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Radiological Criteria for Underground Nuclear Tests

University of California

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RADIOLOGICAL CRITERIA FOR UNDERGROUND NUCLEAR TESTS

by

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ABSTRACT

The radiological criteria for the conduct of nuclear tests have undergone many revisions with the current criteria being 0.17 rad for uncontrolled populations and 0.5 rad for controllable populations. Their effect upon operations at the Nevada Test Site and the current off-site protective plans are reviewed for areas surrounding the Site. The few accidental releases that have occurred are used to establish estimates of probability of release and of hazard to the population. These are then put into context by comparing statistical data on other accidents and cataclysms. The guidelines established by DOE Manual Chapter MC-0524 have never been exceeded during the entire underground nuclear test program. The probability of real hazard to off-site populations appears to be sufficiently low as not to cause undue concern to the citizenry.

I. ISSUE

The decision to execute each nuclear test event rests upon evaluation of the risk to both on-site and off-site personnel with most consideration given to off-site populations for which no protective actions are possible. The evaluation depends upon prediction of the hazard from radiation which might be released from the explosion using predicted, and verified, meteorological conditions inputted to the best appropriate model for prediction of the possible radiation fields which might result from the execution. The decision considers the prediction of hazard together with guidelines established to protect personnel in the possible radiation pattern. These guidelines are contained in the environmental impact statement for operations at the Nevada Test Site; these are consistent with the guidelines established in DOE Manual Chapter 0524. Though the guidelines have become increasingly conservative, no underground nuclear test has produced radiation exposures exceeding current guidelines. Current guidelines are given in Appendix A, abstracted from NVO-176.

II. BACKGROUND

The US atmospheric nuclear test programs which terminated in 1962 were conducted under the radiological restriction of 3.9 Roentgen per operation which derived from an assumed duration of a quarter year and limitation of 0.3 R per week. Prior to 1975 the underground test program had been conducted under the same dose limitation but extended over a year. At that time, MC-0524 contained an exemption clause from the general guidance upon which the operational criteria for testing had been based; since 1975, the manual chapter does not contain this exemption clause. Off-site exposure guidelines had been 3.9 R/yr, not to exceed 10 R/10 yrs and, since 1964, 0.17 R/yr to Las Vegas. In 1975, the 10 R/10 yr changed to 5 rem/30 yr or 15 rem/30 yr depending on control measures available.* The experience of underground test operations has been that no test designed to contain has approached the MC-0524 guidelines of 0.17 rem/yr. Even with the numerous seeps, leaks, and dynamic ventings up to and including Baneberry, there has been no evidence that the safety of anyone off site has been compromised. The maximum measured exposures at locations with populations for events noted were:

1964	Pike	at Cactus Springs	0.055 R
1966	Pin Stripe	at Hiko	0.012 R
1970	Baneberry	at Reed Ranch	0.026 R

Only these three events (of those designed to contain) provided measured off-site doses at populated places in excess of 1 mr since the advent of continuous underground testing in 1962.

Predictions of off-site potential doses for many tests prior to 1975, however, had ranged up to 3.9 R; none of those tests vented. The prediction of radiation doses has been based on the so-called Pike model which scales the event under consideration to the Pike fission yield and meteorological conditions. As Pike was in the low yield range and some tests prior to the TTBT approached a megaton, predicted off-site doses could be expected to far exceed Pike. No event with a yield in excess of 70 kt has had a release and such doses have never been observed. Since current containment procedures were adopted in 1971, a massive venting has never occurred although at present such venting cannot be entirely ruled out for any yield.

III. EFFECT OF RADIOLOGICAL CRITERIA ON OPERATIONS

Limits on the predicted radiological dose to off-site personnel, in the event of an improbable release following an underground nuclear test, impact upon the probability of executing the test under the prevailing meteorological conditions. To assess that impact, the WSNSO/LV made calculations for 100

* For purposes in this report, the Roentgen, rad, and rem (Roentgen-equivalent-man) may be taken as equivalent.

events just prior to 1975 which assumed a massive venting scaled to the Pike event using meteorological conditions at the scheduled event time as presented at the morning briefing. In determining if an event could be conducted, it was also assumed that small populations, including that at the Tempiute Mine, could be gotten out of harms way. The total sample of 100 events included some events with yields in excess of 150 kt--up to about 1 Mt. Results of the study are:

(1) The minimum criteria which would have permitted all 100 events to have been conducted is 40 R.

(2) The minimum criteria which would have permitted all events with yields less than 150 kt to have been conducted is 1.5 R.

(3) The following table presents the percentages of all 100 events which could have been conducted as a function of the various criteria shown:

Criteria (R)	%
5.0	96
3.9	95
2.5	95
1.0	90
0.5	82
0.17	71

(4) The following table presents the percentages of all events with yields less than 150 kt which could have been conducted as a function of the various criteria shown:

Criteria (R)	%
5.0	100
3.9	100
2.5	100
1.0	98
0.5	90
0.17	81

(5) Of the 18 events near 150 kt, 5 could have been conducted (28%) with a limit of 0.17 R.

No estimate was made as to the length of delay but, extrapolating atmospheric test experience, delays up to 28 days could be expected.

IV. OFF-SITE PROTECTIVE ACTION PLAN

In the interest of safety, the possibility of an accidental release of radioactivity is always taken into consideration in planning and conducting an underground nuclear test. Precautions include the preshot prediction of the downwind geographical area that would be affected, an estimate of the maximum radiation exposures which might possibly occur as a result of an accidental release of radioactivity to the atmosphere, and the preshot deployment of Environmental Protection Agency (EPA) mobile monitors in the downwind area for the purpose of conducting radiological monitoring and implementing protective actions where practical to keep public exposures to a minimum. In addition, should a release of radioactivity occur, every practical effort will be made to reduce internal exposures to the lowest practical level, e.g., dairy cows will be placed on dry feed while there is a possibility of there being radioiodine contamination on the forage. At the same time, potentially contaminated milk would be withdrawn and uncontaminated milk substituted for purposes of human consumption.

In addition to the 12 to 24 predeployed mobile monitors which are in radio contact with the control point, the EPA and the DOE (through the USAF) deploys aircraft for aerial sampling and tracking of the debris cloud. Two aircraft are available near ground zero at event time and can provide early estimates of the radiological impact on the off-site population and assist in determining the trajectory. Other aircraft can be dispatched as necessary to continue tracking when it becomes necessary for the prime aircraft to depart.

EPA's Off-Site Protective Action Capability

Remedial actions available for consideration to reduce whole-body exposures and the uptake of radionuclides in the food chain are evacuation, shelter, access control, pasture control, milk control, and food and water control to a lesser degree. Which action, if any, is undertaken will depend largely upon the type of accident and its associated projected doses, the response time available for the conduct of the action, and local constraints associated with a specific site. These constraints vary and include such things as the number of people and their distribution in the impact area, the availability of transportation, the existence of schools and hospitals, the availability of law enforcement personnel, and the presence of people who may refuse to cooperate. Any of these factors, either individually or collectively, can render an action ineffective or impair its effectiveness.

The following summaries by location (counter-clockwise around the NTS), to a distance of about 100 miles from the C.P., attempt to indicate which remedial actions, if any, can effectively be undertaken to avoid or reduce whole-body exposures (Fig. 1) and thyroid doses (Fig. 2). It must be understood that this analysis is strictly subjective, based entirely upon demographic and local constraint information. There has been little or no previous experience to call on for most areas and there are no formal remedial action plans in existence between the nearby communities, city governments, law enforcement personnel, and the DOE/EPA.

1. Whole-Body Exposure Reduction Remedial Actions

Indian Springs - Highway 95 to Las Vegas

Remedial Actions: None

Moapa - Overton - Logandale - Virgin Valley

Remedial Actions: None

These are well-populated areas with people dispersed throughout many hundreds of square miles, making it extremely impractical to take any kind of remedial action.

Highway 93 (between Moapa and Lower Pahranagat, approximately 10 miles south of Alamo)

Remedial Actions: Evacuation, Shelter, Access Control

This area contains few people and should be easily manageable except during the desert bighorn sheep hunting season (October/November). Traffic should also be easily controlled. This area could be extended eastward to include residents (fewer than 50) along the Elgin, Carp, and Rox Road.

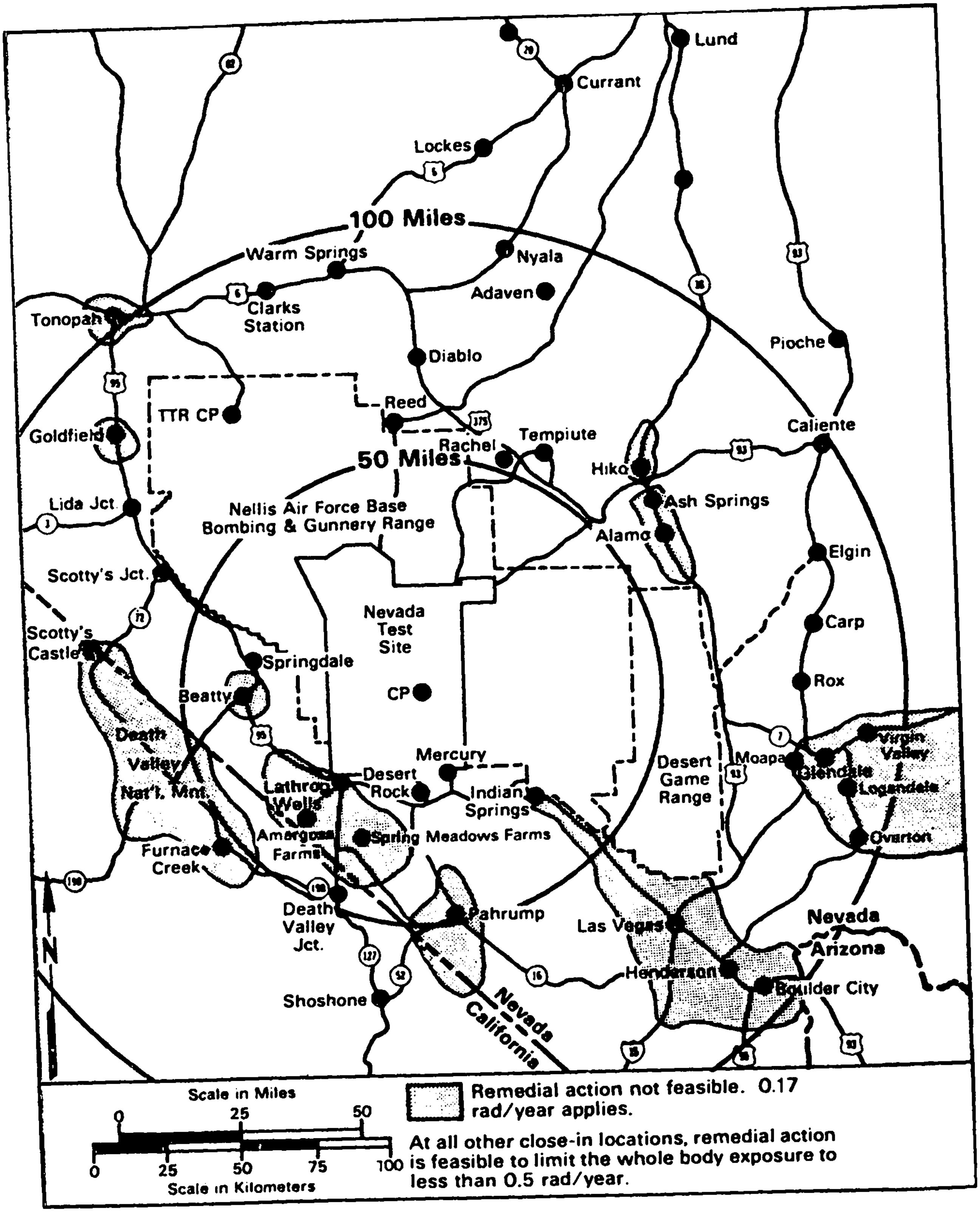

Fig. 1. Feasibility of whole body exposure reduction.

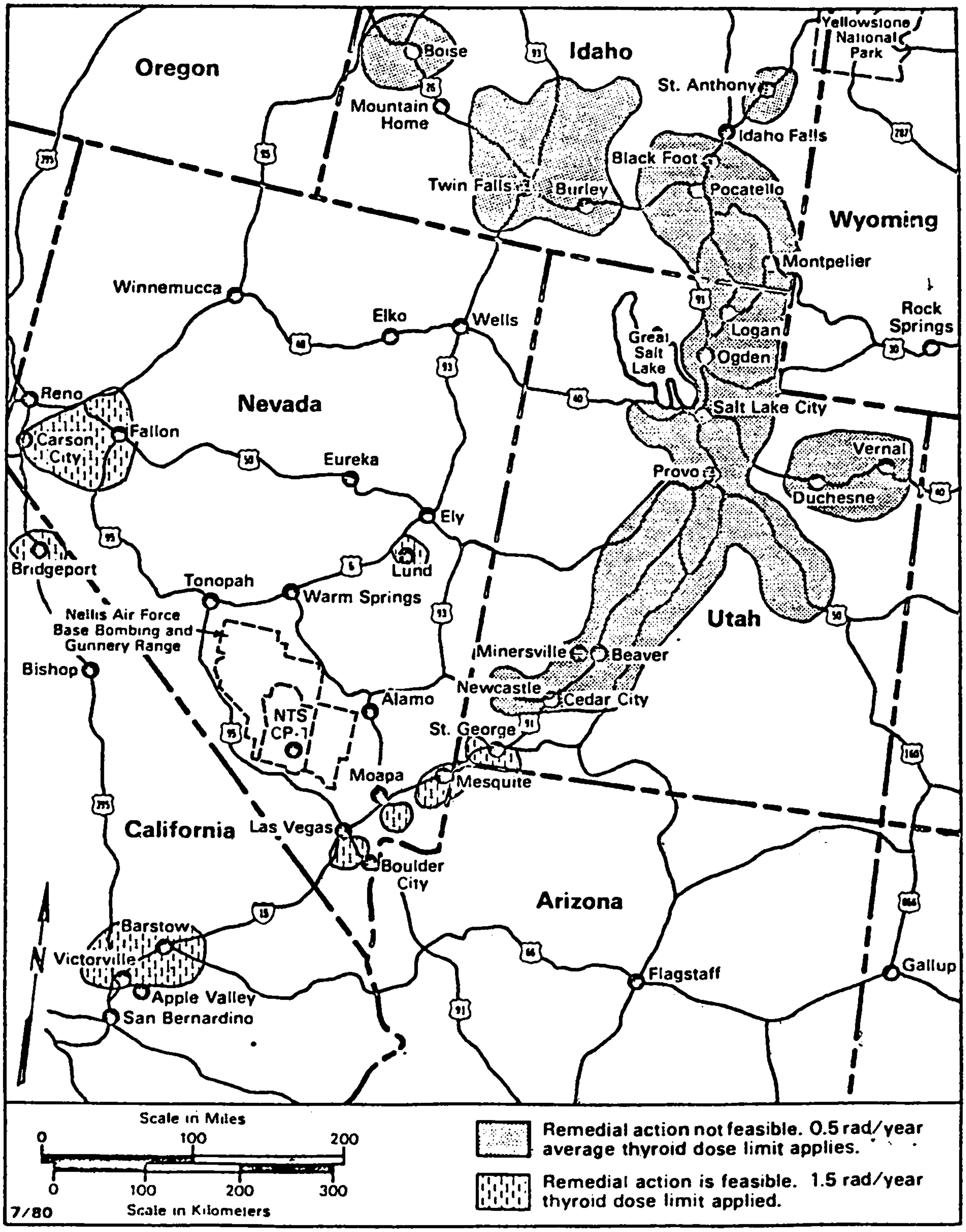

Fig. 2. Feasibility of thyroid dose reduction.

Alamo - Ash Springs

Remedial Actions: Shelter, Access Control

There are approximately 1200 residents dispersed over a reasonably large area. Evacuation would not be practical. We do maintain an updated map of inhabited dwellings in these areas and advising residents to seek shelter is feasible with a lead time of 3 to 4 hours.

Hiko

Remedial Actions: Shelter, Access Control

Hiko is somewhat separated from the Alamo-Ash Springs complex. It is located at the northern end of Pahranagat Valley on the north side of Highway 375. There are about 175 residents dispersed over a reasonably small area. Evacuation is questionable; however, shelter would be possible within a short time frame. Traffic should also be easily controllable. We do maintain an updated map of inhabited dwellings in this area to assist with any protective measures.

Highways 6 and 375 (excluding Tempiute and Rachel)

Remedial Actions: Evacuation, Shelter, Access Control

Off-site monitoring personnel are most familiar with those residents living and working in the environs north of the NTS. Residents along Highway 6, including those at Warm Springs, Site C, and the Hot Creek Ranch, and those people living and working along Highway 375 and north to Nyala and Adaven fall in this category. Standard procedures prior to each test are for the monitors to check on all roads and potentially inhabited locations in these areas on D-1. With this and the pre-event trajectory information, a safety plan is established which carries reasonable confidence that the locations of people at or shortly after event time are known. Approximately 2 hours should be sufficient to clear the close-in Highway 6 or 375 area of people, and 3 to 4 hours would be sufficient to clear out to Nyala-Adaven.

Tempiute and Rachel

Remedial Actions: Evacuation, Shelter, Access Control

These locations have the highest population densities along Highways 6 and 375. Remedial actions can be effected with 2 to 3 hours. Transportation of a portion of the population of Rachel could be required. Temporary shelter for all would be available in the Tempiute Mine.

Tonapah

Remedial Actions: Shelter, Access Control

There are approximately 3600 people living in Tonopah at this time. There are schools, a hospital, and a number of other constraints which make evacuation infeasible. At best, advising residents to seek shelter is possible, but this could be accomplished only with assistance from local law enforcement officers and it would require a minimum of 3 to 4 hours.

Goldfield

Remedial Actions: Shelter, Access Control

There are approximately 500 people living in Goldfield at this time; however, their exact locations are unknown. Evacuation is not considered feasible at this time. Advising residents to remain indoors is possible with assistance from local law enforcement officers. It would require a minimum of 3 to 4 hours.

Highway 95 (Scotty's and Lida Junctions)

Remedial Actions: Evacuation, Shelter, Access Control

With fewer than a dozen inhabited locations along Highway 95, evacuation, shelter, and access control are feasible and could be accomplished in a very short time. Actions taken in the area west of Lida Junction, however, would only be marginally effective since this is not a routinely-covered area.

Springdale - Beatty

Remedial Actions: Shelter, Access Control

At most, we should be able to advise the residents (approximately 700) of this area within 2 to 3 hours to remain indoors during cloud passage. Evacuation would not be feasible.

Death Valley National Monument

Remedial Actions: None

Death Valley National Monument, and in particular the Furnace Creek area, caters to a highly mobile population. During peak periods (winter months), the population of Furnace Creek alone, which usually accounts for at least 80% of the total Monument population, could number about 10,000 to 12,000 people on any given day. Of this number, only a small fraction are park employees and their families. Most visitors stay at one of several Monument campgrounds. The remainder are either passing through or being lodged at the Furnace Creek Ranch or Inn. For these reasons, remedial actions are not feasible during the winter months. Most Monument facilities are now open the year round, although the mobile population is much smaller during the summer months. Remedial actions during the warmer months are doubtful.

Lathrop Wells - Amargosa Farms - Spring Meadow Farms

Remedial Actions: Shelter, Access Control

Until a few years ago, the few people living in these areas could be identified and controlled in the event that some remedial action were necessary. With the introduction of the American Borate and Industrial Minerals Venture mining complexes, there are now 1500-2000 residents living in a 300 to 400 square mile area. Discussions with the local sheriff on possible evacuation have brought to light a number of potential problem areas. These include the lack of transportation available to as many as 50% of the residents, the existence of bed-ridden people, and the fact that there are a number of illegal aliens working on the farms in the area who would probably not cooperate at all. It is our belief that evacuation would not be feasible. Shelter is feasible, as we do keep current a map of all inhabited dwellings in the area.

Pahrump

Remedial Actions: None

There are now more than 3,000 people living in a 600 to 800 square mile area with continued growth expected over the next several years. Remedial actions of any kind would be impractical.

2. Thyroid Dose Reduction Remedial Actions   Following the release of fresh fission products, Iodine-131 is the radionuclide considered most likely to reach concentrations in food which would warrant remedial actions to reduce the projected dose. The important mode of transmission to humans is through the consumption of fresh fluid milk. Iodine-131 can appear in milk within a few hours after its deposition on pasture. The concentrations in milk may reach a maximum in 2 to 4 days, after which the concentrations diminish with an effective half life of 5 days.

In order to protect the population from exposure by the ingestion of contaminated milk, there are two basic alternative actions. These are as follows:

(1) Cow-feed or pasture control to prevent the ingestion of radioactive materials by dairy cattle, or

(2) Milk control either by diverting the milk to other uses that allow the radioactivity to decay before ingestion or by destroying the milk and substituting uncontaminated milk from other areas.

The optimum action would be to prevent, through feed and pasture control, contamination of the milk. This would be followed up by milk control only in contaminated areas where feed and pasture control were not carried out or were not adequate.

EPA's off-site staff has, for the past few years, conducted at least a biannual family milk cow (Fig. 3) and Grade A dairy (Fig. 4) census which takes in the entire State of Nevada, the easternmost counties in California, and the westernmost counties in Utah. This information, which includes such things as the number and location of cows, feeding practices throughout the year, and where the milk is processed, is stored in a computer and, can be retrieved to provide a listing of all milk cow locations in any contaminated sector out to the boundaries of the survey. Within hours, EPA monitors can be collecting milk at these locations.

At all family milk cow locations within the area of our survey, milk can either be purchased by the Government or replaced, whichever the owner prefers. Implementation of remedial actions at the Grade A dairies in Nevada, San Bernardino and Mono Counties in California, and extreme Southern Utah is somewhat more complicated but still feasible. The dairy cattle may have to be removed from contaminated pastures and uncontaminated hay may have to be brought in as a replacement; or, if the cows are being fed stacked hay, the outer bales may be removed to obtain less-contaminated hay. Contaminated milk may be diverted to processed dairy products. These actions may entail Government purchase and transport of alternate hay into the contaminated area, and complex coordination with state and local health departments, dairy associations, etc.

Contamination requiring remedial actions at Grade A dairies in the Utah and Idaho milk shed areas pose insurmountable problems. Execution of a test should be avoided if the associated predicted iodine levels exceed the established guidelines. In addition, caution should be exercised if the possibility of precipitation (scavenging) exists during the passage of the

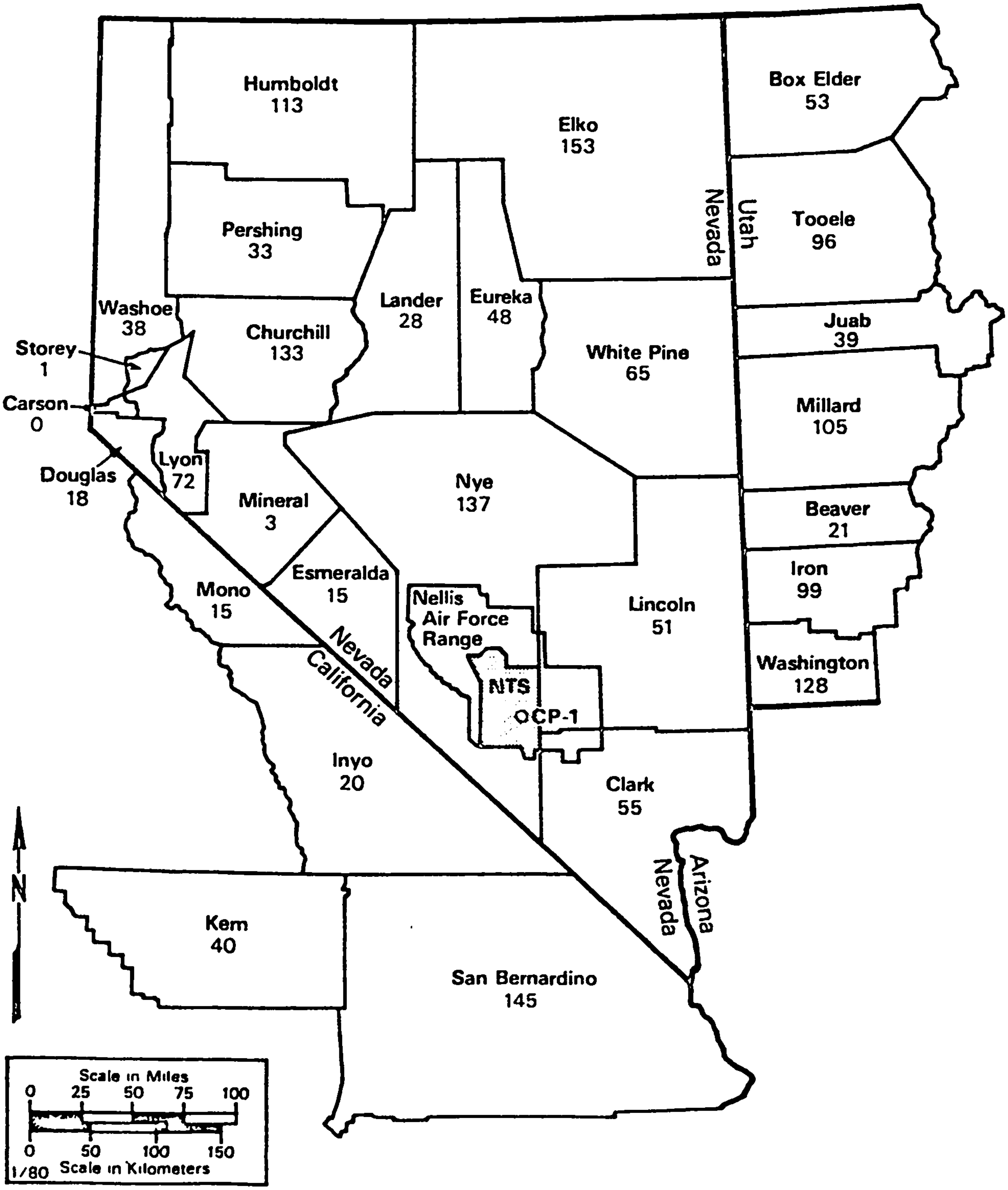

Fig. 3. Family milk cow census.

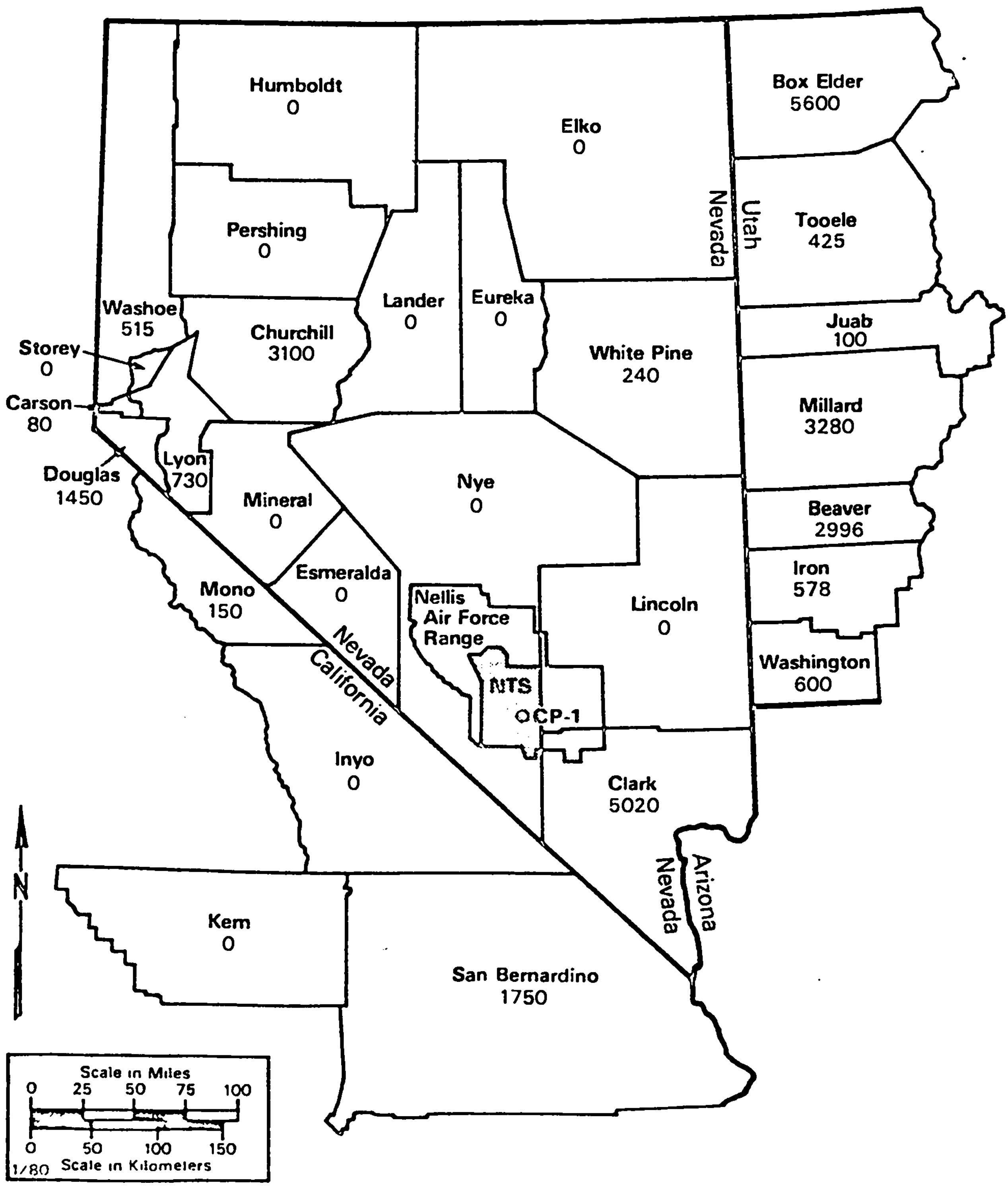

Fig. 4. Grade A dairy cow census.

radioactive debris--even if the predicted dry deposition iodine levels are below the guidelines.

V. THE PROBABILITY OF ACCIDENTAL RELEASES OF RADIOACTIVITY FROM UNDERGROUND TESTS

A. Containment

A principal reason for beginning to conduct nuclear tests underground was to reduce substantially the radioactive fallout. In 1957, a number of such tests demonstrated that with partially stemmed holes at depths of about 500 feet, the fallout was reduced by an order of magnitude. Experimentation also began with various "stemming" designs which were considered to be successful if there were no visible and dynamic releases of radioactivity to the atmosphere. Seeps, defined as an invisible gaseous release of radioactivity unaccompanied by any dynamic behavior, did occur occasionally, and represented such drastic reductions in radioactivity from that experienced in atmospheric tests that frequently no measurement of the quantities of radioactive releases were even recorded.

During and after the test moratorium, 1958-61, several principles became more or less evident. First, it became clear that radioactivity released to the atmosphere should be prevented if possible. Second, proper depths of burial, stemming materials, and stemming procedures were achievable to prevent major releases. Third, an underground environment did not prevent, and could even enhance certain diagnostic measurements for such tests.

By the acceptance of the Limited Test Ban Treaty in October of 1963, enough experience had been gained that there was considerable confidence in containment designs. This confidence rested upon very limited experience, however, for there were only a few tests or experiments aimed at questions concerning containment theory. Further, there were no staffs dedicated to containment to guide efforts into the solutions of particular problems which were to loom large. A contained event provided little insight into questions about the reasons for success or failure of containment. Containment failures were not anticipated since all events were designed to contain. Therefore containment failures were poorly diagnosed. These factors made evaluation of containment design difficult; one was forced to learn the empirical location of the line between containment success and failure without crossing that line --and, in fact, keeping as far from it as possible.

The Baneberry failure in December 1970 triggered decisive action on the part of the Laboratories with increased emphasis on the goal to understand as much as possible about containment, rather than just to achieve containment. Considerable manpower and large numbers of field tests and measurements combined to shed light upon some of the difficulties of the past. The results of this effort are shown in Fig. 5 for each fiscal year since the ratification of the Limited Test Ban Treaty in 1963. The sharp cut-off in seeps is evident, and came about from an alteration in the design of diagnostic and control cable gas blocking and an increase in the depth of burial for small yields. These actions demonstrated that the source of seeps, at least through 1970, was mainly cables. Early in the underground test experience, when there were other important differences in containment designs, some seeps are known to have been within the stemming, and possibly in a few isolated instances, from outside the casing.

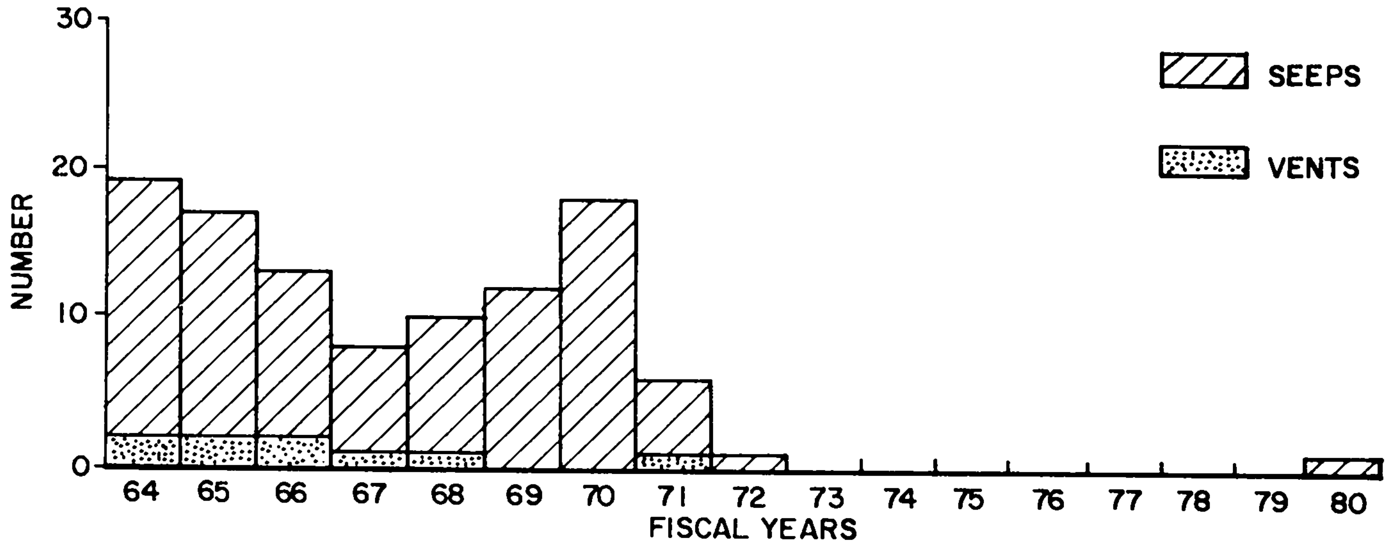

Fig. 5. Number of seeps and vents for fiscal years since LTBT.

The seep which occurred in 1971 was from an event, (Diagonal Line) which was located, designed and constructed prior to Baneberry. Because a seep, should it occur, was expected to be small, and alteration of the event to new designs and specifications would be exceedingly expensive, the event was executed with the old design. A seep did occur, but it was of the kind anticipated and posed no hazard off site.

When the probability of an accident which would release a significant fraction (a few per cent) of the fission products of a nuclear explosion is assessed, attention is drawn to five events. These are Pike, Alpaca, Pin Stripe, Bandicoot, and Baneberry. All five events were expected to contain at the time of their detonation, and none had features which, preshot, had been identified as being likely to increase substantially the probability of a dynamic vent. Dynamic venting occurred on some events for which satisfactory corrective measures appear to have since been found. Except for events buried too shallowly, containment failures have resulted from four causes. These are stemming, cables, pipes, and geologic parameters. Each of these causes has been addressed to reduce the probability of failure to as low a level as possible. The probabilities are now believed and demonstrated to be so low, that the occurrence of a failure must be considered as an accident, comparable in likelihood to "accidents in nature" or to events in the activities of man which are also regarded as accidents. The logic behind such a conclusion follows.

Historically, the first cause for containment failures was lack of an adequate stemming design. This problem has largely been overcome. The probability of such a failure as been demonstrated to be less than 3×10^{-3}. Further, the theory of gas flow through stemming materials is now believed to be understood sufficiently well that new stemming designs could now be made with confidence should that become necessary.

The second principal cause of containment failure, one which has been demonstrated to be of no real hazard off site, seeping through cables, has also been eliminated from our experience since 1971. Continuing care with cable blocks and cable quality control should keep this cause at its present low level of concern. While mechanical, manufacturing, and human failures are certainly possible, it is redundancy in design which makes the probability of such a seep low. Since 1971, the probability of cable gas seeps has been demonstrated to be less than 10^{-2}. The radioactivity transmitted in a seep is expected to be confined to the test site, though there is chance that off-site detection could occur. Experience in the late 50's and early 60's suggests that perhaps 1 seep in 10 might be detected off site. The probability of a cable seep which can be detected off site is believed to be of the order of 10^{-4}, i.e., one in ten thousand.

The third cause of failures to completely contain radioactive gases has been the existence of relatively open pipes coming to the surface or near surface. A close examination of the five tests which have vented by this means since 1963 (Eagle, Diluted Waters, Parrot, Pin Stripe, and Hupmobile), has resulted in considerable enlightenment as to the origin of the difficulties. From each venting experience, lessons were learned which have led to design improvements. The containment of this class of event now appears to rest upon the proper functioning of the stemming and of the mechanical components. The failure probability of such components can be objectively assessed, and thanks to redundant designs, etc., is of the order of 10^{-4}. The complexity of these events is such, however, that the true level of the probability of a surprise should be regarded as being higher, perhaps as much as 10^{-3}. Since an event of this class is relatively rare, and particularly identified, it is possible to take additional operational measures to make certain that the consequence of an accident would be minimized.

The fourth cause--geologic parameters--is quite a difficult problem. Only a few events have been identified in which a fault did play or might have played a part in venting. These events are: Bandicoot, Pike, Pin Stripe, and Baneberry.

Pike and probably Bandicoot were much underburied by current practices. Pike and Pin Stripe had pipes which may have transmitted energy to the fault zone; such geometries are carefully examined with current practices. Bandicoot, executed in 1962 before the LTBT, had a yield which may have been higher than calculated or measured (the crater is large) but also had unique stemming. It had several large diameter air-dielectric cables leading from the top of the diagnostic rack to near the surface and a stemming configuration of coarse material to a level of 50 ft from the surface then a 50 ft layer of fine material. Cavity gases could have been transmitted through the cables to the high-impedance created by the fines plug producing conditions which might have ruptured the casing, transmitting cavity gases to a weak geological structure. Since the signing of the LTBT, Baneberry is the only case of venting which may have been caused by geologic factors with a contribution from improper stemming procedures.

Steps taken post-Baneberry not only resulted in containment designs which prevented gas seeps, but caused the adoption of procedures that called for significant pre-shot geologic explorations and assessments. In addition, exhaustive explorations and research into the Baneberry event site have resulted in an appreciation of the several unusual geologic features of that location. These features are inherently rare for the test site. Should these geologic features appear at a site location in the future, they will likely become known, with present sampling and logging practices and the location can then be avoided. Baneberry is unique in our experience. The probability of the occurrence of unidentified structures has been demonstrated to be less than 3×10^{-3}. With current geologic explorations and analyses, it is probably conservative to estimate the probability of a Baneberry reoccurrence to be less than 10^{-3}.

Unfortunately, a Baneberry type of reoccurrence is not the real concern associated with future failures. The real lesson in the Baneberry experience is that the earth is extremely complicated. Limited opportunities--or resources--are available to thoroughly explore and to understand all facets of site geology. The next containment failure if it occurs is not expected to be a revisitation of the Baneberry difficulties. It will most likely be due to human error of some kind, or to some unique combination of parameters outside of present experience. Thus the true level of the probability of failure because of geologic parameters is unknown. A crude estimate is that it is of the order of one in a thousand.

B. Can the Probabilities of Releases of Radioactivity be Regarded as Accidental?

Initially, we tend to compare "new" hazards with those with which we normally live. A careful inspection of accident statistics is very informative in that it gives a feeling for the way society deals with hazards which occur at various levels of probability.

C. Accidents in the United States

In 1979, there were 103,500 people killed in accidents in the United States.[1] The corresponding population death rate was 47.7 persons per 100,000 population. This can be translated into the probability of a U.S. citizen being killed in an accident being 4.77×10^{-4} per person for 1979.

It has proved to be quite useful to reduce all data to the risk per person per year for comparative purposes. Other units are possible, such as the risk per person per hour exposure, or per person per event, per person per mile, etc. But many risks are difficult to assess if the unit of exposure is too short. The year seems to be an "intermediate" unit, since it can be thought of as a relatively small fraction of a lifetime--providing plenty of time to respond to an unacceptable risk--yet long enough to permit an exposure to a number of hazards concurrently. The question is, how are such risks judged? Which do people tend to take most seriously?

The probabilities per year of a person being killed in the United States by various means are summarized in Table I. The numbers have been derived from statistics 1974 through 1977.[1]

The lowest probability listed in Table I is consistently for deaths due to radiation. Averaged over the past 16 years the probability of death per person was 2×10^{-9}. However, this is an example of a misleading statistic because not everyone in the U.S. had the opportunity to be exposed to a lethal dose of radiation. For those who are working with radiation, the probability of being killed is much higher.

D. Cataclysms

There are some conclusions which can be derived from the number of deaths which occur as a result of cataclysmic events. The greatest recorded loss of life from any earthquake occurred in the Wei-Ho Valley, in China, on February 2, 1556, when 830,000 people died.[2] Though there are not data available giving the number of people exposed to this earthquake, it appears that several million were, judging by present population data and noting that the world's population in 1556 was probably less than one-fourth as large as now. If one assumes there were 4×10^{6} people exposed, and that this earthquake was so severe as to occur only every 10^{4} years, then the probability per person per year, assuming a constant population density, is 2×10^{-5}.

Similar efforts can be made in the analysis of other disasters. Summaries of data available, estimates, outright guesses and assumptions necessary to obtain a rough idea of the probability, P, per person per year of being killed in similar events are given in Table II. The population density of urban areas appears to be increasing more rapidly than the population. If any of the events in Table II were to recur, the number of deaths would probably be larger, perhaps substantially.

As a class, volcanoes appear to be more hazardous than earthquakes, both from the risk per event and the frequency of event. The major reason probably stems from the fact that the area surrounding an old volcano tends to be more fertile than other areas, resulting in an influx of population. Thus, there is a group located at just the right place to suffer from the havoc of a sudden new eruption. If the frequency of eruptions for a particular volcano is too high, the population responds by thinning out. Although populations occasionally have exhibited a collective memory of prehistoric events,[3] the

TABLE 1

ACCIDENTS IN THE UNITED STATES

	1974		1975		1976		1977	
U. S. Population	211,389,000		213,032,000		214,515,000		216,800,000	
Type of Accident	Deaths	Probability/ Person/ Year	Deaths	Probability/ Person/ Year	Deaths	Probability/ Person/ Year	Deaths	Probability/ Person/ Year
Motor Vehicle*	46,402	2.2×10^{-4}	45,853	2.2×10^{-4}	47,038	2.2×10^{-4}	49,510	2.3×10^{-4}
Railway	716	3.4×10^{-6}	608	2.9×10^{-6}	552	2.6×10^{-6}	576	2.7×10^{-6}
Water Transport	1,579	7.5×10^{-6}	1,570	7.4×10^{-6}	1,371	6.4×10^{-6}	1,357	6.3×10^{-6}
Air and Space Transport	1,687	8.0×10^{-6}	1,552	7.3×10^{-6}	1,445	6.8×10^{-6}	1,643	7.6×10^{-6}
Poisoning by Solids and Liquids	4,016	1.9×10^{-5}	4,694	2.2×10^{-5}	4,161	2.0×10^{-5}	3,374	1.6×10^{-5}
Poisoning by Gases and Vapors	1,518	7.2×10^{-6}	1,577	7.4×10^{-6}	1,569	7.4×10^{-6}	1,596	7.4×10^{-6}
Falls	16,339	7.7×10^{-5}	14,896	7.0×10^{-5}	14,136	6.6×10^{-5}	13,773	6.4×10^{-5}
Fires and Flames	6,236	3.0×10^{-5}	6,071	2.8×10^{-5}	6,338	3.0×10^{-5}	6,357	2.9×10^{-5}
Excessive Heat	140	6.6×10^{-7}	190	8.9×10^{-7}	100	4.7×10^{-7}	308	1.4×10^{-6}
Excessive Cold	348	1.6×10^{-6}	359	1.7×10^{-6}	424	2.0×10^{-6}	634	2.9×10^{-6}
Hunger, Thirst, Exposure, Neglect	201	9.5×10^{-7}	257	1.2×10^{-6}	247	1.2×10^{-6}	264	1.2×10^{-6}
Bites and Stings	53	2.5×10^{-7}	50	2.3×10^{-7}	53	2.5×10^{-7}	55	2.5×10^{-7}
Other Accidents Caused by Animals	139	6.6×10^{-7}	128	6.0×10^{-7}	143	6.7×10^{-7}	109	5.0×10^{-7}
Lightning	112	5.3×10^{-7}	124	5.8×10^{-7}	81	3.8×10^{-7}	116	5.4×10^{-7}
Cataclysm	384	1.8×10^{-6}	103	4.8×10^{-7}	212	1.0×10^{-6}	202	9.3×10^{-7}
Drowning	6,463	3.1×10^{-5}	6,640	3.1×10^{-5}	5,645	2.6×10^{-5}	5,961	2.7×10^{-5}
Inhalation and Ingestion	2,991	1.4×10^{-5}	3,106	1.5×10^{-5}	3,033	1.4×10^{-5}	3,037	1.4×10^{-5}
Mechanical Suffocation	1,083	5.1×10^{-6}	998	4.7×10^{-6}	911	4.3×10^{-6}	969	4.5×10^{-6}
Struck by Falling Object	2,070	9.9×10^{-6}	1,897	8.9×10^{-6}	1,875	8.8×10^{-6}	1,947	8.9×10^{-6}
Struck by or Caught Between Objects	521	2.5×10^{-6}	493	2.3×10^{-6}	471	2.2×10^{-6}	443	2.0×10^{-6}
Explosion of Pressure Vessel	57	2.7×10^{-7}	64	3.0×10^{-7}	69	3.2×10^{-7}	58	2.7×10^{-7}
Firearms	2,513	1.2×10^{-5}	2,380	1.3×10^{-5}	2,059	9.7×10^{-6}	1,982	9.1×10^{-6}
Explosives	459	2.2×10^{-6}	389	1.8×10^{-6}	442	2.1×10^{-6}	439	2.0×10^{-6}
Hot Substance, Corrosive Liquid or Steam	216	1.0×10^{-6}	209	9.8×10^{-7}	210	9.8×10^{-7}	181	5.4×10^{-7}
Electric Current	1,157	5.5×10^{-6}	1,224	5.7×10^{-6}	1,041	4.9×10^{-6}	1,183	5.5×10^{-6}
Radiation+	1	4.7×10^{-9}	0	0	0	0	0	0
Machinery	783	3.8×10^{-6}	865	4.1×10^{-6}	768	3.6×10^{-6}	703	3.2×10^{-6}
Surgical and Medical	3,021	1.4×10^{-5}	3,184	1.5×10^{-5}	3,009	1.4×10^{-5}	3,107	1.4×10^{-5}
Other	3,362	1.6×10^{-5}	3,519	1.7×10^{-5}	3,292	1.5×10^{-5}	3,318	1.5×10^{-5}
All Accidents	104,622	4.9×10^{-4}	103,030	4.8×10^{-4}	100,761	4.7×10^{-4}	103,202	4.8×10^{-5}

* In the years 1970-1973, the probability of a motor vehicle accident was 2.7×10^{-4} per person.

\+ In the years 1962-1977 there were 8 deaths attributed to radiation. Averaged over the 16 years, this is a probability of $\approx 2 \times 10^{-9}$ per person per year.

TABLE II

CATACLYSMS

Event	Location and Date	People Killed	People Exposed	Death Probability Per Person Per Event	Estimated Energy Release of Event	Estimated Frequency	Death Probability Per Person Per Year
Earthquake	Wei-Ho Valley, China 1556	8.3×10^5	$\sim 4 \times 10^6$	2×10^{-1}	6500 MT	1 in 10^4 yrs.	2×10^{-5}
Earthquake	Lisbon, Portugal 1755	4.0×10^4	7.8×10^6	5×10^{-2}	3500 MT	1 in 10^4 yrs.	5×10^{-6}
Earthquake	Tokyo, Japan 1923	1.5×10^5	$\sim 3 \times 10^6$	5×10^{-2}	800 MT	1 in 10^3 yrs.	5×10^{-5}
Earthquake	San Francisco, CA 1906	700	2.5×10^5	3×10^{-3}	700 MT	1 in 500 yrs.	6×10^{-6}
Earthquake	Alaska 1964	117	3.0×10^5	4×10^{-4}	120 MT	1 in 100 yrs.	4×10^{-6}
Earthquake	Kansu, China 1920	10^5	1.0×10^7	1×10^{-2}		1 in 10^3 yrs.	1×10^{-5}
Volcano	Martinique 1902	4.0×10^4	6.5×10^4	6×10^{-1}		1 in 10^3 yrs.	6×10^{-4}
Volcano	Iceland 1783	9.0×10^3	4.5×10^4	2×10^{-1}		1 in 10^3 yrs.	2×10^{-4}
Volcano	Tambora 1815	26 Survivors	1.2×10^4	~ 1		1 in 10^3 yrs.	$>1 \times 10^{-3}$
Volcano	Taal 1911	1.5×10^3	1.0×10^4	1.5×10^{-1}		1 in 10^2 yrs.	1.5×10^{-3}
Volcano	Krakatoa 1883	3.6×10^4 (tsunami)	1.8×10^5	2×10^{-1}		1 in 5×10^3 yrs.	4×10^{-5}
Tidal Wave	Galveston, TX 1900	6.0×10^3	3.6×10^4	1.7×10^{-1}		1 in 500 yrs.	3×10^{-4}
Storm Waves	Bay of Bengal 1777	3.0×10^5 (drowned)	10^7	3×10^{-2}		1 in 100 yrs.	3×10^{-4}
Storm, Flood	Holland 1953	1.5×10^3	10^6	1.5×10^{-3}		1 in 100 yrs.	1.5×10^{-5}
Earthquake	Tanshan, China 1976	6.6×10^5	4.0×10^7	1.6×10^{-2}		1 in 10^3 yrs	1.6×10^{-5}

general pattern has been for natural catastrophies to be pretty well forgotten in several centuries.

Though earthquakes often affect people over very large areas, they tend to be "killers" only in very limited areas and only if such areas coincide with high population densities. Nevertheless, they occur with such frequency the world over that they constitute a real hazard to almost the entire population of the world.

E. Levels of Probability and Their Public Acceptance

After study of the probabilities of being killed by the various means given in Tables I and II, it is perhaps permissible to draw some conclusions about the general reaction of society to particular levels of probability.

It would seem that those accidents which have a probability less than 10^{-6} per person per year are not accidents which are of any great concern to the average person. He may or may not be aware, for example, that people die from excessive heat, cold, bee stings, or lightning, etc., but it scarcely concerns him. If he hears of such deaths, he generally ascribes it to bad luck or stupidity. "It can't happen here" is an idea easily held for accidents at this frequency of occurrence.

Those dying from cataclysm in 1973 were few since the probability of being killed in that manner was only 0.9×10^{-6}. At first sight this appears to conflict with Table II, where the probabilities per person per year of dying by cataclysm appears to be much larger. However, there were no real cataclysms in the U.S. in 1973, and a period of time significantly greater than 1 year must be used before a comparison can be made. For example, assuming that a recurrence in 1973 of the Galveston tidal wave of 1900 would again kill 6,000 people, their deaths would increase the total number of people killed in the year by more than 6%. The corresponding probability for the year would be 3×10^{-5} for every person in the U.S. Since those who would actually be exposed to such a hazard along the nation's coastlines would probably be much less than 10% of the total population, the true probability would not be far from those listed in Table II.

When the levels of probability are of the order of 10^{-5}, most everyone is aware that the hazard exists, and mothers frequently caution their children about the danger (e.g., drowning, firearms, poisoning, blows from falling objects, etc.). Aircraft accidents fall at this level, and most people are certainly aware of the hazard. As mentioned above, this particular type of accident is frequently accompanied by lots of publicity, and some people actually do alter their lives by refusing to travel by air, etc., in deference to a risk of this level, but most do not.

When the probability of being killed climbs to 10^{-4}, most of us are quite willing that money--as long as it is public--be spent to decrease the risk. Fences are built to prevent falls, stoplights and traffic regulations are introduced and enforced, and safety campaigns are waged--all with general public approval--in order to decrease such a hazard. (It may be that the accompanying property damage is a significant factor, also.)

When the level of hazard reaches 10^{-3}, people are willing to spend their own money and effort to do something about it. Examples of risks at this level are difficult to find, for they occur only at intervals, and steps are immediately taken to reduce the risk. This level appears not to be acceptable to anyone.

It is curious that so many people apparently lose concern for a hazard--instinctively, it seems--when it has a probability of occurrence of the order of 10^{-6} per person per year, or a frequency of once in a hundred years or so. (The latter point is more easily understood.) As a result, all kinds of groups--in government, industry, military--seem to have independently concluded that if they are able to reduce the probability of a particular hazard to this level, they are satisfied. Many are aware of the existence of such criteria in fuzing and firing components, in accidental detonation of bombs, in failure rate of particular components of airplanes, etc. Another example which can be given is that of legislated public risk.

F. Acceptability of Risks

The determination of the acceptability of various levels of risk can be said to have been made empirically by our society on the basis of finding--by trial, error, and subsequent correction action--an acceptable balance between technological benefit and social cost.

A principal difficulty in today's world is that the time scale of the development of a technology is frequently too short to permit corrective actions if there are "unacceptable" impacts upon the environment or some portion of the population. To some extent, this has been an inherent problem with radioactive fallout; the existence of fallout preceded the recognition of its long-term and long-range effects, and even today, long-time effects upon the world's population are subject to further revelation, and debate.

A second major difficulty associated with the acceptability of risks from nuclear testing is the inability of the average citizen to realize, assess, quantify and appreciate the benefits he derives from the existence of a nuclear stockpile maintained as a deterrent force to today's world.

These two features of nuclear testing--so necessary to see in balance--combine to make descriptions or conclusions about acceptabilities very subjective. There is, for instance, a keen appreciation that activities in which an individual participates on a voluntary basis are judged quite separately from those which are forced upon him. "Involuntary Activities" are herein defined as those which are determined by a governing or controlling body, and include the effects of NTS released radioactivity. C. Starr[4] has pointed to the importance of voluntary risk versus involuntary risks, and has also discussed the importance of Benefit Awareness. A significant and relevant feature of his article is the low level of awareness that the general public has of the benefits it might derive from nuclear activities. Hence, there is tendency for the public to view most of our activities as highly "involuntary" to them, at least in the recent past and at the present time. Dr. Starr's logic demonstrates that the public will probably be very reluctant to accept risks from involuntary activities above the level of 10^{-6} per person per year of exposure.

One way to solve the problem is to force the risk to be so low that all negative aspects can be relatively easily offset by general arguments about benefits. The combination of the probabilities of a death due to NTS nuclear test activities follows:

1. The level of risk for the release of radioactivity detectable off site for any event has been shown to be less than 10^{-2}, i.e., one event per hundred.

2. Only a fraction (less than 10^{-1}) of those events detected off site are calculated to represent any hazard to off-site personnel; thus far in underground testing, no event has presented such a hazard. (Here, a hazard is assumed to exist if dose to the body or to the thyroid is above MC-0524 minimum guidelines.) This reduction is due to the careful selection of shot time, including winds, etc., as described elsewhere in this paper. The risk of a hazardous exposure for anyone is therefore reduced to less than 10^{-3} per event.

3. The probability of a person dying as the result of a radiation exposure may be estimated from medical data.[5] The prompt lethal dose in rem* for 10%, 50%, and 90% deaths

$$LD_{10} = 220 \text{ rem}$$

$$LD_{50} = 285 \text{ rem}$$

$$LD_{90} = 350 \text{ rem}$$

These are beyond any conceivable dose to off-site personnel and more subtle mechanisms must be invoked.

The death rate from leukemia over a period of 15-20 years is in the range 1-2 per 10^6 persons rem. Deaths from cancer are in the range of 50-165 deaths per 10^6 person rems during the first 25 years following exposure.[6] The incidence of malignant thyroid tumors is in the range of 1.6 to 3.0 cases per 10^6 person rems per year; the green forage, cow and milk chain provide a concentration factor of about 100. Using the upper part of the range these translate to the probabilities:

Cause of Death	Probability
Leukemia	2×10^{-6}/rem
Cancer	1.65×10^{-4}/rem
Thyroid tumor+	9×10^{-4}/rem

The thyroid exposure can be effectively controlled through operational control of milk. The probability of a death per rem exposure is thus about 2×10^{-4}.

Combining with the risk per event from (2) and assuming 100 persons may be exposed to a dose of 0.5 rem, the probability of a death, is about 10^{-5} per event assuming no evacuation. Since an evacuation attempt within the fallout area would be made and taking the efficiency of evacuation as at least 90 percent, the probability of a death is less than 10^{-6} per event. (In the

* For this discussion a rem (Roentgen-equivalent-man) is equivalent to a Roentgen or rad.

+ Thyroid tumors can be easily and successfully treated--each one does not represent a death; the probability is high by at least a factor of two.

history of underground testing no individual off site has been exposed to more than about 0.055 R hence the probability of a death per event has been less than 10^{-7}.)

4. The probability of off-site radiation-caused (per person per event) fatality may be assumed acceptable to the average member of the public for a voluntary risk.

5. The current rate of testing is such that it will take over 500 years for 10^4 events, thus the demonstrated rates lead to a prediction of a probability of less than 1 in 200 of an off-site radiation caused fatality in many generations.

VI. SUMMARY

The evaluation of the impact of radiological limits on nuclear test operations show:

1. The probability of delay in execution of nuclear tests rises significantly at off-site radiological exposure limits under 2.5 rad; the current limits are 0.17 and 0.5 rad for uncontrolled and controllable populations.

2. At a limit of 0.17 rad the probability of execution with delays in execution is about 20%. For the higher yield events, delays could be many days, even weeks.

3. Test experience shows that for all events designed to contain, the guidelines of MC-0524 have not been exceeded. This is most probably because no high yield event has had any release.

4. The protective action capability of the EPA can effectively reduce external and internal exposures to small populations. Events with predicted trajectories across areas with populations where controls cannot be effective and where exposures exceeding 0.17 rad should be delayed for meteorological conditions which produce a more acceptable trajectory or exposure.

5. The probability of an accidental release causing a delayed death due to cancer in the off-site population is less than 10^{-6}, a value which statistics and observations show should not cause undue concern to the citizenry.

6. Studies of containment parameters and comprehensive review of the containment methods since Baneberry have markedly reduced all types of release, however the possibility of a massive release cannot at present be ruled out even though it is extremely small.

VII. RECOMMENDATIONS

1. Adherence to DOE MC-0524 guidelines should be continued but should be consistent with the principle of as low risk as practicable.

2. Reevaluation of all data pertinent to containment of underground nuclear tests and release of radioactivity should be made to determine if traditional concepts and models (e.g., the Pike model) are presently germane.

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F. Insure that every precaution has been taken to reduce to the lowest level technically and economically practicable all hazards, both to the public and on-site personnel, from any nuclear test detonation, subsequent post-shot operation, or other NTS operation.

G. Insure that all operations involving the risk of radiation exposure will be planned and executed in accordance with ERDA Manual Appendix 0524, Parts IA and IIA. Conservative area controls shall be installed and the use of forward area personnel and facilities restricted to the minimum essential, with evacuation plans established for all remaining personnel.

H. Insure that the containment design, emplacement, and firing of the test devices plus postshot operations shall be conducted so that the probability of the release of radioactivity in sufficient quantity to be a health hazard either on site or off site is minimized. However, since accidents are always a possibility, the radiation guidelines approved by ERDA for planning nuclear test detonations are predicated on the postulation that a release could occur, and, therefore, require predictions to be made for the maximum potential exposure from each test using the most appropriate hypothetical release model. Thus, the "as low as practicable" concept for operations involving potential radiation exposure is governing, but as a safety precaution an accident model is postulated as a limiting factor. Therefore, in addition to the radiological criteria given in paragraph G above, the following shall also be adopted:

> For tests at the Nevada Test Site, when considering the event day weather conditions and the specific event characteristics, calculations should be made using the most appropriate hypothetical release models which estimate the off-site exposures that could result from the most probable release scenario. Should such estimates indicate that off-site populations, in areas where remedial actions to reduce whole body exposures are not feasible, could receive average whole body doses* in excess of 0.170R/year, the event shall be postponed until more favorable conditions prevail. In addition, events may only proceed where remedial actions against uptake of radionuclides in the food chain are practicable and/or indications are that average thyroid doses* to the population will not exceed 0.5R/year.
>
> In those areas where trained rad-safe monitors are available, where communications are effective, where people can be expected to comply with recommended remedial actions, and where remedial actions against uptake of radionuclides in the food chain are practicable, events may proceed where indications are that individuals in those areas would not

* See paragraph 5.4, FRC Report No. 1, for discussion on the concept of average dose to a suitable sample of the exposed population.

receive whole body and thyroid doses in excess of 0.5R/year and 1.5R/year, respectively.

Should there be any release of radioactive material which may move off site, aircraft and ground radiation monitoring systems will be employed along with detailed meteorological data to predict radioactive cloud trajectories and potential exposure rates at downwind locations. Based upon these predictions and subsequent radiological monitoring observations, every effort will be made to keep total dose commitments from both internal and external emitters to the lowest practicable levels. Remedial actions which are compatible with both a coordinated emergency action plan and the basic philosophy of the FRC Radiation Protection Guidance of July 16, 1964, and May 17, 1965, will be employed to this end.

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