LA-UR- 99-2233

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Title:

SOURCE-TERM AND BUILDING-WAKE CONSEQUENCE MODELING FOR THE GODIVA IV REACTOR AT LOS ALAMOS NATIONAL LABORATORY

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Submitted to:
1999 Safety Analysis Workshop
June 13–18, 1999
Portland, OR

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Source-Term and Building-Wake Consequence Modeling for the GODIVA IV Reactor at Los Alamos National Laboratory

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ABSTRACT

The objectives of this work were to evaluate the consequences of a postulated accident to onsite security personnel stationed near the facility during operations of the Godiva IV critical assembly and to identify controls needed to protect these personnel in case of an extreme criticality excursion equivalent to the design-basis accident (DBA).

The Godiva IV critical assembly is located within the Kiva III facility at Technical Area 18 (TA-18) at Los Alamos National Laboratory. The TA-18 area is located in a canyon surrounded by complex terrain features such as a steep adjacent hillside and tall stands of fir trees. This analysis was motivated by the need to evaluate the air concentrations and radiological exposure consequences to onsite personnel (guards) located within 40–100 m of the facility. GODIVA IV is a highly enriched ^{235}U metal-fuel, fast-burst assembly. The DBA was defined to be a $1.40 pulse prompt critical, which leads to an approximate burst yield of 1.3 x 10^{18} fissions (or about 41.6 MJ). The DBA is postulated to lead to partial melt of the reactor assembly (approximately 10% of the fuel) with subsequent release of fission products to the environment.

Fission-product inventories were determined using the ORIGEN2 and FISSP computer codes using fast-neutron cross sections and assuming three consecutive pulses, each separated by 6 h to allow decay of delayed-neutron precursors. The first two pulses were assumed to be 2.2 MJ (7 x 10^{16} fissions), and the last one was assumed to be the limiting burst of 41.6 MJ. Fission-product inventories were characterized immediately after the limiting pulse and at logarithmically spaced times thereafter. Time-dependent source terms then were used to calculate the consequences to the onsite receptors.

Because of the complex terrain around the Kiva facility and the location of the onsite receptor(s) within the wake cavity of the building, it was decided that no existing dispersion code currently being used in the Department of Energy Complex was able to model the concentrations and consequences adequately. A commercially available computer code called FLOW-3D® was identified as a complex hydrodynamic flow model suitable for application to this situation. The FLOW-3D® code results were benchmarked against new building-wake models for the simple configuration of an isolated building in flat terrain.

This paper presents the methodology and results of the source-term calculations, building ventilation rates, air concentrations, and consequence calculations that were performed using a multidisciplinary approach with several phenomenology models. Identification of controls needed to mitigate the consequences to near-field receptors is discussed.

1.0 INTRODUCTION

Godiva IV is one of several critical assemblies operated by Los Alamos National Laboratory. It is located in the Kiva III facility at the TA-18 complex. Godiva is an enriched-uranium, metal-fuel, fast-burst assembly used by the Laboratory's nuclear weapons program as a neutron generator for instrument calibration and experimentation. Detailed descriptions of the Godiva IV critical assembly machine are given in the TA-18 Safety Analysis Report (SAR) [Ref.1], including its physical and neutronic characteristics.

Upgrades to the facility recently were made to allow security forces to be stationed in bunkers within the facility fence. Previously, security forces were stationed outside the facility fence. An Unresolved Safety Question Determination (USQD) regarding the proximity of the security personnel was submitted to the Department of Energy (DOE), which was later issued as a positive safety concern.

As part of the USQD, security upgrades were evaluated against the Limiting Event Scenario (LES) described in the SAR, which represents an extreme excursion from Godiva inside the Kiva III facility. This limiting event consists of full insertion of the yield-control element as a result of multiple human errors. This event was determined to lead to an accident with a reactivity insertion worth of about \$1.40, producing a burst of approximately 1.3×10^{18} fissions.

Specific concerns raised by DOE during the USQD review included the following.

- The doses at the PIDAS fence immediately outside the facility and the lack of controls in place to prevent security forces from leaving their bunkers and moving toward the facility PIDAS during critical-assembly operations
- The adequacy of the dose calculations at other locations (e.g., the bunkers and site boundary), including those from prompt-neutron radiation if the door is opened or damaged during the postulated accident scenario
- Concerns with the results of the unmitigated (parking lot scenario) dose at the PIDAS fence

The Nuclear Weapon Design Materials & Manufacturing Program Office tasked the Los Alamos Probabilistic Risk and Hazard Analysis Group (TSA-11) to independently evaluate the adequacy of the accident analysis for the limiting event presented by the authorization basis documentation, i.e., the SAR and USQD.

TSA-11 provided a multicomponent analysis [Ref. 2] of the evaluation-basis accident that consisted of

- ORIGEN [Ref. 3] calculations of fission-product generation,
- MELCOR [Ref. 4] calculations of the time-dependent leak rates from the Kiva,
- FLOW-3D® [Ref. 5] calculations of near-field (< 100 m) atmospheric dispersion, and
- MACCS2 [Ref. 6] calculations of far-field (>100 m) atmospheric dispersion and concentration.

The tools and methods used to model near-field atmospheric dispersion in the complex terrain surrounding the Godiva Kiva are the focus of this discussion. Our analysis represents one of the first practical applications of a three-dimensional (3D) turbulent fluid model to the traditionally difficult problem of near-field personnel dose assessment. This effort was complicated further by the time-dependent nature of the building release and of the rapidly decaying fission-product inventory. Post-processing utilities were developed to integrate the accident scenario components into an assessment of total internal and external radiation exposure.

2.0 APPROACH

2.1. Environmental Source Terms for Near-field Transport

ORIGEN calculations provided time-dependent inventories in curies of 605 isotopes, logarithmically spaced in time from 0 at the occurrence of the pulse out to 1.9 hours (6813 s). These isotopes were first tagged with a chemical group number and a damaged-fuel release fraction and then matched with their nuclear-decay half-lives. The total number of atoms at discharge, including the uranium metal assembly, was used as the basis for considering release fractions that composed the initial source internal to the Kiva.

Tables of ICRP-90 dose factors [Ref. 7] for inhalation and immersion in semi-infinite atmospheres of each nuclide were available for only 154 of the isotopes reported by ORIGEN. It was assumed explicitly that the health effects of the missing isotopes were negligible by eliminating them from the inventory. This approach relies on the completeness of the dose tables, which are essentially the same as those approved for use by the DOE in the MACCS2 dispersion model.

Two separate source terms were generated inside the building for the purpose of comparing conservatism. The first released 10% of all atoms and a chemically dependent fraction of the remainder following Regulatory Guides 3.33 [Ref. 8] and 3.34 [Ref. 9]. The second released 10% of all atoms and a fraction of the remainder following DOE-HDBK-3010 [Ref. 10]. Actual time-dependent behavior of the secondary release fraction, which would depend on the cooling rates of the metal matrix, was ignored; all atoms considered in the source were released to the room at the time of discharge. It is important to note that these source fractions were applied to the ORIGEN inventories at all decay time steps. This implicitly assumes that all daughter products have the same chemical behavior as their parents, so that at later times, the chemical groups are represented in the same proportion as in the initial mixture.

Following a facility walkdown and examination of as-built drawings, a MELCOR control-volume model of exfiltration pathways was constructed. This model included exhaust ventilation ducts, door-seal gaps, and instrumentation penetrations that allow material to be drawn from the building as a result of differential pressures induced by ambient winds. Because MELCOR calculations reported cumulative mass-fraction releases for noble gases and for particulate aerosols separately (see Fig. 1), the initial source described above was tracked out of the building in two components. Over any given time interval, the differential release fractions for noble gases and for aerosols was applied to the respective lists of isotopes existing at all ORIGEN evaluation times.

This procedure defines the number of atoms, and hence the activities, that are released during any time step representing a single discrete puff of the longer duration plume. Selection of an appropriate ORIGEN composition at the time of exposure then depends on the sum of the holdup time for the puff before the release and the transport time to the dose receptor. The sum of these times was always rounded to the nearest lower ORIGEN evaluation to apply the most conservative activity levels during exposure at each receptor location.

The FLOW-3D® model used to predict air concentrations has no capability for isotopic decay. Therefore, the time resolution between individual puffs must be high capture the transient nature of the fission-product source. FLOW-3D® was used to disperse a unit-concentration source of approximately 1-m^3 volume from in front of each HVAC outlet shown in Fig. 2. An appropriate temporal resolution for this unit puff is simply the time needed to fill the initial volume at a given steady-state volumetric exhaust rate that MELCOR computes for each wind condition of interest. For a 2-m/s easterly wind, the necessary time interval is approximately 7.7 s.

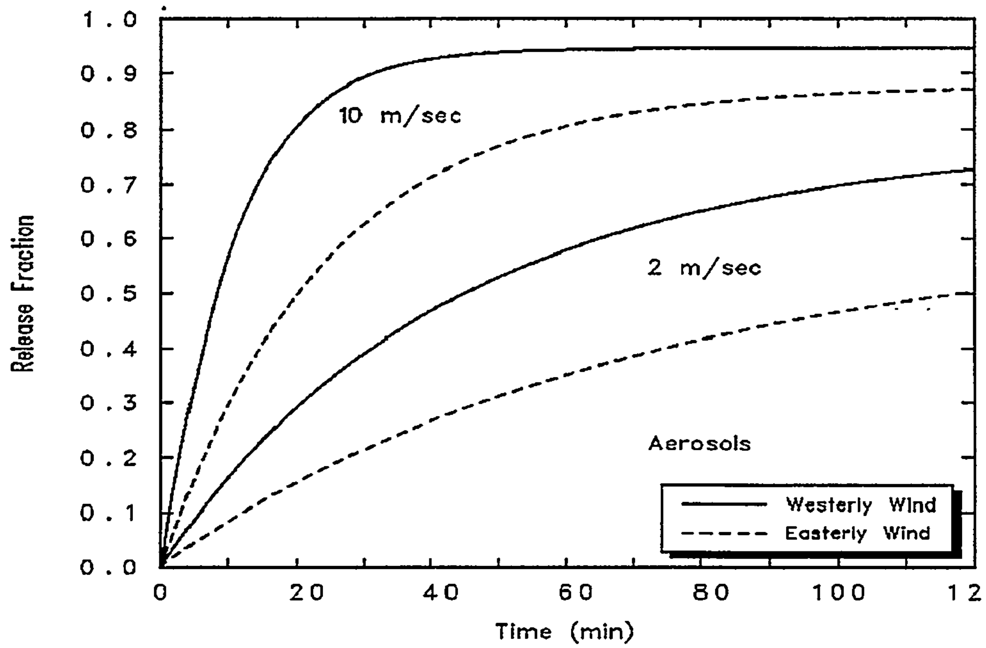

Fig. 1. Cumulative time-dependent leak-path factors from three HVAC vents for particulate aerosols under two conditions of incident wind speed and two conditions of incident direction.

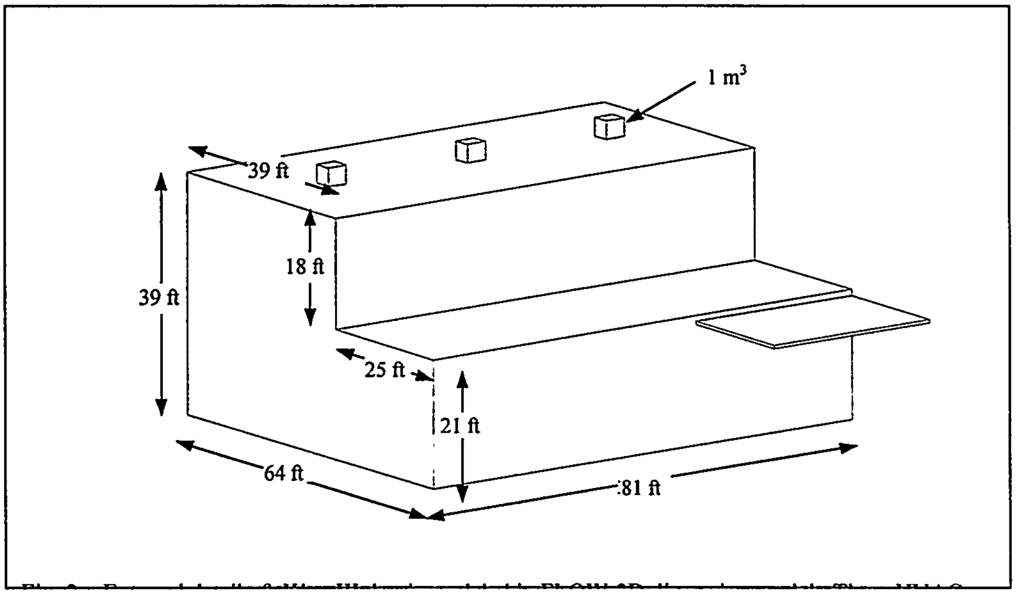

Fig. 2. External dimensions of Kiva III modeled in FLOW-3D® turbulent dispersion calculations. Three HVAC vents on top of the multilevel building provide primary release paths. A delivery shelter on the front perturbs the local wake.

2.2. Wind-Field Modeling Assumptions

To address the difficulties of atmospheric dispersion near large obstacles like the Godiva Kiva and the adjacent wall of a canyon, a computational fluid dynamics (CFD) model called FLOW-3D® was used to compute steady-state wind patterns and fission-product plume trajectories within 200 m. Although a great deal of fidelity may be built into a FLOW-3D® calculation, the results can become overly dependent on assumptions made for the boundary conditions. It is more appropriate that a problem be stylized using simplifying assumptions that preserve conservatism while retaining essential features.

This model focused on the location of the building adjacent to the steep wall of Pajarito Canyon. With the building center placed at the origin, the domain extends 213 m (700 ft) upwind and 213 m downwind along the canyon and 152 m (500 ft) out into an almost-flat drainage basin. The canyon wall rises 15 m (50 ft) over a 76-m (250-ft) run and features a slight depression that shelters the Kiva somewhat from prevailing winds blowing up and down the canyon. Spatial resolutions of less than 2 ft were maintained near the building, and computational mesh planes were forced near all major features of the building.

To conservatively eliminate dilution in an effective wake that is much larger than the building, a thick stand of trees immediately behind the Kiva was neglected. For similar reasons, all surfaces were treated as frictionless, no ground heating was introduced, and cold air conditions of 20 °F were assumed. Given a symmetry plane at a height of approximately 18 m that suppresses flow across the boundary, these conditions faithfully reproduce F-class stability with ground-level, night-time drainage flows.

Constant-velocity boundary conditions were enforced on each end of the domain, and symmetry planes were defined on the top and both sides. Steady-state turbulent wind fields were established by gradually increasing the boundary velocities to the desired magnitude and then monitoring the average turbulent kinetic energy (TKE) in the domain until minor oscillations had damped. Although building-release rates were available from MELCOR calculations for both easterly and westerly incidence, only the easterly (up canyon) wind fields were modeled. This choice was based primarily on the physical location of the postulated dose receptors, but it also incorporates the most geometric complexity of the Kiva into the downwind building wake.

Parametric dispersion calculations were performed by releasing unit-concentration tracer sources into the desired wind fields from each of three HVAC vents on top of the building. Each source had the initial geometry of a 1-m x 1-m x 1-m cube placed just in front of an outlet, but contributions from the three vents quickly merged into a single contiguous plume that followed the streamlines of the wind field.

FLOW-3D® computes time-dependent, instantaneous air concentrations for every cell in the domain. The durations of the dispersion calculations were extended until the bulk of the plumes, as estimated qualitatively by watching relative concentrations, had completely left the domain. Transport times of 10 min were sufficient for 2-m/s winds, and times of 5 min were adequate to track plumes released in 10-m/s winds. Data files of point concentrations on vertical cross sections of the plume were exported from FLOW-3D® for selected downwind locations at 1-s intervals for the first minute and at 10-s intervals thereafter.

2.3. Wind-Field Results

Figure 3 shows plume development near the building for a single puff of tracer material at 1 min following release into a wind field corresponding to 2-m/s boundary conditions. Note the complex spatial structure that is introduced by the bilevel building. Turbulent recirculation zones between building levels and near the base of the Kiva can be identified clearly in plots of the velocity field where the flow reverses and rolls back toward the building.

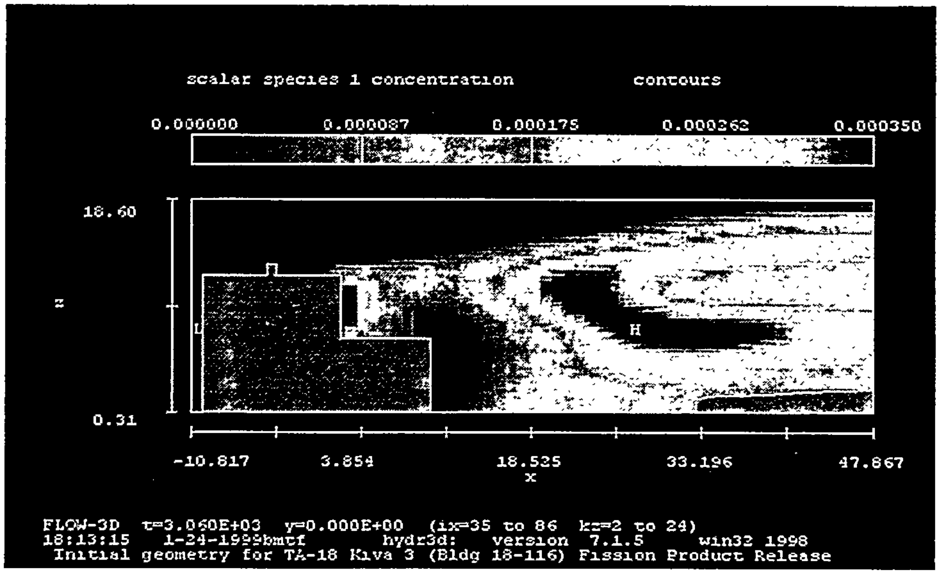

Fig. 3. Plume development at 1 minute following release into a wind field corresponding to 2 m/s boundary conditions. Spatial structure in the plume can be related to building geometry and features of the local wind patterns.

A vertical cross section of the same plume is presented in Fig. 4 at the 45-m distance of the nearest potential dose receptor. Here again, the highly asymmetric structure of the plume can be traced to the geometry of the building and features of the wind field that develop near each of the three HVAC release points. As time progresses past 1 min, the plume is observed to slump to the ground along the slope of the hillside at this vantage point. Plume passage for this single puff is complete in approximately 5 to 7 min. For a wind field corresponding to 10-m/s wind conditions, transport is complete in 2 to 3 min.

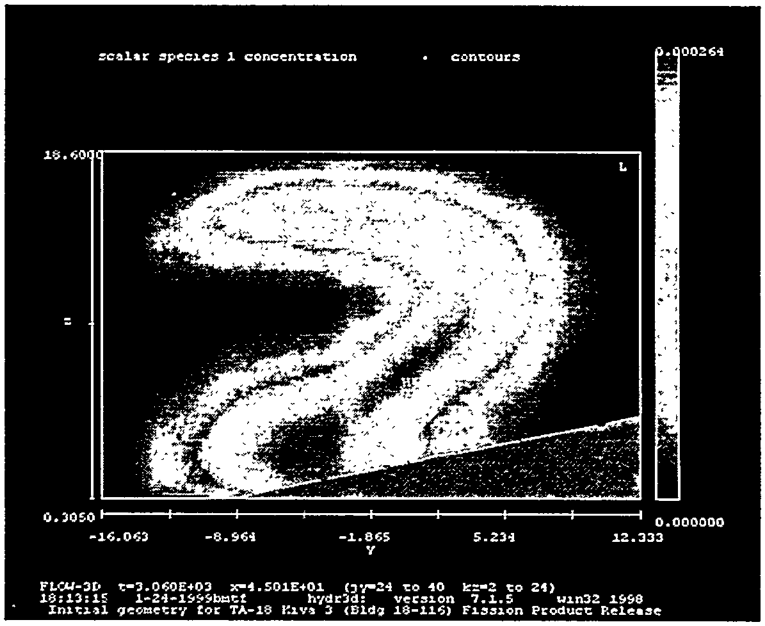

Fig. 4. Vertical plume cross section at a downwind distance of 45 m and a transport time of 1 min for release of fission products into a wind field developed for 2-m/s boundary conditions.

2.3 Dose Compilation

Dependence on exact boundary conditions at the time of an accidental release makes it difficult to predict what location on the ground may receive the maximum dose. For this reason, a hypothetical dose receptor was always positioned at the maximum concentration of a plume cross section regardless of its actual location. For example, in Fig. 4, the maximum, normalized, instantaneous concentration at 1 min and downwind distance of 45 m is approximately 2.6E-4 at a location of Y~0 m and Z~5 m. A new maximum concentration at this distance is found for every time step of plume transport. This approach is consistent with the common use of plume centerline concentrations for Gaussian dispersion models.

Every discrete puff of material that is released into the wind field from the three vents experiences a 5- to 10-min transport history past the dose locations of interest. Figure 3 is a snapshot of this history as a single puff disperses and is distributed spatially. Therefore, the dose effects resulting from a single puff must be integrated over the transport time past the receptor. For this integral, it was assumed that concentrations remain constant between the discrete-time data provided by FLOW-3D® and that the fission-product inventories during the time step are represented by the most recent prior ORIGEN composition. In this manner, conservative dose factors are applied for each interval of exposure time. This process then must be repeated for every discrete puff to obtain estimates of total inhalation and total exposure health effects.

3.0 CONCLUSIONS

Table 1 provides estimates of health effects computed at 45 and 150 m for 1- and 2-h releases in wind fields corresponding to 2- and 10-m/s boundary conditions. In all cases, dose contributions from immersion are slightly less than half of the total. Although it is overly conservative to apply semi-infinite immersion dose factors to a spatially finite plume, no more than a 20% to 30% reduction might be expected from a more rigorous treatment.

Table 1.
Near-field whole-body dose (rem) summary for fission- product release through HVAC vents

	Dose in Rem Wind Speed/Release Duration			
Distance	2 m/s		10 m/s	
(m)	1 hr	2 hr	1 hr	2 hr
45	9.8	10.4	2.0	2.1
150	2.9	3.0	0.65	0.69

Dose estimates obtained by this analysis agreed reasonably well with prior estimates reported in the facility SAR considering the differing levels of details and assumptions. However, it was determined that previous efforts had underestimated building leakage rates and that earlier dose estimates were not based on a comprehensive inventory of nuclides. In general, near-field air concentrations estimated for this problem using FLOW-3D® are lower than those predicted using either simple Gaussian models or correlations for building-wake diffusion available in the literature for simple building configurations. This result was considered reasonable given the complex nature of the structure and the surrounding terrain. Efforts to benchmark the results of the turbulent flow model with atmospheric dispersion data available for simple building configurations are reported in a separate paper.

Near-field doses from fission-product releases postulated from the Godiva assembly were found to be quite sensitive to the combination of building holdup time and rapid nuclide decay near the beginning of the release. Parametric investigation of building release rates using MELCOR revealed that significant dose reductions could be obtained by assuring closure of ventilation louvers during operations and by implementing a program to seal various building penetrations and weather seals. The facility incorporated these suggestions into their technical safety requirements for operation of the Godiva assembly, and the USQ regarding personnel safety within the security perimeter was successfully resolved.

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