressure firehosing or flushing of paved areas and roofs; or from

$$F^{*}_{j\ell k} = R_{\ell k}\, Y_{jk}^{Z_{\ell k}} \quad , \quad Y_{jk} < Y^{o}_{\ell k} \qquad (78)$$

and

$$F^{*}_{j\ell k} = R^{o}_{\ell k} \quad , \quad Y_{jk} \geq Y^{o}_{\ell k} \qquad (79)$$

for high-pressure firehosing or mechanized flushing where $R_{\ell k}$, $\alpha_{\ell k}$, $Z_{\ell k}$, $R^{o}_{\ell k}$, and $Y^{o}_{\ell k}$ are constants whose values depend mainly on the type of surface and method of decontamination; and Y_{jk} is the surface density of the fallout particles in weight per unit area. In general, Y_{jk} is proportional to $I_{jk}(\infty)$.

In previous treatments of the decontamination efficiency functions, the exponential argument is expressed in terms of the total or accumulated specific area work expended in decontamination to achieve a given value of $F_{j\ell k}$; this effort is represented in the above definitions by the product

$p_{\ell k}\,e_{\ell k}$. Thus the conversion of the previously evaluated efficiency coefficients to those of Equations (74), (75) and (76) can be accomplished through

$$K_{\ell k} = K/r_{\ell k} \tag{80}$$

and

$$K^o_{\ell k} = K^o/(r_{\ell k})^{1/3} \tag{81}$$

where K and K^o are the respective values of the previously reported efficiency coefficients in sq ft per equipment-hour and in the cube root of these units.

For a required value of $F_{j\ell k}$ (as deduced from Equation 57), the number of decontamination passes is estimated from

$$p_{\ell k} = (1/K_{\ell k})\ \ell n \left[(1 - F^*_{j\ell k})\Big/(F_{j\ell k} - F^*_{j\ell k})\right] \tag{82}$$

which, when substituted in Equation (68), gives the decontamination operating time. However, the first estimates of the operating times and the RN_{ij} would be made on the basis of a single pass ($p_{\ell k} = 1$) and then to evaluate the entry-time requirements using a minimum of personnel and supplies. In this way, the $F_{j\ell k}$ would have fixed values and the estimates for 2- or 3-pass operations would not be made until the single pass operation resulted in excessive estimates of the operator doses (i.e., lower RN_{ij} values were required for a feasible recovery system).

The results of fitting decontamination test data by the foregoing equations and efficiency functions are presented in the decontamination performance tables of Appendix A. Expected values of $F_{j\ell k}$ are shown as a function of $p_{\ell k}$ for a number of decontamination methods and target surfaces. Estimates are given of the coefficients and parameters essential to the solution of Equations (74) through (77). Those environmental and operational factors known to influence decontamination performance are also included.

Infinite Smooth Plane to Extended Real Plane Conversions

In the development of Equations (42 through (57), the contribution factors and residual numbers are referenced to an infinite smooth plane exposure rate, $I_j(\infty)$. Prior work (References 1 and 2) defined contribution factors and residual numbers with respect to an extended real plane dose rate, $I_j(\text{ext})$. From theoretical and experimental considerations of a plane circular source area, $I_j(\text{ext})$ was found to be very nearly equal to a value of 29 I_o, where I_o equals the unit source strength in r/hr.*

Therefore, the fraction of the extended real plane exposure rate (at 3 feet) at location j that is contributed by sources on surface k is given by

$$C_{jk} = I_{jk}/29 \; I_o \tag{83}$$

where I_{jk} is as defined earlier in Equation (42).

Comparing Equation (83) with Equation (46),

$$C^o_{jk} = C_{jk} \frac{I_j(\text{ext})}{I_j(\infty)} \tag{84}$$

where the ratio of extended to infinite plane dose rates represents the reduction in $I_j(\infty)$ due to terrain roughness and air-attenuation effects. $I_j(\text{ext})/I_j(\infty)$ has been estimated to be about 0.75 when the numerator represents the radiation intensity over an unpaved plane,

Continuing with the development for the real plane case,

$$\sum_{k=1}^{x} C_{jk} = I_j/29 \; I_o = \bar{A}_j \tag{85}$$

where $\bar{A}_j$ is the average attenuation factor for an outside location (such as j) in a target complex. Equation (85) corresponds to Equations (47) and (48) for the smooth plane case such that

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* For the condition of uniformly distributed fallout material, I_o is constant over all the k surfaces contributing to location j. See Appendix B for the definition of I_o and the derivation of $I_j(\text{ext})$.

$$\bar{A}_j = \overline{RN}_j(\infty)\,\frac{C_{jk}}{C^o_{jk}} \qquad (86)$$

From Equations (53), (54), and (55), it is apparent that the decontamination residual number at location j is equivalent to the average decontamination effectiveness for all the k surfaces referred to location j.

$$RN_{ij}(dec) = I'_j/I_j = \bar{F}_j \qquad (87)$$

where I'_j is the summation of the various dose rate contributions to location j after decontamination.

$\bar{F}_j$ (or the ratio I'_j/I_j) is the same for either the smooth or real plane case. Therefore RN_{ij}(dec) applies to the real plane case also. However, the symbol RN^o_3 has been used in the past[2] as the residual number equivalent to the average effectiveness, or, more correctly, $(RN^o_3)_j = \bar{F}_j$. Thus we can write expressions of residual number relative to the extended real plane exposure rate that parallel those represented in Equation (56) and (57) as follows:

$$(RN_3)_j = (RN^o_3)_j \sum_{k=1}^{x} C_{jk} \qquad (88)$$

or

$$(RN_3)_j = \bar{F}_j\,\bar{A}_j = \sum_{k=1}^{x} F_{j\ell k}\,C_{jk} \qquad (89)$$

where (RN.) is called the target reutilization[2] residual number at location j.[*] When multiplied by the ratio C^o_{jk}/C_{jk} or $\sum_{k=1}^{x} C^o_{jk}/\bar{A}_j$, this residual number will become equal to RN_{ij} the residual number given for the smooth plane case in Equations (56) and (57).

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[*] The subscript 3 refers to the third exposure period, the first being the shelter period and the second being the decontamination (or recovery) period.

The foregoing conversions have been presented so that the analysis of residual numbers in the sections to follow may be made in terms of the extended real plane case. This is largely a matter of convenience, since most of the work that will be referenced was developed in this same framework (rather than that of the infinite smooth plane). In addition, the conversion relations provide a means for making the transition from one reference plane to another as the need arises.

Analysis of Parameters Affecting $(RN_3)_j$

Estimates of the target reutilization residual number are required in determining the dose to mission personnel, especially facility operators, since most (if not all) of their exposure time will normally occur in the period following decontamination when $(RN_3)_j$ is in effect. In general, the dose to a group working at location j during this third period can be expressed as

$$(\Delta D_3)_j = (RN_3)_j \int_{t_y}^{t_z} I_j \, dt \qquad (90)$$

where the integral term is to be evaluated between appropriate time limits using any of the forms of solution given by Equations (10) through (13).

Equation (89) indicates that the value of $(RN_3)_j$ is a function of all the individual decontamination effectivenesses $(F_{j\ell k})$ achieved on the various contributing k surfaces. Because of the different method-surface combinations involved and the varying amount of effort expended in each case, the resultant $F_{j\ell k}$ values will all be different. Hence, the evaluation of $(RN_3)_j$ requires that an analysis be made of the factors affecting the decontamination efficiency functions of Equations (74), (75), and (76).* These factors

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* The contribution factors which will also vary for each surface identified with location j must be calculated separately. The methods for obtaining contribution factors for a variety of target components have been worked out in considerable detail in Reference 2 and theirefore need not be repeated here.

are outlined as follows:

- I. Target characteristics
  - A. Structural shielding
  - B. Deposition distribution
  - C. Target surfaces
    - 1. Roofs
    - 2. Paved areas
    - 3. Planting areas
    - 4. Bare ground
    - 5. Stabilized areas
    - 6. Graveled areas
    - 7. Other surfaces
- II. Decontamination methods
  - A. Mechanized
    - 1. Sweeping
    - 2. Flushing
    - 3. Scraping
    - 4. Bulldozing
    - 5. Grading
    - 6. Plowing
  - B. Manual
    - 1. Firehosing
    - 2. Shoveling
    - 3. Sweeping
    - 4. Garden hosing
- III. Decontamination personnel
  - A. Trained
  - B. Untrained
    - 1. Blue-collar oriented
    - 2. White-collar oriented

        3. School oriented
        4. Women

IV. Weather conditions
    A. Temperature
    B. Wind
    C. Precipitation
    D. Humidity

V. Fallout properties
    A. Chemical compositions
        1. Solubility
        2. Adsorptivity
    B. Particle size
    C. Deposition density

VI. Other Contingencies
    A. Availability of water
    B. Drainage conditions
    C. Availability of fuel
    D. Accessibility of surfaces to decontamination methods

It is evident from the length of the list of factors and the inferred interrelationships that it would be very difficult to obtain estimates of $(RN_3)_j$ for all the combinations of factors as a function of overall effort and the corresponding RN_2 values.* Also, lack of data makes it practically impossible to obtain semi-accurate estimates except for the few combinations that have been tested on a limited scale. Until extensive, repetitive, full-scale urban-wide training exercises are conducted, accurate estimates of the parameters needed for decontamination scheduling will not be available. Even

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* RN_2 is the decontamination crew residual number required to estimate the dose accrued during the recovery (or second) period.

then, it would be difficult to predict the outcome for the condition where everyone is under extreme stress. Nevertheless, the scheduling of decontamination requires the evaluation of the problem for the conditional factors listed.

In order to conveniently discuss the relationship between these factors and the equation parameters concerned, it is necessary to write a general expression for the three decontamination efficiency functions in terms of the physical properties involved. If at any time t, the mass of fallout material ($M_{j\ell k}$) per unit area is assumed to be proportional to the number of radioactive atoms (n_{jk}) per unit area, then the fraction of fallout remaining after decontamination will be, according to Equation (49),

$$F_{j\ell k} = \frac{n'_{jk}}{n_{jk}} = \frac{M_{j\ell k}}{(M_o)_{jk}} \qquad (91)$$

where $(M_o)_{jk}$ is the initial mass loading before decontamination.* Letting $Q_{\ell k}$ represent either decontamination efficiency coefficient $K_{\ell k}$ or $3K^o_{\ell k}$ and assuming that $F^*_{j\ell k}$ becomes zero for surface removal methods, the general expression for the decontamination efficiency functions of Equations (74), (75), and (76) is given by

$$\frac{M_{j\ell k}}{(M_o)_{jk}} = F^*_{j\ell k} + (1 - F^*_{j\ell k})\ e^{-Q_{\ell k}\ p_{\ell k}} \qquad (92)$$

or

$$M_{j\ell k} = M^*_{j\ell k} + \left[(M_o)_{jk} - M^*_{j\ell k}\right] e^{-Q_{\ell k}\ p_{\ell k}} \qquad (93)$$

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* $(M_o)_{jk}$ is the same as the Y_{jk} used in Equation (77) to represent fallout surface density. The new notation is introduced for convenient comparison with $M_{j\ell k}$.

where $M^*_{j\ell k}$, which equals the product of $(M_o)_{jk}$ and $F^*_{j\ell k}$, is the mass loading that would remain after a large decontamination effort requiring many passes. It is estimated from the equation given in Reference 1 as

$$M^*_{j\ell k} = (M^*_o)_{j\ell k} \left[1 - e^{-\alpha_{\ell k}(M_o)_{jk}} \right] \tag{94}$$

where $(M^*_o)_{j\ell k}$ is the upper limit of $M^*_{j\ell k}$, a constant for a given method-surface combination, and $\alpha_{\ell k}$ is the spreading coefficient dependent upon the method-surface combination, particle size, and density of deposition. This expression given in terms of surface density of fallout parallels Equation (77) written in terms of the fraction of fallout deposited.

Equation (94) could be substituted into Equation (92) and (93), which in turn could be substituted into Equation (89) to obtain a detailed expression for $(RN_3)_j$. However, it is obvious that the subsequent solution to Equation (89) depends upon the input furnished by the decontamination equations and supporting relationships and parameters of the foregoing development.

Comparing the decontamination factors of the outline with the parameters of the above equations, it can readily be seen that $(M_o)_{j\ell k}$ is associated with the deposition density, item V-C, and deposition distribution, item I-B. The parameter $M^*_{j\ell k}$ is associated with the following: the contaminated surface, item I-C; the decontamination method, item II; weather conditions, item IV; fallout solubility, item V-A, and particle size, item V-B. The parameter $(M^*_o)_{j\ell k}$ is associated with the contaminated surface, item I-C, and the decontamination method, item II. The parameter $\alpha_{\ell k}$ is associated with: the contaminated surface, item I-C; the decontamination method, item II; and the fallout properties, item V. The quantity $Q_{\ell k}$ is associated with: the contaminated surface, item I-C; the decontamination method, item II; the decontamination personnel, item III; the weather conditions, item IV; the surface drainage conditions, item VI-B; the accessibility of the contaminated surface to decontamination methods, item VI-D; deposition distribution, item I-B; and fallout characteristics, item V.

It is obvious that if a different $Q_{\ell k}$ were required for each set of conditions, it would be necessary to list several values. Because of this, it is advantageous to express $Q_{\ell k}$ as a function of at least some of the conditions associated with it. For the same reason, it is desirable to express all the parameters of Equations (93) and (94) as functions of their variously associated decontamination factors. It appears, however, that the parameters must at least be based upon distinct surface-method combinations.

As an example, a tar-and-gravel roof may be firehosed, garden hosed, or manually swept. If the decontamination method chosen is to be firehosing, the first requirement is an adequate water supply, VI-A. The application of the method also requires an adequate hydrant pressure or a pump to provide the needed pressure. This in turn may require fuel for the portable pumps, or fuel or electrical power at the main pumping stations, VI-C. If adequate water and pressure (and perhaps firehoses) were available at the roof or near the roof location rather than at a relatively remote street location, the effort required for the same effectiveness would be less because of accessibility, VI-D. A slightly sloped roof will provide better drainage, VI-B, than a flat roof, and consequently would require less decontamination effort. For fallout deposition on a tar-and-gravel roof, the deposition density, V-C, will have little bearing on the decontamination rate. Larger particles are more readily removed from surfaces by the firehose stream and consequently a greater decontamination effectiveness with increasing fallout particle size, V-B, is achieved with the same decontamination effort. Greater solubility along with surface adsorption, V-A, on the other hand, would cause a decrease in decontamination effectiveness.

Weather conditions, IV, could affect the decontamination process in many ways. A blanket of snow would require an increase in effort, but on the other hand the cold temperature, IV-A, may reduce leaching. In extremely cold weather, not only is human efficiency reduced but partial freezing of the run-off water would cause additional problems. High temperatures, IV-A, on the other hand may soften the tar on the tar-and-gravel roof and cause an increase in the non-removable mass. The effect of wind, IV-B during firehosing is negligible, but its effects prior to decontamination could be considerable. It could even negate the necessity for roof decontamination. The same could be said for a heavy rain, IV-C.

The effectiveness of any organization is vested in the quality of its personnel and the amount of training undertaken by the organization. For these reasons, the trained individual, III-A, is more effective than the untrained individual, III-B. Also, because decontamination by firehosing is physically vigorous, the physically strong are more adaptable to the task than the physically weak, III-B(1,2,3,4). It may be expected that a well-trained organization of selected individuals will be vastly superior to an untrained group.

Equation (93) gives the residual mass, $M_{j\ell k}$, for a given amount of effort. However, the residual mass is proportional to the residual activity only if the radionuclides are homogeneously distributed throughout each particle volume, and if the radionuclides are insoluble. Since decontamination processes are more effective in removing larger particles, the residual activity for a mixture of fallout particles, some with radionuclides fused within its volume and some with radionuclides fused to its surface only, depends upon the relative sizes of the two types of particles and the relative amount of each type.

The radionuclides condensed on or fused into fallout particles from detonations over land surfaces are relatively insoluble.[1] However, since virtually all large cities are adjacent to large bodies of water, the fallout from weapons detonated in the vicinity of these targets could very well be of a more soluble nature. With respect to soluble fallout, two general types of target surfaces are considered: 1) impervious surfaces such as metallic roofs, where the transfer of ionic radionuclides is by chemisorption, and 2) pervious surfaces such as concrete, where ionic solutions physically penetrate and are drawn into the concrete mass by surface tension. Although it is obvious that the pervious surface types will be more difficult to decontaminate, data of this type are incomplete. Chapter 8 of Reference 1 gives a detailed discussion on fallout chemistry and fallout chemical behavior with decontamination.

The effects of particle size and deposition density with respect to effectiveness in Equations (92) and (93) are vested in $\alpha_{\ell k}$ of Equation (94). The efficiency of decontamination, on the other hand, is affected by personnel quality, temperature, thickness of snow (if any), drainage (e.g., slope of roof, number and capacity of drains), and accessibility. These efficiency factors are included in $Q_{\ell k}$ which, because of its dependency on these factors, must be treated as a variable rather than a constant, and takes the form

$$Q_{\ell k} = f\,(F_a, T, P, \eta, \theta) \tag{95}$$

where

F_a is the accessibility
T is the temperature
P is the percentage of trained personnel
η is the snow thickness, and
θ is the roof angle.

The currently available data on tar-and-gravel roof decontamination, with few exceptions, were obtained in temperate climatic conditions, with semi-trained personnel, for near horizontal surfaces (or at least the effects of slope were not reported) and for very favorable accessibility. The $Q_{\ell k}$ value of 2.48 given in Table A.6 of Appendix A for firehosing tar-and-gravel roofing is for the conditions cited. Since most tar-and-gravel roofs fit the "flat" designation, and if climatic conditions are "mild," the temperature, slope, and snow thickness functions may be removed from Equation (95). The remaining factors affecting $Q_{\ell k}$ are personnel quality and accessibility. These two factors either singly or in combination could reduce the value of $Q_{\ell k}$ considerably. Yet they, unlike factors such as temperature, fallout solubility, deposition density, etc. are in the hands of the populace of each urban entity, and consequently the value of $Q_{\ell k}$ need not be reduced because people can be trained and the target complex can be made readily accessible to various decontamination methods by target modification and by refurbishing it or the decontamination organization with the necessary equipment and supplies.

Factors, such as fallout solubility, that affect decontamination effectiveness are weapon detonation consequences which countermeasures cannot control. In some situations, a change in decontamination methods could negate the effects of fallout solubility, but there is no countermeasure to stop rain or any other moisture-producing weather condition. However, the effects of fallout solubility could be countered to some extent by surface adsorptivity. Whether or not such countermeasures should be undertaken depends upon the significance of the solubility-adsorptivity effects on the residual surface activity, the resultant residual number, and the total exposure dose.

A final consideration in the evaluation of $(RN_3)_j$ is the radionuclide composition associated with the various fallout particles. As previously stated, one of the factors affecting the effectiveness of decontamination is the particle size. If radionuclide composition and solubility are also associated with particle size, and since particle size selectivity is an inherent characteristic of decontamination processes, the radionuclide composition of the residual activity will be different from the radionuclide composition of the original fallout deposit. The effects of an altered radionuclide composition are: (1) a change in the effective gamma energy, and (2) a change in the rate of decay. The first effect is manifested by a change in the shielding penetration characteristics, and the second effect causes a change in dose accumulation over various periods of time.

III RESIDUAL NUMBERS FOR FACILITY OPERATORS

The importance of the target reutilization residual number, RN_3, in the estimation of dose to facility operators was mentioned earlier in Chapter II. This and the general expression for dose given by Equation (90) were concerned only with the special (but very likely) case where facility operations were delayed until completion of decontamination. There is always the possibility that operators and other mission personnel might be required to perform important tasks before the initiation of the decontamination effort. It is the intent of this chapter to investigate the implications of such an eventuality with respect to the operator dose and the residual number required in the dose estimation.

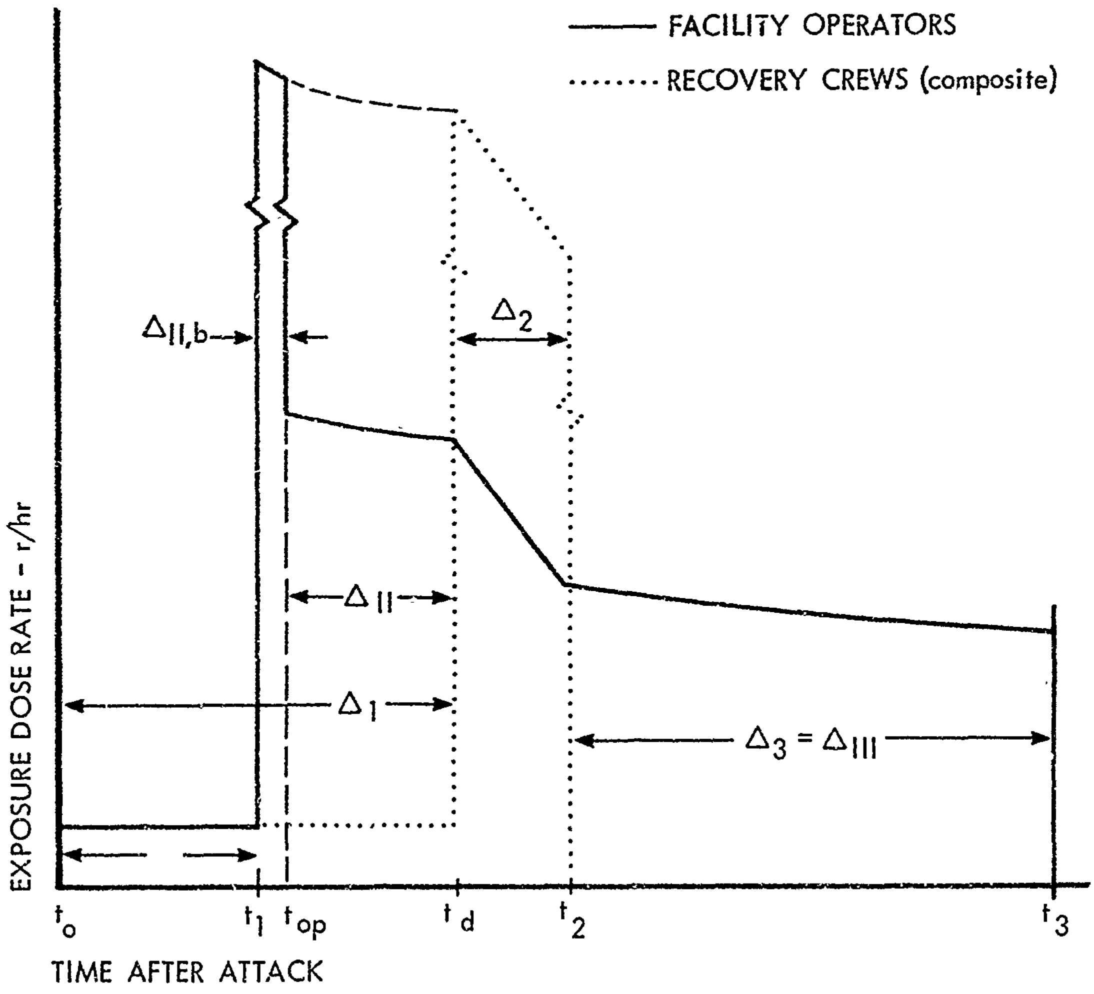
An Equation for Residual Number

Consider the situation depicted by the two dose rate histories shown in Figure 2 . The solid line is the history for a team of facility operators that have left shelter at time t_1, arrived at the facility and started work at time t_{op}, and are staying on duty until time t_3. The dotted line represents the composite dose rate history for a continuous recovery operation initiated at time t_d and terminated at time t_2. The conventional exposure period designations have been reserved in Figure 2 for the recovery crews. Thus, Δ_1, Δ_2, and Δ_3 represent the shelter period, the recovery period, and the target utilization period, respectively. Symbols with Roman numeral subscripts indicate the facility-operator exposure periods.

Using the form given by Equation (14), the operator dose for the transition period, $\Delta_{II,b}$, between shelter exit t_1 and arrival at the facility t_{op} is

Figure 2

EXPOSURE DOSE RATE HISTORIES FOR FACILITY OPERATION AND RECOVERY EFFORT



$$\Delta D'_{II,b} = \bar{A}_j I^o_j \Delta\varphi_{II,b} \qquad (96)^*$$

where $\bar{A}_j$ is the net attenuation factor for an outside location j in the vicinity of a facility within a target complex. The operator dose inside the facility for the period Δ_{II} before recovery may be written as

$$\Delta D'_{II} = A_f \bar{A}_j I^o_j \Delta\varphi_{II} \qquad (97)$$

where A_f is the facility attenuation factor indoors with respect to the exterior radiation sources. From the equations given in Reference 2 to derive RN_2 factors,[≠] an expression for the operator dose during the recovery period Δ_2 becomes

$$\Delta D'_2 = A_f I_j(t_d) \left[\sum_{k=1}^{x} C_{jk} - \frac{1 - \bar{F}}{2} \sum_{k=1}^{s} C_{jk} \right] \Delta_2 \qquad (98)$$

where $I_j(t_d)$ is the exposure rate outdoors at time $t_d = t_{js}$ (dec),

$\sum_{k=1}^{x} C_{jk}$ is the sum of the contribution factors for target surfaces 1 to x identified with location j,

$\sum_{k=1}^{s} C_{jk}$ is the sum of the contribution factors from decontaminated surfaces 1 to s, where $s \leq x$, and

$\bar{F}$ is the composite recovery effectiveness obtained on surfaces 1 to s for the various methods employed.

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[*] The prime mark appearing over the dose symbol D denotes the value is less than the potential dose represented by the product $I^o_j \Delta\varphi$

[≠] The derivation is reviewed in Section IV of this report; see Equations (119) through (124)

The product $I_j(t_d)\Delta_2$ is an approximation of the potential dose outside the facility, which is more precisely determined by $I_j^o \, \Delta\varphi_2$. From Equation (85), $\sum_{k=1}^{x} C_{jk}$ equals the target attenuation factor, $\bar{A}_j$. If the uncleaned surfaces $s+1$ to x are assigned decontamination effectiveness values of F_{jk} equal to 1.0, then $\bar{F}$ will represent the average recovery effectiveness, $\bar{F}_j$, for all contributing surfaces 1 to x. This, in effect, allows s to equal x and $\sum_{k=1}^{s} C_{jk}$ to equal $\sum_{k=1}^{x} C_{jk}$. Applying these changes, Equation (98) takes the simplified form

$$\Delta D_2' = A_f \, \bar{A}_j \, I_j^o \, \Delta\varphi_2 \left(\frac{1 + \bar{F}_j}{2} \right) \qquad (99)$$

The operator dose for the period Δ_3 following recovery is given as

$$\Delta D_3' = A_f \, \bar{A}_j \, \bar{F}_j \, I_j^o \, \Delta\varphi_3 \qquad (100)$$

where the product $\bar{A}_j \, \bar{F}_j$ is the target reutilization residual number $(RN_3)_j$.

The summation of Equations (96), (97), (99), and (100) equals the operator dose D_{op}' for the exposure period from t_1 to t_3. Over this same interval, the potential exposure dose for a reference location 3 feet above an extended (and uniformly concentrated) real plane source of radioactivity is

$$D_{op} = I_j^o \, \Delta\varphi_{1 \text{ to } 3} \qquad (101)$$

according to the form given by Equation (10).

By definition, the ratio of D_{op}'/D_{op} is the residual number for facility operator from which

$$RN_{op} = \bar{A}_j \frac{\Delta\varphi_{II,b}}{\Delta\varphi_{1 \text{ to } 3}} + A_f \, \bar{A}_j \frac{\Delta\varphi_{II}}{\Delta\varphi_{1 \text{ to } 3}} + A_f \, \bar{A}_j \frac{\Delta\varphi_2}{\Delta\varphi_{1 \text{ to } 3}} \left(\frac{1 + \bar{F}_j}{2} \right) + A_f \, \bar{A}_j \frac{\Delta\varphi_3}{\Delta\varphi_{1 \text{ to } 3}} \bar{F}_j \qquad (102)$$

Equation (102) is the general expression for RN_{op} and, in conjunction with Equation (101), will provide a means for estimating operator dose. The attenuation factors can be calculated from target analysis procedures,[2] and the dose rate multipliers are obtained from Figure 3 for the times dictated by the RADEF operational routine and recovery schedule. $\bar{F}_j$ will depend upon the cumulative effect of all the individual decontamination effectiveness, F_{jk}, realized on each surface. Each F_{jk}, in turn, will depend upon the decontamination method and the effort expended. Thus $\bar{F}_j$ must be obtained from Equation (89), which can be rewritten

$$\bar{F}_j = \sum_{k=1}^{x} F_{jk} C_{jk} \Big/ \sum_{k=1}^{x} C_{jk} \qquad (103)$$

where F_{jk} and $F_{j\ell k}$ are taken to be the same since not more than one method is usually used on any given surface.

If, for a particular radiological situation, the expected average recovery effectiveness is likely to be 0.1 or less, $\bar{F}_j$ may not exert a significant influence upon the facility operator residual number. For $\bar{F}_j \leq 0.1$, the value of the third term of Equation (102) will be relatively unaffected. Also, the contribution of the fourth term to RN_{op} could become extremely small, especially when the exposure period Δ_3 becomes short compared with Δ_{II} and Δ_2. Under these conditions, evaluation of Equation (103) and the decontamination efficiency functions [Equations (74), (75), and (76)] may not be required. On the other hand, if expected recovery effectiveness is poor ($\bar{F} \gg 0.1$) and/or Δ_3 is comparatively long, the use of these equations may very well be justified. Each situation will have to be judged on its own merits, taking into account the exposure periods, the decontamination method capabilities, and the significant surface source contributions.

For a number of decontamination situations, the method effectiveness F_{jk} for a given surface is relatively constant. This is due to either

(1) the lack of sufficient test data to determine the coefficients to the decontamination efficiency functions, or (2) the inability to demonstrate any improvement in effectiveness with the increased investment of effort. For these instances, F_{jk} values may be taken directly from appropriate decontamination test results (see Tables A.8, A.9 and A.10 of Appendix A).

Interpretation and Use of RN_{op}

Table 2 contains a solution of Equation (102) for the operator dose rate history given in Figure 2 . It is assumed that the operator team starts for the facility on foot after spending six days in shelter. The transition from shelter to facility takes one hour, which is probably 3 to 4 times longer than it would actually take in a realistic situation. Decontamination operations start after 11 days and last 12 hours. The operators stay in the facility until the end of the 20th day following attack. Arbitrary (but reasonable) values for attenuation factors and composite recovery effectiveness are shown at the foot of Table 2. The dose rate multipliers were read from Figure 3 for the times and periods shown in the left hand columns of Table 2.

Table 2 presents the solution for RN_{op} in parts showing the contribution of each term of Equation (102) and the cumulative effects. The last two columns in the table compare the accumulating operator dose, D'_{op}, with the exposure-dose limits, D^*. The latter were based on the 200 r ERD dose concept (see Reference 3), from which the approximate dose limits are:

190 r in one week
220 r in two weeks
240 r in three weeks

Since t_3 is almost three weeks, the total dose to the operators after leaving the shelter cannot exceed 240 r. From Equation (101) and (102)

$$D'_{op} = I_j^o \, \Delta\varphi_{1 \text{ to } 3} \, RN_{op} = D^* = 240 \text{ r}$$

TABLE 2

SAMPLE CALCULATION OF FACILITY OPERATOR RESIDUAL NUMBER, RN_{op}, AND EXPOSURE DOSE, D'_{op}

Exposure Period	Time After Attack (hr)		φ	$\Delta\varphi$	Equation (102) $RN_{op} = \Sigma$ terms	Residual Number Per Period	Residual Number Cumulative Total	Exposure Dose (r) D'_{op}	Exposure Dose (r) D^*
	t_1	144	2.974						
$\Delta_{II,b}$				0.002	$\bar{A}_j \dfrac{\Delta\varphi_{II,b}}{\Delta\varphi_{1\ to\ 3}}$	0.0042	0.0042	5.2	-
	t_{op}	145	2.976						
Δ_{II}				0.201	$A_f\bar{A}_j \dfrac{\Delta\varphi_{II}}{\Delta\varphi_{1\ to\ 3}}$	0.170	0.1742	186	190
	t_d	264	3.177						
Δ_2				0.013	$A_f\bar{A}_j \dfrac{\Delta\varphi_2}{\Delta\varphi_{1\ to\ 3}}\left(\dfrac{1+\bar{F}_j}{2}\right)$	0.0066	0.1808	193	220
	t_2	276	3.190						
Δ_3				0.140	$A_f\bar{A}_j \dfrac{\Delta\varphi_3}{\Delta\varphi_{1\ to\ 3}}\ (\bar{F}_j)$	0.0118	0.1926	240	240
	t_3	480	3.330						

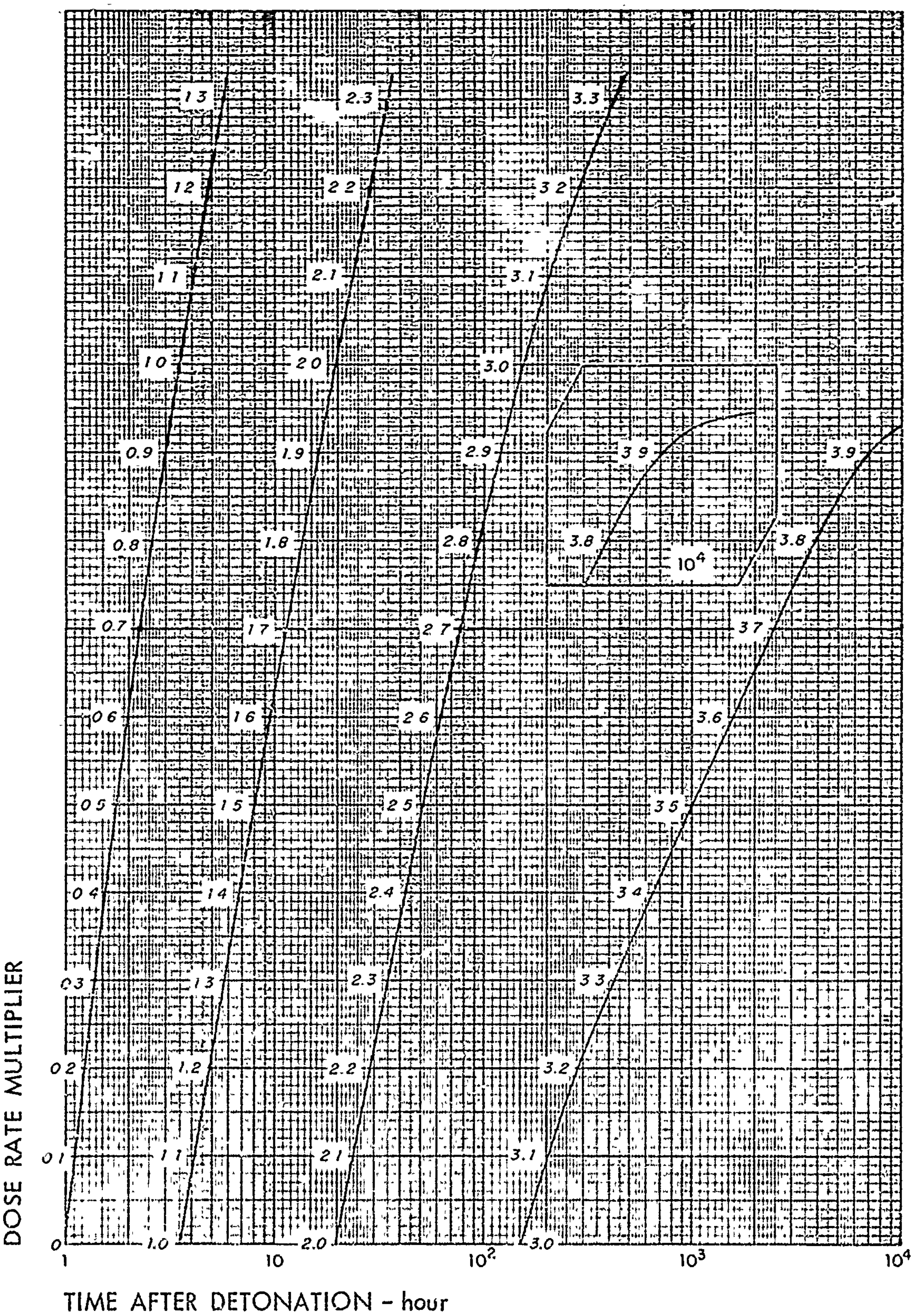
RN_{op} = 0.1926 and upper limit of I_j^o = 3500 r/hr

Note: The following coefficients were used in obtaining the above solution to Equation (102):

$\bar{A}_j = 0.75$, $A_f = 0.4$, $\bar{F}_j = 0.1$, and $\Delta\varphi_{1\ to\ 3} = 0.356$.

Figure 3

DOSE RATE MULTIPLIER CURVES



Substituting 0.356 for $\Delta\varphi_{1 \text{ to } 3}$ and 0.1926 for RN_{op} (from the solution in Table 2), an upper limit was obtained for $I_j^o = 3500$ r/hr. Using this value of standard intensity in Equation (102), the operator dose was computed for each exposure period, and the cumulative totals were taken.

From the entries in Table 2 for this particular example, it is apparent that D'_{op} never exceeded its limiting value D^*. If, during any exposure period, $D'_{op} > D^*$, the system fails. Either the RADEF routine and recovery schedule must be improved or the routine must be limited to some lower and more acceptable standard intensity. No generalizations can be drawn from the results in Table 2. Each radiological problem has to be examined and solved on an individual basis. The example simply demonstrates the method for using Equations (101) and (102) to detect the occurrence of excessive operator dose estimates for any given exposure period and the necessity of adjusting routines and schedules accordingly.

No allowance was made in the foregoing treatment for shelter dose. Where the latter is significant, it must be added to the operator dose before comparing dose accumulations with the exposure limits.

Because Equation (102) used in constructing Table 2 covers the general case, it can be applied by parts to redefine new RN_{op}'s for special cases. That is, the equations used to formulate Equation (102) can be taken separately or in combination to obtain operator dose for other entry and work schemes. Consider the simplest case where facility operators do not enter until after completion of the decontamination task. Their dose would be given by Equation (100) plus a relatively small increment during the time it took to leave shelter and reach the facility.

Using the example of Table 2, the dose would be about 57 r for the given Δ_3 of 8-1/2 days. And the residual number would become

$$RN_{op}(\Delta_3) = \frac{\Delta D'_3}{\Delta D_3} = \frac{\text{Eq. (100)}}{I_j^o \, \Delta\varphi_3} \qquad (104)$$

or

$$RN_{op}(\Delta_3) = A_f \bar{A}_j \bar{F}_j = A_f(RN_3)_j \tag{105}$$

For an emergency task prior to decontamination, say for periods $\Delta_{II,b}$ and Δ_{II}, Equations (96) and (97) would be combined to obtain the operator dose. Table 2 shows that the dose in this case would be 186 r. The expression for the residual number is obtained in the same way as Equation (105).

IV THE DECONTAMINATION CREW RESIDUAL NUMBER, RN_2, FOR SERIALLY AND SIMULTANEOUSLY SCHEDULED OPERATIONS

Reference 2, "Radiological Target Analysis Procedures," describes a systematic technique for estimating decontamination crew residual numbers (RN_2). This estimating technique is applicable to all the decontamination method and target surface combinations currently considered feasible for the radiological postattack recovery period. The resulting set of equations used to calculate a desired RN_2 are capable of taking into account the effects of multiple pass procedures (for a given decontamination method) and the contributions of new source intensities emanating from fallout material redeposited by the decontamination process. Special expressions were derived to distinguish between thin new sources (no self shielding) and thick new sources (self shielding significant). However, all the equations are limited to the consideration of just those changes in crew dose brought about by the decontamination efforts for the method and surface in question. The effects of any prior or simultaneous decontamination of adjacent surfaces on crew dose and hence on RN_2 estimates must be provided for in some other way, i.e., outside of the equations themselves. It is the purpose of this section to derive expressions that will give RN_2 values for realistic recovery operations involving either serial or simultaneous application of decontamination methods to a target complex.

Verification of the Analytical Approach to Estimating RN_2 Values

Because any new development must necessarily be based upon the earlier technique and equations, it is worth examining the validity of one very important assumption that made the derivation of relatively uncomplicated expressions feasible. It was assumed in Reference 2 that because the fallout would be removed (ideally) at a constant rate during a given decontamination pass, the exposure rate I existing in the area would decrease linearly from I_b to I_a (before and after decontamination).* This excluded new source contributions which had to be treated separately and then added in later.

This assumption permitted a straightforward development of the equation for the decontamination crew dose, D_2'. Taking this dose to be equal to the area under the exposure dose rate curve shown in Figure 4,

$$D_2' = \int_b^a I \, dt = \frac{I_b + I_a}{2} (t_a - t_b) \tag{106}$$

The problem of estimating RN_2 (the ratio of D_2'/D_2)† was essentially reduced to finding the appropriate expressions for I_b and I_a.

Exposure dose rate histories of actual decontamination experiments do not reflect the assumed smooth linear transition shown in Figure 4. It would be strange if they did, since new source effects are contained in these histories but not in Figure 4. Nevertheless, the question remains as to whether the technique and equations developed thus far for estimating RN_2 are capable of compensating for the prominent and random deviations observed in experimentally obtained crew exposure-dose-rate histories.[5,6]

The Experimental Case

Table 3 contains the crew dose ratios from the latest tests of a full scale firehosing operation at Camp Parks.[7] The actual exposure dose, d_2', to the firehosing crews was determined from the area under the dose rate history

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* A similar assumption was used in Reference 3, "Introduction to Radiological Defense Planning," in order to write an equation for the limiting exposure dose to evacuees or decontamination crews of operational routine 2.

† D_2 is the potential exposure dose of an individual standing upon an extensive open area uniformly contaminated by radioactive fallout.

Figure 4

LINEAR DECREASE IN DOSE RATE, I, DURING DECONTAMINATION

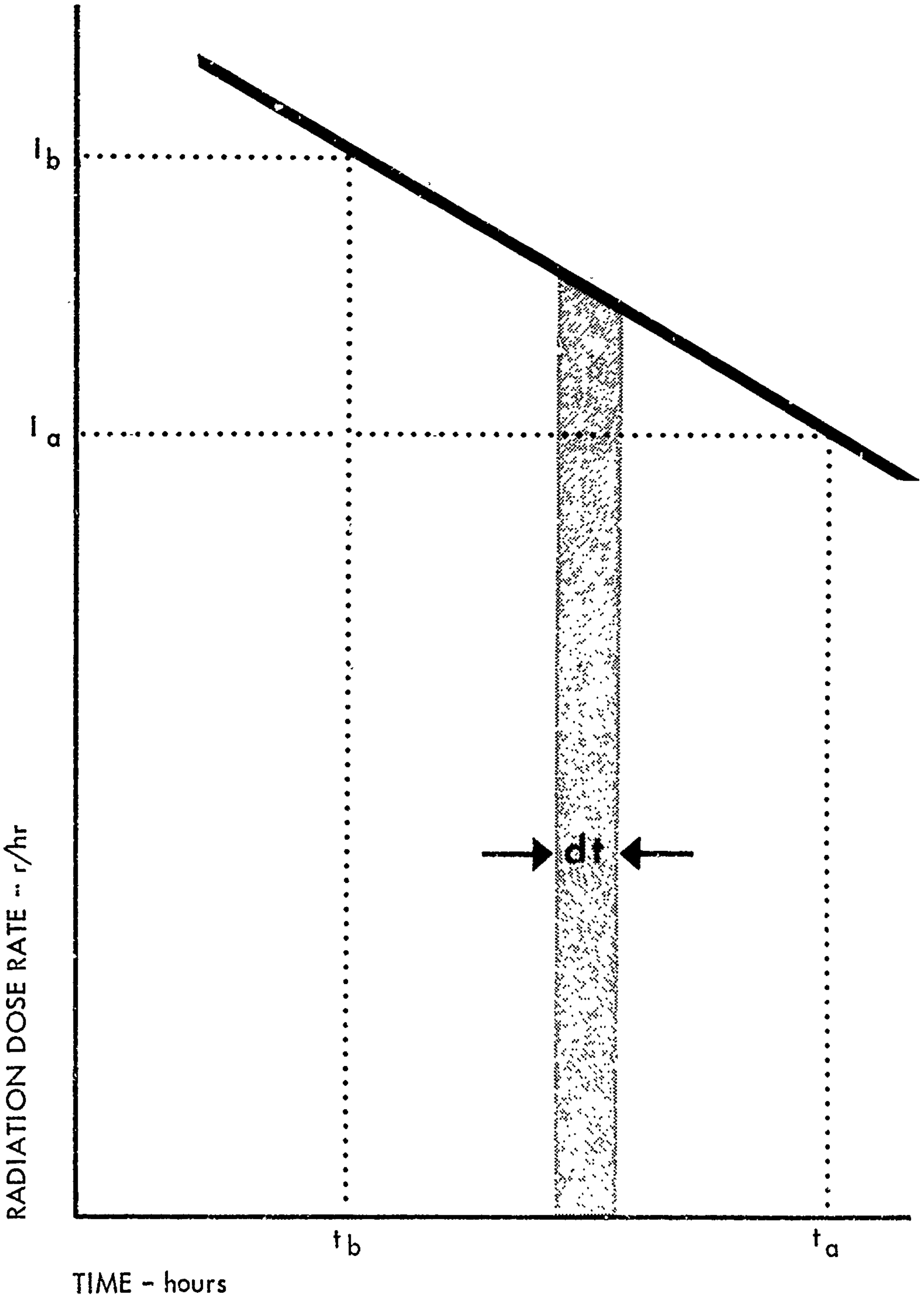

Table 3

EXPERIMENTALLY DERIVED DOSE RATIOS FOR FIREHOSING CREWS

Isolated Test Area: 8,960 ft^2 (32 × 280 ft)

Decon. Crew Designation	Surface Texture	Initial Mass Loading (g/ft^2)	Decontamination Interval Δt (hr)	Initial Exposure Rate I_p (mr/hr)	Potential Exposure d_2 (mr)	Actual Exposure d_2' (mr)	Dose Ratio d_2'/d_2
			Particle Size Range 88-177 μ				
South	Rough	25.02	0.16	32.	5.1	1.1	0.22
North	Smooth	25.02	0.16	33.	5.3	1.3	0.24
South	Rough	92.40	0.225	34.	7.7	2.1	0.27
North	Smooth	92.40	0.225	36.	8.1	1.8	0.22
			Particle Size Range 300-600 μ				
South	Rough	4.43	0.20	18.	3.6	0.76	0.21
North	Smooth	4.43	0.20	17.	3.4	0.82	0.24
South	Rough	24.24	0.23	41.	9.4	2.3	0.24
North	Smooth	24.24	0.23	38.	8.7	2.5	0.29

curves of each test run. The potential dose, d_2, was computed from the product of the decontamination interval, Δt (for one complete coverage of the test street), and the initial exposure rate I_p was measured in the center of the contaminated street. Because there was no contamination on the area surrounding the test street, the ratio of d_2'/d_2 does not equal RN_2. By definition, RN_2 equals the ratio of D_2'/D_2 where both numerator and denominator include the dose rate contribution from outside the immediate surface being cleaned. However, these aspects can all be taken into account in finding the relationship between RN_2 and the ratio d_2'/d_2.

The Hypothetical Example

The special test situation considered here, that of a contaminated street isolated by clean surroundings, can be treated in two parts. As indicated in Table 3, let the exposure rate contributed by the contaminated street to a reference point located three feet above the center of the street be represented by I_p. Now, assume that the surroundings are uniformly contaminated at the same mass loadings shown in Table 3 to a radius of several hundred feet, and let the resultant exposure rate contributed to the same reference point equal I_q. The sum of these two quantities when multiplied by the decontamination interval, Δt, equals the potential dose D_2. That is, for no decontamination

$$D_2 = (I_p + I_q)\,\Delta t = I_b \Delta t \qquad (107)$$

where it is assumed that, since Δt is relatively short and entry times seldom start earlier than two days, corrections for radioactive decay may be neglected.

Because the above conditions correspond to those defining a real extended plane exposure rate, and because Reference 2 approximates this by the quantity 29 I_o, I_b may also be set equal to 29 I_o. Therefore,

$$D_2 = 29\, I_o\, \Delta t \tag{108}$$

where I_o is the unit source strength defined in Section II for a uniformly contaminated surface. From Equation (106), the crew dose during decontamination is

$$D'_2 = \frac{I_b + I_a}{2}\, \Delta t \tag{109}$$

If I_b (before decontamination) equals $I_p + I_q$, then I_a (after decontamination) equals $I'_p + I_q$, where I'_p is the reduced radiation contribution from the decontaminated street. Substituting into Equation (109)

$$D'_2 = I_q \Delta t + \frac{I_p + I'_p}{2}\, \Delta t \tag{110}$$

The second term to the right of the equal sign is the linear estimate of d'_2, using the same assumption required in writing Equation (106). Forming a ratio of Equation (110) to Equation (108),

$$RN_2 = \frac{I_q \Delta t + d'_2}{29\, I_o \Delta t} \tag{111}$$

Returning to Reference 2, the ratio of $I_q/28.9\, I_o$ is defined as the contribution factor C_q for the area surrounding the street. Similarly, the ratio of $I_p/29\, I_o$ equals the contribution factor C_p for the street. Inserting these equalities into Equation (111)

$$RN_2 = C_q + C_p \left(\frac{d'_2}{I_p \Delta t} \right) \tag{112}$$

But, as noted earlier, the product of $I_p \Delta t$ is merely the potential dose d_2, and Equation (112) becomes

$$RN_2 = C_q + C_p \left(\frac{d'_2}{d_2} \right) \tag{113}$$

Thus, after the contribution factors C_p and C_q are obtained, the ratio of d'_2/d_2 from an isolated test case can be used to estimate RN_2 for the case of extensive contamination.

The Analytical Case

Equation (112) will be used together with the results of Table 3 to demonstrate the validity of the technique and assumptions used to calculate values for RN_2. Continuing with the target analysis considerations of Reference 2, the dose ratio may be expressed as follows

$$d'_2/d_2 = \frac{d'_{lin.} + d'_{new}}{d_2} \tag{114}$$

$d'_{lin.}$ is the portion of crew dose due to an assumed linear decrease in the exposure rate I_p, and

d'_{new} is the portion of crew dose due to the new source intensity created by deposits of fallout material collected during decontamination operations.

The prime mark is retained to indicate that an action has been performed to cause a change in the unaltered (potential) dose d_2. From the same reasoning used to formulate Equations (106) and (109)

$$d'_{lin.} = \left(\frac{I_d + I'_d}{2}\right) \Delta t \tag{115}$$

where I_d* is the contribution from the contaminated street to the firehosing crew standing approximately 25 feet from the end of the street prior to decontamination. I'_d is the reduced intensity after decontamination and is equal to the product of I_d and the firehosing effectiveness, F, expressed as the residual fraction of contamination originally present. As in the development of Equation (113), the ratio of $I_d/29\ I_o$ equals the contribution

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* Note that $I_d \neq I_p$ since the latter is referred to the center of the street, not near its end.

factor C_d. Substituting this information into Equation (115)

$$d'_{lin.} = C_d(29\ I_o)\ \frac{\Delta t}{2}\ (1 + F) \qquad (116)$$

where F is the fraction of I_o remaining after decontamination.

That portion of the crew dose attributed to a newly created thin source is given by Reference 2 as

$$d'_{new} = \frac{(1-F)WL}{2\delta^2}\ I_o\ \Delta t \qquad (117)$$

where W and L represent the width and length of the contaminated surface (street), and δ is the average distance between the crew and the new source deposit.

Remembering that $d_2 = I_p \Delta t$ and that $I_p = 29\ I_o\ C_p$, Equations (116) and (117) may be combined to form a new expression for Equation (114) which becomes

$$d'_2/d_2 = \frac{C_d(1 + F)}{2\ C_p} + \frac{(1 - F)WL}{2\ C_p(29\ \delta^2)} \qquad (118)$$

The solution to this equation depends largely upon the geometry of the contaminated street and its surroundings. Using the test surface, environmental conditions (physical and radiological), and firehosing performance characteristics used previously in organizing Table 3, the following inputs to Equation (118) were derived:

1. Street surface area, WL: 8960 ft^2 (32 × 280 ft)
2. Street contribution factors as referenced to--
   - the center of the street, $C_p = 0.482$
   - 25 ft from end of street, $C_d = 0.039$
3. Distance between crew and new source, $\delta = 40$ ft.

The values for C_p and C_d were calculated from the appropriate methods and equations described in Reference 2. The average magnitude of δ was determined from photographs of actual firehosing tests showing the spacing between the nozzleman's position and the point where the spent runoff water redeposited the fallout simulant. Removal effectiveness*, F, varied for each test run according to changes in surface condition (as well as in decontamination rate and effort). This variation is shown in column (1) of Table 4 which gives the solution to the short form for Equation (118). This is

$$d_2'/d_2 = A(1 + F) + B(1 - F) \qquad (119)$$

where $$A = \frac{C_d}{2C_p} = \frac{0.039}{2(0.482)} = 0.0406$$

and $$B = \frac{WL}{2C_p(29\delta^2)} = \frac{8950}{58(0.482)40^2} = 0.201$$

Table 4 presents the results in column (4), while the experimentally derived dose ratios from Table 3 are repeated in column (5) for ready comparison. These entries were then used to solve Equation (113) for the analytically and experimentally derived RN_2 values shown in columns (6) and (7), respectively. Because this hypothetical situation assumes uniform contamination beyond the test street over an extensive plane area, and because no target shielding by structures is involved, the value of C_q in Equation (113) will be equal to $1 - C_p$. This is due to the fact that, by definition, the sum of the contribution factors referenced to a common location (in this case, the center of the street) must equal the target attenuation factor at that same location. That is, $C_p + C_q = \bar{A} = 1$, and, since $C_p = 0.482$, $C_q = 0.518$.

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* The residual fraction, F, is measured experimentally from the ratio of I_p'/I_p. This will equal I_d'/I_d for the isolated case only.

Table 4

ANALYTICALLY DERIVED DOSE RATIOS FOR CREWS FIREHOSING STREETS

Decon Crews	Surface Texture	Mass Loading (g/ft^2)	Residual Fraction F (1)	$A(1+\bar{F})$ ($A = 0.0406$) (2)	$B(1-F)$ ($B = 0.201$) (3)	d_2'/d_2 Analytical, Eq. 118 (4)	d_2'/d_2 Experimental, Table 3 (5)	RN_2 Analytical, Eq. 113 (6)	RN_2 Experimental, Eq. 113 (7)
				Particle Size Range 88-177µ					
South	Rough	25.0	0.084	0.045	0.183	0.228	0.22	0.628	0.62
North	Smooth	25.0	0.031	0.042	0.193	0.235	0.24	0.631	0.63
South	Rough	92.4	0.070	0.043	0.186	0.229*	0.27	0.628	0.65
North	Smooth	92.4	0.011	0.041	0.198	0.239*	0.22	0.633	0.62
				Particle Size Range 300-600µ					
South	Rough	4.43	0.054	0.043	0.189	0.232	0.21	0.630	0.62
North	Smooth	4.43	0.036	0.042	0.193	0.235	0.24	0.631	0.63
South	Rough	24.2	0.023	0.042	0.195	0.237	0.24	0.632	0.63
North	Smooth	24.2	0.025	0.042	0.195	0.237	0.29	0.632	0.66
					Averages	0.234	0.24	0.631	0.63

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* When adjusted for secondary source effects, the dose ratios become 0.277 and 0.230 and RN_2's become 0.651 and 0.628 for south and north crews respectively.

Analytical versus Experimental

Comparison of the entries in columns (4) and (5) of Table 4 indicates that the agreement between analytically calculated and experimentally derived dose ratios is excellent. On the average the calculated values are within 2.5% of the experimental values. For all practical purposes, the calculated and experimental values of RN_2 are, on the average, essentially the same see columns (6) and (7) . From this agreement it can be concluded that, for firehosing at least, the analytical approach to estimating RN_2 values is quite reliable. Furthermore, it is valid to assume a linear decrease in the radiation contribution from the surface being decontaminated.

The importance of the new source effects should be emphasized here. Had this contribution been ignored in the foregoing example, the estimate of dose ratios would have been a factor of 5 too small, and the resultant RN_2 values would have been 15% too small. This error is a direct function of the size (and shape) of the area being decontaminated. It should also be pointed out that the influence of the removal effectiveness, F, upon the dose ratio, and hence upon RN_2, is not significant in the example for values of $F < 0.1$.

A Further Refinement

Both Tables 3 and 4 indicate that each of the four tests reported was performed with two crews, one on the south and one on the north side of the street. Because they progressed along a common front with a distance of 15 to 20 ft separating them, it would be expected that the doses, dose ratios and RN_2 values for each team would be essentially the same for a given test run. The calculated dose ratios from column (4) of Table 4 support this reasoning, but the experimental dose ratios from column (5) do so in only two out of the four tests. One of these nonconforming tests, the one with the heaviest mass loading (92.4 g/ft^2), can be readily explained. However, the disparity between experimental dose ratios of the last test (24.2 g/ft^2 mass loading) in Table 4 cannot be resolved. There is no apparent reason why the dose ratios in this test should have varied any more than did the dose ratios shown for the first test in Table 4, a test conducted at the same nominal mass loading (25 g/ft^2). The difference in particle size range for these two tests is certainly not a factor. For want of any concrete evidence, and in view of the especially close agreement between the calculated dose ratios for the two crews, one is forced to suspect the reliability of the larger experimental dose ratio (0.29) for the north crew in the nonconforming test run.

The difference between the south and north experimental dose ratios for the 92.4 g/ft^2 test (Table 4) was probably due to a change in the decontamination procedure. Because of the heavy mass loading and the accelerated buildup of material in front of the fire stream, it was not possible to push all the fallout simulant from one end of the test street to the other--a total distance of 280 ft. Therefore, the crews were instructed to form a windrow of fallout material midway through the test, skip over it, and start anew on the remaining half of the street. In so doing, it was necessary to leave this deposit along the south curb to avoid a driveway directly opposite to the north. As a result, the south crew (which spent more time in the proximity of the deposit) received more dose than the north team.

A detailed calculation was made using further refinements to the foregoing equations to account for the effects of this secondary new source deposit. The results of this investigation showed that the larger experimental dose ratio shown for the south crew could be duplicated analytically to within 2-1/2% (see footnote to Table 4). The improvement in the dose ratio for the north team was not great (4%), but it was in the right direction. Also, in the latter case, the error was not as great prior to application of the more sophisticated technique.

If the anomaly mentioned earlier (for the 24.2 g/ft^2 test) can be largely discounted, the above results demonstrate the additional capability of the analytical methods for obtaining RN_2 values. Not only are these target analysis techniques reliable, but they appear highly sensitive to complex variations and can be used to evaluate the variations.

RN_2 Values For Serially Scheduled Decontamination Operations

The foregoing treatment established the validity of the methods and equations developed to date for estimating RN_2 values. It is the purpose of this section (and the one that follows) to formulate expressions that will account for the side effects of prior or simultaneous recovery operations occurring in areas alongside the one to which a desired RN_2 is referred. Consider the case of a serially scheduled recovery operation, where each component of a built-up complex is decontaminated in turn according to some predetermined priority listing. Assume that one or more components have been decontaminated. What, then, is the effect of this prior action upon the RN_2 for crews engaged in the current decontamination of a given surface?

Basic Expressions for Initial Decontamination

Before this question can be answered, it is necessary to review some of the previous target analysis work[2] and list the equations that are basic to the problem. For the case when recovery operations have not yet been initiated, the intensity to the crews just before the initial decontamination of a given surface k is given as

$$I_b = 29\ I_o \sum_{i=1}^{q} A_i^s\ C_i \qquad (120)$$

and

$$I_b = 29\ I_o \left[A_k^s\ C_k + \sum_{i=1}^{q} A_i^s\ C_i \right] \qquad (121)$$

where I_o is the unit source strength in r/hr

A_i^s is the equipment attenuation factor with respect to radiation sources on any contributing surface

C_i is the contribution factor for the i^{th} surface*

A_k^s is the equipment attenuation factor with respect to radiation contributions from the cleaned surface k

C_k is the contribution factor for k

q equals the total number of contributing surfaces

After surface k has been decontaminated (by a single pass operation), the exposure rate to the crews is

$$I_a = 29\ I_o\ F_k A_k^s C_k + 29\ I_o \sum_{i=1}^{q-1} A_i^s C_i + I_N \qquad (122)$$

where F_k is the decontamination effectiveness expressed as the fraction of I_o remaining after the first pass and I_N is the intensity attributed to any newly created source. Because the new source effects are best handled separately, the I_N term is temporarily dropped from Equation (122). Rearranging Equation (121) and substituting into Equation (122) without I_N, the exposure rate after decontamination becomes

$$I_a = I_b - 29\ I_o\ (1 - F_k) A_k^s C_k \qquad (123)$$

where the collection of terms in the right hand member following the minus sign represents that fraction of the original radiation contribution from surface k removed by decontamination.

For the assumed linear decrease from I_b to I_a, the dose to the decontamination crew is given by Equation (109). Substituting Equation (120) for I_b

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* According to Equation (85), $C_i = I_i/29\ I_o$ where the i subscript refers to any surface.

and Equation (123) for I_a, Equation (109) may be rewritten

$$D = 29\ I_o \left[\sum_{i=1}^{q} A_i^s\ C_i - \frac{(1-F_k)\ A_k^s C_k}{2} \right] \Delta t \qquad (124)$$

Dividing through by 29 I_o Δt--which, from Equation (108), equals potential dose D_2--an expression for the decontamination crew residual number is obtained:

$$RN_2 = \sum_{i=1}^{q} A_i^s\ C_i - \frac{(1-F_k) A_k^s C_k}{2} \qquad (125)$$

This equation is identical to that given in Reference 2 and is applicable to the operational situation where there are no effects due to any prior decontamination effort.

Effect of Prior Decontamination

Now, suppose that one of the contributing surfaces g had been previously decontaminated to an effectiveness F_g. Then the exposure rate to the crew at the start of the current decontamination of surface k will be equal to the sum of three separate contributions as follows:

$$I_b = 29\ I_o\ A_k\ C_k + 29\ I_o\ F_g\ A_g\ C_g + 29\ I_o \sum_{i=1}^{q-2} A_i^s\ C_i \qquad (126)$$

where the 1st term represents the surface to be currently decontaminated, the 2nd term represents the surface previously decontaminated, and the 3rd term represents the sum of the surfaces remaining to be decontaminated.

The exposure rate after decontamination may still be given by Equation (123), if I_b is understood to be as given by Equation (126). Before making the necessary substitution for I_b and I_a into the dose equation, it is advisable to rewrite Equation (126) as the difference between the total contribution and that removed by prior decontamination. Thus

$$I_b = 29\, I_o \left[\sum_{i=1}^{q} A_i^s\, C_i - (1-F_g)\, A_g^s\, C_g\right] \tag{127}$$

Substituting Equations (123) and (127) into Equation (109) results in

$$D_2' = 29\, I_o \left[\sum_{i=1}^{q} A_i^s\, C_i - (1-F_g)\, A_g^s\, C_g\right] \Delta t$$

$$-29\, I_o\, \frac{(1-F_k)\, A_k^s\, C_k}{2}\, \Delta t \tag{128}$$

Again dividing through by 29 I_o Δt, the residual number becomes

$$RN_2 = \sum_{i=1}^{q} A_i^s\, C_i - (1-F_g)\, A_g^s\, C_g - \frac{(1-F_k)\, A_k^s\, C_k}{2} \tag{129}$$

By repeating the above procedure, equations can be derived for both dose and residual number that include the effects of prior decontamination on several surfaces. These more general expressions are:

$$D_2' = 29\, I_o \left[\sum_{i=1}^{q} A_i^s\, C_i \quad \sum_{i=1}^{\ell-1} (1-F_i)\, A_i^s\, C_i\right] \Delta t$$

$$-29\, I_o\, \frac{(1-F_k)\, A_k^s\, C_k}{2}\, \Delta t \tag{130}$$

and

$$RN_2 = \sum_{i=1}^{q} A_i^s\, C_i - \sum_{i=1}^{\ell-1} (1-F_i)\, A_i^s\, C_i - \frac{(1-F_k)\, A_k^s\, C_k}{2} \tag{131}$$

where ℓ equals the number of surfaces cleaned by all decontamination efforts (prior plus current). The ℓ-1 term refers to the total number of surfaces cleaned by prior decontamination. As the recovery operation progresses, ℓ approaches q, and when all surfaces but one have been decontaminated, ℓ equals q.

Comparing Equations (125) and (131) reveals that the general expression for RN_2 differs only in the addition of a term (the second one to the right of the equal sign) which corresponds to the radiation contribution removed by all prior decontamination. Obviously, prior decontamination tends to reduce the RN_2 factor identified with a given surface and decontamination method. As more and more of the contributing surfaces in a target complex become decontaminated, RN_2 will continue to grow smaller. The rate of decline will depend upon the scheduling sequence, the decontamination effectiveness, the relative size and orientation of surfaces, the structural and equipment shielding factors, and the new source contributions. By careful planning and scheduling, the decrease in RN_2 can be controlled so that minimum values will be in effect at the opportune time. This would be desirable when the recovery operation is confronted by stubborn surfaces requiring more than the normal share of the decontamination effort and available dose. Equation (131) may be further generalized to take into account two additional factors affecting RN_2, namely, the effect of multiple decontamination passes and the effect of the new source contribution I_N. Appropriate equations have already been worked out in Reference 2. Incorporation of these expressions with Equation (131) provides RN_2 factors for three situations defined by the magnitude of the new source intensity (as created by the decontamination process).

<u>Case 1.</u> No significant new source

$$RN_2\ (p) = \sum_{i=1}^{q} A_i^s\ C_i - \sum_{i=1}^{\ell-1} (1-F_i)\ A_i^s\ C_i - \frac{(2-F_{p-1} - F_p)_k\ A_k^s\ C_k}{2} \qquad (132)$$

where p refers to the pass number on surface k, and a subscript p-1 equal to zero (p=1) makes the particular effectiveness value become unity (F_o=1.0).

<u>Case 2.</u> A thin new source (no self-shielding)

$$RN_2\ (p) = \text{Eq.}(132) + \frac{(F_{p-1} - F_p)}{29\delta^2}\ \frac{(WL)}{2}\ A_N^s \qquad (133)$$

where A_N^s is the equipment attenuation factor with respect to the new source contribution. The remaining symbols are as indicated for Equations (120) and (121).

Case 3. A thick new source (significant self-shielding)

$$RN_2\ (p) = \text{Eq.}(132) + \frac{(F_{p-1} - F_p)\ WL\ A_N^s}{29\ \delta^2\ x^2}$$

$$\cdot \left[\frac{3}{\mu^2}\ (1 - e^{-\mu x}) - e^{-\mu x}\ (x^2 + \frac{3x}{\mu})\right] \qquad (134)$$

where x is the source thickness in cm, and μ is the linear adsorption coefficient normally given in the units of cm^{-1}. The thickness x can be estimated from the following formula

$$x = 30.5\ (F_{p-1} - F_p)\ \frac{WL\ M_o}{wc\rho} \qquad (135)^*$$

where wc is the area dimension of the new source in ft^2

M_o is the original mass concentration of fallout in g/ft^2

ρ is the bulk density of the fallout particles in g/ft^3

30.5 is the conversion factor from ft to cm

Corresponding estimates of $D_2'(p)$ may be obtained by multiplying Equations (132) (133) and (134) through by 28.9 $I_o\ \Delta t$.

It will be noted that the bracketed term in Equation (134) is somewhat different from the one given in Reference 2 for Case 3. Since the publication of that report, an improved method for deriving mathematical expressions of the crew dose and RN_2 resulting from a thick new-source contribution has been developed. This derivation is given in Appendix C. Comparisons between methods show that the former one overestimated the new-source dose

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* If $x < 1.0$ cm, use Equation (133). See Appendix B for explanation.

contribution at a constant value of 20% for a source deposit thickness of $1 < x < 20$ cm. The later method also demonstrates that, when x reaches a depth of 100 cm, the new-source contribution becomes constant. For instance, using an adsorption coefficient of $\mu = 0.10 \text{ cm}^{-1}$, the bracketed term attains a maximum value of 300 for $x \geq 100$ cm.

When dealing with multiple pass situations, the third term in Equation (132) takes into account all effects due to previous passes 1 through p-1 on surface k. Care must be exercised so as not to confuse these effects with those of prior decontamination on adjacent surfaces, and not to make an unnecessary separate adjustment to the second term of Equation (132). A superfluous correction of this kind will result in abnormally small RN_2 factors. This does not rule out the possibility of multiple pass operations during prior decontamination. The second term of Equation (132) must be expanded so that the effects of extra passes may be applied to each surface before obtaining the summation represented.

Results of Sample Calculations

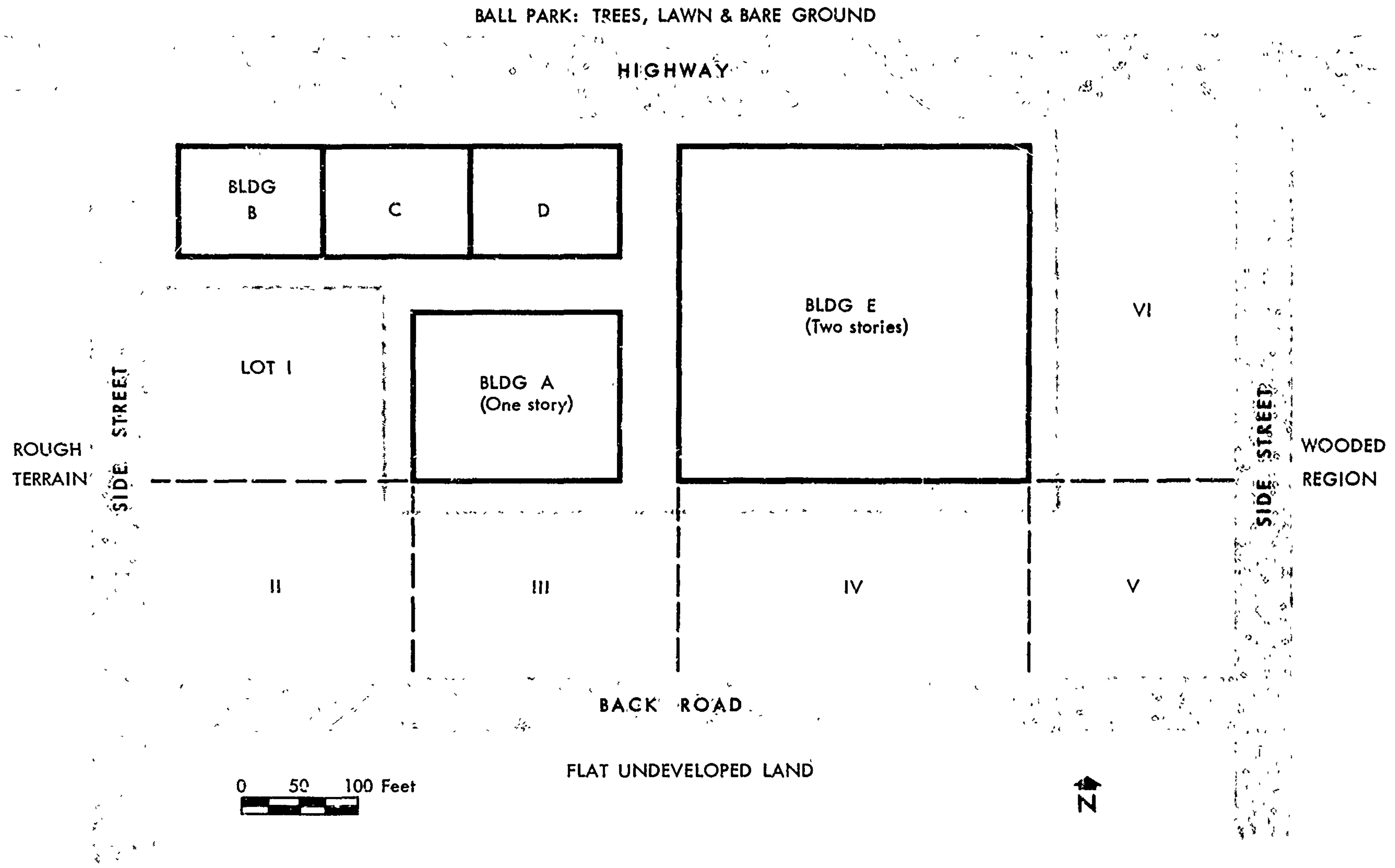
A series of sample calculations were made to test the application of the foregoing equations and to observe the effects of prior decontamination upon crew residual numbers for a serially scheduled recovery operation. For this trial example, a hypothetical shopping center was selected as shown in Figure 5. The conditions and assumptions for the radiological recovery of this particular target complex are listed below.

Problem: Plan the decontamination of the entire block of five buildings and the adjoining six parking lots so that it can be used as a staging area for the nearby community.

Assumptions:

1. Target area has been uniformly contaminated with a fallout concentration of 50 g/ft^2. Fallout particle size range is

Figure 5
SMALL SHOPPING CENTER



88-177μ.[*]

2. Ample manpower, skills, equipment, and supplies (including water) are available.
3. Recovery crews have been adequately sheltered and are starting the operation at a time compatible with their available dose.
4. The highway and the adjacent sidewalk have been previously decontaminated by street sweepers to an effectiveness of $F_i = 0.10$.

Plan of Attack: Recovery routine is to be conducted in two phases. Clean eastern half of block first to gain early use of building E. Then clean western half. The operational sequence for the first phase is listed in Table 5, together with estimates of expected decontamination effectiveness. Firehosing is to be used throughout as as the primary decontamination method.

From the above conditions, Equation (133) may be written in a slightly simplified form suitable for this example.

$$RN_2 = \sum_{i=1}^{q} C_i - \sum_{i=1}^{\ell-1} (1-F_i) C_i - \frac{1-F_k}{2} C_k + \frac{1-F_k}{29\delta^2} \frac{(WL)}{2} \qquad (136)$$

The major task in solving Equation (136) consists in computing the values of the contribution factors C_i and C_k. These values change for each step of the decontamination sequence and must be recomputed each time. The computational procedure used for the shopping center has followed that outlined for target analysis in Reference 2. The arithmetic detail was reduced by keeping each surface considered for current decontamination rather large. That is, except for the roof of building E, the operational sequence of

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[*] These conditions would occur 90 miles downwind from a 25 MT surface burst. At 50% fission, the standard intensity is about 6,000 r/hr.

Table 5

OPERATIONAL SEQUENCE AND EXPECTED EFFECTIVENESS FOR FIRST PHASE DECONTAMINATION EFFORT

	Target Surface	Decontamination Procedure	F
1.	Lot VI and east sidewalk	Hose from north to south. Start at east edge, finish at west edge.	0.12
2.	Lot V	Same as above.	0.12
3.	East side street	Hose north to south.	0.25
4.	Roof of Bldg. E	Hose by quadrants. Start in N.E. quadrant and work clockwise.	0.05
5.	Lot IV and south sidewalk	Hose east to west. Start at north edge, finish at south edge.	0.12
6.	Back road, eastern half only	Hose east to west. Repeat on second pass.	0.25 0.05

Simplifications:

1. Although a support effort in a real situation would be required to remove the fallout collections formed during firehosing, the effects of this activity are not included in the example.

2. New source accumulations are presumed to be less than 1.0 cm. in depth, therefore, Equation (133) for the thin new-source case will be employed.

3. The mass thickness of all building elements is assumed to have a constant value of 25 psf.

4. Since equipment shielding is negligible, $A_j^s = A_N^s = 1$.

5. Recovery of the western half of the shopping center is not included in the example.

Table 5 was not broken down to the degree that would actually be required to implement the recovery of the shopping center. For the purposes of this example, however, the gross approach was found to be satisfactory, and the two-fold or threefold increase in computational effort needed for more detailed consideration is not justified.

The results of these computations and their proper substitution into Equation (136), together with the other inputs, are shown in Table 6. Equation (136) is written across the top of the table, so that each term constitutes a column heading. The target surfaces are listed down the left hand side of the table in the order that they were decontaminated. Opposite each surface is entered the contribution corresponding to that portion of Equation (136) appearing in the column heading above it. In this way, Table 6 provides a complete picture of what happened to RN_2 during serially scheduled decontamination operations. In addition, the relative effects of prior decontamination, current decontamination, and new source contributions are clearly displayed.

It is apparent from the tabulated entries that the proximity of a building influences the magnitude of the resultant RN_2 factors achieved at ground level. For instance, the RN_2 shown for lot V is 7% less than that given for lot IV, even though the latter is decontaminated after lot V. Further away from the building, however, both the side street and the back road exhibit marked benefits from prior decontamination. The RN_2 values for these surfaces are essentially the same and are 7% to 8% less than the RN_2 shown for lot V.

For a structure as large as building E, the radiation contributions (skyshine included) from roof to ground (and vice versa) are negligible. Consequently, the effects of prior decontamination at one level are undetectable at the other. In the case of building A, which is only half as tall as building E and has less than one-third the roof area, the

Table 6

EFFECTS OF SERIALLY SCHEDULED DECONTAMINATION ON RN_2

		Contributions								
		Original		Prior Decon.		Current Decon.		New Source		Σ	Without Prior Decon. Effects
	Surface S_k	$\sum_{i=1}^{q} C_j$	$-$	$\sum_{i=1}^{\ell-1} (1-F_i) C_i$	$-$	$\frac{1-F_k}{2} C_k$	$+$	$\frac{1-F_k}{29\delta^2} - \frac{WL}{2}$	$=$	RN_2	
1.	Lot VI	0.838		0.0		-0.356		+0.5		0.98	0.98
2.	Lot V	0.980		-0.038		-0.334		+0.29		0.90	0.94
3.	East Side St.	0.984		-0.15		-0.225		+0.21		0.82	0.97
4.	Roof Bldg. E										
	N.E. Quad.	0.854		-0.001		-0.344		+0.12		0.63	0.63
	S.E. Quad.	0.854		-0.039		-0.344		+0.12		0.59	0.63
	S.W. Quad.	0.854		-0.055		-0.344		+0.12		0.58	0.63
	N.W. Quad.	0.854		-0.093		-0.344		+0.12		0.54	0.63
5.	Lot IV	0.86		-0.030		-0.356		+0.5		0.97	1.00
6.	Back Road	0.99		-0.15		-0.225		+0.21		0.83	0.98
	2nd Pass	0.99		-0.15		-0.511		+0.056		0.40	0.55

additional prior decontamination of lots I, II, and III causes a reduction of about 8% in the RN_2 for the roof decontamination crew. The decrease in RN_2 values from decontamination of the roof of building E reaches a maximum of 14% in the last (N.W.) quadrant.

A general column by column comparison of the tabulated entries indicates that the contributions of current decontamination and the newly created source have the greatest effect on the RN_2 value. The effect of prior decontamination is least, except in the case of a second or third pass when the new source contribution becomes extremely small. On the last line in Table 6, it is seen that for the second firehosing pass on the back road, the negative contribution of the current decontamination more than doubled. This occurred because the effects of the previous pass are preserved in the third term of the equation for residual number, which in this case was $\frac{2-F_1 - F_2 C_k}{2}$ (where the subscripts refer to the pass made).

A short calculation was made to determine under what circumstances, if any, the effect of prior decontamination might equal (or exceed) that of current decontamination. It was found that this could occur only for a special and operationally improbable combination of conditions, namely:

1. Surface k is the last one scheduled for decontamination
2. It is surrounded by the previously cleaned area
3. The area of surface k is of the order of 10^4 ft^2 or less
4. There is no significant target shielding from buildings or other structures
5. Effectiveness F_k is no worse than the average value achieved by prior decontamination

The last column of Table 6 was included to demonstrate what the RN_2 factors would have been if the effects of prior decontamination had been ignored. Comparing these entries with those in the column alongside shows that prior decontamination can cause decreases in RN_2 estimates as large as 15% for single pass operations and 27% for a two pass operation. Thus, for serially scheduled recovery routines, the reduction in RN_2 factors due to prior decontamination may be significant and should be taken into account. Ignoring these reductions will cause overestimations of crew dose, thereby delaying decontamination start times and/or increasing manpower requirements.

RN_2 Values for Simultaneously Scheduled Decontamination Operations

A special case of simultaneous decontamination was treated earlier in the first major section of this chapter. The situation involved the decontamination of a city street by two firehosing crews working within 15 or 20 feet of each other. The first and third tests shown in Table 4 indicated that because each crew operated in essentially the same radiation field, the exposure doses and RN_2s of each crew were practically the same for a given test run. Thus, no special equations were required to analyze this particular situation. However, differences in RN_2 factors are anticipated when decontamination crews are separated to the extent that the radiation intensities within which they are working are different. This section will treat two possibilities for operationally achieving such a condition.

Effects of Simultaneous Decontamination

Consider the situation where two crews are scheduled to simultaneously clean two adjoining surfaces, X and Y. Each surface is so wide that the teams are never closer to each other than 50 to 75 feet. To ensure that the crews are working in different radiation fields, it is assumed that the surface bordering X and opposite from Y has been previously decontaminated to an effectiveness F_g. The surface bordering Y and opposite from X has not been decontaminated. With appropriate adjustments of the subscripts, Equation (127) may be used to express the starting intensity to crew X just prior to decontamination of surfaces X and Y

$$I_b(X) = 28.9\ I_o \left[\sum_{i=1}^{q} A^s_{i,X}\ C_{i,X} - \left(1-F_g\right) A^s_{g,X}\ C_{g,X} \right] \tag{137}$$

where the double subscripts identify first the contributing surface and second the receiver or reference location.

Since it is safe to assume that the individual exposure rate to crews X and Y contributed by surfaces X and Y, respectively, will decrease linearly during a constantly progressing decontamination effort, the combined exposure rate to crew X contributed by both surfaces X and Y will also decrease linearly. Therefore, the exposure rate to crew X after decontamination is, according to Equation (123)

$$I_a(X) = I_b(X) - 28.9\ I_o \left[(1-F_X)\ A^s_X\ C_X + (1-F_Y)\ A^s_{Y,X}\ C_{Y,X} \right] \tag{138}$$

where the collection of terms to the right of the minus sign represents the reduction of the initial contribution from surfaces X and Y by the simultaneous decontamination effort.

At this point, it is necessary to establish a convenient means of differentiating between the two separate actions comprising simultaneous decontamination without always having to identify the surfaces. The action occurring on the surface of reference will be considered the <u>current</u> decontamination. In Equation (138), this happened on surface X. The action occurring on the remaining surface will be called the <u>concurrent</u> decontamination. In Equation (138), this involved surface Y. These designations will simplify and clarify the material that is to follow.

Substituting the above expressions for $I_b(X)$ and $I_a(X)$ into Equation (109) and dividing the result by potential dose, $28.9\ I_o\ \Delta t$, the residual number for crew X becomes

$$RN_2\ (X) = \sum_{i=1}^{q} A^s_{i,X}\ C_{i,X} - (1-F_g)\ A^s_{g,X}\ C_{g,X} - \frac{(1-F_X)\ A^s_X\ C_X + (1-F_Y)\ A^s_{Y,X}\ C_{Y,X}}{2} \tag{139}$$

In the same way, the residual number for crew Y

$$RN_2\ (Y) = \sum_{i=1}^{q} A^s_{i,Y}\ C_{i,Y} - (1-F_g)\ A^s_{g,Y}\ C_{g,Y} - \frac{(1-F_Y)\ A^s_Y\ C_Y + (1-F_X)\ A^s_{X,Y}\ C_{X,Y}}{2} \qquad (140)$$

And more generally, when prior decontamination consists of several methods and surfaces,

$$RN_2\ (X) = \sum_{i=1}^{q} A^s_{i,X}\ C_{i,X} - \sum_{i=1}^{\ell-2} (1-F_i)\ A^s_{i,X}\ C_{j,X} - \frac{(1-F_X)\ A^s_X\ C_X - (1-F_Y)\ A^s_{Y,X}\ C_{Y,X}}{2} \qquad (141)$$

where, as before, ℓ equals the number of surfaces cleaned by all decontamination efforts (prior, current, and concurrent) and ℓ-2 refers to the total number of surfaces cleaned by prior decontamination.

When Equation (141) is compared with Equation (131), it is evident that RN_2 factors for simultaneous operations differ from RN_2 factors for serial operations by a single term,

$$- \frac{(1-F_Y)\ A^s_{Y,X}\ C_{Y,X}}{2}$$

This term represents the reduction by concurrent decontamination in the radiation contribution of surface Y to crew X. Thus, prior, current, and concurrent decontamination efforts combine to decrease RN_2 and hence, the dose to decontamination crews. The magnitude of this decrease due to simultaneous operations will be treated later in this chapter. But first it is necessary to consider the effects of extra passes and newly created sources. From Equations (132), (133) and (134), general expressions for the three basic new-source conditions may be written for simultaneous decontamination operations as follows.

Case 1. No significant new source

$$RN_2\,(X)_p = \sum_{i=1}^{q} A^s_{i,X}\, C_{i,X} - \sum_{i=1}^{\ell-2} (1-F_i)\, A^s_{i,X}\, C_{i,X}$$

$$- \; 1/2\,(2-F_{p-1} - F_p)_X\, A^s_X\, C_X$$

$$- \; 1/2\,(2-F_{p-1} - F_p)_Y\, A^s_Y\, C_{Y,X} \qquad (142)$$

where p equals the number of passes on surfaces X and Y, and p-1 equals zero (p=1) makes the particular effectiveness value equal to unity ($F_o = 1.0$).

Case 2. A thin new source (no self shielding)

$$RN_2\,(X)_p = \text{Eq.}(142) + \left[\frac{(F_{p-1} - F_p)}{29\,\delta^2}\;\frac{WL}{2}\;(A^s_N)\right]_X$$

$$+ \left[\frac{(F_{p-1} - F_p)}{29\,\delta^2}\;\left(\frac{WL}{2}\right)\;(A^s_N)\right]_{Y,X} \qquad (143)$$

where A^s_N is the equipment attenuation factor for new source contributions from the respective surfaces being decontaminated.

Case 3. A thick new source (significant self shielding)

$$RN_2\,(X) = \text{Eq.}(142) + \left[\frac{(F_{p-1} - F_p)}{29\,\delta^2\,x^2}\;(WLA^s_N)\right]_X$$

$$\cdot\left[\frac{3}{\mu^2}\,(1 - e^{-\mu x}) - e^{-\mu x}(x^2 + \frac{3x}{\mu})\right]_X +$$

$$\left[\frac{(F_{p-1} - F_p)}{29\,\delta^2 x^2}\;(WLA^s_N)\right]_{Y,X}$$

$$\cdot\left[\frac{3}{\mu^2}(1 - e^{-\mu x}) - e^{-\mu x}(x^2 + \frac{3x}{\mu})\right]_{Y,X} \qquad (144)$$

where the linear adsorption coefficient and the new-source deposit thickness x are as described for Equations (134) and (135).

Residual numbers for crew Y may be found from Equations (142), (143) and (144) by interchanging subscripts X and Y. Also, estimates of dose $D_2'(X)_p$ may be obtained by multiplying these same equations by 28.9 I_o Δt.

Results of Sample Calculations

Two trial examples employing the foregoing development were investigated to observe the effects of simultaneous decontamination on two adjoining surfaces. Figure 6 displays the two situations under consideration and indicates the size, shape, and orientation of the surfaces. For either situation, the following conditions and assumptions hold:

1. Surfaces X and Y have been contaminated to the same degree and are to be decontaminated by an equivalent firehosing effort to an effectiveness F = 0.10.
2. The two simultaneous operations are to start at the locations and progress in the directions shown by the arrows in Figure 12.
3. Because the areas of surfaces X and Y are equal, the separate decontamination efforts will start and finish together.
4. New source accumulations are assumed to be less than 1.0 cm. thick; hence, Equation (143) for the thin new-source case will be used.
5. The equipment attenuation factor has been set equal to 1.0, thereby allowing a nonsignificant but convenient simplification of Equation (143).
6. The support effort needed to remove new source collections and the effects of this effort are not considered in the examples.

By use of target analysis techniques in conjunction with the above conditioned inputs, Equation (143) was solved for sample situations I and II and the results entered in Table 7. The simplified version of Equation (143), as it

Figure 6

TWO SITUATIONS FOR SIMULTANEOUS DECONTAMINATION

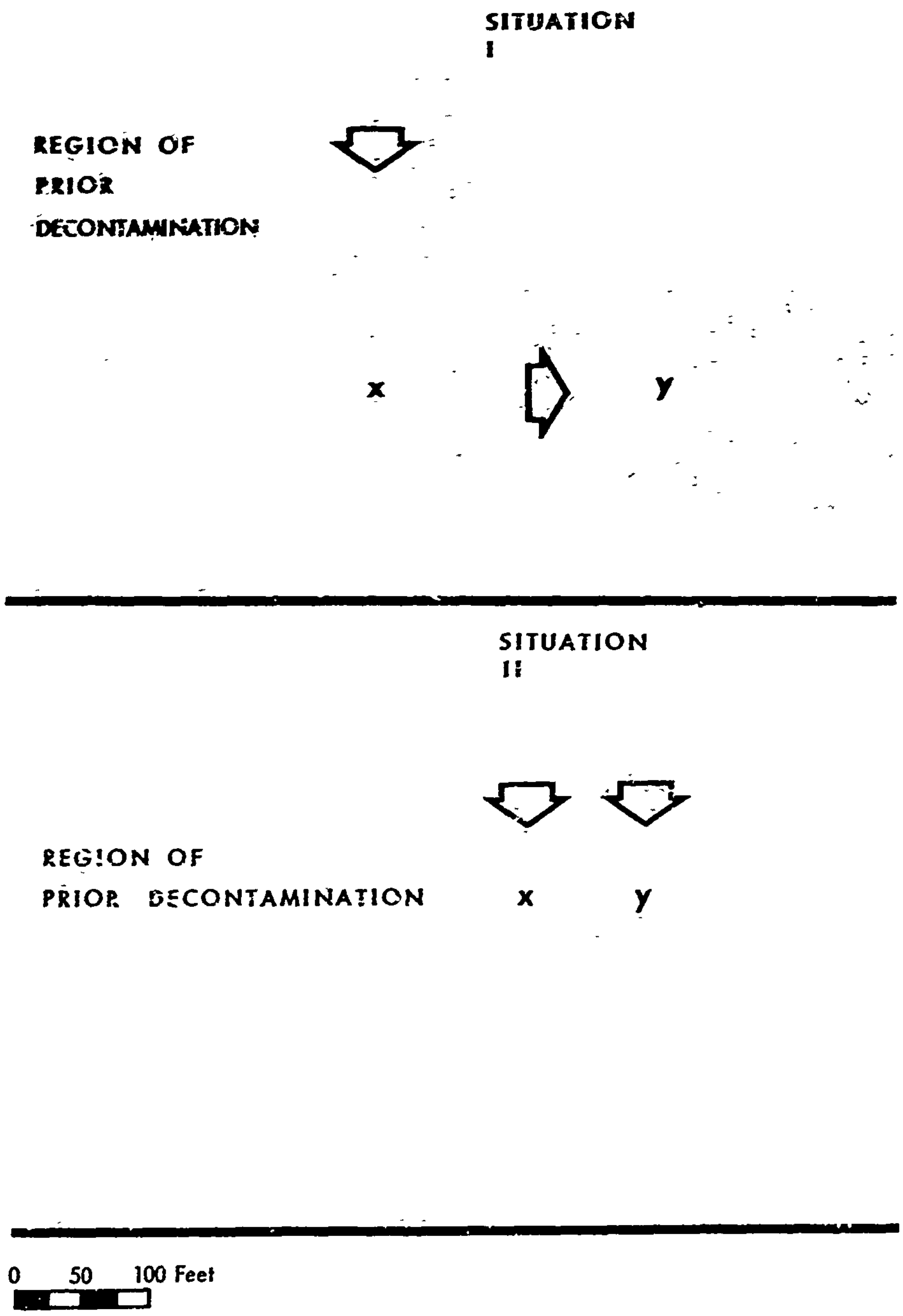

Table 7

EFFECTS OF SIMULTANEOUSLY SCHEDULED DECONTAMINATION ON RN_2

Contributions	Terms of Equation (143)	Situation I		Situation II	
		Crew X	Crew Y	Crew X	Crew Y
1. Predecontamination total	$\sum_{i=1}^{q} C_{i,X}$	1.0	1.0	1.0	1.0
2. Prior decontamination	$-\sum_{i=1}^{\ell-2} (1-F_i)C_{i,X}$	-0.098	0	-0.137	-0.121
3. Current decontamination	$-\frac{1}{2}(1-F_X)C_X$	-0.35	-0.35	-0.260	-0.260
4. Concurrent decontamination	$-\frac{1}{2}(1-F_X)C_{Y,X}$	-0.016	-0.011	-0.029	-0.029
5. Current new Source, X	$+\frac{1-F_X}{29\delta_X^2}\left(\frac{WL}{2}\right)_X$	0.485	0.485	0.218	0.218
6. Concurrent new Source, Y on X	$+\frac{1-F_Y}{29\delta_{Y,X}^2}\left(\frac{WL}{2}\right)_{Y,X}$	0.014	0.014	0.046	0.046
7. $\sum$ of terms	$= RN_2$	1.035	1.138	0.838	0.854
8. Concurrent decontamination effects ignored		1.051	1.149	0.868	0.883
9. Concurrent new source ignored		1.021	1.124	0.792	0.808
10. Combined effects ignored		1.036	1.135	0.827	0.837

applies to the examples, is displayed vertically in the left half of the table. Each of the six terms of the equation is identified (in the first column) with respect to the source of its contribution to the resultant RN_2. The calculated values of these separate contributions are given in the body of the table for each crew and situation. The summation of these values equals the RN_2 factors shown on line 7.

At the foot of Table 7 is a set of entries showing what the RN_2 values would have been if the effects of the concurrent decontamination effort had been ignored. Equation (143) indicates there are two such concurrent effects: the negative contribution of fallout removal (No. 4 in the table), and the positive contribution of the newly created source (No. 6 in the table). The special entries are estimates of these effects singly (lines 8 and 9) and in combination (line 10).

An examination of the various entries in Table 7 produces some interesting findings. Consider situation I first, where crews X and Y were seldom closer to each other than 200 ft. It is immediately apparent that the concurrent decontamination effort had little effect on the RN_2 values shown for either crew. The difference in RN_2 values can be attributed almost solely to the difference in prior decontamination effects shown on line 2. Comparison of the special entries at the foot of the table with the RN_2 values on line 7 indicates that

1. Ignoring the negative contribution of concurrent decontamination results in an RN_2 that is too large by 1 to 1.5%
2. Ignoring the positive contribution of the concurrent new source gives an RN_2 that is too small by 1 to 1.5%
3. Ignoring both contributions has the compensating effect of reducing the error in RN_2 to less than 0.3%

For situation I, then, the effects of simultaneous decontamination could have been neglected, and Equation (133) could have been used with excellent results.

In situation II, crews X and Y are assumed to maintain an average distance of 75 feet between each other because of the orientation and narrow width of the surfaces. Despite this reduction in spacing between mutual contributors and receivers, the effects of simultaneous decontamination are little more significant than in situation I. Although the resultant RN_2 factors are both smaller than before, their difference can again be charged completely to the difference in prior decontamination effects (see line 2). From the special entries at the foot of Table 7, ignoring the separate effects of the concurrent decontamination effort introduces errors in the RN_2 estimates ranging from +3% to -5.5%. These errors are 2 to 5.5 times larger than comparable errors in situation I. However, these errors also tend to cancel out when the effects of the concurrent fallout removal and the concurrent new source are combined, since the resultant RN_2 estimates on line 10 are short of the values shown on line 7 by only 1.5 to 2%. Therefore, like the previous example, Equation (133) could have been used without incurring any serious error in the RN_2 estimates for either crew X or crew Y.

In the final analysis, it is difficult to envision a realistic situation wherein simultaneous decontamination effects would be worth considering.* For an actual target complex, the very small contributions found in the above idealized example would be further reduced by the intervening shielding of buildings, curbs, traffic dividers, and other barriers. In addition, maintaining simultaneous decontamination operations on two adjacent surfaces over a time interval that is long enough to affect RN_2 may not be practical. For example, if the area of surface X is considerably smaller than that of surface Y, or surface X requires a fast mechanized method while surface Y

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* Even when the compensating effect of a concurrent new source is eliminated by applying the conditions of Equation (142) (no significant new source), the contribution of simultaneous decontamination to RN_2 is only 1.7 to 3% for situation I and 5% for situation II.

is accessible to only slow manual methods—in either case, the period of simultaneous operations will be short compared to the total time needed to decontaminate surface Y. Hence, for surface X there are essentially no concurrent decontamination effects. For surface Y the situation is treated in two stages, where the first considers only current decontamination and the second is handled as a simple case of serial decontamination (prior plus current). Thus, the need for special equations to correct RN_2 factors for the effects of simultaneous decontamination operations cannot be justified—particularly in view of the accuracy of previously developed expressions.

V DECONTAMINATION ORGANIZATIONAL REQUIREMENTS

Decontamination Rate

The size and makeup of the decontamination organization required by any urban community depends upon the decontamination rate that is maintained from decontamination start to decontamination completion. A serious constraint on the decontamination rate that can be maintained by a decontamination organization of given size and makeup is the limiting exposure dose. Thus, if the maintenance of a required decontamination rate would make decontamination completion attainable only at the cost of overexposures, the decontamination organization is considered inadequate. In any event, before a calculation on organizational requirements to meet fallout exigencies can be made, it is necessary to establish a required decontamination rate.

The required decontamination rate and also the required decontamination start time depend upon the needs of the community in the postattack period. If it is assumed that shelter occupancy is to be terminated after two weeks, then other radiologically acceptable living sites must be made available within the two weeks. On the other hand, there does not appear to be any compelling reason for scheduling a mass shelter exodus at a specified time. Rather, it is more to be expected that people will start leaving shelters when it becomes less objectionable to face the decreasing fallout environmental hazard than to continue residence in a deteriorating shelter environment. Because of the variations in the protection provided by the shelters and in the rate of living condition deterioration among the shelters, as well as variations in the external environment at each shelter location, shelter exit within a community may be expected to take place over an extended period. The required decontamination rate and required decontamination start time may also hinge upon the time that various vital facilities within the community must be activated.

Since no criteria currently exist for determining required decontamination rates for various postattack conditions, a reasonable decontamination rate is chosen to demonstrate calculations of decontamination organizational requirements as a function of exposure dose constraints. From Reference 8, the decontamination rate of 0.5 square mile per 10,000 population during the first week of decontamination, starting 2 weeks after fallout arrival, will be used in the example calculations that follow. The decontamination organization size required for any other chosen decontamination rate will merely be proportional to the rate ratio.

Shelter Postures

The standard intensity where decontamination is deemed necessary depends upon the dose history of the individuals while in shelter and their potential exposure upon re-use of the fallout area. The calculation of individual total exposures requires the specification of a shelter posture. The scheduling of decontamination based upon a single shelter protection factor (PF) will not produce the same results as that from scheduling decontamination based upon a mixed PF shelter system. In a mixed PF shelter system, the people in the poorer shelters would be handicapped by a larger shelter dose. On the other hand, the people in better shelters but in the same external fallout environment would be exposed to a smaller shelter dose, and consequently they would be able to engage in decontamination tasks over a longer period of time without becoming overdosed.

Because of this feature, three postulated shelter postures will be used in the following analysis. These three shelter postures are identical to those described in Reference 8. They are described as existing (average PF distribution in urbanized areas of SMSAs throughout the U.S.[9]), 40 PF minimum, and 100 PF minimum, and are shown in Figure 7 as a function of their PF distribution. As can be seen, the PF distributions of the improved shelter systems are merely the raising of the lower PF values to the specified PF minimums.

Contamination Levels

A major criterion for determining the decontamination organizational requirements is the fallout pattern intensities in the area to be recovered. The higher the intensities and the larger the area of high intensities, the greater will be the organization size requirements. Although the fallout pattern for surface detonated weapons in the megaton range is large and may very easily cover an entire metropolitan area, the variations in the contamination levels within a metropolitan area are expected to be large. Therefore, whereas it is reasonable to analyze decontamination organizational capabilities based upon uniform contamination levels for a small community, as was demonstrated in Reference 8, it would be incorrect for large communities such as the combined urbanized areas in a standard metropolitan statistical area. On the other hand, the fallout intensity levels and the fallout intensity gradients in a fallout pattern depend upon (among other factors) the weapon size and the location in the fallout pattern. For this reason, it is necessary to choose a fallout contour pattern to demonstrate the analytical procedure.

Shown in Figure 8 is a map of the combined urbanized areas in the San Jose SMSA with the downwind fallout pattern of a 5 MT, 100% fission

Figure 7

ACCUMULATIVE SHELTER PF DISTRIBUTION FOR CITIES WITHIN SMSAs

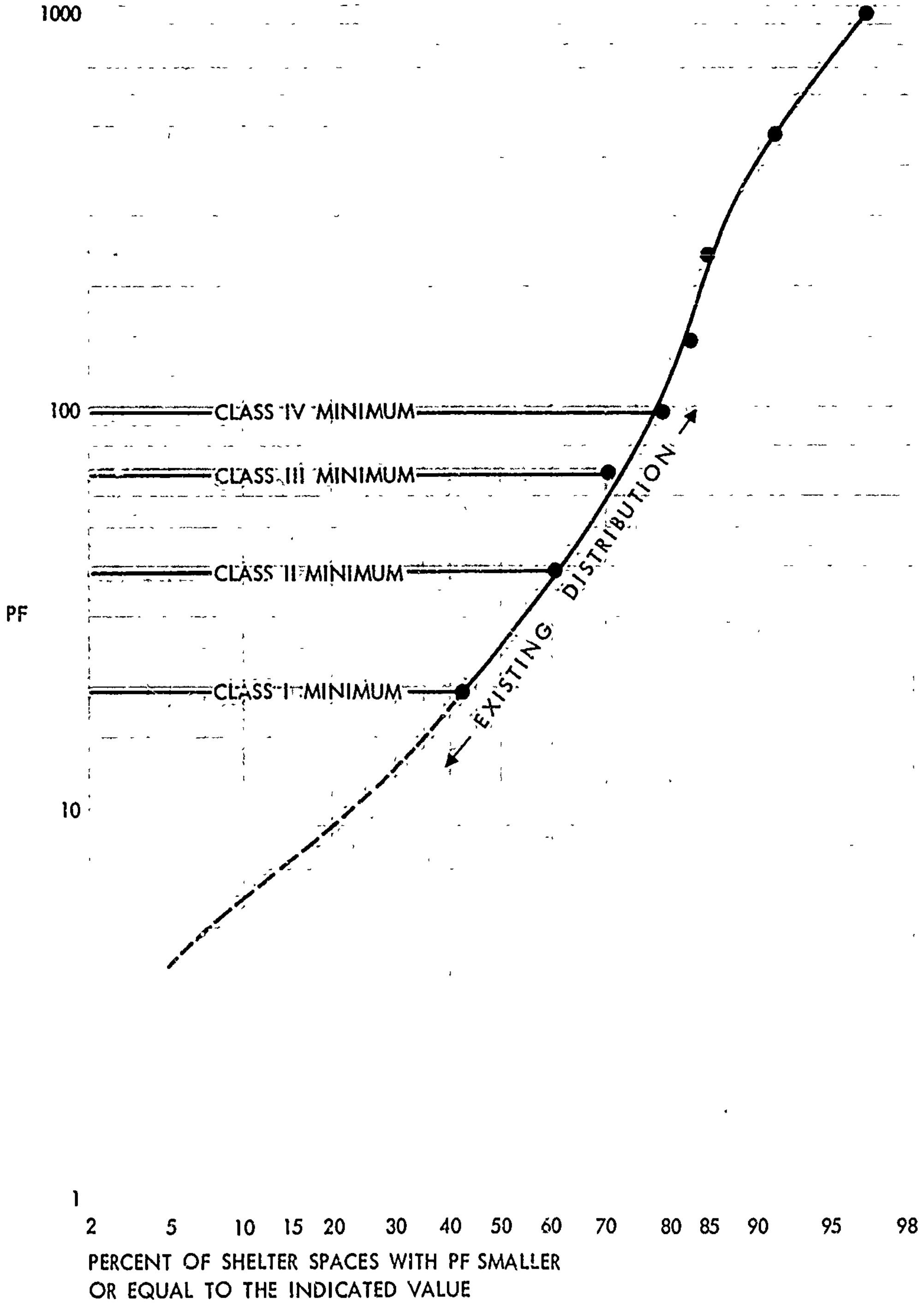
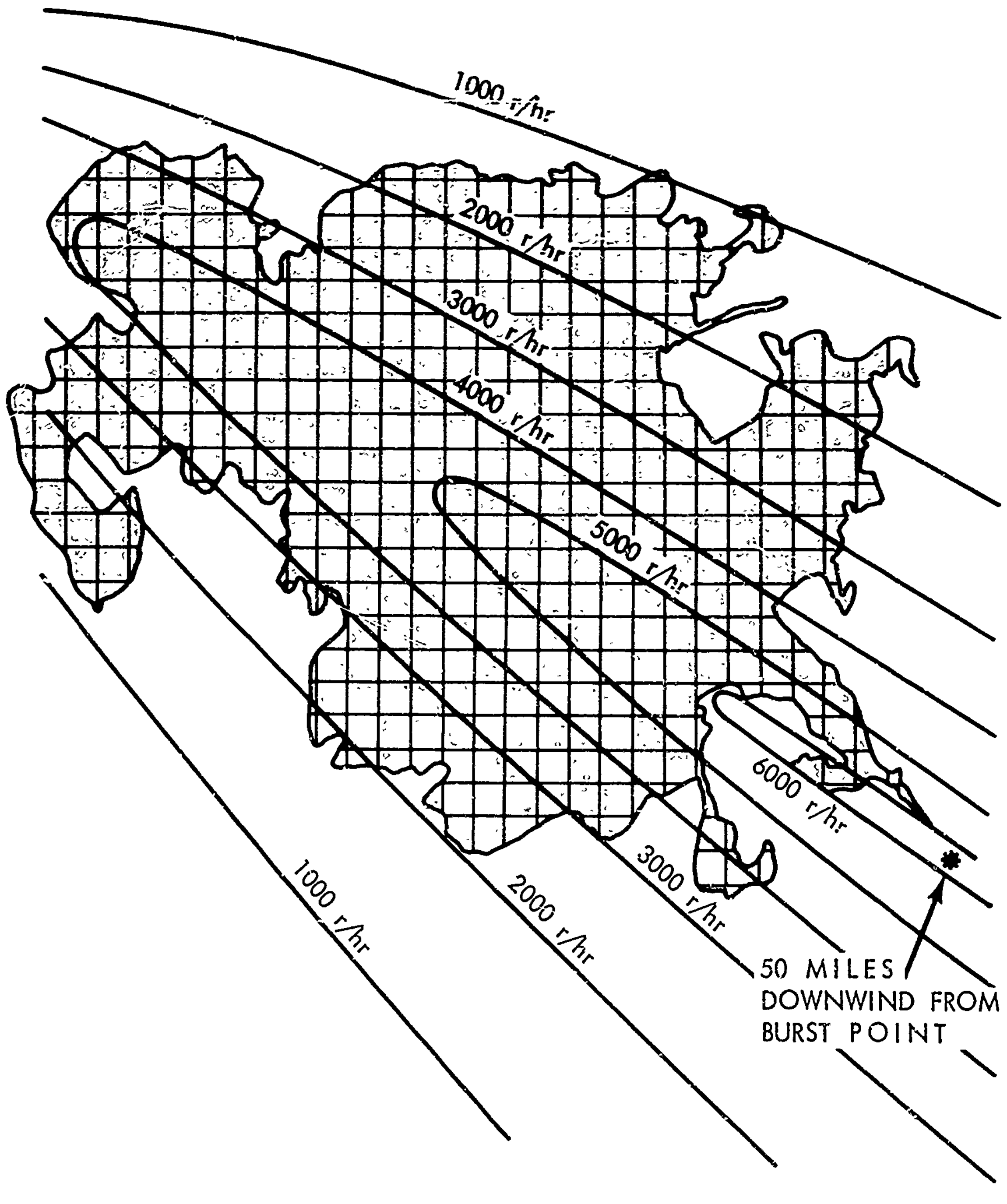


Figure 8

FALLOUT PATTERN OVER URBANIZED AREAS IN SAN JOSE SMSA



weapon, that was surface detonated in San Francisco, superimposed. The wind direction in this case is assumed to be from the northwest and the assumed windspeed is 15 mph. The contour values indicated are the equivalent instrument readings at one hour for the total deposited fallout as calculated from the Miller Fallout Model.[10] The standard intensities, I_s, are estimated to be 1.33 times the instrument values, and the standard intensities for a 50% fission weapon of the same yield are estimated to be 0.665 times the instrument reading contours shown.

Analytical Procedure

The urbanized areas within the various contour values in Figure 8 were measured and then plotted as a function of standard intensity in Figure 9. By combining the shelter distributions of Figure 7 with the 50% fission standard intensity distribution of Figure 9, the 1 week exposure doses for an effective fallout arrival time of 1 hour are plotted in Figure 10 for the existing shelter distribution, the 40 PF minimum shelter distribution, and the 100 PF minimum shelter distribution. As can be seen, 50% of the people in the existing shelter system would have accumulated a 1 week shelter dose in excess of 200 r. According to the assumption in Reference 8, the shelter system is inadequate for the fallout condition, and the system fails.

With the minimum 40 PF and the minimum 100 PF shelter systems, less than 50% of the population (20% for the minimum 40 PF shelter system and 0% for the minimum 100 PF shelter system) would accumulate 1 week shelter doses in excess of 200 r. Consequently, if less than 10% of the non-overexposed population were needed to perform the required decontamination effort without incurring overexposures, then the combined countermeasure of shelters and decontamination will successfully effect recovery.*

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* Reference 8 assumed a maximum decontamination organization of 10% of the urban population.

Figure 9

STANDARD INTENSITY DISTRIBUTION
(FALLOUT PATTERN IN SAN JOSE)

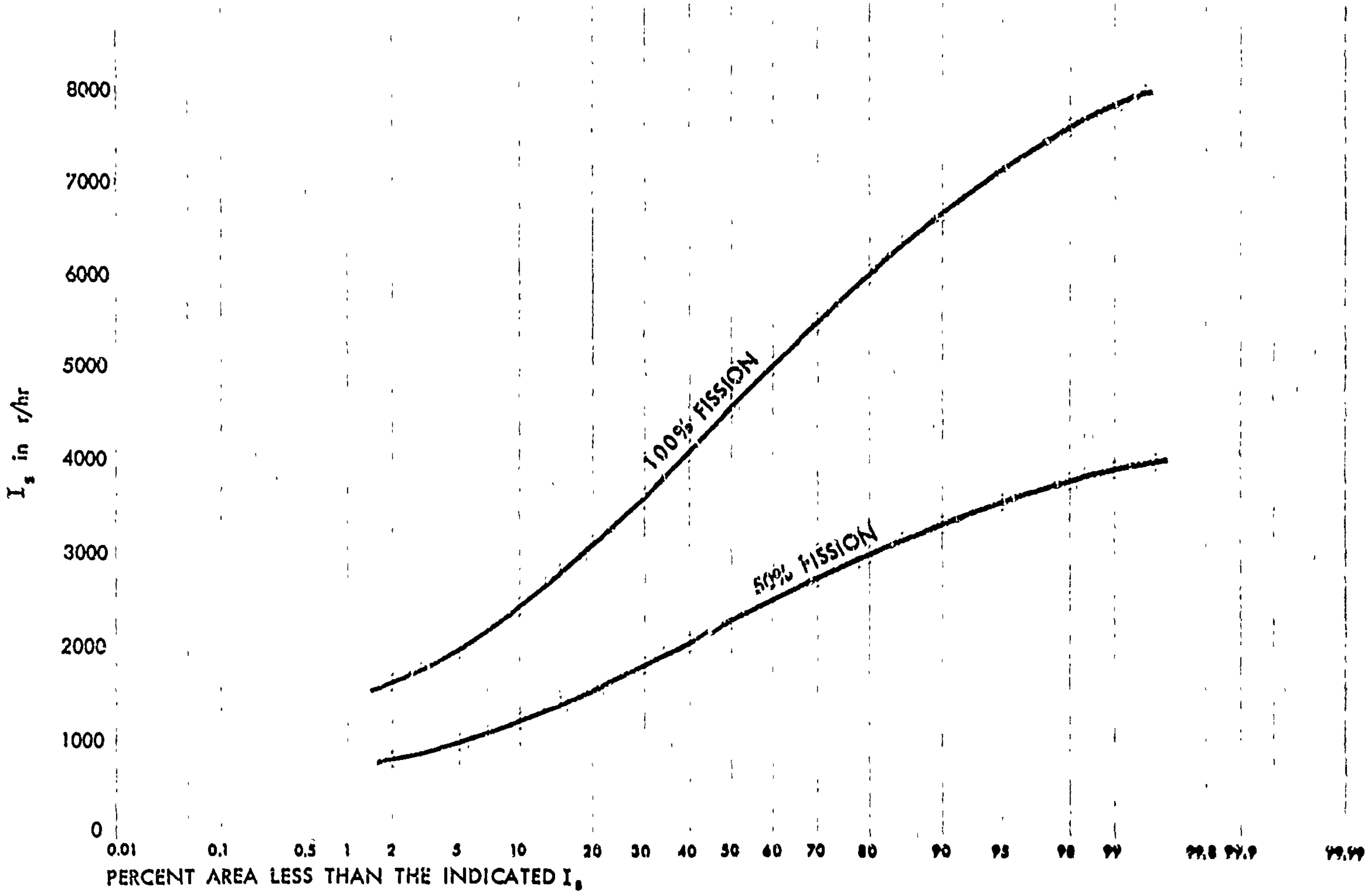
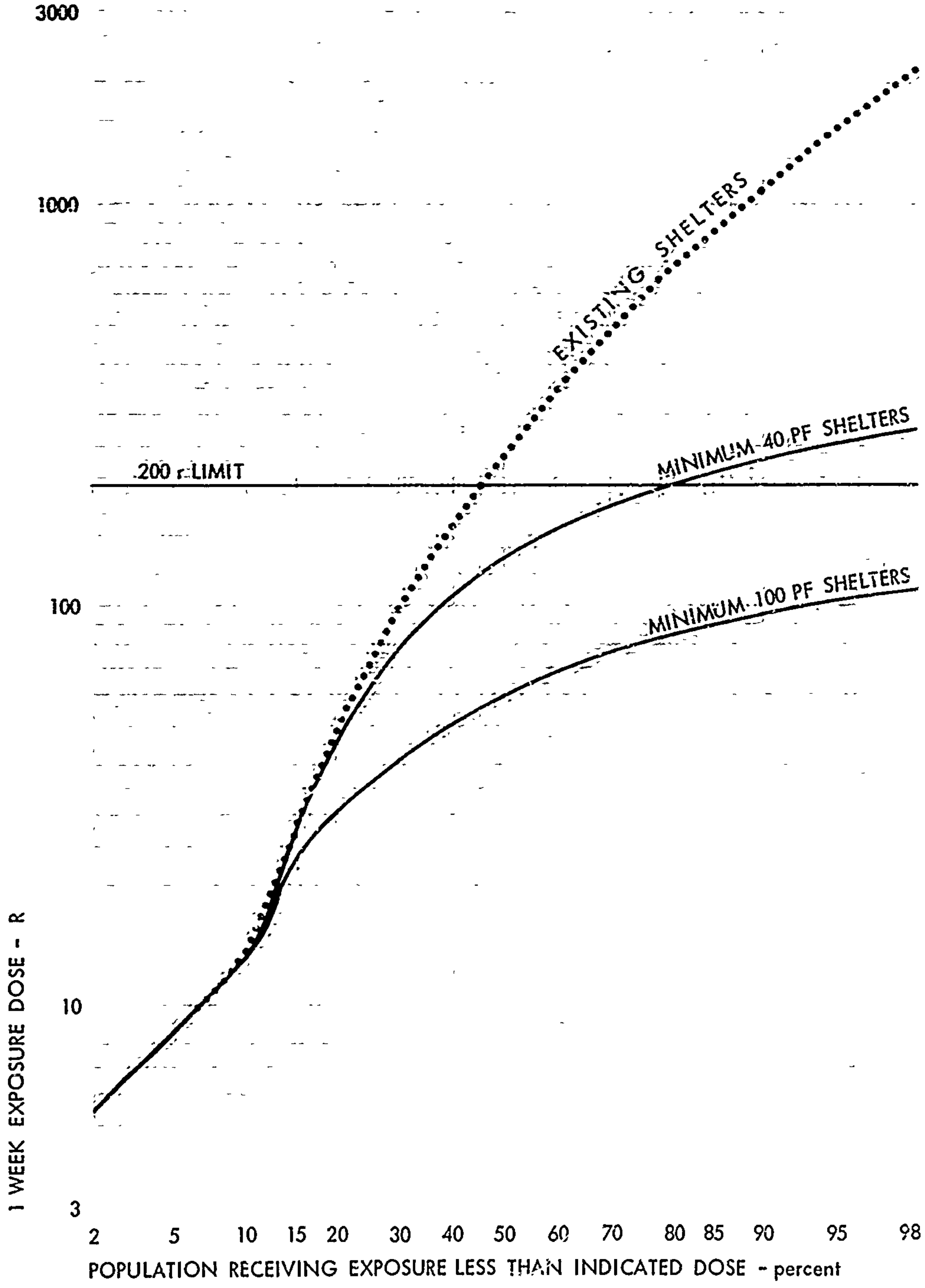


Figure 10

SHELTER EXPOSURE DOSE DISTRIBUTION, FOA = 1 HOUR



The decontamination effort required is expressed as

$$E_r = \sum \gamma_n \beta_n \rho_{\gamma\varphi} \qquad (145)$$

where γ_n is the standard intensity distribution

β_n is the PF distribution of shelters

$\rho_{\gamma\phi}$ is the required effort (hours) for standard intensity and PF

The decontamination effort required per person on a total population basis to decontaminate 0.5 square mile of area per 10,000 people during the third week after an attack is given in Figure 11 for the PF distributions cited as a function of standard intensity (taken from Reference 8). By summing the decontamination effort required in Figure 11 according to the standard intensity distribution (50% fission) in Figure 9, the decontamination requirements are obtained for the example fallout pattern and urbanized area. The required decontamination effort summation is presented in Table 8.

To determine the size of the decontamination organization for the required decontamination effort, the available effort that can be provided by 10% of the population is calculated for the standard intensity distribution. The available effort is expressed as

$$E_A = \sum \gamma_n \beta_n \alpha_{\gamma\varphi} \qquad (146)$$

where $\alpha_{\gamma\phi}$ is the available effort (hours) for standard intensity and PF. Figure 12, taken from Reference 8, is a plot of the average available hours for the PF distributions cited as a function of standard intensity for a decontamination organization made up of 10% of the population.

Figure 11

DECONTAMINATION EFFORT REQUIRED TO OBTAIN ACCEPTABLE TARGET REUTILIZATION RESIDUAL NUMBERS

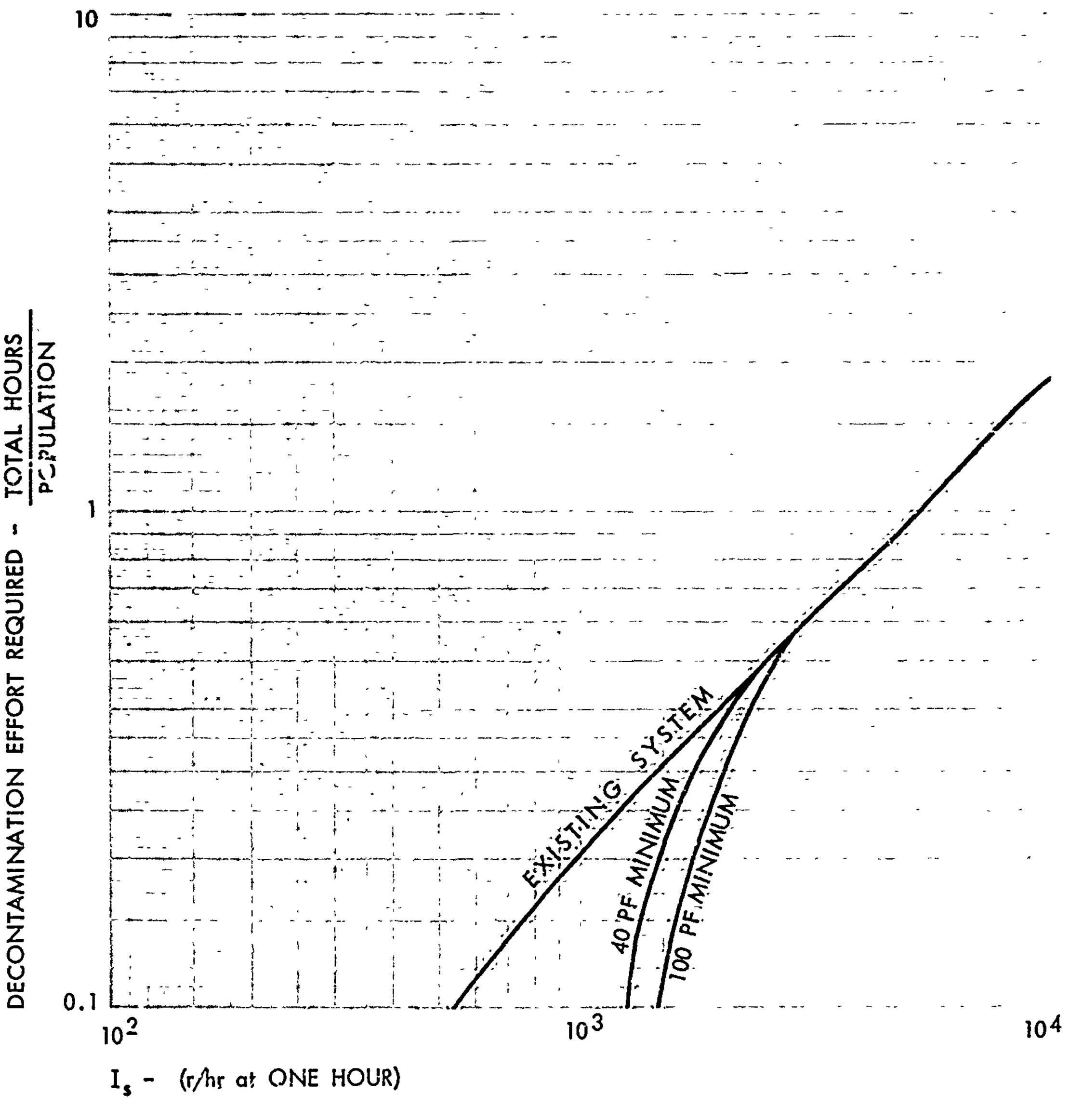


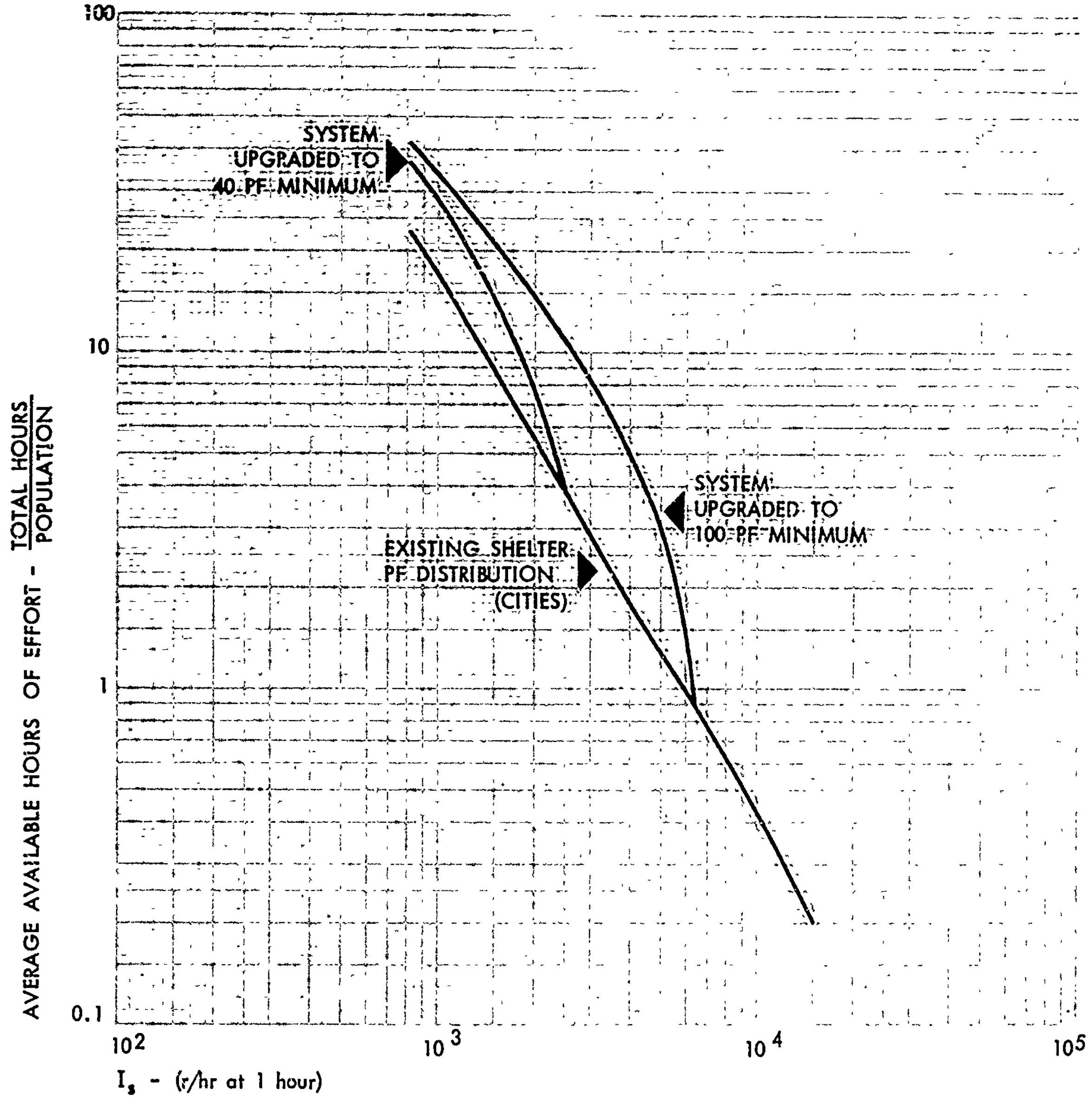
Table 8

REQUIRED DECONTAMINATION EFFORT

Distribution Percent	$\bar{I}_s$ r/hr	Hours per Person (Total Population) Existing Shelters	Minimum 40 PF	Minimum 100 PF
0-10	975	0.200	0	0
10-20	1390	0.285	0.170	0
20-30	1680	0.345	0.280	0.177
30-40	1930	0.395	0.360	0.265
40-50	2170	0.440	0.420	0.350
50-60	2400	0.490	0.475	0.435
60-70	2630	0.530	0.530	0.510
70-80	2870	0.575	0.575	0.575
80-90	3150	0.630	0.630	0.630
90-100	3570	0.700	0.700	0.700
Total		4.59	4.14	3.64
Total/10		0.459	0.414	0.364

Figure 12

AVAILABLE EFFORT WITH TEN PERCENT DECONTAMINATION PERSONNEL



If the summation of the decontamination effort available from Figure 12 according to the 50% fission standard intensity distribution in Figure 9 is multiplied by 10, and the total is divided into the required hours per person from the previous summation, the size of the decontamination organization expressed as a percent of the population is obtained for the 50% fission case. The available decontamination effort summation is presented in Table 9. The percent of the population that is required for decontamination is 0.414/55.26 or 0.75% for the minimum 40 PF shelter system, and 0.364/80.8 or 0.45% for the minimum 100 PF shelter system.

Whereas a decontamination organization of 0.92% is indicated for the existing shelter system, system failure had already been assumed because more than 50% of the population had overexposures while in shelter. It should also be noted that if the mean standard intensity of 2,300 r/hr rather than the particular distribution (see Figure 9) were used to obtain the required and available decontamination efforts from Figures 11 and 12, incorrect larger size requirements for decontamination organizations would result.

To obtain a perspective of the example problem, the urbanized area of the San Jose SMSA measures about 250 square miles and has a population of about 500,000. Three-fourths of 1% of the population is 3,700 decontamination personnel and one-half of 1% of the population is 2,500 decontamination personnel. At a decontamination rate of 0.5 square mile per 10,000 population per week, the overall decontamination rate is 25 square miles per week, and the decontamination of all the urbanized areas would require 10 weeks. A decontamination procedure that includes mass participation in the decontamination task as a means of shortening the overall decontamination time is discussed in a following section.

Table 9

AVAILABLE DECONTAMINATION EFFORT

Distribution Percent	$\bar{I}_s$ r/hr	Hours Per Person (Total Population)* Existing Shelters	Minimum 40 PF	Minimum 100 PF
0-10	975	84	84	84
10-20	1390	84	84	84
20-30	1680	72	84	84
30-40	1930	57	82	84
40-50	2170	47.5	61	84
50-60	2400	40.2	44	84
60-70	2630	35	35	84
70-80	2870	30.8	30.8	84
80-90	3150	26.3	26.3	75
90-100	3570	21.5	21.5	61
Average		49.83	55.26	80.80 hr/person

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* Maximum hours per person per week is set at 84 hours.

The analytical procedure for estimating the required size of the decontamination organization is thus demonstrated for a particular urbanized area located at a particular location downwind from a particular weapon burst. The same procedure is applicable for any fallout condition, shelter system, or exposure criteria.

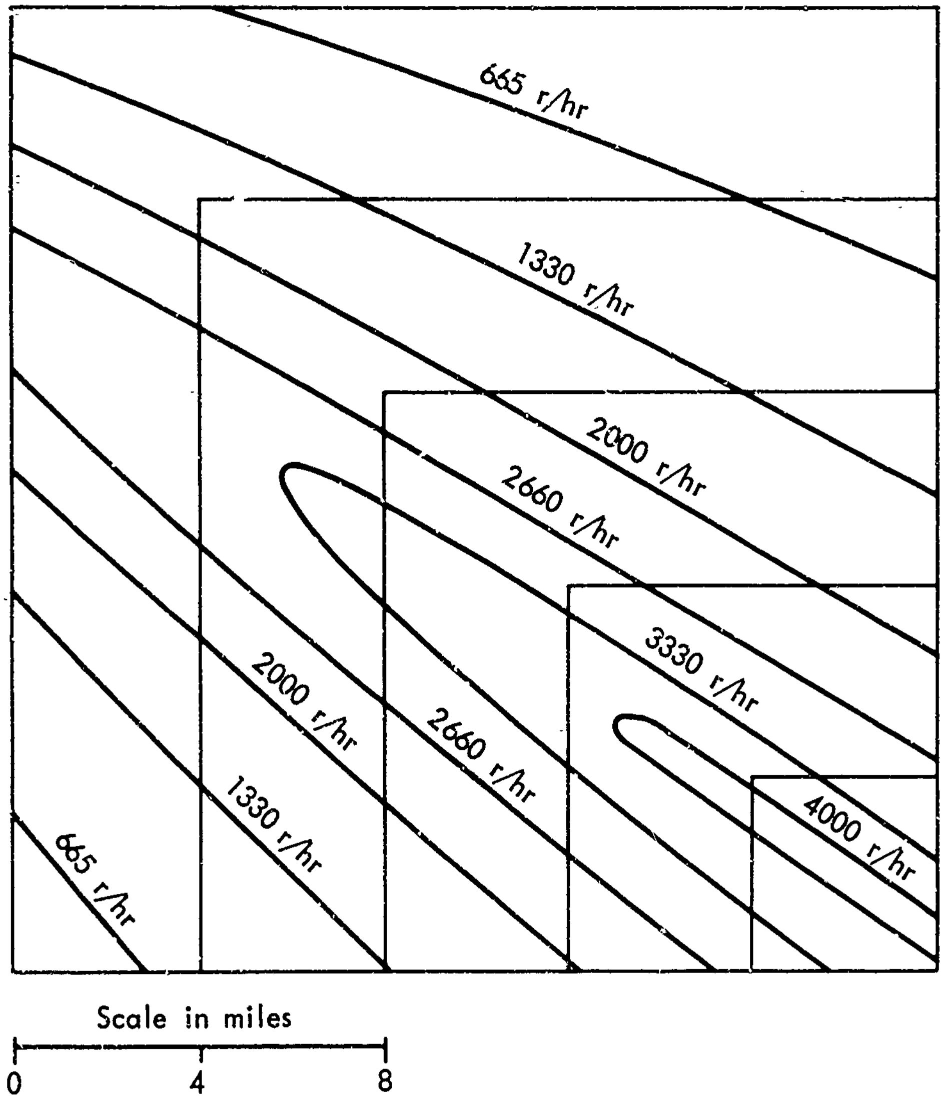
Area Size

Because the fallout pattern size is large when compared to urban entities within a SMSA, an urban entity of small areal expanse preparing for the worst fallout condition would require a larger decontamination organization on a per person basis than an urban entity of large areal expanse with the same population density. To demonstrate the effect of urban area size on decontamination organization requirements, the fallout pattern of Figure 8 (standard intensities for 50% fission) is superimposed over square areas of various sizes in Figure 13. If it is assumed that the worst fallout condition could develop anywhere on Figure 13, then all communities within Figure 13 would be required to prepare for the worst condition. The area representing the worst condition in Figure 13 is the smallest square area located at the lower right corner of the figure. This small area represents 16 square miles. Because the high intensity fallout area is limited in size, the mean standard intensity, based upon area, decreases from the worst condition with increasing area size. Consequently, if all the communities within Figure 13 organized decontamination preparations collectively as a unit rather than independently, a smaller percent of the population would be sufficient to cope with the worst fallout condition.

By measuring the standard intensity-area distribution within each of the squares in Figure 13 and determining the decontamination requirements

Figure 13

5 MT - 50% FISSION - SURFACE BURST STANDARD INTENSITY CONTOURS OVER SQUARE SURFACE AREAS



for each area represented by the squares, one obtains the decontamination organizational requirements as a percent of the population. These requirements are plotted as a function of area size in Figure 14. The curves were calculated for a fallout arrival time of 1 hour. As can be seen, the percent of the population required for decontamination varies significantly even though the population density is assumed to be constant. For instance, if the population density is 2,000 people per square mile, then the size of the decontamination organization for the various area sizes is as shown in Figure 15. The number of decontamination personnel required is seen to initially increase linearly with increasing area and then to increase at a decreasing rate with increasing area. The reasons for the leveling off of decontamination personnel requirements for large areas are two: (1) only a small fraction of the increment of increased area requires decontamination, and (2) the decontamination personnel from the increment of increased area are exposed to smaller shelter doses due to the lower fallout intensities at their shelter locations and consequently can work longer hours without incurring overexposures.

The decontamination organization size requirements in number of decontamination personnel per square mile (based upon a population density of 2,000 per square mile) are compared in Table 10 for various community areas planning the capability to independently handle the worst condition in the example. The advantage of pooling the resources of several communities into a single sphere of decontamination operations planning appears to be overwhelming; however, the management of such an organization is not without penalties. Although the organization sizes given, even for the larger areas, will provide a recovery rate proportional to the area size (including areas that do not require decontamination), the recovered areas will generally be less accessible to people sheltered in the heavier fallout areas, and there will also be a requirement for

Figure 14

PERCENT OF POPULATION REQUIRED FOR DECONTAMINATION

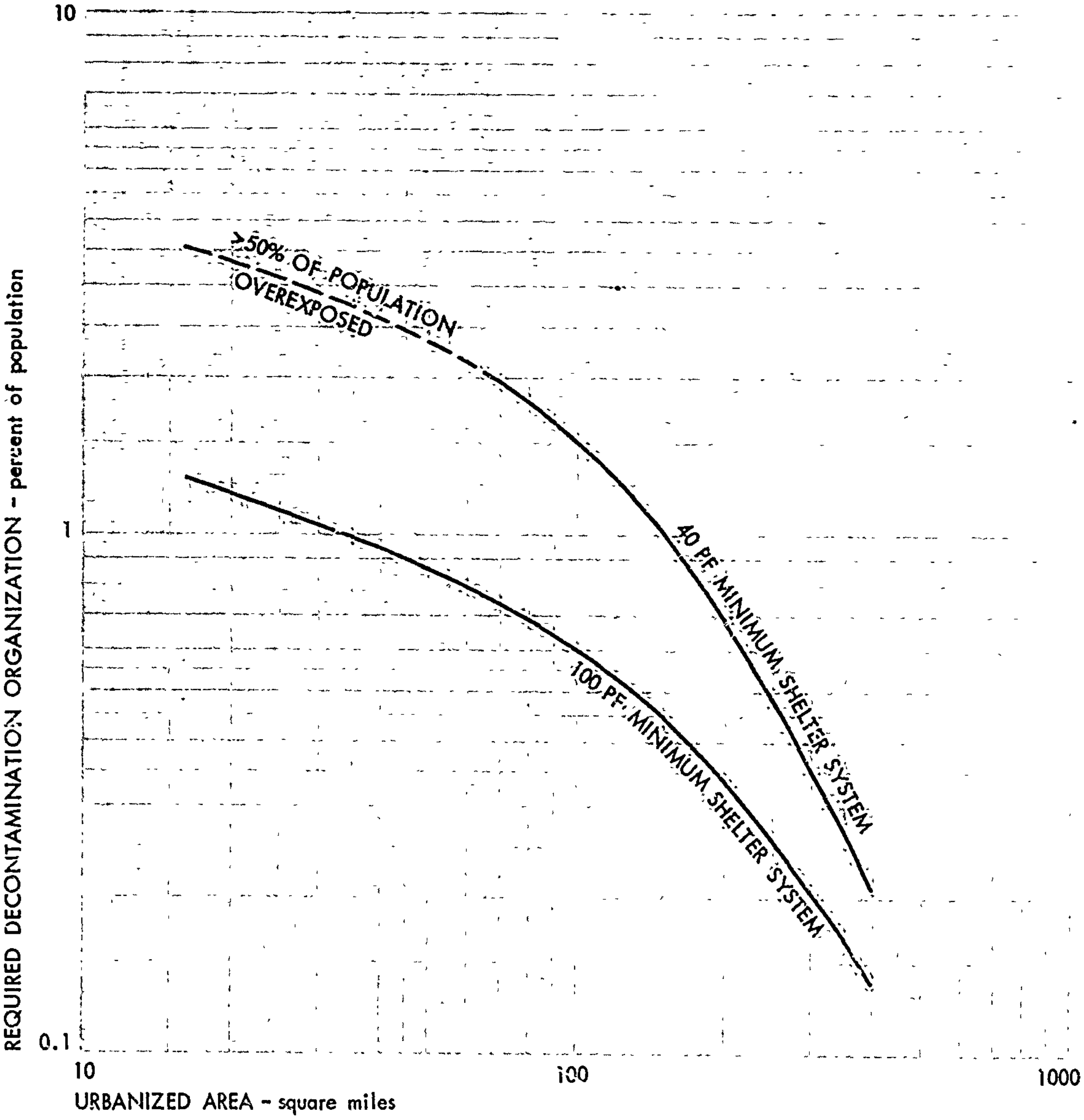


Figure 15

DECONTAMINATION ORGANIZATION SIZE

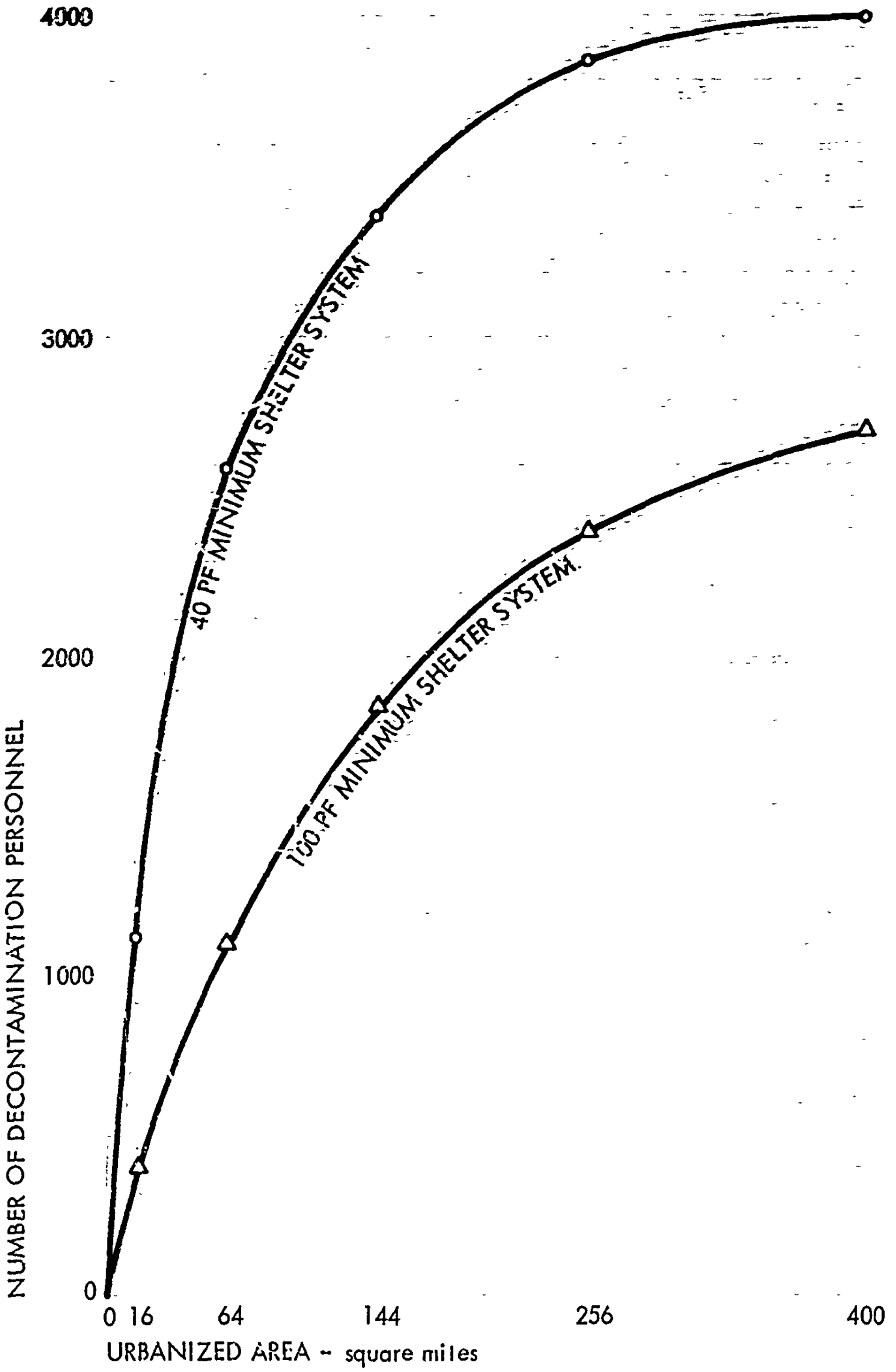


Table 10

DECONTAMINATION ORGANIZATION SIZE REQUIREMENTS

Independent Operations Area (sq. miles)	Number of Decontamination Personnel (per sq. mile*) 40 PF Minimum Shelter Distribution	100 PF Minimum Shelter Distribution
16	70	25
64	40	17.2
144	23	12.8
256	15	9.4
400	10	6.8

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* Based on a population density of 2,000 per square mile.

certain members of the decontamination organization to decontaminate areas remote from their shelter locations.

The choice of an areal size for independent operations requires consideration of both the advantages and disadvantages of increasing or decreasing the area.

VI THE CASE FOR MASS DECONTAMINATION

In postulated heavy nuclear attacks upon the U.S.A., only very limited areas (~5%) had fallout radiation standard intensities that exceeded 20,000 r/hr. These areas are generally located very close to destroyed target complexes. Because of this finding and the excessive delay that would be required before target complexes not destroyed but contaminated to standard intensities in excess of 20,000 r/hr could be recovered, attention is focused only on the recovery of target complexes that are less contaminated. They not only represent virtually the entire country but also are generally recoverable by decontamination.

When the recovery of an entire urban complex by decontamination alone using the various procedures recommended in the literature is considered, the effort that can be simultaneously applied is not limited by manpower or radiation dosage but by available equipment and supplies. For instance, a group of five street sweepers may decontaminate pavements at a combined rate of 2 x 10^5 sq ft/hr. At this rate, 10 square miles of pavements would require 1400 hours--almost two months of continuous operation. If we consider the decontamination of lawns and planted areas with mechanical equipment, it would take 10 small tractor-type scrapers almost two years to decontaminate 10 square miles of lawns and planted areas that are in their normal configurations within urban or suburban complexes. It will also require a long time to decontaminate roofs and various areas by firehosing.

Table 11 lists the estimated supplies, equipment, manpower, and skills required to decontaminate 30 square miles of urban complex. Although the number of recovery personnel employed at any time is relatively small,

Table 11

MEN AND DECONTAMINATION EQUIPMENT REQUIREMENTS PER 30 MI^2 OF URBAN AREA

(20% Roofs, 40% Planted Areas, 40% Paved)

Decontamination Schedule (24 hrs/day)		30 Days	60 Days	90 Days
Motorized sweepers		12	6	4
Motorized scrapers (large)		24	12	8
Powered scrapers (small)		120	60	40
Loaders (front end)		48	24	16
Trucks (dump)		180	90	60
Firehosing set-ups		48	24	16
Pumpers (if needed)		(24)	(12)	(8)
Water consumption (gal/hr)		15×10^4	7.5×10^4	5×10^4
Shovels (hand)		240	120	80
Brooms (hand)		60	30	20
Men (force at all times)		900	450	300
Men (per day)		3,000	1,500	1,000
Men (total force)*		12,000	6,000	4,000
Skills	Motorized sweeping	240	120	80
	Motorized scraping	120	60	40
	Power scraping	1,200	600	400
	Loading	780	390	260
	Hauling	3,000	1,500	1,000
	Manual work force	6,000	3,000	2,000
	Supervision	660	330	220

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* Based upon approximately no dosage while in shelter.

the daily number and the total number of people employed for the decontamination operation are substantial because of the limiting effect of radiation dosages. The total work forces given are those required to obtain the earliest recovery. The work forces may be reduced by the expediency of delaying the decontamination start time, but recovery will also be delayed.

The manual work force listed under skills require some nominal amount of training. Special skills such as that required to operate a motorized scraper with proficiency are also required of a large number of people. With a population density of 2,000 people or more per square mile, there are adequate people for decontamination participation. It is the number of motorized equipment, especially motorized earth moving equipment, and the associated skilled personnel that are perhaps unattainably large. For this reason, the longer decontamination schedules are more in the realm of feasible operations. Even this requires the stockpiling of large amounts of decontamination equipment and supplies and the training of large numbers of people in decontamination with mechanized equipment.

Unless the fallout standard intensity is very high, however, the reclamation of non-vital areas at later times does not require a high degree of effectiveness to permit target complex re-entry and utilization. For instance, Figure 16* shows that for a contaminating event with I_s = 7,000 r/hr and an effective $RN_3 = 0.1$, these areas could be occupied after 2 weeks of shelter stay in a good shelter by decontamination personnel and nondecontamination personnel alike. Since the decontamination of an entire city to a relatively high degree of effectiveness will normally require months of effort, the advantages of a less effective decontamination effort with mass participation is investigated. Again referring to

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* These curves were constructed from the exposure dose equation of reference 2, and RN values were obtained by target analysis procedures.

Figure 16

URBAN COMPLEX REOCCUPATION TIMES

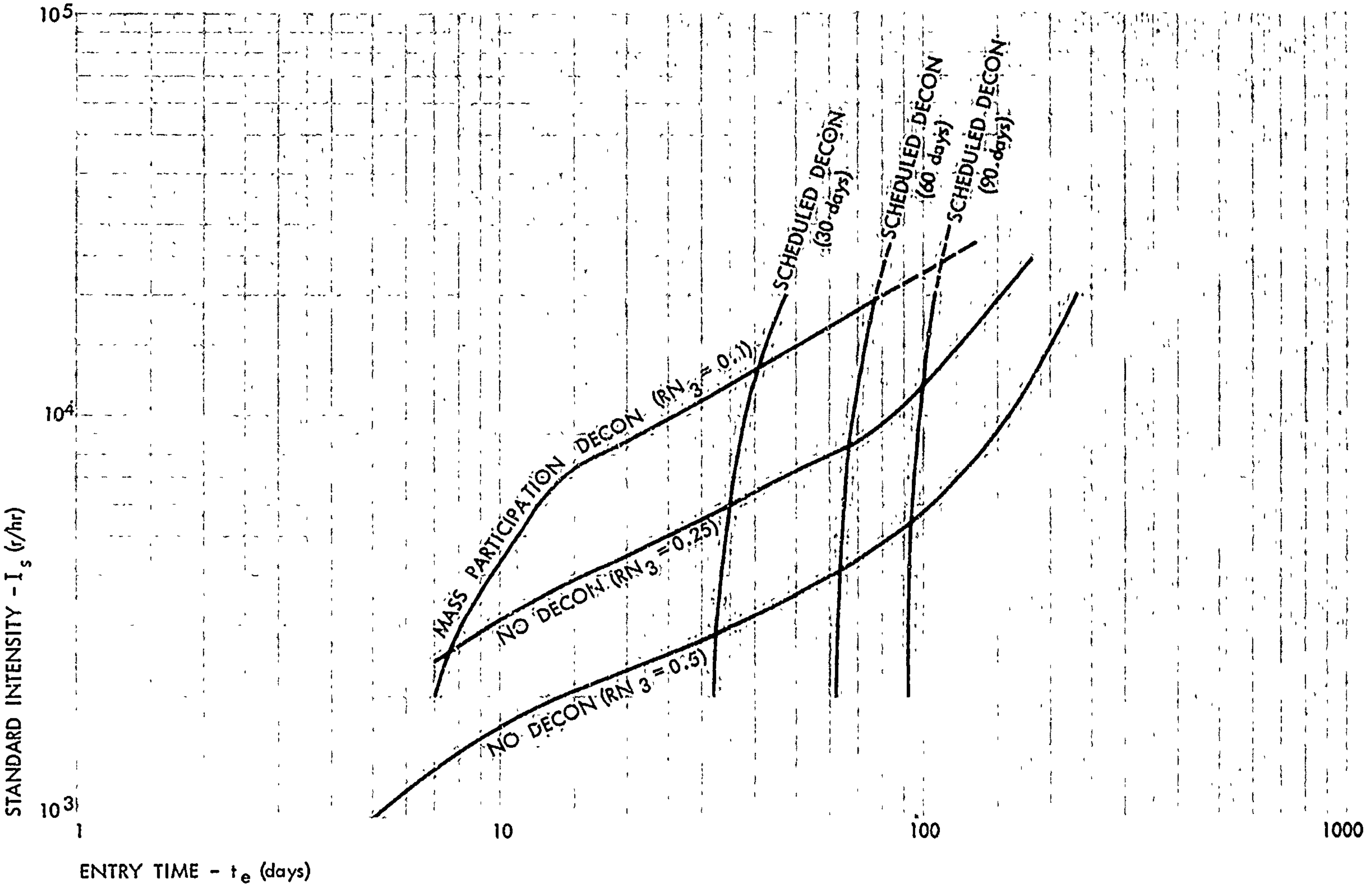


Figure 16, no decontamination is required for I_s values less than 2,000 r/hr if the shelter stay (good shelter) is 2 weeks. This of course does not mean that it would not be advantageous to conduct decontamination operations. Decontamination would always reduce the radiation exposure dosage. At slightly higher standard intensities, only a moderately effective decontamination effort is required to render target complexes habitable. To obtain maximum coverage per unit time, methods that provide simultaneous participation by a very large portion of the population must be employed. These methods are manual methods.

Because of the slow rate of manual methods (area/man-hour), the total manhours required will be greater than that of mechanized methods. In order that the decontamination time may be shortened to only a few days, virtually every able person will be required to participate. Thus, the use of the earliest urban complex recovery time requires the exposure of a large percentage of the urban population to the maximum feasible radiation dosage. The manual decontamination methods are manual sweeping and garden hose flushing of contaminated "hard" surfaces and spading of planted areas. The importance of the retention of fallout by shrubbery and trees remains unevaluated; but if necessary, they may be rinsed or removed. Along with the actual removal of fallout from contaminated surfaces, equipment must be available for handling and hauling the fallout and associated rubbish to dump areas.

Figure 16 also gives the urban complex entry times for no decontamination, low effectiveness decontamination with mass participation, and scheduled conventional decontamination efforts lasting 30, 60 and 90 days, and for various standard intensities. As indicated in Figure 16, urban complex entry without decontamination, at the entry times given for various standard intensities, would subject the entire urban population to the limiting dosage of 700 r/yr. Decontamination by mass participation and by manual methods would subject a large portion of the urban population

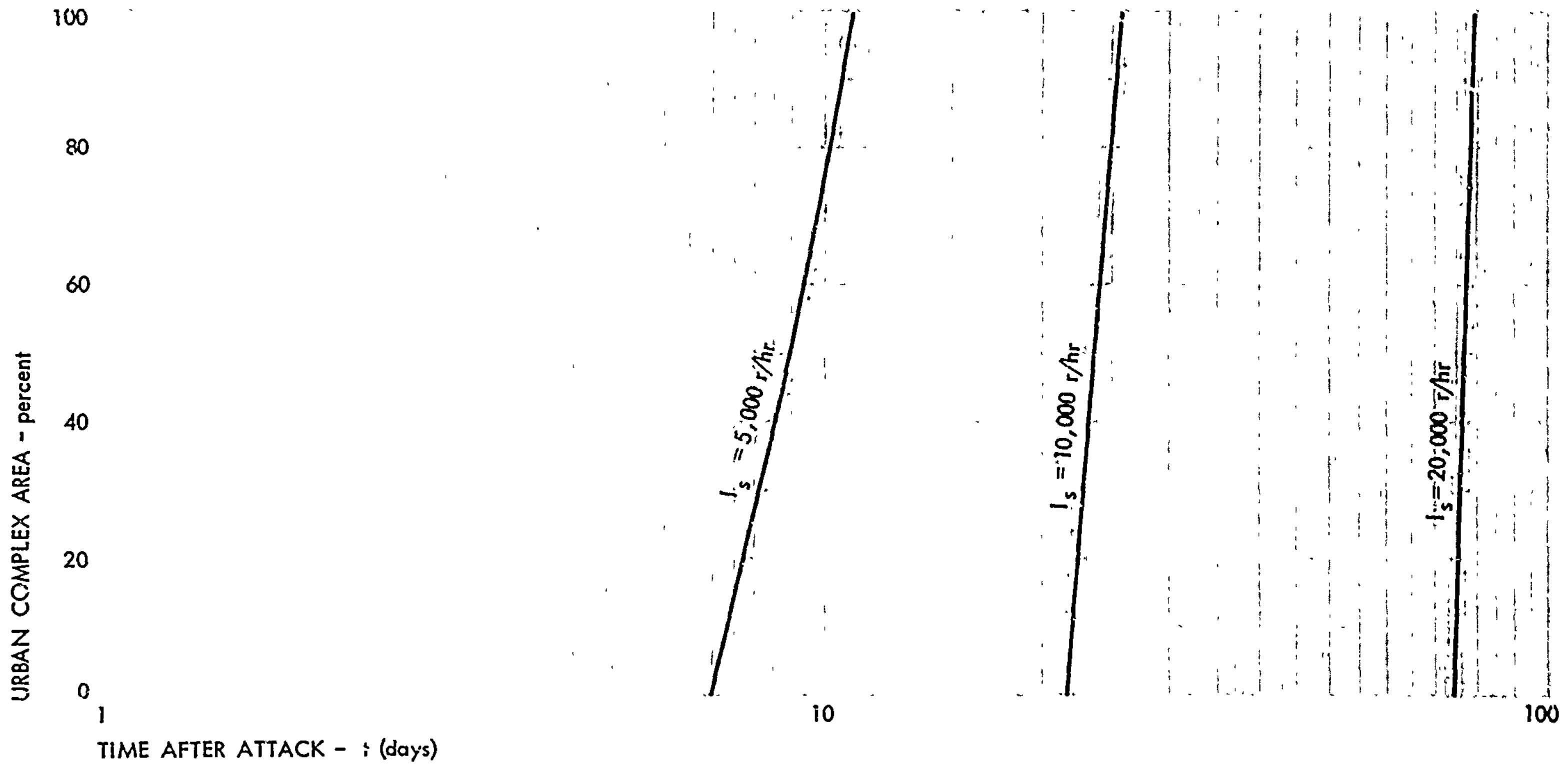
tion to the same dosage. The slower scheduled decontamination operations using maximum employment of mechanization would subject a much lower percentage of the urban population to high radiation dosages.

The urban population densities in the U.S.A. range from about 2,000 people per square mile to over 7,000 per square mile. Using an average density figure of 4,000/sq mi and assuming that about 75% of the population are able to put forth decontamination efforts, the area requiring decontamination per able body is 1 x 10^4 sq ft. The rates of decontamination by the manual methods suggested, except for spading, have not been established but they are rather fast compared with spading. Thus, if 3,600 sq ft of the 10,000 sq ft were lawn and planting areas, and the amount of shrubbery were minimal, the spading time, at 150 sq ft per man-hour, would be 24 hours. If it is also assumed that the remaining roof and paved surfaces could be decontaminated within 8 hours, urban decontamination could be completed with four 8 hour days. More densely populated communities would require less time. For communities not as densely populated, the required decontamination time would not only be longer, but because of the additional decontamination exposure, it would be necessary to delay the decontamination operation (stay in shelters longer).

Urban recovery with mass participation using manual decontamination methods is particularly attractive in the range of fallout standard intensities below 10,000 r/hr. For instance, at 5,000 r/hr, urban complexes could be completely recovered within 11 days after the attack, and at 10,000 r/hr, they could be completely recovered within 26 days after the attack (refer to Figures 16 and 17). By conventional methods, firehosing, motorized sweeping, etc., only about half of the urban area could be recovered for the same standard intensities at these times (see Figures 18 and 19). On the other hand, at standard intensities of 15,000 and 20,000 r/hr, the reliance upon manual methods and mass participation would require the entire urban population to stay in shelters 50 and 80 days, respectively.

Figure 17

FRACTIONAL RECOVERY BY MASS DECONTAMINATION
FOR VARIOUS STANDARD INTENSITIES



Because decontamination by conventional methods permits the gradual evacuation of shelters, partial urban area re-use could be initiated at earlier times. Figures 18, 19, and 20 give the percentages of urban complex area that could be recovered by conventional decontamination operations, scheduled for 30 days, 60 days, and 90 days, prior to recovery by mass manual participation methods. Relief from shelters is thus achieved for large numbers of people at an earlier date by conventional decontamination methods.

The choice of mass manual participation or the scheduled conventional decontamination approach depends upon the available decontamination equipment and supplies, the urgency for the recovery of a part of the urban complex complex or for the entire urban complex, the standard intensity, and the acceptance of the ensuing radiation dosage distribution. Operationally, depending upon the standard intensity, it is reasonable to expect that some vital urban complex units will require earlier attention--i.e., urban complexes will contain areas that must be scheduled for decontamination (conventional methods) at earlier times according to importance. If the conventional decontamination operations are then joined by mass manual participation at the propitious moment, the earliest maximum areal recovery at any time will result. Figure 21 gives the conventional decontamination start times for 30, 60 and 90 day decontamination schedules, the propitious times that they are to be joined by starting mass manual participation, and the urban decontamination completion times for the coordinated efforts.

The conventional decontamination start times are a function of only the standard intensity and the limiting dosage criteria, and consequently they are the same regardless of the number of people and equipment (but not the type) simultaneously employed (see Table 11). As shown by Figure 21, for a standard intensity of 10,000 r/hr, conventional

Figure 18

FRACTIONAL RECOVERY BY CONVENTIONAL DECONTAMINATION WHEN $I_s = 5000$ r/hr

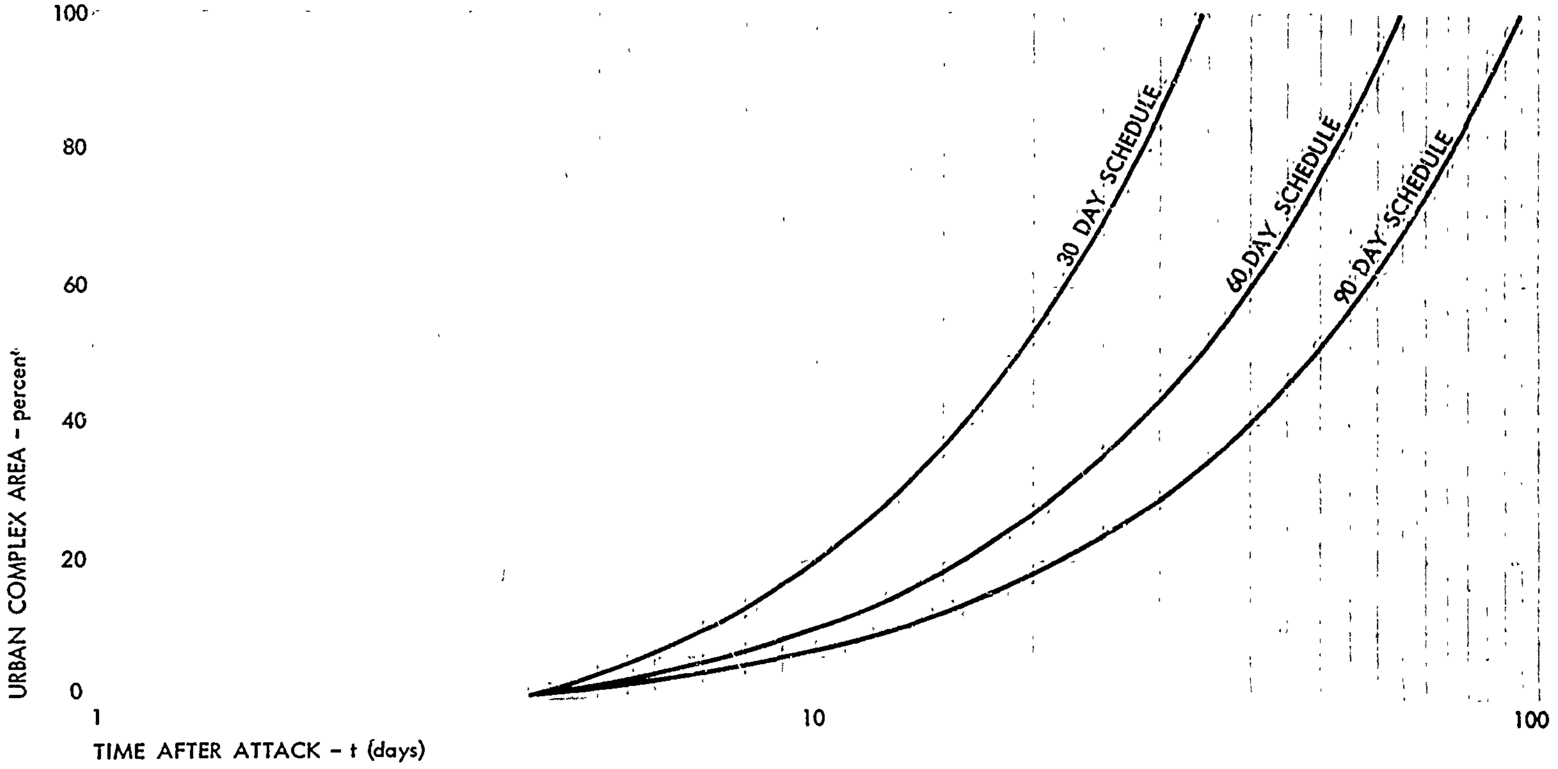


Figure 19

FRACTIONAL RECOVERY BY CONVENTIONAL DECONTAMINATION WHEN I_s = 10,000 r/hr

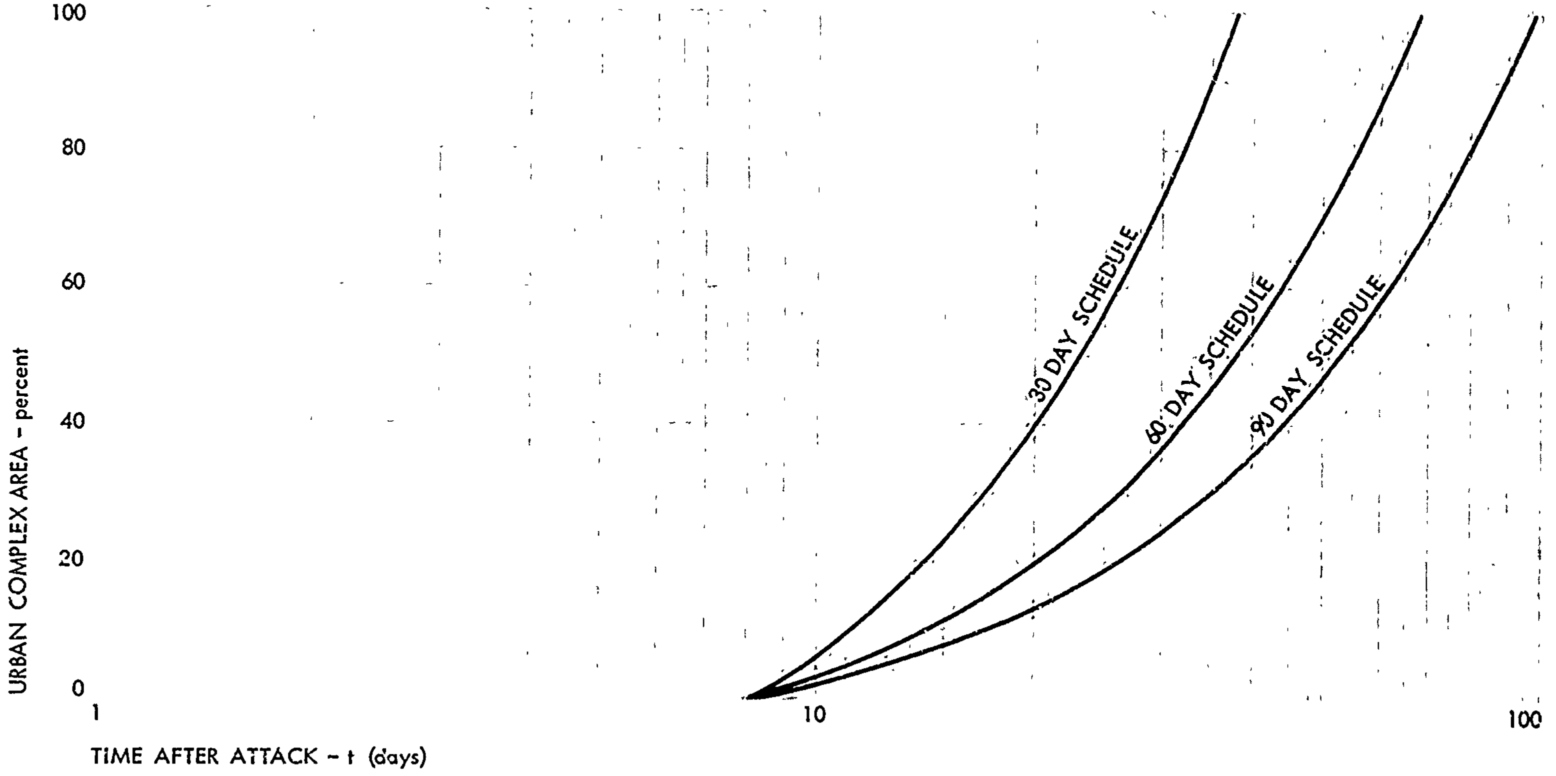


Figure 20

FRACTIONAL RECOVERY BY CONVENTIONAL DECONTAMINATION WHEN I_s = 20,000 r/hr

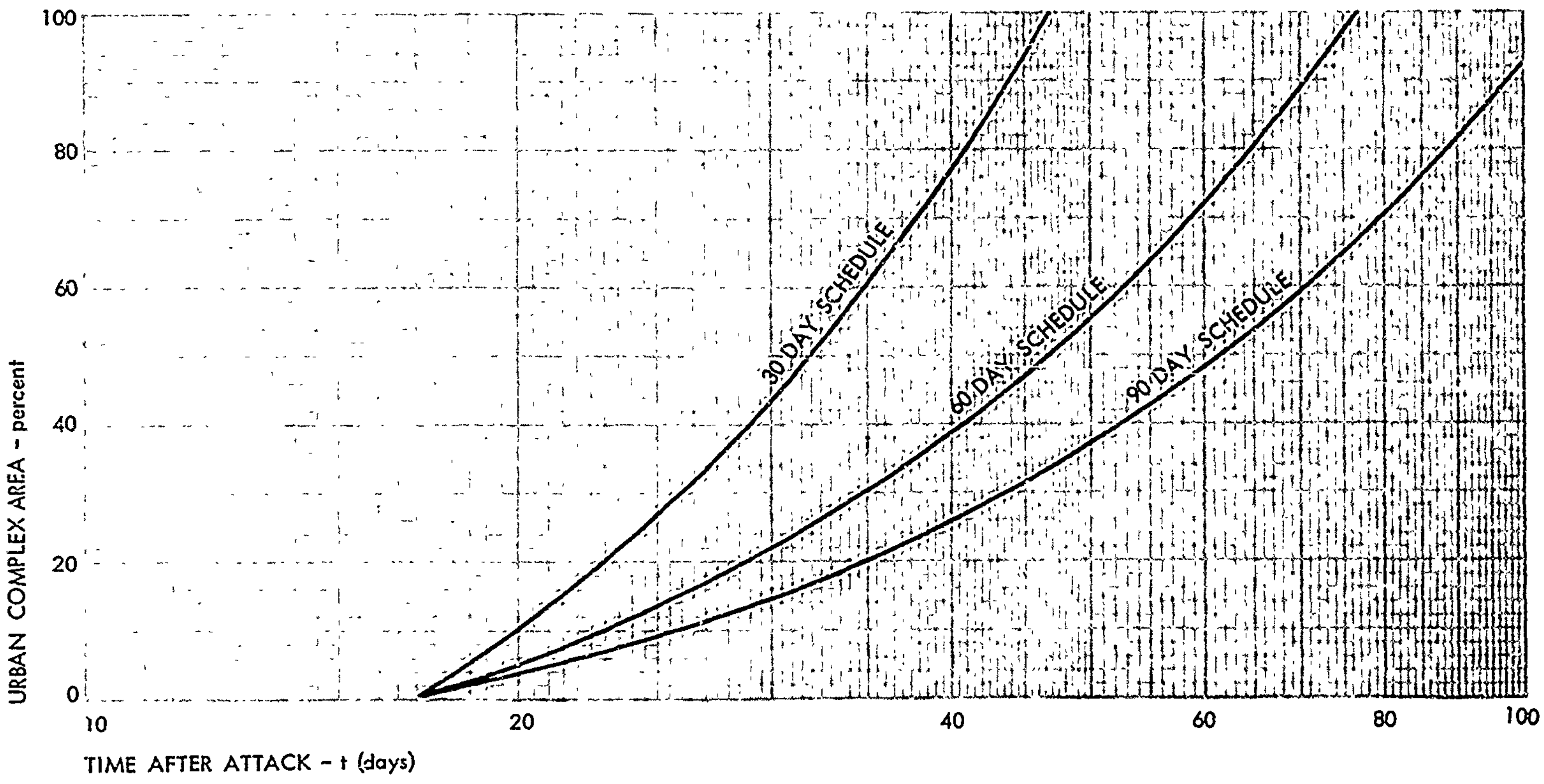
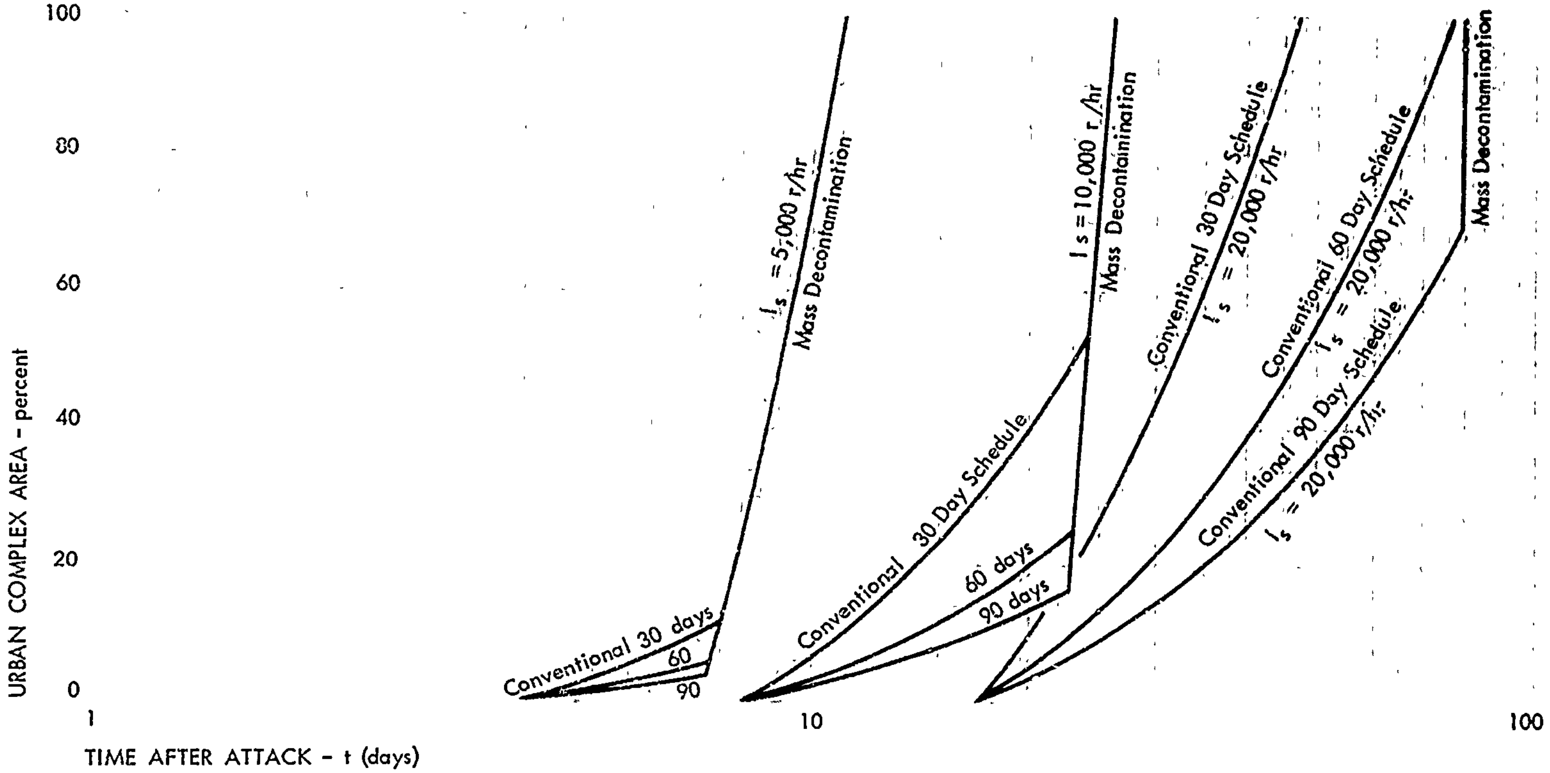


Figure 21

FRACTIONAL RECOVERY FOR CONVENTIONAL AND MASS DECONTAMINATION COMBINED, AT VARIOUS STANDARD INTENSITIES



decontamination may be started on the 8th day after the attack. Since the schedule calls for urban decontamination completion by conventional methods 30 days after the decontamination start time, one-third of the urban complex is recovered in 10 days or 18 days after the attack. Late on the 23rd day after the attack, half of the urban complex is recovered, and on the 24th day conventional decontamination is joined by mass participation with manual methods. The entire urban complex is recovered two days later, on the 26th day after the attack, which is 12 days earlier than by conventional decontamination alone (see Figure 19, 30 day schedule). For a standard intensity of 20,000 r/hr. however, the entire urban complex is recovered on the 47th day by conventional methods only. Mass participation in this case would not noticeably shorten the urban complex recovery time, unless conventional decontamination were conducted on a 90 day schedule. Under this condition, participation of mass decontamination for one day would cut the completion time back from the 107th day (anticipated for conventional decontamination alone) to the 80th day.

VII SUMMARY AND CONCLUSIONS

The planning and scheduling of decontamination operations should be designed to limit the exposure dose to decontamination crews, and, at the same time, decrease the exposure dose for later operations. Therefore, procedures were developed for making approximate estimates of start times that would allow minimum exposure to groups of people in both decontamination and facility operations. Related expressions were written for obtaining allowable dose and required effort estimates. The relationships among decontamination effectiveness, methods, effort, surfaces, radiation levels, and fallout mass loading were also reviewed. Tabular solutions of the decontamination efficiency functions were compiled showing the effects of the various operational and environmental factors on decontamination effectiveness and equation parameters.

The importance of the target utilization residual number $(RN_3)_j$ in estimating the exposure dose to facility operators was demonstrated. Equations defining $(RN_3)_j$ in terms of decontamination effectiveness and relative dose rate contricutions were developed. A detailed analysis of these equations revealed a host of influencing factors. These were organized into six categories, i.e., (1) target characteristics. (2) decontamination methods, (3) decontamination personnel, (4) meteorological conditions, (5) fallout characteristics, and (6) other contingencies. Some of the more important parameters included target configuration and component surface characteristics, decontamination method capabilities and cleaning equation coefficients, crew and operator skills, weathering effects, fallout density, distribution, and particle size, availability of services (water, fuel or power), and accessibility of areas. These and other factors were discussed in terms of their influence on decontamination effectiveness and hence $(RN_3)_j$ so as to reveal their relative importance and any probable need for further study.

The problem of facility operator dose was explored as a part of the development of the concept for maximizing personnel utility. An appropriate expression for operator residual number, RN_{op}, was derived. Through use of a sample calculation, it was shown that the real value of the equation for RN_{op} lies in its being applicable by parts. Thus, the operator dose for any exposure period(s) can be predicted and compared against the limiting ERD criteria.

The effects of serially and simultaneously scheduled recovery operations on decontamination crew dose were investigated. General expressions of decontamination crew residual number, RN_2, were written for three classes of anticipated surface source conditions:

1. No significant new source created during the decontamination process
2. A thin new source created, but no self shielding involved
3. A thick new source created, and self shielding taken into account

Sample calculations indicated that the effects of prior decontamination from serially scheduled operations are probably more important than the effects of concurrent decontamination during simultaneously scheduled operations. The latter are essentially negligible when thin new source deposits are created. If there are no new source deposits, concurrent decontamination can cause small decreases in RN_2 (as much as 5%). Prior decontamination effects, however, exhibit a capability for reducing RN_2 factors by as much as 15% for a single decontamination pass and 27% for a double pass operation. It is also concluded that the effect of prior decontamination on RN_2 will seldom exceed (or even equal) the absolute magnitude (+ or -) of the current decontamination or new source contribution, for a single pass operation.

The next step in the analysis was to devise a countermeasure system evaluation procedure for determining the size of the decontamination organization required as a function of fallout pattern effects and the shelter distribution. Using this procedure, the percent of total population required for decontamination was observed to drop by factors of 3-1/2 to 7 (depending on whether the minimum shelter PF was 100 or 40) as city area increased from 16 to 400 square miles. Although the total number of decontamination personnel increased with city area, the rate of change decreased significantly for city areas greater than 100 square miles. The evaluation procedure outlined is applicable for any fallout condition, shelter system, or exposure criteria.

Recovery of an entire community by a specific decontamination organization depending on conventional urban methods and equipment may require one to several months. Therefore, planners should not overlook the latent potential of mass participation by the populace using household procedures such as sweeping with hand brooms and flushing with garden hoses. A procedure has been developed to obtain a complementary mass participation start time for various contamination conditions, decontamination organizations, and decontamination start times. The effective scheduling of mass decontamination efforts to augment those of the official decontamination organization demonstrated a capability to accelerate recovery completion times by many days--for certain expected combinations of standard intensity and conventional decontamination period.

It is recommended that these collective findings together with the results of the target analysis and decontamination scheduling studies be incorporated within the Recovery Model Development Program. Specifically, decontamination and dose control models should be developed to delineate the technical parameters associated with postattack recovery operations and to estimate the cost and effectiveness of implementing radiological countermeasures.

REFERENCES

1. Miller, Carl F., Fallout and Radiological Countermeasures, Volume II, Project IMU-4021, Stanford Research Institute, Menlo Park, California, January 1963.

2. Lee, Hong, Radiological Target Analysis Procedures, Project MU-5069, Stanford Research Institute, Menlo Park, California, March 1966.

3. Miller, Carl F., H. Lee, and J. D. Sartor, Introduction to Radiological Defense Planning, Stanford Research Institute, Menlo Park, California, May 1965.

4. Douglass, J. D., Jr., Calculating the Total Dose Received During a Brief Exposure in a Fallout Environment, Research Memorandum RM 156-4, Research Triangle Institute, Durham, North Carolina, March 1964.

5. Owen, W. L. and J. D. Sartor, Radiological Recovery of Land Target Components--Complex I and II, USNRDL-TR-570, U.S. Naval Radiological Defense Laboratory, San Francisco, California, May 1962.

6. Owen, W. L. and J. D. Sartor, Radiological Recovery of Land Target Components--Complex III, USNRDL-TR-700, U.S. Naval Radiological Defense Laboratory, San Francisco, California, November 1963.

7. Wiltshire, Lyman L., and W. L. Owen, Three Tests of Firehosing Technique and Equipment for the Removal of Fallout from Asphalt Streets and Roofing Materials, USNRDL-TR-1048, U.S. Naval Radiological Defense Laboratory, San Francisco, California, January 17, 1966.

8. Lee, Hong, Summary of Radiological Target Analysis Procedures for Decontamination Scheduling, Project MU-5069, Stanford Research Institute, Menlo Park, California, October 1966.

9. Goodrich, D. W., Utilization of Existing Shelters in Metropolitan Areas, Stanford Research Institute, Menlo Park, California, February 1965.

10. Miller, Carl F., Fallout and Radiological Countermeasures, Volume I, Project IMU-4021, Stanford Research Institute, Menlo Park, California, January 1963.

Appendix A

DECONTAMINATION PERFORMANCE TABLES

A large number of decontamination experiments have been conducted to determine the fallout removal effectiveness of various candidate methods and procedures.* Most of the later experiments were designed to obtain estimates of the efficiency coefficients and other parameters required to solve Equations (74) through (77). As a result, it has been possible to obtain discrete solutions to these equations for certain method-surface combinations and fallout conditions. The findings are presented in Tables A-1 through A-7.

The appropriate decontamination efficiency function appears at the head of each table. Values of the various equation parameters are shown as a function of fallout particle size range (psr), initial mass loading $(M_o)_{jk}$, and number of cleaning passes $p_{\ell k}$. The residual mass $M_{j\ell k}$ and minimum residual mass $M^*_{j\ell k}$, corresponding to $F_{j\ell k}$ and $F^*_{j\ell k}$, are also given. In the case of wet methods, the water required per pass $w_{\ell k}$ is also included.

The rate of area coverage $r_{\ell k}$ is not shown, since it is the reciprocal of specific effort $e_{jk\ell}$. However, values for the working rate $r'_{\ell k}$ are given. This parameter represents the maximum rate of coverage when there are no operational losses due to turn around time, trip overlap, and increased redeposition of fallout material alongside successively cleaned strips.

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* A compilation of the results from these tests in terms of both the environmental and operational parameters affecting decontamination performance is contained in the following reference:

Owen, W. L., F. K. Kawahara and L. L. Wiltshire, Radiological Reclamation Performance Summary, Vol. I, Performance Test Data Compilation, USNRDL-TR-967, U.S. Naval Radiological Defense Laboratory, San Francisco, California, October 1965.

Thus, $r'_{\ell k}$ is always equal to or greater than $r_{\ell k}$, since the latter is an operational rate embracing the effects of all these losses. The approximate ratio of $r_{\ell k}$ to $r'_{\ell k}$ is indicated at the bottom of each table.

Additional information may be found at the foot of the tables regarding such performance factors as manpower requirements, forward speed, gear selection, and nozzle pressure. Where the test data permitted, estimates of the constants in Equation (77) were made and entered in the tables. These include $\alpha_{\ell k}$, the spreading coefficient, and $(M_o^*)_{j\ell k}$ the upper limit of $M_{j\ell k}^*$, where $(M_o^*)_{j\ell k}$ is ec to the $R'_{\ell k}$ of Equation (77).

For certain decontamination experiments, the data were of no use to the efficiency functions. Either no attempt was made to perform multiple pass tests, or as in the case of plowing and sod cutting, additional passes were deemed inadvisable. Tables A-8 to A-10 contain the results of these single pass tests. The entries are limited to the basic parameters describing decontamination performance and effectiveness. In general, the data do not permit the determination of any particle size or mass loading effects.

TABLE A-1

FIREHOSING OF ASPHALT SURFACES

$$F_{j\ell k} = F^*_{j\ell k} + \left(1 - F^*_{j\ell k}\right) e^{-K_{\ell k}\, p_{\ell k}}$$

Particle Size Range psr (μ)	Mass Loading $(M_o)_{jk}$ (g/ft^2)	Working Rate $r'_{\ell k}$ $\left(\frac{1000\ ft^2}{hr}\right)$	Water Req'd.* $w_{\ell k}$ (gal/ft^2)	Specific Effort $e_{jk\ell}$ $\left(\frac{nozl\text{-}hr}{1000\ ft^2}\right)$	No. of Passes $p_{\ell k}$ -	Residual Mass $M_{j\ell k}$ (g/ft^2)	Residual Fraction $F_{j\ell k}$ (%)	Efficiency Coefficient $K_{\ell k}$ -	Min.Resdl. Mass $M^*_{j\ell k}$ (g/ft^2)	Min.Resdl. Fraction $F^*_{j\ell k}$ (%)
				Smoothly Textured Asphalt						
88-177	25	22.2	0.27	0.045	1	0.70	2.8	5.40	0.58	2.3
					2	0.58	2.3			
	90	18.6	0.32	0.054	1	1.20	1.32	4.80	0.45	0.50
					2	0.45	0.50			
300-600	5	26.4	0.23	0.039	1	0.33	6.6	2.85	0.06	1.2
					2	0.076	1.5			
	25	22.2	0.27	0.045	1	1.20	4.8	3.10	0.11	0.44
					2	0.16	0.64			
					3	0.11	0.44			
				Roughly Textured Asphalt						
88-177	25	22.2	0.27	0.045	1	1.8	7.2	4.05	1.4	5.6
					2	1.4	5.6			
	90	18.6	0.32	0.054	1	6.4	7.1	2.88	1.39	1.54
					2	1.7	1.9			
					3	1.4	1.55			
300-600	5	26.4	0.23	0.039	1	0.36	7.2	3.35	0.19	3.8
					2	0.19	3.8			
	25	22.2	0.27	0.045	1	0.72	2.9	4.0	0.27	1.08
					2	0.27	1.08			

Manpower required: 2 to 3 men per nozzle

Rate of Coverage: $r_{\ell k} = r'_{\ell k}$

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* At 75 psi nozzle pressure, standard fire nozzle, 5/8 in. tip diam.

TABLE A-2

"CONVENTIONAL" AND "IMPROVISED" FLUSHING OF PAVED SURFACES

Concrete and Asphalt Streets, $F_{j\ell k} = F^*_{j\ell k} + \left(1 - F^*_{j\ell k}\right)e^{-3K^o_{\ell k}} P^{1/3}_{\ell k}$

Particle Size Range psr (μ)	Mass Loading $(M_o)_{jk}$ (g/ft^2)	Specific Effort $e_{jk\ell}$ $\left(\frac{\text{Flshr-hr}}{1000\ \text{ft}^2}\right)$	No. of Passes $P_{\ell k}$ -	Residual Mass $M_{j\ell k}$ (g/ft^2)	Residual Fraction $F_{j\ell k}$ (%)	Efficiency Coefficient $3K^o_{\ell k}$ -	Min.Resdl. Mass $M^*_{j\ell k}$ (g/ft^2)	Min.Resdl. Fraction $F^*_{j\ell k}$ (%)
			Smoothly Textured Concrete					
44-100	20	0.0060	1	0.27	1.35	6.56	0.24	1.20
and			2	0.24	1.20			
74-177	100	0.0060	1	1.50	1.50	4.70	0.61	0.61
			2	0.88	0.88			
150-300	20	0.0060	1	0.096	0.48	6.53	0.065	0.32
and			2	0.072	0.36			
300-600	100	0.0060	1	0.75	0.75	5.05	0.058	0.058
			2	0.20	0.20			
			Roughly Textured Asphalt					
44-100	20	0.0060	1	0.64	3.20	4.16	0.34	1.70
and			2	0.47	2.35			
74-177	100	0.0060	1	0.86	0.86	5.18	0.31	0.31
			2	0.47	0.47			
150-300	20	0.0060	1	0.18	0.90	4.99	0.037	0.185
and			2	0.078	0.39			
300-600	100	0.0060	1	0.66	0.65	5.14	0.073	0.073
			2	0.20	0.20			

Manpower required: one man per flusher unit.

Forward speed: $S_{\ell k} = 6$ mph.

Working rate: $r'_{\ell k} = 285\ (10^3 ft^2/hr)$

Rate of coverage: $r_{\ell k} \simeq 2/3\ r'_{\ell k}$ due to stream overlap between trips and redeposition of fallout alongside cleaned strips

Water required: 0.13 gal/ft^2 at 40 psi nozzle pressure for conventional flusher and 0.11 gal/ft^2 at 85 psi nozzle pressure for an improvised flusher

TABLE A-3

"CONVENTIONAL" MECHANIZED SWEEPING OF PAVED SURFACES

Asphalt or Concrete Streets, $F_{j\ell k} = F^*_{j\ell k} + \left(1 - F^*_{j\ell k}\right) e^{-K_{\ell k} p_{\ell k}}$

Mass Loading	Forward Speed	Working Rate	Specific Effort	No. of Passes	Residual Mass	Residual Fraction	Efficiency Coefficient	Min.Resdl. Mass	Min.Resdl. Fraction
$(M_o)_{jk}$	$S_{\ell k}$	$r'_{\ell k}$	$e_{jk\ell}$	$p_{\ell k}$	$M_{j\ell k}$	$F_{j\ell k}$	$K_{\ell k}$	$M^*_{j\ell k}$	$F^*_{j\ell k}$
(g/ft^2)	(mph)	$\left(\frac{1000\ ft^2}{hr}\right)$	$\left(\frac{swpr\text{-}hr}{1000\ ft^2}\right)$	-	(g/ft^2)	(%)	-	(g/ft^2)	(%)
			WAYNE-450: $\alpha_{\ell k}$ = 0.032 and $(M^*_o)_{j\ell k}$ = 2.0						
25	7.0	180	0.0110	1	3.7	14.8	2.21	1.1	4.4
				2	1.4	5.6			
				3	1.1	4.4			
50	6.0	156	0.0128	1	5.4	10.8	2.54	1.6	3.2
				2	1.9	3.8			
				3	1.6	3.2			
100	5.2	132	0.0152	1	6.8	6.8	3.0	1.9	1.9
				2	2.1	2.1			
				3	1.9	1.9			

Particle size range: 5 to 275 μ.
Manpower required: one man per sweeper unit.
Gear selection: second of three forward gears.
Rate of coverage: $r'_{\ell k} \simeq 1/2\ r'_{\ell k}$ due to an estimated 50% broom overlap between trips.

TABLE A-4

"VACUUMIZED" MECHANIZED SWEEPING OF ASPHALT STREETS

$$F_{j\ell k} = F^*_{j\ell k} + \left(1 - F^*_{j\ell k}\right) e^{-K_{\ell k} P_{\ell k}}$$

Mass Loading $(M_o)_{jk}$ (g/ft^2)	Forward Speed $S_{\ell k}$ (mph)	Working Rate $r'_{\ell k}$ $\left(\frac{1000\ ft^2}{hr}\right)$	Specific Effort $e_{jk\ell}$ $\left(\frac{swpr\text{-}hr}{1000\ ft^2}\right)$	No. of Passes $P_{\ell k}$ -	Residual Mass $M_{j\ell k}$ (g/ft^2)	Residual Fraction $F_{j\ell k}$ (%)	Efficiency Coefficient $K_{\ell k}$ -	Min.Resdl. Mass $M^*_{j\ell k}$ (g/ft^2)	Min.Resdl. Fraction $F^*_{j\ell k}$ (%)
			TENANT-100: $\alpha_{\ell k} = 0.012$ and $(M^*_o)_{j\ell k} = 1.14$						
20	4.0	84	0.024	1	1.2	6.0	3.0	0.24	1.2
				2	0.29	1.45			
				3	0.24	1.2			
50	4.0	84	0.024	1	3.0	6.0	3.0	0.50	1.0
				2	0.6	1.2			
				3	0.5	1.0			
100	4.0	84	0.024	1	5.8	5.8	3.0	0.80	0.8
				2	1.0	1.0			
				3	0.8	0.8			
			TENANT-80: $\alpha_{\ell k} = 0.021$ and $(M^*_o)_{j\ell k} = 5.32$						
20	4.6	84	0.024	1	5.1	25.5	1.72	1.85	9.25
				2	2.4	12.0			
				3	2.0	10.0			
50	4.6	84	0.024	1	11.8	23.6	1.72	3.5	7.0
				2	5.0	10.0			
				3	3.8	7.6			
100	4.6	84	0.024	1	21.3	21.3	1.72	4.7	4.7
				2	7.8	7.8			
				3	5.2	5.2			

Particle size range: 5 to 275 µ.
Manpower required: one man per sweeper unit.
Gear selection: second of three forward gears.
Rate of coverage: $r_{\ell k} \simeq 1/2\ r'_{\ell k}$ due to an estimated 50% broom overlap between trips.

TABLE A-5

DECONTAMINATION OF OPEN FIELDS BY MECHANIZED EARTH MOVING AND AGRICULTURAL EQUIPMENT*

$$F_{j\ell k} = e^{-K_{\ell k} p_{\ell k}}$$

Method and Equipment	Surface and Condition	Working Rate $r'_{\ell k}$ $\left(\frac{1000\ ft^2}{hr}\right)$	Specific Effort $e_{jk\ell}$ $\left(\frac{equip\text{-}hr}{1000\ ft^2}\right)$	No. of Passes $p_{\ell k}$ -	Residual Fraction $F_{j\ell k}$ (%)	Efficiency Coefficient $K_{\ell k}$ -
		Surface Removal				
Scraping 2 to 4 in. deep: 8 cu.yd. capacity	Moist turf	36	0.055	1	0.16	6.45
	Tilled soil: dry or moist	30	0.067	1	1.0	4.60
				2	0.01	
	Hard ground	24	0.083	1	3.5	3.35
				2	0.13	
Grading and scraping 2 in. deep	Moist turf	29	0.117	1	2.1	3.85
				2	0.045	
	Tilled soil	40	0.083	1	4.5	3.1
				2	0.20	
	Hard ground	33.5	0.10	1	1.8	4.0
				2	0.034	
Grading 2 in. deep: 8 to 12 ft. blade	Hard ground	36	0.042	1	4.3	3.15
				2	0.18	
Bulldozing	Hard ground	13.8	0.183	1	1.1	4.5
		Burial in Place				
Plowing 10 in. deep: 3 share gang	Tillable ground	18 to 27	0.083	1	20	-
Rototilling 8 to 10 in.deep by 4 in.wide	Tillable ground	21.5	0.050	1	<40	-

Manpower required: one man per equipment unit.

Rate of coverage: $r_{\ell k} = 0.4$ to $0.7\ r'_{\ell k}$ due to turn around and maneuvering losses between trips.

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* Decontamination effectiveness not considered to be affected by either particle size or mass loading.

TABLE A-6

FIREHOSING FLAT TAR AND GRAVEL ROOFS*

$$F_{j\ell k} = F^*_{j\ell k} + \left(1 - F^*_{j\ell k}\right) e^{-3K^o_{\ell k}} p^{1/3}_{\ell k}$$

Working Rate	Water Required** Fire	Water Required** Flare	Specific Effort	No. of Passes	Residual Fraction	Efficiency Coefficient	Min. Resdl. Fraction
$r'_{\ell k}$	$w_{\ell k}$		$e_{jk\ell}$	$p_{\ell k}$	$F_{j\ell k}$	$3K^o_{\ell k}$	$F^*_{j\ell k}$
$\left(\frac{1000\ ft^2}{hr}\right)$	(gal/ft^2)		$\left(\frac{nozl\text{-}hr}{1000\ ft^2}\right)$	-	(%)	-	(%)
0.54	1.1	0.7	0.185	1 2	10 6	2.48	2
0.30	2.0	1.2	0.33	1	2 - 6	Note: Single pass at slower rates more effective than 2 passes at fastest rate.	
0.18	3.3	2.1	0.55	1	0.5 - 2		

Manpower required: 3 men per nozzle.
Rate of coverage: $r_{\ell k} = r'_{\ell k}$.

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* Decontamination effectiveness and equation coefficients are relatively unaffected by (1) particle size, (2) mass loading, (3) loose or fixed gravel, or (4) type of nozzle.

** At 75 psi fire nozzle pressure or 150 psi flare nozzle pressure.

TABLE A-7

HOSING OF SLOPED COMPOSITION-SHINGLE ROOFS*

$$F_{j\ell k} = F^*_{j\ell k} + \left(1 - F^*_{j\ell k}\right) e^{-3K^o_{\ell k}\, p^{1/3}_{\ell k}}$$

Mass Loading	Working Rate	Water Required* Flare Nozzle	Water Required* Fire Nozzle	Specific Effort	No. of Passes	Residual Mass	Residual Fraction	Efficiency Coefficient	Min.Resdl. Mass	Min.Resdl. Fraction
$(M_o)_{jk}$	$r'_{\ell k}$	$w_{\ell k}$		$e_{jk\ell}$	$p_{\ell k}$	$M_{j\ell k}$	$F_{j\ell k}$	$3K^o_{\ell k}$	$M^*_{j\ell k}$	$F^*_{j\ell k}$
(g/ft^2)	$\left(\frac{1000\ ft^2}{hr}\right)$	(gal/ft^2)		$\left(\frac{nozl\text{-}hr}{1000\ ft^2}\right)$	-	(g/ft^2)	(%)	-	(g/ft^2)	(%)
10	32	0.11	0.14	0.031	1	0.91	9.1	2.70	0.26	2.6
					2	0.58	5.8			
					3	0.46	4.6			
25	28	0.13	0.16	0.036	1	2.04	8.16	2.83	0.60	2.4
					2	1.28	5.12			
					3	1.02	4.08			
40	24	0.15	0.18	0.042	1	2.95	7.37	2.96	0.92	2.3
					2	1.86	4.65			
					3	1.47	3.67			
75	19	0.19	0.23	0.053	1	4.78	6.34	3.18	1.70	2.27
					2	3.01	4.02			
					3	2.43	3.24			
100	15.5	0.23	0.28	0.064	1	5.24	5.24	3.40	2.0	2.0
					2	3.37	3.37			
					3	2.80	2.80			

Particle size range: 5 to 275 μ.
Manpower required: 3 men per nozzle.
Rate of coverage: $r_{\ell k} = r'_{\ell k}$
Spreading Coefficient: $\alpha_{\ell k} = 0.0067$
Upper Limit of $M^*_{j\ell k}$: $(M^*_o)_{j\ell k} = 4.0$

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* Direct hosing at roof level with experimental flare nozzle at 120 psi or lobbing of water streams from ground with standard fire nozzle at 40 psi.

TABLE A-8

DECONTAMINATION OF COMPOSITION SHINGLE ROOFS BY SLOW MANUAL METHODS - SINGLE PASS OPERATIONS ONLY

Method or Equipment	No. of Men	Working Rate $r'_{\ell k}$ $\left(\frac{1000\ ft^2}{hr}\right)$	Specific Effort $e_{jk\ell}$ $\left(\frac{equip\text{-}hr}{1000\ ft^2}\right)$	Residual Mass $M_{j\ell k}$ (g/ft^2)	Residual Fraction $F_{j\ell k}$ (%)
Vacuuming	1	0.55	1.82	1.6	3.2
Garden Hosing:					
at 8 psi	1	1.50	0.67	6.0	12
at 35 psi	1	4.4	0.23	8.5	17
Corn broom	3	2.2	0.45	9.0	18
Street broom	3	4.8	0.21	15.5	31

Particle size range: 150 to 300 μ.

Mass loading: $(M_o)_{j\ell k} = 50\ g/ft^2$.

Rate of coverage: $r_{\ell k} = r'_{\ell k}$.

Water required: $w_{\ell k} = 0.093\ gal/ft^2$ at 8 psi and 0.068 at 35 psi for the respective working rates given.

TABLE A-9

DECONTAMINATION OF SMALL PAVED AREAS AND WALKWAYS BY SLOW MANUAL METHODS - SINGLE PASS OPERATIONS

Surface and Condition	Method or Equipment	No. of Men	Working Rate $r'_{\ell k}$ $\left(\frac{1000\ ft^2}{hr}\right)$	Water Required $w_{\ell k}$ (gal/ft^2)	Specific Effort $e_{jk\ell}$ $\left(\frac{equip\text{-}hr}{1000\ ft^2}\right)$	Residual Mass $M_{j\ell k}$ (g/ft^2)	Residual Fraction $F_{j\ell k}$ (%)
Concrete, wet	Corn broom	3	3.9		0.85	5.0	<10.0
Concrete, dry	Vacuuming	1	1.45		0.75	0.75	1.5
	Garden hosing at 35 psi	1	1.8	0.20	0.60	0.85	1.7
	Corn broom	3	6.0		0.55	1.9	3.9
	Street broom	3	5.4		0.60	2.5	5.0
Asphalt, dry	Vacuuming	1	1.1		1.0	0.35	0.7
	Garden hosing at 35 psi	1	.78	0.23	1.4	1.2	2.4
	Corn broom	3	5.0		0.65	4.6	9.2
	Street broom	3	6.4		0.50	8.0	16.0
Macadam, dry	Vacuuming	1	0.66		1.70	0.4	0.8
	Garden hosing at 35 psi	1	0.84	0.40	1.4	1.0	2.0
	Corn broom	3	2.5		1.4	10.5	21.0

Particle size range: 150 to 300 μ.
Mass loading: $(M_o)_{jk} = 50\ g/ft^2$.

Rate of coverage: $r_{\ell k} < r'_{\ell k}$ due to nonproductive time losses.

TABLE A-10

DECONTAMINATION OF LAWNS AND YARDS BY MECHANIZED, SEMI-MECHANIZED, AND MANUAL METHODS - SINGLE PASS OPERATIONS.*

Method and Equipment	Surface and Condition	No. of Men	Working Rate $r'_{\ell k}$ $\left(\frac{1000\ \text{ft}^2}{\text{hr}}\right)$	Specific Effort $e_{jk\ell}$ $\left(\frac{\text{equip-hr}}{1000\ \text{ft}^2}\right)$	Residual Fraction $F_{j\ell k}$ (%)
	Surface Removal				
Sod cutting with 12 in. blade	Lawn: accessible, well conditioned turf	2	1.7	0.8	1.1
	Lawn: accessible, sparse rock-laden turf	2	1.6	0.75	1.6
	Lawn: confined and obstructed, wet turf	3	1.3	1.1	1.6
Scraping with light duty farm tractor	Lawn: confined, obstructed, well conditioned turf	2-3	1.8-4.2	0.6-0.3	<14.0
Hand shoveling 2 to 3 in. layer into wheelbarrow	Lawn: same as above	4	0.7-1.8	1.5-0.6	<12.0
	Gravel laden turf or ground	4	1.25	0.9	12.0
Hand shoveling 1/2 in. layer	Thawing ground	4	1.9	0.6	12.0
	Burial in Place				
Garden plowing 4 to 6 in. deep	Tillable ground: grass 5 to 8 in. high	1	1.75	0.7	55
Hand spading 0 to 8 in. deep	Same as above	4	1.45	3.0	42

Rate of coverage: $r_{\ell k} < r'_{\ell k}$ due to turn-around time losses, overlapping of successive trips, etc.

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* Decontamination effectiveness is essentially unaffected by either particle size or mass loading.

Appendix B

DERIVATION OF THE EXTENDED REAL-PLANE DOSE RATE $I_j(\text{ext})$

The estimate of the reference dose rate $I_j(\text{ext})$ is based on the application of the inverse square law to a radioactive source spread uniformly over an extensive plane surface. Neglecting the effects of air attenuation and buildup, the dose rate, I_j, at a height, h, over the center of a smooth disk source of radius, r, is derived from the general expression

$$I_j = I_o 2\pi \int_o^r \frac{rdr}{h^2 + r^2}$$

or

$$I_j = I_o \pi \, \ell n \, 1 + \frac{r^2}{h^2} \qquad \text{(B.1)}$$

The textbook solution of the disk source problem is given by Hine and Brownell* in the form

$$I_j = \frac{A_c \Gamma}{r^2} \, \ell n \; 1 + \frac{r^2}{h^2} \quad . \qquad \text{(B.2)}$$

Setting these two expressions equal to each other and cancelling terms, the unit source strength becomes

$$I_o = \frac{A_c}{\pi r^2} \Gamma = q\Gamma \qquad \text{(B.3)}$$

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* Hine, Gerald J., and Gordon L. Brownell, Radiation Dosimetry, Academic Press, New York, 1956.

where

A_c is the total activity (in ci or mc),

q is the concentration of activity per unit area,

Γ is the specific gamma dose rate constant.

Γ has the dimensions of cm^2 - r/mc - hr, and, to be consistent, q must be dimensioned in mc/cm^2. Their product reduces to r/hr, which according to Eq. (B.3) represents the dimensions of I_o.

However, the unit source strength, I_o, carries a deeper connotation than is indicated by its dimensions. Because Γ is defined as the dose rate at a given distance from a point source, the unit for this quantity is often expressed in r/mc - hr at one cm (in air). Multiplying this by q(mc/cm^2) results in the unit expression (r/hr)/cm^2 at one cm for I_o. Thus, in general, the source strength, I_o, is numerically equal to the dose rate at unit distance from a point source whose activity is equal to that contained within a unit area of surface contamination.

It is obvious from Eq. (B.1) that I_j will increase indefinitely as the radius, r, increases. Experimental data obtained with a directional gamma detector at Operation Plumbbob[*] supplied the limiting value of r. At a detector height of three feet, the radiation contributions beyond a distance of 300 feet were found to be negligible for an open ground surface. Thus, from Eq. (B.1), the estimate of the reference dose rate, I_j(ext), at three feet above the center of an extended real plane surface of uniformly distributed fallout becomes

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[*] Strope, W. E., Evaluation of Countermeasures System Components and Operational Procedures, Operation Plumbbob, Project 323,-WT-1464, USNRDL, San Francisco, California, September 1959.

$$I_j(\text{ext}) = I_o \pi \, \ell n \;\; 1 + \frac{300^2}{3^2}$$

or

$$I_j(\text{ext}) = 28.9 \; I_o \quad . \qquad \text{(B.4)}$$

Since the limiting value of r is not known to more than two significant figures, the estimate of $I_j(\text{ext})$ is set equal to 29 I_o. Because Eq. (B.4) incorporates experimental conditions, it represents an air-attenuated dose rate. Thus, the value of 29 I_o includes the attenuation resulting from both average air thickness and average terrain roughness effects.

Appendix C

DERIVATION OF CREW DOSE FOR A THICK NEW SOURCE

The effects of self shielding for a source having a thickness of x cm may be represented as

$$A_s = (1 + \mu x)\, e^{-\mu x} \qquad (C.1)$$

where μ is the linear absorption coefficient, and $1 + \mu x$ is an approximation of the buildup factor $B(X)$ due to multiple scattering through the source material. From Reference 2, the intensity, I_N, for a finite new-source deposit at time τ after start of decontamination (first pass) is given by

$$I_N(\tau) = \frac{(1-F_1)\, WL\, I_o\, A_N^s\, A_s}{\delta^2} \qquad (C.2)$$

where the symbols in the right hand member have the same meanings as they did previously in Equations (135), (136) and (137).

Because Equation (C.2) was based upon the assumption that decontamination progresses at a constant velocity, say V, the thickness of the source also must necessarily increase at a constant velocity, say v. Thus, both L and x may be expressed as functions of τ;

$$L = V\tau \text{ and } x = v\tau$$

Substituting Equation (C.1) into Equation (C.2), incorporating the above relations, and then integrating over τ results in an expression for crew dose due to thick new-source contributions.

$$D_2'(N) = \int_o^T \frac{(1-F_1)\, WL\, I_o\, A_N^s}{\delta^2}\,(1 + \mu x)e^{-\mu x}\, d\tau$$

$$= \frac{(1-F_1)\, WVI_o\, A_N^s}{\delta^2} \int_o^T \tau(1 + \mu v\tau)\, e^{-\mu v\tau}\, d\tau \qquad (C.3)$$

or
$$D_2'(N) = \frac{(1-F_1)\ WVI_o\ A_N^s}{\delta^2\ v^2}\left[\frac{3}{\mu^2} - \frac{3}{\mu^2 e^{\mu v\tau}} - \frac{3\ v\tau}{\mu e^{\mu v\tau}} - \frac{v^2\ \tau^2}{e^{\mu v\tau}}\right] \qquad (C.4)$$

converting back into terms of x and L

$$D_2'(N) = \frac{(1-F_1)\ WLI_o\ A_N^s}{\delta^2\ x^2}\ \tau\left[\frac{3}{\mu^2}\left(1-e^{-\mu x}\right) - e^{-\mu x}\left(x^2 + \frac{3x}{\mu}\right)\right] \qquad (C.5)$$

and

$$RN_2(N) = \frac{(1-F_1)\ WL\ A_N^s}{29\ \delta^2 x^2}\left[\frac{3}{\mu^2}\left(1-e^{-\mu x}\right) - e^{-\mu x}\left(x^2 + \frac{3x}{\mu}\right)\right] \qquad (C.6)$$

which corresponds to the expression used in Equation (136).

For the case of a relatively thin new source, there will be no self shielding. Therefore, the term $(1+\mu x)e^{-\mu x}$ becomes unity, and Equation (C.3) simplifies to

$$D_2'(N) = \frac{(1-F_1)\ WVI_o\ A_N^s}{\delta^2}\int_o^\tau \tau\ d\tau$$

$$= \frac{(1-F_1)\ WVI_o\ A_N^s}{\delta^2}\left(1/2\ \tau^2\right) \qquad (C.7)$$

Substituting for V and dividing by $D_2 = 28.9\ I_o\ \tau$

$$RN_2\ (N) = \frac{(1-F_1)\ WL\ A_N^s}{2\ \delta^2\ 29} \qquad (C.8)$$

which is the form found in Equation (135).

If the absorption coefficient, μ, is taken to be approximately 0.1 for fallout material, the bracketted term in Equation (C.6) becomes 1/2 when x equals 1 cm. Under these conditions, Equation (C.6) is the same as Equation (C.8). Thus, a deposit depth of x = 1 cm may be used as an approximate boundary condition for determining whether the occasion calls for the thin source Equation (135) or the thick source Equation (136).

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13. ABSTRACT

Previous investigations on the analysis, planning, and scheduling of radiological recovery operations have recognized and identified many related and important problem areas. This report treats several of these problems and derives methods and analytical expressions appropriate to their solution. Procedures are developed for estimating decontamination start times with minimum total exposure to groups of people engaged in either decontamination or facility operations. Methods of forecasting exposure doses to decontamination crews and facility operator crews are revised, to simplify evaluation of the effect of prior and concurrent decontamination operations on the effective residual number for a prescribed postattack routine. A technique is devised for relating the size of decontamination organizations to the dimensions of the area to be decontaminated and the surviving populations in urban areas. The final problem explored is the effect of increased size (and number) of decontamination crews on the decontamination completion time.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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facility operation						
start time						
exposure dose						
recovery effort						
residual number						
shelter exit time						
allowable dose						
standard exposure rate						
contribution factors						
fallout particles						
decontamination efficiency						
decontamination performance						
target characteristics						
fallout properties						
shelter distribution						
organization size						
mass decontamination						
urban area						
urban population						