RADIONUCLIDE DETECTION THRESHOLD IN THE LOP NOR REGION

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ABSTRACT

A study was conducted to explore the capability to estimate the threshold for measuring radionuclides escaping from a hypothetical nuclear test within the boundaries of the nuclear test site near Lop Nor, China. A point near the geographic center of the test site, 41.6º north by 86.6º east, was chosen as the hypothetical point of release. The Hybrid Single-Particle Lagrangian Integrated Transport Model (HYSPLIT) was used to model airflow from that point outward for several days for start dates on the first and sixteenth of each calendar month in 2001. HYSPLIT results were compared to Operational Multi-scale Environment Model with Grid Adaptivity (OMEGA). The dilution of the air masses from the site at various contour intervals was calculated and combined with the stipulated minimum detectable concentrations of xenon-135 and barium-140 to produce estimates of the minimum detectable yield (MDY). The minimum estimate of the MDY for each planned sampling location in the International Monitoring System (IMS) in the vicinity of Lop Nor was obtained to provide an overall assessment of the environmental sampling array. Because the fraction of fission products that escape to the environment from a nuclear test is an intuitive estimate, the MDY is only accurate to order of magnitude, at best, but can be used as a figure-of-merit for comparison purposes. The fraction of particulates that escape to the environment was estimated as 0.1 percent. The fraction of noble gasses that escape to the environment was estimated as 10 percent. The MDY ranged from less than 0.1 kiloton to more than 1000 kilotons, depending on location, elapsed time, and the fission product measured. Using the assumptions described above, the planned IMS particulate station array was found to be capable of detecting debris from low yield nuclear explosions during every period analyzed.

OBJECTIVE

Estimate the minimum detectable yield (MDY) for a hypothetical nuclear test at Lop Nor given that 10 percent of the noble gas fission products and 0.1 percent of the particulate fission products escape the test cavity and that the planned international monitoring system sensors are in place and achieving the minimum detectable concentration (MDC) specified in the Comprehensive Nuclear-Test-Ban Treaty (CTBT), 30 μBq for ^{140}Ba and 1 mBq for ^{135}Xe.

RESEARCH ACCOMPLISHED

Background and Assumptions

It is well known that nuclear explosions produce fission products and that the mix of fission products, the relative amounts of various radionuclides, is peculiar to particular fission processes. Fission products found in the environment, therefore, can be attributed to a nuclear explosion or other nuclear fission processes with a high degree of confidence.

Fission products released into the environment have readily detected nuclear explosions that have occurred in the atmosphere. The first nuclear explosion by a country other than the United States was detected by the collection of radioactive fission products thousands of miles downwind of the test site. However, a nuclear device buried deeply enough underground to avoid making a crater will release many fewer fission products into the atmosphere.

Finding information on fission products collected following underground nuclear explosions is difficult. The United States has conducted a robust program that analyzes air samples for the presence of fission products; however, the results are classified. Other countries have also collected environmental samples and analyzed them for fission products, but data from underground nuclear explosions is sparse. This creates severe difficulties in estimating the fraction of fission products that escape the test cavity in an underground explosion. In addition, the conditions for any particular underground nuclear explosion can vary widely and affect the amount of fission products that reach the atmosphere by orders of magnitude.

Fission products in the form of noble gasses, such as xenon, are highly mobile and not chemically reactive. They can reasonably be expected to percolate through porous earth and escape the cavity of an underground nuclear explosion. Particulate fission products are less likely to escape the test cavity. The fireball will release energy to the surrounding material and rapidly cool. If the hot gasses are trapped underground long enough to cool, the fission products that are solid at environmental temperatures will precipitate and tend to collect on the walls of the test cavity. They are likely to escape to the environment only if they remain gaseous long enough to pass through the porous ground or if the explosion ejects the soil overburden resulting in a crater. Xenon-135 was used to represent noble gas fission products because it is strongly indicative of a recent nuclear explosion. Barium-140 was used to represent particulates because it is used as a standard for assessing detector performance.

The Nuclear Treaty Programs Office selected the known Chinese nuclear test site near Lop Nor as the area of interest for our analysis. No historic, empirical data on which to base estimates of the fraction of fission products that would escape an underground test cavity were available. Therefore, the fraction of fission products that escape to the environment from a particular test is an intuitive estimate. The value used for xenon, ten percent, is thought to be conservative, but the value used for particulates, 0.1 percent, is probably quite high. A device deeply buried and properly stemmed might exceed the MDY estimated in this paper significantly and go undetected, depending on the fraction of the fission products that actually escape to the environment. That is, if the device is properly buried and stemmed, no particulate will escape. If the testing agency buries the device too shallowly or uses improper stemming techniques, then heavy venting will occur and a large fraction of the particulate fission products will escape to the environment. Therefore, the MDY is accurate to order of magnitude, at best, and should be used only as a figure of merit for comparison purposes. The detection limits of the radioisotopes were obtained by using the CTBT stipulated values, 30 μBq for ^{140}Ba and 1 mBq for ^{135}Xe.

Atmospheric Transport

Seismologists at the Center for Monitoring Research (CMR) selected a point near the geographic center of the Chinese test site near Lop Nor as the location to focus their efforts at improving analysis. For consistency, the nuclear scientists chose the same point. This point, 41.6º north by 86.6º east, was chosen as the point of release for a hypothetical plume of debris from an underground nuclear test. HYSPLIT[1] was chosen as the application for modeling atmospheric transport from the test site to planned IMS sampler locations. It was compared to OMEGA[2], a more precise atmospheric transport model. HYSPLIT was used for the bulk of the analysis because it is easier to operate and produces results in a fraction of the time that OMEGA requires.

Model plumes were started at 0600 Universal Time Coordinated (UTC) on the first and 16th day of each calendar month in 2001. Default values were used for all HYSPLIT options except pollutant release rate. The default pollutant release rate in HYSPLIT is one unit in one hour and this was thought to be not representative of a plume release from an underground nuclear explosion. The release rate was chosen as 0.0833 units per hour for 12 hours, so that one unit was released over 12 hours at a constant rate. It is not known whether this approximately represents a typical plume from an underground nuclear explosion. However, it was deemed to be more representative than the default value.

Each run was continued for ten days or 240 hours. HYSPLIT provided contour plots of the average, normalized pollutant concentration every 12 hours. These concentration contours were translated into MDY contours using the algorithm described under Minimum Detectable Yield.

International Monitoring System (IMS) Sensor Array

Particulate and gaseous radionuclide sensors planned to be deployed for the International Monitoring System (IMS) were treated as existing in there planned locations for the purposes of determining detectability of the hypothetical nuclear explosion. Relevant, planned IMS sensors are listed in Table 1 and their geographic locations are displayed in Figure 1.

Table 1. Planned International Monitoring Stations in East Asia

Station Code	Location			Sensor Type	IMS stipulated Minimum Detectable Concentration
	Latitude	Longitude	Place Name		
MNG45	47.9	105.3	Ulan Bator, Mongolia	Noble Gas	1 mCi for Xe-135
MNP45	47.9	105.3	Ulan Bator, Mongolia	Particulate	30 µCi for Ba-140
RUP56	59.6	112.6	Peleduy, Russia	Particulate	30 µCi for Ba-140
RUP59	53.9	84.8	Zalesovo, Russia	Particulate	30 µCi for Ba-140
CNP21	36.0	104.2	Lanzou, China	Particulate	30 µCi for Ba-140
CNG21	36.0	104.2	Lanzou, China	Noble Gas	1 mCi for Xe-135
CNP20	40.0	116.4	Beijing, China	Particulate	30 µCi for Ba-140
CNG20	40.0	116.4	Beijing, China	Noble Gas	1 mCi for Xe-135
CNP22	23.1	113.3	Guangzhou, China	Particulate	30 µCi for Ba-140
CNG22	23.1	113.3	Guangzhou, China	Noble Gas	1 mCi for Xe-135
RUP58	43.7	131.9	Ussuriysk, Russia	Particulate	30 µCi for Ba-140
THP65	14.1	100.6	Bangkok, Thailand	Particulate	30 µCi for Ba-140
THG65	14.1	100.6	Bangkok, Thailand	Noble Gas	1 mCi for Xe-135
PHP52	14.5	121.0	Quezon City, Republic of the Philippines	Particulate	30 µCi for Ba-140
JPP37	26.5	127.9	Okinawa, Japan	Particulate	30 µCi for Ba-140
JPP38	36.3	139.1	Takasaki, Japan	Particulate	30 µCi for Ba-140
JPG38	36.3	139.1	Takasaki, Japan	Noble Gas	1 mCi for Xe-135

Figure 1. The Lop Nor Test Site and Relevant IMS Sensor Locations

Minimum Detectable Yield

Let *MDY* be the minimum detectable yield, *FPY* be the fission product yield of the isotope for which *MDY* is to be calculated, $t_{1/2}$ be the half-life of the isotope, *f* be the fraction of the fission product that escapes the test cavity to the environment, *Conc* be the diluted concentration of the plume at the sampling site based on HYSPLIT calculations, _*T* be the time elapsed between the source event and the collection of the sample, and *MDC* be the minimum detectable concentration of the isotope activity at the sampling site. Then, since there are 1.45×10^{23} fissions per kiloton of yield[3], the event will be detected if:

$$MDY \geq \frac{MDC}{1.45 \times 10^{23} \times FPY \times \frac{\ln 2}{t_{1/2}} \times f \times EXP(-\frac{\ln 2}{t_{1/2}} \times T) * Conc} \quad (1)$$

The half-lives used were obtained from the CMR radionuclide library used in radionuclide sample analysis. The fission product yield was obtained from Los Alamos report LA-UR-94-3106 (ENDF-349), the England and Rider tables of compiled fission product yields. The normalized concentration, *Conc*, was entered into equation 1 and the resulting MDY was calculated for each 12-hour period.

The fission products are decaying and the center of the air mass from the plume is moving. As shown in Figure 2, for points some distance from the source, the MDY will start infinitely large then drop in a delta function to some value as the leading edge of the air mass reaches the point of collection. The MDY may then decrease as the concentration at that point increases with the approach of the center of the air mass, before increasing again either because of decreasing concentration of the plume or because the fission product activity is decaying away.

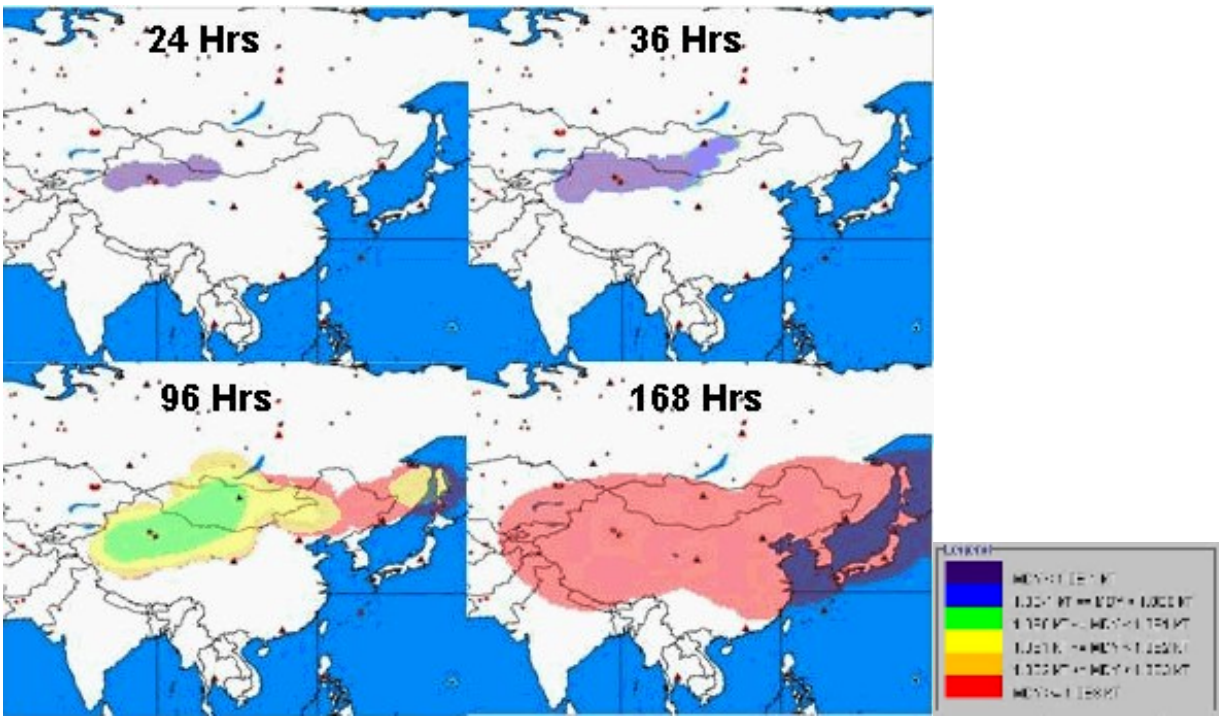

Figure 2. Progression of ^{135}Xe plume from hypothetical underground nuclear test at Lop Nor China.

The twice-daily plots were compiled to make a plot of the minimum MDY obtainable over the region around the hypothetical source location for each particular release and for each of the radionuclides being analyzed, as in Figure 3. The minimum MDY reached at planned sampling locations throughout 2001 was studied to obtain an overall assessment of the efficacy of the planned air-sampling network.

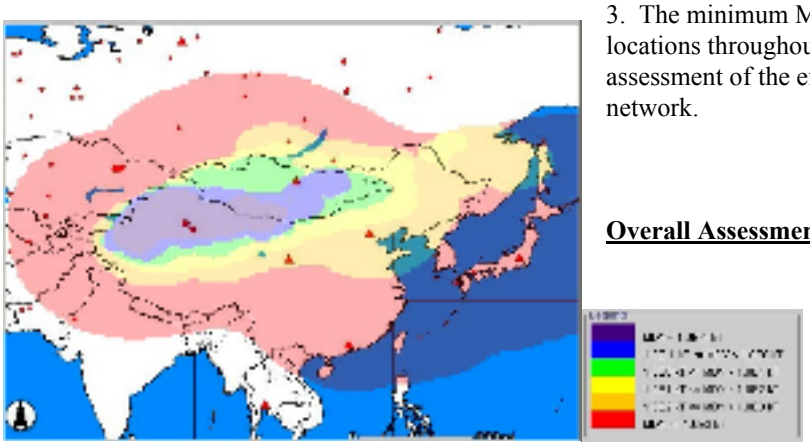

Figure 3. Example of MDY plot for ^{135}Xe.

Overall Assessment

Comparison of OMEGA and HYSPLIT Results

OMEGA is considered by many to be the most accurate atmospheric transport model available. It uses a fine scale grid and Lagrangian dispersion methods in both the horizontal and vertical planes. Its algorithms include calculations to account for planetary boundary layer effects that occur near the Earth's surface. The planetary boundary layer has a significant effect on atmospheric transport in rough terrain. However, it takes a long time to run a problem using OMEGA. HYSPLIT is considered to be less accurate than OMEGA, but it has the advantage of running much faster so that several problems can be modeled in a day. OMEGA was used to provide a baseline comparison for HYSPLIT, improving confidence in HYSPLIT results. HYSPLIT was then used to model the remaining problems.

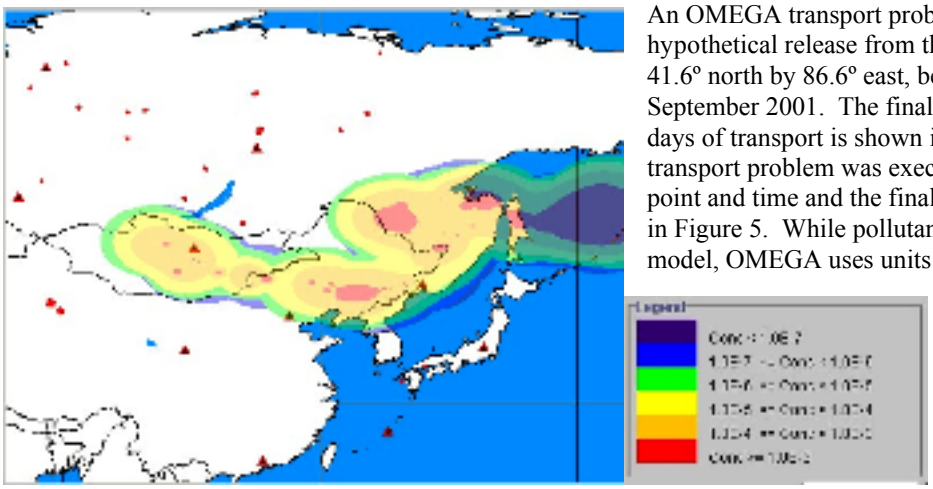

Figure 4. Plot of OMEGA predicted concentrations from plume emanating

An OMEGA transport problem was executed on a hypothetical release from the Lop Nor origin point, 41.6º north by 86.6º east, beginning at 0600 UTC on 10 September 2001. The final concentration plot after ten days of transport is shown in Figure 4. A HYSPLIT transport problem was executed with the same release point and time and the final concentration plot is shown in Figure 5. While pollutant mass is normalized in each model, OMEGA uses units of ng/m^3 while HYSPLIT uses kg/m^3, therefore, the HYSPLIT concentration values must be multiplied by a factor of 10^{12} to compare to OMEGA concentration values. In both models the center of the plume proceeded eastward at approximately the same rate. The centerline of the two plumes followed approximately the same path, however, the OMEGA plume separated into multiple globules while the HYSPLIT plume remained one continuous mass. Also, the centerline of the OMEGA model plume followed a path to the north of the HYSPLIT model. The centerline of the OMEGA model plume passed over Sakhalin Island while the centerline of the HYSPLIT model plume passed over Honshu, the largest island of Japan. In addition, the HYSPLIT plume diffused much more north and south of the centerline of travel compared to the OMEGA plume. Finally, the concentration values of the HYSPLIT plume are an order of magnitude smaller than the OMEGA values.

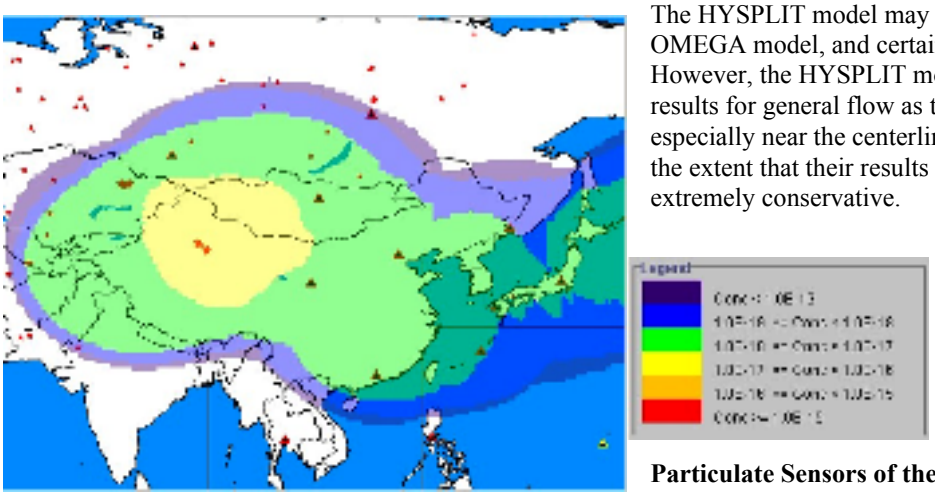

Figure 5. Plot of HYSPLIT predicted concentrations from plume emanating from Lop Nor, China on

The HYSPLIT model may not be as accurate as the OMEGA model, and certainly the results are different. However, the HYSPLIT model provides similar results for general flow as the OMEGA model, especially near the centerline of the plume flow and to the extent that their results are different, HYSPLIT is extremely conservative.

Particulate Sensors of the IMS Array

The planned array of particulate sensors should provide sufficient coverage of the Lop Nor region. The HYSPLIT model shows that a plume emanating from a test site in the Lop Nor region and carrying as little as 0.1 percent of the ^{140}Ba produced by a nuclear detonation can be detected down to less than 1 kiloton TNT equivalent yield during all months of 2001, the year for which atmospheric transport was modeled. Figure 6 shows the composite MDY for the Lop Nor ACD baseline. It must be emphasized that the technology almost certainly exists among countries with experience in nuclear weapons testing to test underground in a way that provides a high level of confidence that no particulate debris will escape the test cavity. The 0.1 percent debris release was chosen for comparison purposes and much less, or even no, particulate debris may escape. However, over the years there have been reports of accidental and intentional releases of significant amounts of debris from the cavities of

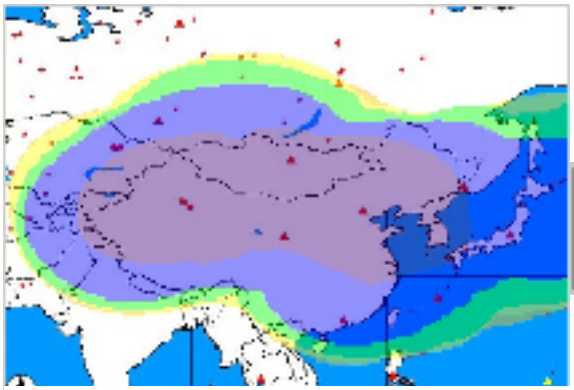

Figure 6. Plot of MDY for Ba-140 from hypothetical test at Lop Nor on 10

underground nuclear tests.[4] A tenth of a percent, or much more, of the particulate debris may escape under the right circumstances.

Radioxenon Sensors of the IMS Array

The planned array of noble gas, or radioxenon, sensors is not sufficient to provide reliable coverage of the Lop Nor region. Although a plume escaping from a test cavity near the center of the test range would reach several sensors, the travel time involved will often allow the ^{135}Xe to decay below the minimum detectable activity before samples can be collected and measured. Figure 7 shows the composite MDY for the Lop Nor ACD baseline. The planned IMS radioxenon station array was found to be capable of detecting debris from a nuclear explosion of 1 kiloton or greater during 9 out of 24 periods analyzed, 10 kilotons or greater 5 out of 24 periods, and 100 kilotons or greater 8 periods out of 24 analyzed. The planned array of radioxenon stations could not be relied on to detect an explosion of 1000 kilotons during 2 of the 24 periods analyzed. The twice-monthly assessment of the capability to detect effluent from underground nuclear explosions is summarized in Table 2 below.

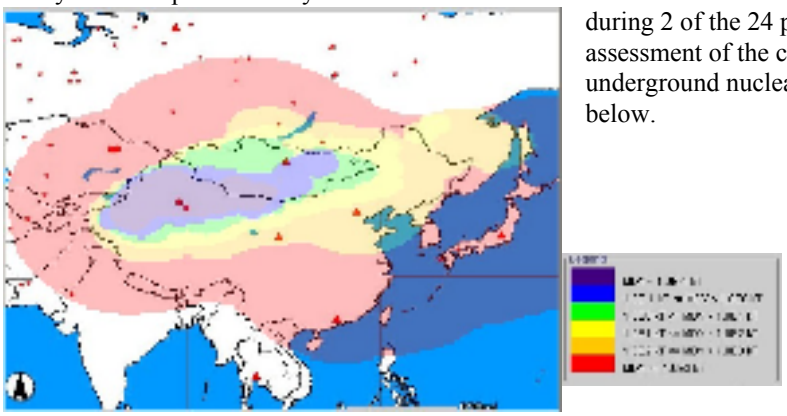

Figure 7. Plot of MDY for Xe-135 from hypothetical test at Lop Nor on 10

Table 2. Twice-monthly assessment of sensor detection capability for 2001.

Probability of Detection										
	MDY ^{135}Xe, IMS Sensor Array					MDY ^{140}Ba, IMS Sensor Array				
Month	Good	Marginal	Poor	MDY (kt TNT)	No. of Stations	Good	Marginal	Poor	MDY (kt TNT)	No. of Stations
1 Jan	X			<1	1	X			<0.1	2
16 Jan	X			<1	1	X			<0.1	2
1 Feb			X	<100	2	X			<0.1	2
16 Feb			X	<1000	1	X			<1	3
1 Mar	X			<0.1	1	X			<0.1	2
16 Mar	X			<1	1	X			<1	2
1 Apr		X		<10	2	X			<1	3
16 Apr		X		<10	1	X			<1	2
1 May	X			<1	1	X			<0.1	1
16 May			X	<100	1	X			<0.1	1
1 Jun		X		<10	2	X			<1	2
16 Jun			X	<1000	1	X			<1	2
1 Jul		X		<10	2	X			<1	2
16 Jul			X	<100	2	X			<1	4
1 Aug		X		<10	1	X			<1	3
16 Aug			X	<100	1	X			<0.1	1
1 Sep	X			<1	1	X			<1	3
16 Sep			X	<100	1	X			<1	2
1 Oct			X	<100	2	X			<1	3
16 Oct	X			<0.1	1	X			<0.1	1
1 Nov		X		<10	1	X			<1	1
16 Nov			X	<100	1	X			<0.1	3
1 Dec			X	<100	1	X			<1	3
16 Dec	X			<1	1	X			<0.1	1

Optimization of Future Station Deployments

Additional radioxenon sampling sites were selected and analyzed to see if the detection capability could be improved. Adding stations in Mongolia at 45.4 degrees north latitude by 91.1 degrees east longitude and at 43.0 degrees north latitude by 96.6 degrees east longitude, along with a station in Kazakhstan at 42.7 degrees north latitude by 79.9 degrees east longitude would improve detectability significantly. The sensors are listed in Table 3 and shown in Figure 8. With these additional stations the sensor array would be assessed as detecting effluent from nuclear explosions below 1 kiloton yield during every period analyzed, as shown in Table 4.

Table 3. Recommended sensor locations to enhance IMS Radioxenon array.

Station Code	Location			Sensor Type	IMS stipulated Minimum Detectable Concentration
	Latitude	Longitude	Place Name		
MNGX1	45.4	91.1	Chinese Border, Mongolia	Noble Gas	1 mCi for Xe-135
MNPX2	43.0	96.6	Chinese Border, Mongolia	Noble Gas	1 mCi for Xe-135
AZGX3	42.7	79.9	Chinese Border, Kazakhstan	Noble Gas	1 mCi for Xe-135

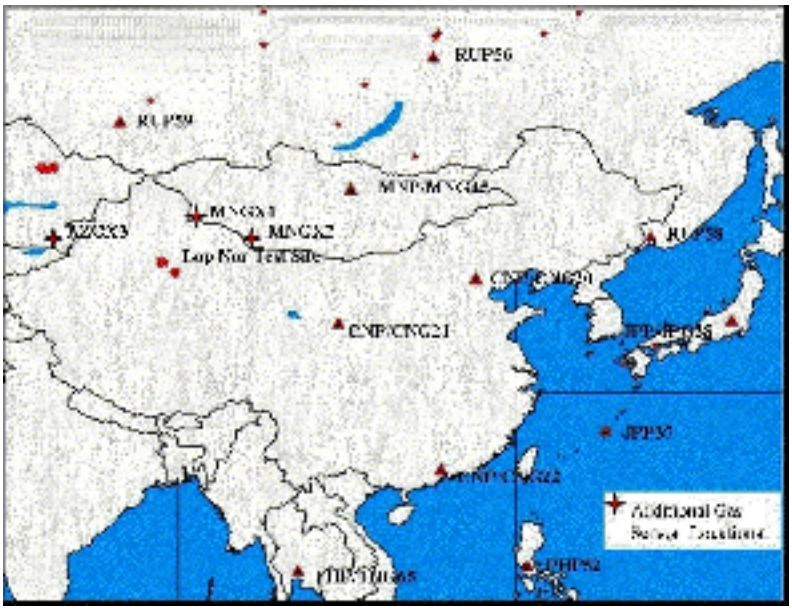

Figure 8. Recommended additional sensors to enhance detection capability of IMS network for Lop Nor.

Table 4. Twice-monthly assessment of sensor detection capability for 2001 with additional sensors.

Probability of Detection										
	MDY ^{135}Xe, Recommended Enhanced Array					MDY ^{140}Ba, IMS Sensor Array, No Enhancements Recommended				
Month	Good	Marginal	Poor	MDY (kt TNT)	No. of Stations	Good	Marginal	Poor	MDY (kt TNT)	No. of Stations
1 Jan	X			<0.1	2	X			<0.1	2
16 Jan	X			<0.1	2	X			<0.1	2
1 Feb	X			<0.1	1	X			<0.1	2
16 Feb	X			<0.1	1	X			<1	3
1 Mar	X			<0.1	2	X			<0.1	2
16 Mar	X			<0.1	1	X			<1	2
1 Apr	X			<0.1	2	X			<1	3
16 Apr	X			<0.1	1	X			<1	2
1 May	X			<0.1	1	X			<0.1	1
16 May	X			<0.1	1	X			<0.1	1
1 Jun	X			<1	1	X			<1	2
16 Jun	X			<0.1	1	X			<1	2
1 Jul	X			<0.1	1	X			<1	2
16 Jul	X			<0.1	1	X			<1	4
1 Aug	X			<0.1	2	X			<1	3
16 Aug	X			<0.1	1	X			<0.1	1
1 Sep	X			<0.1	1	X			<1	3
16 Sep	X			<0.1	2	X			<1	2
1 Oct	X			<1	1	X			<1	3
16 Oct	X			<0.1	4	X			<0.1	1
1 Nov	X			<0.1	1	X			<1	1
16 Nov	X			<0.1	1	X			<0.1	3
1 Dec	X			<0.1	1	X			<1	3
16 Dec	X			<1	3	X			<0.1	1

CONCLUSIONS AND RECOMMENDATIONS

Planned Radionuclide Monitoring Array

The planned IMS radionuclide monitoring array is insufficient to provide reliable coverage of the Lop Nor region, unless particulates escape the test cavity. Xenon-135, the fission product most likely to provide proof of a nuclear detonation, will frequently decay to below detectable limits before it can be collected and measured, because of the length of time required for transport. While the array of particulate sensors is probably as good as achievable, it is also true that it is much easier to contain particulate fission products within the test cavity.

The most effective solution for the Lop Nor region would be the addition of three radioxenon collection and measuring stations. Two should go in Mongolia near the Chinese border and near the coordinates 45.4 degrees north by 91.1 east and 43 degrees north by 96.5 east. The third should go in Kazakhstan, also near the Chinese border and near the coordinates 42.7 degrees north by 79.9 degrees east. A less expensive alternative may be to substitute one of the additional stations in Mongolia for the planned station near Ulan Bator. However, both additional stations in Mongolia would be needed to lower the estimated MDY to less than 10 kt under the conditions described in this paper. No cost/benefit analysis was attempted in this study and issues affecting the positioning of sampling sites at the specified locations has not bee examined.

Future Work

Two major efforts need to be accomplished to expand and refine the analysis performed so far. The period reviewed needs be expanded over several years in an effort to see any seasonal variation and to determine if the monthly airflow does follow a predictable pattern. In addition, the HYSPLIT diffusion model needs to be optimized for particulates and rerun for ^{140}Ba.

It has been implicitly assumed that the airflow in each period examined during calendar year 2001 is typical of that period for any calendar year. This may or may not be true. Several years of data have been processed with the HYSPLIT model to assess this issue. The current availability of archived meteorological data was sufficient to allow five years, from 1997 through 2001, to be analyzed. This period of time will also permit identification of seasonal patterns. The model runs have been completed; however, the large volume of data could not be analyzed in time to be included in this paper.

HYSPLIT can be run as a diffusion model, more applicable to gaseous pollutants, or as a dispersion model, more applicable to particulate pollutants. Since the debris will not escape a properly stemmed test cavity unless it is a gas, it seemed sensible to run HYSPLIT as strictly a diffusion model. Late in the analysis it was recognized that a particulate such as ^{140}Ba might escape the test cavity as a gas then soon precipitate. It would then behave as other particulates and its atmospheric transport might be better modeled that way. It is not clear whether running HYSPLIT in the dispersion mode would provide a better representation of particulate debris dispersal. Consideration should be given to running the HYSPLIT model in the dispersion mode with values entered for dry deposition of barium particulates.

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