Appendix F
ALOHA Hazardous Gas Dispersion Model

Dispersion Modeling of Hydrogen Sulfide at Cimarex Rands Butte Project Using ALOHA

Prepared for

Cimarex Energy

Prepared by

SWCA Environmental Consultants

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Prepared for

Bureau of Land Management
Pinedale Field Office

Prepared by

SWCA Environmental Consultants
1043 Coffeen Avenue, Suite D
Sheridan, Wyoming 82801
(307) 673-4303
www.swca.com

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1.0 INTRODUCTION

The proposed development and production of the complex gas mixture of the Madison Formation has been proposed by the Cimarex Energy (Cimarex) in the Rands Butte Gas Development Project (Project) Environmental Assessment, located in southwestern Sublette County, Wyoming. The Project would produce a gas mixture that includes the presence of hydrogen sulfide (H_2S), carbon dioxide (CO_2), and natural gas, as well as helium and other natural gas liquids such as ethane, propane, and butane. Development and production of large reserves of natural gas and helium from the Madison Formation has been hampered by the presence of high concentrations of CO_2, a greenhouse gas, and toxic H_2S gas.

The presence of H_2S within the gas stream presents threats to human health as well as other biological receptors. Re-injection of H_2S and CO_2 back to the Madison Formation is the proposed method of disposal through the use of an acid-gas injection well. This acid-gas would comprise a mixture of 94% CO_2 and 6% H_2S. If a release of H_2S were to occur at concentrations above levels considered to be a risk to an organism's health, a rapid response to a possible emergency situation and evacuation may be necessary.

An applied model, the ALOHA (Areal Locations of Hazardous Atmospheres) model, is presented in this study which predicts the areal extent of a leak or rupture of the proposed Project. The purpose for the application of the ALOHA Model is to provide predictive estimates of potential impacts to human health and safety for the general public. Model output was in the form of 17 dispersion diagrams of the distance from area of leakage to levels of concern for H_2S under a range of atmospheric conditions commonly occurring in the Rands Butte Project Area (RBPA).

With the use of a predictive air dispersion model, it can be shown that a release of a chemical, in this case H_2S, will disperse out from the source in a predictive nature. The output produced from the predictive air dispersion model is presented within this report.

2.0 ALOHA MODEL DESCRIPTION

The ALOHA Model, developed jointly by the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Environmental Protection Agency (EPA), is a computer program designed to model potential chemical releases, as well as thermal radiation and overpressure related to toxic chemical releases resulting from, fires, and/or explosions (EPA and NOAA 2007).

2.1 MODEL DEVELOPMENT AND PURPOSE

ALOHA is a dispersion model that requires the input of simple, easily obtainable local data to determine areas of concerns regarding significant threshold values for toxicity for a chemical of concern. These data include climatic conditions such as ambient air temperature, wind speed, as well as atmospheric stability. Other data inputs include the chemical of concern, the source, and physical properties of the release such as temperature and pressure of the chemical, and volume of chemical released.

Dispersion through the lower atmosphere is the movement of a mass of air and the chemicals in that mass by both advection (downwind) and diffusion (crosswind) (EPA and NOAA 2007). ALOHA applies two types of models to calculate the downwind movement and concentration levels of gaseous dispersion: Gaussian and heavy gas dispersion model. Gaussian dispersion assumes the development of a normal bell-shaped concentration level as the chemical moves downwind. The concentration axis perpendicular to the downwind air movement spreads out at the same time the peak of the bell curve becomes shallower. The concentration levels of the toxic air mass decrease as the chemical disperses downwind. A heavy gas dispersion model assumes that at the first release of a heavy gas, which is heavier than the surrounding air mass, the gas will sink and slowly spread out downwind. As the gas cloud starts to disperse downwind, the gas cloud becomes more diluted and accelerates dispersion of the gas by diffusion.

ALOHA will also model a chemical that is a gas under normal pressure and temperature but is stored or transported as a liquid under high pressure. If a release occurs when the chemical is pressurized, a two-phased release of both a liquid and a gas will occur. This is termed a flash-boiling release as the liquid rapidly vaporizes to a gas as the product disperses from the release site. The relatively low concentration of H_2S in the byproduct gas stream under investigation for the Rands Butte Project, in combination with the high concentration of CO_2 which remains gaseous under high pressure, eliminates the concern for flash-boiling release in the model.

2.2 MODEL LIMITATIONS

Because ALOHA is a simple dispersion model not requiring detailed input, it has limitations in predicting actual conditions which may occur under the following environmental conditions:

- very low wind speeds;
- very stable atmospheric conditions;
- wind shifts;
- particulates or chemical mixing; or
- concentration patchiness, particularly near the release source; or
- terrain steering effects (EPA and NOAA 2007).

Based on these factors the model for the Project included only wind speeds of a minimum 5 miles per hour (mph), unstable atmospheric conditions, and only the chemical release of H_2S were included in the model to reduce the effect of these limitations. However, since the Project source location for H_2S gas leak occurs near steep terrain with potential for downslope gas dispersion effects, model results will not be completely accurate and final interpretation of gas dispersion for the Project must take into account the drainage patterns of the Project Area.

3.0 MODEL INPUTS FOR THE CIMAREX PROJECT

Because of ALOHA's limitations in modeling chemical mixtures, only the H_2S component of the gas stream was modeled. Since the Cimarex Project is a continuous stream process and does not hold sour gas in tanks during processing, the inflow and outflow pipelines would contain the largest volume of sour gas at any given time. In the event of a pipeline rupture the total volume of H_2S that could be released into the atmosphere is calculated based upon the following parameters:

- Area of pipe, assuming complete rupture;
- Length of pipeline containing acid-gas;
- Total volume of pipeline;
- Gas release duration;
- Gas release rate;
- The concentration of H_2S in pipeline.

SWCA evaluated the Cimarex proposed sour gas operations to determine the parameters to input into the ALOHA model to estimate the maximum potential gas dispersal using these parameters. Three scenarios were evaluated and modeled as possible worst case gas release scenarios:

- A rupture at the sour gas pipeline;
- A rupture at the acid-gas injection wellhead or acid-gas pipeline without added check valve technology;
- A rupture at the acid-gas pipeline with added check valve technology.

The operation of the Madison Formation production wells would deliver raw sour-gas to the M&HRF plant for processing. The 1.45 mile pipeline would carry a gas stream containing an H_2S concentration of approximately 3.6% by volume. During normal production, based upon the total length (7,656 ft) and inside diameter of the pipeline (5.187 in), the total volume of H2S would be just over 44 cubic. Based on this calculation, a release of H_2S from the production wells and the adjoining sour-gas production pipeline would not result in a worst case scenario.

Due to the gas stream processing at the M&HRF (i.e., the removal of the salable methane and helium, as well as the produced water), the H_2S concentration transported to the acid-gas injection well will be greater than the concentrations transport from the gas wells to the M&HRF. Gas processing at the M&HRF would increase the concentration of H_2S as a component of the waste gas stream, and transport it under pressure to the acid-gas injection wellhead for disposal. The total distance from the M&HRF to the acid-gas injection well is 1.45 miles (7,656 feet) and would contain the highest expected concentration and volume of H_2S, consisting of a mixture of CO_2 (94%) and 110 cubic feet of H_2S (6%). The acid-gas mixture would be transported to the acid-gas well in a 6.625-inch outside diameter pipeline; the inside diameter of the pipeline is

5.1870 inches, and would be injected at the well head under a constant pressure of 2,250 pounds per square inch-gauge (psig).

Cimarex design includes a check valve feature in the acid-gas pipeline leading from the M&HRF to the injection wellhead and other sour gas pipelines pipelines. A check valve is a mechanical valve located mid-way in the pipeline length, which allows gas to flow in one direction only from the M&HRF to the injection well. If the direction of gas flow reverses because of a potential failure of the pipeline including a pipeline rupture, the valve closes and isolates gas behind the valve, effectively cutting the potential volume of the release in half. The total volume of gas released from the pipeline with an installed check valve would therefore be about 55 cubic feet at any given time of operation, based on pipeline diameter and operational pressure.

Based on these evaluations, the worst worst-case scenario for gas release would occur at the acid gas injection pipeline without the added check valve technology. The total volume of H_2S that could be released into the atmosphere in the worst case scenario is calculated based upon the following parameters:

- Area of pipe, assuming complete rupture: 0.239 square foot (34.47 square inches).
- Length of pipeline containing acid-gas: 7,656 feet.
- Total volume of pipeline: 1,830 cubic feet.
- Concentration of H_2S in pipeline: 6% of gas.
- Gas release duration: 1 minute.
- Gas release rate: 85.3 pounds/second.

Based on the worst-case calculation the total volume of gas released would be 5,119 pounds and 110 cubic feet of H_2S. However, model runs were also included for the lower total volume calculations of 55 cubic feet and 44 cubic feet of H_2S.

In addition to the three potential volumes of a potential gas release, other model inputs included the following parameters and variables that are typical of the RBPA and would affect the distance of dispersal should an accidental release occur:

- Wind direction (West);
- Wind speed (5 and 30 miles per hour (mph));
- Air temperature (0, 45, 75 degrees Fahrenheit (°F));
- Atmosphere stability (Unstable and Moderately unstable);
- Humidity (25% and 50%); and
- Cloud cover (0% and 50%).

4.0MODEL OUTPUTS FOR THE CIMAREX PROJECT

The ALOHA model output includes H_2S levels of concentration (LOCs) based upon concentration levels of increasing threat to safety for any biological receptors which may be located within the specific LOC. Distances from the H_2S source to the extent where the LOC is expected to be present are based upon model inputs. Table 1 shows the levels of concentration and toxicity for H_2S. Based on this information, concentrations of 10 parts per million (ppm), 100 ppm, and 500 ppm were identified as output LOCs.

Table 1. Hydrogen Sulfide Physical Effects at Specified Concentrations.

Concentrations (ppm)	Physical Effects
0.13	Minimal perceptible odor.
10	Obvious and unpleasant odor. OSHA Permissible Exposure Limit (PEL) (8-hour exposure).
15	OSHA Short-term Exposure Limit (15-minute exposure).
100	Impairs the sense of smell in 3 to 15 minutes. Immediately dangerous to life and health.
500	Dizziness, breathing stops in a few minutes. Needs prompt artificial respiration.
700	Unconscious quickly. Death would result if not recued promptly.
1000	Unconscious immediately, followed by death within minutes.

*Table obtained from ConocoPhillips EP Lower 48 Health, Safety, and Environmental Handbook (2006).
ppm = parts per million

Table 2 provides a list of inputs for each successive model run based on a range of climatic conditions which could be encountered at the RBPA. The model output for each set of conditions is shown graphically in Section 5.0. Results for the distance to LOC from each ALOHA model run are also listed within the table.

ALOHA modeling results show the volume of H_2S present (110 cubic feet) during the operation of the RBPA. A release of this volume of gas at the following climatic conditions would be considered the worst-case scenario:

- west wind of 30 mph;
- air temperature of 45 degrees Fahrenheit or greater; and
- a moderately unstable atmosphere.

The model predicts that location of any biological receptor within a 10 ppm LOC may require notification and/or evacuation within a range of 1.3- to 3.8-mile distance from the potential H_2S release. The area where the safety of any human may be in question and an evacuation may be necessary ranges from 0.63 to 1.50 miles from a potential source. A mandatory evacuation for any biological receptor would be necessary within distances of 0.27 to 0.73 mile from a potential release of H_2S. Areal extent diagrams for the LOCs under different modeled conditions are presented in Section 5.0 of this report.

The nearest residences from any production activities within the RBPA site are about 4.2 miles from the M&HRF site. The ALOHA Model indicates that greatest distance of dispersal from any potential release source of H_2S with a LOC for human health and safety within the RBPA site is 3.8 miles. Based upon the results of this modeling study, no mandatory evacuations of the general public would be necessary should a leak occur from the Project, unless real-time site monitoring of onsite conditions decrease.

This predictive model indicates that, in the rare event of an accidental severe leak or rupture, the proposed Project would not endanger human health and safety of the general public within the RBPA. With the added check valve technology, H_2S monitoring equipment, automatic shut down, and emergency response measures contained in the Cimarex Emergency Contingency Plan, the general public would not be in danger in the event of a H_2S leak in the future. However, any personnel working outdoors in the vicinity of the M&HRF, acid-gas injection well or sour gas wells would require immediate personal protective measures, as identified in the Emergency and Contingency Plan.

Table 2. ALOHA Model Output for Climatic Conditions with Levels of Concentration Distance.

Figure #	Volume of H_2S Release (cf)	Wind Direction	Wind Speed (mph)	Air Temperature (°F)	Atmosphere Stability*	Humidity (%)	Cloud Cover (%)	Level of Concentration Distances (miles)		
								10 ppm	100 ppm	500 ppm
1	110	W	5	75	B	25	50	2.80	1.30	0.73
2	110	W	30	75	D	25	50	3.80	1.50	0.64
3	110	W	5	75	B	50	0	2.80	1.30	0.73
4	110	W	30	75	D	50	0	3.80	1.50	0.63
5	55	W	5	75	B	25	50	2.60	1.10	0.61
6	55	W	30	75	D	25	50	2.90	1.00	0.44
7	110	W	5	45	B	50	50	2.70	1.30	0.72
8	110	W	30	45	D	50	50	3.70	1.40	0.62
9	55	W	5	45	B	25	50	2.60	1.20	0.63
10	55	W	30	45	D	25	50	2.80	1.00	0.43
11	110	W	5	0	B	5	50	1.30	0.63	0.36
12	110	W	30	0	D	5	50	2.80	1.00	0.40
13	55	W	5	0	B	25	50	1.40	0.66	0.38
14	55	W	30	0	D	25	50	2.10	0.70	0.27
15	44	W	30	75	D	25	50	2.70	0.92	0.39
16	44	W	30	45	D	25	50	2.00	0.64	0.25
17	44	W	30	0	D	25	50	1.90	0.61	0.24

* B = Unstable; D = Moderately Unstable

°F = degrees Fahrenheit
cf = cubic feet
mph = miles per hour
ppm = parts per million
W = west

5.0 ALOHA MODEL OUTPUT DIAGRAMS FOR CIMAREX PROJECT

The diagrams that follow show the three identified LOCs for potential release of H_2S under specified atmospheric conditions and leak parameters, as identified in Table 1.

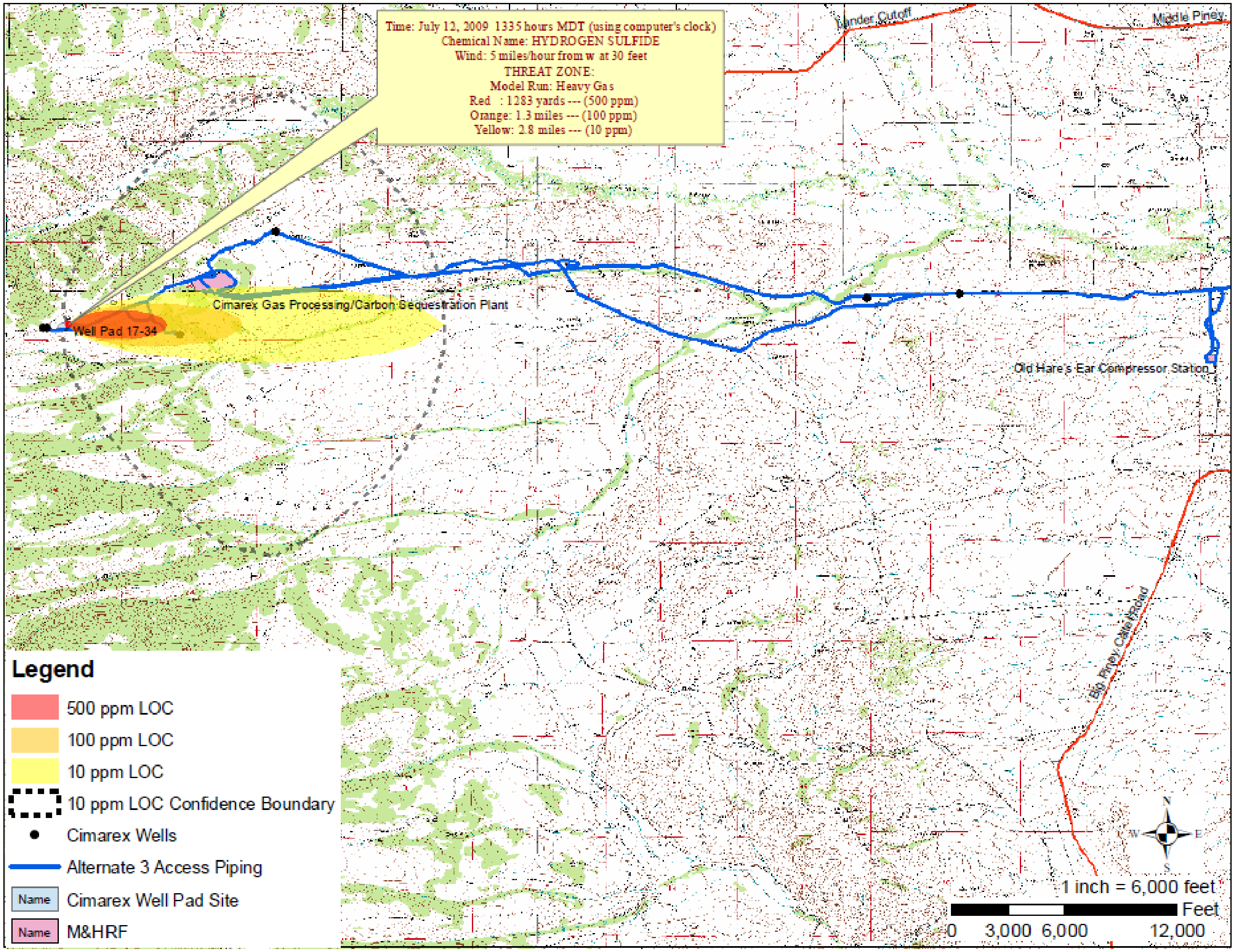

Figure 1. Modeled LOC for H2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 5 mph, 75° F, Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.

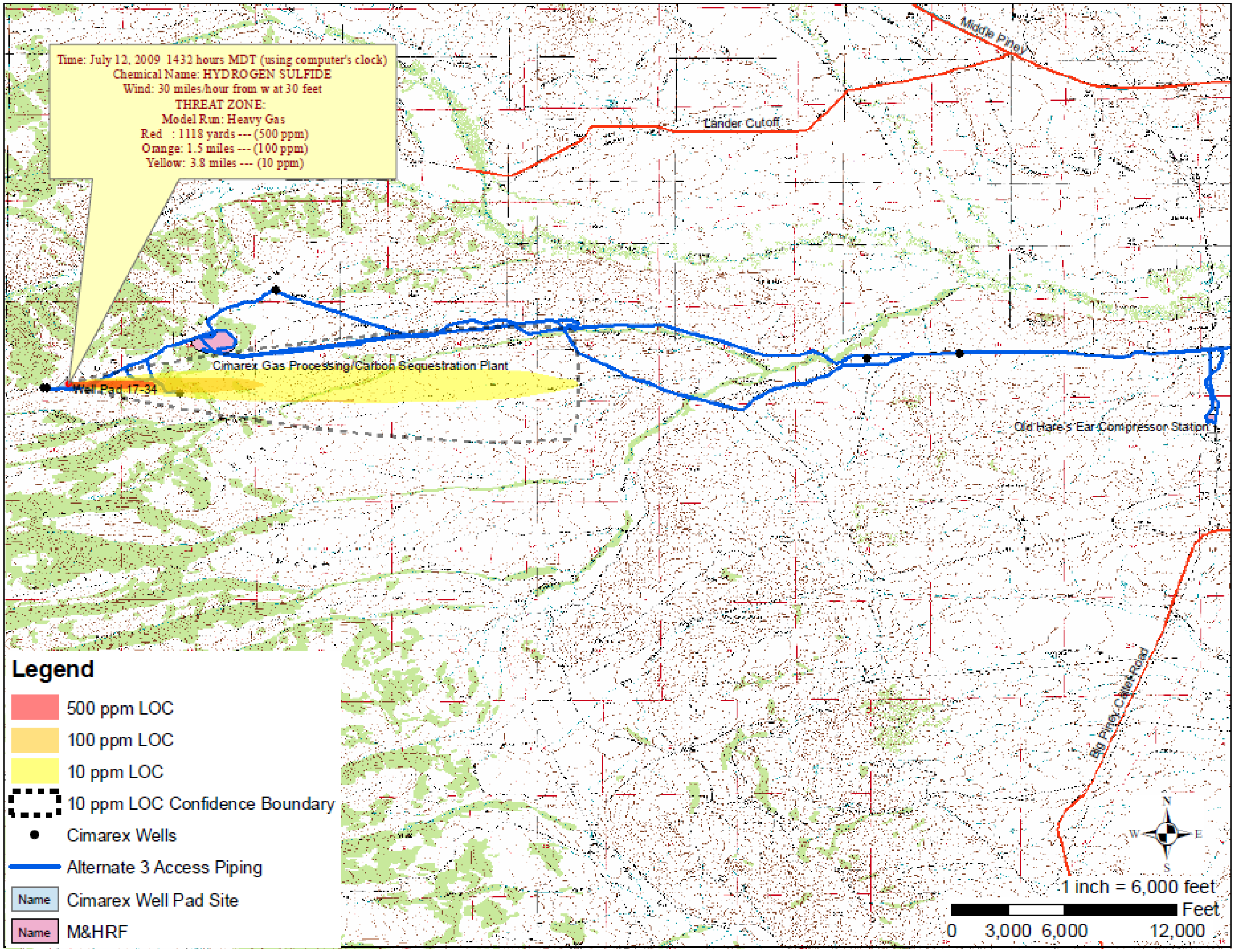

Figure 2. Modeled LOC for H_2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 30 mph, 75° F, Moderately Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.

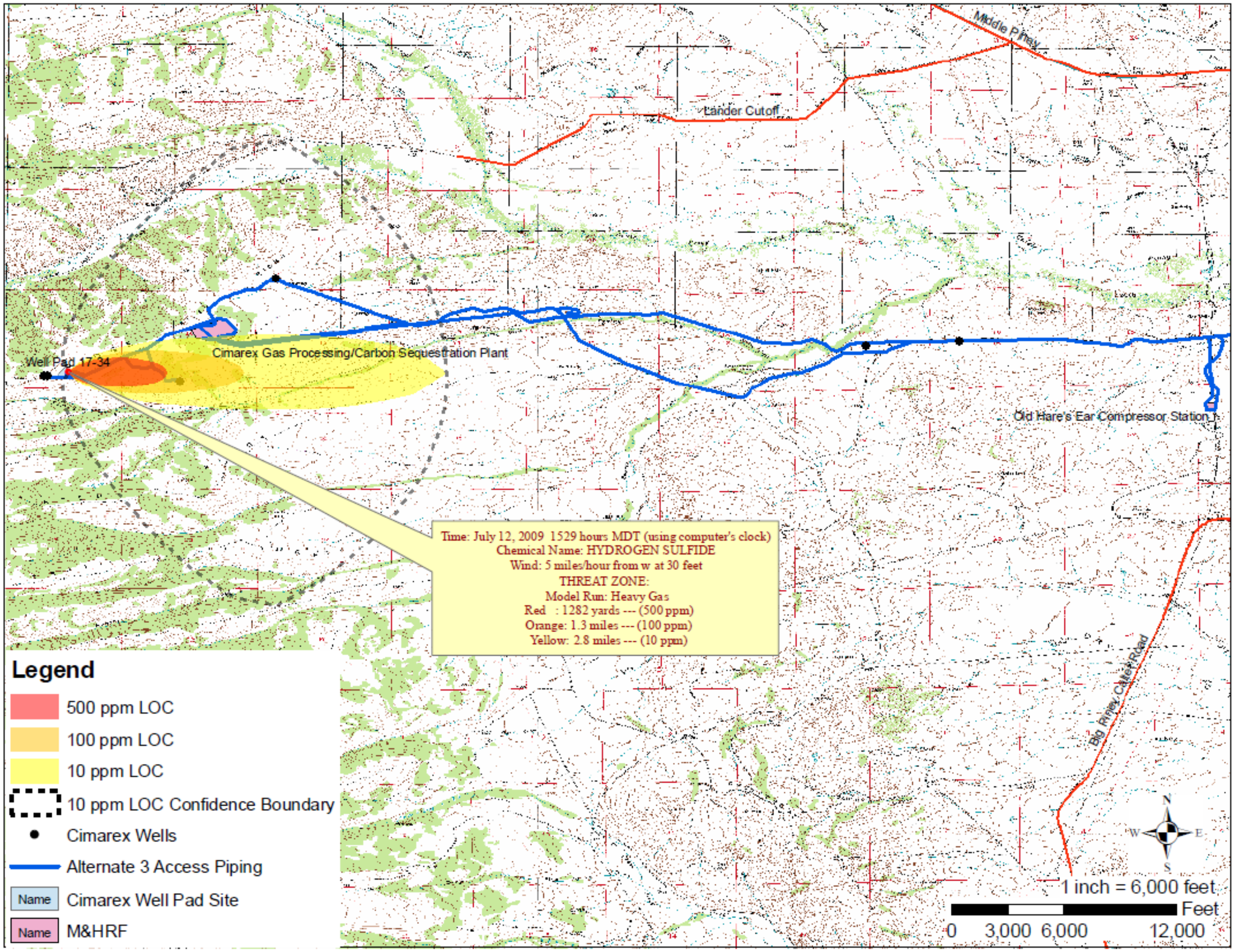

Figure 3. Modeled LOC for H2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 5 mph, 75° F, Unstable Atmosphere, 50% Humidity, and 0% Cloud Cover.

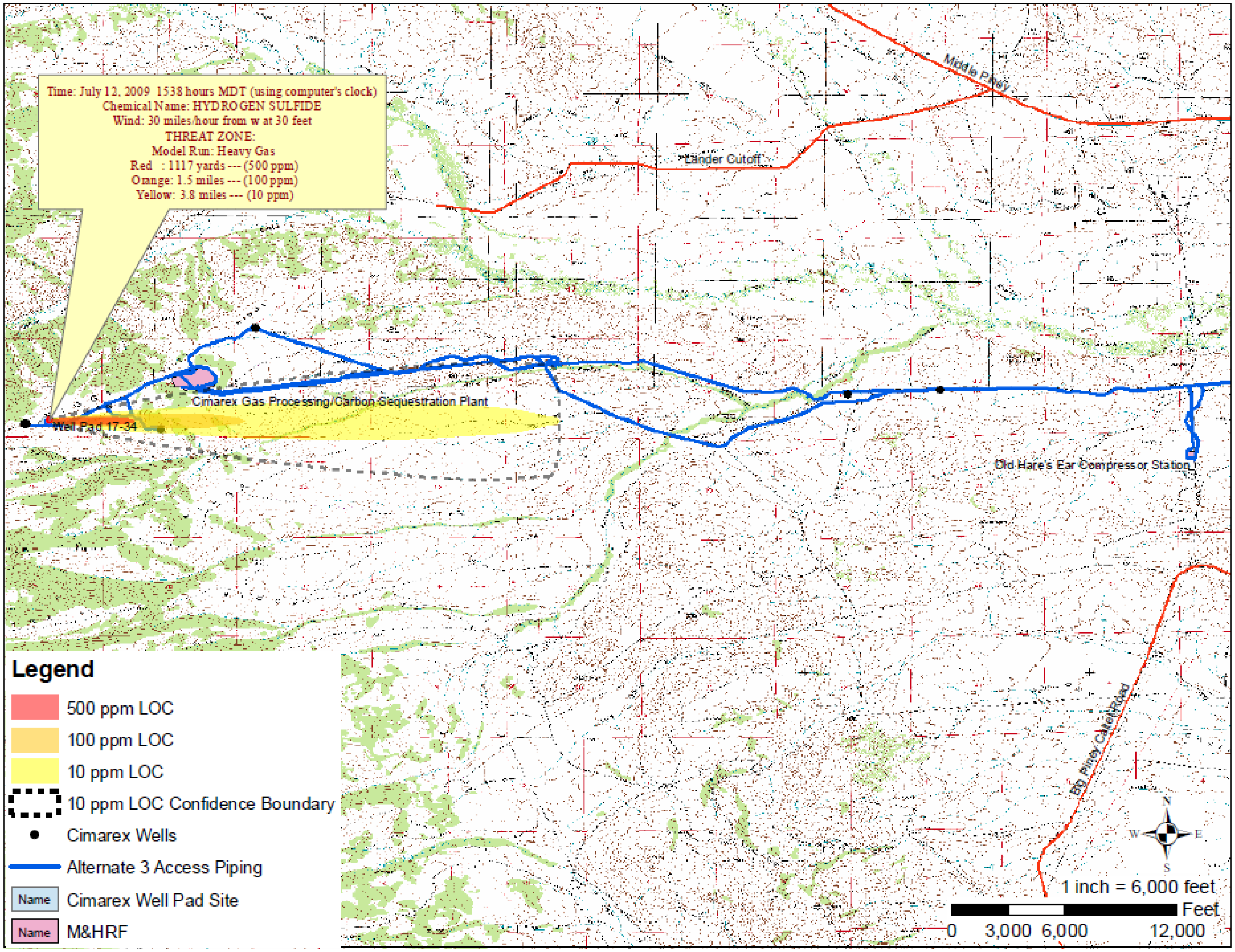

Figure 4. Modeled LOC for H2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 30 mph, 75° F, Moderately Unstable Atmosphere, 50% Humidity, and 0% Cloud Cover.

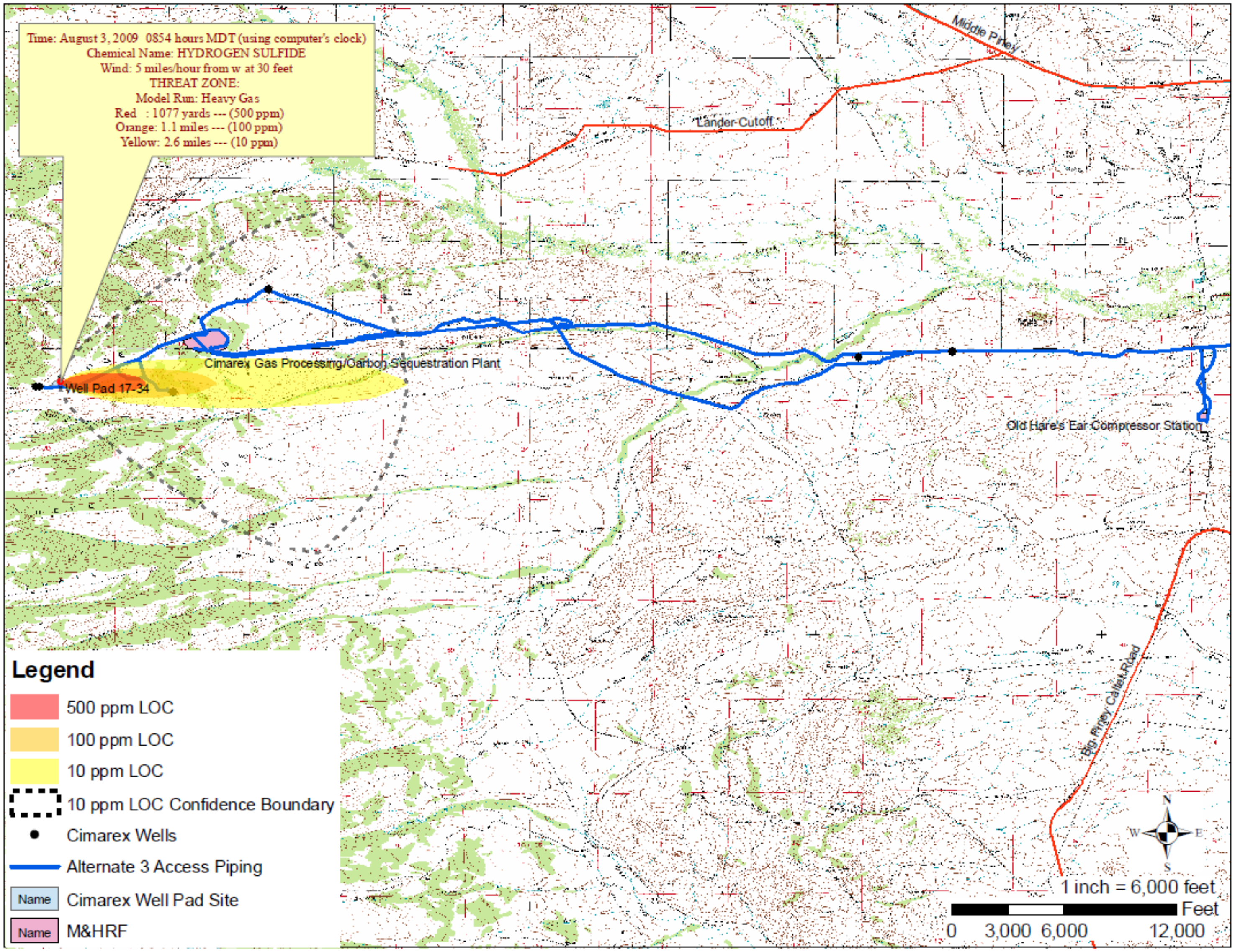

Figure 5. **Modeled LOC for H2S Release at Acid-gas Injection Well (With Check Valve) with West Wind at 5 mph, 75° F, Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.**

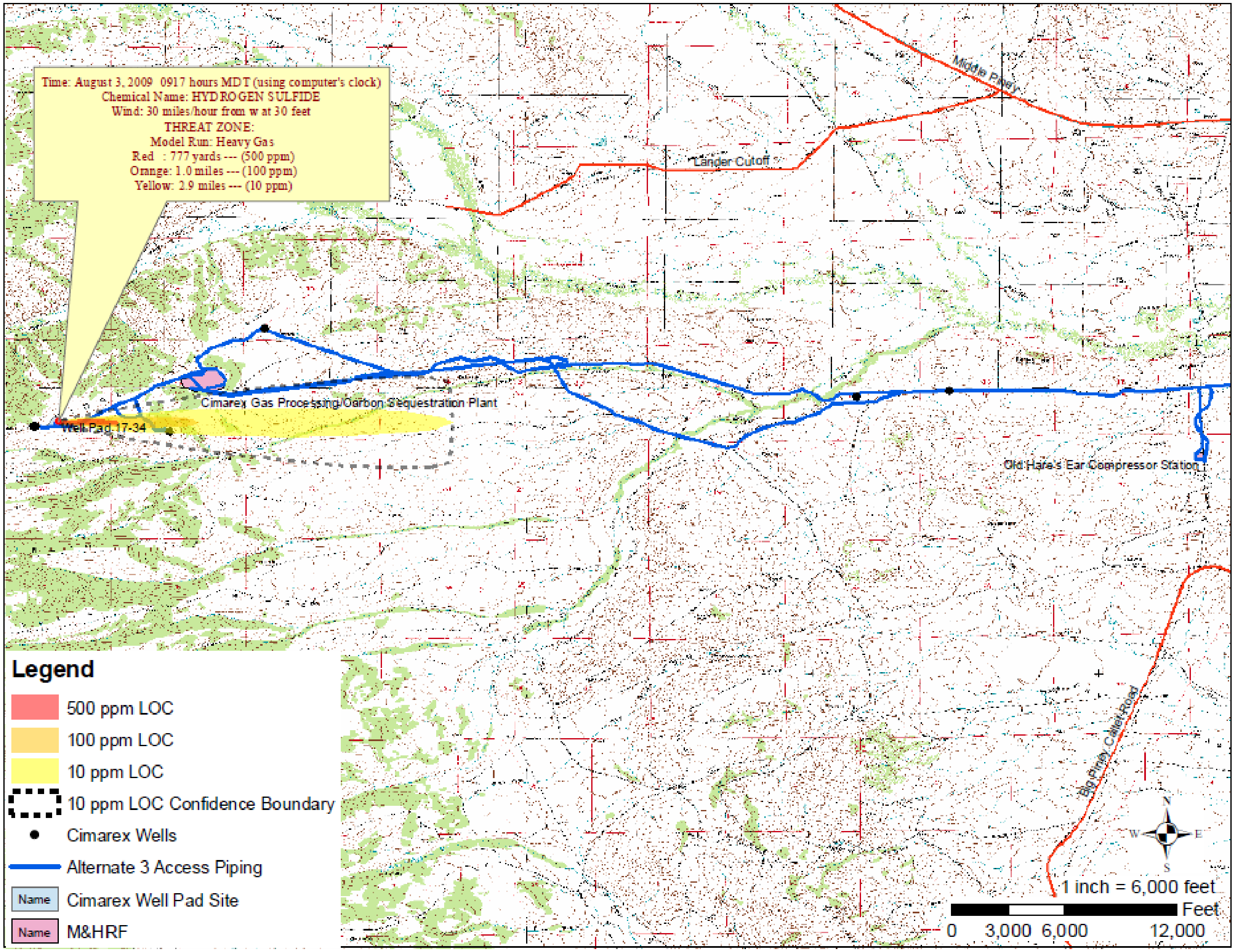

Figure 6. **Modeled LOC for H2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 30 mph, 75° F, Moderately Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.**

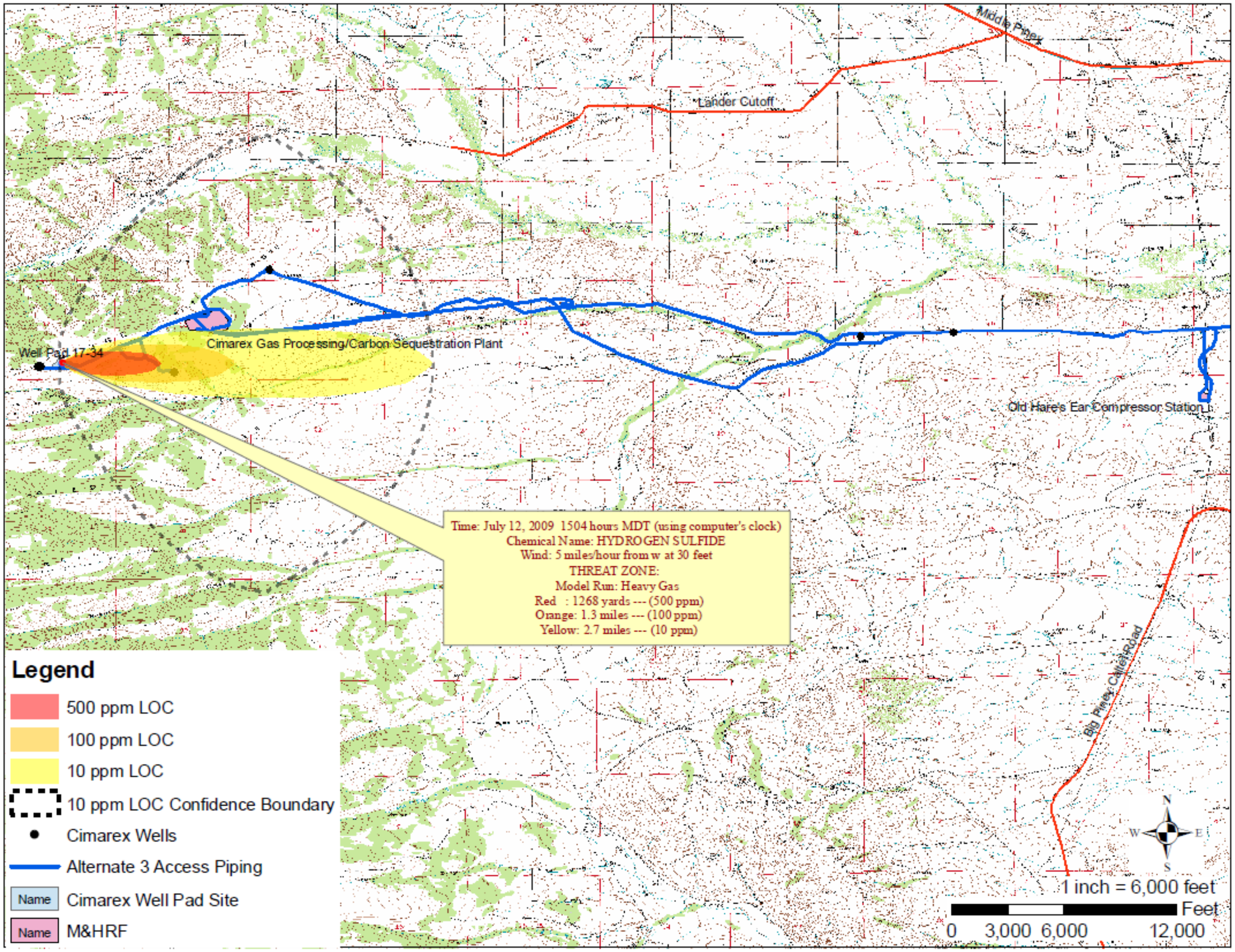

Figure 7. Modeled LOC for H2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 5 mph, 45° F, Unstable Atmosphere, 50% Humidity, and 50% Cloud Cover.

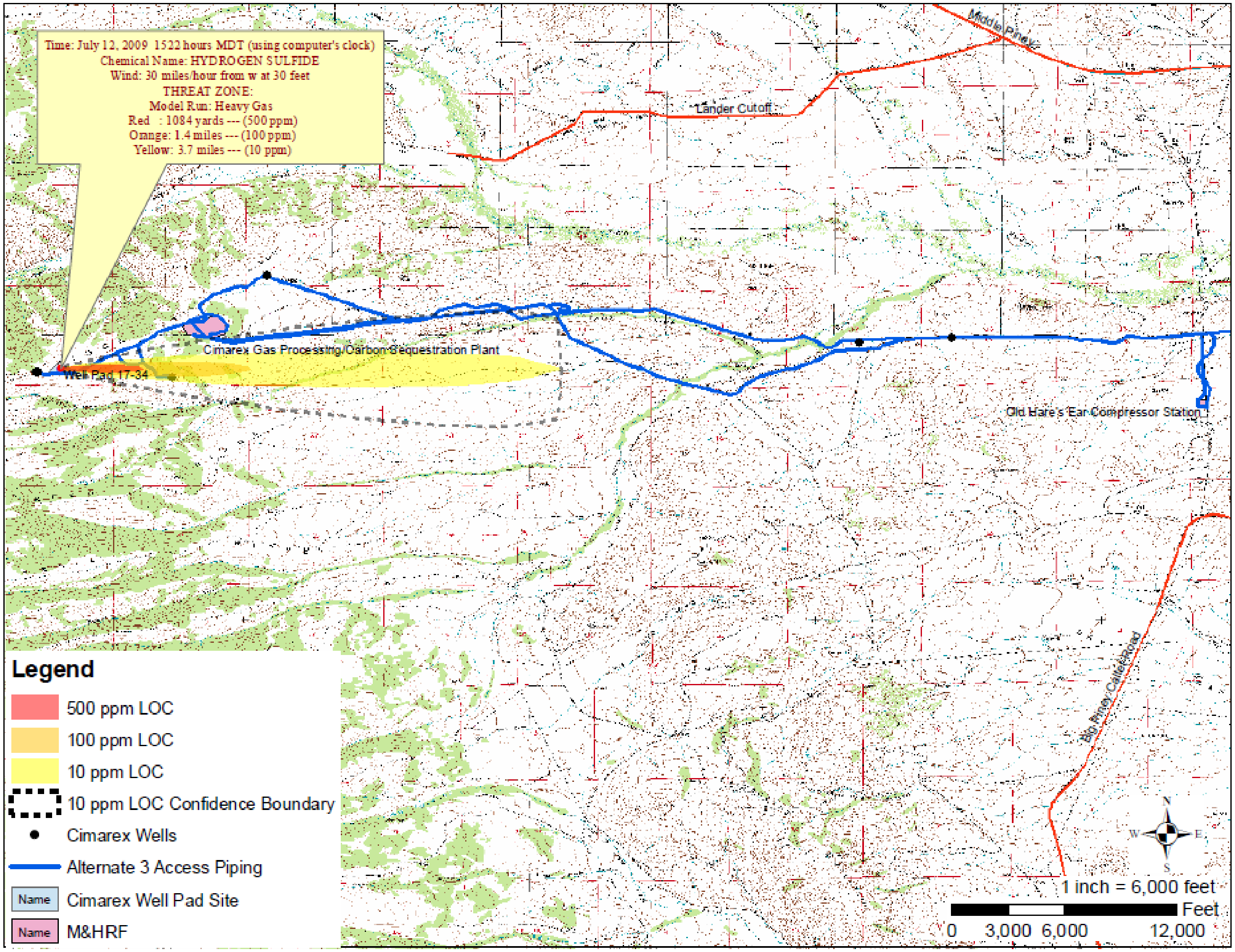

Figure 8. Modeled LOC for H2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 30 mph, 45° F, Moderately Unstable Atmosphere, 50% Humidity, and 50% Cloud Cover.

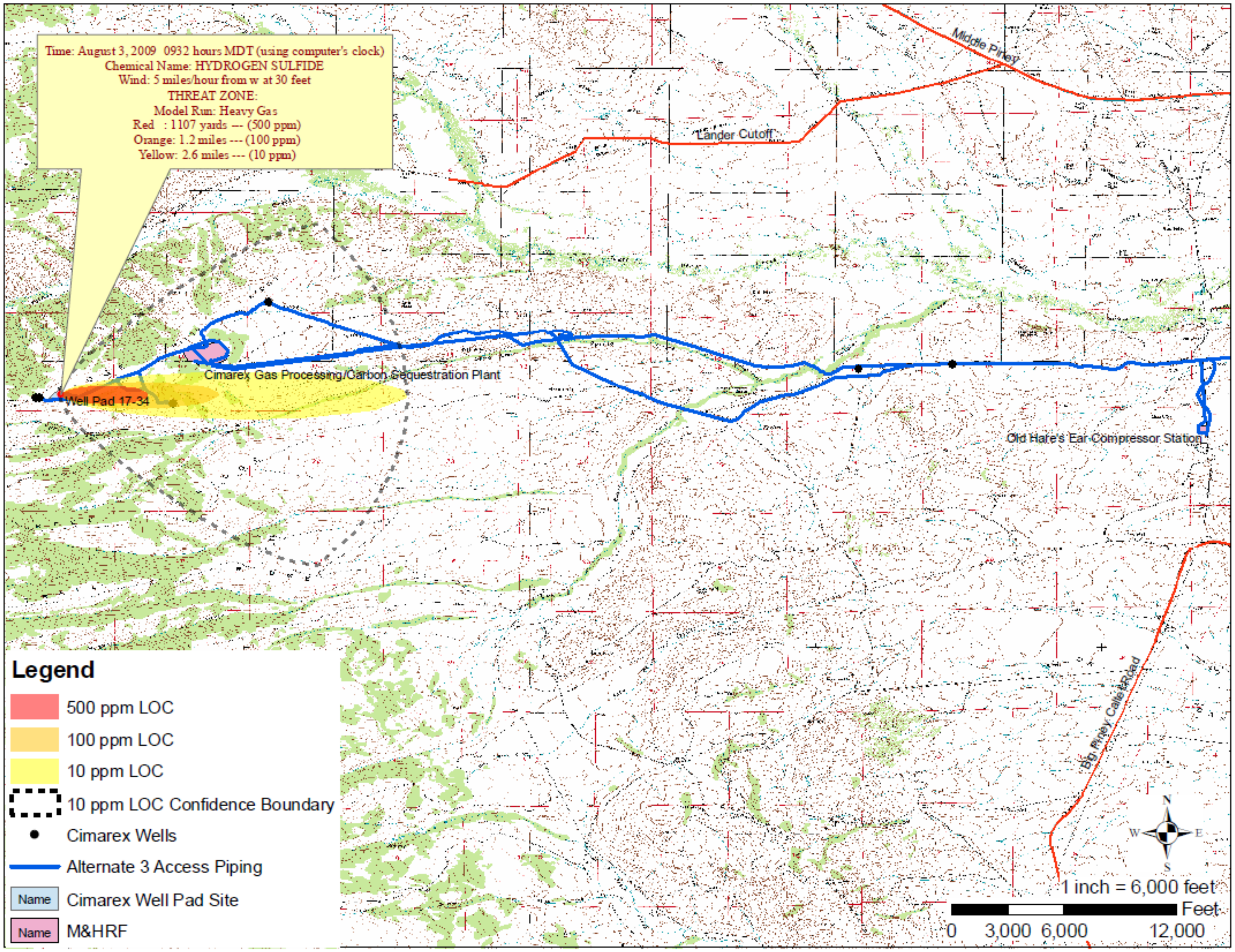

Figure 9. **Modeled LOC for H2S Release at Acid-gas Injection Well (With Check Valve) with West Wind at 5 mph, 45° F, Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.**

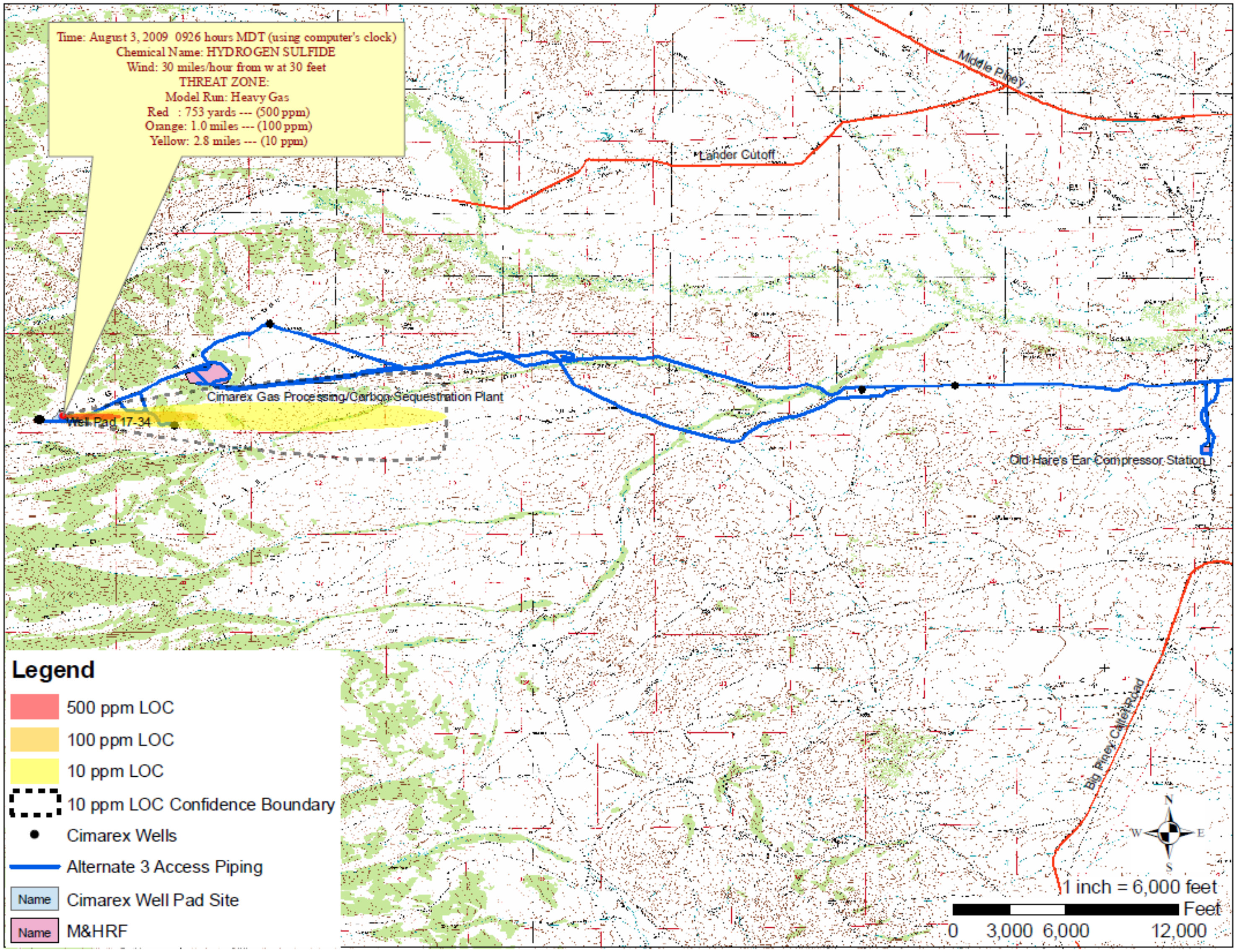

Figure 10. Modeled LOC for H2S Release at Acid-gas Injection Well (With Check Valve) with West Wind at 30 mph, 45° F, Moderately Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.

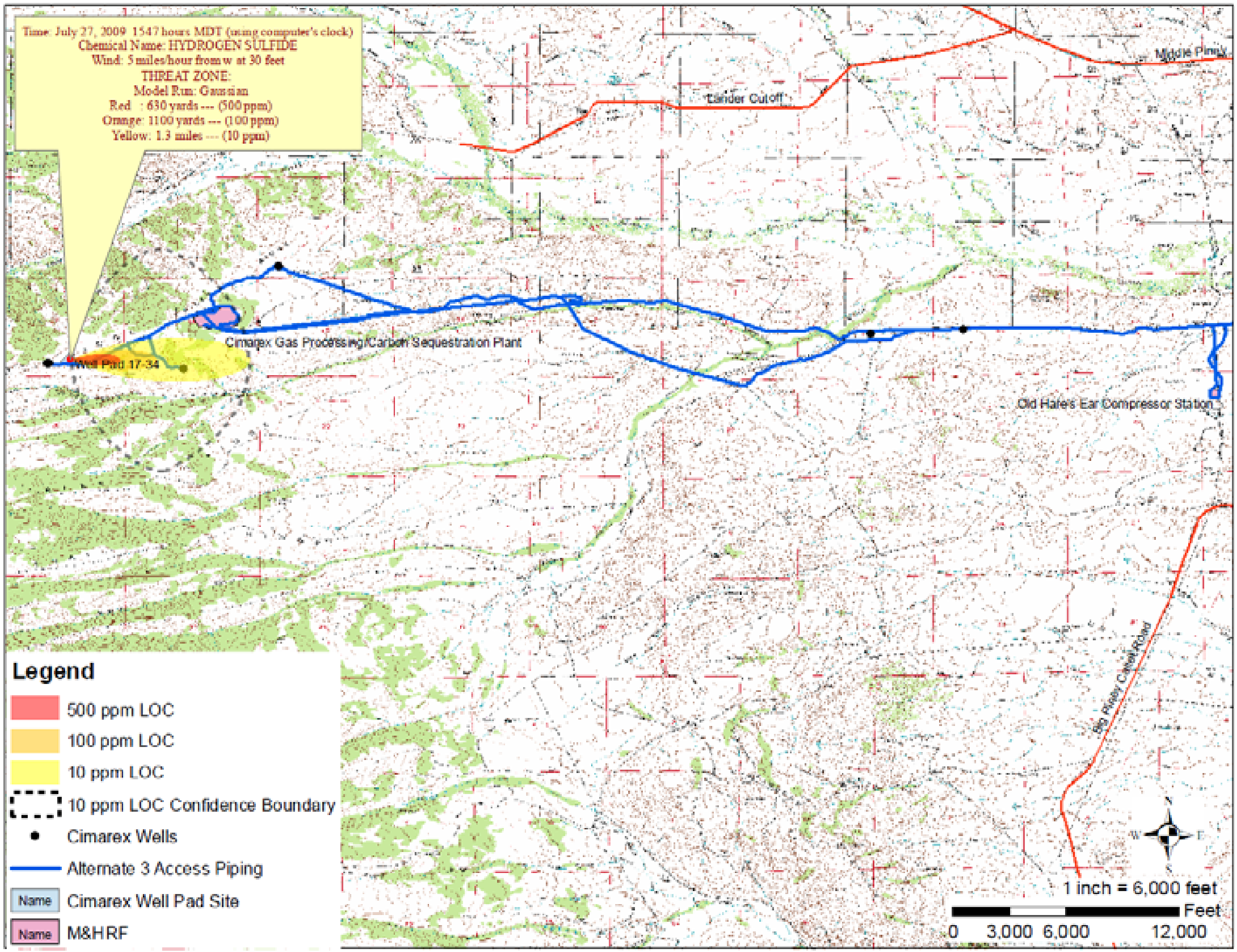

Figure 11. **Modeled LOC for H_2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 5 mph, 0° F, Unstable Atmosphere, 5% Humidity, and 50% Cloud Cover.**

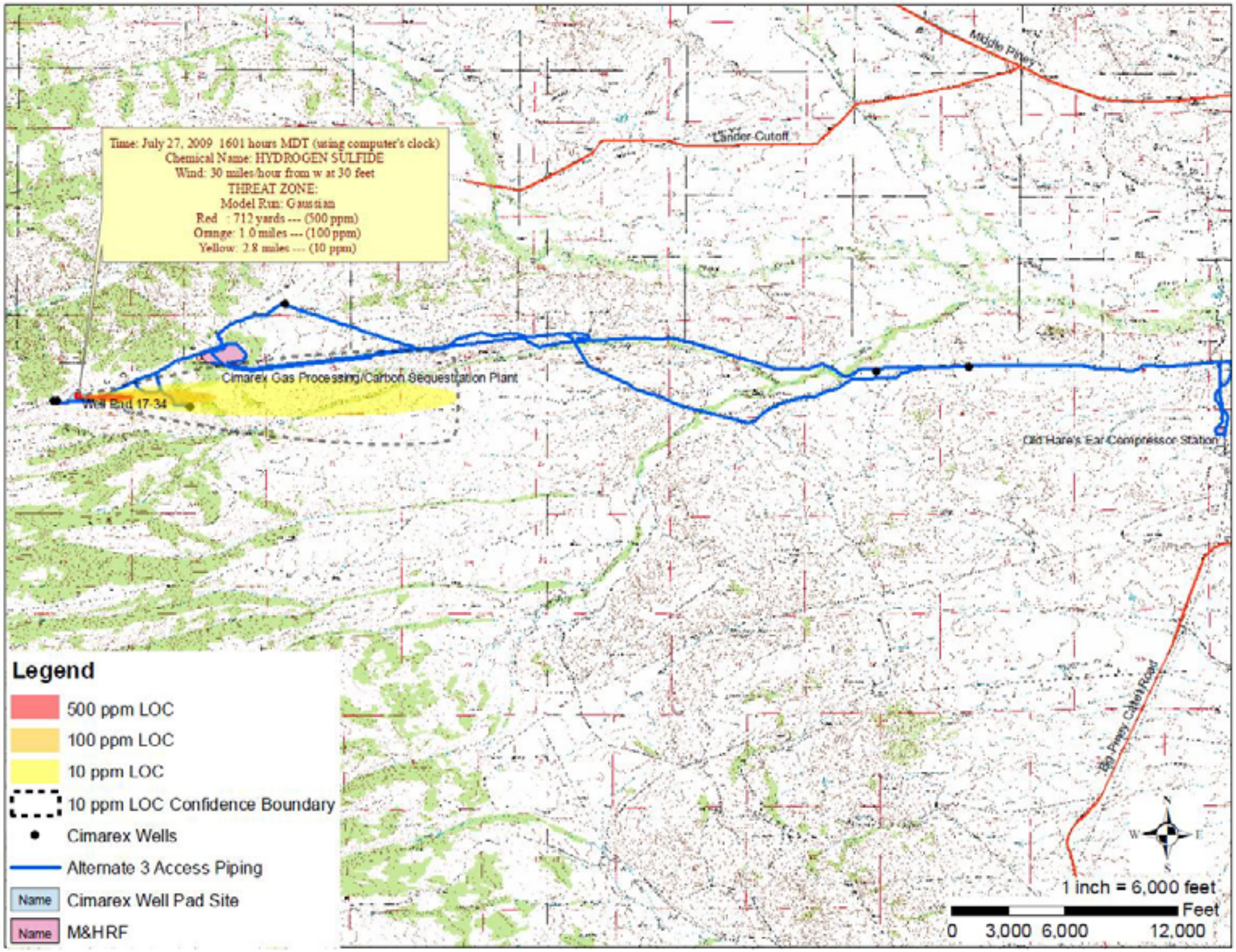

Figure 12. Modeled LOC for H2S Release at Acid-gas Injection Well (No Check Valve) with West Wind at 30 mph, 0° F, Moderately Unstable Atmosphere, 5% Humidity, and 50% Cloud Cover.

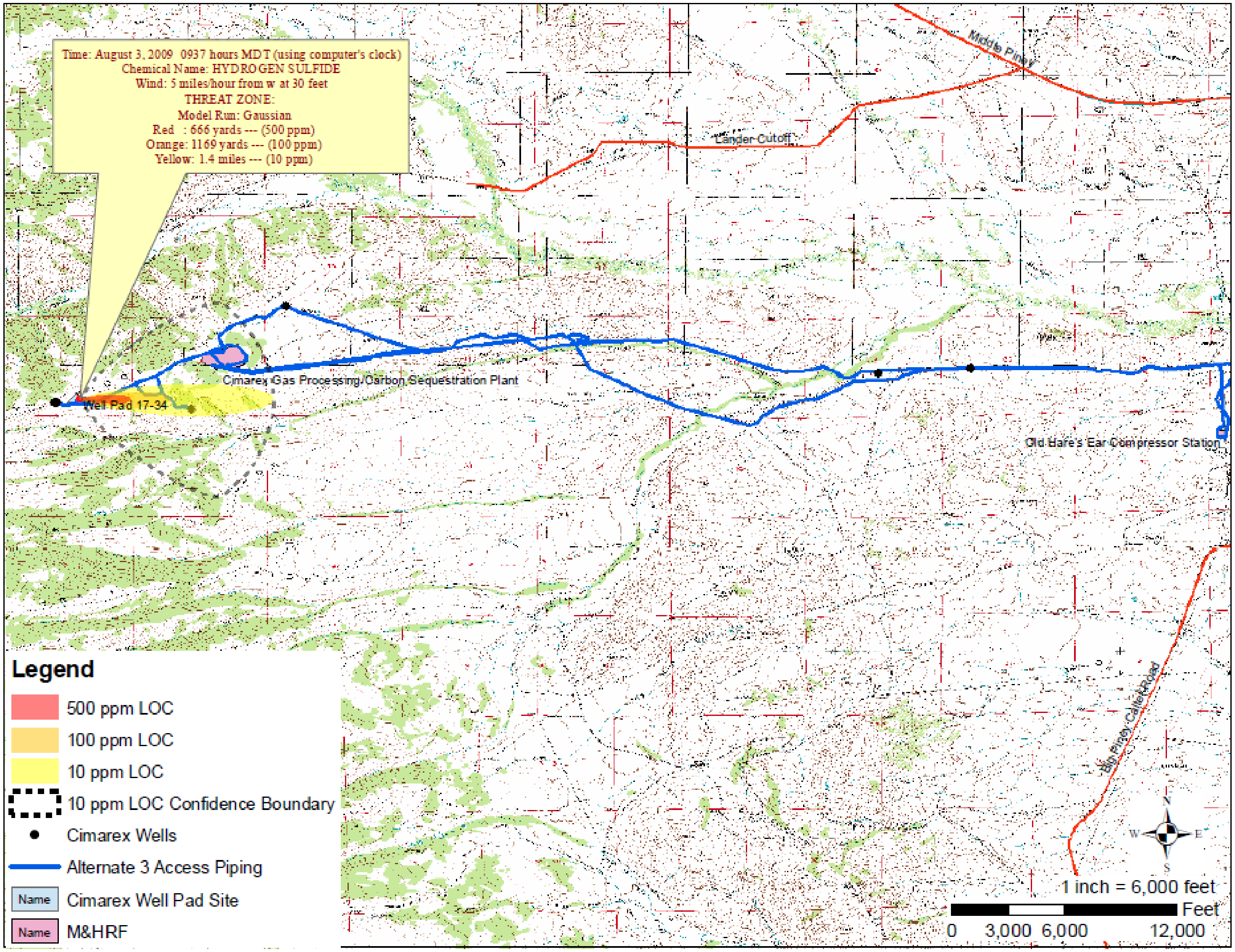

Figure 13. Modeled LOC for H2S Release at Acid-gas Injection Well (With Check Valve) with West Wind at 5 mph, 0° F, Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.

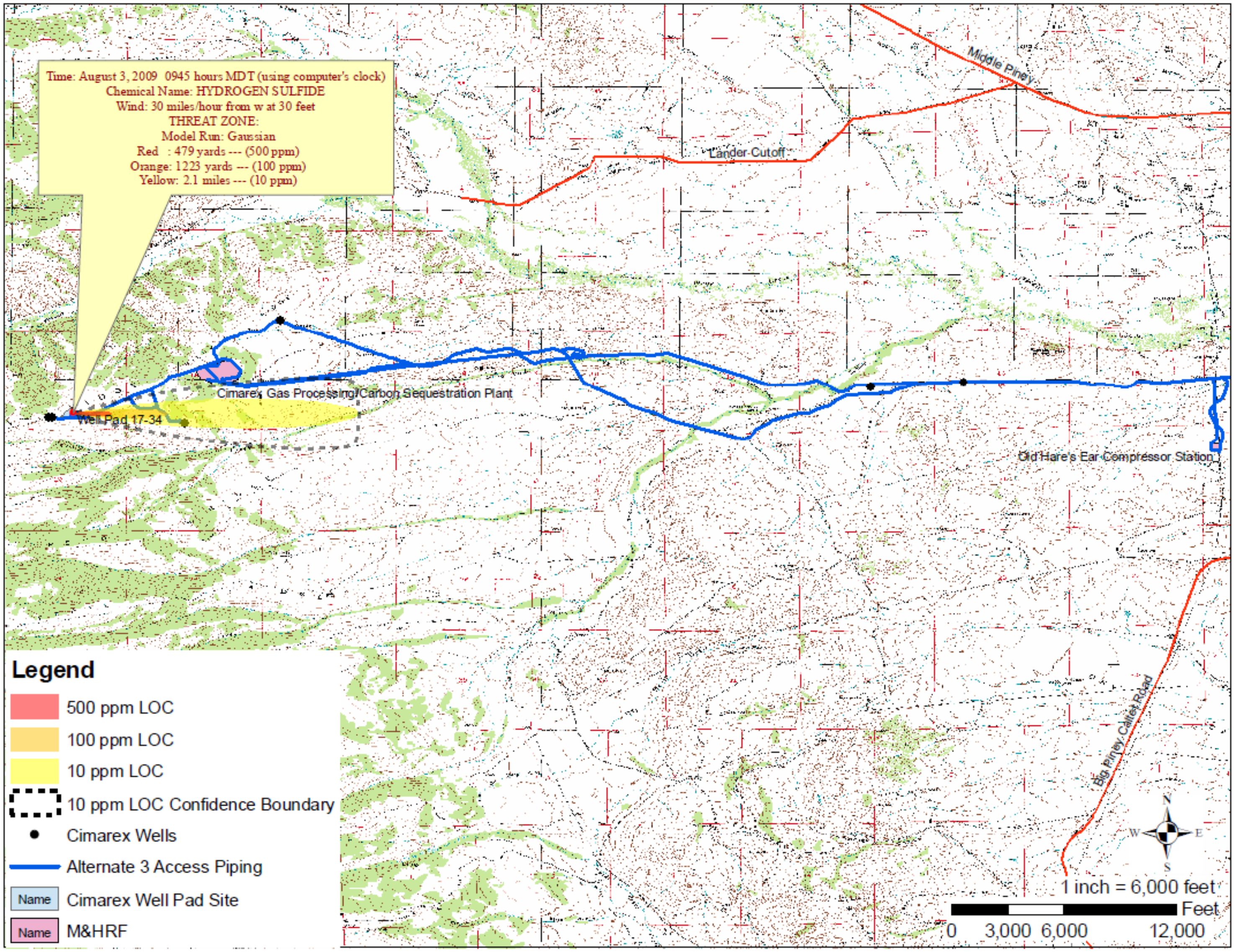

Figure 14. Modeled LOC for H2S Release at Acid-gas Injection Well (With Check Valve) with West Wind at 30 mph, 0° F, Moderately Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.

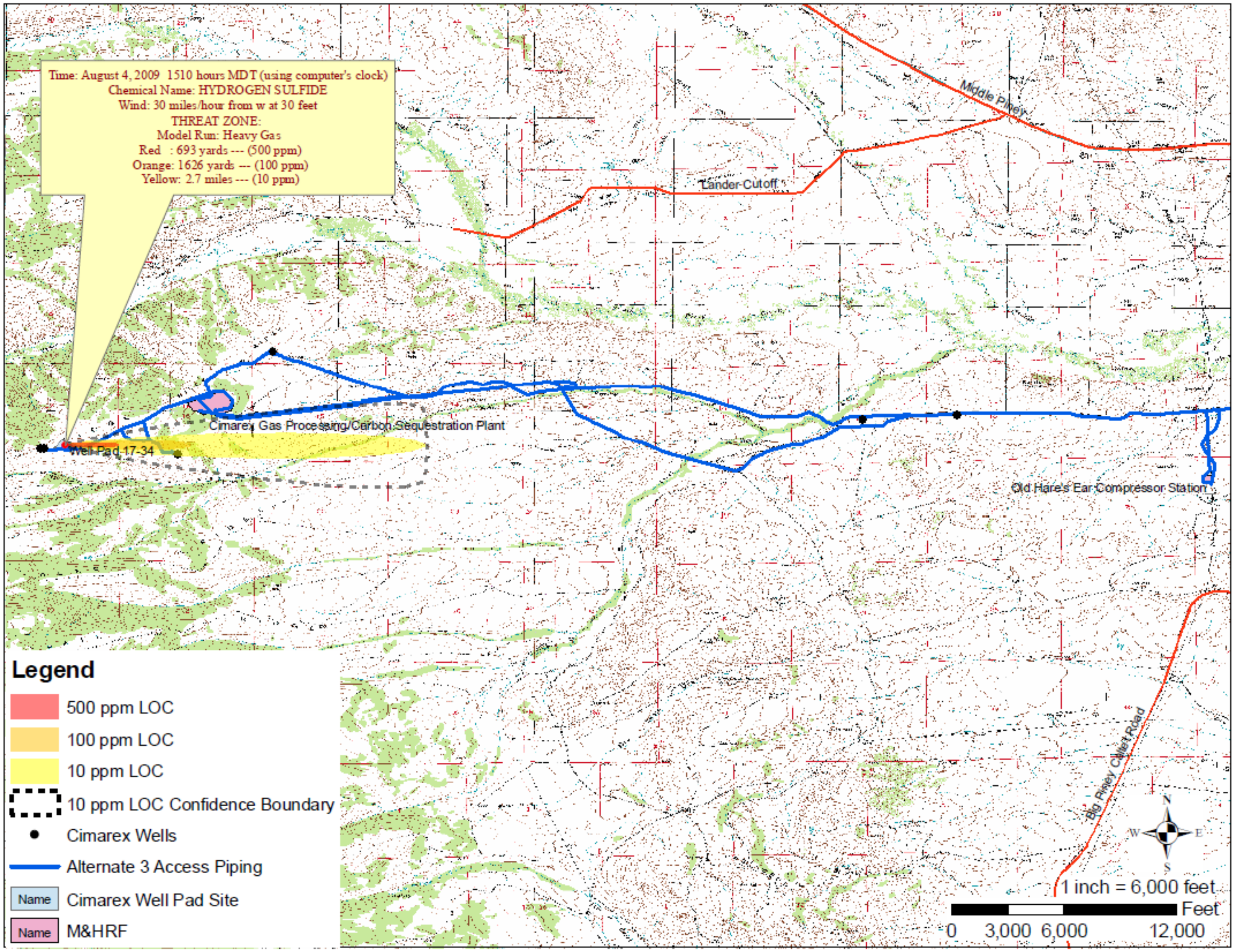

Figure 15. Modeled LOC for H2S Release at Sour Gas Production Well with West Wind at 30 mph, 75° F, Moderately Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.

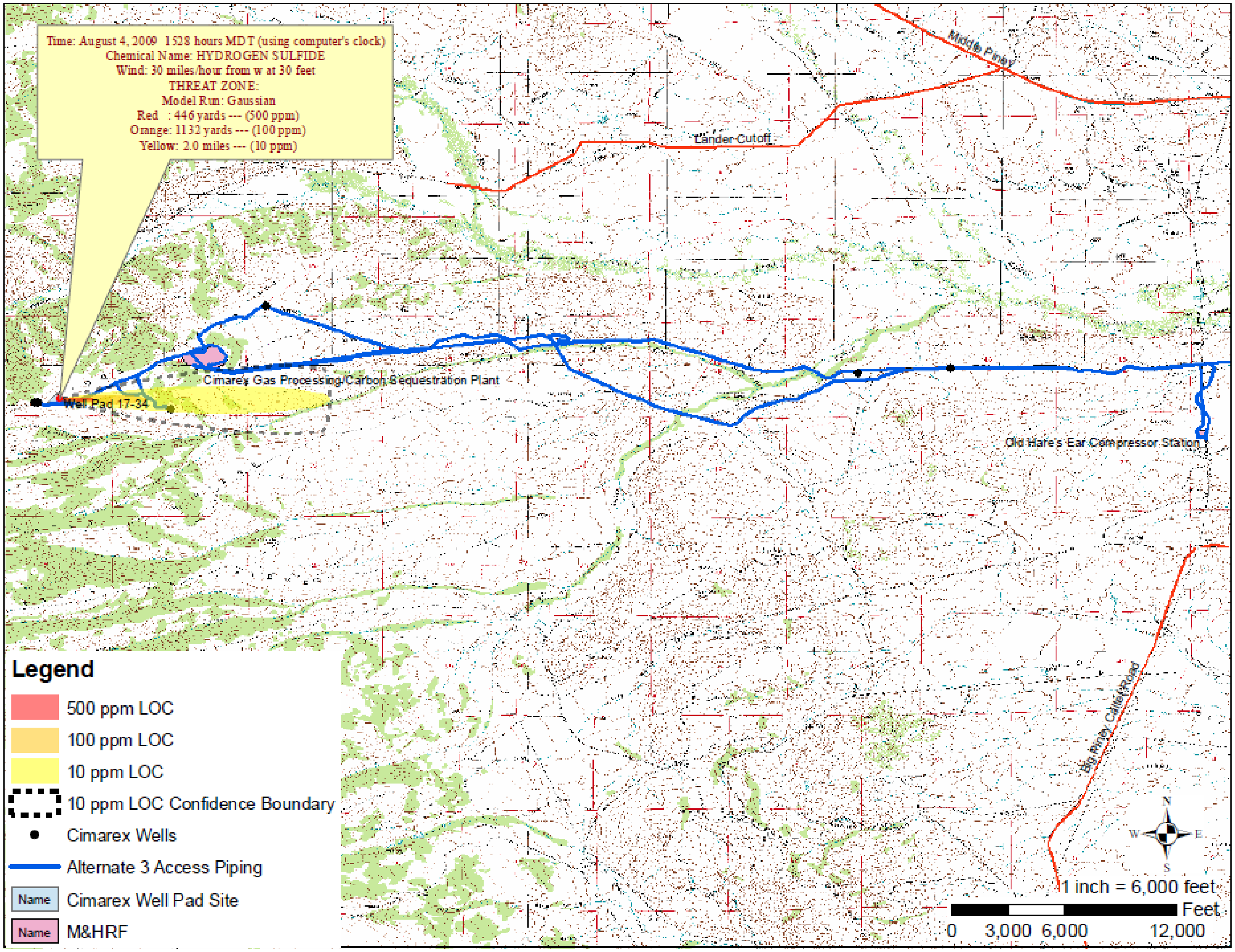

Figure 16. Modeled LOC for H2S Release at Sour Gas Production Well with West Wind at 30 mph, 45° F, Moderately Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.

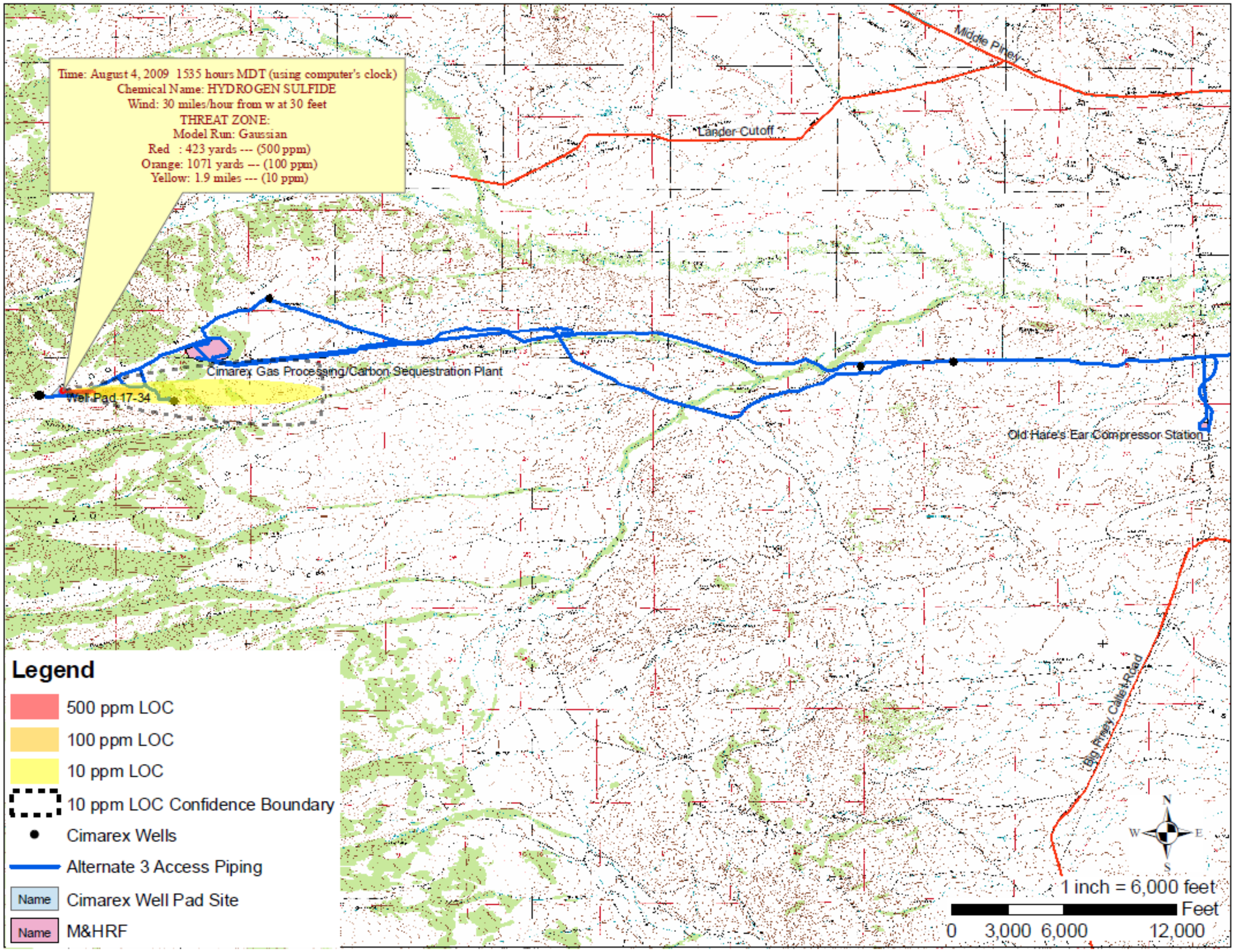

Figure 17. Modeled LOC for H2S Release at Sour Gas Production Well with West Wind at 30 mph, 0° F, Moderately Unstable Atmosphere, 25% Humidity, and 50% Cloud Cover.

6.0 REFERENCES

U.S. Environmental Protection Agency and National Oceanic and Atmospheric Agency (EPA and NOAA). 2007. ALOHA User Manual. The Cameo Software System, Washington, DC.