Science and Global Security, 15:31–47, 2007

ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929880701319820

Routledge
Taylor & Francis Group

Estimation of the Electromagnetic Radiation Emitted from a Small Centrifuge Plant

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Centrifuges used to enrich uranium utilize an electric motor to spin the rotors to high speeds. The current flowing in these motors emits electromagnetic radiation. This article presents a model that estimates the strength of the radiation as a function of distance from the centrifuge plant. It discusses the dependence of the radiative power on the size of the plant, the noise sources at the frequencies at which the motors operate, and means of detecting the signal from a centrifuge enrichment facility. According to the findings, a plant running 1,000 P-2 type centrifuges emits electromagnetic radiation that should be detectable in a 0.5–3 kilometer range in the absence of shielding.

INTRODUCTION

Centrifuge technology is fast becoming the method of choice for uranium enrichment globally. The main advantage of this technology is that it requires much less energy than the gas diffusion process.[1] In addition it is a very modular design and hence the capacity can be built incrementally. Although the diffusion process is technically simpler to implement, this hurdle for the centrifuges is fast becoming obsolete with advances in computer modeling and materials. Because of these advantages and almost zero particle emissions, it has also become the favorite technology for clandestine enrichment facilities. Iran's enrichment facility at Natanz is an example, shown in Figure 1.[2]

Received 16 August 2006; accepted 13 December 2006.
The author is grateful to Prof. Frank von Hippel for his many insightful suggestions in both the technical and editorial aspects of this work. The author also thanks Prof. Harold Feiveson and Dr. Zia Mian for their helpful suggestions and Dr. Alexander Glaser for his guidance in setting up the experiment in the Appendix.
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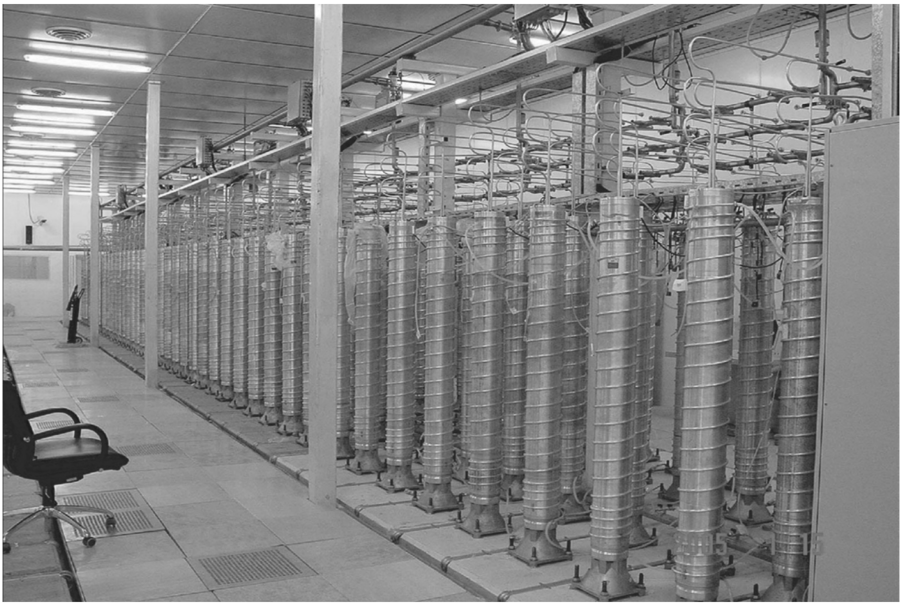

Figure 1: Iran's enrichment facility at Natanz, which reportedly has 164 centrifuges in operation.

The separation performance of the gas centrifuge depends on its physical characteristics given by the length (L), radius (r), and the angular velocity (ω). The separative capacity scales as $(\omega r)^2 L$.[3] It also depends on the flow rates of the feed and extraction gases and on the strength of the countercurrent flow. Depending on the design, the output of a centrifuge measured in separative work unit per year (SWU/yr) can vary significantly. The basic parameters of centrifuges commonly in use are given in Table 1.[3]

In an enrichment plant, many centrifuges are cascaded together to give the required enrichment and output. For example a cascade based on Urenco's TC-12 design would require at least 2750 centrifuges to enrich fuel for a 1 GWe reactor, which needs about 110,000 SWUs/yr.[4]

If a country wanted to build a small facility with Pakistan's P-2 centrifuges to produce 25 kg of 90% enriched uranium annually, it would require about

Table 1: Basic parameters for contemporary centrifuges.

Type	P-1	P-2	Russia	Urenco (TC-12)	U.S.
Rotor material	Al	MS	CFRC	CFRC	CFRC
Circumferential speed (m/s)	350	500	700	700	700
Length (m)	1–2	1	<1	3–4	12
SWU/yr	1–3	5	10	40	300

MS: Maraging Steel, CFRC: Carbon-fiber Resin Composite.

1,000 units.[5] This plant would consume about 200 kW of power[3] and would have an area of approximately 500 square meters.[6] These numbers make it very hard to detect a plant from satellite imagery. For centrifuge plants, the 1-m resolution satellite images do show details, for instance the 1-m images of Pakistan's Kahuta plant show the production areas in the north and south of the facility perimeter from which the scale of enrichment can be estimated.[7] However, this still means that other information to identify the rough location of a clandestine centrifuge plant is required. This was clear in the case of Iran's Natanz facility where the location had to be identified by the opposition group, which revealed Iran's nuclear program.[8]

Wide-area environmental sampling is believed to be a potential solution for detecting secret enrichment facilities although it certainly has its limitations. Wide-area environmental sampling means the collection of environmental samples (e.g., air, water, vegetation, soil, smears of dust collected from hard surfaces) at a set of locations specified by the IAEA for the purpose of assisting the association to draw conclusions about the absence of undeclared nuclear material or nuclear activities over a wide area.[9]

Wide-area atmospheric monitoring techniques are much harder to employ for the detection of centrifuge plants as the emissions are very small. Any leaks in the pipes are inward because the pressure in the flow pipes and the centrifuges is below atmosphere. Moreover wide-area environmental sampling can be very costly and has to be implemented carefully as the cost of the method can rise dramatically with the area covered.[10] Hence most schemes that are proposed employ a selected area to be covered in a particular region. This could result in potential "holes" in the region claimed to be covered by wide area atmospheric sampling.

The problems and limitations of both these detection methods show that there is a need to further explore ways to detect clandestine facilities. The rest of the article explores the possibility of detecting centrifuge plants through their electromagnetic signature radiated in the atmosphere.

DETECTION OF ELECTROMAGNETIC RADIATION GENERATED BY CENTRIFUGES IN THE ATMOSPHERE

Centrifuges run at very high speeds to separate the isotopes of uranium as noted in Table 1. The centrifuge rotor spins at these high speeds with the help of an electrical motor. An AC electric motor[11] carries an alternating current in its wires that radiates electromagnetic waves. The strength of the electromagnetic radiation will vary as a function of the distance from the plant and depending on the number of centrifuges there will be a maximum distance at which these waves will be detectable. The detection distance will also depend on the electromagnetic noise level at the particular site.

Motors

Electromagnetic motors are based on the fundamental principle that there is a mechanical force on any wire when it is conducting electricity while contained within a magnetic field. The force is described by the Lorentz force law and is perpendicular to both the wire and the magnetic field. In a rotary motor, the rotating part (usually on the inside) is called the rotor, and the stationary part is called the stator. The rotor rotates because the wires and magnetic field are arranged so that a torque is developed about the rotor's axis.

In an AC motor, the stator windings are supplied an alternating current in such a way that the magnetic field developed around the stator opposes the permanent magnetic field from the rotor. This makes the rotor move and it rotates to align its north pole to the south pole of the electromagnet wound on the stator. As the current changes direction in the stator, the polarity of the electromagnet switches and hence the rotor keeps spinning. Each winding on the stator is called a pole and there are a minimum of two poles in a motor.

An AC motor can work more efficiently if a polyphase current is supplied to the stator coils. The stator coils displaced physically in space and excited by alternating currents that are displaced in time, generate a revolving magnetic field and the rotor magnet then "follows" this rotating magnetic field.[12] In addition, more than two poles are generally employed per current phase.

There are two fundamental types of AC motors: (1) synchronous motors (Figure 2), which rotate at exactly the supply frequency or submultiple of the supply frequency and (2) the induction motor, which runs at a speed slightly less than the supply frequency or a submultiple of it.

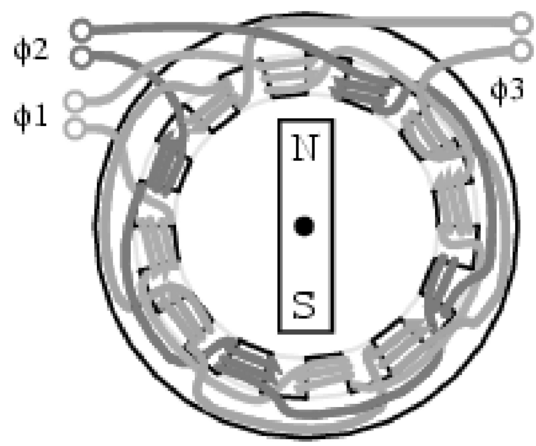

Figure 2: Schematic of a 3-phase ($\phi 1, \phi 2, \phi 3$) synchronous AC motor. The stator windings show 2 pairs of poles for each phase. The radius of the stator coil windings is "b." The rotor in the middle is made from a permanent magnet.

The speed of the motor is given by,

$$Speed(Hz) = \frac{2 \times f}{p} \quad (1)$$

where f is the frequency of the AC supply and p is the number of poles of the motor per phase. For the motor shown in Figure 2, $p = 4$.

Model to Estimate the Electromagnetic Radiation Emitted by a Motor

The windings of the motor can be modeled as a loop of wire carrying an AC current. The effect of each winding section is independent of the other, and hence the total radiative power can be approximated by multiplying the effect of a single loop with the total number of windings N. For the model, consider a uniform harmonic current $i(t) = Icos(\omega t)$ around the circumference of the loop of radius b. This is an elemental magnetic dipole (Figure 3) with a vector phasor magnetic moment,

$$\mathbf{m} = \mathbf{a}_z I\pi b^2 = \mathbf{a}_z m\,(A.m^2). \quad (2)$$

One is interested in estimating the electromagnetic power radiated at a distance R from the center due to the dipole.[13] The general expressions for the electric and magnetic fields are fairly complicated and hence it is instructive to look at their behavior in the near and far field. These two regions of the fields are defined relative to the wavelength (λ) of the EM wave, which in turn is determined by the frequency of the current. As will be discussed in the later sections, the frequency of the centrifuge motors is in the kHz range, which gives the wavelength in hundreds of kilometers. Hence the near field defined

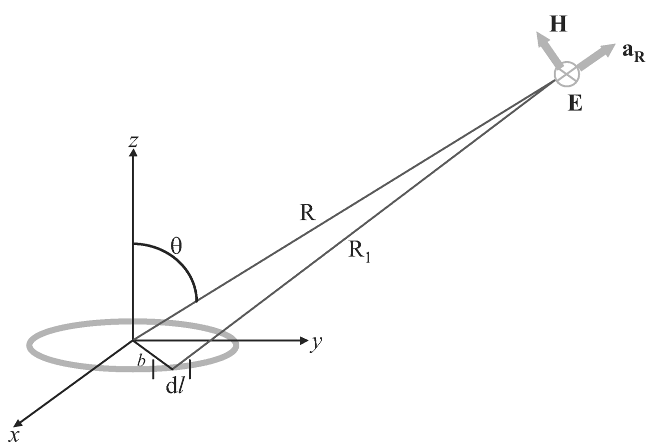

Figure 3: Elemental magnetic dipole. This article is interested in estimating the electromagnetic power radiated at distance *R* from the center due to the dipole.

by $R \ll R_c = \lambda/2\pi$ is the applicable region for the present purposes and the fields strengths are then given by[14]

$$E_\phi = \frac{j\omega\mu_0 m}{4\pi R^2} sin\theta \tag{3}$$

where $j = \sqrt{-1}$.

$$H_R = \frac{m}{4\pi R^3} 2cos\theta \tag{4}$$

$$H_\theta = \frac{m}{4\pi R^3} sin\theta \tag{5}$$

Electric field antennas are optimally of the same order as the wavelength of the emitted wave. For such low frequency waves electric fields would therefore be harder to detect. Magneto-meters on the other hand are much smaller and therefore more portable. Hence, concentrate on the detection of magnetic field, in particular the radial component in the near field region.

It should be noted that, in the case of an AC motor, the magnetic field from the moving rotor and the changing magnetic field of the stator produce a back emf in the stator. The current induced in the stator due to this back emf is in the opposite direction to I in Equation 2. Hence for the motor I is an effective current flowing through the windings. It can be determined from measuring the current flowing through the motor or estimated from the power rating of the motor if the voltage supplied to the motor is known.

Testing the Model

In order to test the model, it was applied to a small two-pole AC motor running from the main 60 Hz power supply. The AC motor is a Radio Shack computer fan motor with a current consumption of 0.13 *amp* and a coil radius of ~2 cm, which gives $m = 1.6 \times 10^{-4}$ $amp{-}m^2$. For a 60 Hz electromagnetic wave, the wavelength is 5000 *km* and $R_c = \lambda/2\pi = 796$ km. Hence all the measurements shown later for this motor are in the near field range and Equations 3, 4 and 5 apply. These equations have to be multiplied by the number of turns, N for the motor.

The results of the measurements are shown in Table 2.[15] The measured results depend on the direction of the measurement, θ. The maximum of the field is in the axial direction where $\theta = 0$ and $H_R = m/2\pi R^3$. The measured values shown in column two are in this direction and were taken between 2 cm and 28 cm from the motor. If the results are plotted on a log-log scale (Figure 4), the slope at larger distances gives the exponential dependence on the distance R. As the data shows the value 2.9 from the measured data is in excellent agreement with the modeled value of 3. From the fit of the data is found $N = 600$. By taking the motor apart, the author counted approximately 550 to 650 turns. The calculated numbers for large distances are shown in column three of Table 2.

Table 2: Measurements and calculations for a small AC motor.

Distance (*cm*)	**Measured B-field** ($\times 10^{-7}$ *Tesla* (T))	**Calculated B-field** ($\times 10^{-7} T$)
2	1200	—
4	660	—
6	350	—
8	200	—
10	130	—
12	85	—
14	59	59
16	42	40
18	30	28
20	22	21
22	17	16
24	13	12
26	10	10
28	8	8

The data for the motor shows that this very simple model is in quantitative agreement with the measured data.

Applying the Model to a Centrifuge Motor

The centrifuges considered in this article are comparable to the Pakistan owned P-2 designs that operate at 500 m/s tangential velocity (Table 1). They have a capacity of 5 SWU/year and a power requirement of 200 watts each.[3] As

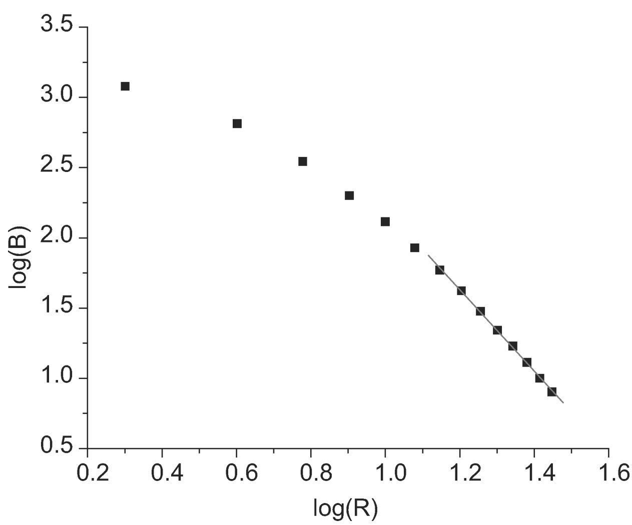

Figure 4: Log-log plot of the magnetic field of the AC motor. The linear fit of the data at large distances (red line) gives an exponential *R* dependence of 2.9, in excellent agreement with the model.

noted earlier, for producing 25 kg of 90% enriched uranium one would require 1,000 P-2 centrifuges.

The P-2 design is based on the Urenco G-2 model.[16] The outer radius of the G-2 rotor is approximately 7.4 cm,[17] which for the assumed tangential velocity of 500 m/s translates to a rotational frequency of about 1 kHz.[18] Assume a three phase,[11] 8-pole per phase[19] AC motor with the rotor spinning at this speed. For this speed, the frequency of the supply voltage will be 4 kHz (Equation 1). $R_c \sim 12\,km$ in this case and hence any distance up to 4 km would be considered in the near range. A 200-Watt motor at 200 V RMS utilizes a peak current of 1.4 amps and this corresponds to an average of about 0.5 amps per phase. Assume a 1,000 turn,[20] $(2 \times 5)\ cm^2$ coil winding area,[21] which gives $m = 0.5 \times 10^{-3}\ amps{-}m^2$ (Equation 2) for a pair of poles per phase. Because the study is assuming 4 pairs of poles per phase and a 3-phase supply, adding the magnetic field vectorially gives an effective $m = 4 \times 0.5 \times 10^{-3} = 2 \times 10^{-3}\ amps{-}m^2$.[22]

The casing of the motor depends on the specific design. The article gives, calculations for a motor not enclosed in a casing, along with numbers for a 10 mm and 50 mm aluminum casing.[23] With the motor fully enclosed in a metal casing as shown in Figure 1, the skin depth, δ of the magnetic field needs to be taken into account. δ is defined as the distance through which the amplitude of the wave decreases by a factor of ~0.37 and is given by $1/\sqrt{\pi f \mu \sigma}$. σ is the conductivity of the metal. For an aluminum casing, $\delta \sim 1.25\ mm$ at 4 kHz.

Table 3 shows the figures for an enrichment plant containing 1,000 centrifuges. If one assumes a random distribution of the phase of each motor, then there is a square root dependence of the number of motors on the total field strength. Hence for a 10,000 centrifuge plant, the numbers in Table 3 will be scaled by 3.2.

If the aluminum casing is indeed around 50 mm then it would be impossible to detect any radiation signal even at 10 meters from the plant. Even with a much thinner aluminum casing of the order of 10 mm, the signal strength will be hardly detectable beyond a few hundred meters as will be shown in the next section.

Another factor to consider is an underground plant. Wet soil has a conductivity (σ) of 0.1 siemens/m[24] and with a volumetric water content of about 0.3,

Table 3: Estimate of the magnetic field strength of an enrichment plant containing 1,000 centrifuges as a function of distance and shielding.

	B-field (*T*)		
Distance (*m*)	**No casing**	**10 mm Al casing**	**50 mm Al casing**
10	0.12×10^{-7}	4×10^{-12}	8×10^{-26}
100	12×10^{-12}	4×10^{-15}	8×10^{-37}
2,000	16×10^{-16}	4×10^{-19}	8×10^{-33}

the dielectric permittivity (ϵ_r) is 10.[25] At 4 kHz this would make the wet soil a good conductor[26] and $\delta = 36\ m$. Therefore unless the plant is buried 30–40 meters underground, it is not going to have a significant effect on the strength of the magnetic field in Table 3. The conductivities of dry soil and concrete are lower than the wet soil and hence the effect on the signal strength will be even lower.

Noise Level and Detection Methods

The actual noise level at a certain location will vary greatly with the electromagnetic noise sources. These include industrial plants, radio transmitter stations and proximity to urban areas in general. However, most of the noise at low frequencies is generated by natural causes like lightning.[27] Hence, do an analysis of the signal to noise ratio by only taking natural sources into account.

The most significant source of noise at the ELF and VLF range is that generated by lightning discharges. Lightning discharge is an electrical breakdown current that may flow from the cloud to ground or within thunderclouds. The discharge currents generate transient radio pulses termed “atmospherics” or “sferics” typically lasting 1–10 ms (see Figure 5). It has been estimated that about 2,000 thunderstorms are in progress around the world at any time.[28]

Noise power of sferics has been measured at various places around the world. The data is collected away from power lines and industrial noise sources to ensure that the signal measured is from lightning. In order to use concrete numbers for the article, the author took two particular measurements recorded at Colorado and California. A summary of the noise spectral density of the

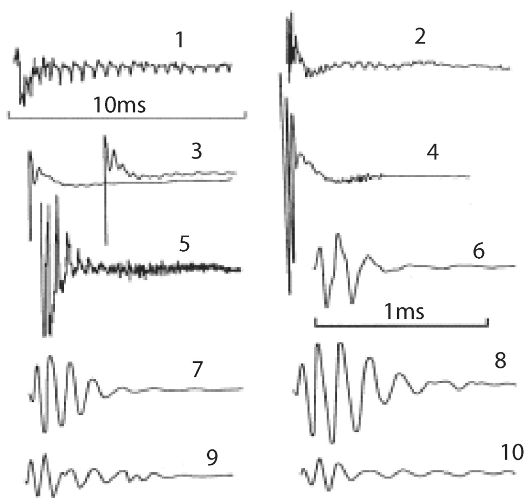

Figure 5: Typical atmospheric waveforms. Traces 1–5 were recorded with a 10 ms timebase. Traces 6–10 were recorded with a timebase of slightly longer than 1 ms.

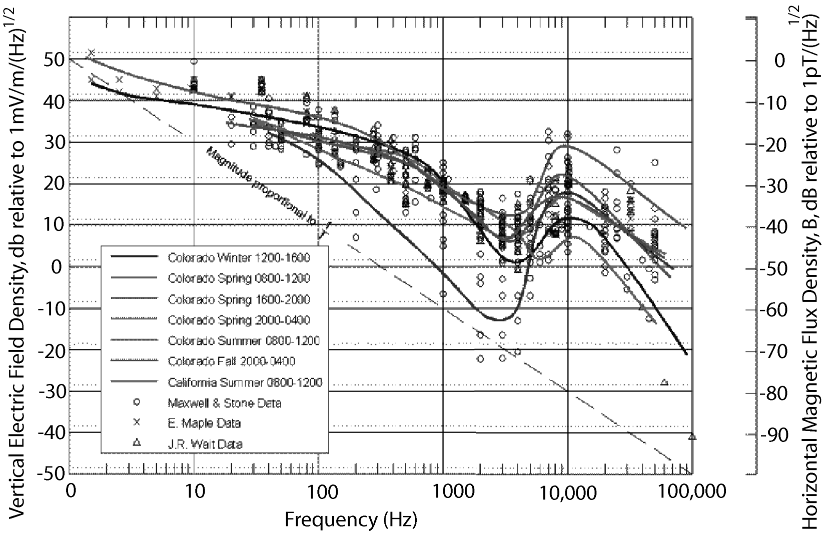

Figure 6: Noise spectral density in the frequency range 1–100 kHz measured in different regions and at different times of the year.

earth-ionosphere waveguide at these two locations is presented in Figure 6.[29] As the figure shows the noise density depends on many factors including seasons and time of day in addition to the location.

Based on Figure 6 the noise level averaged over 3 months in the Colorado region is −40 dB (dB in this graph is defined as 20log(x)) with respect to 1 $pT/\sqrt{Hz}$ at 4 kHz. This translates to a noise level of 10 $fT/\sqrt{Hz}$. On the other hand, in California during the summer, the noise level is −60 dB with respect to 1 $pT/\sqrt{Hz}$ at 4 kHz. This corresponds to 1 $fT/\sqrt{Hz}$. A receiving filter with a Q factor of 100 will have a bandwidth of 40 Hz at 4 kHz.[30] This would translate into a total noise of 6.5 fT in California to about 65 fT in Colorado.

Various characteristics of the atmospheric noise can now be employed to design filters to reduce its power. From Figure 5, it is clear that a simple clipping filter would reduce the noise from nearby thunderstorms.[31] The peak in the beginning of the noise data can be attenuated with a clipping circuit and analysis shows that this would reduce the noise by a factor of 10.[32] Hence the noise level would be 0.65 fT to 6.5 fT and with a signal to noise ratio (SNR) of 2, one would be able to detect a signal of about 1.3 fT to 13 fT. Table 4 shows the distance at which a centrifuge plant of a particular size will produce a field in this range.

As can be seen in Table 4, the detection distance is only about 0.5–3 km if the motor is not shielded. If the motor is enclosed in the aluminum casing, which is 10 nm thick or more, the detection distance is within a few hundred meters from the plant.

There are a number of ways that can be employed to increase the SNR for a particular detection scheme. Because the characteristics of the sferics

Table 4: Estimate of the detection distance for centrifuge plants of various sizes and for magnetic noise levels in the range 6.5 fT to 65 fT. The first number in each entry corresponds to the lower noise level. For 50 mm Al casing and in the presence of only the lowest noise level the detection distance is less than 10 m.

	Detection distance		
Centrifuges	**No casing**	**10 mm Al casing**	**50 mm Al casing**
100	1.4 km; 650 m	100 m; 40 m	$<$10 m
1000	2.1 km; 1 km	150 m; 70 m	$<$10 m
10,000	3.1 km; 1.4 km	220 m; 100 m	$<$10 m

do not change over long distances, the noise levels can be characterized very well for a specific region and hourly/seasonal variations. With this information at hand a filter can be designed to match the noise characteristics rather than using a general purpose clipper circuit. In addition, data can be collected over an arbitrarily long time and with statistical techniques, the noise levels can be reduced even further.

CONCLUSION

The simple model presented here shows that any long range detection of centrifuge plants through their electromagnetic signature in the atmosphere is not possible. However, within 0.5–3 kilometer range of the plant, this might be a viable technique if there is no aluminum casing present around the motor. If the motor is encased in aluminum that is more than 10 mm thick, the detectablity of a clandestine plant is reduced to within a few hundred meters.

Some assumptions pertaining to the design of the motors and their usage have been made in this work; for example, the power consumption and the size of the motors. These parameters have been deduced from the literature available and may need to be adjusted based on better information. However the overall conclusion of the article should not change because the two most important factors in determining the signal strength are the cubic dependence of attenuation on distance and the skin depth of the aluminum casing. With these two factors, even if the size and power of the motor are doubled, and the noise reduced by $10\times$, the detection distance will only be $\sim 1\ km$ for motors enclosed in a 10 mm aluminum casing at a plant running 1,000 centrifuges.

A similar analysis can be done for the electric field detection of the signal by determining the signal strength from Equation 3 and comparing it to the noise levels in Figure 6. In California, the electric field noise levels are -10 dB with respect to 1 $\mu V/m/\sqrt{Hz}$, which translates to an absolute level of 2 μV/m for a bandwidth of 40 Hz. As in the case of the magnetic field detection setup, assuming a 10 dB gain from filtering and SNR of 2, one needs 0.4 μV/m of

Table 5: Estimate of the detection distance for centrifuge plants of various sizes and for electric noise levels in the range 2 μV/m to 20 μV/m. The first number in each entry corresponds to the lower noise level.

Number of centrifuges	Detection distance (No casing)
100	350 m; 110 m
1000	600 m; 200 m
10,000	1100 m; 340 m

signal from the centrifuge plant. Similarly, for the noise levels in Colorado, the signal strength of the electric field will have to be 4 μV/m. From Equation 3 the electric field strength in the near region is estimated. Table 5 summarizes the results for the detection of electric field for different plant sizes at two different noise levels with no shielding of the motor. Comparing it to Table 4, it is evident that even with a very long antenna, the distances at which the electric field can be detected reliably is smaller than for the magnetic field.

Another possibility is to try to detect noise signals in the power lines. Centrifuge plants use frequency converters to run the AC motors at high speeds, and these circuits do generate noise that may be coupled to the power lines. A description of a simple experiment in this regard and its results are discussed in the Appendix for a single 1 Hp frequency converter attached to a 400 Hz, 7/8 HP motor. In this experiment the author did not observe any signature on the power line that would give an indication of a frequency converter and a motor running at 400 Hz.

NOTES AND REFERENCES

1. The gas diffusion method requires about 2500 kWh/SWU whereas centrifuges need about 100 kWh/SWU. From Donald R. Olander "The Gas Centrifuge," *Scientific American* 239 (1978), 2, 37–43.

2. M. Saeidi, Vice President for Planning and International Affairs, Atomic Energy Organization of Iran, presentation at the Annual Symposium of World Nuclear Association, 2005, www.worldnuclear.org/sym/2005/pdf/Saeidippt.pdf

3. Victor Gilinsky, Marvin Miller, and Harmon Hubbard, "A Fresh Examination of the Proliferation Dangers of Light Water Reactors," October 2004, Nonproliferation Policy Education Center, www.iranwatch.org/privateviews/NPEC/perspexnpeclwr102204.pdf

4. A modern power reactor has a design burn-up of about 53 MWd/kg and uses 4.4% enriched fuel. About one third of the thermal energy is successfully converted to electricity. 53 MWd/kg/3=17.7 MWe-days/kg. At 90% capacity factor, a 1 GWe reactor would use (1000 MWe x 365days x 90% / 17.7 MW(e)d/kg) = 18.6 tons. A less modern reactor operating at lower burn-ups (say, 41 MWd/kg) would require about 24 metric tons. The separative work required to produce enriched fuel is based on a value function: V(e)=(2e-1)ln[e/(1-e)]. The total SWUs required per kilogram is V(ep)-V(et)-Fx[V(ef)-V(et)], where the subscripts p, f, t represent product, feed, and tails respectively; and F is the mass of feed per kilogram, given by (ep-et)/(ef-et). For a kilogram of 4.5% product, assuming natural uranium feed (ef=0.000711), 0.32% tails (et=0.00032), 10.7 kg of feed is required, and 6.0 SWUs. For 18.6 metric tons, this is 110,000 SWUs.

5. For 1 kg of HEU, the amount of natural uranium needed is F = (ep-et)/(ef-et) = 236kg and SWU/yr = 190/yr at a tail concentration of 0.32%. For 25 kg of HEU, the amount of material required for a first generation implosion bomb, the amount of natural uranium needed is 5900 kg and the number of SWUs required are 4750/yr. If Pakistani P-2s are employed with a capacity of 5 SWUs a year, one would need about 1,000 centrifuges. The number of centrifuges will go down by about 70% if the clandestine facility is fed 4.4% enriched uranium as feed for 25 kg of HEU output. For a feed of 4.4% enriched uranium and a tail concentration of 0.32%, the number of SWUs required for 25 kg of 90% enriched uranium is 1,500. This would require 300 P-2 centrifuges. This number will drop further to about 160 centrifuges if the tail concentration is allowed to increase to 2% at the clandestine facility. This increase of the tail concentration would come at an expense of an increased feed requirement. Hence if the tail concentration increases to 2%, the amount of 4.4% enriched uranium feed needed for 25 kg of HEU will be 917 kg as opposed to 547 kg for 0.32% tail concentration.

6. Based on aerial views of existing centrifuge facilities, the typical area is about 10 SWU/yr per square meter for a plant built with the P-2 centrifuges. From Alexander Glaser, "Beyond A. Q. Khan," *International Network of Engineers and Scientists Against Proliferation Bulletin* (2004), 23, 50–54 (http://www.inesap.org/bulletin23/art13.htm) and private communication with A. Glaser.

7. Hui Zhang, "Strengthening IAEA Safeguards Using High Resolution Commercial Imagery," Symposium on International Safeguards, Vienna, 2001, http://bcsia.ksg.harvard.edu/BCSIA_content/documents/ViennaSATpaper.pdf

8. David Albright and Corey Hinderstein, "The Iranian Gas Centrifuge Uranium Enrichment Plant at Natanz: Drawing from Commercial Satellite Images," 2003, http://www.isis-online.org/publications/iran/natanz03_02.html

9. D. W. Swindle, R. L. Pearson, N. A. Wogman and P. W. Krey, "Screening of Potential Sites for Undeclared Nuclear Facilities in Environmental Monitoring for Nuclear Proliferation," *Journal of Radioanalytical and Nuclear Chemistry* 248 (2001), 3, 599–604.

10. P. W. Krey and K. W. Nicholson, "Atmospheric Sampling and Analysis for the Detection of Nuclear Proliferation," *Journal of Radioanalytical and Nuclear Chemistry* 248 (2001), 3, 605–610.

11. IAEA specifications for nuclear and dual use items specifies a multiphase AC motor in the frequency range of 600–1000 Hz and power range of 50–2000 VA. Hence only AC motors will be considered in this work. See INFCIRC/254/Rev.6/Part 1 (Nuclear Specific Items) (2003) for details, www.iaea.org/Publications/Documents/Infcircs/2003/infcirc254r6p1.pdf.

12. For details of a polyphase motor, see, e.g., C. S. Siskind, *Induction Motors* (McGraw Hill, 1958); P. L. Alger, *Induction Machines* (Gordon and Breach Publishers, 1995); C. Concordia, *Synchronous Machines* (Wiley, 1951).

13. The mathematical details for the model can be found in any elementary text on Electromagnetic waves. See, e.g., D. Cheng, "Antennas and Radiating Systems" in *Field and Wave Electromagnetics* (Prentice Hall, 1989, 2nd edition), 600–671.

14. For atmosphere, the magnetic field **B** is related to the magnetic field intensity **H** by the relation $\mathbf{B}=\mu_0\mathbf{H}$ where $\mu_0=4\pi \times 10^{-7}$ H/m in SI units.

15. The measurements were made with a hand-held magneto-meter, ELF 50D by Walker Scientific.

16. *Nuclear Fuel*, 27 February 2006.

17. *Nuclear Fuel*, 26 May 2003.

18. This is the standard frequency for the G-2 design, *Nuclear Fuel*, 24 December 1990.

19. In Iraq, in the early nineties, completed stators were found during inspections with 24 ferritic magnets mounted on each stator. For a 3-phase motor this means 8 poles per phase. *Nuclear Fuel*, 20 January 1990.

20. This number is based on motors with similar or higher power rating and size.

21. The North Korean orders of aluminium casing tubes were 1200 mm in length, which according to officials could be used for a 1000 mm G-2 rotor, plus the additional space required in the rotor assembly by top and bottom suspension bearings and a motor. If half of this additional area is taken by the motor, the motor height would be about 10 cm. The stator coils would be about half the height of the motor giving a length of 5 cm. The width of the coil is constrained by the circumference of the motor. If the motor fits in the aluminum tubing as suggested in the article, then the radius of the stator would be $\sim$8 cm as the inner diameter of these tubes is 168 mm. To fit 24 coils, each coil is limited to a width of $\sim$2 cm. *Nuclear Fuel*, 26 May 2003.

22. Adding the magnetic field vectorially gives a multiplicative factor of $2.6^{*}1.5 \sim 4$. 2.6 is from the fields of the 4 pairs of poles of the same phase and 1.5 is from adding the magnetic fields from the three different phases. For details of this calculation see C. Siskind, Chapter 1 in *Induction Motors* (McGraw Hill, 1958).

23. The North Korean orders of aluminum tubes were 52 mm thick, which according to a western official were within the thickness specifications for the tubing required for centrifuges. *Nuclear Fuel*, 26 May 2003.

24. J. Q. Shang and R. K. Rowe, "Detecting Landfill Leachate Contamination Using Soil Electrical Properties," *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 7 (2003), 1, 3–11.

25. T. Miyamoto, T. Annaka, and J. Chikushi, "Extended Dual Composite Sphere Model for Determining Dielectric Permittivity of Andisols," *Soil Sci. Society. Am. J.* 69 (2005), 23–29.

26. For a good conductor, $\sigma/2\pi f\epsilon_r\epsilon_0 \gg 1$. At 4 kHz, this value is 1×10^5 for wet soil.

27. R. Barr, D. L. Jones, and C. J. Rodger, "ELF and VLF Radio Waves," *Journal of Atmospheric and Solar-Terrestrial Physics*, 62 (2000), 1689–1718; S. L. Bernstein, M. L. Burrows, J. E. Evans, A. S. Griffiths, D. A. McNeill, C. W. Niessen, I. Richer, D. P. White, and D. K. Willim, "Long Range Communications at Extremely Low Frequencies," *Proceedings of the IEEE*, 62 (1974), 3, 292–312.

28. R. Barr, D. L. Jones, and C. J. Rodger, "ELF and VLF Radio Waves," *Journal of Atmospheric and Solar-Terrestrial Physics* 62 (2000), 1689–1718.

29. E.L. Maxwell and D.L. Stone, "Natural Noise Fields 1cps to 100 kc," *IEEE Transactions on Antennas and Propagation*, AP-11 (1963), 3, 339–343.

30. Q of a bandpass filter is defined as $f_o/\Delta f$. f_o is the center frequency of the filter and Δf is the bandwidth. Q factors of 100 are very common and hence this is used in the analysis.

31. The attenuation of the lightning noise is in the order of 100 s to 1,000 s of kilometers and hence nearby storms include storms in this range.

32. S. L. Bernstein, M. L. Burrows, J. E. Evans, A. S. Griffiths, D. A. McNeill, C. W. Niessen, I. Richer, D. P. White, and D. K. Willim, "Long Range Communications at Extremely Low Frequencies," *Proceedings of the IEEE*, 62 (1974), 3, 292–312.

33. VFD is from the Korean company LG, model number iG5008-2.

34. The oscilloscope has a 1,000-point data buffer and hence 1 second signals were acquired at a time, which gives a resolution of 500 Hz at the Nyquist rate.

APPENDIX

Centrifuge plants running with an AC motor require a frequency converter. The frequency converter converts the supply voltage frequency (50–60 Hz) into the appropriate frequency required for the centrifuges. Solid-state converters in common use these days first convert the input AC signal into DC and then use an appropriate chain of inverter circuits connected in a loop to produce the required output frequency. Because "cross-talk" between the input and output of any circuit is unavoidable, the output of the frequency converter could couple into the main power supply and hence show an increased noise level at the particular output frequency.

In order to see if this increase in noise level is indeed present in the main power lines, the author performed a simple experiment. A 3-phase variable frequency drive[33] (VFD) with a 3-phase output capacity of 1 HP, and a frequency range of 0–400 Hz was used. The output of the VFD was connected to a 3-phase 400 Hz motor with a capacity of 7/8 HP. The VFD was run from a 208 V 3-phase main line. An oscilloscope was attached to the same 3-phase main line approximately 2 feet away.

The signal on the main line was first measured with the VFD and the motor switched off.[34] Figure 7 shows Fourier transform spectra of the acquired sinusoid signal at 60 Hz.

Next the VFD was switched on, and the motor was run at 400 Hz. The Fourier transform spectra of the signal measured on the power line approximately 2 feet away is shown in Figure 8. By comparing the Fourier spectra in

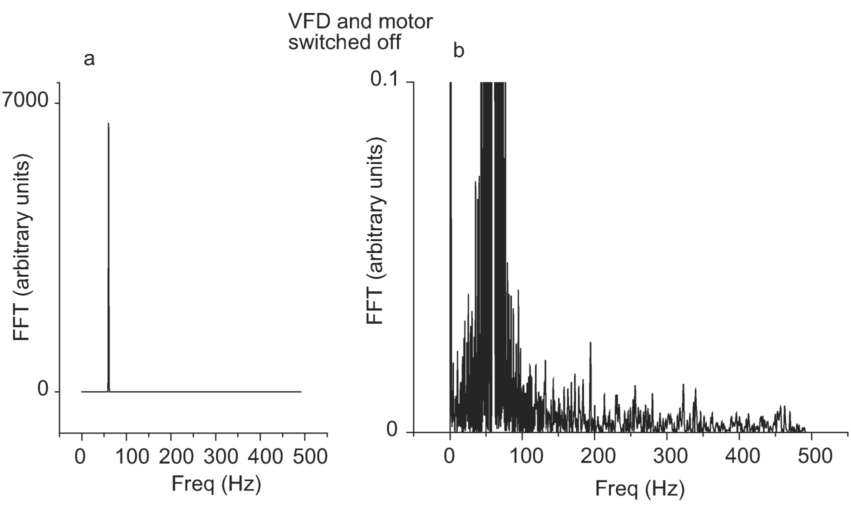

Figure 7: (a) Fourier transform spectra of the 3-phase 208 V, 60 Hz main line signal with the VFD and motor switched off. (b) Zoomed in version of (a) to show noise at different frequencies.

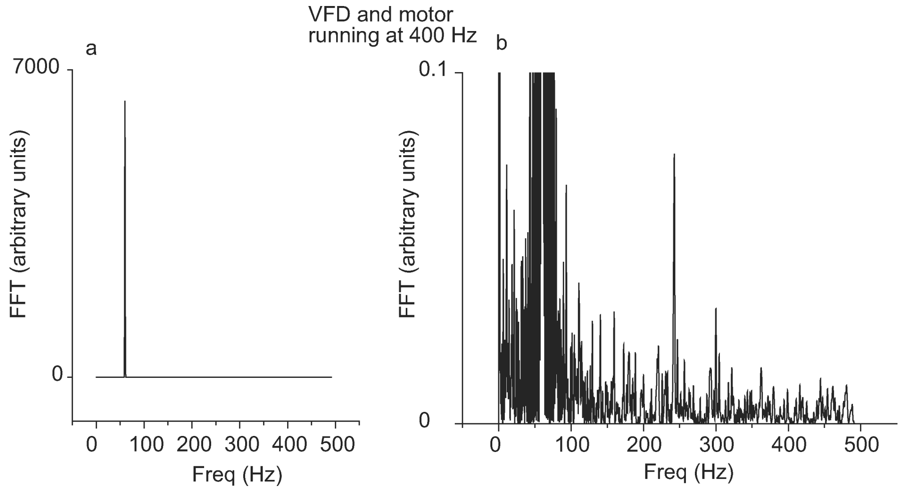

Figure 8: (a) Fourier transform spectra of the 3-phase 208 V, 60 Hz main line signal with the VFD and motor running at 400 Hz. (b) Zoomed in version of (a) to show noise at different frequencies.

the two figures it can be seen that there is no obvious increase in the signal at 400 Hz. However, across all frequencies an increase is seen in noise when the VFD and the motor are running. One way to quantify this is to take the sum of the power in 50 Hz intervals between 200 and 400 Hz. Then for each interval if one takes the ratio between the sums when the motor is running to when the motor and the VFD are switched off, one should get a number higher than 1. This is indeed the case as seen in Figure 9. As an example, the black point at 300 Hz is obtained by summing the noise power between 250 to 300 Hz when

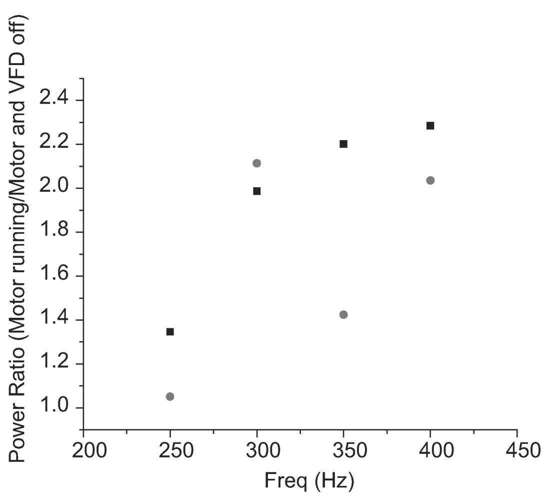

Figure 9: Ratio of noise power summed up in 50 Hz intervals. See text for details.

the motor is running. This number is divided by the sum of the noise power between 250 to 300 Hz when the motor and VFD are switched off. The value of $\sim$2 says that the noise in this frequency range is doubled when the VFD and the motor are running. The black and the red symbols are for two different time captures of 1 s data when the motor and the VFD is turned on.

From the graph in Figure 9 it is evident that the noise coupled from the VFD into the main power lines is broadband and not simply at the operating frequency of the current provided to the motor (400 Hz in this case).