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Technical Basis for Dose Reconstruction[*]

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The purpose of this paper is to consider two general topics: Technical considerations of why dose-reconstruction studies should or should not be performed and methods of dose reconstruction. The first topic is of general and growing interest as the number of dose-reconstruction studies increases, and one asks the question whether it is necessary to perform a dose reconstruction for virtually every site at which, for example, the Department of Energy (DOE) has operated a nuclear-related facility. And there is the broader question of how one might logically draw the line at performing or not performing dose-reconstruction (radiological and chemical) studies for virtually every industrial complex in the entire country.

The second question is also of general interest. There is no single correct way to perform a dose-reconstruction study, and it is important not to follow blindly a single method[†] to the point that cheaper, faster, more accurate, and more transparent[‡] methods might not be developed and applied.

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[†] Even the recommendations of a presumably knowledgeable committee assembled by the National Research Council (1995) seem to convey a message of, "Let's keep on doing things the way we do now."

[‡] A method is transparent if it can be explained to the general public without invoking an oftentimes unwarranted leap of faith; such a quantity is important to credibility. A statement that "Model X was used," is completely non-transparent.

History of Dose-Reconstruction Studies at DOE Facilities in the United States

A brief history[§] of major radiation-related dose-reconstruction studies at DOE sties in the United States is provided in Table 1. Much early activity was related to the Nevada Test Site (NTS) (Church et al. 1990), where nuclear weapons were tested in the atmosphere from 1951 through 1958. This dose-reconstruction study for the nearby states was undertaken and performed by the DOE itself. The next site of major interest was the Hanford Works (plutonium production and separation), after it was revealed in 1986 that large quantities of radioiodine had been released during the early years of the plant's operation (see Cate et al. 1990). This study was begun by the DOE, but authority and responsibility for it were transferred to the Centers for Disease Control and Prevention (CDC) (Miller et al. 1994). After these beginnings, dose reconstructions became quite fashionable. The dose-reconstruction study at the Fernald Feed Materials Production Center (uranium processing) was begun by the CDC at the request of the U.S. Congress (Miller et al. 1994), as was the National Cancer Institute's study of thyroid dose to the entire country from testing of nuclear weapons at the NTS (Wachholz 1990).

Studies at the Rocky Flats Plant (plutonium machine shop), the Oak Ridge Site (three major facilities, including a gaseous diffusion plant for uranium

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[§] Of course, the first major dose-reconstruction study was that undertaken for the survivors of the atomic bombings in Japan. These reconstructed doses have moved in stepwise fashion from the Tentative 1957 Doses (Arakawa 1960; Auxier 1977) to the Tentative 1965 Doses (Milton and Shohoji 1968; Auxier 1982) to the Dosimetry System 1986 (Roesch 1987). The last major revision occurred only after it was overwhelmingly apparent that the T65 Doses contained major discrepancies (Loewe and Mendelsohn 1981). Unfortunately, there are still major unresolved questions about the neutron doses to the survivors in Hiroshima (Straume et al. 1992). There is, perhaps, no better illustration of the pitfalls of conducting an epidemiologic study with major devotion to developing data for the dependent variable and only grudging attention given to defining data for the independent variable.

enrichment and a facility for the production and fabrication of parts for weapons), and the Idaho National Engineering Laboratory (reactor research and development; chemical processing to recover highly enriched uranium) have been undertaken at the request of the states; the studies at Rocky Flats and Oak Ridge are actually being directed by the States of Colorado and Tennessee, respectively (Miller et al. 1994). Studies at the Idaho National Engineering Laboratory and the Savannah River Site (plutonium and tritium production and separation) are being conducted by the CDC at the request of the DOE (Miller et al. 1994).

An open question is how many more dose-reconstruction studies might be undertaken in the future and whether such studies are really needed or useful. Completed dose-reconstruction studies have been expensive. The NTS and the Hanford studies have cost a few tens of millions of dollars each.

Reasons for Undertaking a Dose-Reconstruction Study

Some of the reasons for undertaking a dose-reconstruction study are indicated in Table 2. The most compelling reason is that there have been large releases of radionuclides that can be presumed to have had some biologic effect. This was clearly the case with the NTS, where more than 100 tests of nuclear weapons devices were conducted in the atmosphere with a cumulative yield of approximately 1 Mt (Church et al. 1990). Another emotionally compelling reason is the revelation of formerly classified data that indicates a substantial release of radionuclides took place, but without knowledge of the public concerned. This was the case with the Hanford Works (see Cate et al. 1990), where it was revealed in 1986 that large quantities of ^{131}I had been released. Much of these releases occurred during 1945, when the early production runs of Pu were being done under great time pressure and without prior experience. A particularly troublesome revelation was that one significant (but minor compared to those earlier) release occurred in 1962 as part of a "controlled-release experiment" (Heeb 1994). As far as is known to the author, the reason for this deliberate release has not yet been revealed to the public.

Other reasons for undertaking a dose reconstruction pertain to social justice. It is not at all uncommon to find that the public living in the vicinity of an atomic or industrial plant (or other source of emissions) believes that it has been harmed by the emissions from the plant. Such beliefs can be profound and can be greatly enhanced if the public also feels that it has been *wronged* by the withholding of information. In such cases the desire or demand for social justice may compel a dose-reconstruction and an epidemiologic study by investigators independent of those responsible for the emissions.

Another reason for undertaking a dose-reconstruction study is as a precursor for an epidemiologic study. That is, a dose-reconstruction study might be undertaken solely as a means of providing the independent variable for a study of risk factors. This does not seem to be a very persuasive reason by and of itself, although one attendee at a recent workshop (see NRC 1995) asserted that this is the only reason that could justify a dose-reconstruction study. However, except in rare circumstances such as the Chernobyl accident (Balonov 1995) or emissions from the Mayak Industrial Association (Degteva 1995; Kossenko 1995), it seems unlikely that there has been or will be sufficient collective dose to provide a meaningful study of radiogenic risk factors.

Finally, there are many of us who simply love the challenge of dose reconstruction, particularly for those cases that seem to be intractable. This is not offered as a justification for the undertaking of a major study, but many scientific studies have been conducted solely because someone *wanted* to do them. This, of course, is not at all unusual in science; the only compelling need is to find someone who can supply the funds.

A Case History for the Nevada Test Site Studies

As mentioned above, the Nevada Test Site was the subject of the first modern dose-reconstruction study. In addition, all of the planned epidemiologic studies have now been completed and published (Stevens et al. 1990; Kerber et al. 1993). Thus, consideration of the NTS as a case study offers a unique opportunity to assess what has been learned and what might be used as a guide for the future.

A commitment to conduct the NTS dose-reconstruction study was made by the DOE in 1979 (DAAG 1987). This followed a long-simmering public unease about the possible health effects of these NTS tests,[**] other tests by the U.S. in the Pacific, and tests conducted by the USSR. Peaks of concern were noted in the late 1950s and the early 1960s when Congressional Hearings (U.S. Congress 1957, 1959, 1963) were

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[**] Atmospheric tests were stopped at the NTS in 1958, but several other shallowly buried tests or experiments not designed for containment were conducted. The last such experiment was Schooner in 1968. The last major, unplanned release resulted from Baneberry in 1970. A list of all U.S. tests conducted at the NTS and at other locations is provided in DOE (1994).

held. The Limited Test Ban Treaty signed in 1963 resulted in the relaxing of much immediate concern about the health effects from current tests in the Pacific, but specific concerns about the past tests in Nevada resurfaced in the late 1970s. An underlying cause was the controversy surrounding reports that low doses of radiation might be implicated in increases of cancer incidence in workers at the Hanford Works (Mancuso et al. 1977) and at the Portsmouth Naval Shipyard (Najarian and Colton 1978). More specifically, the report in 1976 of a case of leukemia in a former military person who was present at the NTS during the Smoky test in 1957 led the Centers for Disease Control to start in 1977 an epidemiologic study[††] of military personnel present during the Smoky test (Caldwell et al. 1980, 1983). In February 1979 Lyon et al. (1979) published a paper that was widely viewed as indicating that there had been a radiogenic increase in leukemia[‡‡] in Utah children exposed to fallout. These reports led to several new Congressional Hearings (e.g., U.S. Congress 1979), demands from governors in the affected states for the release of all information on fallout, a report from Congress entitled "The Forgotten Guinea Pigs" (U.S. Congress 1980), the filing of thousands of claims, and

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[††] The preliminary report (Caldwell et al. 1980) found that nine cases of leukemia had occurred in 76% of those contacted of the 3,224 men exposed at Smoky, whereas 3.5 would have been expected. A later report (Caldwell et al. 1983) provided a more complete follow-up (95.5% contacted) of these men and a study of other cancers. The more complete results were 10 cases of leukemia with 4.0 expected. However, there were 112 cases of all neoplasms, whereas 117.5 were expected, and leukemia was the only site showing a statistically significant increase in incidence rate; these and other results led the authors to summarize that, "...the leukemia findings may be attributable either to chance, to factors other than radiation, or to some combination of risk factors possibly including radiation."

[‡‡] This paper actually reported that the mortality rate for childhood leukemia in "high fallout counties" was *lower* than that of the entire state for low exposure cohorts (1944–1950 and 1959–1975), but that it equaled the rate in the entire state for the high exposure cohort (defined as Utah residents under the age of 15 in 1951–1958). However, the mortality rates from all cancers for the high-exposure cohort in the "high fallout counties" actually *decreased by a factor of two* from that observed for the 1944–1950 low exposure cohort. It is also now clear that the Lyon et al. demarcation of high and low fallout counties was markedly wrong (Beck and Krey 1983; Beck and Anspaugh 1991).

eventually to two major law suits. In addition there were nagging concerns about the correctness of the external exposures (Dunning 1959) reported for surrounding communities from the NTS tests, and an evaluation of internal doses had not been done; the latter by itself was a problem that had led to considerable controversy (Knapp 1963; Mays 1963; Reiss 1963).

From the above it seems obvious that there was a compelling need to conduct a dose-reconstruction study for the NTS; a more realistic question is why it took so long for it to be initiated. The initial commitment made on 28 March 1979 was only "...to collect, preserve, and disseminate historical data related to radioactive fallout and health effects from nuclear testing." (DAAG 1987). A later commitment was made on 8 June 1979 "...for reconstructing, insofar as possible, estimates of the exposures to the off-site public from nuclear testing at the NTS, and the doses to these individuals resulting from the exposures." (DAAG 1987) This latter commitment was rather weak, as at that time there was no assurance that such a reconstruction could actually be accomplished. This dose-reconstruction study for the NTS became known as the Off-Site Radiation Exposure Review Project (ORERP).

The results of the ORERP dose-reconstruction study have now been widely published in a variety of articles, including more than ten in a special November 1990 issue of the journal *Health Physics*. Other results are still in press and some are in preparation.

Some of the key results of the ORERP and collaborative studies are as follows:

- The historical estimates of external exposure reported by Dunning (1959) were essentially correct (Beck and Krey 1983; Anspaugh and Church 1986; Anspaugh et al. 1990; Henderson and Smale 1992; Haskell et al. 1994).
- Some initial estimates of infant-thyroid dose from the ingestion of ^{131}I and other radioiodines for event Harry in 1953 were essentially correct (Anspaugh et al. 1990).
- Only for the thyroid did the internal dose exceed or even attain a substantial fraction of the dose from external exposure (Ng et al. 1990).
- The calculated collective whole body dose from external exposure was 10,000 person-Gy for the areas considered in the western U.S. (Henderson and Smale 1992).
- The collective thyroid dose from internal exposure for the same areas in the western U.S. was 140,000 thyroid-Gy (Whicker et al. in press).

With use of the intermediate results (Beck and Anspaugh 1991; Grossman and Thompson 1993; Thompson et al. 1994) of the ORERP dose-reconstruction study, investigators at the University of Utah have completed epidemiologic studies designed to look for the two outcomes judged to be more likely to be detected in the affected population. These two outcomes are leukemia and childhood-thyroid cancer.

The leukemia study (Stevens et al. 1990) used a population-based, case-control design. Both cases and controls were required to meet these criteria among others: 1) Been born before 1 November 1958 and 2) Died between 1 January 1952 and

31 December 1981 while a resident of Utah. There were 1177 cases of leukemia found to meet all criteria; one or more controls were matched by year of death, age, and sex to each case. The number of controls totaled 5330. Individual bone-marrow doses were calculated for each case and control (Simon et al. 1994). The median bone-marrow dose from fallout for all cases and controls was 3.2 mGy, which can be compared to the bone-marrow dose from natural background of 0.7 mGy y^{-1}. Data were examined in the form of conditional logistic regression analysis of odds ratios with dose. For all forms of leukemia combined, no significant effect was found. A significant association ($p = 0.005$)[§§] was found for a defined subgroup: Acute leukemias discovered from 1952–1963 among those individuals younger than 20 years at exposure. No significant associations were found for other subgroups.

The thyroid study (Kerber et al. 1993) examined a cohort originally defined in the late 1960s of 4818 children; 2687 of these children were enrolled in grades 5 through 12 in 1965–1970 in Washington County, Utah, and in Lincoln County, Nevada, two counties judged to be heavily impacted by fallout; the other 2131 children were of a similar age and lived in Graham County, Arizona, a county judged suitable for a control. Reports of the original study indicated that two carcinomas were found, one in Nevada and one in Arizona; evidence for any radiation effect on thyroid disease was judged to be statistically insignificant (Rallison et al. 1975). Some members (2579; limited to white non-Hispanics still living in the three-state area) of the original cohort were re-examined in 1985 and

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[§§] This association is based upon five cases of acute leukemia as shown in Table 3 of Stevens et al. (1990); also there were only 17 cases of leukemia (total except those with chronic lymphocytic leukemia) in the high dose group, all of whom resided in Washington County, Utah.

1986; interviews were also conducted of the parents of all but 53 subjects in order to provide input data for calculation of individual-thyroid doses for the subjects in all three states[***] (Till et al. 1995). A total of 2473 persons were included in the analysis of the data for the period prevalence of 1965 through 1986 (Kerber et al. 1993). There were 56 subjects with thyroid nodules, 19 with neoplasms (adenoma plus carcinoma), and eight with papillary carcinoma (no follicular carcinomas occurred among the analyzed subjects). A statistically significant positive dose-response trend was observed for neoplasms (p = 0.019), but not for thyroid nodules (p = 0.16) or for carcinomas (p = 0.096).

What can be generalized from the results of the NTS dose-reconstruction and epidemiologic studies? First, although the public and the U.S. Congress (1980) seem to have a rather opposite impression, it is very difficult to find an effect in the local population that might be attributed to the releases from the NTS. The results of the epidemiologic studies are plagued (or blessed) by a small number of cases, and any observed associations are weak or confined to smaller subgroups. On the other hand, the releases from the NTS were very large; some of the relevant numbers are summarized in Table 3. These results will be used later to derive some suggested boundary conditions for the conduct of dose-reconstruction and epidemiologic studies. However, one conclusion seems inescapable: If an effect cannot be demonstrated readily for the NTS, it is not likely that an effect will be demonstrated in the public at other DOE facilities.

[***] The "control" group in Arizona was not truly unexposed; individual doses for these subjects were calculated, also.

Intermediate Results for the Hanford Study

The Hanford Environmental Dose Reconstruction (HEDR) has also been completed. One supporting analysis is that of the amount of ^{131}I released from the site; this value is approximately 3 × 10^{16} Bq (Heeb 1994), about 200 times less than the amount released at the NTS. Unfortunately, the HEDR results (Farris et al. 1994a) do not provide an estimate of collective thyroid dose, but it is not likely to be higher than that from the NTS.[†††] Thus, although the follow-on Hanford Thyroid Disease Study (Davis 1995) was mandated by Congress, the possibility of statistically meaningful results is questionable. Once this study is completed, however, it will provide one more comparison point against which other proposed studies might be judged.

Methods of Dose Reconstruction

One observation from the NTS and HEDR studies is that such detailed studies are very expensive. The NTS epidemiologic studies were also very expensive and barely yielded results of statistical significance. Another point to be examined is whether much simpler methods might be employed to provide an approximate value of collective dose that might then be used to judge whether a detailed dose-reconstruction study or an epidemiologic study might be useful. As an aid to this discussion, methods of dose reconstruction are indicated in Table 4; an attempt has

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[†††] This comparison is not obvious. The releases from NTS were lofted to a high altitude by the explosions, so that some significant fraction of ^{131}I was carried beyond the analysis area. Also, the distances from the release point to the nearer populations were much shorter at Hanford.

been made to arrange the methods in an hierarchy of relative reliability. Unfortunately, the characteristic of reliability appears to scale directly with cost. Other considerations are important as well; some methods do not have sufficient sensitivity for application in many situations now being encountered.

The most satisfactory dose reconstruction would be based upon some measurement made on a biological sample drawn from every individual of concern. This is actually possible in some cases. For example, the measurement of stable translocations in chromosomes of circulating lymphocytes can be performed using the technique of chromosome painting (Lucas et al. 1995). This technique has a sensitivity of about 100 mGy, but is time consuming and expensive; to date the technique has only been used successfully in a small number of cases. Another technique that measures a sample of biologic material is electron paramagnetic resonance (EPR) analysis of dentine (Haskell et al. 1995). The EPR technique is now finding wide application to assess doses to liquidators of the Chernobyl accident, although the technique is subject to uncertainties that can result in significant errors. Many of these uncertainties will be resolved by future research and intercomparison studies. The application of the technique, however, requires the extraction of a tooth, and the EPR analysis is also time-consuming and expensive. A sensitivity of 100 mGy or less may be achievable routinely in the future.

If biologic samples can not be measured, the next line of choice might be (at least for external dose) to measure some natural dosimeter taken from the home environment of each individual. Thermoluminescence analysis of bricks, tiles, porcelain and other ceramic materials has been used very successfully for this purpose. One requirement is that the materials must have been fired to "zero" the dosimeter at some known time in the fairly recent past. The sensitivity of this method is around 50 mGy, and the method has provided very valuable input to the dose-reconstruction studies for the atomic bomb survivors (Maruyama et al. 1987), for the population nearby the NTS (Haskell et al. 1994), and for the population living downstream of the Mayak plutonium-production facility (Bougrov et al. 1995). Similar sensitivities and usefulness appear to be possible with optically stimulated luminescence of fired quartz (Godfrey-Smith and Haskell 1993) and of porcelain and its glazing (Poolton et al. 1995); this technique has yet to be applied widely, but it is simpler than that of thermoluminescence and may be more cost-effective under some conditions.

The analysis of environmental residues as a dosimetric tool is an old, well established technique that dates to the early studies of fallout and efforts to determine the resulting doses (e.g., UNSCEAR 1962). One of the major components of such studies was to measure for ^{90}Sr both the deposition rate through the use of a variety of collectors and the cumulative deposition through the analysis of samples of undisturbed soil. A major practitioner of these studies in the United States was the Atomic Energy Commission's (now the Department of Energy's) Health and Safety Laboratory [now the Environmental Measurements Laboratory (EML)].[‡‡‡] The data from EML were used extensively by the UNSCEAR (1982) in refining the dose estimates from global fallout.

[‡‡‡] Some of their work is summarized briefly in Hardy and Krey (1971).

One of the more significant events effecting the concern for dose reconstruction was the massive 1969 Pu fire at the Rocky Flats Plant.[§§§] Members of the Colorado Committee for Environmental Information (CCEI) did not believe assurances that no significant amounts of Pu had been released by this fire, and they collected and analyzed a series of soil samples from around the plant. Their results for about half of the samples were so provocative that they sent a preliminary report (Martell et al. 1970b) to the then Chairman of the Atomic Energy Commission, Glenn Seaborg. On the basis of their partial results, they estimated that, "...curies to tens of curies have been deposited in offsite areas." This was in marked contrast to the data from the Plant; their records indicated that only 42 mCi had been released through the stacks (Hammond 1971).

The expertise of the EML in collecting and analyzing soil samples was immediately brought to bear on this problem; their results (Krey and Hardy 1970) confirmed those of the CCEI; however, it eventually became clear that the Rocky Flats Plant numbers for releases through the stacks were essentially correct, also. The major point of release was determined to be not the stacks, but a large number of barrels used to store Pu-contaminated machine oil; these barrels corroded and leaked the contaminated oil onto the ground from where the Pu was dispersed by wind and man-caused disturbances (Hammond 1971; Poet and Martell 1972). The estimated inventory of Pu deposited off site was reported by Krey (1976) as 3.4 ± 0.9 Ci on the basis of soil-sampling and -analysis results.

[§§§] Generally contemporary information about the fire and other releases of Pu from the Rocky Flats Plant is provided in Hammond (1971) and Martell et al. (1970a).

These surprising results for the Pu contamination at the Rocky Flats Plant led to the extensive use of soil-sampling programs at other sites. Other off-site areas were found to have unexpected levels of Pu contamination, including the NTS (Anspaugh 1992) and the Mound Plant in Ohio (Rogers 1974). The finding for the NTS was not a particular surprise, but the result for the Mound Plant was. Again, the off-site Pu contamination was found to be the result of non-routine operations. In this case the cause was an unusual storm that washed contaminated soil away from an area where a leaking pipe used to transfer Pu in solution was being uncovered and repaired. The main point, however, is that the measurement of accumulated depositions in soil samples has proven to be an extremely useful tool not only in identifying unknown releases, but in quantifying the magnitude as well.

Sophisticated measurements (^{137}Cs deposition density, $^{239+240}$Pu deposition density, and the ratio of ^{240}Pu-to-^{239}Pu) of soil samples collected from Utah were also very useful in defining the deposition in Utah that had come from the NTS, even though the majority of ^{137}Cs and Pu had come from global fallout (Beck and Krey 1983). These same techniques were used more broadly in a multi-state area to define the contamination from the NTS (McArthur and Miller 1989), and the results became one of the primary inputs for the County Data Base (Beck and Anspaugh 1991).

Another closely related technique is the use of external gamma-exposure-rate measurements. Obviously, such exposure rates are derived from the radionuclides deposited on the ground, and, if the relative amounts of radionuclides are known, it is relatively straightforward to define the deposition densities of even hundreds of different radionuclides based upon a single measurement of exposure rate. Such exposure-rate data were routinely collected after every nuclear test at the NTS at nearby locations. These data were collected and preserved in a database (Grossman and Thompson 1993), which became the primary input for the Town Data Base (Thompson et al. 1994), which became in turn the primary input for the reconstruction of external and internal doses in the local area (Henderson and Smale 1990; Ng et al. 1990; Whicker et al. 1990). Data on the relative abundances were calculated based upon the content of fissile and other materials and on the spectrum of neutron energies (Hicks 1990). The other key data were the radionuclide-specific conversion factors for deposition density to external gamma-exposure rate; these values were calculated for more important radionuclides by Beck (1980).

These techniques have been found to have wide application. For example, following the Chernobyl event, it was possible to infer doses over very broad areas with the knowledge of the relative mixture of radionuclides released and either the deposition density of one or more radionuclides or the measured external gamma-exposure rate from radionuclides deposited on the ground (Anspaugh et al. 1988; UNSCEAR 1988).

The results calculated with the use of the last three methods listed in Table 4 become much more uncertain in many cases. The use of a computed source term and an atmospheric transport model was specifically rejected for the ORERP dose-reconstruction study in favor or the more direct and useful measurements that were available. Plans to use a meteorological model to derive ^{131}I-deposition densities for the study of radioiodine doses to the entire country were abandoned, because of the unreliable results (Hoecker and Machta 1990). Other studies performed as part of the ORERP found that it was not possible to reproduce fallout patterns with primary input data. However, it was found that meteorological models were useful tools in extending known patterns downwind (Cederwall and Peterson 1990). One reason for the failure of models of atmospheric transport in this case was the episodic and short-term nature of the releases.

On the other hand, when releases occur over long-time periods the ability of atmospheric transport models to provide accurate time-integrated values is much improved. Thus, the results from the HEDR, which depended almost entirely on defining the source term and then using an atmospheric transport model (Farris 1994a) should be reasonably accurate. There was also no other viable choice for the HEDR project. No environmental residues were left that could be used to define the trace of the only radionuclide of importance, ^{131}I. The source of the ^{131}I was known precisely, the release fractions were known (essentially 100% of the decay-corrected inventory during the early days), and it was possible to derive rather good estimates of the release rates (Heeb 1994).

If the release is not known or not readily knowable on the basis of the analysis of environmental residues, then the release must be inferred. Such inferences can be subject to very large errors, especially if large amounts of very long-lived materials are processed. As the results at the Rocky Flats Plant and the Mound Plant showed, the purported release data may not even account for the major releases that occurred.

Depending upon the purpose and the desired accuracy of the dose reconstruction, it may be preferable to dispense with an atmospheric transport model and to attempt a simple estimate of the collective dose from an inferred release. As a scoping calculation, this can be very useful. Such techniques have been discussed in WHO (1983)[****] and IAEA (1985); Cohen (1984) has also provided some useful general methods for this problem. Of course, it is not possible to estimate the dose to individuals.

An Example Calculation for the Rocky Flats Plant

After seemingly heroic attempts at defining the source term for the Rocky Flats Plant, it is this author's opinion that the results are still the same as those Martell et al. reported in 1970: That there were curies to tens of curies deposited in offsite areas. This number was stated to be 3.4 ± 0.9 Ci by Krey (1976). From WHO (1983) the effective dose equivalent per unit activity of ^{239}Pu released from nuclear installations to the air is 10^{-10} man-Sv Bq^{-1}. Thus, although the real release was essentially at ground level, we can estimate that the collective dose resulting from this release must have been about 10 man-Sv or less. Using an estimate of approximately 0.05 cancers Sv^{-1} (ICRP 1991), we can estimate that this might result in the probability of not even one fatal cancer.

The logical question is, why are we so concerned about Rocky Flats? Clearly, the social issues are dominating. In point of fact, there have been three public

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[****] The results in WHO (1983) are based on the long-term, detailed studies of the UNSCEAR, e.g., UNSCEAR (1976, 1982).

relations disasters at Rocky Flats. The first was the finding of Pu offsite by a local citizens' group, and not the Plant personnel. A second disaster, not mentioned previously, was the finding of a substantial release of tritium offsite in 1973 (Colorado Council 1993); again, this finding was not by the Plant personnel, but by the Colorado Department of Health.[††††] The final public relations disaster was the well publicized raid by the FBI and the EPA enforcement arm. The fact that the latter invasion found essentially nothing that they were seeking seems to have been forgotten. However, it is clear that the local public feels they have been wronged by the operators of the Plant, and there seems to be little choice but to perform extensive studies to reassure this public.

What Do We Know About Fernald?

The Feed Materials Production Center at Fernald, Ohio, is another production plant that processed very large amounts of stable material, in this case uranium. The Plant has also been the subject of substantial controversy and many lawsuits with the success of the plaintiffs' cases leading to law suits at virtually every similar facility in the country. There is also an ongoing dose-reconstruction study (Miller et al. 1994; Voillequé 1995), and there has been an extensive soil-sampling and analysis program (Stevenson and Hardy 1993). Both of these efforts have focused on the airborne release of uranium, although there are other problems of radon emissions and groundwater contamination by uranium (Hamilton et al. 1994).

[††††] Plant personnel actually had no reason to suspect that the tritium was onsite. The tritium was an unknown contaminant in material shipped to Rocky Flats by the Lawrence Livermore National Laboratory.

Fernald is of particular interest now, because of the enormous conflict that appears to exist between the results of the application of two of the methods of dose reconstruction indicated in Table 4. In reality, the conflict is narrowly confined to inferences of how large the source term was for uranium. The study of environmental residues has been reported by Stevenson and Hardy (1993) and is based upon the analysis of uranium in hundreds of soil samples collected in the near offsite area. Their average estimate of the material deposited in the offsite area is 2130 kg (1.4 Ci or 53 Gbq); their highest estimate is 6140 kg (4.1 Ci or 152 Gbq). On the other hand, the source term derived by Voillequé (1995) on the basis of examining plant-process records is stated to be 200,000 to 900,000 kg. This enormous difference might be explained by the bulk of the latter estimate having been retained within the plant boundary. If the material had actually gotten offsite, there is no reason to believe that it would not still be there.

Cohen (1984) estimates that the probability of human intake for material released to the air is 5×10^{-6} (inhalation) and 3×10^{-3} for release to the ground (ingestion); the dose-conversion factors for U are 2×10^{-6} (inhalation) and 6×10^{-9} Sv Bq^{-1} (ingestion) (Eckerman et al. 1988). The resulting calculation for collective effective dose equivalent is about 2 man-Sv. Again, it is reasonable to conclude that there is little scientific justification for either a dose-reconstruction or an epidemiologic study.

What Can We Learn from the Past?

Our experience in dose-reconstruction in the U.S. can be summarized rather briefly. First, the major studies have been very expensive, in the tens of millions of dollars. Second, even for the NTS, where the releases were large and the resulting collective doses were appreciable, it has been very difficult to find a statistically significant biologic effect. The results of the thyroid study at Hanford are not yet available, but it will be surprising if the results will be any more conclusive than those from the NTS study; this conclusion follows from the rather similar numbers for the size of the population and the doses involved (Davis et al. 1995). Third, for most of the other sites in the U.S. there is little reason to believe that releases or doses could be even remotely comparable to those from the NTS.

A recommendation might logically be made to set some boundary conditions on the results of scoping calculations (such as the examples indicated above) on individual doses and collective doses that might be used to determine whether a major study should be done or not. The author's suggested boundary conditions are

Collective effective dose	10,000 man-Sv
Dose to maximum individual	0.4 Sv

If either of these conditions should be exceeded, then a more detailed dose-reconstruction study might be warranted or of interest.

The exact boundary values, of course, are not so important. What is significant is that so many studies are now being undertaken with screening values orders of magnitude less than the above suggestions. If the social justice issues are compelling, then the studies might be done regardless of the screening values. A key question is whether communities will be satisfied with screening analyses. Another question for federal and state agencies is whether they will be willing to continue to fund major studies.

As a final point, it seems compelling that credibility of any dose-reconstruction study is a precious commodity. It is absolutely essential that any major dose-reconstruction study should receive rigorous peer review at all stages and should conclude with all major results published in the peer-reviewed scientific literature.

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Table 1. Major dose-reconstruction studies at DOE facilities in the United States.

Site	Object of assessment	Reference
	Completed	
Nevada Test Site	Hypothetical individuals	Henderson and Smale (1990)
		Ng et al. (1990)
		Bouville et al. (1990)
	Collective	Henderson and Smale (1992)
		Whicker et al. (in press)
	Specific individuals	Simon et al. (1995)
		Till et al. (1995)
Hanford Works	Hypothetical individuals	Farris et al. (1994a)
		Farris et al. (1994b)
	In process	
Fernald Feed Materials Production Center		Miller et al. (1994)
Rocky Flats Plant		Miller et al. (1994)
Oak Ridge Site		Miller et al. (1994)
Idaho National Engineering Laboratory		Miller et al. (1994)
Savannah River Site		Miller et al. (1994)

Table 2. Reasons why dose-reconstruction studies may be undertaken.

- Known large releases that can be presumed to have a biologic effect
- Stunning revelation of formerly classified data
    - Operational releases
    - Deliberate releases with public exposure
- Social justice
    - The public believes it has been harmed.
    - The public believes it has been wronged.
- To advance knowledge of risk factors
- "Because it's there."

Table 3. Characteristics of the releases from the Nevada Test Site.

Characteristic	Value
Number of atmospheric tests	>100
Approximate total yield	1×10^6 tonnes
Approximate energy release[a]	1×10^{15} cal
Fission-product atoms created[a]	3×10^{26}
Cesium-137 released[a]	6×10^{15} Bq
Iodine-131 released[a]	6×10^{18} Bq
Collective external dose[b]	1×10^4 Gy
Collective thyroid dose[c]	1×10^5 Gy

[a] These values follow from the 1 Mt total yield and conversions provided in Glasstone and Dolan (1977).
[b] From Henderson and Smale (1992)
[c] From Whicker et al. (in press)

Table 4. Methods of dose reconstruction.

- Individual biologic analysis
    - Chromosome translocation analysis of circulating lymphocytes
    - Electron paramagnetic analysis of teeth
- Dosimetry of materials in homes
- Analysis of environmental residues
    - Deposition densities, past or current
    - External gamma-exposure rates (past)
- Known releases, plus atmospheric models
- Inferred releases, plus atmospheric models
- Known or inferred releases