236
5/24/89 JS ②

NVO-314
UC-41

NVO-314

A REVIEW OF AERIAL RADIOLOGICAL SURVEYS OF NEVADA TEST SITE FALLOUT FIELDS 1951 THROUGH 1970

DECEMBER 1987

UNITED STATES DEPARTMENT OF ENERGY
NEVADA OPERATIONS OFFICE
LAS VEGAS, NEVADA

DISCLAIMER

Printed in the United States of America.

Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS price codes
Printed copy: A02
Microfiche copy: A01

NVO--314

DE89 011289

A REVIEW OF AERIAL RADIOLOGICAL SURVEYS OF NEVADA TEST SITE FALLOUT FIELDS 1951 THROUGH 1970

Z. G. Burson
Project Scientist

EG&G Energy Measurements, Inc.
Las Vegas, Nevada

This Document is UNCLASSIFIED

C. K. Mitchell

C. K. Mitchell
Classification Officer

MASTER

This work was performed by EG&G Energy Measurements, Inc. for the United States Department of Energy under Contract Number DE-AC08-83NV10282.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

Aerial surveys of offsite fallout radiation fields from the Nevada Test Site began in the early 1950s and continued throughout the above-ground testing period. The results of the aerial surveys were used to support ground data in determining the extent of the fallout patterns.

For the series of tests conducted in 1953 and 1955, the primary uncertainty of the results was knowing the location of the aircraft. Navigation was made from aeronautical charts of a scale 1:1,000,000, and errors in location of several miles were experienced. Another problem was that exposure rate readings made in the aircraft of 1 milliroentgen per hour or lower were not reliable. Exposure rate measurements above 1 milliroentgen per hour were more accurate, however, and are considered reliable to within a factor of two or three in predicting 3-foot exposure rate levels.

For the 1957 series, the aircraft position data were quite accurate. Ground-level exposure rates predicted from aerial data obtained by the United States Geological Survey aircraft for the five-detector array were considered reliable to within ±40% or better for most of the surveys. When the single detector was used, the accuracy decreased to about a factor of two. Relative count rates obtained by the aircraft operated by the Atomic Energy Commission, Raw Materials Division, are probably valid, but quantitative determinations of 3-foot exposure rates are not.

The Aerial Radiological Monitoring System performed all the aerial surveys in the 1960s. However, the air-to-ground conversion factors used were too low. Using a corrected conversion factor, the predicted 3-foot exposure rates should be valid to ±40% in most fallout fields if all other parameters are considered.

PREFACE

A review was made of the literature and records available at the United States Department of Energy's Coordination and Information Center in Las Vegas, Nevada, pertaining to aerial surveys of terrain radiation produced by the Nevada Test Site fallout fields during the period 1951 through 1970. Categories of reports reviewed were under the agency listings of: WT, NYO, USGS, EG&G, Inc. and UCRL. Approximately 100 documents were reviewed.

Although extensive, this review was not comprehensive. Not all documents referring or relating to aerial surveys were reviewed and not all individual data points were examined. However, a sufficient review of documents and data was made to fulfill the purpose of this report, which is to evaluate the usefulness of the results in light of today's aerial survey technology. In addition, the review considered possible errors and uncertainties in the original data, as well as how the results were used in developing the fallout patterns. Finally, recommendations are given on how best to use the results today in evaluating or reassessing the original fallout patterns.

CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

1. INTRODUCTION

Aerial radiological surveys were performed as early as 1948 in the United States when the United States Geological Survey (USGS) began using this technique to search for uranium deposits.[1] At about this same time, the Canadians also began developing an aerial prospecting technique, and the United States Air Force began testing radiological instruments in aircraft for intelligence purposes.

The first functional detector system used for prospecting contained an array of 19 Geiger tubes. Later, sodium iodide crystals replaced the Geiger tubes in the detector systems.[1]

During the 1950s and early 1960s, development efforts were directed toward four separate missions:

1. **Prospecting**—development of very sensitive detectors and survey techniques for searching for uranium deposits.
2. **Civil Defense**—development of detectors and survey techniques for quickly assessing the extent of fallout distribution in the event of nuclear war.
3. **Military application**—development of aerial survey techniques generally confined to locations very close-in to a nuclear detonation.
4. **Background monitoring**—development of the Aerial Radiological Measuring System (ARMS) for background radiation surveys as part of an emergency response capability.

No separate effort appears to have been made to develop aerial techniques for assessing the fallout radiation generated by nuclear tests at the Nevada Test Site (NTS). Techniques developed for the four missions listed above were simply applied, as appropriate, to the fallout assessment problem.

A brief history of the development of aerial measurement systems is presented in Section 2. In the early 1950s, all the aerial survey results were reported with essentially no interpretation, explanation, or discussion. Three main sources of error and uncertainties were recognized. Aircraft altitude and position were the first problems to be addressed. These are discussed in Section 3. Air-to-ground correlations remained the primary uncertainty in aerial survey assessment of fallout fields throughout the 1960s. This problem is discussed in Section 4.

Data obtained from aerial surveys were used extensively from 1953 through 1970 to assist in quickly estimating the fallout radiation patterns. Both air and ground measurements were used, as applicable, to develop the original contours. Aerial survey results were used to support ground data, not vice versa, because aerial survey techniques were still under development and many uncertainties existed in the application of these techniques. However, ground measurements were not made extensively, and scientists relied on the aerial survey results to extend the fallout patterns. This occurred particularly during 1957 and in the 1960s when aerial survey results were more reliable. Historical data for selected tests are reviewed in Section 5.

The review effort is summarized in Section 6, which also presents conclusions regarding use of conversion factors.

During the early days of nuclear testing at the NTS, a series of tests was assigned an "operation" name. Individuals thoroughly familiar with the nuclear testing program customarily refer to all tests in a given year by the assigned operation. Because this procedure could confuse less familiar individuals, the following table provides a summary of the operations referenced in this report. Few of the individual tests are referenced by name.

Operation Name	Period of Testing	Number of Tests
BUSTER JANGLE	10/22/51 - 11/29/51	7
TUMBLER SNAPPER	04/01/52 - 06/05/52	8
UPSHOT-KNOTHOLE	03/17/53 - 06/04/53	11
TEAPOT	02/18/55 - 05/15/55	14
PLUMBBOB	05/28/57 - 10/07/57	29
HARDTACK II	09/12/58 - 10/30/58	37

Several tests conducted during the 1960s are referenced without including the operation name. However, in each case, the year of the test is provided.

2. DEVELOPMENT OF AERIAL MEASUREMENT SYSTEMS

The Military first tested a "radiac" instrument system in an aircraft during 1951 to develop the techniques for conducting rapid aerial radiological surveys. The system consisted of a simple radiac instrument, dc amplifier, and recorder. Extrapolating the results to ground level produced sufficient agreement with ground-level readings to warrant further testing.[2]

Some simple additions and modifications to the detection and recording system were made in 1952.[2] Close-in onsite aerial surveys were emphasized during 1951 and 1952, although some offsite surveys were conducted.[3] The aerial survey techniques continued to be used during 1953 to determine the extent of the fallout patterns onsite or close-in to a nuclear detonation.

For extended surveys offsite, longer-range aircraft and a wider variety of aerial survey instruments were used. Initially, it was not certain whether aerial survey data would be useful. Fallout patterns for the Badger and Simon tests (sixth and seventh in the 1953 series) were plotted from the aerial survey data alone, then compared to the ground data. Reference 4 indicates that the correlation was excellent; however, by today's standards the correlation was poor.

The aircraft utilized for the 1953 surveys consisted of one C-47 and two L-20s. Most of the surveys were flown at an altitude of 500 ft. Fallout patterns were determined from the combined results of both aerial and ground data.

Three radiation detector systems were used during this time period: the MX-5, the T1B, and the Scintelog. All the instruments were calibrated using cobalt-60 sources.

The MX-5 was a Geiger counter, the energy response of which changed slightly in mixed radiation fields since the energy spectrum of fission products changes with time. The spectrum of radiation fields also changes with height above the ground.

The T1B was an ion chamber with an energy response reasonably flat with energy. In 1953 it was considered the primary instrument for both aerial and ground measurements. The T1B had a slow response time, however, and measurements below 1 milliroentgen per hour (mR/h) were not reliable.

The Scintelog was a new, experimental scintillation detector developed by the Atomic Energy Commission's New York Operations Office. Both sodium iodide and plastic scintillators were tested. The output was recorded in mR/h on a recorder. The plastic scintillator was essentially energy-independent for detecting gamma rays having energies above 80,000 electron volts (80 keV),[5] while the sodium iodide scintillator was not. Both detectors had a fast response time.

Agreement among the three detector systems was generally within a factor of two or three, although in some cases a factor of 10 was observed.* In high radiation fields, the MX-5 and Scintelog were unreliable. In low radiation fields (below 1 mR/h), the T1B readings tended to be too high. A study was made (by the author of this report) of the ratio of T1B readings to the Scintelog readings above 1 mR/h. The average ratio was 2.0, but the spread was from 0.1 to 6.2.

Aerial measurement techniques were not highly developed by 1953. Reference 4 states that "the T1B ion chamber instrument was found to be the most suitable survey meter for this type work." However, in a recent analysis of historical data collected after the Nancy test (second test in

---

* An error of a factor of two means the measured value probably lies within the range defined as a result of dividing or multiplying by two. For example, if the measured value is 80, a factor of two error means that the real value lies between 40 and 160.

1953), Steadman[6] indicated that a much better correlation between air and ground results was found with the Scintelog readings than with either the MX-5 or T1B results. It was determined empirically that a 1-mR/h Scintelog reading at 500 ft above ground corresponded to 25 mR/h directly below at 3 ft above the ground.

Aerial radiological surveys of fallout in 1955 apparently were conducted by the Military using C-47 aircraft and AN/PDR-27C and AN/PDR-29 radiation detection instruments. The surveys were generally flown at 300 to 500 ft above the ground. The air operations are described in Reference 7, and the resulting contours from the aerial data are presented; however, the raw data and any discussion of calibration, operational techniques, uncertainties, or applications are not included.

Civil Defense monitoring techniques[8] using aerial surveys were developed during 1955. This research project developed air-to-ground conversion factors and other correction factors useful in aerial surveys. However, Civil Defense aircraft and detector systems were not used to measure radiation offsite.

Aerial radiological survey techniques for Civil Defense purposes were further developed during 1957.[9] Again, however, there is no evidence that this project was used to assist in offsite radiation monitoring.

Prior to 1957 many improvements had been made in aerial survey techniques for uranium prospecting. The techniques were tested for environmental monitoring on the Met shot (Operation TEAPOT, 1955) and again during a fall environmental survey[10] in 1956. The success during the fall survey led to the full use of the United States Geological Survey (USGS) aircraft on survey operations for 11 detonations during the 1957 series.[11] The primary detector system consisted of five sodium iodide crystals. Errors and uncertainties due to aircraft altitudes and positions were greatly reduced by the use of reliable radioaltimeters and by carefully marking known locations on strip charts recording the radiation data. However, some uncertainties still remained in the air-to-ground conversions. A rather thorough description of the USGS aircraft and equipment is given in References 1 and 11 and further discussed later in this report.

Assistance for delineation of hot spots was provided during 1957 by the U.S. Atomic Energy Commission (AEC) Raw Materials Division (RMD) aircraft from Grand Junction, Colorado, which also used sodium iodide crystals. This aircraft, a Super Piper Cub, was equipped with Mount Sopris scintillation counters, Model SCI29-3, coupled to Welltab recorders.[11] Apparently, the aircraft and equipment were not as advanced as the USGS system, nor was the equipment calibrated in fallout fields. The system's primary function was to define the pattern edges of anomalies to give direction to ground survey teams; it was not intended to obtain quantitative data.[12]

There were 37 nuclear detonations in 1958 during Operation HARDTACK II, of which 13 were at or near ground surface. The remaining 24 tests were detonated in shafts, tunnels, or from balloons, which resulted in a relatively small amount of offsite fallout. All the surface or near-surface detonations were low yield, the highest being 90 tons.

The amount of offsite fallout in 1958 was very small compared to 1957. The USGS aerial survey capability was available during the 1958 tests and was used to survey fallout fields from four detonations in order to evaluate the usefulness of surveying very low fallout radiation levels.[10,12] The detectors, however, could not adequately measure these low levels.[12] Since the offsite fallout radiation levels were minimal, no formal reports were written.

The USGS aerial survey system became known as the Aerial Radiological Monitoring System (ARMS I) in the late 1950s. Because the USGS was anxious to discontinue radiation survey operations, the Atomic Energy Commission (AEC) in 1959 asked Edgerton, Germeshausen and Grier (now EG&G/EM) to develop a revised aerial survey system.[13] This system became known as ARMS II and later just ARMS.

The ARMS I aircraft was a DC-3 operated by the USGS. The detector system consisted of an array of five sodium iodide, thallium-activated [$\mathrm{NaI(T\ell)}$] crystals, each 4 in. in diameter by 2 in. thick. Lead shielding surrounded the sides of the detectors. A small single crystal, 1-1/2 in. in diameter by 1 in. thick, was used in higher radiation fields. The sensitivity ratio of the five-crystal array to the small single crystal was measured[14] to be 35 ±5 to 1.

The ARMS II aircraft was a Beech Model 50 Twin Bonanza. The primary detector was a single large $\mathrm{NaI(T\ell)}$ crystal, 9 in. in diameter by 3 in. thick. A smaller detector, 1 in. in diameter by 3 in. thick, was used in higher radiation fields. Gamma spectral capabilities were added to complete the ARMS II system. The sensitivity ratio of the large crystal to the small crystal was reported[15] to be 190 ±3 to 1. A total of 65 measurements of data was used to determine the ratio.

Both the ARMS I aircraft (USGS) and the ARMS II aircraft (EG&G) were used for aerial surveys of the fallout fields from the Danny Boy, Sedan[10] and Small Boy[16] tests (all in 1962). After 1962, only the ARMS II aircraft was used.

The primary function of ARMS II was to obtain baseline background radiation survey data around facilities maintaining or utilizing radioactive materials. Such baseline information would allow a quick assessment of the change in radiation levels in the event of a nuclear accident. Accident response remains a major part of the aerial survey program.[17]

Although background radiation surveys were the major effort of ARMS II during the 1960s, aerial survey support was also provided for all tests at the NTS producing radiation detectable offsite.

During 1964 through 1966, three $\mathrm{NaI(T\ell)}$ detector systems were used by ARMS II: a 9-in. by 3-in. crystal for high sensitivity, a 3-in. by 3-in. crystal for medium sensitivity, and a 3/4-in. by 3/4-in. crystal for low sensitivity.[18] As measured over typical radiation fields, the ratio of sensitivities for the 9-in. by 3-in. crystal to the 3-in. by 3-in. crystal was 5.2:1 and for the 9-in. by 3-in. crystal to the 3/4-in. by 3/4-in. crystal, 210:1.

The ARMS II also supported the Nevada Aerial Tracking System (NATS)[19] for cloud tracking. During the Palanquin (1965) and Pin Stripe (1966) surveys, the ARMS II carried a 9-in. by 4-in. crystal (probably borrowed from the NATS because the 9-in. by 3-in. crystal was being repaired or replaced).

In 1967 the $\mathrm{NaI(T\ell)}$ crystal systems were replaced with an array of fourteen 4-in. by 4-in. crystals.[15] The ARMS continued to use this array through 1970.[20] Though modified since 1970, the ARMS equipment continues to be available, if needed, for monitoring tests at the NTS.

A summary of the use of aerial surveys during this time period to assess the offsite fallout radiation fields is given in Table 1.

Table 1. Aerial Radiological Surveys of Fallout Fields

Operation	Year	Agency	Aircraft	Instruments	Intended Altitude (ft)	Comments
BUSTER-JANGLE	1951	Military	(a)	Simple Radiac	(a)	First attempt - close-in data
TUMBLER-SNAPPER	1952	Military	(a)	Simple Radiac	(a)	Continued evaluation
UPSHOT-KNOTHOLE	1953	Military	C-47	MX-5, T1B & Scintelog	500	Surveyed all shots (Harry as far as 250 miles)
			L-20	MX-5, T1B & Scintelog		
TEAPOT	1955	Military	C-47	AN/PDR-27C AN/PDR-29	300 - 500	Surveyed all shots
PLUMBBOB	1957	USGS	DC-3	NaI(Tℓ) Crystals	500 ±25	Surveyed 11 shots, usually on D+1, out to 500 miles when shot schedule permitted
		USAEC	Piper Cub	NaI(Tℓ) Crystals	50 - 500	Surveyed "hot" spots, usually on D+2 or D+3
HARDTACK II[b]	1958					
	1959 - 1963	EG&G, Inc.	Twin Bonanza	NaI(Tℓ) Crystals	500	One 9-in. by 3-in. detector
	1964 - 1966	EG&G, Inc.	Twin Bonanza	NaI(Tℓ) Crystals	500	Three detector system: (1) One 9-in. by 3-in. detector (2) One 3-in. by 3-in. detector (3) One 3/4-in. by 3/4-in. detector
	1967 - 1970	EG&G, Inc.	Twin Bonanza	NaI(Tℓ) Crystals	300	An array of 14 4-in. by 4-in. detectors

[a] Data unavailable

[b] Minimal offsite aerial surveys conducted (radiation levels were too low)

3. UNCERTAINTIES IN AERIAL MEASUREMENTS

The primary objective of the aerial surveys was to determine the extent of the fallout patterns and to pinpoint the centerline.[21] A secondary objective was to obtain qualitative radiation measurements as precise as possible, given the state-of-the-art of the aerial survey techniques. In general, ground-based readings were used to determine radiation levels at specific points of interest. However, aerial data were used to estimate ground-level readings with some reliability. Precise positioning became more important with the development of survey techniques.

Table 2 lists some uncertainties associated with aerial survey results when predicting radiation levels 3 ft above the ground. The uncertainties are divided into two categories: first order and second order. The first order uncertainties could contribute errors up to a factor of 10 or higher if ignored or handled improperly. In general, the second order uncertainties would individually contribute ±50% or less to the predicted ground exposure rates if ignored or handled improperly. Each category is discussed separately.

Table 2. Uncertainties Associated With Aerial Survey Results

First Order	Second Order
Altitude Variations (±200 ft)	Energy Response
Aircraft Position	Aircraft Attenuation
Locality of Source	Instrument Response Time
Scale Changes	Altitude Variations (±100 ft)
	Air Temperature and Pressure
	Ground Roughness and Terrain Features
	Temperature Drift
	Background Separations
	Aircraft Contamination
	Rate Dependence, NaI(Tl)

3.1 FIRST ORDER UNCERTAINTIES

3.1.1 Altitude Variations (±200 ft)

Reference 4 reports that if errors of 100 to 200 ft in altitude occurred for a survey altitude of 600 ft, an error of 50% in ground-level predictions would result. Surveys over hills, valleys, and ravines without accurate altimeters would produce these altitude variations. Errors of this magnitude would be expected during the period 1953 through 1955.

In 1957 an altitude compensator (AC) that adjusted the count rate to an equivalent 500-ft altitude was installed on the USGS aircraft. It is believed that this system was functioning properly most of the time.[21] It is not likely that errors of ±50% or more in ground-level predictions due to altitude variations occurred often in 1957 or thereafter.

3.1.2 Aircraft Position

Relating the aircraft's exact position to radiation measurements was very difficult in the early days of aerial surveys. Reference 4 indicates that in 1953 the maps used by the aerial survey teams were the 1:1,000,000 scale aeronautical charts (1 in. equals 15.75 miles) as shown in Figure 1.

During Operation UPSHOT-KNOTHOLE (1953), a coordinate system was used to report the aerial survey data (see Table 3). It is implied in Reference 4 that the aircraft was sent to given coordinate intersections to make measurements. The intersections were 8 to 10 miles apart (8 miles if in the east and west directions or 10 miles if in the north and south directions). Several of these locations were many miles from any ground features easily recognized from the aircraft.

The radiation measurements could all be valid, but pinpointing them on such a map would be very difficult and, in most cases, inaccurate unless well known road junctions or other features were nearby. One can guess that aircraft position uncertainties of several miles existed in areas away from recognized features. How these uncertainties were treated or how the measurements were used or adjusted to ground measurement locations are not known.

This does not, however, mean that the aerial data are useless. If there were sufficient ground-based measurements across the fallout path, the aerial data could be used to interpolate between ground-based measurements. The data would still be valid, but the exact position would be in question.

For Operation TEAPOT (1955), the uncertainty of the aircraft position is assumed to be about the same as for Operation UPSHOT-KNOTHOLE (1953).

During Operation PLUMBBOB (1957), however, great improvements were made in determining the position of the aircraft. Regarding the USGS aircraft, the following quote is taken directly from Reference 11:

> The flight patterns were, in actuality, a series of straight line bearings over predetermined visual reference points across terrain as level as practicable. The initial flight line was begun before the edge of the fallout pattern at approximately right angles, and continued past the opposite boundary of the pattern. A series of such traverses at increasing distances from ground zero provided data from which the areas of fallout contamination were delineated. The direction of traverses was often controlled by roads in order to maintain the accuracy of the plot.
>
> In the absence of cultural features, dead-reckoning navigation was employed with reasonable accuracy for distances up to ten miles under calm atmospheric conditions. An air speed of 140 ±20 mph was maintained at an altitude of 500 ±25 ft above ground level using a DC-3 aircraft. A position plot was maintained by an observer, utilizing a view finder, who marked the position of the aircraft on a map and at the same time actuated a marking system over recognized visual reference points. The marking system placed fiducial marks on all record tapes and camera film. The flight was also recorded by a 35-mm, gyro stabilized, continuous strip-film camera.

Even with the care described above in determining the aircraft position, errors and uncertainties were possible. In today's surveys, for instance, where sophisticated navigational and aircraft location determination techniques are applied, errors in position still sometimes occur. Road junctions and terrain features often look different from the air. Beginning or ending surveys on the wrong road junctions or some other feature is not uncommon, particularly with

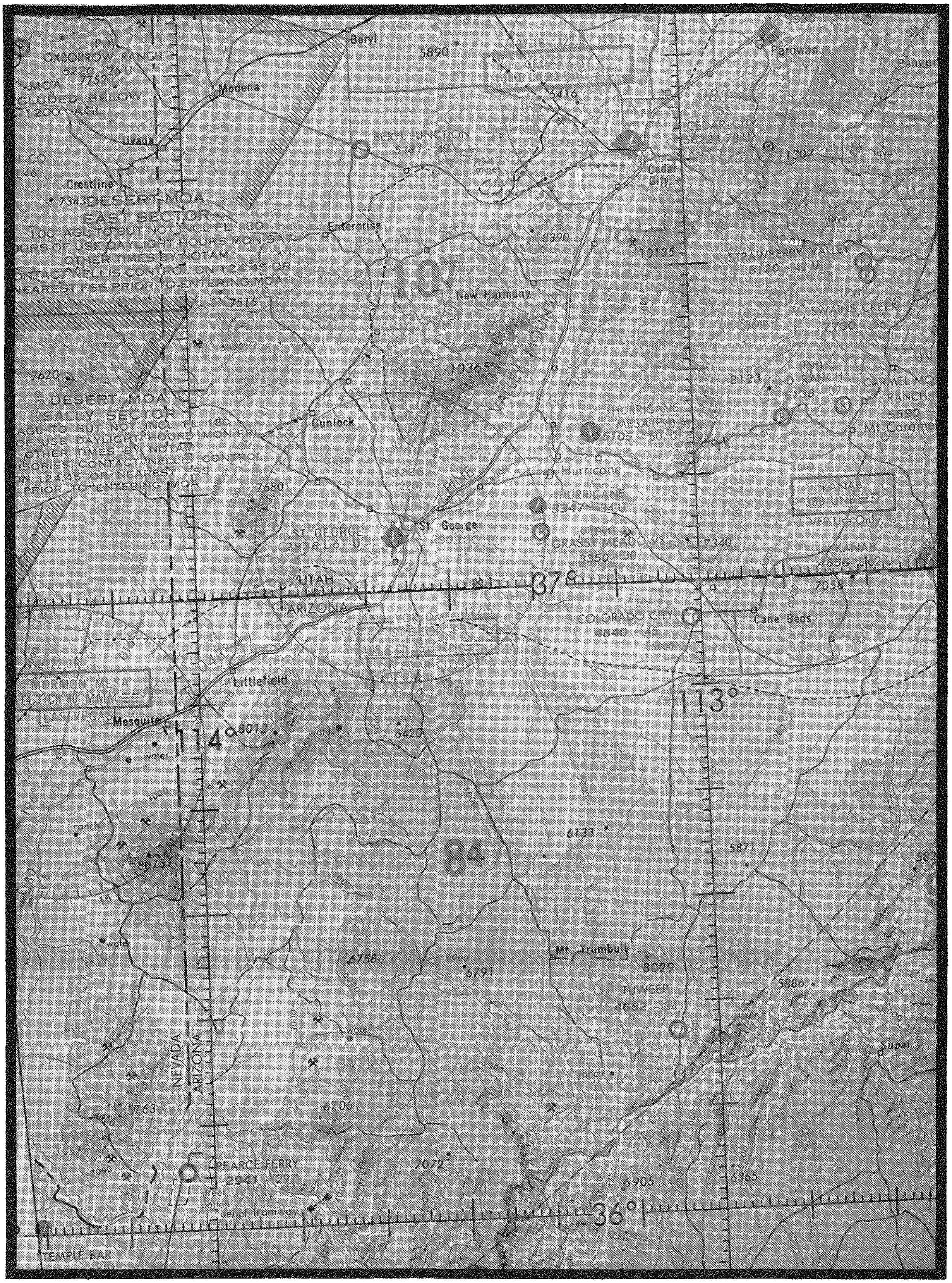


FIGURE 1. *1:1,000,000 SCALE AERONAUTICAL CHART*

Table 3. Coordinate System Used In Rad-Safe Operations (From Reference 4)

Grid	Longitude	Grid	Longitude	Grid	Latitude	Grid	Latitude
A	116°00'W	ZA	116°10'W	25	40°00'N	41	37°20'N
B	115°50'W	ZB	116°20'W	26	39°50'N	42	37°10'N
C	115°40'W	ZC	116°30'W	27	39°40'N	43	37°00'N
D	115°30'W	ZD	116°40'W	28	39°30'N	44	36°50'N
E	115°20'W	ZE	116°50'W	29	39°20'N	45	36°40'N
F	115°10'W	ZF	117°00'W	30	39°10'N	46	36°30'N
G	115°00'W	ZG	117°10'W	31	39°00'N	47	36°20'N
H	114°50'W	ZH	117°20'W	32	38°50'N	48	36°10'N
I	114°40'W	ZI	117°30'W	33	38°40'N	49	36°00'N
J	114°30'W	ZJ	117°40'W	34	38°30'N	50	35°50'N
K	114°20'W	ZK	117°50'W	35	38°20'N	51	35°40'N
L	114°10'W	ZL	118°00'W	36	38°10'N	52	35°30'N
M	114°00'W	ZM	118°10'W	37	38°00'N	53	35°20'N
N	113°50'W	ZN	118°20'W	38	37°50'N	54	35°10'N
O	113°40'W	ZO	118°30'W	39	37°40'N	55	35°00'N
P	113°30'W	ZP	118°40'W	40	37°30'N	56	34°50'N
Q	113°20'W	ZQ	118°50'W				
R	113°10'W	ZR	119°00'W				
S	113°00'W	ZS	119°10'W				
T	112°50'W	ZT	119°20'W				
U	112°40'W	ZU	119°30'W				
V	112°30'W	ZV	119°40'W				
W	112°20'W	ZW	119°50'W				
X	112°10'W	ZX	120°00'W				
Y	112°00'W	ZY	120°10'W				
Z	111°50'W	ZZ	120°20'W				

new and inexperienced pilots and/or navigators. The probability of error increases as the survey altitude decreases. Nevertheless, positional data in 1957 and thereafter is considered very good, particularly for areas where cultural features were clearly indicated on the aeronautical charts. In addition, the strip film provided backup when the aircraft position was in question.

Nothing could be found in the literature about the uncertainty associated with determining the position of the U.S. AEC RMD aircraft (Piper Cub).

During the 1960s, the ARMS II used an along-track and cross-track Doppler navigation system. Trundle[18] estimates that after linear corrections were applied to the raw data, a positioning error on the order of 0.15 mile (about 800 ft) was possible.

3.1.3 Locality of Source

Aerial radiological detection systems average the radiation levels produced by gamma-emitting radionuclides existing over an area of several acres. At 3 ft above the ground, the area "seen" by a hand-held survey meter is much smaller. For example, at an altitude of 500 ft, the area sampled on the ground is on the order of 1000 times greater than the area sampled by a detector held at 3 ft, and several million times greater than for a single soil sample a few inches across.

If the source of radiation is not uniform over a large area, air-to-ground conversion factors will be in error. The conversion factor assumes the source to be uniformly distributed over a large area compared to the area sampled by the aerial detector system (at a 500-ft altitude the area sampled is considered to be 1500 ft in diameter). Corrections must be made if the source, or localized radiation, is smaller than this. Correction factors to be applied to the air-to-ground conversion factor are given in Table 4 for sources of finite dimensions.[22,23] For example, assume the air-to-ground conversion factor is 10 for an altitude of 500 ft over a uniform fallout field. If measurements were 1.0 mR/h (at 500 ft) over a contaminated area measuring only 650 ft in diameter, the conversion factor would then be 20 (instead of 10) and the radiation level 3 ft above the ground would be about 20 mR/h, not 10 mR/h.

Table 4. Finite-Source Correction Factors*

Diameter of Contaminated Circular Area (ft)	Correction Factor
80	100
160	25
325	6
650	2
1000	1.4
2000	1.1
∞	1.0

*Estimated for the total gamma flux arriving at a detector at a 500-ft altitude[22,23]

Ground-level exposure rates predicted from aerial survey data could contain large errors in situations where radiation levels fluctuated rapidly with distance. Over fallout fields this could occur near ground zero, but errors would be minimal at other locations.

3.1.4 Scale Changes

In 1953 and 1955, aerial surveys were made using survey meters. Scale changes were necessary when radiation levels changed by an order of magnitude. If an error were made in reading the scale setting, the radiation level recorded would contain an error of a factor of 10 (or 100 or 1000 depending on the instrument in use). Even though the literature does not mention any scale reading errors, such misreading of the survey meters was possible and probably sometimes occurred.

During Operation PLUMBBOB (1957), scale changes were made on the strip chart by changing the sensitivity dial. Generally, the sensitivity reading and number of crystals used were written on the strip chart. When this information was not written on the chart, it was necessary to go back to a time on the chart when the information was known and follow the changes one would expect the operator to make. This is one set of evaluations that the Program Staff performed in 1957 before data were used to construct the isopleth maps.[12] Examination by this author of some of the strip chart data and count rates and exposure rates written on maps did not reveal any errors in the results because of scale changes.

During the 1960s, the ARMS II recorded the data on punched paper tape. Later, in the laboratory, the data tapes were read electronically and the results printed for easy readability.[18]

3.2 Second Order Uncertainties

3.2.1 Energy Response

The gamma-ray energy emitted by fission products changes with time. The energy response of ionization chambers, such as the T1B, is reasonably flat with energy. This means that a calibration made at one gamma-ray energy level (such as 0.667 MeV for cesium-137) or at a specific time after shot detonation can be applied to measurements of gamma rays from another energy level (such as 1.25 MeV for cobalt-60) or at another time after shot detonation.

The Geiger counter, such as the MX-5, however, is more sensitive to spectral changes. Accuracy, therefore, is not as good as with ion chambers when measurements are made in radiation fields of mixed gamma-ray energies.

$NaI(T\ell)$ crystal detector systems are also sensitive to spectral changes, particularly as applied to count-rate to exposure-rate conversion factors.

Figures 2 and 3 show measurements made by the USGS detector system as a function of energy and as a function of age of the fallout fields.[1] A factor of 10 difference is noted for single gamma-ray energies from 0.4 to 2.0 MeV. The difference is small, however, in count-rate ratios from 3 ft to 500 ft over fallout fields 2 days and 13 days old. This is because of the dominance of air-scattered radiation counted by the $NaI(T\ell)$ crystals.

Figure 4 shows relative air-to-ground correlation factors for $NaI(T\ell)$ crystals for different ages of fallout fields.[24,25,26] The maximum error possible for $NaI(T\ell)$ crystals would be 20%. This means that if a conversion factor derived for fallout conditions 4-1/2 days after a nuclear detonation were applied to count rates measured over a fallout field at H+12 hours,* the predicted ground-level exposure rates would be 20% too low. For all other calibration and measurement times, the error would be less.

3.2.2 Aircraft Attenuation

The aircraft skin attenuates gamma radiation entering the aircraft and arriving at the detector system. Reference 8 gives an aircraft attenuation factor of 1.25 for light aircraft. In all cases, the aircraft attenuation factor is already incorporated in air-to-ground conversion factors from calibration measurements. What is important, however, is that the detector system remain in the same location within the aircraft for both surveys and calibrations. Note the difference in conversion factors when the T1B was in the cockpit versus the cargo compartment (Figures 5 and

---

*H+12 hours means 12 hours after a nuclear detonation.

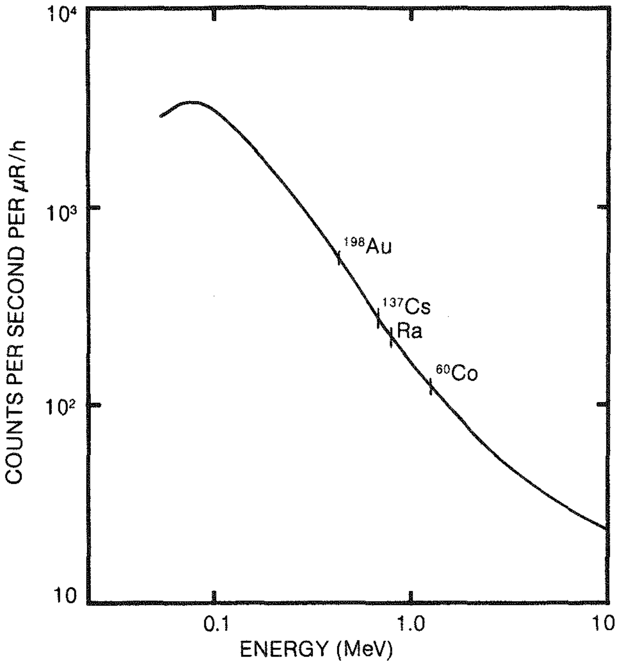
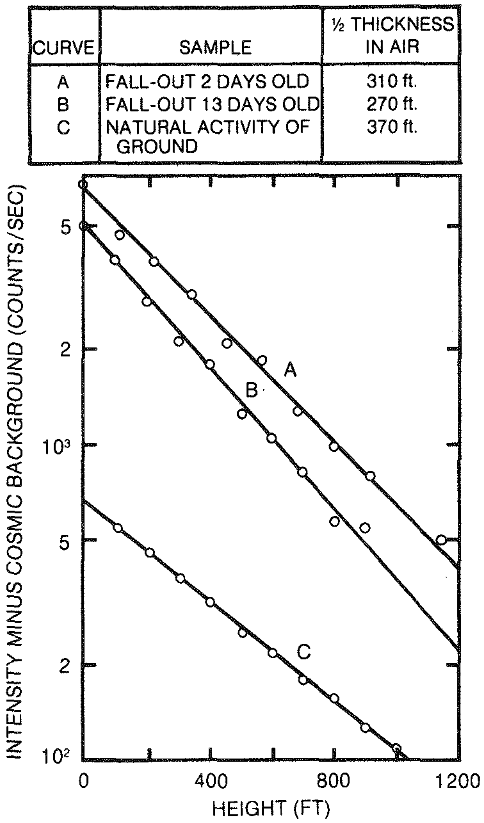


FIGURE 2. ***SENSITIVITY OF EQUIPMENT AS A FUNCTION OF ENERGY. (Taken directly from Reference 1, redrawn for clarity)***



CURVE	SAMPLE	½ THICKNESS IN AIR
A	FALL-OUT 2 DAYS OLD	310 ft.
B	FALL-OUT 13 DAYS OLD	270 ft.
C	NATURAL ACTIVITY OF GROUND	370 ft.

FIGURE 3. ***VARIATION OF RADIATION FROM A BROAD SOURCE VS HEIGHT. (Taken directly from Reference 1, redrawn for clarity)***

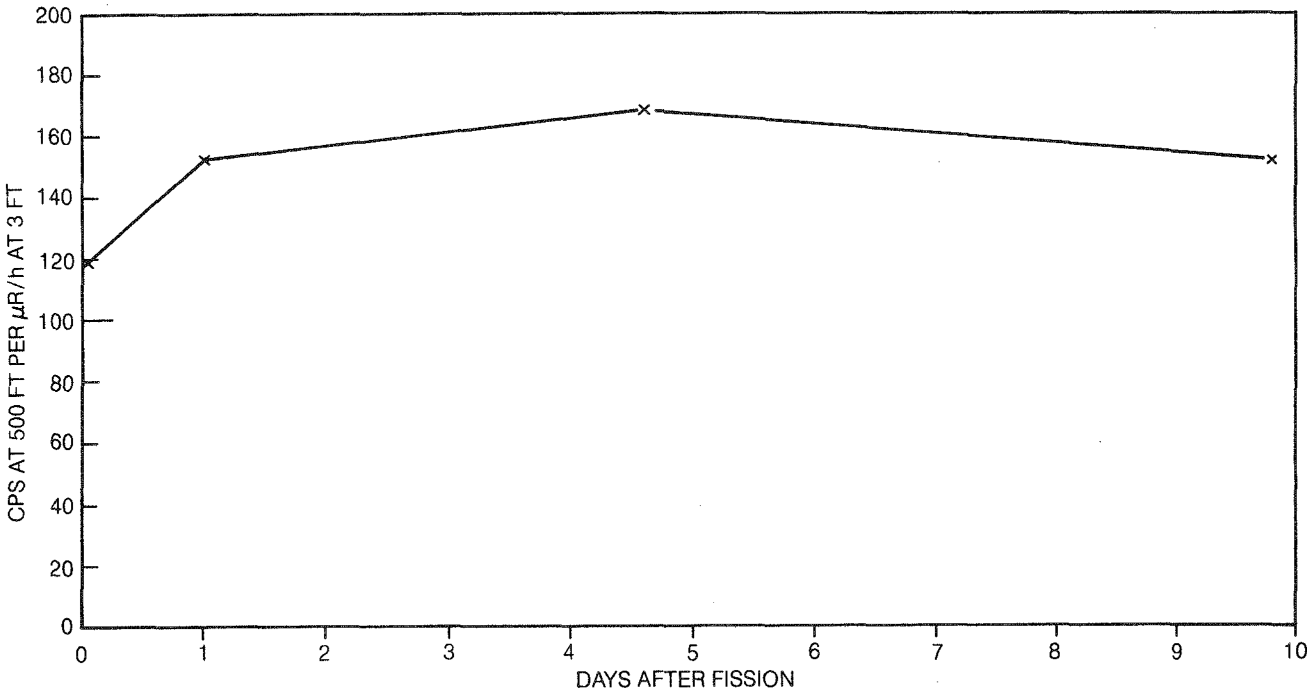


FIGURE 4. ***RELATIVE AIR-TO-GROUND CORRELATION VS FISSION FALLOUT AGE FOR SODIUM IODIDE CRYSTAL DETECTORS***

6). It is also important that the detector system be placed in a location that is not strongly influenced by fuel tank attenuation. Otherwise, aircraft attenuation would vary with fuel level.

3.2.3 Instrument Response Time

In 1953 and 1955 when the T1B instrument was used, a response time of as much as 30 seconds occurred. This could result in an error of one-half mile in predicting ground-based radiation levels. Reference 11 reports for Operation PLUMBBOB (1957) an instrument lag time from 400 to 750 ft depending on the time constant. No correction was made for instrument response time, generally, because the scale of the maps used to record the data (8 to 15 miles to the in.) did not warrant correction. Also, for offsite surveys the radiation levels did not change rapidly within a short distance (i.e., 750 ft). Therefore, a lack of correction did not strongly influence the results.

3.2.4 Altitude Variations (±100 ft)

Figures 5 and 6 also show radiation measurements as a function of altitude. An error of ±100 ft at an altitude of 500 ft produces about a 35% error in the results. Prior to 1957 accurately calibrated radio and radar altimeters were not available.[4] Errors of 100 ft or more were expected with the old barometric altimeters because they only inferred the height above ground rather than measuring the distance as can be done with radio signals. The inferred height was actually a function of air pressure and temperature; discrepancies could be quite large over desert valleys. During Operation PLUMBBOB (1957), however, more accurate survey altitudes were determined; Reference 11 indicates that an altitude of 500 ±25 ft was maintained.

When flying over hills and valleys, it was impossible, however, to maintain an altitude of 500 ft. A section of strip chart from the Smoky test (August 1957) is shown in Figure 7. The "AC out" designation indicates that the second mode of correcting for aircraft altitude changes was being used. The numbers 9446, 9451, and 9456 refer to fiducial marks on the strip chart corresponding to known reference points on the ground. The designation "sens 50" refers to the scale setting on the strip chart; that is, the count rate was 50 times the reading on the chart.

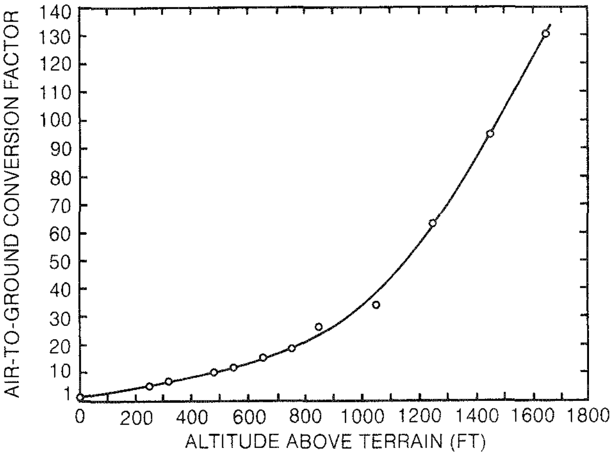


FIGURE 5. ***CURVE FOR C-47 SURVEY WITH T1B. Readings were taken in the cargo compartment (19 April 1953). (Taken directly from Reference 4, redrawn for clarity)***

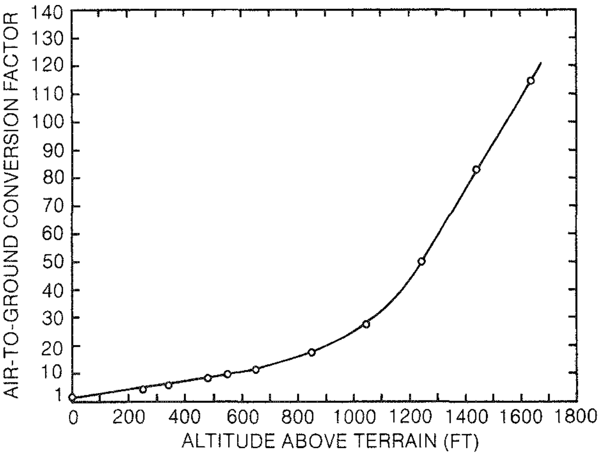


FIGURE 6. ***CURVE FOR C-47 SURVEY WITH T1B. Readings were taken in the cockpit (19 April 1953). (Taken directly from Reference 4, redrawn for clarity)***

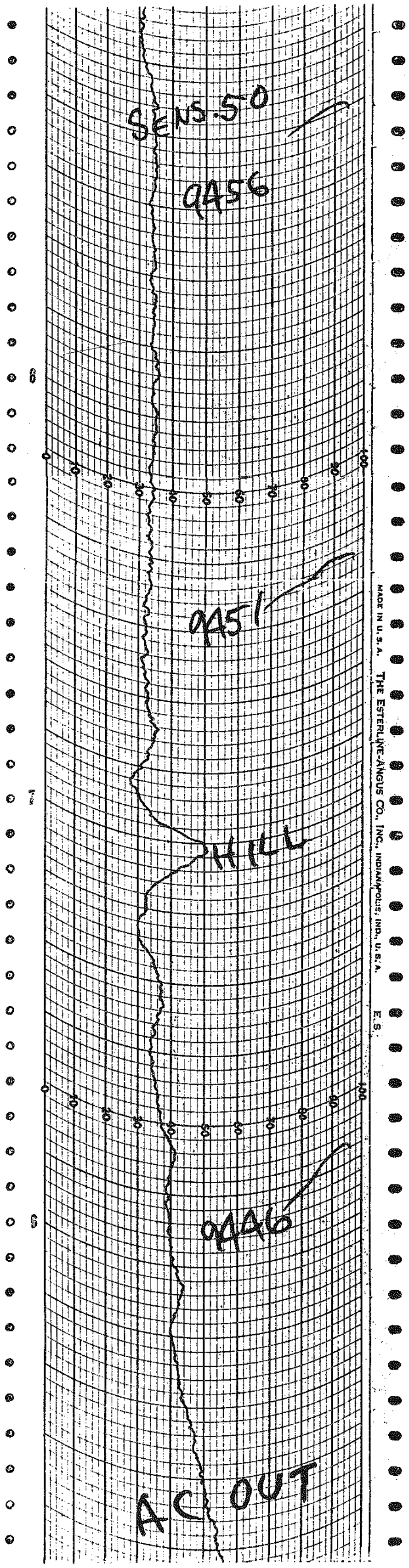


FIGURE 7. ***SECTION OF STRIP CHART FOR THE SMOKY TEST (enlarged for clarity)***

Note the hill in the center of the strip chart (Figure 7). The count rate gradually decreases from 2000 counts per second (cps) to 1750 cps except over the hill, where the count rate increases to 2500 cps (an increase of 33%). This increase was probably caused by a decrease in altitude above the ground at the peak of the hill rather than an increase in terrain radiation. Note also the slight decrease in count rate on either side of the hill, which was probably caused by the aircraft climbing in altitude before reaching the hill then descending to survey altitude after passing over the hill. Even though the "altitude compensator" was probably functioning, it did not fully compensate for changes in count rates caused by gross changes in altitude.

3.2.5 Air Temperature and Pressure

Radiation levels are a function of the air mass thickness between the aircraft and the ground and this, in turn, is a function of air temperature and pressure as well as altitude, the latter being the dominant factor. The air is thinner at higher altitudes and, therefore, air-to-ground conversion factors are different. However, the difference is small. A conversion factor for 500 ft above the ground at an elevation of 6000 ft above sea level is about 10% less than at an elevation of 2000 ft above sea level. This small uncertainty was not considered in the aerial surveys of fallout fields during above-ground testing.

3.2.6 Ground Roughness and Terrain Features

At an altitude of 500 ft, detector systems average large areas on the ground (several acres). Measurements made at 3 ft above the ground are strongly influenced by radiation levels in the immediate vicinity of the detector (tens of ft). Therefore, severe ground roughness, sharp terrain changes, or major structures influence ground-based measurements more than those made by aerial surveys. In most cases, however, the uncertainty in the application of aerial survey results to 3-ft exposure rates would be less than 25% (maximum 50%) as a result of ground roughness and terrain features if the air-to-ground conversion factors were derived in actual fallout fields. If ground roughness effects are totally ignored, a factor of two error could occur in the prediction of 3-ft exposure rates. The influence of ground roughness on conversion factors is discussed further in Section 4.

3.2.7 Temperature Drift

Temperature effects on ion chambers or Geiger counters are considered negligible. A greater uncertainty occurs with NaI(Tℓ) crystals. For Operation PLUMBBOB (1957) and later series the discriminator was set at 50 keV, allowing all gamma rays above 50 keV to be counted. Figure 8 shows count rates for different discriminator settings. Large temperature drifts could produce small gain changes in the settings. This uncertainty, however, is not likely to be more than a few percent at the 50-keV setting.

3.2.8 Background Separations

Natural background radiation levels generally vary from 0.005 to 0.020 mR/h. If natural terrestrial radiation levels are measured from an aircraft, data processing procedures must account for non-terrestrial background components. However, in surveying fallout radiation fields where radiation levels of 0.1 mR/h and above were of concern, it was not necessary to account for the natural background radiation levels. This uncertainty would be less than 20% at 0.1 mR/h and negligible at 1 mR/h.

3.2.9 Aircraft Contamination

During Operation UPSHOT-KNOTHOLE (1953) the survey aircraft was generally launched at H+2 hours. It was expected that air contamination would be experienced at some locations. The plane utilized air filter systems to assist in evaluating the impact of this uncertainty on the measurements. Reference 27 states that the contamination received by the aircraft was low and did not interfere with the mission. An examination of the data in Reference 4 indicates that aircraft contamination occurred on rare occasions, but that the influence on the results was small.

The same techniques probably applied to Operation TEAPOT (1955), although there is nothing in the literature concerning aircraft contamination.

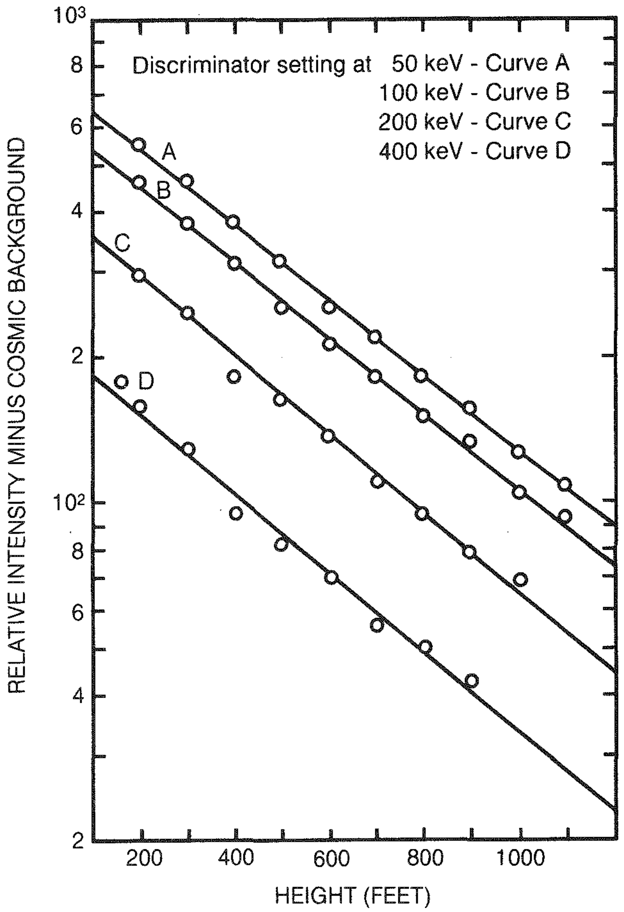


FIGURE 8. *ALTITUDE CURVES WITH VARIOUS DISCRIMINATOR SETTINGS TAKEN ABOVE A FLAT MESA CONTAINING NATURAL GROUND RADIOACTIVITY. (Taken directly from Reference 1, redrawn for clarity)*

During Operation PLUMBBOB (1957) aerial surveys were not conducted until the day following the detonation (designated as D+1). On at least two occasions the aircraft was contaminated. When this occurred, the survey was terminated and the aircraft returned to base for washdown.[21] After decontamination, the survey was resumed. The data taken while the aircraft was contaminated were not used or reported.

3.2.10 Rate Dependence, NaI(Tℓ)

Exposure rate dependence is considered negligible for Geiger counters and ion chambers over the range used for aerial surveys. For NaI(Tℓ) crystals, however, there is a rate dependence. When a light pulse is received inside the photomultiplier tube, the system shuts itself off until that pulse is processed and recorded. The time required amounts to microseconds (μs). This dead time is common to all scintillation systems. Modern electronic systems can measure the dead time and thereby display results as counts per live time. The early systems did not have this capability.

Figure 9 shows a calculated relationship for theoretical count rates and observed count rates, assuming resolving times of 2, 10, and 40 microseconds (μs) and random counting. For example, for a resolving time of 10 s and an observed count rate of 50,000 cps, the theoretical count rate would be 100,000 cps. At this count rate the uncorrected air-to-ground conversion would be in error by a factor of two.

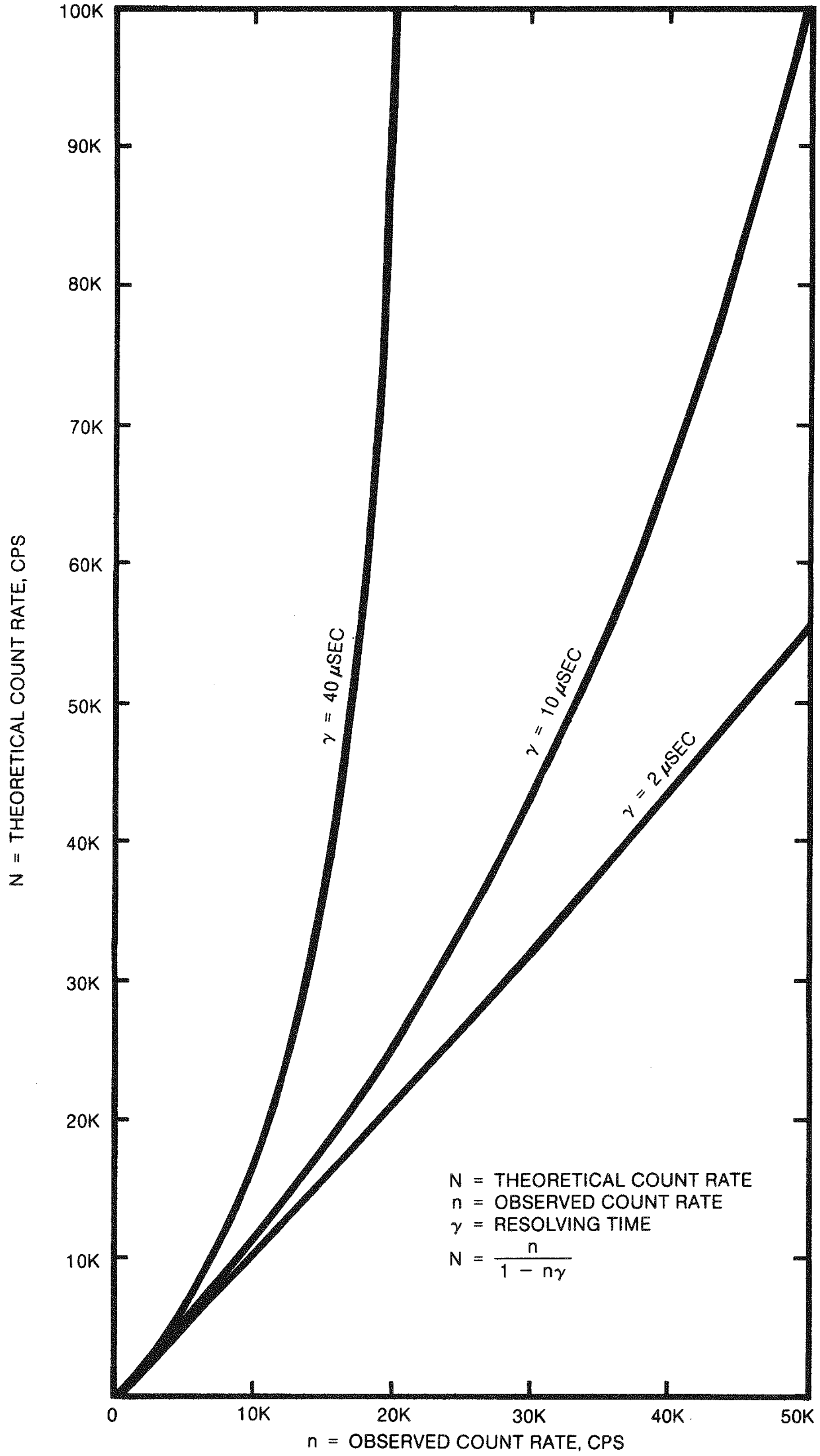


FIGURE 9. ***RELATIONSHIP OF THEORETICAL AND OBSERVED COUNT RATES***

However, Reference 11 states that the USGS five-crystal array and the single crystal were "used interchangeably depending on the required counting rate." This indicates that the scientists were aware of the count rate problem and corrected for it by changing to the single, smaller crystal as the count rate increased. It is not certain what the dead time loss was in the USGS system. In describing the ARMS II counting system, Trundle[18] states "the present system has an overall dead time of 2.1 ±0.1 μs, compared to a dead time of 40 ±2 μs for the original system." The "original system" referred to an earlier version of the ARMS II counting system rather than the USGS system used during Operation PLUMBBOB. A resolving time of 10 μs would be more likely for that time period (late 1950s).

Examination of the strip charts for Operation PLUMBBOB confirmed that the scientists were aware of the count rate problem. Maximum count rates plotted on the strip charts were determined by a sensitivity dial setting. Maximum count rates available were 1,000, 2,000, 5,000, 10,000, and 20,000 cps. The five-crystal array was used until the count rate reached 20,000 cps, then the single crystal was used. The maximum possible reading with the single crystal was also 20,000 cps, since both detector systems used the same count rate meter output. The single crystal was smaller, and therefore much less sensitive to radiation levels than the five-crystal array. When the count rate from the five-crystal array was 20,000 cps, the exposure rate at 3 ft above the ground was 0.40 mR/h; but when the single crystal was used, a much higher radiation level was required to produce 20,000 cps. This radiation level varied from 8 to 80 mR/h, depending on the shielding surrounding the single crystal.

At the maximum observed count rate of 20,000 cps, the theoretical count rate would have been 25,000 cps, an error of only 25% assuming a resolving time of 10 μs. Most of the time the uncertainty was less than this. It appears that these dead time losses were corrected for in the data. In Figure 10 it is noted that the observed count rate and the count rate written on the strip chart were the same for Plane 950 for 10,000 cps and below. For observed count rates above 10,000 cps, some correction was apparently made for dead time losses.

Little is known about the count rates for the U.S. AEC RMD Piper Cub system. The crystals were small, 1.5 in. in diameter and 1.25 in. thick. The number of crystals used was not given in the literature. Measurements of radiation fields greater than 5 mR/h should be suspect. As mentioned earlier, however, this aircraft was not used to obtain quantitative measurements.

Dead time losses were not a problem in the ARMS II equipment used during the 1960s[18] because the resolving time was very short (2.1 μs) and three detection systems were used for three levels of sensitivity.

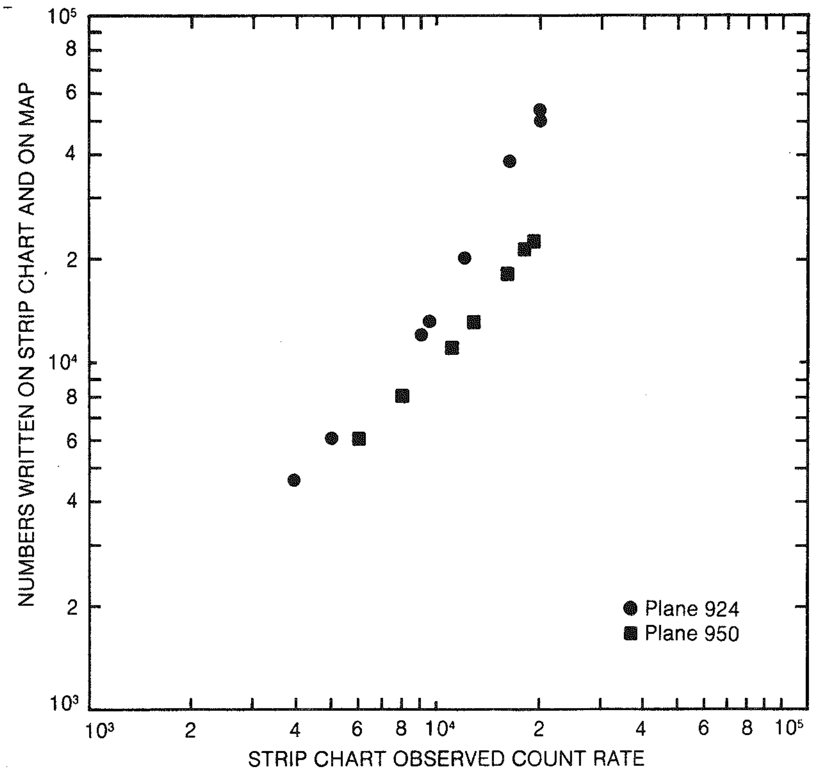


FIGURE 10. ***STRIP CHART RESULTS FOR THE FIVE-CRYSTAL ARRAY FOR OPERATION PLUMBBOB***

4. AIR-TO-GROUND CORRELATIONS

4.1 General

The development of techniques for aerial surveys of terrestrial radiation levels began in the late 1940s and continues today. Improvements have been made in instrumentation, recording equipment and aircraft positioning, as well as in the knowledge of radiation field measurement techniques. A continuing area of uncertainty, however, is in relating the results of aerial surveys to meaningful values at ground level.

Considerations that produce uncertainties in air-to-ground correlations are (1) energy and angular response of the detectors, (2) energy spectrum of the source, (3) locality of the source (vertical and horizontal distribution), (4) roughness of the ground, and (5) flight altitude. These elements can produce uncertainties of ±25% or more in air-to-ground conversion factors, even with today's technology.

In converting aerial data to ground-level values, it is important to note that aerial radiological detection systems average the radiation levels over an area of several acres. If the isotopic content is not uniform over these large areas, the differences can be great. The difference between data obtained with the airborne system and that obtained from ground measurements is in the area covered in a single measurement, as discussed earlier. For an ideal uniform distribution extending over a large area, each type of measurement should, in principle, lead to the same results. In practice, however, it is not unusual to find differences in radiation levels from point to point on the ground, even over relatively uniform ground surfaces.

Air-to-ground conversion factors were empirically determined for most detector systems in the 1950s and 1960s. Conversion factors were a function of altitude and were different for each detector and aircraft system. If the conversion factor measurements were made under the same conditions as the actual surveys, uncertainties of other parameters were minimized. For instance, if the calibrations and fallout surveys were made with the same aircraft, detector systems, and altitude over fallout fields of the same age and for the same radiation levels, then errors due to energy response, aircraft attenuation, altitude variations, and rate-dependence would be minimal.

Improvements in air-to-ground correlations were very rapid in the early 1950s. By 1955 ground-based readings could be predicted to ±50% from aerial data if all parameters were carefully considered.[8] In actual practice, however, achieving this accuracy was more difficult. If a real fallout field occurred today, ground-level exposure rate predictions from aerial survey data would not be expected (in the author's judgement) to agree with ground-based measurements to better than ±25% for single measurement points.

4.2 1953

The aerial survey data obtained during Operation UPSHOT-KNOTHOLE (1953) was used to help define the direction and location of the hot line and to supplement the ground-based readings in defining the fallout patterns. A high degree of accuracy and precision was not needed to accomplish these goals.

Figures 5, 6, and 11 give air-to-ground conversion factors (taken from Reference 4) developed in 1953. At a 500-ft altitude the conversion factor varied from 8 to 12, depending on the aircraft used and detector location within the aircraft. Since Steadman[6] found a conversion factor of 25 for the Scintelog, this instrument was probably miscalibrated. As previously stated, examination of the aerial data in Reference 4 indicates that the ratio of T1B readings to Scintelog readings was about a factor of 2.0. The implication is that the T1B was calibrated correctly but was inconsistent in its response, while the Scintelog was more consistent in its response but calibrated incorrectly.

Reference 8 indicates that the T1B readings in aircraft could predict ground-level readings to ±50%. This probably referred to a reproducibility confidence level for repeat surveys over the same location in sequence. In actual practice, prediction of ground levels over different locations at different times (as Steadman[6] found) was no better than a factor of two or three and sometimes a factor of 10. Much of this uncertainty, however, could relate to the uncertain location of the aircraft.

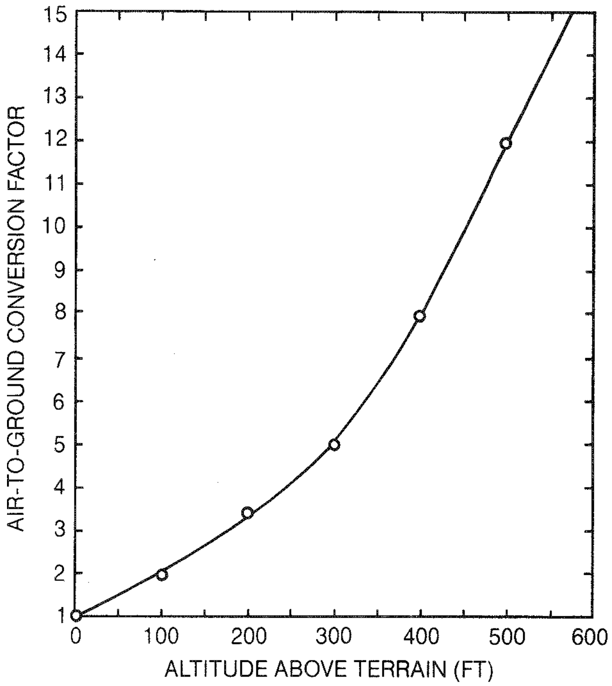


FIGURE 11. ***CORRELATION CURVE FOR READINGS TAKEN OVER GROUND ZERO 17 DAYS AFTER THE ANNIE TEST (HELICOPTER SURVEY WITH T1B). (Taken directly from Reference 4, redrawn for clarity)***

Using the T1B results above 1 mR/h and an air-to-ground conversion factor of 10, the ground-level predictions should be valid to within about a factor of two or three (author's judgement). This assumes an altitude of 500 ft and that the location of the aircraft was well known.

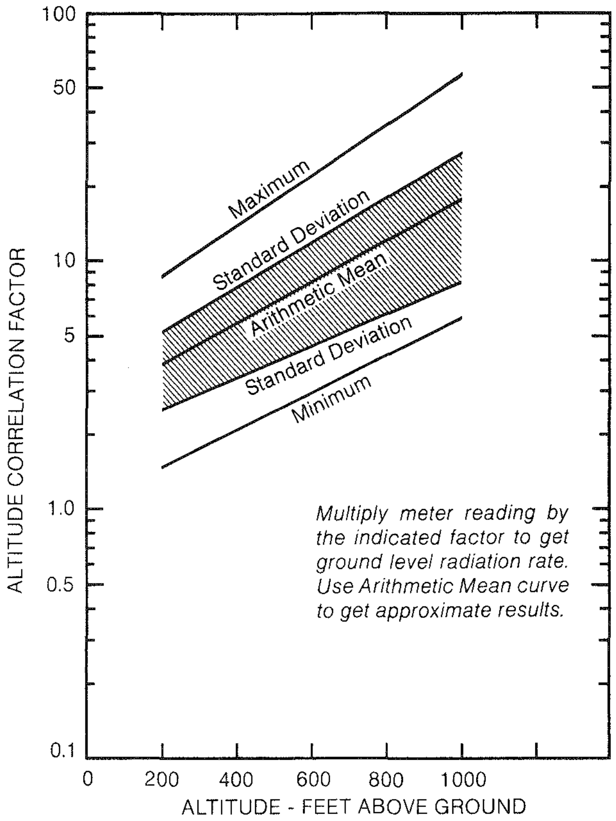
Better predictions can be made using the Scintelog results and a factor of 25 for air-ground conversions. However, uncertain locations will still be a problem. Empirical derivation of air-to-ground conversion factors for each event in the UPSHOT-KNOTHOLE (1953) series would probably produce the best predictions.

4.3 1955

Reference 7 implies that the Military performed all offsite, extended, terrain surveys during Operation TEAPOT (1955). The surveys were conducted with C-47 aircraft utilizing AN/PDR-27C and AN/PDR-29 ion chambers. No reference was found which gave air-to-ground correlations for these instruments. Reference 8, however, gives air-to-ground correlations for the CD V-710, CD V-700, AN/PDR-T1B, and AN/PDR-39 instruments. Air and ground measurements were made on five different flights at five different times after detonation over 146 separate and distinct points in several fallout fields. The results from all the flights are shown in Figure 12, which was taken directly from Reference 8. The resulting spread in the data indicates that precise prediction of ground-level exposure rates could not be achieved from the aerial data. The results also show, however, that prediction of ground-level readings to within a factor of two could be made for most situations (above 1 mR/h) if aircraft position and altitude were well known.

Since the Military performed all offsite, extended, terrain surveys for Operation TEAPOT (1955) as well as for Operation UPSHOT-KNOTHOLE (1953), it is assumed that similar instruments and techniques were used. It seems reasonable, however, to assume that some improvements had been made since 1953. At the end of Operation UPSHOT-KNOTHOLE three recommendations had been made concerning aerial surveys: (1) obtain a more accurately calibrated radio or radar altimeter for better altitude determinations, (2) obtain new 1:250,000 scale aeronautical charts for better determination of aircraft position, and (3) obtain more accurate determination of the air-to-ground correlation factors.[27]

Altitude and position uncertainties had probably been reduced somewhat by 1955, but air-to-ground correlations undoubtedly remained at about the same level of uncertainty. Based on these assumptions, it is concluded by the author that ground-level radiation exposure rates predicted from aerial surveys were probably accurate within a factor of two or three for most surveys.



Multiply meter reading by the indicated factor to get ground level radiation rate. Use Arithmetic Mean curve to get approximate results.

FIGURE 12. ***ALTITUDE CORRELATION FACTORS (1955) FOR INTERPRETING AERIAL SURVEY RADIATION RATES AS GROUND-LEVEL RADIATION RATES FOR LIGHT AIRCRAFT FLYING AT MINIMUM SPEEDS (70 TO 80 MPH). (Taken directly from Reference 8, redrawn for clarity)***

4.4 1957

Reference 11 discusses the aerial radiometric surveys conducted during Operation PLUMBBOB (1957). A USGS aircraft (DC-3) surveyed the fallout path on D+1 at an altitude of approximately 500 ft. The detectors consisted of an array of five NaI(Tℓ) crystals, and a single NaI(Tℓ) crystal. The crystals were used interchangeably, depending on the required count rate.

An empirically derived air-to-ground conversion factor was obtained over fallout fields from three tests:[11] Boltzmann, Hood, and Smoky (all 1957), each on D+1. The values of 50,200 ±10% cps, 48,500 ±12% cps, and 50,300 ±12% cps, respectively, were found to equal 1 mR/h at 3 ft above the ground. The standard deviation among the measurements was ±12%. Only the most reliable ground and aerial survey data were used. On this basis, a mean conversion factor of 50,000 cps at 500 ft equals 1 mR/h at 3 ft above the ground was used to convert the aerial data to ground intensity values for all aerial surveys in this series. This value applied to the five-crystal array. These detectors had a combined surface area of 126 square in., making a conversion factor of 397 cps at 500 ft equals 1 mR/h at 3 ft for each square in. of detector surface area. This compares well with conversion factors used today in aerial surveys.

In his recent reanalysis, Steadman[28] compared the aerial survey results with 343 ground-based data points for the Smoky test by normalizing all values to equivalent H+12 mR/h.* He found a ratio of 49,000 cps/mR/h, which is very close to the 50,000-cps value given in Reference

---

* Equivalent H+12 mR/h refers to the exposure rate values that would have existed 12 hours after detonation.

11. However, he found a wide range of values (12,000 to 100,000) and a high standard deviation (19,000 or ±38%). Other uncertainties included in Steadman's study were altitude, single-to-five-crystal ratio, collection times, and decay times; these uncertainties probably contributed to the wide range of values and the high standard deviation. The USGS[11] estimated the internal accuracy of the aerial survey system to be ±5%.

In a separate study of the Boltzmann event, Steadman[29] found a conversion factor for the five-crystal array to be 65,000 cps. However, only a few aerial and ground values were used.

A conversion factor of 50,000 cps is recommended by the author to be used for all events in the PLUMBBOB series. Reference 11 suggests that ground level exposure rates can be predicted from aerial surveys to an uncertainty of ±12%. In carefully controlled repeat surveys over a common area a standard deviation among values of ±12% might be possible. However, considering all aspects and uncertainties in actual surveys of fallout fields to establish radiation patterns, an uncertainty of ±40% would be more appropriate.

Unfortunately, the five-crystal array could not measure radiation fields above approximately 1/2 mR/h at the 3-ft level. Because of the count rate dependence of the counting system, count rates above 20,000 cps were not useful. At higher levels, the single crystal was used. Data were recorded on a strip chart using different sensitivity levels. An equivalent cps for the five-crystal array was extracted from the single-crystal results and written on the strip charts and later transcribed onto maps. Calibration of the single crystal was done using radium sources.[21] It is possible that a ratio of single-crystal-to-five-crystal array responses was obtained using calibration sources.

In examining the raw strip chart data for Operation PLUMBBOB, four complications were noted:

1. Equivalent count rates written on the strip charts for the first few events were corrected when transcribed to final maps. This correction sometimes was as much as a factor of two. This was probably a result of finalizing an air-to-ground conversion factor and the single-to-multiple crystal count rate ratios.
2. Later in the series a second USGS plane was used. The strip chart levels and the count rates written on the strip charts appeared to be different for the two planes. These differences are noted in Figure 13. Part of this difference could be accounted for by different dead time losses in the recording systems (see Section 3.2.10).
3. Halfway through the 1957 series (shot Shasta), the small crystal was changed, shielded or modified to be less sensitive on Plane 950. Its sensitivity is questioned for the Smoky test (see Section 5.2.2).
4. During the aerial survey of the Boltzmann fallout patterns, the sensitivity of the single crystal changed by a factor of two.

Steadman,[29] in reviewing the Boltzmann fallout data, found that a "conversion factor of 1150 cps at 500 ft to 1 mR/h at ground level applied to the single-crystal data collected prior to crossing the fallout centerline west of Warm Springs. In contrast, a conversion factor twice as high, 2300 cps to 1 mR/h, was found to apply to the single-crystal data recorded after that time."

Steadman's review of the Boltzmann data indicated the ratio of count rates from the five-crystal array to the single crystal to be about 20 before reaching Warm Springs and 40 after passing Warm Springs. A detailed review by the author of the strip charts from several events indicated that the ratio was considered to be approximately 40 to 50 for Plane 924, 20 to 25 for Plane 950 before the Shasta test, and 100 to 200 thereafter.

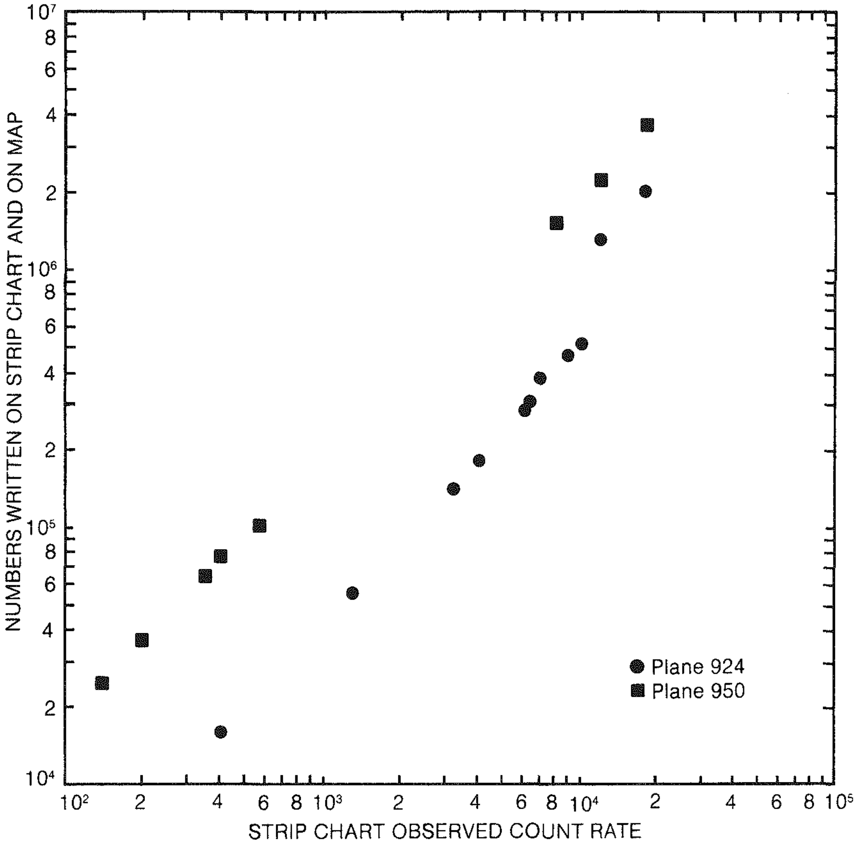


FIGURE 13. ***STRIP CHART RESULTS FOR THE SINGLE CRYSTAL FOR THE SMOKY TEST***

All the data from the single crystal were written as equivalent five-crystal array results both on the strip chart and on the maps. These equivalent five-crystal array results in counts per second can be divided by 50,000 cps to obtain exposure rates 3 ft above the ground. These results are probably not reliable to better than a factor of two if the single crystal was used.

After the USGS plane had surveyed the fallout path, further delineation of exceptional areas was accomplished by ground teams or two aerial survey teams using Super Piper Cubs from the U.S. AEC RMD. These aircraft were also equipped with NaI(Tℓ) crystals. The number of detectors used is not given, although it is assumed that different detector combinations were used depending on the count rate. One of the Priscilla (June 1957) strip charts had the words "Inst. #2" written on it. At a later point in the strip chart "Using Inst. #1" was written and the recorded count rate changed, indicating that the detector had been changed.

Reference 11 indicates that the U.S. AEC RMD detector system was calibrated using a point source of radium rather than over actual fallout fields. Some sensitivity of the radiation detectors to air turbulence was noted. Surveying usually began at 50 ft above the ground and increased in altitude by 100-ft increments, depending on radiation intensity. Air-to-ground conversion factors were never obtained or used. Count rates from the detector systems were converted to exposure rates and these values, in mR/h, were written on the strip charts. The values were applicable to the exposure rates ***at flight altitude*** (not at 3 ft), since no common altitude was flown and quantitative ground-level values were not intended from the aerial survey results.

Relative values from the AEC RMD surveys were useful, however. Steadman[29] found that if he increased the strip chart readings near Warm Springs for the Boltzmann event by a factor of five, the results were very compatible with the ground monitoring data.

4.5 1961 Through 1970

4.5.1 General

Aerial surveys of the fallout field from the 1957 Windscale reactor accident[30] in England proved to be very valuable in quickly assessing the radiation hazards from accidents. This stimulated the United States to develop the Aerial Radiological Monitoring System (ARMS),[13] dedicate it to environmental monitoring of background radiation around nuclear facilities, and make it available for emergency response to radiation accidents.

The ARMS (either ARMS I or ARMS II) was also made available for NTS support and provided offsite monitoring of all fallout fields from NTS events from 1961 through 1970. It continues to be available today for this task, if needed.

During the time period 1961 through 1970 many different air-to-ground conversion factors were used. Surveys were usually made at an altitude of 500 ft from 1961 through 1967. After 1967, an altitude of 300 ft was more common.

A conversion factor of 50,000 cps at 500 ft equals 1 mR/h 3 ft above the ground for the ARMS II 9-in. by 3-in. detector was used for surveys of the Danny Boy, Sedan, and Small Boy events in 1962.* For the Pike event, March 1964, and the Sturgeon event, April 1964, a value of 25,000 cps was used.* From 1968 through 1971 a value of 460,000 cps was used for an altitude of 300 ft for the ARMS II 4-in. by 4-in. detector system.

References 10, 16, 19, and 31 present several conversion factor measurements made over fallout fields at various times and distances from ground zero for the ARMS II 9-in. by 3-in. detector. The conversion factors ranged from 26,000 to 128,000 cps over fallout fields. A detailed discussion of these conversion factors is presented in Section 4.5.5.

Even though conversion factors were measured in actual fallout fields during the above-ground weapons testing events, the need for better understanding of radiation propagation through the air and the need for standardization of calibrations prompted the scientists to set up a calibration range for aerial surveys. Davis and Reinhardt[14] set up the range in 1960 at the NTS using extended arrays of cobalt-60 and cesium-137 sources.

The scientists relied heavily upon conversion factors obtained from the calibration range even though the conversion factors measured in fallout fields showed values from two to four times higher. Because of many uncontrolled parameters, the scientists tended to discount measurements in actual fallout fields in favor of the results from the calibration range, the conditions of which were highly controlled.

The primary difference, however, between measurements over the calibration range and measurements in actual fallout fields was caused by ground roughness. Fallout particles tend to settle in cracks in the ground and at the lower parts of small irregularities in the ground surface.

---

*Information derived by the author from unpublished reports at EG&G Energy Measurements, Inc.

The effect of this is to attenuate the gamma radiation arriving at a point 3 ft above the ground but to have little effect at aerial survey altitudes. The ground roughness effect was not well understood in the early 1960s.

A conversion factor of 25,000 cps at 500 ft equals 1 mR/h at 3 ft had been derived from measurements over the calibration range by the ARMS II aircraft. Reference 16 states that a value of 77,000 was derived from measurements made during Operation PLUMBBOB but due to "insufficient information, an approximate average value of the two conversion factors given previously was selected. . .thus, 50,000 counts/sec at 500 ft was taken to indicate 1 mR/h at 3 ft" for the Small Boy measurements.

The author reviewed various aspects relating to conversion factors by examining several sets of data in light of current technology. The review (as presented in Sections 4.5.2 through 4.5.6) resulted in determining the best or most probable conversion factor to use during the time period 1961 through 1970.

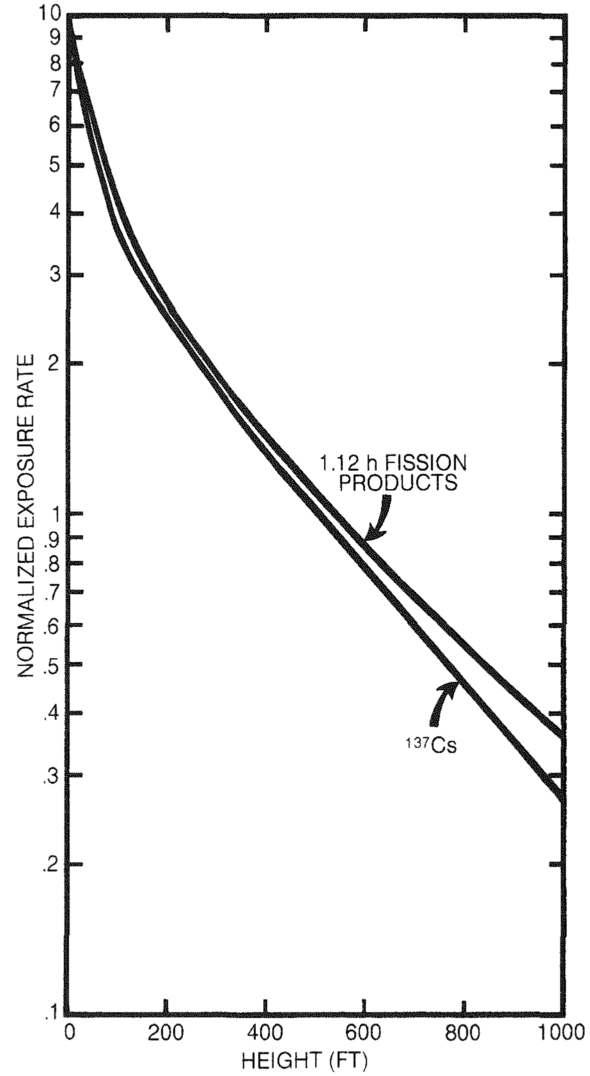


FIGURE 14. ***NORMALIZED EXPOSURE RATES ABOVE INFINITE SMOOTH PLANES OF FISSION PRODUCTS AND CESIUM-137. (Taken directly from Reference 22)***

4.5.2 Calibration Range

During November 1960 an extended calibration range was set up in Frenchman Flat at the Nevada Test Site for aerial survey calibrations.[14] The range was a grid of separate cobalt-60 and cesium-137 sources (500 each) covering an area 2000 ft on a side. The sources were placed slightly above ground so that no shielding was interposed between the sources and detectors.

The ARMS II measurements over this range indicated a conversion factor of 25,000 cps per mR/h for cesium-137. Cesium-137 is slightly better than cobalt-60 for representing the fallout field for fresh fission products[22] (one to three days after detonation).

The radiation field of 2000 ft on a side was essentially equivalent to an infinite field for the 3-ft measurements but was only 90% of an infinite field for the aerial surveys at 500 ft.[22] Therefore, the conversion factor for an infinite smooth plane of cesium-137 would have been 27,500 cps (25,000 × 1.1).

The theoretical exposure rates,[22] as a function of height above the ground for both a cesium-137 source and fission products (early time) for an infinite smooth plane, are shown in Figure 14. The exposure rate 500 ft above a fallout field is 8% higher than over a cesium-137 field when both are normalized to a 3-ft height. Therefore, the conversion factor for an infinite smooth plane of early time fission products would have been 29,700 cps (27,500 × 1.08). The conversion factor for later times after fission would be slightly different, but these data were not readily available for comparison.

The roughness of the ground in reducing the radiation levels at 3 ft has the largest effect on the conversion factor from the calibration range. The effect is illustrated in Figure 15. Note that ground roughness attenuates the gamma radiation arriving at 3 ft much greater than at 500 ft. Fallout radiation travels long distances in air with very little attenuation. Radiation originating from particles behind rocks or in crevices will be attenuated by these rocks or earth before reaching the detector 3 ft above the ground. This effect was not well understood and, therefore, sometimes ignored during the 1950s and early 1960s.

A separate experiment was conducted during the Small Boy event to help determine the effect of ground roughness on radiation fields.[32] Energy and angular distribution measurements were made, as well as exposure rates versus height above the ground, over three different types of terrain covered with fallout. The types of terrain included a dry lake bed, a plowed field, and rough desert.

It was found that the radiation field above the dry lake bed (a terrain as smooth as nature provides) was about 30% less than would have occurred over perfectly smooth terrain. It was postulated that the fallout particles tended to collect in cracks in the soil. The rough desert terrain reduced the radiation levels by about 50%.

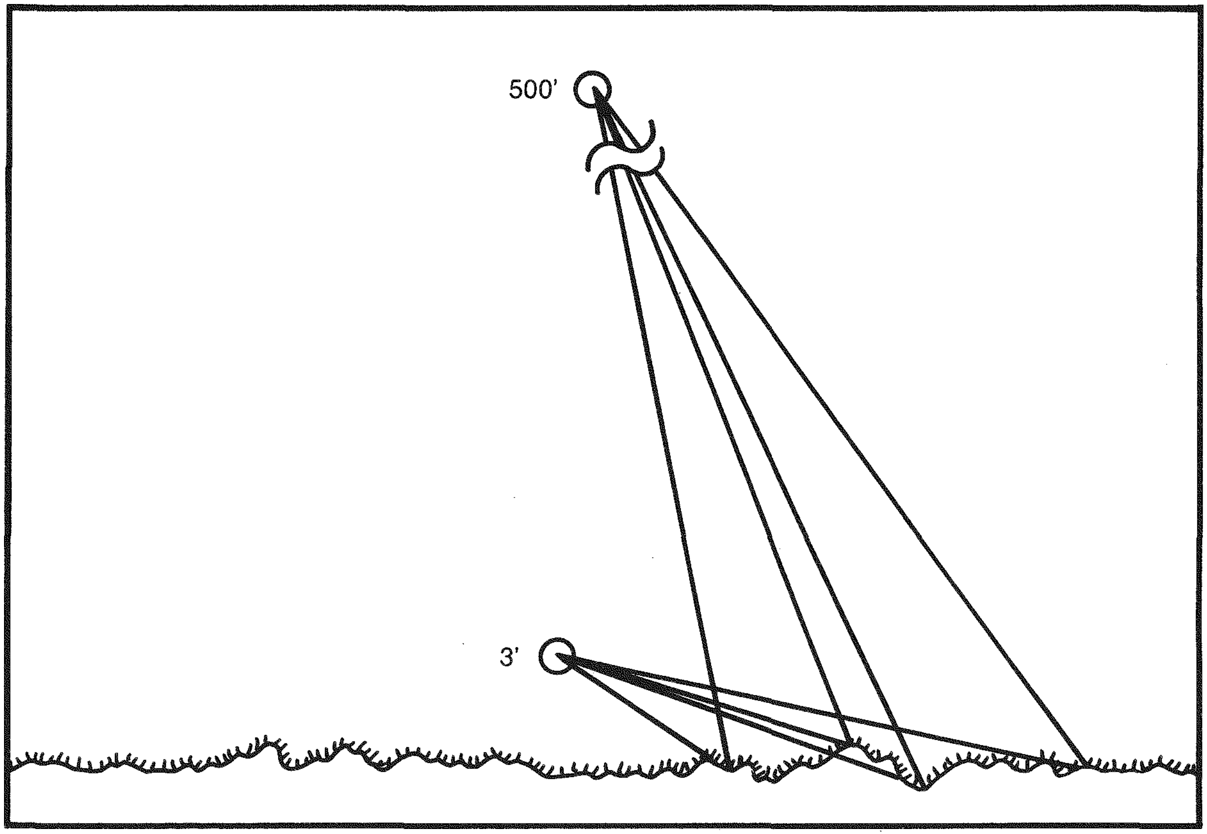


FIGURE 15. ***ILLUSTRATION OF LIMITATIONS IN DETECTING SURFACE CONTAMINATION DUE TO GROUND ROUGHNESS***

Other studies tend to confirm that roughness of the ground is the primary cause of fallout radiation levels being about a factor of two lower than those above a smooth plane for the same concentrations.[33]

Considering the effect of ground roughness, the conversion factor obtained from the calibration range and applied to a fallout field on rough desert terrain would have been 59,400 cps (29,700 × 2).

4.5.3 Crystal Sensitivity Ratios From Today's Calibrations

The current Aerial Measuring System (AMS) utilizes 20 NaI(Tℓ) detectors, each 5 in. in diameter and 2 in. thick. A natural terrestrial calibration range near Lake Mead is used for calibration purposes. A comprehensive set of calibration measurements has been made, both at altitudes above the ground by aerial surveys and at ground level by analysis of soil samples and evaluation of ion chamber measurements.[34] The conversion factor for the AMS at 500 ft over natural terrestrial radiation is 609,000 cps per mR/h.

The volume of the 20 detectors for the AMS is 785 cubic in. and the combined face and side surface area is 1021 square in. The ARMS II aircraft used a single crystal 9 in. in diameter and 3 in. thick. This detector had a volume of 191 cubic in. and a combined surface area of 148.4 square in. The ratios of ARMS II/AMS volume and surface areas are 24% and 14.5%, respectively.

Both the current AMS data recording system and that of the ARMS II recorded all counts from the NaI(Tℓ) crystals above 50 keV.

Considering the sensitivities of the two types of detector systems to natural radiation at 500 ft, it has been calculated that the ARMS II detection would have been 17.3% as sensitive as the AMS 20-detector array.[35] The conversion factor for the ARMS II detector system then, would have been 105,000 cps for natural terrestrial radiation. Detector sensitivities and predicted conversion factors are given in Table 5.

The author, in another study,[33] discussed the differences in conversion factors for aerial surveys over natural terrestrial radiation and fallout deposited on various surfaces. The study estimated the conversion factor for fallout on rough desert terrain to be 11% less than natural terrestrial radiation for an altitude of 500 ft. Considering this difference, the conversion factor for the ARMS II system above fallout fields derived from current calibration data would have been 93,500 cps.

4.5.4 Crystal Sensitivity Ratios From USGS PLUMBBOB Measurements

Many air-to-ground measurements were made during Operation PLUMBBOB and the conversion factor was determined to be 50,000 cps at 500 ft equals 1 mR/h at 3 ft over fallout fields.[11] Recent reanalysis of the PLUMBBOB data along with many ground-based measurements indicated that a conversion factor of 50,000 was valid for most events.[36]

The volume of the USGS five-crystal array was 62.8 cubic in. and the face surface area was 62.8 square in. The ratio of the two volumes (ARMS II crystal to USGS crystals) was three and the ratio of the two surface areas was 2.4. However, when considering the sensitivity of the two systems, calculations indicate that the ARMS II crystal should have been a factor of 1.78 more sensitive than the USGS system (see Table 5). Therefore, the conversion factor for the ARMS II

Table 5. Comparison of NaI(T*l*) Detector Sensitivities and Predicted Conversion Factors for Fission Products

Detector(s)														
No.	Diameter (in)	Thickness (in)	System	Period of Use	Shielding	Volume (in³)	Face Surface Area (in²)	Side Surface Area (in²)	Fraction of Area Shielded[a]	Attenuation by Shield	Interaction Ratio at 500 keV[b]	Effective Area of Face[c] (in²)	Effective Area Shielded[d] (in²)	Conversion Coefficient[e] [cps at 500 ft/ mR/h at 3 ft]
5	4	1	USGS	1957	None	62.8	62.8	12.6	—	—	0.60	37.7	—	60,000
5	4	1	USGS	1957	1/2" on sides	62.8	62.8	12.6	0.17	0.90	0.60	—	31.9	53,000
1	1-1/2	1		1957	None	1.77	1.77	4.71	—	—	0.60	1.06	—	1,700
1	1-1/2	1		1957	1/2" on sides	1.77	1.77	4.71	0.73	0.90	0.60	—	0.36	600
1	1-1/2	1-1/4		1957	None	2.21	1.77	5.89	—	—	0.66	1.17	—	2,000
1	1-1/2	1-1/4		1957	1/2" on sides	2.21	1.77	5.89	0.77	0.90	0.66	—	0.36	600
6	4	2	ARMS I	1957-60	1/2" on sides	151	75.4	151	0.66	0.90	0.84	63.3	—	104,000
1	9	3	ARMS II	1961-67	None	191	63.4	84.8	—	—	0.90	57.2	—	93,500
14	4	4	ARMS	1968-70	None	704	176	704	—	—	0.96	169	—	277,000
20	5	2	AMS	Current	None	785	393	628	—	—	0.84	330	—	542,000[f]

[a] This represents the case where the source is isotropically distributed around detector.

[b] Reference 35.

[c] Effective area + face area × IR (no shield) or face area × IR × (1 - % shield × attenuation) (shielded).

[d] Effective area after shielding + effective area × % shielding × attenuation.

[e] Normalized to 20 5" × 2" detectors calibrated at Lake Mead test line at 500 ft above ground level.

[f] 609,000 for natural radiation reduced by 11% to apply to fission products.

system above fallout fields, derived from USGS PLUMBBOB calibrations and considering crystal sensitivity ratios, would have been about 90,000 cps (50,000 × 1.78).

As noted in Table 5, the predicted conversion factor for the USGS system used on Operation PLUMBBOB was 53,000 cps. This lends confidence that the value of 50,000 cps used during the PLUMBBOB series was a valid conversion factor.

4.5.5 ARMS II Fallout Measurements

In an attempt to more carefully determine a conversion factor for fallout fields, several air-to-ground correlation measurements were made using the ARMS II aircraft detector system. Each is discussed in detail in this section. The values ranged from 26,000 to 128,000 cps. It should be noted that a range of values is expected. The effective energy of the gamma rays emitted changes with time after fission. Some changes with location and type of burst (subsurface, surface, etc.) also contribute to the differences because of fractionation and the presence of activation products. This means that applying a single conversion factor to all fallout fields can only be a representative value and involves uncertainty because of the above conditions. Uncertainties also existed in the ground-based measurements used to obtain the air-to-ground conversion factors.

Reference 16 indicates that the equipment for ARMS I had measured a conversion factor of 77,000 cps during Operation PLUMBBOB. However, the confidence in the measurement was low because the survey meter readings at 3 ft varied by at least a factor of two. Also, there was no indication whether this was one aerial measurement or several. Nevertheless, it was an actual calibration measurement in a fallout field using the same equipment used during aerial surveys of fallout fields and will, therefore, be considered. Table 5 shows the ARMS I detector system to be 10% more sensitive than the ARMS II detector system. Therefore, a conversion factor of 70,000 cps would have been measured by ARMS II.

The results of the Sedan air-to-ground calibration measurements, (47,000, 52,000 and 85,000 cps) are given in References 10 and 16 without discussion. Sedan was an underground detonation. The energy spectrum was probably not typical of material deposited from surface bursts.

The Small Boy fallout pattern was surveyed by ARMS II in East Indian Spring Valley on D+3. In another study,[32] 3-ft exposure rate measurements were made at two locations. Equivalent H+24 hour exposure rate values were 5.56 mR/h at position A and 4.31 mR/h at position B. Interpolated and decay-corrected ARMS II count rates were 700,000 and 550,000 cps over positions A and B, respectively. These values indicate conversion factors of 126,000 and 128,000 cps per mR/h. The two conversion factors measured are in good agreement. However, these values are not to be taken as absolute because of the large correction necessary for fallout decay. A multiplication factor of 3.7 was necessary to correct the count rates obtained at D+3 to be valid at D+1, assuming a $T^{-1.2}$ decay rate. (Quinn[37] has shown that a $T^{-1.2}$ decay rate was valid for the Small Boy event between D+1 and D+3.)

On July 5 and 10, 1962 a special study was made to measure count-rate to exposure-rate conversion factors for four-day-old fallout (Sedan) and three-week-old fallout (Des Moines).[31] The two areas were 25 to 30 miles apart. Ground data were taken four days apart using a Victoreen 440 survey meter. The instrument was sensitive to Beta radiation. Locations were chosen in nearly uniform radiation fields of large dimensions so that the airborne detector reviewed a nearly infinite field. Both locations were of nearly the same radiation level. The two conversion values (26,000 and 42,000 cps) were lower than any other values measured, possibly because the ground-based detector measured some Beta radiation.

Giving each measurement equal value, the average air-to-ground conversion factor measured in actual fallout fields, applicable to the 9-in. by 3-in. ARMS II detector, was 72,000 cps.

4.5.6 Summary of Conversion Factors

A summary of conversion factors for ARMS II surveys for 1961 through 1967, as derived from four different considerations, is given in Table 6. The average of the four values is approximately 79,000 cps per mR/h.

The four values were weighted equally. There did not seem to be any compelling reason to weigh any one value higher than another. The lowest value was derived from the extended source calibration range, while the other three values were reasonably close to the average.

Table 6. ARMS II Conversion Factor Considerations

	cps/mR/h	cps/mR/h
Original Extended Calibration Range (1960)		
a. For cesium-137 sources on a 2000-ft grid	25,000	
b. Extend to infinite distance	27,500	
c. Apply cesium-137 results to fallout	29,700	
d. Consider ground roughness, final value		**59,400**
Crystal Sensitivity Ratios from Today's Calibrations		
a. 20 detectors, 5 in. × 2 in., for natural radiation	609,000	
b. One detector, 9 in. × 3 in., considering sensitivity ratios	105,000	
c. Apply natural radiation results to fallout, final value		**93,500**
Crystal Sensitivity Ratios from USGS PLUMBBOB Measurements		
a. Five detectors, 4 in. × 1 in. (USGS)	50,000	
b. One detector, 9 in. × 3 in., considering sensitivity ratios, final value		**90,000**
ARMS II Fallout Measurements		
a. PLUMBBOB	70,000	
b. Sedan		
20 miles from ground zero	47,000	
35 miles from ground zero	52,000	
60 miles from ground zero	85,000	
c. Small Boy		
Position A	126,000	
Position B	128,000	
d. Special Study		
Des Moines - 3-week-old fallout	42,000	
Sedan - 4-day-old fallout	26,000	
e. Average - fallout measurements, final value		**72,000**
Average of the four considerations		**79,000**

5. REVIEW OF HISTORICAL DATA

To assist in assessing the validity of the data reviewed, some of the data were examined in detail. The UPSHOT-KNOTHOLE (1953) series aerial survey data are listed in tables in Reference 4. A summary of the aerial survey data for Operation PLUMBBOB (1957) is given in Reference 11, while the raw data are archived in the DOE's Coordination and Information Center (CIC) in Las Vegas, Nevada, in the form of strip charts and maps. Some of these data were examined in detail to further evaluate the usefulness and limitations of the aerial survey results.

5.1 Operation UPSHOT-KNOTHOLE - 1953

The T1B readings given in Reference 4 for five tests were converted to 3-ft values for H+12 hours and plotted on maps. Air-to-ground conversion factors were taken directly from Figure 6. Extrapolation to H+12 hours assumed the $T^{-1.2}$ decay rate. Only T1B data were used because only this instrument was considered reliable. The data positions used were those given in Table 3. The data were plotted with different symbols representing values within exposure rate categories at locations given in Reference 4. Where appropriate, the results are plotted separately for data taken on test day and D+1.* For comparison purposes, the aerial data are overlaid on the fallout contours constructed at the end of Operation UPSHOT-KNOTHOLE.

Data from the Badger and Simon tests were considered first, even though they were numbers 6 and 7 in the series. Reference 4 indicates that the aerial data from these two tests were used as special cases to show the usefulness of the aerial surveys.

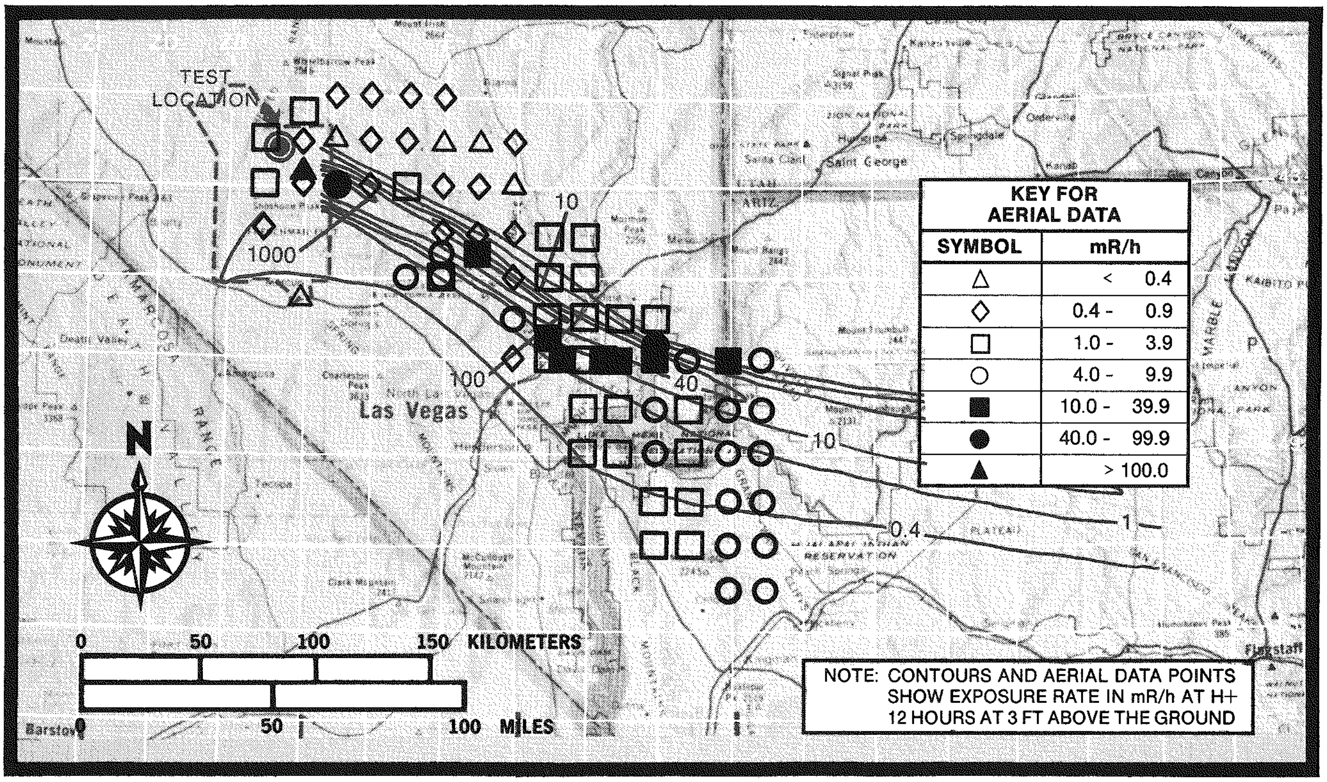
5.1.1 Badger

The aerial survey data taken on test day and D+1 are shown in Figures 16 and 17 as symbols overlaid on the fallout patterns. Data values taken on D+1 were much higher than those of the data taken on the day of the test. The purposes of the surveys were probably different. It is postulated by the author that the intent of the first day's survey was to go to an intersection and make a measurement, whereas the intent of the survey on D+1 was to find the center of the fallout path, make a measurement, and estimate the nearest intersection. Considering that the intersections were 10 miles apart (north and south) and that the highest radiation level in the center of the fallout path was only two or three miles wide, the differences are understandable.

For the aerial data to be reconciled to the ground-based fallout patterns, one must accept a location error of 5 to 10 miles and a conversion factor error of 5 to 10 in predicting the 3-ft exposure rates from the aerial data. Otherwise, the agreement is very poor. For example, in Figure 17 the aerial survey data point at grid H47 on D+1 shows an H+12 hour exposure rate at 3 ft of 60 mR/h. The location of the hot line (40 to 100 mR/h), as shown by the contours, crosses the highway about 10 miles northeast of the H47 grid location. The equivalent H+12 hour exposure rates measured at 3 ft ranged from 0.4 to 0.9 mR/h at the location reported by the aircraft. It is doubtful if ground-based measurements would be in error for positions along the highway. The T1B reading was 2.6 mR/h in the aircraft at a 400-ft altitude at 12:45 p.m. on D+1. The conversion to 3 ft at H+12 (60

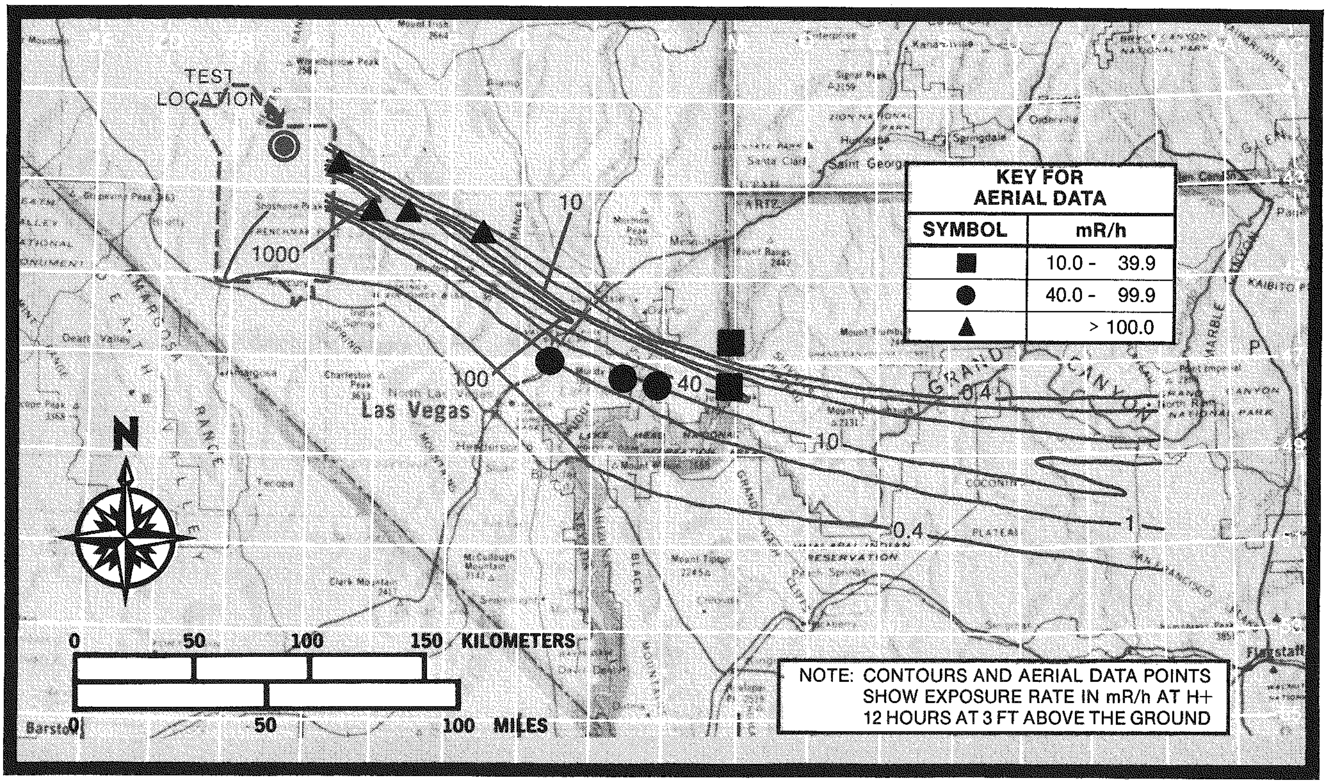
---

* D+1 refers to the day after the test, D+2, the second day after the test, etc.



NOTE: CONTOURS AND AERIAL DATA POINTS SHOW EXPOSURE RATE IN mR/h AT H+ 12 HOURS AT 3 FT ABOVE THE GROUND

FIGURE 16. *AERIAL SURVEY DATA OVERLAID ON FALLOUT PATTERN — BADGER D DAY*



NOTE: CONTOURS AND AERIAL DATA POINTS SHOW EXPOSURE RATE IN mR/h AT H+ 12 HOURS AT 3 FT ABOVE THE GROUND

FIGURE 17. *AERIAL SURVEY DATA OVERLAID ON FALLOUT PATTERN — BADGER D + 1 DAY*

mR/h) should be valid to within a factor of two. The problem appears to be pinpointing the location of the plane. Quinn,[38] in his review of the Badger data, also found very little agreement between the aerial and ground data.

5.1.2 Simon

The data for the Simon test are shown in Figures 18 and 19. Much of the aerial data taken on test day ranged from 0.4 to 10 mR/h. There are two problems with the data. First, most of the readings in the aircraft at the time of measurement were 0.1 or 0.2 mR/h. The T1B readings at these low values would not be very reliable and, therefore, the results are questionable.

The second problem is that many of the measurements were made at altitudes from 1000 to 1500 ft above the ground. Air-to-ground correlations are poor at these altitudes. Furthermore, the actual altitude flown could easily have deviated ±200 to 300 ft from that reported.

As presented in Figure 19, the aerial survey data show the center of the hot line reasonably well except for point Q47. On D+1 at 12:45 p.m., the T1B reading in the aircraft was 4.6 mR/h. The remarks section of Reference 4 made the statement, "20 miles wide." It is assumed this meant that the same reading applied to a strip 20 miles wide east and west, not north and south. The predicted 3-ft value at H+12 hours of 140 mR/h is probably valid (wherever the aircraft was). The aircraft crew could have misjudged their location, although a 20-mile error that close to the Grand Canyon seems unlikely.

Steadman,[39] in his reanalysis of the Simon data, concluded that the original fallout pattern (as shown in Figures 18 and 19) was in error. The pattern actually turned southeast rather than continuing east. The aerial measurement results at position Q47 were of great importance in this conclusion.

5.1.3 Annie

Annie was the first test in the UPSHOT-KNOTHOLE series. This was the first time aerial surveys were used for terrain surveys offsite. The data are shown in Figure 20. No surveys were made on D+1.

There are several problems with the data. As shown in Figure 21, the center of the hot line, as predicted from the aerial data, is inconsistent. The highest radiation levels on each north-south line were plotted and a serpentine pattern resulted. This would be highly unlikely. There are two readings given for position E44: 80 mR/h (highest for that line) and 0.4 mR/h (lowest).[4] The reading at F44 is the lowest on the F line, while the reading at G44 is the highest for the G line. The implication is that the pilot was lost most of the time or confused as to the direction of travel.

In Reference 4 the aerial data were converted to H+1 hour intensity. Many of the T1B readings were less than 1.4 mR/h and were ignored in the conversion to H+1 hour intensity. The reason for this is not known. Perhaps they did not anticipate using the data at these low levels since this was the first aerial survey. A reading of 1.4 mR/h in the aircraft at the time of the aerial survey converts to about 5 mR/h at 3 ft at H+12 hours. If the readings of 1.4 mR/h and below were considered invalid, most of the data below 10 mR/h in Figure 20 would be invalid.

In summary, aerial data for 10 mR/h and below at 3 ft for H+12 hours may be invalid. Data above 10 mR/h are considered valid, but the location is suspect. The only location that should be

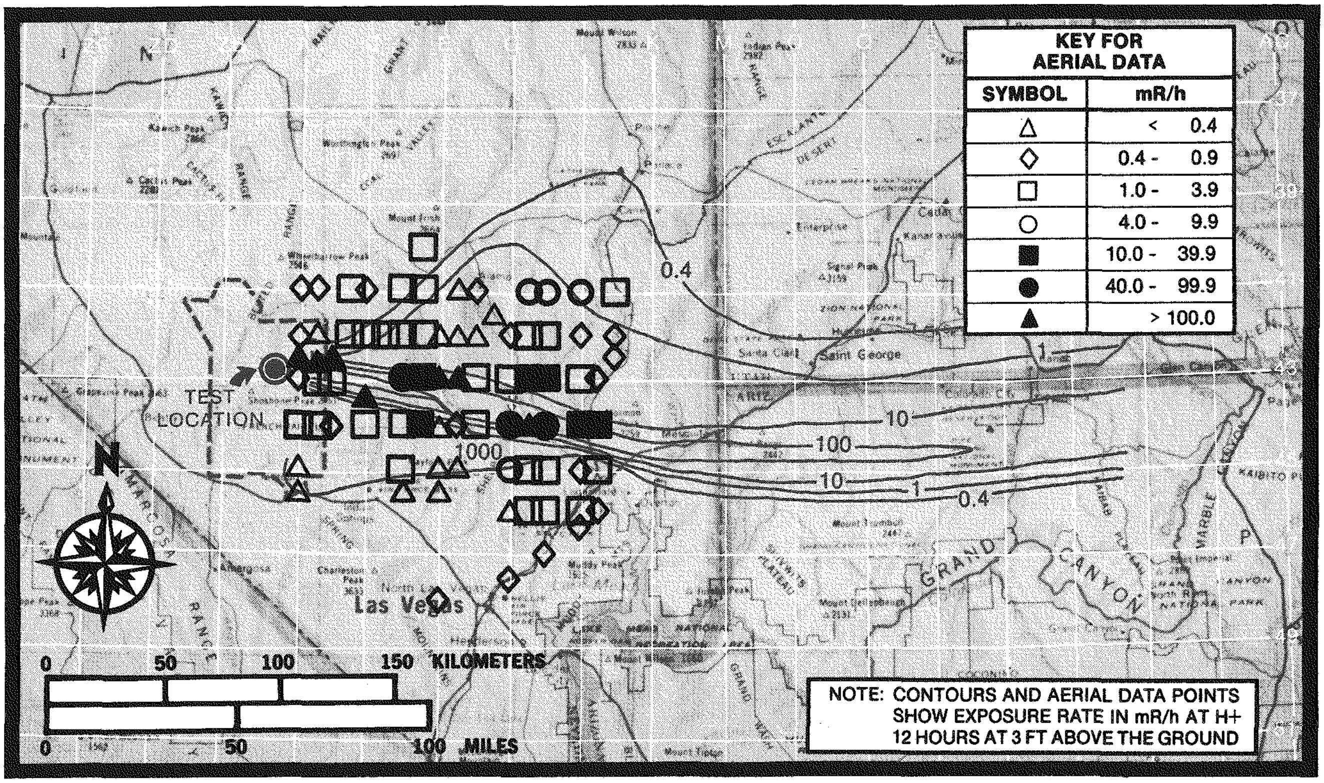


FIGURE 18. *AERIAL SURVEY DATA OVERLAID ON FALLOUT PATTERN — SIMON D DAY*

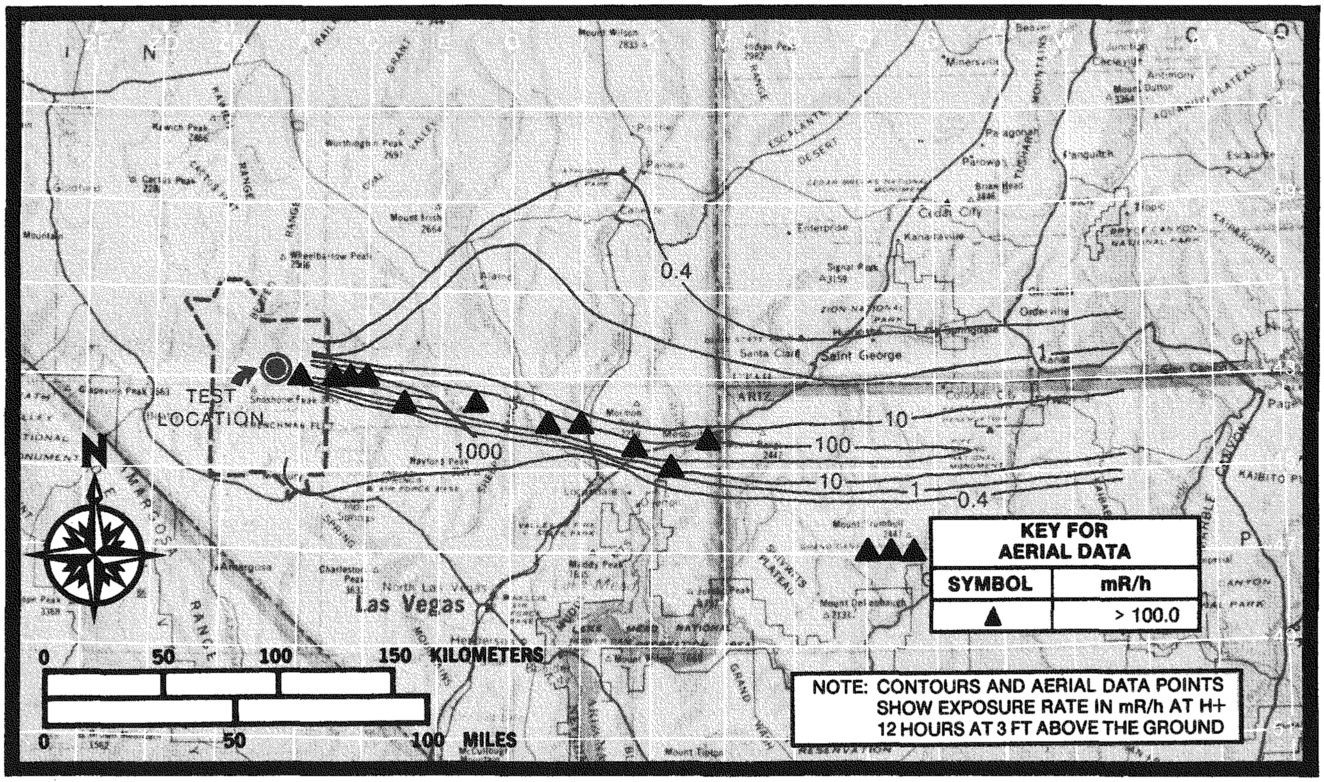
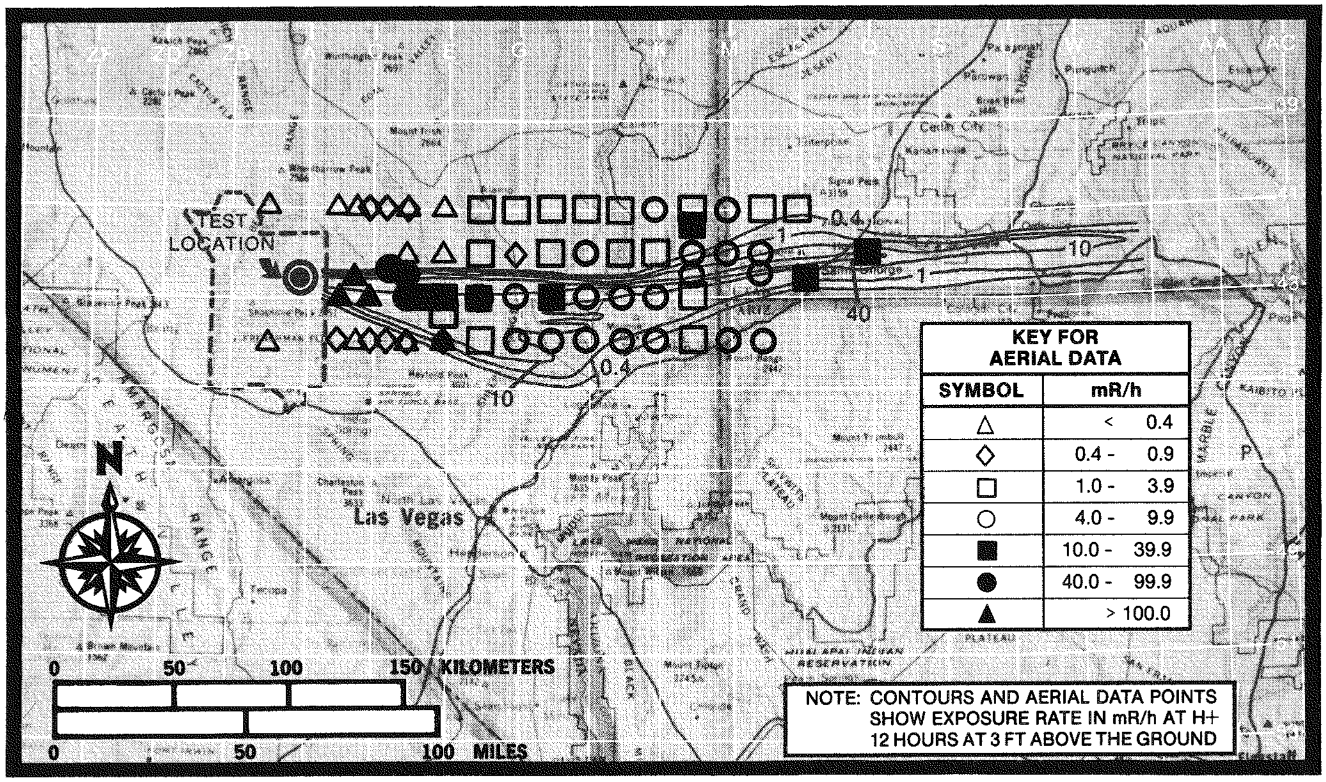


FIGURE 19. *AERIAL SURVEY DATA OVERLAID ON FALLOUT PATTERN — SIMON D + 1 DAY*



NOTE: CONTOURS AND AERIAL DATA POINTS SHOW EXPOSURE RATE IN mR/h AT H+ 12 HOURS AT 3 FT ABOVE THE GROUND

FIGURE 20. ***AERIAL SURVEY DATA OVERLAID ON FALLOUT PATTERN — ANNIE***

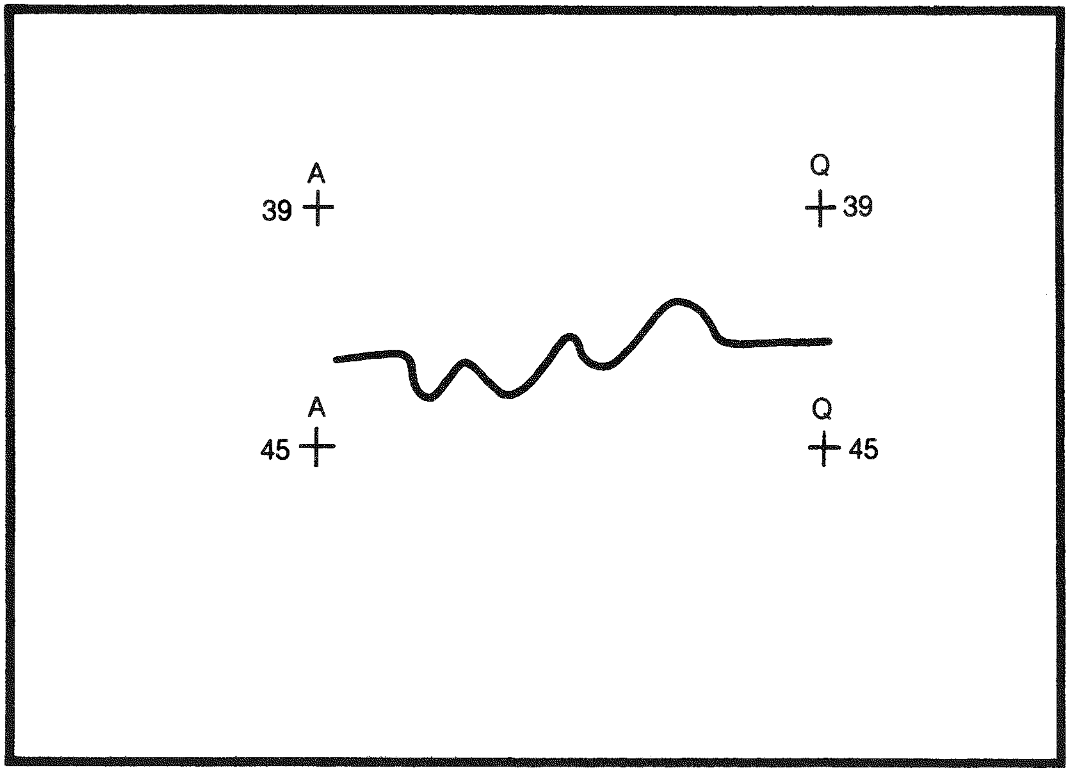


FIGURE 21. ***CENTER OF HOT LINE FOR SHOT ANNIE INDICATED BY UNCORRECTED AERIAL SURVEY DATA***

considered accurate was St. George, Utah. The position information in Reference 4 indicates "St. George" rather than a coordinate intersection. Measurements over St. George were made at 11:26 a.m. on shot day at a 600-ft altitude. The T1B reading was 4 mR/h. This converts to 20 mR/h at 3 ft at H+12 hours.

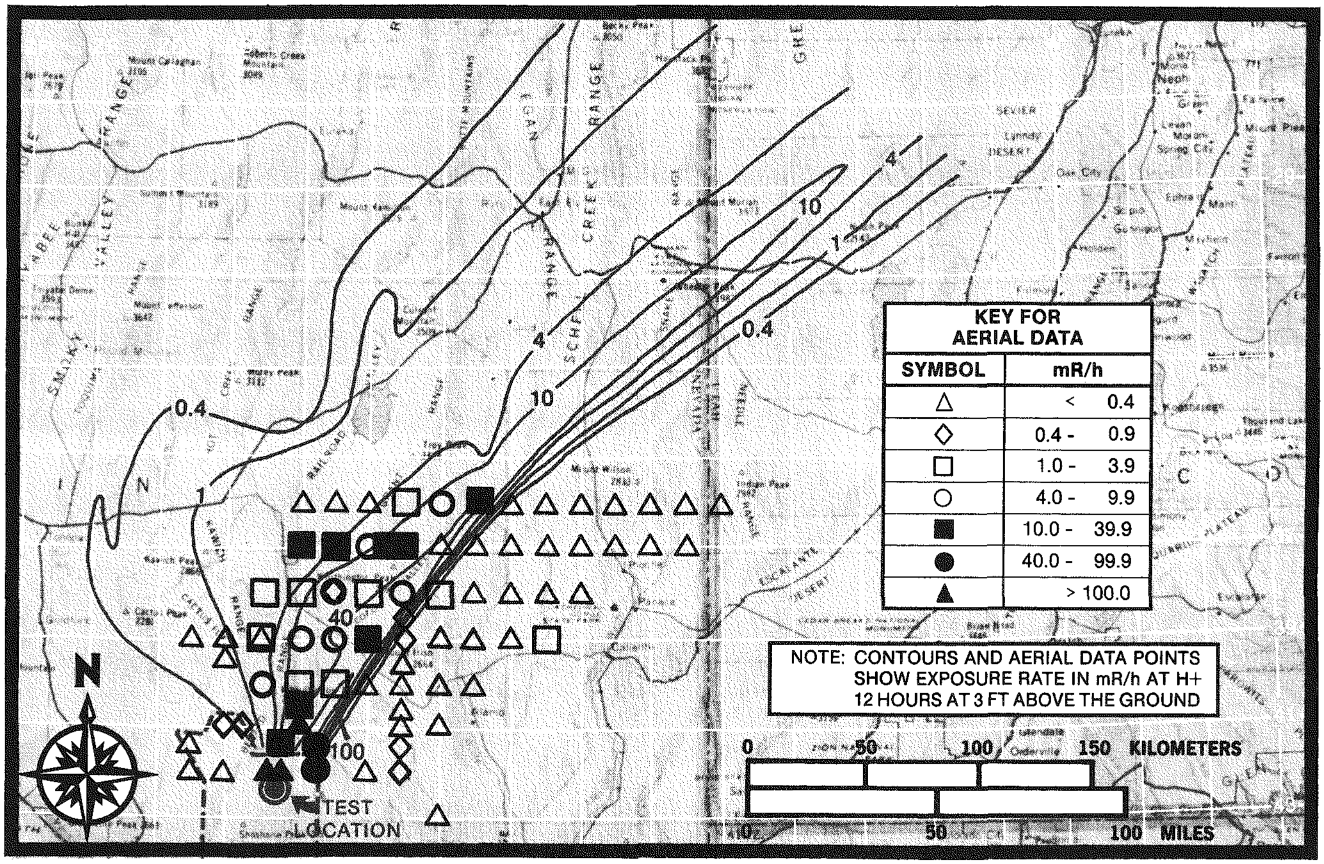
5.1.4 Nancy

The aerial survey data for the Nancy test are shown in Figure 22. These data appear to have problems similar to those of the Badger, Simon, and Annie tests—aircraft position uncertainty.

5.1.5 Harry

Harry was the last test on a tower in the UPSHOT-KNOTHOLE series. Aerial survey data were taken on both test day and D+1. The data are shown in Figures 23 and 24. There are several problems with the data.

On test day (Figure 23) all the data taken in Utah and Arizona are suspect. These data were all taken at 1500- to 2500-ft altitudes above the ground with T1B readings of 0.5 mR/h or less. The conversion factors from these altitudes were unreliable. The T1B readings were also unreliable at these low readings.



KEY FOR AERIAL DATA

SYMBOL	mR/h
△	< 0.4
◇	0.4 - 0.9
□	1.0 - 3.9
○	4.0 - 9.9
■	10.0 - 39.9
●	40.0 - 99.9
▲	> 100.0

NOTE: CONTOURS AND AERIAL DATA POINTS SHOW EXPOSURE RATE IN mR/h AT H+12 HOURS AT 3 FT ABOVE THE GROUND

FIGURE 22. *AERIAL SURVEY DATA OVERLAID ON FALLOUT PATTERN — NANCY*

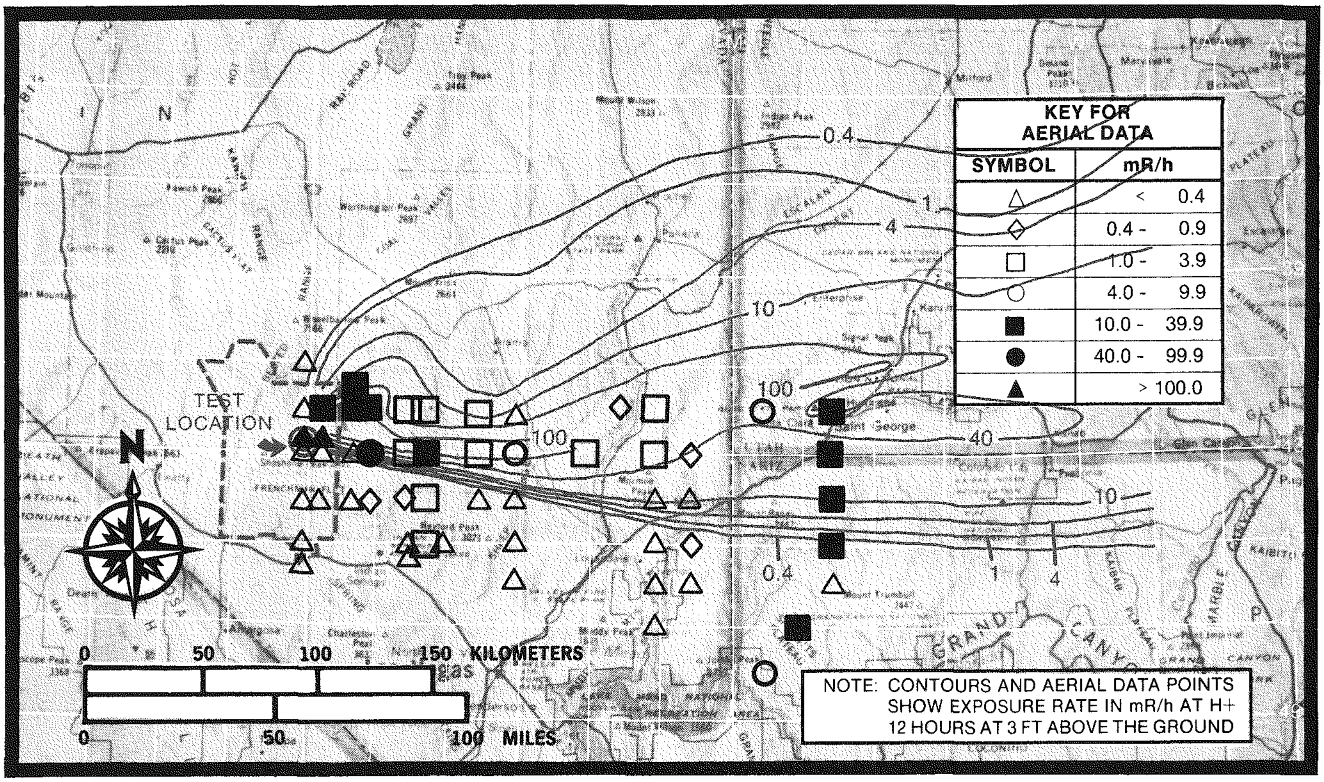


FIGURE 23. *AERIAL SURVEY DATA OVERLAID ON ORIGINAL FALLOUT PATTERN — HARRY D DAY*

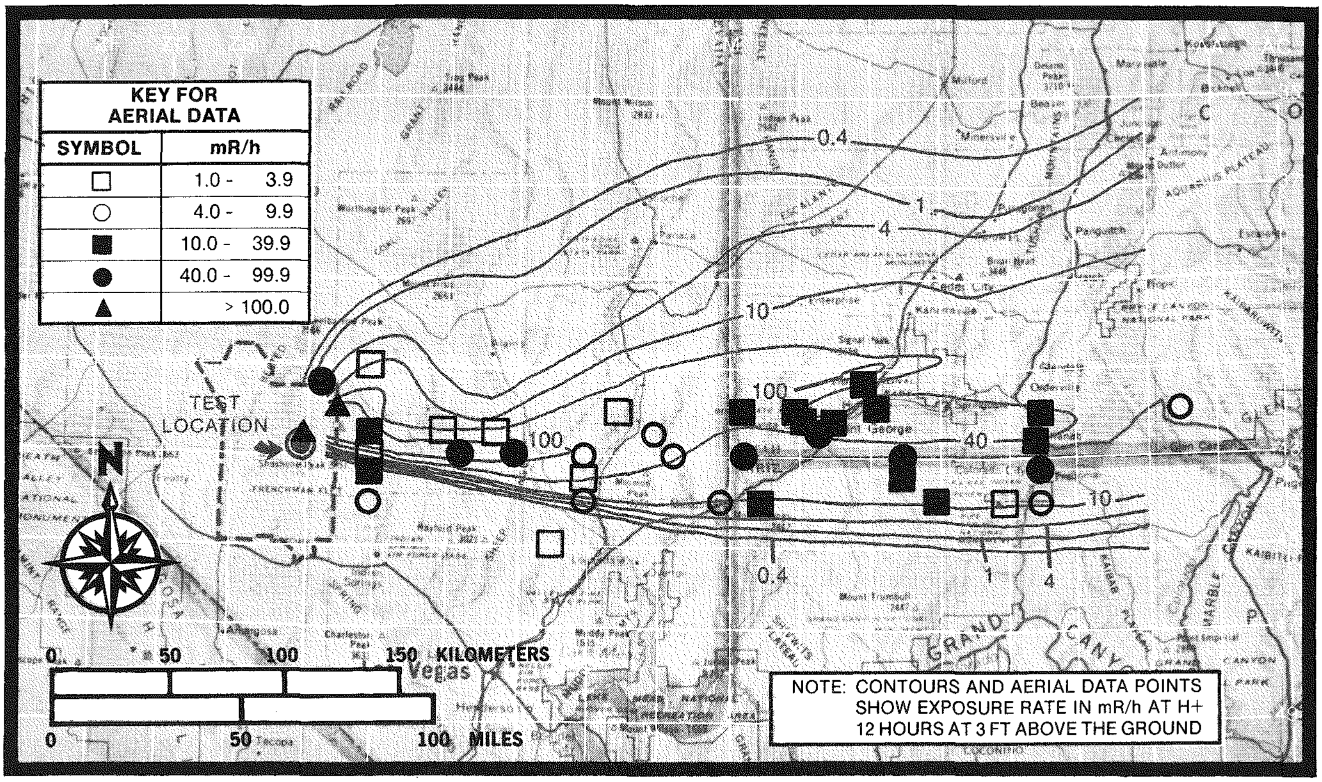


FIGURE 24. *AERIAL SURVEY DATA OVERLAID ON ORIGINAL FALLOUT PATTERN — HARRY D + 1 DAY*

Most of the readings taken on D+1 were also less than 1 mR/h. Therefore, the data shown in Figures 23 and 24 below 10 mR/h at H+12 hours at 3 ft are not considered reliable. The aerial data indicated the highest radiation levels to be several miles south of the hot line as indicated by the contours. This is the same for both test day and D+1. Uncertainty in aircraft position probably contributed heavily to these differences.

The aerial data indicates a "cold" area north of Glendale, on both test day and D+1. While the T1B readings were all less than 1 mR/h in this area and are considered unreliable, they are unreliable on the high side; i.e., at the low readings, the instrument was likely to read too high. It was possible that a "cold" spot occurred in the radiation field north of Glendale, or that the hot line was very narrow and the aerial survey team missed it both days. It is most probable that the aircraft's position was simply not known accurately enough to allow the aerial data to influence the drawing of the fallout contours.

5.2 Operation PLUMBBOB - 1957

Great improvements were made in 1957 in navigation and aircraft position determination. Continuous count rate plots on strip charts provided radiation readings across fallout paths. Fiducial marks were placed on the strip charts to coincide with known locations on the ground; these marks were also placed on the maps and provided reasonable assurance of USGS aircraft location at all times.

Great improvements were also made in sensitivity. Sodium iodide crystal detectors provided reliable readings of radiation fields far below the 1 mR/h range. Measurements above 20 mR/h (at the 3-ft level), however, were not possible early in the series because of count rate limitations. All surveys by the USGS aircraft were made on D+1 or later.

5.2.1 Boltzmann

Boltzmann was the first test in the Operation PLUMBBOB series. This was also the first time the USGS aircraft with the "new" equipment was used for terrain surveys of offsite fallout radiation fields.

The first leg (Arc III) of the survey was from Tonopah to Warm Springs along Highway 6. The original strip chart was examined and the data extracted and plotted in Figure 25. Notes on the strip chart were very clear as to location, the number of crystals used, and sensitivity settings.

From the data taken on the first leg of the survey, a conversion factor for the single crystal was estimated to be 1250 cps at 500 ft equals 1 mR/h at 3 ft. This compares well to Steadman's[29] estimate of 1150 cps. The data shown in Figure 25 also contains an estimated correction for dead time losses. (The observed count rate of 20,000 cps was probably equivalent to 25,000 cps actual count rate.)

The data shown in Figure 25 are believed by the author to be reliable and to agree with the fallout pattern for the Boltzmann test. Note that the radiation levels were off scale about six miles west of Warm Springs. Note also the wide pattern, averaging 2 to 3 mR/h, 10 to 20 miles west of Warm Springs. The small variations in aerial data in this area are probably a true representation of the radiation levels. Altitude variations probably did not influence the data since the aircraft was following a highway. Highways change altitude gradually, allowing the aircraft to maintain a given altitude over the road.

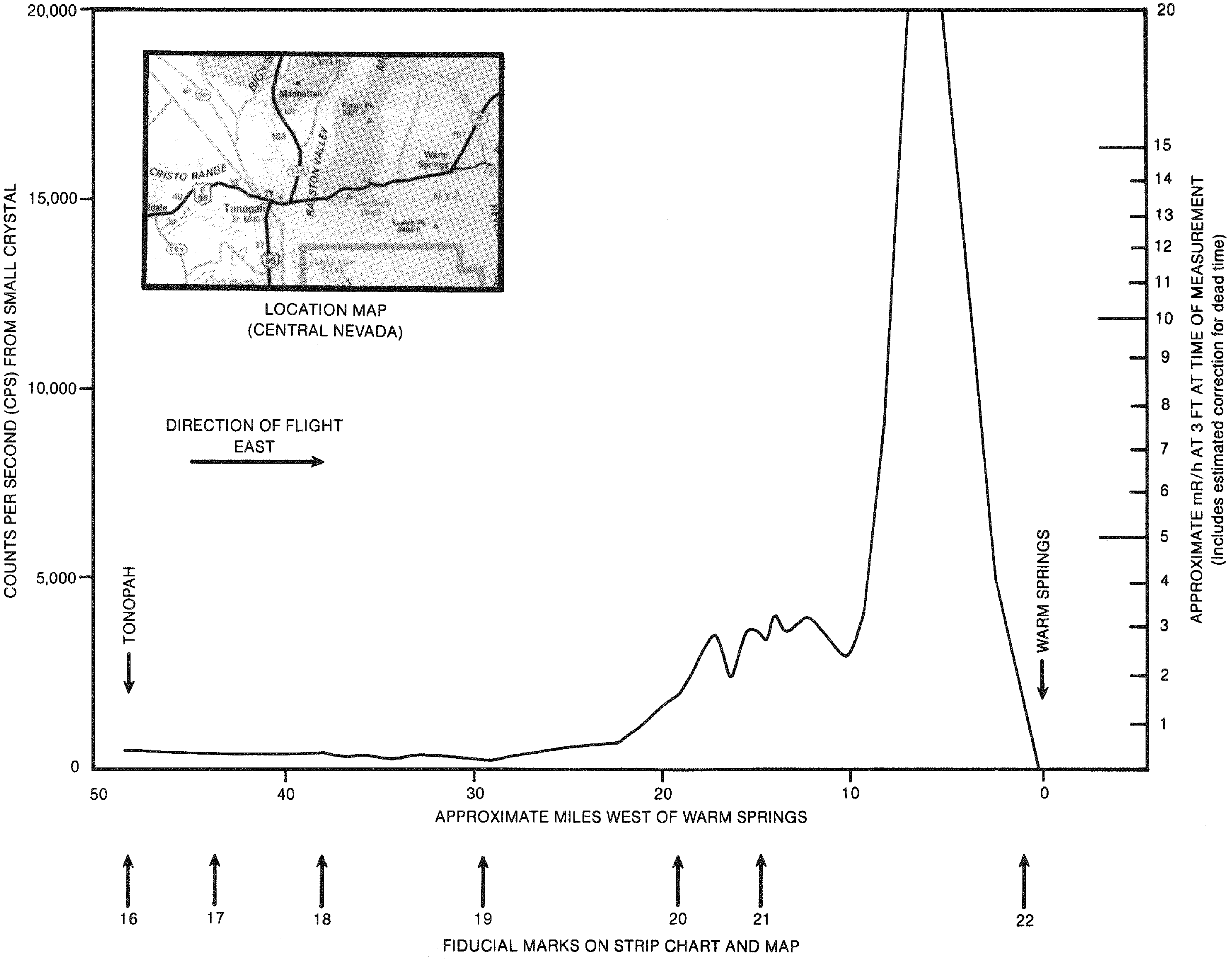


FIGURE 25. ***AERIAL SURVEY DATA, D + 1, SHOT BOLTZMANN, ARC III***

The second leg of the survey was along Arc IV, located about 28 miles north of the first leg. These data are plotted in Figure 26. The hot line off-scale readings occurred between fiducial marks 31 and 32.

The three peaks in the aerial data west of the hot line, again, are probably a true representation of the radiation levels and not a result of altitude variations since the aircraft was still following a road. There were very few markings on the strip chart as to the number of detectors used and sensitivity settings. An educated guess was made by the author on sensitivity settings based on whether the count rates were going up or down and by following the data both east and west until reliable sensitivity settings were found. If errors in sensitivity settings were made, the errors would be a factor of 2 or 2.5 in count rates. The author feels that these peak radiation levels are accurate.

The strip chart from the U.S. AEC RMD Piper Cub was examined for the survey near Warm Springs. This survey was done on D+3, probably at low altitudes. The relative count rates across the pattern (along Highway 6) generally agreed with those in Figure 25, including the small deviations in the data west of the hot line. The quantitative conversion to exposure rates at 3 ft, however, should not be relied upon for the following reasons:

1. Possible dead time errors (the number of crystals used is not known).
2. Air-to-ground calibrations were not done over fallout fields.
3. The aircraft was not intended for quantitative measurements.

If locations are well marked on the strip chart and can be followed on the map, the aircraft's position determination is probably reliable. However, one must remember that in flying at low altitudes, designated locations pass by quickly and errors in designation can be made very easily.

5.2.2 Smoky

Several aerial surveys were made of the radiation fallout fields from the Smoky test. The surveys were conducted on D+1, D+3, D+4, and D+5. A modified single-crystal detector had been installed in Plane 950 for the previous test (Shasta) to allow measurements of higher radiation fields. The design goal was to be able to record 4,000,000 cps (equivalent to the five-crystal array). This would allow measurement of a 3-ft exposure rate of 80 mR/h. The results of the aerial survey for the Shasta test had indicated that the sensitivity for the new detector system had to be revised.[40] The notification letter of the correction factor revision was prepared on August 28, 1957, just three days before the Smoky test. A careful examination of the strip chart indicated that the new detector's sensitivity still remained in question for the Smoky surveys.

The results of two separate surveys of the same area are shown in Figure 27. The surveys were conducted across the northern border of Utah and Colorado. The first survey was conducted on D+3 and the direction was west to east. The second survey (east to west) was conducted on D+4. The radiation levels on D+4 were expected to be about 30% lower than on D+3.

Figure 27 also shows the count rates measured on D+4 are lower than those measured on D+3. A large discrepancy occurs, however, in the vicinity of fiducial mark 38. On D+4, the five-crystal array was used during the survey but on D+3, the single crystal was used. It appears that the single crystal should have recorded an equivalent count rate of about 23,000 cps rather than the 35,000 cps written on the strip chart. It is concluded by the author that some, if not all, of the single-crystal readings for the Smoky test were 35% too high. Steadman,[28] however, after careful review of all the Smoky data, did not reach the same conclusion.

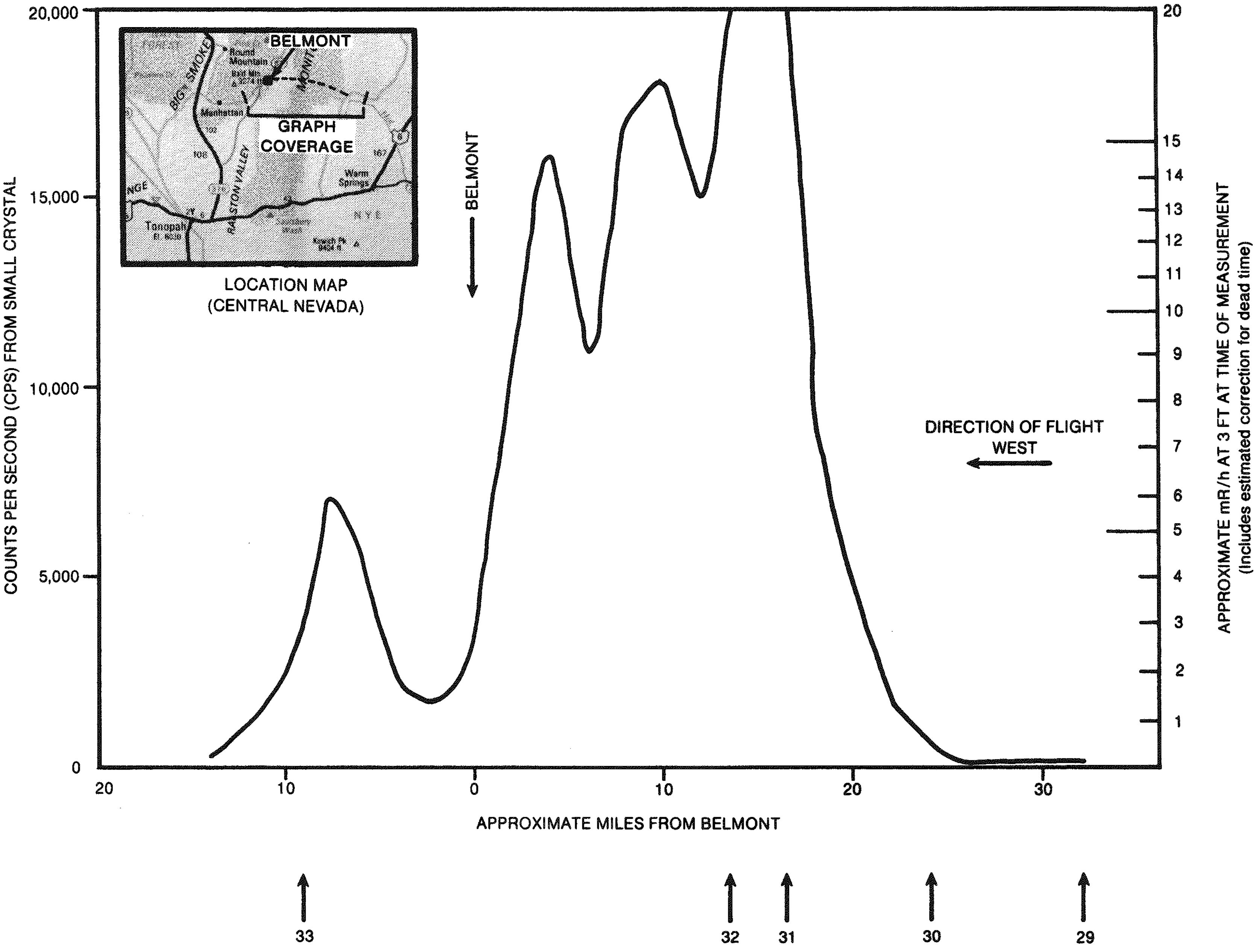


FIGURE 26. ***AERIAL SURVEY DATA, D + 1, SHOT BOLTZMANN, ARC IV***

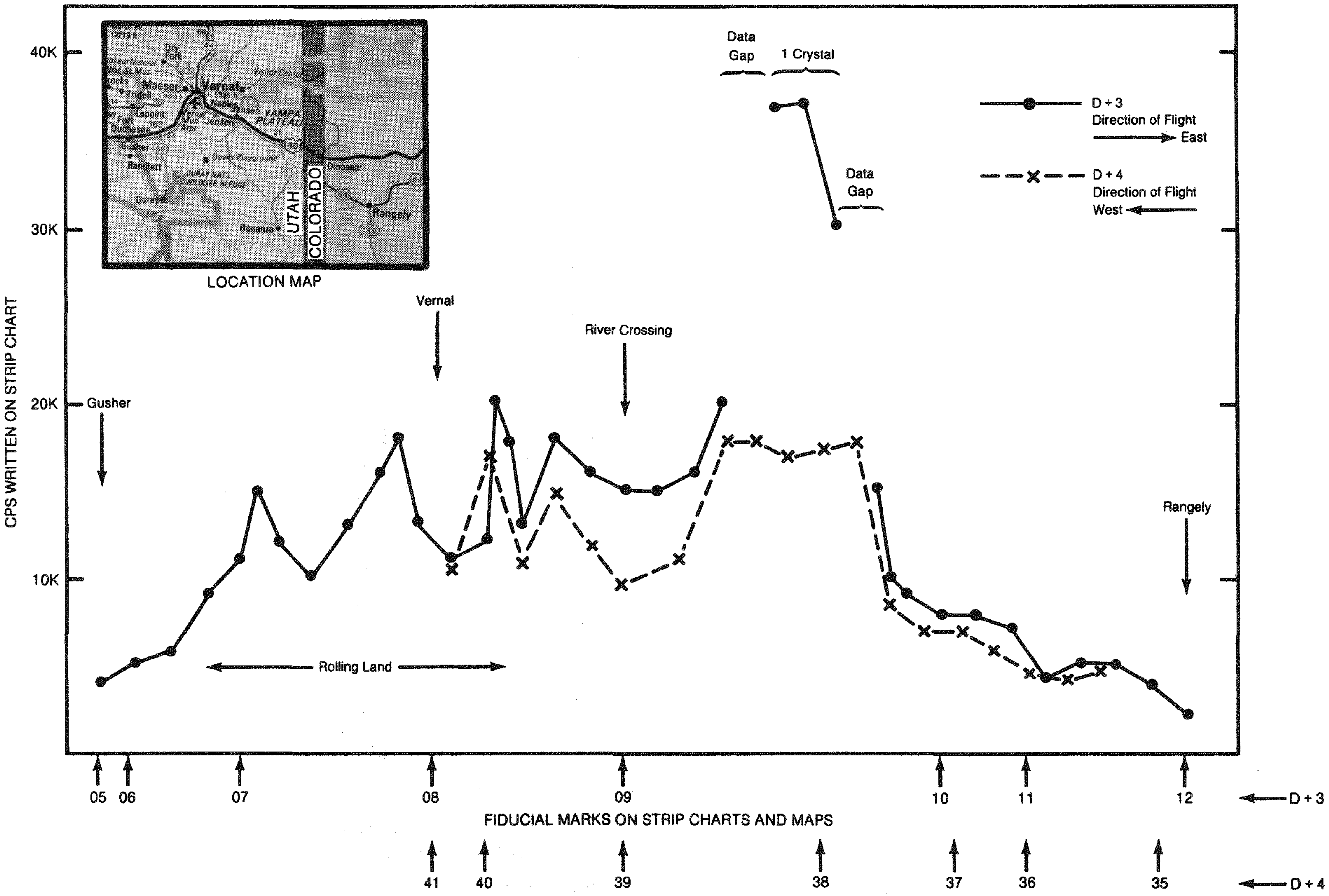


FIGURE 27. ***AERIAL SURVEY DATA, D + 3 AND D + 4, SHOT SMOKY, NORTHERN UTAH AND COLORADO***

It is also noted that the words "rolling land" were written on the strip chart for several miles on either side of Vernal. The peaks in the aerial survey data in this area are probably caused by altitude variations due to this rolling terrain.

Figure 28 shows the results of an aerial survey on D+4 in southern Wyoming. The fallout pattern had included an area of enhanced radiation near Rock Springs, derived directly from the aerial data. Note that on both sides of Rock Springs the single crystal was used. Assuming the single crystal was reading 35% too high, as indicated by Figure 27, the maximum reading would be 30,000 cps rather than the 45,000 cps that produced the high radiation levels.

5.3 Small Boy Event (1962)

Aerial surveys by the ARMS II aircraft were made of the fallout patterns from the Small Boy test on D+1 through D+5. An area of enhanced radiation east of Provo, Utah was found by the aerial surveys. The exposure rates reached an equivalent H+24 hour radiation level of 4 mR/h using a conversion factor of 50,000 cps at 500 ft equals 1 mR/h 3 ft above the ground. These results, taken directly from Reference 16, are given in Figure 29.

Raw data from the ARMS II surveys during the 1960s were not available for examination. However, using the suggested conversion factor of 79,000 cps given in Section 4, the area of enhanced radiation shown in Figure 29 was redrawn as presented in Figure 30. Note that the highest equivalent H+24 hour exposure rate was reduced to 2.5 mR/h. The inside patterns were also redrawn. Since there were no ground-based readings between the aerial survey lines, it did not seem appropriate to the author to disconnect the higher radiation level contours. The results in Figure 30 are given in H+24 hour exposure rates, rather than H+12 hour exposure rates, so that the original ARMS II data as presented in Figure 29 can be compared.

Quinn et al.[37] reviewed all the Small Boy data recently and found ground-based measurements to be consistent with the revised aerial survey results as presented in Figure 30.

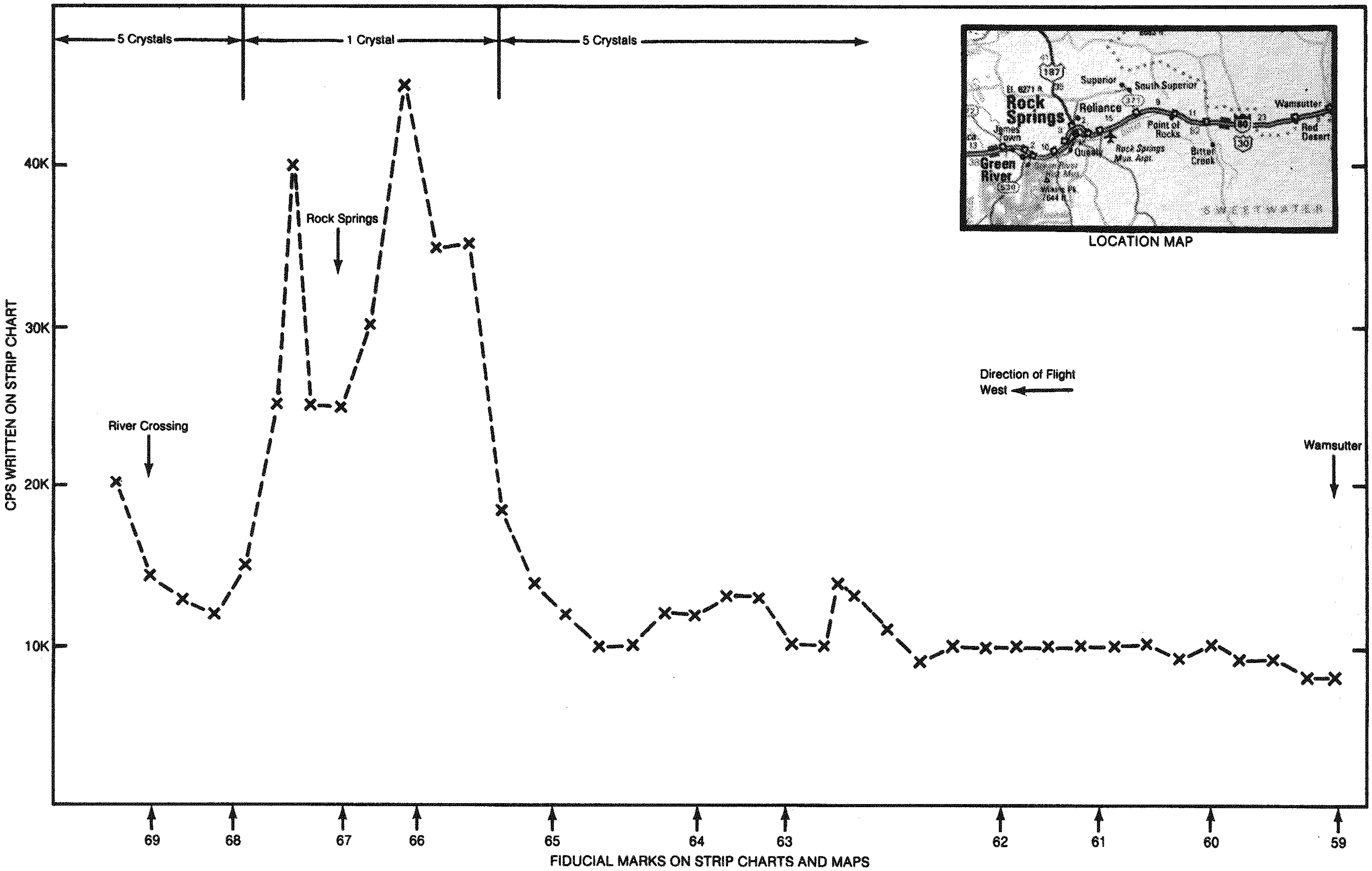


FIGURE 28. ***AERIAL SURVEY DATA, D + 4, SHOT SMOKY, SOUTHERN WYOMING***

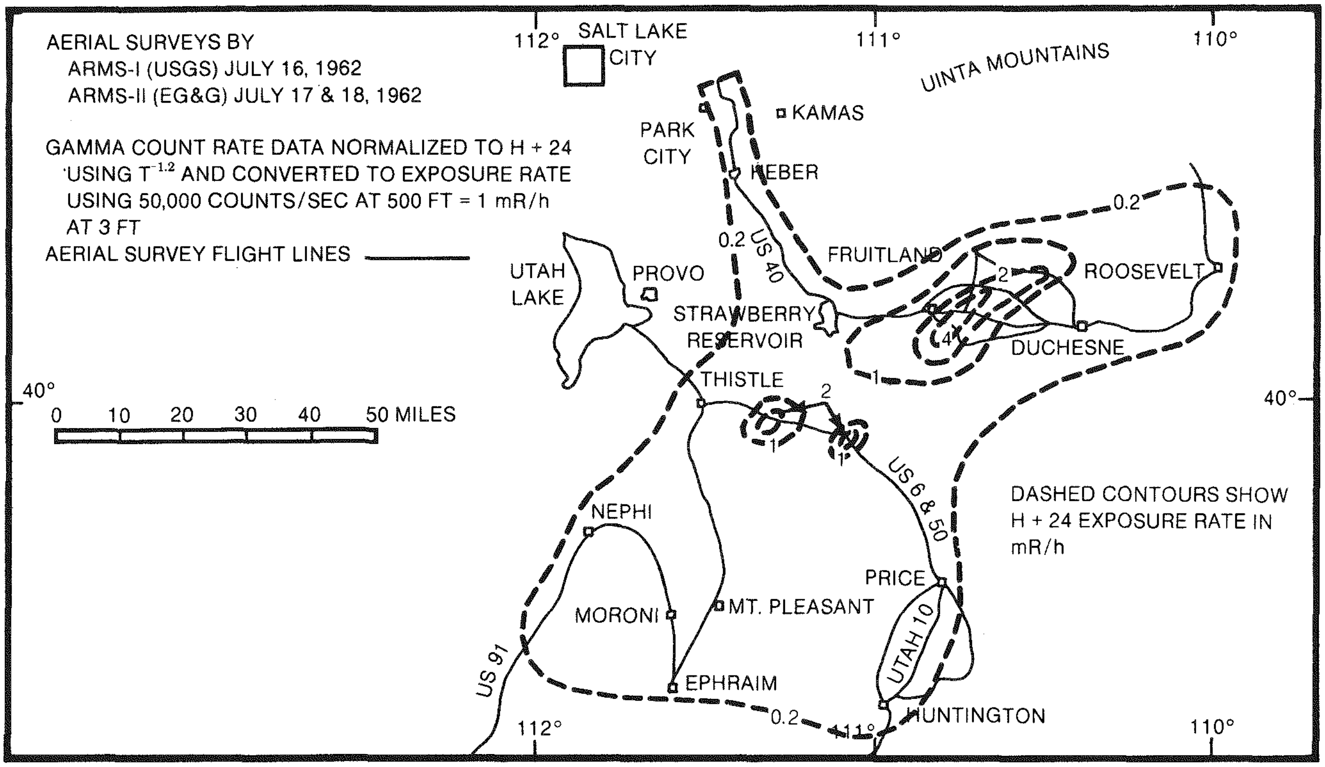


FIGURE 29. ***FALLOUT PATTERN IN FRUITLAND AREA, SMALL BOY TEST. (Taken directly from Reference 16, redrawn for clarity)***

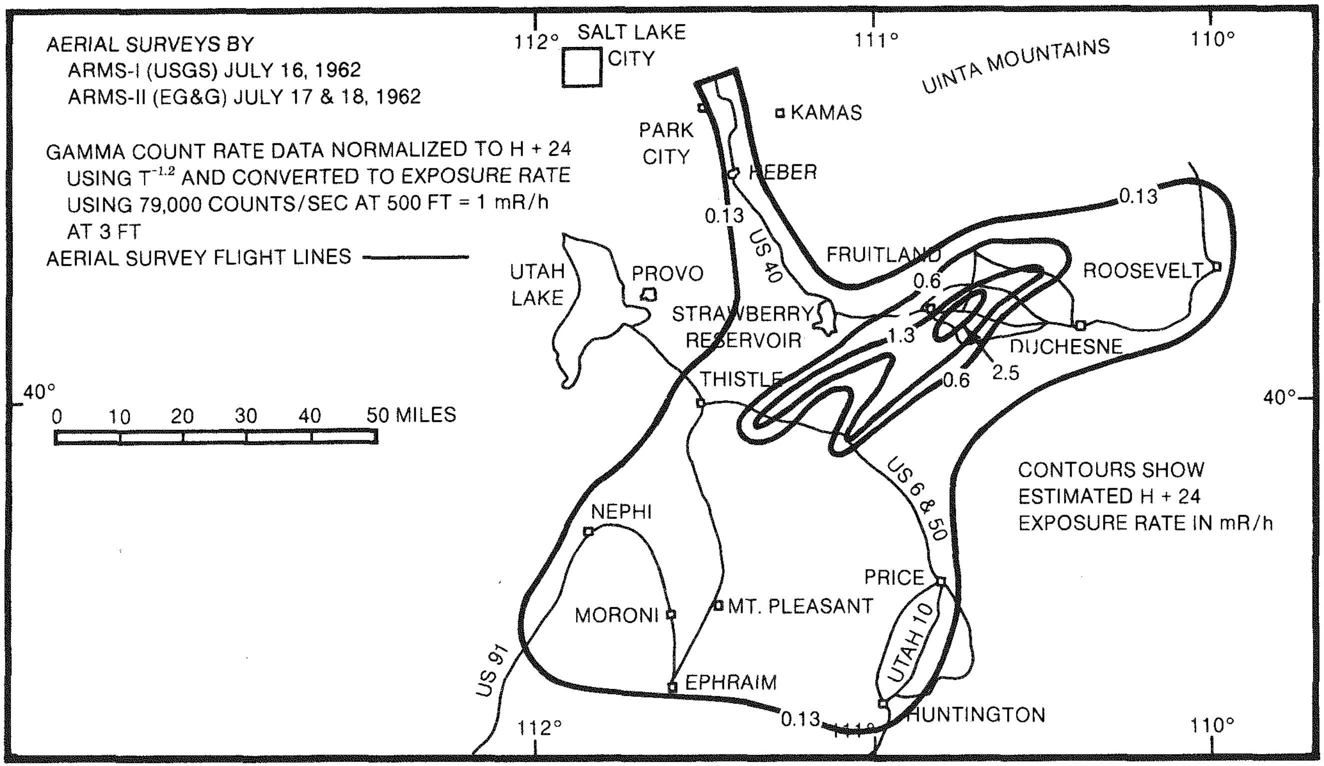


FIGURE 30. ***REVISED FALLOUT PATTERN IN FRUITLAND AREA, SMALL BOY TEST. (Revised 1984)***

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A review was made of aerial surveys of terrain radiation produced by the NTS fallout fields during the period 1951 through 1970. The purpose was to evaluate the usefulness of the results in light of today's aerial survey technology and to make recommendations of how best to use the results in reevaluating or reassessing the original fallout patterns.

The data from aerial surveys were used from 1953 through 1970 to assist in estimating the offsite fallout radiation patterns. In general, the aerial survey results were used to support the ground data, not vice versa. However, no evidence was found in the literature of total rejection of aerial data for any purpose except where it was too low to be meaningful or where the aircraft position was in error.

6.1 1953 - Operation UPSHOT-KNOTHOLE

Operation UPSHOT-KNOTHOLE was the first test series in which aerial surveys were used for offsite terrain radiation assessment. The primary purpose was to assist in defining the location and direction of the hot line. The aerial data were not routinely added to ground-based readings to define the fallout patterns. The aerial survey techniques, developed in 1951 and 1952 by the Military, continued to be used in 1953. Surveys were made at a 500-ft altitude using survey meter-type instruments—the MX-5, the T1B, and a Scintelog.

The T1B readings in aircraft of 1 mR/h or less were not considered reliable. The resulting radiation levels at 3 ft (about 10 mR/h) are, therefore, not reliable. The uncertainty, however, is on the high side. That is, the values at 3 ft are not likely to be higher than those predicted from the aerial survey data.

If the T1B readings in aircraft were above 1 mR/h and if the altitude was less than 1000 ft, the converted radiation levels at 3 ft (above 10 mR/h) are considered reliable, probably within a factor of two or three.

Better predictions may be made by using the Scintelog results and a factor of 25 for air-to-ground conversions. Empirical derivation of air-to-ground conversion factors for each event in the UPSHOT-KNOTHOLE series is recommended.

The primary problem encountered during the aerial surveys, however, was aircraft location. Navigation was made from aeronautical charts scaled at 1:1,000,000, making terrain features difficult to interpret. Grid intersections were 8 to 10 miles apart. The hot line areas of highest radiation readings were many times only two to three miles wide. The conclusion reached by the author after examining the data is that the designated locations could be in error by many miles.

Predicted data at 3 ft (above 10 to 40 mR/h at H+12 hours), however, are still valid, even though the aircraft's location was uncertain. There are no data points predicted from aerial surveys that show radiation levels greater than those obtained from ground surveys along the hot line.

6.2 1955 - Operation TEAPOT

During Operation TEAPOT the aerial radiological surveys of the fallout fields were conducted by the Military at 300 to 500 ft above the ground using AN/PDR-27C and AN/PDR-29 survey instruments in C-47 aircraft. Very little information could be found in the literature as to raw data, calibration, operational techniques, uncertainties, or applications.

Conclusions and recommendations given for the UPSHOT-KNOTHOLE series are applicable to the TEAPOT series.

6.3 1957 - Operation PLUMBBOB

By 1957 great improvements had been made in aerial survey techniques for uranium prospecting. The success of these techniques led to the full use of the United States Geological Survey (USGS) aircraft (DC-3) for 11 tests of the PLUMBBOB series.

Errors and uncertainties due to aircraft altitudes and positions were greatly reduced by reliable radioaltimeters and by indicating known locations on strip charts recording the radiation data. Some uncertainties still remained in air-to-ground conversions.

Radiation surveys were made at 500 ± 25 ft above the ground using one of two systems: (1) an array of five NaI(Tl) crystals, 4 in. in diameter and 1 in. thick; or (2) a single NaI(Tl) crystal, 1.5 in. in diameter and 1 in. thick. The two sets of crystals were used interchangeably, depending upon the intensity of radiation measured.

For the five-crystal array, a conversion factor of 50,000 cps at a 500-ft altitude equals 1 mR/h at 3 ft above the ground is a good value to use, in general, for all events in the PLUMBBOB series. If sufficient and valid aerial and corresponding ground data can be located, an empirically determined conversion factor for each event would be more appropriate. If not, a value of 50,000 is recommended. The resulting predicted 3-ft exposure rates should then be reliable to an uncertainty of ±40% or better for most of the surveys.

A greater uncertainty exists in the results of the single-crystal measurements. All the data from the single crystal were given as equivalent five-crystal array results on the strip charts. These results can be divided by 50,000 to obtain exposure rates in mR/h 3 ft above the ground. Nothing could be found in the literature on the ratio of single-to-five crystal count rates other than what was written on the strip charts. The results derived from the single crystal are not likely to be reliable to better than a factor of two.

During Operation PLUMBBOB assistance for delineation of areas of enhanced deposition was provided by the AEC's RMD aircraft, which also used sodium iodide crystals. The survey's primary mission was to define the pattern edges of anomalies to give direction to ground survey teams, not to obtain quantitative data.

6.4 1958 - Operation HARDTACK II

The amount of offsite fallout from Operation HARDTACK II was small compared to Operation PLUMBBOB. The USGS aerial survey capability was available, if needed. However, since offsite fallout radiation levels were near background, no formal reports were written.

6.5 1961 THROUGH 1970

Most of the aerial radiological surveys in the 1960s were performed by ARMS I and II, outgrowths of the USGS system. Sodium iodide detectors continued to be used. Gamma spectral measurements were added to the ARMS II capabilities.

Air-to-ground conversion factors remained the primary uncertainty in aerial surveys throughout the 1960s. During this time period, many different air-to-ground conversion factors were used. A conversion factor of 50,000 cps at 500 ft equals 1 mR/h 3 ft above the ground for the ARMS II 9-in. by 3-in. detector was used for surveys of the Danny Boy, Sedan, and Small Boy events in 1962. For the Pike event, March 1964, and the Sturgeon event, April 1964, a value of 25,000 cps was used.

A special review of the conversion factors relating to this period is presented in Section 4.5. The review indicated that the conversion factor used (50,000 cps) was too low. It is recommended by the author that a conversion factor of 79,000 cps/mR/h be applied to all aerial survey results for Small Boy. This revised conversion factor produces results consistent with ground-based measurements.[37] All converted 3-ft exposure rates currently in the Small Boy reports should be divided by a factor of 1.58.

This same conversion factor (79,000 cps/mR/h) should also be applied to the remainder of the ARMS II data for 1961 through 1967. From 1968 through 1971, when ARMS II used the 14-crystal detector array of 4-in. by 4-in. crystals, a conversion factor of 460,000 cps is recommended to convert count rates at 300-ft altitude to exposure rates 3 ft above the ground. If these values are used, the resultant 3-ft exposure rates should be valid to ±40% in most fallout fields if all other parameters are accounted for. For specific fallout fields where many aerial and ground data points are given, an empirical value could be derived that may be more accurate.

REFERENCES

1. Davis, F.J. and P.D. Reinhardt, 1957. "Instrumentation in Aircraft for Radiation Measurements," *Nuclear Science and Engineering*, 2:713-727.

2. Operation UPSHOT-KNOTHOLE Project 6.10. *Evaluation of Rapid Aerial Radiological Safety Operation.* Report No. WT-758.

3. Gwynn, P.S., Lt. Colonel, USAF, December 1952. *Operation TUMBLER-SNAPPER, Radiological Safety, Report to the Test Director.* Report No. WT-558 (Del).

4. Operation UPSHOT-KNOTHOLE. *Radiological Safety Operation.* Report No. WT-702(REF).

5. Grayson, R., June 27, 1984. Personal communication, U.S. Department of Energy, Environmental Measurement Laboratory.

6. Steadman, C.R., Jr.; N.C. Kennedy; and V.E. Quinn, July 1984. *Analysis of Operation UPSHOT-KNOTHOLE Nuclear Test Nancy Radiological and Meteorological Data.* Report No. NVO-282.

7. Operation TEAPOT. *Technical Air Operation*. Report No. WT-1206 (EX).

8. Operation TEAPOT. *Civil Defense Monitoring Techniques*. Report No. WT-1164.

9. Operation PLUMBBOB. *Aerial Monitoring Operations Development*. Report No. WT-1485.

10. Edgerton, Germeshausen and Grier, Inc., May 1967. *Sedan Project 62.80c Aeroradioactivity Survey*. Report No. CEX-62.80c.

11. Operation PLUMBBOB, *Projects 37.1, 37.2, 37.2a, 37.3 and 37.6 Distribution, Characteristics, and Biotic Availability of Fallout, Operation PLUMBBOB*. Report No. WT-1488.

12. Larson, K.H., November 27, 1984. Personal communication, Larson to Burson.

13. Merian, R.F.; J.G. Lackey; and J.E. Hand, February 1961. *Aerial Radiological Monitoring System I. Theoretical Analysis, Design and Operation of a Revised System*. Report No. CEX-59.4.

14. Davis, F.J. and P.W. Reinhardt, Eds., 1962. *Extended- and Point-Source Radiometric Program*. Report No. CEX-60.3. Oak Ridge National Laboratory.

15. Anderson, C.N., et al., December 1969. *Aerial Radiological Measuring Surveys (ARMS) Systems and Procedures Employed Through FY 69*. Report No. EGG-1183-1457.

16. Edgerton, Germeshausen and Grier, Inc., May 1967. *Small Boy Project 62.80b Aeroradioactivity Survey*. Report No. CEX-62.80b.

17. Beers, R.H. et al., September 1983. *Airborne Cloud Tracking Measurements During the Three Mile Island Nuclear Station Accident*. Report No. EGG-10282-1009.

18. Trundle, A.S. III, and E.J. Story, October 1967. *Aerial Radiological Measuring System, Part IV, Equipment and Procedures Through Fiscal Year 1966*. Report No. CEX-59.4.

REFERENCES (Continued)

19. Story, E.J.; A.S. Trundle, III; and D.H. Bundy, December 1966. *Nevada Aerial Tracking System (NATS) Procedures and Equipment Employed Through FY 1966*. Report No. EGG-1183-1288.

20. *Aerial Radiological Measuring System (ARMS) Systems and Procedures Employed Through FY 71*. August 1973. Report No. EGG-1183-1526. EG&G, Inc.

21. Meuschke, J., March 2, 1983. Personal communication, Meuschke to Nutley, R., DOE.

22. Spencer, L.V., June 1, 1962. *Structure Shielding Against Fallout Radiation from Nuclear Weapons*. NBS Monograph 42, National Bureau of Standards.

23. Boyns, P.K., January 1984. *An Aerial Radiological Survey of the Oak Ridge Reservation, Date of Survey: June 1980*. Report No. EGG-10282-1001.

24. Fritzsche, A.E., 1983. Personal communication, EG&G/EM.

25. French, R.L., May 1, 1964. *Gamma-Ray Energies and Angular Distributions Above an Infinite Fallout Field*. Report No. RRA-T43.

26. O'Dell, A.A., July 15 1971. Personal communication, O'Dell to Burson.

27. Operation UPSHOT-KNOTHOLE, *Radiological Safety Operations*. Report No. WT-817.

28. Steadman, C.R., Jr.; N.C. Kennedy; and V.E. Quinn, March 1984. *Analysis of Operation PLUMBBOB Nuclear Test Smoky Aerial Radiological Data*. Report No. NVO-275.

29. Steadman, C.R., Jr.; N.C. Kennedy; and V.E. Quinn, September 1983. *Analysis of Operation PLUMBBOB Nuclear Test Boltzmann Radiological and Meteorological Data*. Report No. NVO-260.

30. Williams, D.; R.S. Cambray; and S.C. Maskell, 1959. *An Airborne Radiometric Survey of the Windscale Area, October 19-22, 1957*. Report No. AERE-R2890. Atomic Energy Research Establishment, Harwell, England.

31. Hand, J., September 26, 1962. *ARMS-II Count Rate to Dose Rate Conversion*. S-217-R, unpublished EG&G data.

32. Huddleston, C.M., et al., 1964. *Ground Roughness Effects on the Energy and Angular Distribution of Gamma Radiation from Fallout*. Report No. CEX-62.81 (Final). EG&G, Inc.

33. Burson, Z.G. et al., 1972. *Technical Procedures for Characterizing the Terrestrial Gamma Radiation Environment by Aerial Surveys*. Report No. EGG-1183-1559. EG&G, Inc.

34. Artuso, J.F., September 1982. *Comparison of Exposure Rates Derived by Pulse Height Conversion with those Measured with an Ionization Chamber*. Report No. EGG-1183-2457. EG&G Energy Measurements Group.

35. Clark, H.W., 1983. Personal communication, EG&G/EM.

REFERENCES (Concluded)

36. Steadman, C.R., Jr., 1983. Personal communication, NOAA/WSNSO.

37. Quinn, V.E.; N.C. Kennedy; and C.R. Steadman, August 1984. *Analysis of Operation DOMINIC II Small Boy Radiological and Meteorological Data*. Report No. NVO-285 U.S. Department of Energy.

38. Quinn, V.E., April 1986. *Analysis of Operation UPSHOT-KNOTHOLE Nuclear Test Badger Radiological and Meterological Data*. Report No. NVO-299, U.S. Department of Energy.

39. Steadman, C.R., Jr., 1987. Personal communication, NOAA/WSNSO.

40. Petty, A.J., August 28, 1957. Personal communication, Office Memorandum, Petty to K.H. Larson.