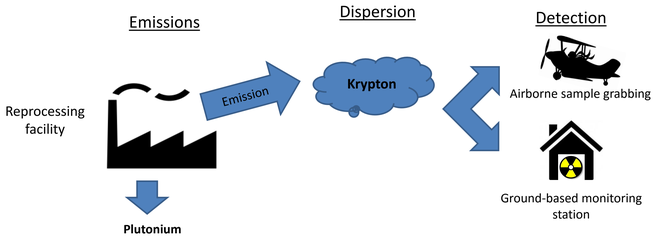
Monitoring known and undeclared reprocessing plants with krypton-85

Michael Schoeppner
Princeton University, Program on Science and Global Security, schoeppner@princeton.edu
Alexander Glaser (Princeton University), Sara Pozzi (University Michigan)
Consortium for Verification Technology (CVT)

Krypton-85 as a tracer

Krypton-85 is an environmental tracer released during reprocessing. It can potentially be used to detect previously unknown reprocessing plants and to remotely monitor known facilities. As a fission product krypton-85 is contained in the spent fuel, and due to its noble gas characteristics it is difficult to contain and thus released during a reprocessing campaign into the atmosphere.



Once airborne the plume is subject to transport by prevalent winds and dispersed. The concentration is diluted over time and distance, but can be detected downwind from the reprocessing plant.

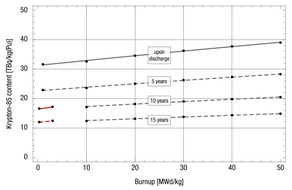
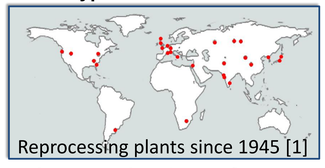
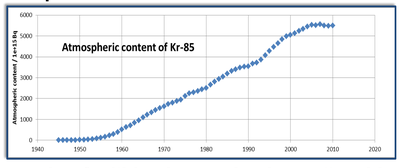


Figure 1: Krypton-85 activity per produced kg of plutonium in spent fuel over burnup. The black lines are for power reactor fuel, upon discharge and various ages before opened for reprocessing. The red lines are for a plutonium production reactor (heavy water) and the dashed red line for 5-year-old spent fuel.

Background today

Ongoing reprocessing since 1945 and the associated release of krypton-85 led to an omnipresent atmospheric background [1]. The only loss process for krypton-85 is its radioactive decay with a half-life of 10.76 years. As long as more krypton-85 is released than is decaying, the background was increasing. Only in recent years reduced krypton-85 emissions led to an equilibrium between emissions and decay.





Over the years the plumes from reprocessing facilities have mixed equally with the Earth's atmosphere creating a baseline of about 1.3 Bq/m³ [2,3]. This is the minimum concentration found virtually everywhere around the world. Downwind from reprocessing plants the plumes from recent emissions create fluctuations on top of this baseline concentration.

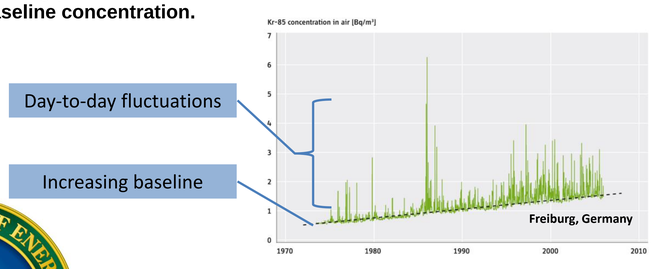


Figure 2: Time series of krypton-85 concentrations at Freiburg, Germany [4]. The monitoring station is located downwind from reprocessing plants at La Hague and Sellafield.

Monitoring known reprocessing plants

Several options exist to monitor known reprocessing plants:

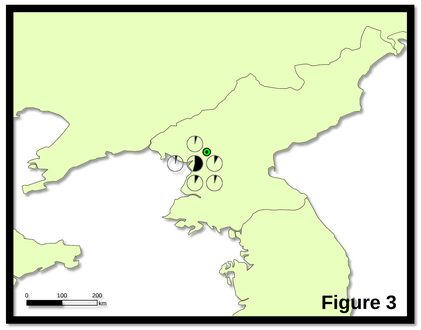
- **When the plant operator is fully cooperative and the design of the plant allows it, the preferred and most informative method to monitor a known reprocessing plant is to apply IAEA safeguards, i.e. access to the plant itself.**
- **When comprehensive safeguards are not possible inside of a plant, e.g. for technical or political reasons, a radiation monitor to detect krypton-85 could be installed on top of the stack or off-site up to a distance of 10-50km.**
- **The last resort for cases when monitoring is opposed by the plant operator and even the host country is long-distance remote monitoring of atmospheric krypton-85 concentration.**

Case study: Yongbyon, North Korea

Estimated plutonium production:
8 kg(Pu) per year

Assumption:
Steady reprocessing at rate of spent fuel production.

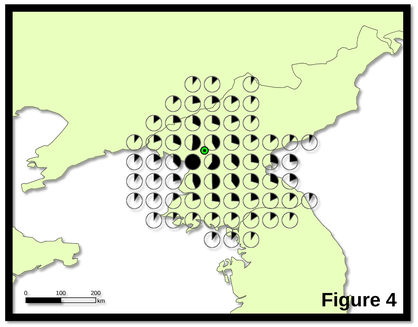
Result:
Not detectable in neighboring countries.



Hypothetical plutonium production:
100 kg(Pu) per year
Alt: 8 kg(Pu) per year

Assumption:
Steady reprocessing at rate of spent fuel production.
Alt: Rapid reprocessing of backlog spent fuel.

Result:
Detectable in neighboring countries.



Detecting undeclared reprocessing plants

A proper understanding of the krypton-85 background is the basic requirement to detect the emissions from unknown facilities. Simulations of the emissions from active reprocessing plants over the course of one year show that the fluctuations in the krypton-85 concentration mainly happens in the Northern Hemisphere due to all reprocessing plants being located there.

Based on estimated and reported krypton-85 emissions the plumes from 10 active reprocessing plants have been simulated for four weeks after release.
The highest fluctuations are found in Europe due to emissions from La Hague and Sellafield.

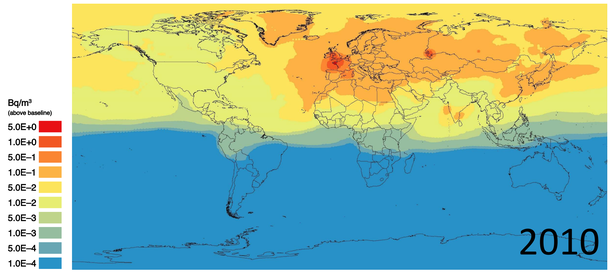


Figure 5: Fluctuations for the year 2010; shown is one geometric standard deviation above the baseline.

Additional simulations of a fictional reprocessing plant in South America with a high production rate of 400 kg plutonium per year show the footprint of krypton-85 concentrations. It is also apparent that such a facility in Europe would likely stay undetected. Only available emission data from known active reprocessing plants would allow a prediction of a sample concentration and thus the detection of unusual measurements.

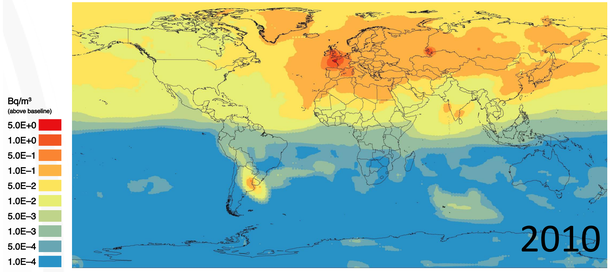


Figure 6: Based on Figure 5, but with an additional (fictional) reprocessing plant in South America.

The affected area with a confidence interval at least 10% above the background is calculated to be a =175,000 km². Compared with the Earth's total landmass area A =149 million km² it is possible to calculate the probability to detect the clandestine facility. When taking n random samples the probability to get a sample with elevated Kr-85 concentration from the clandestine facility is $p = 1 - (1 - {}^{a}/_{A})^{n}$. For 1000 samples the probability is 69.1%, and for 100 samples it is still 11.1%.

Conclusions

Monitoring known facilities: **Depending on the geographical boundary conditions and the plutonium separation rate, the monitoring of known facilities can be possible, but must be hand-tailored to the circumstances.**

Detecting undeclared facilities: **With the current background level only larger reprocessing activities would be detectable. Ongoing reprocessing prevents detections in large parts of the Northern Hemisphere. A stop in the krypton-85 emissions and a subsequent decay of the background would increase the detection probability.**

References

[1] Simulation of atmospheric krypton-85 transport to assess the detectability of clandestine nuclear reprocessing, Jens Ole Ross (Dissertation, University of Hamburg, 2010)
[2] Kr-85 Activity Determination in Tropospheric Air, Report 2014, Clemens Schlosser et al.
[3] Variability of atmospheric krypton-85 activity concentrations observed close to the ITCZ in the southern hemisphere, Andreas Bollhoefer et al. (J. Environmental Radioactivity, 2014)
[4] Global Fissile Material Report 2007, International Panel on Fissile Materials.

National Nuclear Security Administration