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Detecting Clandestine Reprocessing Activities in the Middle East

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ABSTRACT
Remote monitoring of krypton-85 from undeclared reprocessing of spent nuclear fuel could be part of a fissile material cut-off treaty, could serve as an additional measure for the IAEA safeguards system to monitor compliance with the Non-Proliferation of Nuclear Weapons Treaty, and could be an important verification tool of a reprocessing moratorium or Nuclear Weapon Free Zone in the Middle East or East Asia. Atmospheric transport modelling is applied to determine the area over which krypton-85 emissions from undeclared reprocessing activities at various levels in the Middle East would still be detectable against the high krypton-85 background from reprocessing in historical weapon programs in the United States and USSR as well as more recent and ongoing commercial reprocessing in France and the U.K. Analysis of annual wind flow over Israel's Dimona facility, the only operating reprocessing site in the region, suggests that a known reprocessing plant could be monitored with one or a few fixed monitoring stations. Random air sampling for krypton-85 analysis, perhaps using drones, may be feasible for reliable and timely detection of clandestine reprocessing plants against the krypton-85 background but would require on the order of 50–100 air samples per day. Ending reprocessing at La Hague in France and at Sellafield in the UK and the resulting decline of the krypton-85 background over time would reduce to about 10 the number of daily samples required to monitor the Middle East.

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Introduction

A nuclear weapons free zone (NWFZ) prohibits the development, production, testing, possession, stationing, or use of nuclear weapons inside a designated territory. A Nuclear Weapon-Free Zone in the Middle East (MENWFZ) has been discussed for decades by various organizations and groups. Recently the idea has been receiving renewed attention following the agreement on limits on Iran's nuclear program.[1] A 1974 proposal by Iran and Egypt for the establishment of a NWFZ was endorsed in a resolution by the United Nations General Assembly.[2] Furthermore, a report from the UN Office for Disarmament Affairs had proposed in 1991 that the zone would

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include the countries of the Arab League plus Iran and Israel.[3] All of those countries, except for Israel, are already parties to the Non-Proliferation Treaty (NPT).

The separation of plutonium by the chemical reprocessing of spent nuclear fuel is one means for obtaining fissile material for a nuclear weapon. Reprocessing also has civilian applications, but none can currently be economically justified.[4] New reprocessing plants therefore can be taken as an indicator of a possible nuclear weapons agenda. A regional ban on reprocessing could also be part of a Fissile Material Cutoff Treaty (FMCT). Undeclared plutonium separation is already prohibited under the NPT. The ability to verify with high confidence the absence of reprocessing therefore is critical to the verification of a regional NWFZ or FMCT, and would greatly increase the verifiability of the NPT.

In either case, verification of compliance would be essential. Compliance could be verified by mutual inspections or by a newly formed regional organization in collaboration with the IAEA.

As analyzed in previous research,[5] reprocessing plants release krypton-85, a 10.76-year half-life noble gas that is created as a fission product during the irradiation of nuclear fuel. When fuel rods are dissolved to extract the plutonium, krypton-85 is released, enters the off-gas stream and, at some point, is released into the atmosphere. The resulting plume of krypton-85 is subject to prevailing wind conditions and is gradually dispersed, but its atmospheric concentration remains detectable within a certain distance downwind.[6] Other research has demonstrated the general feasibility of atmospheric krypton-85 concentrations based on measurements taken downwind from civilian reprocessing plants.[7]

The detectability of clandestine reprocessing plants via their krypton-85 emissions is analyzed for various scenarios in the Middle East below. The goal is to determine the number and locations of air samples required to ensure timely detection of reprocessing activities in the region.

Reprocessing of spent fuel to separate plutonium

Plutonium is most commonly produced by separating it from irradiated nuclear fuel using the PUREX (plutonium uranium extraction) method by dissolving spent nuclear fuel in nitric acid.[8] The plutonium is extracted from the nitric acid solution in a light organic solvent. During the dissolution of the spent fuel rods, krypton-85 is released and enters the off-gas stream of the facility.

The only known reprocessing plant in the Middle East is located in Israel at the Negev Nuclear Research Center near Dimona. Israel acknowledges the existence of the center including the operation of a heavy water reactor, but claims its purpose to be for general nuclear research and does not acknowledge the existence of the underground reprocessing plant. The Dimona facility is not under international safeguards. Historically, heavy water and graphite moderated reactors fueled by natural uranium have been the primary reactor types used for producing weapon-grade plutonium.[9]

Another example of a clandestine nuclear activity in the region was the Syrian reactor at the Al Kibar site that was destroyed by Israeli bombing in 2007. The facility was allegedly for military purposes, specifically for plutonium production, which was confirmed in May 2011 by the IAEA.[10]

Clandestine reprocessing programs require a source of plutonium. Because plutonium is produced by neutron absorption in uranium, irradiated nuclear fuel from a local reactor could be used as a source. However, irradiated uranium could also be imported from outside the country, e.g., in the form of spent nuclear fuel. Thus, the presence of unsafeguarded reactors can be an indicator but is not a necessary condition for a clandestine reprocessing program.

Industrial scale reprocessing plants that separate ton quantities of plutonium per year take years of planning, commissioning, and testing to meet modern regulatory standards. However, it has been argued that an existing facility of another type (e.g., dairy, wine, or oil processing plant) could be remodeled within a year to function as a "quick and simple" reprocessing plant for producing enough plutonium for a few bombs.[11] Compared to an industrial facility, as found in nuclear weapon states and Japan, such a facility might have safety and radiation protection problems, but might nonetheless produce weapon-usable quantities of plutonium.

The IAEA defines a significant quantity (SQ) of nuclear material as "the approximate quantity of nuclear material in respect of which […] the possibility of manufacturing a nuclear explosive device cannot be excluded."[12] For plutonium-239, this threshold is set at 8 kg for a first-generation nuclear device including losses during manufacturing. A quick and simple reprocessing plant, as described above, with a capacity to process 50 tons of heavy metal (tHM) from light water reactor spent fuel per year[13] could separate enough plutonium-239 for a single bomb in about a week.[14]

Remote detection of reprocessing plants

The amount of krypton-85 present in spent fuel depends on the type of fuel, the irradiation time and storage time before reprocessing. In previous studies, it has been determined that spent fuel contains a minimum of about 1.6E+13 Bq of krypton-85 per kilogram of weapon-grade plutonium before allowing for krypton-85 decay.[15] This means that for an SQ of plutonium, i.e., 8 kg, about 1.28E+14 Bq of krypton-85 would be released from fresh spent fuel into the off-gas system of the facility. Reprocessing activities produce large volumes of waste gases. It is technically possible, but difficult and expensive, to extract the krypton-85 from the gas stream and retain it in the facility. Potential methods, such as cryogenic distillation, fluorocarbon absorption, carbon dioxide absorption, and selective physical adsorption, have been demonstrated on a laboratory scale and could capture 99% or more of the krypton.[16] Given the required technical level of expertise and lack of previous deployment of these methods, however, the following scenarios assume that all the krypton-85 from a quick and simple clandestine reprocessing plant would be released into the atmosphere.

Figure 1. Regional overview. Shown in gray are the countries that are considered for a MENWFZ, in dark gray countries with nuclear programs or ambitions, and in light gray countries without.

The concentration of krypton-85 in the atmosphere has been increasing since reprocessing started on an industrial scale in 1945. After being well mixed with the global air masses for decades, historic releases have led to a baseline level around the world. In 2010, the baseline level was 1.36 Bq/m^3 in the Northern Hemisphere and 1.30 Bq/m^3 in the Southern Hemisphere.[17] The Northern Hemisphere concentration is greater because all major reprocessing plants have been built in the Northern Hemisphere and there has been slow mixing across the equator.

Elevated concentrations of krypton-85 above baseline alone do not indicate clandestine reprocessing activities. Higher concentrations could be caused by known facilities, such as La Hague in France and Sellafield in the United Kingdom, which are responsible for over 90% of krypton-85 emissions worldwide. The downwind effects of krypton-85 plumes of known industrial reprocessing plants must also be considered in any analysis.

Countries to be monitored

The proposed region for the MENWFZ, shown in Figure 1, contains 24 countries covering 15.1 million km^2. Of these countries, ten have or have had nuclear programs or announced nuclear ambitions, covering a total of about 9.8 million km^2 within the proposed region: Algeria, Egypt, Iran, Iraq, Israel, Jordan, Libya, Saudi Arabia, Syria, and the United Arab Emirates (see Table 1). Most of the research reactors listed in Table 1, however, could not produce significant quantities of plutonium in a year.[18] Except for Israel, these countries are signatories to the NPT, which means that their current or upcoming reactors and spent fuel are under safeguards.

Table 1. Past, present or planned nuclear programs of countries in the Middle East.[32]

Country	Nuclear program
Algeria	Two research reactors, uranium deposits
Egypt	Two research reactors, plans to acquire nuclear power reactors
Iran	Research, power reactors and uranium mines and mills.
Iraq	Abandoned nuclear weapon program
Israel	Heavy-water reactor, reprocessing plant, nuclear weapons
Jordan	Research reactor, plans for a civilian nuclear power program
Libya	Research reactor, abandoned nuclear weapon program
Saudi Arabia	Plans for a civilian nuclear power program
Syria	Reactor at Al Kibar (destroyed), miniature neutron source reactor
United Arab Emirates	Four power reactors under construction

This paper discusses the detectability of reprocessing plants under four scenarios in each of two regional cases. In the first case, all countries proposed for the MEN-WFZ are included. In the second regional case, in which only limited resources are available, only the countries with existing or planned nuclear programs are included.

In principal, the task of detecting clandestine reprocessing activities can be divided into the detection of unknown facilities and the monitoring of known facilities.

Monitoring of known facilities

As Dimona is the only known reprocessing plant in the region, it is used here as a case study for the remote monitoring of a known facility. However, the following analysis could also be applied to other sites of special interest. It is assumed that Dimona separates about 18 kg of plutonium per year.[19] This would result in an annual emission rate of at least about 2.9E+14 Bq of krypton-85.[20] Forward simulations of the plume dispersion for emissions at that rate are conducted to show the detectability against the background downwind from Dimona. The simulations have been done with the Lagrangian particle dispersion model Flexpart 8.23,[21] and Global Forecast System (GFS) historical meteorological data at 0.5° spatial resolution provided by NCEP.[22] For each day of 2010, a plume originating at Dimona has been simulated for 7 days. The fraction of days on which emissions from Dimona would be observable against the background at downwind locations is shown in Figure 2. In this study, to be counted as observable, the total krypton-85 concentration in the simulation must exceed two combined standard deviations from the detector uncertainty and the background fluctuations caused by other reprocessing facilities.

As shown in Figure 2, a facility need not be surrounded by monitoring stations. A station a few kilometers downwind from the facility (same grid cell on the map) would yield the most frequent coverage. Since detectability decreases over distance, the station should be as close as possible. In cases where the station needs to be located further away, placement according to local wind patterns would maximize detection probability. Taking Dimona as an example, two or three stations in the most common wind directions would be sufficient for nearly constant monitoring.

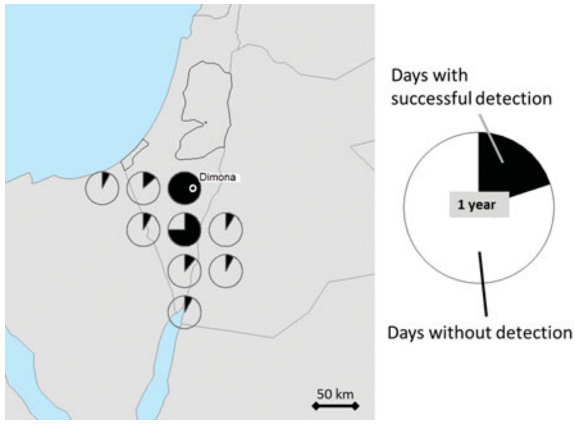

Figure 2. Dimona and probabilities to detect an elevated krypton-85 concentration assuming continuous operation with about 18 kg plutonium per year. The map shows possible locations for fixed monitoring stations on a grid of 50 km. The most common wind directions are towards south-southeast and west-southwest.

Every facility is subject to a special wind pattern that, if utilized correctly, can minimize the number of needed monitoring stations and maximize the detection probability of krypton-85 emissions. Multiple stations could virtually cover all possible downwind directions to counter timed batch releases aimed to circumvent detection. It would be highly unlikely that a proliferator could schedule the reprocessing and off-gas process to await an unlikely wind pattern to avoid detection by fixed monitoring stations.

Batch emissions from the Dimona facility would lead to higher probabilities of detection – but naturally only following the days when krypton-85 is emitted. However, if a krypton retention system would be successfully realized for a facility of this size, remote sampling methods would be unable to detect unusually high krypton-85 concentrations and would make it necessary to decrease the distance to the facility or apply stack emission monitoring. The current scientific literature does not show the existence of a krypton retention system beyond laboratory application.[23]

Detecting clandestine reprocessing facilities

To determine the detectability of an active, clandestine reprocessing plant in this region, krypton-85 emissions from multiple, hypothetical plants have been followed with atmospheric transport modeling. A total of 16 notional locations have been situated across the Middle East to cover all regions and various meteorological conditions, see Figure 3. The parameters determining the detectability are discussed in the following sections.

Emission profiles

The krypton-85 emission rates are based on three different reprocessing rates. The plumes and their detectability are simulated for 1 SQ per week, 1 SQ per month,

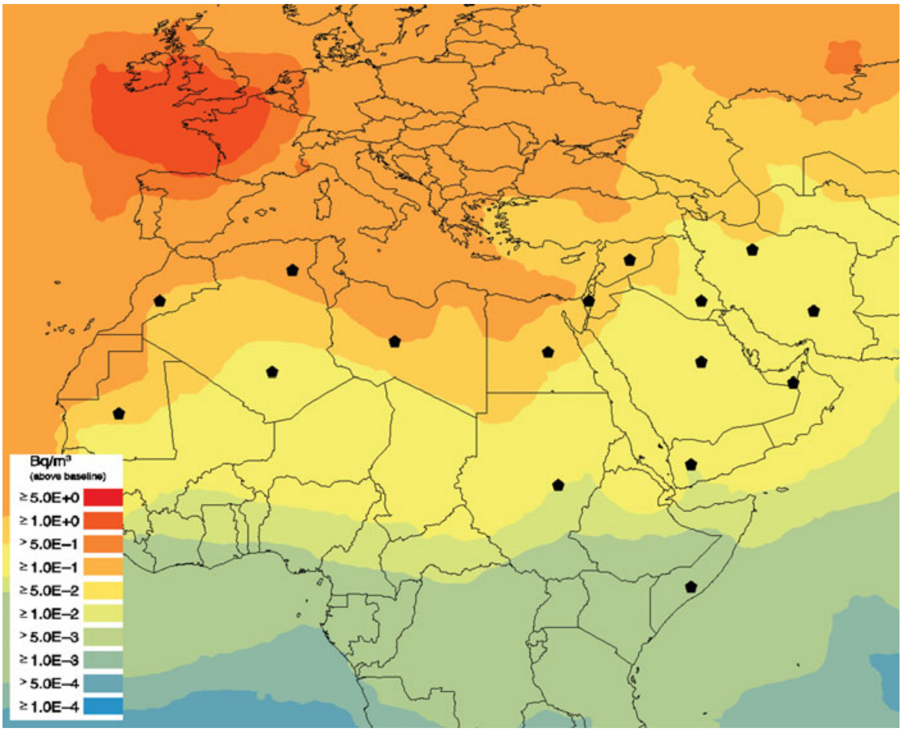

Figure 3. One standard deviation of atmospheric krypton-85 concentration above the background of ~1.36 Bq/m³. The reprocessing plant at La Hague is the largest and closest emitter of krypton-85. Recent emissions from La Hague are responsible for most of the background fluctuations. Other known sources in Europe and the Middle East are Sellafield, United Kingdom, and Dimona, Israel, of which the latter would not be active in a MENWFZ. The black markers show the locations of different simulated emissions from a hypothetical reprocessing plant. These locations are used to determine the average detectability of an assumed clandestine reprocessing facility in the Middle East.

and 1 SQ per year to represent various sized operations. It should be noted that 1 SQ per week and even 1 SQ per month would be quite large reprocessing programs if sustained over time.[24]

Gaseous effluents from industrial facilities are usually released in batch emissions. Also, the emissions from a reprocessing plant can take various forms, depending on throughput of spent fuel, the design of the off-gas system and the schedule of operation. To take various emission schemes that a proliferator might choose into account, two emission profiles are considered in the simulations. First, the emissions are assumed to be constant over time. Secondly, the emissions are released as a batch only on one day per week. The emission pattern of a clandestine facility might be somewhere between these two variants. For the following calculations of the detectability, both emission profiles are considered.

Background concentration scenarios

Various background scenarios are considered in the analysis. Today's concentration background consists of two components: an almost homogeneous baseline

Table 2. Overview of scenarios: Two different sets of countries that could be monitored in a MENWFZ; three different rates of plutonium production to account for various scales of operation; two emission profiles to account for the most adverse batch emissions; four background scenarios to include today's and future background levels.

Regions	• Arab League, Israel and Iran (24 countries, 15.1 million km²) • Countries with nuclear programs or plans (10 countries, 9.8 million km²)
Release locations	• 16 hypothetical locations
Plutonium-separation rates (1 SQ = 1 significant quantity = 8 kg of plutonium)	• 1 SQ per week • 1 SQ per month • 1 SQ per year
Emission profiles	• Continuous • One day per week
Background scenarios	• Today's baseline and fluctuations • Today's baseline without fluctuations • 10 years after declared reprocessing ends • 30 years after declared reprocessing ends

due to the long-term accumulation of krypton-85 in the atmosphere, and a short-term increase due to recent emissions from active industrial reprocessing plants. If krypton-85 emissions from declared facilities were stopped, due either to a general abandonment of reprocessing or the retention of krypton-85, the short-term peaks in the concentration due to the wandering plumes from the industrial facilities would vanish within a few days and the baseline level would start to decay with a half-life of 10.76 years.

Four scenarios for the krypton-85 background are considered below: today's baseline with today's emissions[25]; and today's baseline without fluctuations as if declared reprocessing has just ended, 10 years after cessation, and 30 years after.

Simulation of emissions from clandestine facilities

For each location, the emitted krypton-85 plume has been followed for 10 days of transport time after release.[26] Emissions have been simulated for daily releases over the course of one year so that seasonal effects can be included. As with the previously described simulations, these simulations used the particle dispersion model Flexpart and meteorological data at 0.5° spatial resolution provided by NCEP.[27] The output concentrations are representative for the air within the Planetary Boundary Layer, with a height that can vary from a few hundred meters to two kilometers depending on meteorological conditions and time of day.

For each of the 16 locations, the dispersion of assumed emissions has been calculated for the year 2010 and daily snapshots of the plume have been stored. Based on the daily snapshots, the area of detectability can be determined for each of the locations and for every day of the year. The scenarios considered are listed in Table 2.

Random sampling and detection threshold

From previous studies,[28] it has become clear that today's atmospheric background of krypton-85 is too high to allow wide-area environmental sampling based on fixed monitoring stations because the necessary density of monitoring stations would be prohibitively costly. Therefore, this paper considers a monitoring regime based on mobile sampling of the lower atmosphere up to a few hundred meters in altitude. In this scenario, a certain number of air samples are taken per day at random locations within the monitored area. Then the air samples would be delivered to one of possibly several regional laboratories, where they would be analyzed for their krypton-85 concentration. With current procedures, air samples of about 10 m^3 are typical,[29] but could be compressed for easier transport. Next-generation krypton-85 detectors based on magneto-optical atom traps could reduce the required sample volume down to about 1 liter,[30] which would further facilitate sampling and transport.

Any air sample is expected to contain the baseline concentration of krypton-85. Explanations for an elevated concentration could be random measurement errors, emissions from declared facilities, or emissions from clandestine facilities. The measurement uncertainty is assumed to be 3%. Based on the emissions from declared facilities, the standard deviation of the atmospheric concentration at each location has been calculated with atmospheric transport modelling, see Figure 3. The emission patterns of known reprocessing plants are not published. Therefore, constant emissions throughout the year have been assumed for the calculation of the background fluctuations to serve as a general detection criterion.

Atmospheric transport modelling was applied to simulate krypton-85 plumes for sixteen hypothetical locations in the Middle East. The area in which each plume would result in a detectable concentration elevated above the background was calculated. "Elevated" in this study was defined as exceeding two standard deviations of the combined detector uncertainty and the fluctuations due to upwind declared facilities. The resultant footprint represents the size of the area where air samples would yield a successful detection of krypton-85 if there were a clandestine reprocessing plant in operation. To calculate the general detectability of one clandestine facility over a larger area, these footprints were averaged over one year and all sixteen locations. The size of the footprint depends not only on the meteorological conditions, but also on the assumed emission patterns (constant or batch), the overall reprocessing rate and the background conditions, for which all combinations were considered. The various locations can exhibit a variation in the footprint size of about a factor of two in both directions from the average.

Timeliness of detection

A clandestine facility that only slowly separates plutonium will have a small footprint where krypton-85 can be measured above background. However, the detection of such a facility is not as urgent as a facility with a higher output of plutonium. The detection goal is assumed to be the detection of a clandestine reprocessing plant within the time it needs to produce 1 SQ of plutonium. The time lines and emission levels are illustrated in Figure 4 for three different reprocessing rates.

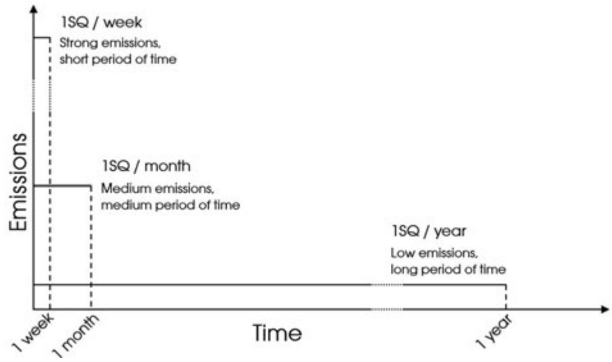

Figure 4. Qualitative timelines and emission levels for different plutonium separation rates. The production of 1 SQ of plutonium (8 kg) creates at least 1.28E+ 14 Bq of krypton-85. The emission level and emission time depend on the production rate of plutonium. A high plutonium production rate leaves a larger footprint and is easier to detect, but allows less time for a detection before 1 SQ has been produced. Accordingly, a low plutonium production rate may be more difficult to detect due to its lower emissions, but it allows more time for detection before 1 SQ has been produced.

Calculation of the detectability

Once the average footprint for detectability of a clandestine reprocessing plant a is determined, the probability p of taking an air sample with a two-standard deviation elevated krypton-85 concentration within a region of size A can be calculated. When taking n samples within the large area A at random locations the probability p of taking at least one sample from subarea a is

$$p = 1 - \left(1 - \frac{a}{A}\right)^n$$

When sampling on multiple days d at random locations within the area A, the overall probability P for at least one successful detection is calculated by

$$P = 1 - (1 - p)^d$$

When aiming for a certain detection probability P, the number n of samples needed per day over multiple days d can be calculated by

$$n = \frac{ln\,(1 - P)}{d \cdot ln\left(1 - \frac{a}{A}\right)}$$

In the following, a desired detection probability of $P = 90\%$ is used to calculate the number of samples needed.

Results

This section presents the numbers of random air samples needed per day to achieve 90% probability to detect hypothetical clandestine reprocessing plants in the Middle East. As described above, two different regional extents in the Middle East are considered.

Table 3. Number of samples per day at random locations in all Middle Eastern countries to ensure 90% detectability of clandestine reprocessing plants. Results for continuous emissions and batch emissions on one day per week are usually close together with an uncertainty of 5%; only where a range is given the difference is significantly higher. The ranges for low reprocessing rates for most background scenarios are much larger with the higher number stemming from continuously low emissions quickly dissipating into the background, while the lower number is for batch emissions which are more easily detected.

Plutonium separation rate Timely detection within	1 SQ/year 365 days	1 SQ/month 30 days	1 SQ/week 7 days
Background and active emissions today	85–310	90	92
Background today without emissions	60–190	72	75
Background 10 years after emissions stopped	33–45	38	36
Background 30 years after emissions stopped	9	9	8

If all member states of a MENWFZ are monitored equally, a total of 15.1 million km^2 must be covered. Table 3 lists the numbers of samples that need to be taken per day at random locations across this area in order ensure 90% detectability of clandestine reprocessing plants. With today's background baseline concentration and fluctuations from declared reprocessing plants, less than 100 samples must be taken per day to detect large- and medium-scale reprocessing within the time required to separate an SQ of plutonium. The emission profile, as discussed above, does not have a large impact on the detectability of these reprocessing rates; the results vary only by about 5%. However, for the detection of small-scale reprocessing between 85 and 310 samples would be needed, depending on the emission profile. When low and continuous emissions are dispersed in the background, they become undetectable quickly within a relatively short distance, which makes detection difficult and requires more random samples. On the other hand, if at the same low reprocessing rate emissions are released as a batch once per week, the plumes remain detectable above the background over a larger area and the detection probability is similar to higher reprocessing rates. The same reasoning explains the range of 60 to 190 samples per day for this reprocessing rate in today's background level without fluctuations, while higher reprocessing rates are detectable with about 80 samples per day independent of the emission profile. However, in a future scenario when emissions from declared reprocessing have stopped and the background has decayed for 10 or 30 years, the numbers of needed samples per day go down in a similar manner to about 40 or 10 respectively.

The number of samples can be further reduced if only member states that have nuclear capabilities or announced nuclear infrastructure plans are monitored, in which case the area to be covered would be reduced to 9.8 million km^2. The countries that are left out from the focused verification scheme are closer to the equator, where equatorial wind patterns are responsible for a rather vertical transport of air masses, making plumes harder to detect in the horizontal plane. Table 4 shows that the number of needed samples is decreased by a factor of about 2 for each scenario down to about 50 samples per day for large- and medium-scale reprocessing under current conditions, even though the area to be monitored has been reduced only by one third. Small-scale reprocessing activities on the order of 1 SQ per year

Table 4. Number of random samples per day only in the Middle Eastern countries with nuclear capabilities or ambitions to ensure 90% detectability of clandestine reprocessing plants. The values are averaged over the hypothetical locations only in monitored countries. Results for continuous emissions and batch emissions on one day per week are usually close together with an uncertainty of 5%; only where a range is given the difference is significantly higher. The ranges for low reprocessing rates for most background scenarios are much larger with the higher number stemming from continuously low emissions quickly dissipating into the background, while the lower number is for batch emissions which are more easily detected.

Plutonium separation rate Timely detection within	1 SQ/year 365 days	1 SQ/month 30 days	1 SQ/week 7 days
Background and active emissions today	50–150	52	51
Background today without emissions	35–95	41	41
Background 10 years after emissions stopped	20–25	21	20
Background 30 years after emissions stopped	5	6	5

would again result in a range of 50 to 150 random samples per day depending on the emission profile. For future scenarios when the background has decayed for 10 or 30 years, the number of random samples will align for all reprocessing rates to about 20 or 5 per day respectively.

In summary, except for low emission rates with continuous emissions in a high background scenario, the numbers of needed samples per day are about equal for the timely detection of reprocessing plants of various sizes.

Implementation

Collecting tens or a hundred air samples daily over a larger region would present a logistical challenge. The results from Table 3 and Table 4 can be used to balance verification goals, technical feasibility, and financial budgets, and adjust them over time. To achieve the collection of 50 to 100 samples per day across the Middle East or part of it, the most feasible sampling system would be multiple small airplanes or drones, or a few reconnaissance-type aircraft with longer range flying along varying routes and taking multiple air samples per flight. An example of the latter is shown in Figure 5, where three to five aircraft could be sent on daily missions to collect samples at locations that have been randomly chosen before the flight. The air samples could be sent to a central or a few regional laboratories to be analyzed for its krypton-85 concentration.

The detection probability could be further increased with strategic search patterns to cover the area more effectively, e.g., by ensuring a minimum number of samples per country or by avoiding blind spots on too many successive days.

Once the air sample is taken, the transport and analysis may not be time-sensitive from a purely technical point of view, because of the long half-life of krypton-85, but a quick analysis might be desirable for a timely detection of small facilities and to provide confidence in a treaty. Next-generation krypton-85 detectors would allow smaller air samples and shorter measurement times of a few hours, and thus greatly facilitate sampling and analysis.[31]

Figure 5. A possible realization of a verification system that takes air samples at random locations. Airplanes or drones starting from a few airports could take samples within a certain area to most effectively cover the region to be monitored.

The two reprocessing plants in Sellafield are scheduled for closure by 2021 or within a few years thereafter, depending upon their throughputs in completing their existing contracts. This will reduce the background fluctuations over Europe and the Middle East. If La Hague also stopped emitting krypton-85, the fluctuations over the Middle East would almost completely disappear, increasing detectability over time (or lowering the logistical effort to maintain a 90% detection probability). As shown in this study, a decreasing krypton-85 background would greatly facilitate the detectability of clandestine reprocessing activities.

Alternatively, to foster the verifiability of a MENWFZ, La Hague (and Sellafield) could provide stack emission data of krypton-85 to make the fluctuations more predictable. Atmospheric transport modelling could be used to predict the concentration in an air sample for a given time and location. This would make it possible to explain false positive detections of high concentrations and therefore add to the reliability of the verification regime.

If Israel decided to join a MENWFZ or a regional FMCT without answering questions about Dimona's past, wide area environmental sampling could make site access avoidable. Unless an effective krypton-85 capture system has been installed, the absence of ongoing reprocessing at Dimona would become verifiable.

Conclusion

There is a high krypton-85 concentration in the atmosphere from legacy military reprocessing programs, mostly in the United States and Soviet Union during the Cold War, and from civilian reprocessing activities, mostly in La Hague in France and Sellafield in the United Kingdom. This makes it difficult to effectively monitor any treaty that would ban reprocessing for nuclear weapon purposes. Nonetheless, remote monitoring of krypton-85 from undeclared reprocessing could be part of a fissile material cut-off treaty, could serve as an additional measure for the IAEA safeguards system to monitor compliance with the NPT, and could be an important verification tool of a reprocessing moratorium or Nuclear Weapon Free Zone in the Middle East or East Asia. The current atmospheric background concentration of krypton-85 makes it particularly challenging to remotely detect clandestine reprocessing activities at unknown locations and is too high to permit effective and economic wide-area environmental monitoring using fixed stations. However, local sampling programs or fixed stations could be focused to verify the inactivity at known or suspected reprocessing facilities such as Dimona.

For clandestine reprocessing plants at unknown locations, the collection of air samples at random locations over longer periods of time can lead to a timely detection before a SQ of plutonium is separated.

This analysis of the effectiveness of random sampling programs, four krypton-85 emission scenarios were considered: current emissions from La Hague in France and Sellafield in the United Kingdom continue; the current background level without further emissions from ongoing reprocessing at La Hague and Sellafield; the background 10 years after the end of civilian reprocessing; and, the background 30 years after the end of civilian reprocessing. It shows that for the Middle East today, where Israel's Dimona facility is the only operating reprocessing plant, about 50 random air samples per day could be sufficient to ensure a 90% detection probability of medium size clandestine reprocessing plants in Middle Eastern countries with nuclear programs or ambitions. Monitoring all Middle Eastern countries, even those without nuclear plans, would require about 100 random samples per day.

For both regional cases, continuous emissions from smaller reprocessing plants are more difficult to detect under current background conditions and would require collecting up to about three times as many samples per day. However, batch emissions would make even smaller reprocessing plants as detectable as larger operations.

Collecting numerous samples per day across the Middle East could be done using a fleet of small planes or drones, or long range aircraft flying taking multiple samples per flight. The samples would need to be sent to a central laboratory or regional laboratories to be analyzed. However, collecting tens or a hundred of air samples daily over a larger region would be challenging. A cessation of large scale, civilian krypton-85 emissions from reprocessing at La Hague as well as at Sellafield would over time drastically reduce the necessary number of samples required to monitor the Middle East; ultimately less than 10 random samples per day could be needed. As the krypton-85 background falls, smaller reprocessing operations would inevitably become as detectable as larger ones.

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25. As described in M. Schoeppner, "Present and future potential of krypton-85," the background emissions from known reprocessing plants are averaged over the course of one year. The following reprocessing plant emissions (TBq/y) are being considered: Lanzhou (China) 3.59E+14, La Hague (France) 2.26E+17, Kalpakkam (India) 2.40E+14, Trombay (India) 2.40E+14, Dimona (Israel) 2.88E+14, Tokai (Japan) 1.80E+10, Nilore (Pakistan) 2.88E+14, Mayak RT-1 (Russia) 1.40E+16, Zheleznogorsk (Russia) 3.60E+15, Sellafield (UK) 4.53E+16. As described in the section on Emission Profiles, constant emissions for every day over the year, and batch emissions on one day per week have been considered.
26. The simulation of the plumes serves as a basis for different background scenarios. For today's background, including fluctuations from recent emissions, even the plume from

industrial facilities would become undetectable after a few days. However, in scenarios with lowered background, the plume can remain detectable for longer.

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