AN ANALYSIS OF EFFECTS OF NUCLEAR ATTACKS ON TUCSON AND PHOENIX

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INTRODUCTION.—The problem of worldwide fallout of radioactive fission products from peacetime nuclear bomb tests has, in recent years, received both careful scientific attention and wide public discussion. It is remarkable that the vastly more serious problems that would arise in the event of actual nuclear war have, by comparison, received only slight scientific notice and almost no public discussion. The problems confronting a population under nuclear attack are exceedingly complex scientific problems that will only be grasped by the public at large after they have been analyzed and repeatedly interpreted to the public by many scientists.

But even when given predictions based on theoretical damage calculations such as those to be presented here, the layman will probably not immediately accept the dire implications. The person who has not himself carefully traced through the inexorable sequence of physical processes initiated by detonation of a nuclear weapon and who is not himself accustomed to drawing quantitative inferences from theoretical or semi-theoretical arguments is all too likely simply to reject the nuclear attack inferences as unpleasant speculations or to pass them off with some superficially fatalistic remark. This likelihood makes it all the more urgent that more scientists perform an interpretive role in what is a vitally important educational program. No matter how viewed, it is indispensable that all members of the public be made much more clearly aware of what can happen to them in event of nuclear war. The present analysis of effects of nuclear attacks on two Arizona cities is chiefly aimed at the intermediate goal of providing members of the Arizona scientific community with reference data that might prove useful to them in carrying out this interpretive function whenever opportunity arises.

As will be made clear below, there are a number of regional characteristics that make survival in Arizona a distinctly different problem from that of survival in other geographical areas under nuclear attack. On the other hand, many of the basic bomb phenomena that pose these problems will be essentially the same for Arizona as for any other area. Quantitative information on high-yield bomb phenomena has recently been made available through publication by the United States Atomic Energy Commission of its report, *The Effects of Nuclear Weapons* (AEC, 1957). This report has been my principal source of bomb-effect data in preparing the present analysis. Scientifically trained persons will find it very informative; but I would fear that the layman could not fully develop from it the image of bomb destruction that lies latent in its many equations, graphs, and nomograms.

In addition to the above main reference, a very useful supplementary discussion, particularly informative on physiological and genetical topics, has been published still more recently by the Government of India (India, 1958). Beyond these two major references, one finds only a handful of scientific papers on the present subject, a measure of the dangerously limited attention that has thus far been given to the question of the prospective nature of nuclear warfare.

Never before in man's history have questions of the detailed mechanics of warfare been so intimately the concern of the civilian population. Never before have such questions been interwoven so tightly with complex technical matters.

DISCUSSION OF ASSUMPTIONS.. — It will be assumed here that the two most likely targets of nuclear attack in Arizona are the Tucson and Phoenix areas. Ground zero, the point of hypothetical bomb detonation, will be taken to be within the boundaries of Davis-Monthan AFB for the case of Tucson, but will be put in the downtown area in the case of Phoenix. More specifically, Tucson ground zero will be set at the intersection of Ajo Way and Swan Road extended, while Phoenix ground zero will be arbitrarily set at Central and Van Buren. Granting target value to such points, it remains obvious that ballistic errors could shift ground zero several miles in any direction, but this probability will not be considered in the followng discussion.

It wll be assumed that an enemy weapon of 20 MT yield (1 MT = explosive energy equal to that of 1 megaton TNT) is delivered to each target. In support of the reasonableness of this assumption the following points may be noted: (1) A weapon of 20 MT yield is adopted in the Indian analyses (India, 1958) as the "nominal high-yield weapon." (2) In the 1957 Holifield Subcommittee discussions of Operation Sentinel, an analysis of a hypothetical nuclear attack on this country, it was reported that weapons of 5, 10, and 20 MT were assumed to be delivered to selected target cities, suggesting that capability of delivery of a 20 MT weapon must now be reckoned with (Joint Com. on At. Energy, 1957, Pt. 1, pp. 135-141). Hence Tucson, at least, must be regarded as a potential 20 MT target because it is the site of one of only thirty-odd continental SAC (Strategic Air Command) bases, and it is widely recognized that SAC bases are now highest-priority targets for a would-be aggressor. (3) Release of 20 MT requires fission of only about a ton of fissile materials. This much net fission might reasonably be expected (India, 1958) to result from packaged weapons weighing, say, five to ten tons. In late 1958 an Atlas missile sent into an orbit of 900-mile apogee height a last-stage vehicle weighing over four tons; Russia has already done much better. Thus it seems prudent to assume that advances in weaponry and missile propulsion will place 20 MT warheads at the disposal of potentially hostile ICBM (intercontinental ballistic missile) groups in the near future, if, indeed, this possibility has not already been realized. (4) Finally, for the case of Tucson, further reason for regarding 20 MT as not only reasonable but possibly even too low a weapon yield is found in the fact that Davis-Monthan AFB is currently under consideration as a prospective ICBM launching site. It has been estimated (Lapp, 1959) that to knock out the type of reinforced-concrete subterranean launching installations that are planned for such sites, enemy weapons must combine megatonnage and accuracy such as to impose blast overpressures of 100 psi upon these "hardened sites." Present missile accuracies, Lapp concludes, would dictate use of enemy weapons of well over 20 MT yield against such sites, 100 MT being not too much from an aggressor's viewpoint.

In all, the 20 MT assumption seems quite justifiable, albeit speculative. Assumption of a 5 MT or 10 MT weapon for the Phoenix attack might seem militarily more reasonable, but for simplicity of analysis, a 20 MT yield will be assumed for both cases.

Finally, it will be assumed that a *surface burst* rather than an air burst occurs at each target. It is ominously significant that all 2500 megatons which were assumed to be delivered to a total of 144 American cities in the Operation Sentinel paper-exercises were taken to be surface bursts. Although certain types of blast effects and all types of thermal radiation effects are much more injurious from air bursts than from surface bursts, the potential killing power of weapons in the megaton range resides above all in the *local fallout*, and, as we shall see below, this potential can only be realized in surface bursts.

Having set out the assumptions to be used, we may next examine the consequences of surface detonation of 20 MT weapons at the specified ground-zero locations in Tucson and Phoenix. It will be convenient to consider, in turn, blast effects, initial nuclear radiation effects, thermal radiation effects, and local fallout effects, and then to discuss questions of evacuation and survival of persons living near the hypothetical target areas.

BLAST EFFECTS. — The first category of bomb damage, blast effects, will be discussed in three parts: fireball- and crater-formation, shock-wave destruction, and aerodynamic drag destruction.

Fireball- and crater-formation. — The energy-yielding fission process is accomplished within a time of the order of a microsecond after detonation, the attendant energy release raising to a very high temperature and pressure the fission products, the fissile but unfissioned residue, and the weapons case, all of which are rendered gaseous as a result of the million-degree temperatures developed. The sudden expansion of these incandescent gases forms the *fireball*, sets up an intense *shock wave*, and blasts out a large *crater* (in the case of surface bursts). The fireball rapidly expands to a maximum diameter of about two miles in a time of the order of ten seconds for the case of a 20 MT weapon, and concurrently accelerates buoyantly upward. Attaining maximum vertical velocities of the order of several hundred feet per second, the fireball and entrained air ascend through the entire troposphere and on into the stratosphere, the mushroom cloud reaching maximum altitudes of about 85,000 feet in a total elapsed time of only about ten minutes after detonation. (Unless otherwise specified, all numerical magnitudes are to be assumed applicable just to the 20 MT surface bursts here considered.)

A crater of diameter about 3500 feet and central depth 300 feet is formed, and a portion of the removed soil and rock is blasted up into the fireball before the latter can get away in its buoyant ascent. It is this entrapped fraction of total crater-debris that becomes the vehicle for bringing back to earth the radiologically lethal fission products in the form of the local fallout.

A crater three-fifths of a mile across and of depth equal to the height of a 25-story building is impressive even in a state containing Diablo Crater and the Lavender Pit, but the total number of casualties and the total material damage directly attributable to crater-formation comprises only a minute fraction of the overall bomb effect. A much more potent feature of the explosion is the shock wave, which we consider next.

Shock-wave destruction. — A hemispherically expanding shock wave propagates out from ground zero, initially with speeds of the order of four or five times that of sound, too fast for the material expansion of the fireball to keep pace, giving rise to early "breakaway" of the shock front from the fireball proper. As the shock front passes a given object, there occurs a sudden rise of pressure exerted on that object. The excess of post-shock pressure over initial barometric pressure is termed the *overpressure*. As the shock wave diffracts around any large building, a very large overpressure acts selectively upon that side of the building nearer ground zero during the time required for the shock to propagate along the building to the far side. If the building or object is not too small and its ultimate strength not too great, the unbalanced lateral force may act for long enough (impulse great enough) to cause the structure to fail. Such damage is said to result from *diffraction loading*, since it takes place during the period within which the wave is engulfing (diffracting around) the structure. Well-closed buildings (and automobiles) also suffer an overall crushing action even after engulfment by the shock, but this type of damage is conveniently lumped together with true diffraction damage. In both of these cases, the degree of damage proves to be chiefly dependent upon the magnitude of the peak overpressure, and hence falls off with increasing radial distance from ground zero at a rate fairly accurately predictable from shock-hydrodynamical laws.

For reference use, the distance-variations of several parameters associated with the shock wave from a 20 MT surface burst are displayed in Table 1. For each of three radial ranges (r) in miles from ground zero, there is shown the peak overpressure (p) in pounds per square inch (psi), the shock-wave arrival time (t_a) in seconds, the duration of the positive overpressure phase (t_d) in seconds, the maximum wind speed (V_m) in miles per hour, and the associated peak dynamic pressure (q) in psi. The last two quantities will be of interest in the later discussions of *drag damage.*

Table 1. Distance-variation of several shock-wave characteristics for a 20 MT surface burst. See text for definitions of tabulated quantities.

r (mi)	p (psi)	t_a (sec)	t_d (sec)	V_m (mph)	q (psi)
5	10	11	7	300	2.3
10	3.4	30	10	115	0.27
15	1.8	51	12	70	0.07

From bomb-test data and from other considerations, extensive tables and graphs (AEC, 1957) have been prepared for use in estimating diffraction damage under a wide variety of specified conditions. For the hypothesized conditions of the Arizona attacks, one finds from these reference data that wood-frame houses will be *totally destroyed* out to about 8 miles from ground zero as a result of occurrence of peak overpressures of up to about 5 psi out to that distance. Brick houses, so common in southern Arizona, suffer damage in apparently the same way at about the same peak overpressures as do wood-frame houses (AEC, 1957, photographs, pp. 128-134). Only specially reinforced houses of non-standard type can remain standing after passage of a shock with 5 psi overpressure. Wood-frame and brick houses will, furthermore, be "badly damaged" (i.e., frames shattered so that structures are for the most part collapsed and will require major repairs before they could again be lived in except on emergency basis) out to a radius of about 17 miles, and will be "moderately damaged" (i.e., will have windows broken, doors blown in, and interior partitions cracked) out to a radius of 40 miles from ground zero. In Figures 1 and 2 the areas concentric with ground zero at Tucson and Phoenix within which the first of these three damage categories prevails have been indicated by 8-mile-radius circles. In Figure 2, which has been drawn to a smaller scale to permit delineation of longer-range bomb effects (that would be of more concern near Phoenix due to the presence of numerous surrounding communities), there is also shown the 17-mile limit of "badly damaged" homes that would require extensive or even prohibitive repairs before they could be made livable. Figure 2 reveals that in event of a 20 MT attack on Phoenix, *all* homes will be demolished not only throughout all of Phoenix proper but also eastward to Tempe, southward to the South Mountain Park area and northwestward to the edge of Glendale, many being destroyed even in Scottsdale and Tolleson. Homes will be partially collapsed in such distant communities as Mesa, Chandler, Goodyear and Marinette because even that far from ground zero the shock wave will arrive, about one minute after detonation, with peak overpressures in excess of 1.5 psi.

Although I know of no population-density data suitable for use in deducing from Figures 1 and 2 the expected number of persons whose homes would be destroyed, familiarity with the case of Tucson leads me to estimate that at least 90 per cent of the population of greater Tucson would find itself homeless within a bit under half a minute (see Table 1) after detonation. Inspection of photographs (AEC,

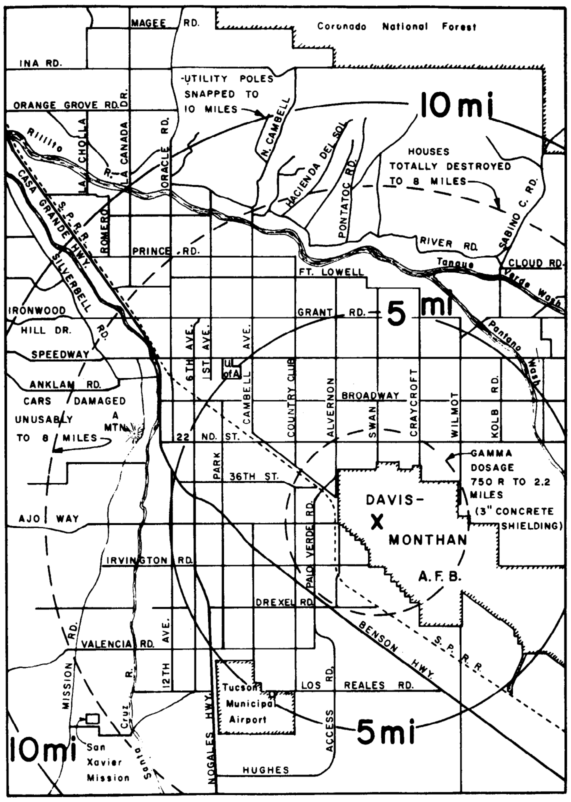

FIG. 1

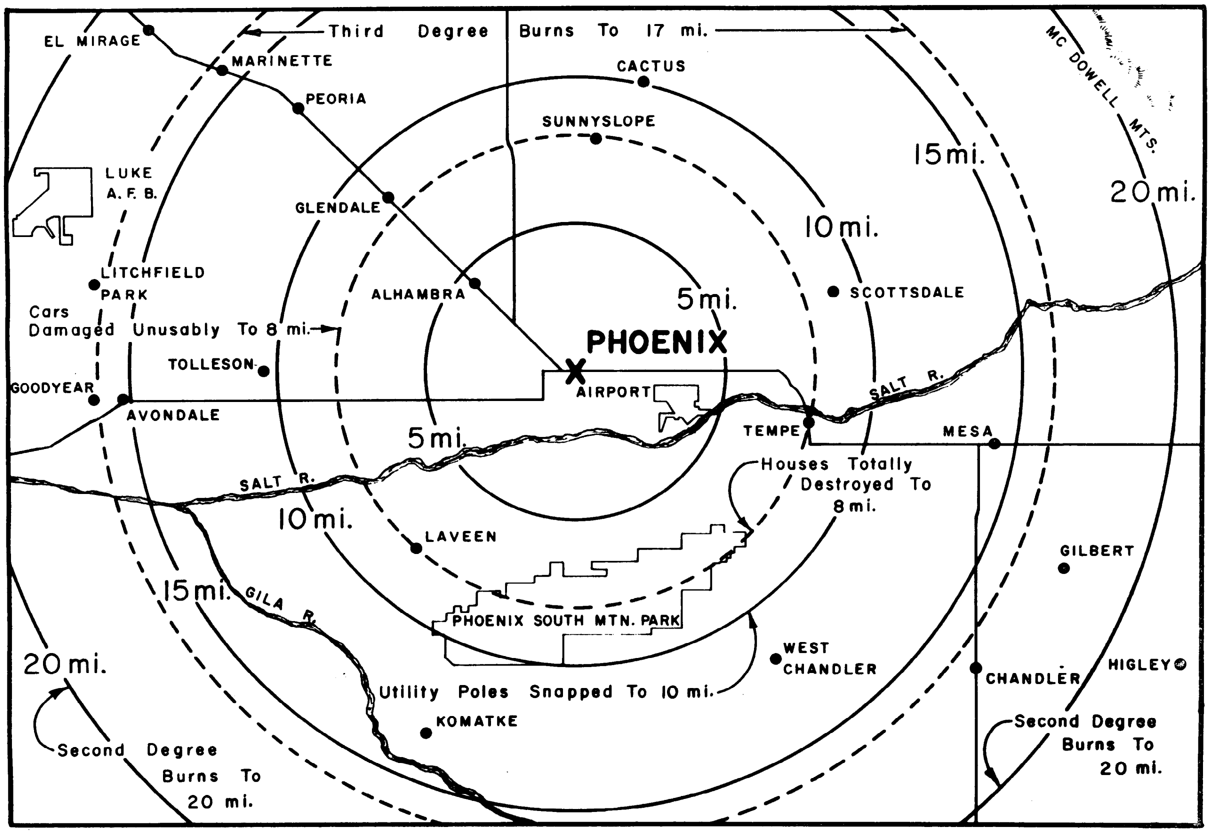

FIG. 2

Figs. 1, 2. Some effects of nuclear attacks at Tucson and Phoenix, respectively.

1957) of typical homes subjected to diffraction damage at the 5 psi level suggests that a heavy majority of the persons who were inside those homes at instant of shock-wave arrival would be dead or seriously injured within that same period of time as a result of mechanical injuries sustained during demolition of their homes. The Japanese experience strongly confirms this.

Multi-story brick buildings of the general grade of construction found in apartment houses would be totally destroyed out to a radius of rather more than 5 miles, and multi-story buildings with heavy reinforced-concrete frame and walls would be totally destroyed out to about 4 miles from ground zero and would be unusably damaged out to well over 5 miles. Thus, total destruction or heavy structural damage would be inflicted on Tucson Medical Center, U. S. Veterans Hospital, University of Arizona, and all downtown buildings in the case of Tucson, and similarly on the Arizona State Hospital, the U. S. Indian School, Grand Canyon College and all structures in the heart of Phoenix. All buildings and facilities at the municipal airports of both cities would be leveled.

Automobiles and other vehicles may be damaged both by diffraction loading (bodies crushed, frames sprung) and as a secondary result of the type of drag loading to be discussed in the next section, as well as by impacts from secondary missiles (rocks, bricks, timbers) torn from nearby structures. Nomograms for use in estimating vehicle damage are available only for the case of heavy trucks. Class C damage to heavy trucks implies "turned over and displaced, badly dented, frames sprung, need major repairs" and is found to occur within about an 8-miles radius of ground zero for a 20 MT surface burst. Passenger cars will suffer such damage to an even greater range from ground zero than will trucks due to the generally lighter construction of cars. But conservatively taking 8 miles as the radial limit of the area within which vehicles of all types would need major repairs before being drivable, one sees that evacuation of most of the surviving population of Tucson would have to be carried out without benefit of cars or trucks. About the same number of persons would face foot-evacuation in Phoenix, but this number would, of course, represent a smaller fraction of the total population of greater Phoenix. Widespread destruction of vehicles, along with other insuperable obstacles to vehicular evacuation, appear to have been ignored in current civil defense planning, possibly on the now outdated assumption that pre-attack warning will be received in time to evacuate before detonation.

Aerodynamic drag destruction. — Coming immediately after arrival of the shock wave are the high-speed winds that blow just behind the shock front itself. In Table 1, the values of V_m, the maximum air velocity developed just behind the shock wave, are given for three radial ranges from ground zero. In meteorological terminology, these blast winds would be spoken of as tornadic to well beyond 5 miles radius and of hurricane intensity to well beyond 10 miles. When so described, their ability to add appreciably to total bomb damage may seem more obvious. It is important to note that many types of structures inherently invulnerable to diffraction damage are demolished by drag damage during passage of these post-shock winds. Such objects as radio towers, utility poles, and trees have component members only a few inches or feet in thickness, so the shock wave, even when it has slowed down to sonic speeds, will advance from the near to the far side in a millisecond or less, too brief a time to produce much diffraction damage. That is, the total *impulse* delivered to such small objects during the diffraction period is too small to be very significant; and, of course, simple crushing action on the usually solid members of this class of objects is quite insignificant. But as the shock passes on and the post-shock winds rise to velocities of the magnitude indicated in Table 1, areodynamic drag forces build up to values that may be well beyond the ultimate strength of the structures and failure occurs. Some objects fail due to combined diffraction loading and drag loading, automobiles being a case of great importance. After having the hood and top crushed and the frame sprung during the first millisecond after arrival of the shock front, the car may be rolled along the ground or flung bodily against resistant structures by drag forces.

For present purposes, primary interest centers on two very common types of drag-vulnerable objects — wood utility poles (telephone and power poles) and trees. In Tucson and Phoenix, unlike cities in areas with more abundant vegetation, blown-over trees will be generally less of an evacuation problem than blown-over utility poles, but even the generally sparse and generally low trees typical of Arizona cities would so litter streets with branches and limbs as to greatly complicate vehicular evacuation even if no other obstacles to motorized evacuation existed.

Experience with storm damage of a variety of types leads to the rule-of-thumb (AEC, 1957) that 30 per cent of trees of average type go down at about 100 mph, and 90 per cent go down at 140 mph. Using the appropriate scaling laws, one finds that in the hypothesized attack, 90 per cent of the trees within somewhat over 8 miles from ground zero will go down and 30 per cent will go down out to almost 11 miles. Even in an area with only 30 per cent of all trees down, it takes little imagination to see the sharply reduced probability of being able to use a car for evacuation purposes. A single tree blown across a driveway might prevent car-evacuation by an elderly couple or by a household in which the father was at work, or might at least delay evacuation for an hour or two — a delay that could be rendered fatal by fallout.

The distance from ground zero out to which wood utility poles are snapped depends upon whether one considers poles with lines arrayed transversely or radially, since in the former case, aerodynamic drag forces exerted on the wires add to pole drag in building up a large bending moment near the pole base. The AEC nomograms yield a radius of about 10 miles (peak post-shock wind velocity over 110 mph, Table 1) for the distance from ground zero to the limit of the area within which poles bearing *radial* lines will snap, and 13 miles for the corresponding limit to which poles carrying *transverse* lines will go down.

Referring to Figures 1 and 2, one sees that this implies that *all* wood telephone and power poles throughout greater Tucson would go down, and that the same would be true not only in Phoenix proper, but even in Tempe, Scottsdale, Sunnyslope, and Glendale. Drive through any one of these communities examining the network of lines and poles, visualize all of these thrown down in ray-like pattern pointing away from ground zero, and estimate the finality with which this would eliminate hope of vehicular evacuation of these cities. Even in wide arterial streets within a ten-mile radius of ground zero, where fallen poles alone might not rule out slow go-around traffic, the maze of wires festooned over trees and houses and sagging erratically across the streets would preclude penetration by vehicles for tens of hours even if there were all-out effort by all survivors to clear the streets. But survivors have not tens of hours, only tens of minutes, in which to evacuate before fallout begins to arrive from the stratospheric mushroom cloud, so utility-pole damage alone would dictate evacuation *on foot*, even if vehicle damage did not also require walking evacuation.

Because utility-pole failure, by itself, so adversely influences evacuation prospects, and because pole-failure is one of the few types of bomb damage simple enough to be roughly analysed in terms of basic physical principles, I have made an effort to check the above figures derived from the published damage-nomograms. From a local telephone company I have determined that 35 feet is a good working average pole-height and 10 inches a reasonable basal diameter. Western red cedar is the most widely used type of pole in this area and has an ultimate fiber stress of about 5600 psi (Kurtz, 1942). The problem becomes that of estimating whether the maximum fiber stress near the 10-inch diameter base of a 35-ft cedar pole carrying a plausible number of lines of reasonable diameter and span will exceed 5600 psi just after the shock wave passes. Numbers and sizes of lines vary considerably, but it will be reasonable to consider six lines of 200-ft span, each of 0.30-in diameter, strung transversely at 10 miles from ground zero, where Table 1 shows peak wind speeds of 115 mph occurring. The Reynolds number for airflow about a pole under these conditions is found to be about $6x10^5$, that for airflow about the wires only $2x10^4$. The drag coefficent for a cylinder at the latter Reynolds number is 1.2, but for the former is only about 0.3 (assuming development of a fully turbulent boundary layer above the critical Reynolds number near $4x10^5$). The bending moment due to wire-drag may be assumed to operate through a lever-arm of 30 ft (wires averaging 5 ft below pole top), but the pole-drag behaves as a uniformly distributed load, if we ignore pole-taper. The section modulus at the base is here about 100 in^3, and hence the total bending moment at the base, found on the above basis to be $5.7x10^5$ in-lb, implies a maximum fiber stress of about 5700 psi, slightly in excess of the ultimate strength of western red cedar. Hence one would expect the pole to snap near the ground under the assumed conditions. It will be seen that this calculation, taken alone, indicates that pole-failure with transverse lines should be observed only to radii slightly greater than 10 miles from ground zero in contrast to the 13-mile limit previously derived from the AEC nomograms. However, it seems likely that the latter not only incorporate more reliable statistics on pole-size, line-size and line-span than used here, but also include empirical allowance for physical effects that transcend simple wind-tunnel experience with respect to drag forces on cylinders, so the present calculation will only be regarded as showing that the published data on pole-damage must be essentially realistic.

As an indication of probable density of barricading utility lines per unit length of city thoroughfare, I have made counts in Tucson of the number of overhead lines crossing measured stretches of various streets. On main thoroughfares well within the city, counts taken over a total of 13 miles averaged 60 transverse lines per mile. On secondary streets in residential areas, where numerous feeder lines are strung, a 5-mile check gave 95 lines per mile, or about 50 per cent higher than for main streets. If we assume that a survivor using a hypothetically undamaged car must drive a half-mile on residential streets to get to an arterial street, and then must drive, say, three miles to be entirely outside the metropolitan area, he must expect that some 220 utility lines will be down transverse to his route. Even if only a small fraction of these were sagging above ground, suspended on partially collapsed homes or untoppled trees, they would constitute a highly effective barrier to vehicular evacuation, even ignoring the downed poles themselves. Perhaps herein we have one facet of nuclear-bomb-damage whose human consequences can be vividly imagined by laymen if suitably emphasized.

INITIAL NUCLEAR RADIATION EFFECTS. — It has become customary to identify as the "initial" nuclear radiation that which is emitted from the fireball within the first *minute* after detonation. The basis for this is arbitrary, yet simple in principle: the rapidity with which buoyant forces act to accelerate the fireball implies that in about one minute the fireball and its radioactivity is carried several miles aloft, too far above the earth's surface for even the most energetic gamma rays to penetrate the atmosphere below to cause injury to persons on the ground.

The gamma dosage received by persons near ground zero depends upon the nature and thickness of absorptive material shielding them. For gammas of energy range typical of initial radiation (average energy about 4.5 mev), the half-value thicknesses (depth of shielding required to halve the gamma flux) of several common materials run as follows (AEC, 1957): steel, 1.5 in; concrete, 6 in; dirt, 7 in; and wood, 23 in. Probably 3 in of concrete equivalent shielding is a reasonable average for city-dwellers as a whole, which implies an almost negligible shielding factor of 1.3. From the scaling laws for predicting gamma dosage, one finds for the hypothesized conditions that persons behind 3 in of concrete will receive an essentially lethal dose of 750 r (roentgens) out to 2.2 miles radius from ground zero. Beyond this circle the gamma dosage diminishes extremely rapidly so already at 3 miles from ground zero the dosage is only 30 r. The physical explanation is that the atmosphere has a half-value thickness of about 1000 ft for the gammas.

Whole-body dosage of 750 r is lethal in the sense that death is nearly certain within a time of the order of a *few weeks*. The persons irradiated would, however, note no *immediate* effects other than a tingling sensation in the skin. But all of this is really of only academic interest, for although this destiny of dying of radiation sickness within a few weeks is established with the speed of light, real and immediate death of these lethally irradiated persons near ground zero is effected only a few seconds later when the actual shock wave arrives with peak overpressures of about 45 psi followed by blast winds of over 800 mph sweeping over the rubble. The conclusion seems almost inescapable that there will never be nuclear-attack deaths directly attributable to the effects of initial nuclear radiation. If one is not adequately shielded from the gamma radiation he is surely not adequately shielded against the tremendous blast effects characteristic of the area within the two or three miles of ground zero wherein this type of radiation death is even possible. (Radiation death from local fallout, it must be emphasized, is quite another matter. In the above we have considered only gamma irradiation from the fireball itself during the first minute after detonation.)

THERMAL RADIATION EFFECTS. — The incandescent fireball acts roughly as a blackbody emitter whose effective temperatures start in the million degree range. A peculiar phenomenon that prevents almost all the radiation from leaving the fireball in the early stages is the shock-heating that produces a hemispherical shell of air that is opaque to the short-wavelength emissions from the fireball during the first millisecond or so before the fireball temperatures fall to more terrestrially common values. Subsequently, the decrease in intensity of the shock-heating as the shock wave expands and grows less intense unmasks the fireball at about a second after detonation, at which time the effective emission temperature is near 8000° centigrade. Then, during the period from about 2 to 20 seconds after detonation, the ascending fireball acts as an exceedingly dangerous thermal radiator, whose effects we now consider.

Two thermal radiation effects become of human importance: *flash-burning of skin* and *ignition of inflammable materials.* Both are less severe for surface bursts than for air bursts, since in the former case the fireball is still low over ground zero when emitting most intensely, and the usual low-lying dust as well as actual objects (trees, buildings) impose more absorption on the radiations under these geometrical conditions than in the case of an air burst at several thousand feet above terrain. Experience indicates that by taking 60 per cent of the distance at which a given radiative energy is received from a typical air burst one gets the corresponding distance for that energy in a surface burst.

One finds, in this way, that the effective thermal radiation loads are here 160 cal/cm^2 at a radius of 5 miles from ground zero, 36 cal/cm^2 at 10 miles, 16 cal/cm^2 at 15 miles, and 12 cal/cm^2 at 20 miles. On the other hand, for the time-temperature characteristics of a 20-MT fireball, the energy required for a first-degree skin burn is 4 cal/cm^2, for a second-degree burn 8 cal/cm^2, and for a third degree burn 11 cal/cm^2. Therefore, in the hypothetical Tucson and Phoenix attacks, third-degree burns will be received by persons caught in the open within about 17 miles of ground zero, second degree burns within about 20 miles, and first-degree burns out to about 27 miles (see Figures 1 and 2). The seriousness of any of these three classes of burns is a function of total skin-area burned, of course. Clothing of some types will afford protection, but severe burns can be received right through many fabrics of the light weight commonly used for shirts and dresses most of the year in southern Arizona.

Noting from the above results that the radiative loads received within 10 miles of ground zero exceed *three times* the intensities sufficient to inflict *third-degree* burns, one must conclude that throughout all of Tucson and Phoenix proper, persons who happen to be outdoors and who do not take evasive action within seconds of detonation will suffer very severe flash burns on face, hands, and other exposed or thinly protected areas. (It is relevant to recall that about a third of the World War II Japanese A-bomb fatalities resulted from such flash burns from air bursts emitting only a thousandth of the radiation of the 20 MT weapon here considered.) Anyone with presence of mind to take immediate cover upon appearance of the first fireball glow can eliminate much of the danger of thermal radiation burn if he happens to be many miles from ground zero, since the total damage is spread over about 20 seconds. Very near ground zero, however, one would absorb 11 cal/cm^2 too quickly to make evasive action so decisive (e.g., at 5 miles from ground zero, one could absorb 11 cal/cm^2 in only about 2 seconds).

The immediate thermal radiation danger to persons caught in the open at moment of detonation does not end with skin burns, however, for these persons may find their clothing ignited by the thermal radiation. Of the fabrics whose ignition thresholds are published, those most representative of the types of clothing common in southern Arizona run as follows: cotton corduroy (brown), 11 cal/cm^2; cotton shirting (tan), 13 cal/cm^2; cotton denim, used (blue), 13 cal/cm^2; and cotton sheeting, unbleached, washed (cream), 30 cal/cm^2. Comparing these ignition requirements with the intensities cited above, we conclude that almost any typical clothing would flash into flames within Tucson and Phoenix proper; and most clothing would, in fact, be ignited in exposed locations out to somewhat beyond 15 miles from ground zero (e.g., in Mesa and Peoria or in Vail and Sahuarita). Little imagination is required to see how greatly the problems of evacuation and sheer survival are magnified by the probability that very large numbers of persons in the target communities will receive severe burns, either from direct radiation or from burning clothing. Or, put in still more vivid (but, I believe, not unrealistic) terms, one may reflect upon the way in which a *single family's* evacuation efforts might be slowed down or brought to a halt by thermal radiation burns suffered by only a *single member* of the family. Target-area hospital facilities would either be destroyed or so damaged that nothing like adequate first-aid treatment for victims with burns and other injuries would exist, needless to say.

Turning next to ignition of fires in materials other than clothing, we find that coarse grass, igniting at about 16 cal/cm^2, would flash into flame out to 15 miles, and fine grass, igniting at only about 10 cal/cm^2, would be in flame out to beyond 20 miles from ground zero. Leaves of deciduous trees (12 cal/cm^2 ignition threshold) would be aflame to about 20 miles, dry pine needles to about 14 miles. The Tucsonan would, within a half-minute after detonation, find most of the front range of the Catalina Mountains a nearly solid bank of flaming vegetation. The radiative ignition of grass and leaves would precede arrival of the post-shock winds for all points beyond about seven or eight miles from ground zero. Perhaps the winds would extinguish the flames in some cases, but in others these winds would probably serve chiefly to increase the fires. In any event, it seems very likely that throughout an area extending for many miles around ground zero, fires would be developing in the ignited and wind-strewn litter, adding still further physical and psychological obstacles to evacuation. Running water would almost certainly be unavailable for use in fighting such fires. Nevertheless, the chance of a major conflagration, a storm-fire, seems small since the average tonnage of combustible vegetation per acre is much lower in Arizona cities than, say, in cities in the East. Somewhat offsetting this advantage is the disadvantage that ignitibility is much greater for dry than for moist plant materials. Large numbers of small fires would seem the reasonable prediction, except in the foothills grasslands areas (e.g., Catalina foothills area north of Tucson) where the vegetation density might be sufficient to carry the fire, thus creating locally serious hazard to evacuation and possibly even to survival.

It is very much more problematical to try to estimate numbers of casualties from thermal radiation effects than from blast effects because radiation injury depends so critically on degree of exposure to the rays from the fireball. An extremely rough guess would be that, at any one time of the *daylit* period, some 10 per cent of the population might be out of doors in exposed spots (very much lower at night). The Japanese experience shows that persons near windows or other openings in houses may also be seriously burnt, but it is not possible to allow quantitatively for this contingency. On the 10 per cent assumption, some 20,000 persons in Tucson and 30,000 persons in Phoenix proper would receive third-degree burns on exposed skin surfaces and suffer from probably still more serious clothing burns due to almost 100 per cent certainty of ignition of clothing on all persons out of doors within ten miles of ground zero. The number of burn casualties outside of the limits of these two cities would also be significant, especially in the Salt River Valley area with its numerous small communities surrounding Phoenix.

LOCAL FALLOUT EFFECTS. — The last bomb effect to be considered here is also chronologically the last to occur but is by far the most serious hazard to survival after nuclear attack when weapons in the megaton range are involved.

The surface-burst fireball blasts into itself some million tons of debris (a small fraction of the total soil and rock removed in crater-formation at ground zero), instantly vaporizes it, and mixes the resultant gases with the gaseous fission products as the fireball buoyantly ascends. Within about a minute later the fireball, now several miles aboveground, has radiatively and expansively cooled to the boiling point of the soil materials and then to their solidification point (order of 2000° centigrade), during which two stages the soil materials recondense into droplets and then solidify to form tremendous numbers of very small solid particles upon which the fission products may themselves condense. Apparently an efficient process, this sequence of events puts the radioactive fission products on particles whose terminal fall velocities are large enough to bring them back down to earth before their radioactive decay has reduced their general activity below the radiological danger point.

The result: This *local fallout* of contaminated particles covers the ground for *thousands of square miles* around and downwind from the target area with a lethally intense though invisible film of gamma-emitting dusts over which it will be unsafe to walk for post-detonation times of the order of many *days.* As dangerous as are the blast- and radiation-effects previously discussed, the radiological effects of local fallout are much worse. "For the thermonuclear weapons now in development and production, the direct effects of the explosive energy sink into relative insignificance when compared with their radiological effects" (India, 1958, p. 7).

Local fallout must be carefully distinguished from the currently-occurring *worldwide fallout* of bomb-test radioactivity. The latter is, by contrast, very slow and of low intensity since it results from air bursts or else from low-yield tower bursts, neither of which provides soil debris particles to bring down the fission products in their early state of intense activity. Megaton surface bursts, on the other hand, begin delivering the fission products, via local fallout, to the countryside within an hour or less, at which time the contaminated dusts still act as sources of gamma radiations of great penetrating and killing power.

A striking characteristic of mushroom-cloud formation is the cloud's almost immediate horizontal expansion to radii of tens of miles once it enters the stable stratosphere. For the 20 MT weapons here considered, the mushroom cloud will spread out (Kellogg, and others, 1957) to a radius of about *30 miles* within about *ten minutes* after detonation. That is, ten minutes after the hypothetical Phoenix detonation a massive cloud will stretch from Buckeye to Apache Junction, from Maricopa to New River; and the Tucsonan would find himself under a cloud reaching from Pantano to beyond Marana, from Oracle to about Amado. Pacific bomb-test experience indicates that final stabilized mushroom-cloud radii of as much as 50 miles may occur. What will be the subtle psychological effect exerted on already stunned target-area personnel by the almost instantaneous imposition of this huge dark cloud above them?

But there are worse than psychological hazards in the cloud, for it will be radioactively contaminated out to a radius of at least 20 miles, so it is from a disc of 40-mile diameter concentric with ground zero that the rain of radioactive dust starts down.

What this means to the evacuee is that he must very quickly get some 20 miles out from ground zero if he is to be sure of avoiding the local fallout. When wind-drift is taken into account, one sees that a critically important point is to evacuate towards the upwind direction, where "upwind" means with respect to the vector-resultant wind throughout the entire layer from about the level of the stratospheric mushroom cloud down to the ground. Mere surface wind information is of no help, for the vector-resultant wind for the entire troposphere may be 180° opposed to the surface wind (e.g., the August afternoon surface wind at Tucson is almost invariably from the northwest, but the mean fallout drift for August is *towards* the northwest; here is an instance where a little knowledge may be a fatal thing).

The U. S. Weather Bureau has for several years been computing twice-daily fallout winds at about sixty upper-air observing stations throughout the country in order to have available, at any moment, fallout winds no more than 12 hours old. In Arizona it is the Tucson Weather Bureau office that is currently performing this function. To indicate the Arizona areas that are most likely to be subjected to local fallout, I have plotted in Fig. 3 the locally available data for the ten months, November-August, 1958-59. Each plotted point in the figure represents the calculated distance and direction towards which fallout particles of a particular size (220 micron diameter, density 2.5 g/cm^3) would have drifted during fall from the 80,000-ft level on a particular day (not indicated in the figure). Such particles require three hours to fall 80,000 ft, so Figure 3 presents 3-hr drift loci. Available evidence (Kellogg, and others, 1957) suggests that only about 15 per cent of the local fallout comes down on particles as large as or larger than 220 microns in diameter, so it is important to note that most of the fallout from 80,000 ft travels much farther than the points of Figure 3 indicate. However, because the bulk of the fission products effectively start their fall not from near the top at 85,000 ft, but from a mean height of perhaps 60,000 ft, nearer the base of the mushroom cloud, one may take these points as tolerably good indicators of average fallout drift for all particle sizes and all heights of origin. (The actual fallout process involves innumerable trajectories for a continuum of particle sizes and for a continuous distribution of heights of origin. Hence a really detailed prediction of fallout patterns can only be carried out through use of high-speed electronic computation (Kellogg, and others, 1957).

In Figure 3, the points for the two summer months of July and August, 1959, are distinctively symbolized with crosses to bring out the fact, exceedingly important to the Arizonan, that the mean fallout drift during the summer rainy season is almost opposite to that for the other eight plotted months (triangles). To emphasize this significant point, I have computed and plotted in Figure 3 four different *mean monthly fallout* trajectories (solid curves

FIG. 3

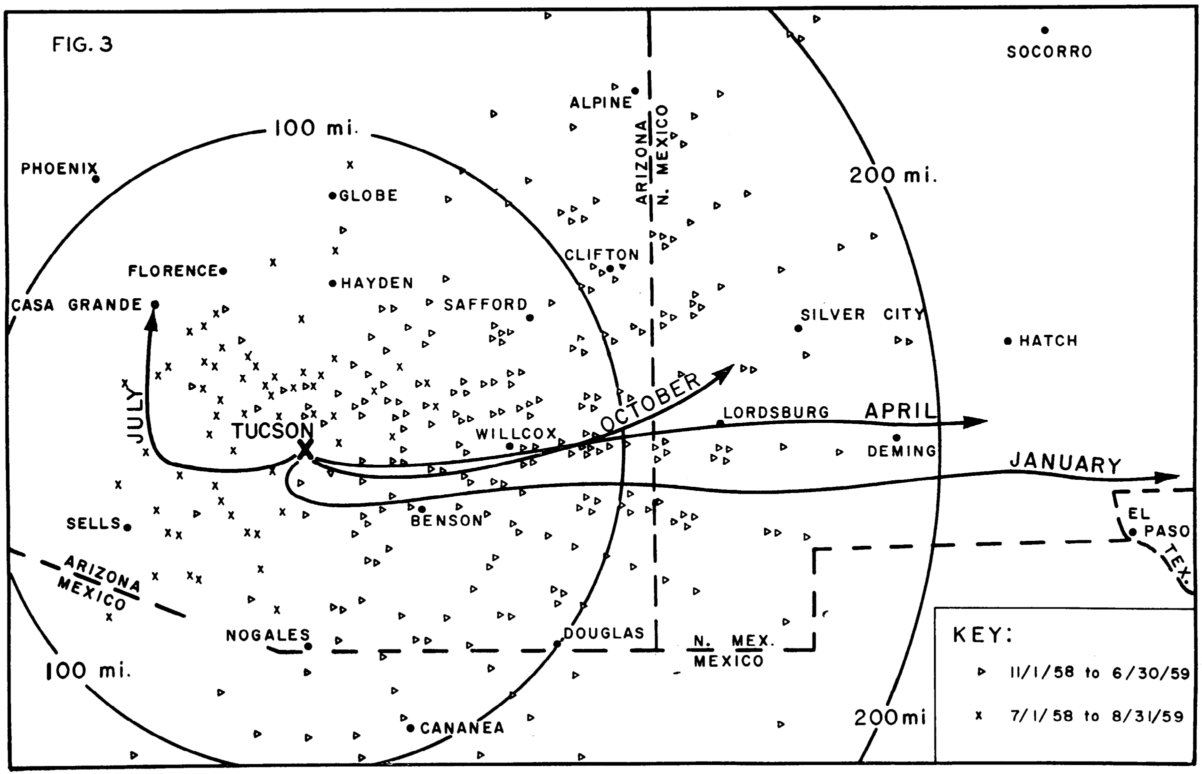

Fig. 3.—Radiological fallout data for Tucson.

in figure) for particles whose diameters are equal to the median diameter observed in actual bomb-tests, namely 100 microns. Such particles fall to the ground in about six hours from the 75,000-ft height of origin assumed in calculating these trajectories. The wind data were ten-year means for the period 1946-55 (Ratner, 1957). Examination of these four trajectories plus study of the mean wind data for the other eight months of the year showed that southern Arizona mean fallout vectors point almost due east throughout all the year except during July and August, when southeasterly upper-airflow prevails. It is a point of some meteorological interest and of considerable importance to the potential evacuee that a peculiar 90-degree bend occurs in the July (and August) mean trajectory. This results from mean east-to-west drift of particles while they are still falling through the stratosphere followed by mean south-to-north drift while falling from the tropopause to the surface.

The Tucson fallout data of Figure 3 are almost equally applicable to Phoenix, since there are usually only very slight differences in upper-air wind speeds and directions over the 100-mile distance separating Tucson and Phoenix. That is, one may simply translate these patterns bodily, bringing ground zero onto Phoenix to infer the downwind fallout problems associated with a Phoenix attack.

The ground-level dosage rates vary with weapon yield and with meteorological conditions and, of course, with time. It has been established that the variation with time since detonation, t, may be reasonably well described by a $t^{-1.2}$ decay law, a composite of many different exponential decay laws of many different radioactive fission products. Thus, every sevenfold increase in time since detonation brings roughly a tenfold reduction in ground-level dosage rate (once all the fallout destined to reach a given spot has arrived there). Consider, for example, a locality such as Willcox or Globe in winter, with west-to-east drift. No gamma-active dusts would arrive until perhaps two hours after the attack. But after that elapsed time, the dust would start sifting down, and the gamma-dosage rate would begin to climb as more and more of the finer dusts arrived. Maximum dosage rate might occur in Willcox or Globe at about six to eight hours after detonation, for not only will most of the dust particles that have fall-times greater than this tend to drift right on over Willcox or Globe, but also, of course, all the fission products, whether on the ground or still settling to the ground, are losing their activity as time progresses. If we take 7 hours after detonation as the time of peak ground-level dosage rate, then in view of the $t^{-1.2}$ law, the dosage rates will be down to about 10 per cent of their peak value in about 49 hours (7 times 7 hours) after the attack. By about two weeks (7 times 7 times 7 hours) after attack, the dosage rate at Willcox or Globe would be down to only one per cent of its peak value.

The question of human importance is that of the magnitude of these varying dosage rates as compared with the lethal whole-body dose of about 750 r (lethal in the sense that radiation sickness would bring death in a few weeks, *not* immediately). So many different meteorological conditions can occur that only average values can be given. From bomb-test data, it has been deduced that for a 20 MT surface burst, 48-hour integrated whole-body doses equal to or greater than 750 r may be expected to exist around the target and in downwind areas comprising a total of from 2,000 to 20,000 square miles. We may take 10,000 square miles as a representative 48-hour lethal-dose area for a 20 MT surface burst. Exposure over more than 48 hours will obviously yield somewhat greater total dosage and, more important, even outside the above-specified area, persons will be exposed to what may for them be lethal dosages, since the whole-body dose at which 50 per cent fatality-rate occurs is only about 450 r. A 48-hour integrated dose of 450 r can prevail over an area as great as 30,000 square miles with certain wind conditions (Kellogg, and others, 1957).

Since the contaminated portion of the mushroom cloud itself has a diameter of about 40 miles, and since a small amount of spreading will occur, we must imagine a 50-mile-wide swath, extending some 200 miles downwind from Tucson or Phoenix, within which everyone not heavily shielded against gamma radiation will receive, in two days subsequent to the attack, fatal doses of radiation. Such communities as Superior, Miami, Globe, Benson, and Willcox are therefore radiologically about as vulnerable as are the target cities of Tucson and Phoenix. Furthermore, Figure 3 reveals convincingly that variations of the actual upper winds from their average west-to-east direction are great enough and frequent enough that Casa Grande, Florence, McNary, Showlow, and Springerville would be within the lethal-dosage fallout areas extending downwind from Phoenix on many days, while Tombstone, Bisbee, Douglas, Safford, and Clifton are frequently within Tucson's lethal-dosage fallout area. Persons in any of these areas would have to leave their homes and go to an area not contaminated by fallout from still other targets or else stay for a period of the order of two weeks in some kind of underground shelter that gave a protection factor high enough to match the local dosage rates. Simply to stay aboveground and go about one's work anywhere within the entire 10,000-square-mile area would insure the sequence of nausea, vomiting, and hemorrhaging that ends in death due to the complex and deep-seated physiological damage loosely described as "radiation sickness."

EVACUATION AND SURVIVAL. — Although numerous air-raid sirens have been set up in cities such as Tucson and Phoenix, recent ICBM developments make them of dubious value: Tucson is about 15 minutes by ICBM from the Anadyr Peninsula of Siberia where potentially hostile missile launching pads now exist (Galloway, 1957). Even if subsonic manned aircraft are the only nuclear bombing threat at date of this writing, it is safe to predict that this situation will change within only a few years to threat of hostile 15-20,000 mph ICBM's. At that time "evacuation" can have only one meaning — evacuation *after* attack.

The quantitative bomb-damage estimates outlined above show all too convincingly (at least to those who see them as following logically from the physical laws governing bomb phenomenology) that evacuation of Tucson and Phoenix would be an incredibly difficult task. Consider Tucson. In the hypothetical attack discussed here, nine-tenths of Tucson's homes are estimated to be demolished, many going down about the heads of their owners, immediately creating a mass of perhaps 175,000 homeless persons, many already dead or seriously wounded from mechanical injuries, others severely burned by direct thermal radiation skin-burns or by burns from clothing radiatively ignited. Another 25,000 Tucsonans in the fringe areas would be confronted with badly damaged homes and with non-fatal but serious mechanical and radiation injuries. All of this within a minute after detonation. Over most of the city, cars and trucks would have been rendered undrivable by blast damage, but even if drivable, the presence of barricades of power and telephone lines and utility poles lying across block after block of streets, with trees and building debris interstrewn, would preclude evacuation by car from all points closer than a dozen miles from ground zero. For the bulk of the survivors the alternatives would simply be those of walking or staying.

Consider first the alternative of staying near one's home. T ostay would not be to survive unless one had adequate shielding from the fallout radiations that begin, near ground zero, within about a *half hour* or less after detonation, due to heavy fallout from the *stem* of the mushroom cloud. On the *upwind* side of ground zero, at radial distances of rather more than 10 miles, one might stay without more than mild radiation sickness and sequelae. On the downwind side, departure would be imperative, but the only possible way to go would be to circle around the soon-to-be contaminated area several miles out from ground zero. This circumnavigation of the stem-fallout area, however, is almost impossible on foot. There simply is not time enough at fast walking speed. Thus blast-survivors on the *downwind* side of the target and not far enough out to be able to escape fallout in vehicles are certain to be fallout victims. Note, however, that all of these people would, for a few weeks, be alive, though incapacitated after half a day or so by the heavy radiological injury sustained in skirting the immediate blast area.

In other geographical regions, the usual recommendation of taking refuge in one's basement offers something like a tenfold protection factor from gamma radiations originating on dust deposited on the roof or on the surrounding yard. This happens not to be nearly enough protection close to ground zero under most wind conditions, so it is often recommended that the home owner dig from his basement into the adjacent subsoil to take advantage of shielding by the soil. But in any event, the typical Arizonan will not have to weigh the latter decision, for he has no basement. Inquiry at a large local home-building firm brought the estimate that only a fraction of one per cent of existing southern Arizona homes have basements. Public buildings with basements might offer partial shelter for a tiny fraction of the survivors of the first minute's destruction, but beyond that, the informed person would know that (if he is not in the essentially doomed downwind sector) he must get out from under the contaminated portion of the mushroom cloud, and get out exceedingly quickly. Delay beyond *tens of minutes* would be very serious, viewed radiologically. But what family could ordinarily hope to assemble its members from schools and places of work in tens of minutes to begin walking rapidly out of town? Very few, I fear, so evacuation may be a process with peculiar sociological selectivity.

Nevertheless, we may briefly examine the prospect of walking-evacuation of Tucson or Phoenix for persons on the upwind side of ground zero and located, say, 5 to 10 miles out. In the winter months this alternative is not too hopeless if we overlook the family-assembly difficulty and the low probability of any sample of four or five persons in Tucson or Phoenix being entirely uninjured and hence in walking condition. By making all possible haste, one might move westward (assuming west-to-east airflow aloft) fast enough compared to fallout descent rates that he would suffer only mild radiation sickness. Furthermore, in winter, the problem of getting drinking water is less urgent. Tucsonans, for example might get into the Avra Valley and be lucky enough to get water within a half-day, though food would quickly become a limiting factor because of lack of towns with any residual food stocks in that region west of Tucson. The Phoenix evacuee is distinctly better off in winter.

But in *summer* foot evacuation from any southern Arizona city is a nearly futile venture. From May to September, temperatures are so high that most persons cannot walk (assuming daylight attack) much more than ten to fifteen miles without water, whereas upper winds are much lighter, demanding *greater* upwind flight to get out from under the only slowly drifting contaminated cloud. On a June day with maximum temperature of 101°F, I found that I could cover slightly over 12 miles in three hours after drinking to full capacity at the start, but had lost 10 lb and was near exhaustion at the end of that stint. This personal experiment agreed well with the results of extensive studies carried out with troops in desert areas in the Southwest during World

War II (Adolph and others, 1947). *Fifteen to twenty miles* is the greatest distance to which troops in *excellent physical condition* can walk without water under average daytime southern Arizona summer conditions, judging from the Army experience. But with a contaminated radius of about 20 miles and light winds aloft, *every survivor who is to remain a survivor* will have to go roughly this distance and with no running water available anywhere along the route due to blast damage of water systems. For the young and old members of the population, this would thus be an impossible trek to make, despite its urgency. Mere thermodynamics of water consumption and questions of physical fitness impose limits to escape by foot from the target areas in summer. Even on the upwind side of ground zero in summer, the fraction of the population that could avoid lethal radiation dosage would fall very low except beyond about fifteen miles out from ground zero where vehicular evacuation would be possible. Put in the context of the Phoenix attack, a majority of Tempe residents fleeing southeastward in July or August would not be able to move fast enough and far enough towards possible temporary haven in, say, Mesa (haven in the sense of probably providing some drinking water) before receiving many hundreds of roentgens, so most of them would be almost as sure to be radiologically killed as would the more obviously doomed residents of Glendale. Tucsonans are much worse off: On the average in July and August, Davis-Monthan AFB lies upwind of almost all of metropolitan Tucson, so a summer attack could radiologically eliminate essentially the entire population of Tucson.

Actually, this discussion of evacuation and survival can make no claim even to topical completeness, for I am not weighing psychological questions of human response to the calamity itself. Studies of what are, by comparison, small-scale disasters show that a kind of dazed paralysis often immobilizes uninjured persons for several hours after the disaster. Since there are no carefully practiced evacuation procedures for nuclear attack, everyone will be on his own, and a state of shock that prevents intelligent action within fifteen or twenty minutes of detonation will insure radiological death for tens of thousands of residents not blast-killed but still close enough to be in the stem fallout area on the upwind side (those on the downwind side, to repeat, are essentially doomed). Add shock to the high probability that *families* will not be able to assemble for flight, and the overall psychological obstacles become as great as the purely physical obstacles.

Nevertheless, if nuclear attack must be reckoned with, it is clear that detailed knowledge of bomb phenomena is the indispensable requirement in taking advantage of every circumstance following an attack. At present such knowledge is, I believe, nearly nonexistent in the population, so its presentation to the public is urgently needed. Given much more detailed information as to the awesome prospects of nuclear warfare, we might even take more active steps to prevent their realization.

LITERATURE CITED

ADOLPH, E. F., and associates. Physiology of man in the desert. New York, Interscience Publ., 357 pp.

AEC. 1957. Effects of nuclear weapons. United States Atomic Energy Comm. Washington, U. S. Govt. Print. Off., 579 pp.

GALLOWAY, E. 1957. Guided missile implications. Mil. Rev. 37: No. 3, 3-16.

India. 1958. Nuclear explosions and their effects. Government of India. Delhi, Publ. Div., 276 pp.

Joint Comm. on Atomic Energy. 1957. The nature of radioactive fallout and its effects on man. Hearings, Special Subcom. on Radiation. Washington, U. S. Govt. Print. Off., 1008 pp.

KELLOGG, W. W., R. R. RAPP, and S. M. GREENFIELD. 1957. Close-in fallout. J. Meteorol. 14:1-8.

KURTZ, E. B. 1942. The lineman's handbook. New York, McGraw-Hill, 650 pp.

LAPP, R. E. 1959. Fallout and home defense. Bull. Atomic Sci. 15:187-191.

RATNER, B. 1957. Upper-air climatology of the United States. U. S. Weather Bur. Tech. Paper 32. Washington, U. S. Govt. Print. Off., 199 pp.