# North Korea Centrifuge Capabilities (U)

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# Contents

# 1 (U) EXECUTIVE SUMMARY

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(U/~~/FOUO~~) Our report concludes with a list of possible intelligence indicators for the various steps, most already well-known; these are not repeated in this summary.

## 2 (U) INTRODUCTION

(U~~//FOUO~~) On June 15, 2009, responding to threatened UN sanctions, North Korea stated, "enough success has been made in developing uranium-enrichment technology . . . to allow the [necessary?] experimental procedure. The process of uranium enrichment will be commenced." [redacted] DOE (b)(3)

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## 2.1 (U) JASON Charge

(U~~//FOUO)~~ The formal charge to JASON is as follows:

(U~~//FOUO)~~ "The Director of National Intelligence's North Korea Mission Manager, in conjunction with the National Counter Proliferation Center and the National Intelligence Officer for Weapons of Mass Destruction request the JASONs undertake a summer study on the topic of North Korea's technical prowess and ability to construct and operate a uranium enrichment centrifuge capability. The Study will have as goals:

- (U~~//FOUO)~~ Determine if North Korea is technically capable of building centrifuges, constructing an enrichment facility, and operating centrifuges with little or no outside assistance.
- (U~~//FOUO)~~ Examine those North Korean industries, processes, and/or technologies that are analogous or might provide a useful foudation to those needed in centrifuge construction and operation."

## 2.2 (U) Organization of this Report

(U~~//FOUO~~)The PowerPoint briefing slides that accompany this report as Appendix A are an integral part of the report. While the narrative text in this report is self-contained, we will not repeat in the report body the figures and photographs that are in the briefing slides; rather, as they are discussed they will be referred to here by slide number.

This report is organized as follows:

(U~~//FOUO~~) In Section 3, we set the stage by discussing the large differences between modern (say, post-1985) manufacturing practices in the industrialized world, and those practices that are likely to be the norm in North Korea, a country whose industry is mostly (but not completely!) caught in what we might think of as a pre-1960 time warp. [redacted] ODNI (b)(3)

(U~~//FOUO~~) In Section 4, we review the basics of gas centrifuge physics and engineering. While this topic is covered in many open-source publications, the summary given here is necessary for understanding the basis of our subsequent conclusions.

(U~~//FOUO~~) In Section 5 we discuss in turn the various "long poles" or hurdles that may face NK, and assess whether and how they might reasonably be expected to overcome them.

(U~~//FOUO~~) In Section 6, we attempt to consolidate our assessments into a notional timeline and to draw some conclusions.

(~~U//FOUO~~) In Section 7, we suggest intelligence indicators (most already recognized by others) that could potentially shed light on where NK is along the timeline.

## 2.3 (U) Acknowledgments

(~~U//FOUO~~) [redacted]

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# 3 (U) MANUFACTURING APPROACHES

(U//~~FOUO~~) We begin with a discussion that might seem peripheral to the subject at hand, but, we think, is in fact central: How does modern, U.S. and developed world, manufacturing practice differ from what we expect North Korea to be capable of?

## 3.1 (U) Modern Manufacturing in the Developed World

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## 3.2 (U) Avoiding Mirror Imaging

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## 3.3 (U) Best Guesses for NK Practices

(U~~//FOUO~~) We have attempted to crystalize the discussions of the two preceding sections into a set of plausible, perhaps even likely, design and manufacturing practices that North Korea might bring to bear on a gas centrifuge effort. These are the practices that, in the rest of this report, we will apply to the specifics of centrifuge design.

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### 3.3.1 A previous US effort at avoiding mirror imaging

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# 4 (U) CENTRIFUGE BASICS

(U//~~FOUO~~) We now turn to the physics and engineering basics of gas centrifuge design. The figures in Slides 10 and 11 should be consulted at this point.

## 4.1 (U) Basic Ideas Due to Zippe

(U//~~FOUO~~) The enduring basic ideas of uranium separating gas centrifuges are due to Gernot Zippe, who developed them in the USSR in the 1940s and 1950s, and then re-implemented them in the US in the late 1950s [2]. [redacted]

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(U//~~FOUO~~) [redacted]

(U//~~FOUO~~) A Zippe-derived centrifuge has these key features (see Slides)

- (U//~~FOUO~~) It uses high g-forces to create a vacuum on-axis, where it is fed. Thus seals between the rotating and fixed components are not needed.
- (U//~~FOUO~~) It uses a slow counter-current, circulating between the top and bottom of the vertical centrifuge to create what amounts to an internal cascade (further explanation later), and to obviate the need for precise positioning of the product and tailing scoops in the radial direction.

- (U~~//FOUO~~) Its top magnetically suspended bearing naturally allows acceptable wobble without damage, and also reduces the load on the bottom needle-bearing.

- (U~~//FOUO~~) It maintains vacuum around the cylindrical rotor by a simple helical groove, the so-called "molecular pump", machined into the vacuum case. The molecular pump has no moving parts.

- (U~~//FOUO~~) It is powered by an electric motor that uses the bottom rotor end-cap as a passive magnetic rotor; there are no rotating electrical components.

- (U~~//FOUO~~) It may, but need not, have bellows that allow operation above the first one or two resonance frequencies (more on this below).

## 4.2 (U) Physics Performance and Scaling Laws

(U~~//FOUO~~) Zippe-derived centrifuges involve an elegant interplay between their physics and engineering features. The essential physics has two parts:

(U~~//FOUO~~) First, under the high g-force of the rotation, heavier $U^{238}$, as $UF_6$, diffuses radially outward, while lighter $U^{235}$ diffuses radially inward. In equilibrium, this would produce a concentration difference only $\sim 1\%$ over a useful density range.

(U~~//FOUO~~) However, second, the counter-current causes enriched product to move slowly axially upward, while depleted tailings move slowly axially downward. Since the $\sim 1\%$ gradient is refreshed radially during this slow drift, the result is a kind of cascade that produces a concentration difference of as much as $\sim 20\%$ between the top and bottom of the rotor.

(U~~//FOUO~~) The maximum rate of separative work of a countercurrent gas centrifuge is given by Dirac [4]:

$$\delta U_{max} = \rho D \left( \frac{(M_2 - M_1)(\omega r)^2}{2 k_B T} \right)^2 \frac{\pi}{2} Z \tag{4-1}$$

where $\rho$ is the gas density and $D$ its self-diffusivity (the product is independent of density for dilute gases), $M_2$ and $M_1$ are the molecular masses of the gases to be separated, $\omega$ is the angular velocity, $r$ is the cylinder outer radius, $v = \omega r$ its peripheral speed and $Z$ is its length.

(U~~//FOUO~~) The separative power is essentially independent of the gas density, although this enters indirectly through the effect of kinematic viscosity ($\propto 1/\rho$) on the countercurrent flow pattern.

(U~~//FOUO~~) Expressed in kg-SWU units (where 5000 kg-SWUs produces about 20 kg of HEU), equation (4-1) can be written as

$$\frac{\text{kg-SWU}}{\text{year}} \approx 10 \left( \frac{300\,^\circ\text{K}}{T} \right) \left( \frac{M_2 - M_1}{3\,\text{amu}} \right)^2 \left( \frac{v}{400\,\text{m/sec}} \right)^4 \left( \frac{Z}{1\,\text{m}} \right). \tag{4-2}$$

[redacted] DOE (b)(3) In equation (4-2) one sees how the capacity of a centrifuge scales against nominal values of length $Z$ and rotor circumferential velocity $v$, the two most important parameters.

(U~~//FOUO~~) Empirically, according to data presented by Whitley [4], $\rho D \propto T$, although elementary kinetic theory for monatomic gases would suggest a scaling $\propto T^{1/2}$. The origin of the discrepancy may lie in the coupling between vibrational and translational degrees of freedom. In diatomic molecules vibrational frequencies of bonds involving first period elements such as N, O and F are generally at energies $\mathcal{O}(1000\text{-}2000)\,^\circ\text{K} \times k_B$, and are not much excited at room temperatures. In $UF_6$ the frequencies are lower, partly because with a heavy atom at one end of the bond the reduced mass is greater by a factor of about 2, and partly because with a total of seven atoms some of the modes are at lower frequencies than a simple diatomic stretching mode. Superelastic collisions may make the effective (momentum transfer) mean free path an increasing function of temperature, thus increasing $D$ at higher temperatures.

(U~~//FOUO~~) At fixed peripheral speed the separative power is independent of radius. This may appear surprising, but the relative drift speed is proportional to the centripetal acceleration $v^2/r$, and hence inversely proportional to the radius, canceling the proportionality of the surface area. The difference in equilibrium mix fractions depends only on the peripheral velocity and is independent of radius if the velocity is held constant. Cohen [3] points out that the radius is chosen for mechanical reasons.

(U~~//FOUO~~) We also note the dependence on temperature. This is not steep, and is limited by the rapid falloff of $UF_6$ vapor pressure as temperature decreases (the equation is invalid and separatory power falls off rapidly if the vapor density is so low that it enters the free molecular flow regime). A modest degree of cooling is readily provided if the vacuum case (coupled radiatively to the rotor) is cooled by wrapping it with chilled water pipes. A more important benefit of even modest cooling may be the large reduction of vapor density on axis (by a factor of 45 between 273°K and 323°K, if $v = 400$ m/s). This relaxes demands on the molecular pump and decreases sensitivity to manufacturing imperfections that limit its performance. It also reduces windage loss. Creep, a significant issue with aluminum (but not steel) rotors, decreases rapidly as temperature is lowered. Cooling may be an indicator of problems with rotor tolerance or of the use of aluminum rotors.

## 4.3 (U) Importance of Rotor Material Strength

(U~~//FOUO~~) The great sensitivity to $v$ is apparent in equation (4-2), and explains why material strength (or, more accurately, strength-to-weight ratio) is the most severely stressed design parameter in gas centrifuges. Centrifuge rotors are made out of high strength-to-weight materials: maraging steel, aluminum alloy, or (with modern technology) carbon fiber reinforced polymers. We discuss this further in Sections 4.6 and 5.4.

## 4.4 (U) Maintaining the Counter-Current Flow

(U~~//FOUO~~) The counter-current flow is rising in the interior of the rotor and descending near its wall. This sense of flow is driven by two effects, acting together:

- (U~~//FOUO~~) Most of the energy dissipation, typically estimated at about 30 W per centrifuge, occurs at the bottom as bearing friction and motor inefficiency. Like water in a pot heated on a stove, the warmed gas at the bottom tends to rise. At the rotor wall this rise is hindered by viscous friction (a rough estimate shows that, for a gas pressure at the wall of 0.1 bar, the Reynolds number of countercurrent flow at 1 m/sec is roughly 30; this would decrease in inverse proportion to the density, but even at $Re = 30$ viscous drag is significant), setting up an upward flow in the interior.
- (U~~//FOUO~~) The bottom scoop is immersed in the supersonic azimuthal flow, and is a significant source of drag. This drives an Ekman circulation very similar to the classical Ekman pumping driven by friction at the bottom of a stirred vessel (which is why azimuthal stirring of a coffee cup rapidly mixes its contents, and why the fluid rotation damps much faster than the naïve viscous damping time). Because the rotation at the height of the scoop (or the bottom of the coffee cup) is slowed by drag, the radial pressure gradient there is reduced. Hence

there is a downward vertical pressure force at the rotor wall that drives fluid downward (from higher layers with a larger centrifugal pressure gradient) into the slower layer, with a return flow nearer the rotor axis. The rotating baffle separates the countercurrent flow from the drag of the upper scoop, which would tend to drive the flow in the opposite direction.

## 4.5 (U) Cascade Principles

(U~~//FOUO)~~ The quadratic depeudence on the mass difference and the centripetal acceleration (itself proportional to the square of the peripheral speed) results from these factors coming in twice: once in the sedimentation force and once in the difference in equilibrium mix fractions.

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A well engineered and operated centrifuge could thus produce separatory work at a rate of about 5 kg-SWU per meter of length. Significantly lower values are likely until extensive operational experience is obtained; Kemp (his Fig. 2.4) suggests that for a moderate degree of optimization 2 kg-SWU/(m-yr) may be realistic.

(U~~//FOUO~~) Dirac's original report is not easily obtained. A succinct treatment (and the definitive theory of cascades) is given by Cohen [3]. Although issued by a major publisher this can also be hard to find (a xerox copy is in the JASON library). Whitley [4] is the most convenient reference, but contains some typographical errors.

## 4.6 (U) Instabilities and Bellows

(U) An excessively narrow and long centrifuge has very little flexural stiffness, hence low resonant (critical) frequencies that are independent of wall thickness. At fixed $v$, the rotation rate $\omega/2\pi \propto 1/r$. If the rotor is to be operated below the first critical speed (lowest flexural resonance), it must have a length-to-diameter ratio

$$Z/d \leq 1.85(E/\sigma)^{1/4}. \tag{4-3}$$

This follows from Whitley's Eq. 4 (Part II, p. 70): $Z/d \leq (1.85/v^{1/2})(E/\rho)^{1/4}$, taking $v^2 = \sigma/\rho$. If $v^2 < \sigma/\rho$ then the limit on $Z/d$ is somewhat relaxed, but efficient separation ($\delta U_{max} \propto v^4$ at constant $E/\sigma$ and $\delta U_{max} \propto v^{3.5}$ at constant $E/\rho$) requires $v$ to be as large as possible.

(U) It may seem surprising that a result for infinitesimal oscillations of an elastic tnbe should depend on its peripheral velocity (gyroscopic effects are negligible), or, eliminating $v$, on its yield strength. The dependence on $v$ arises from using Rayleigh's (*The Theory of Sound* 1877) equation for the flexural mode frequency, equating it to the rotational frequency $\omega = v/r$.

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(U~~//FOUO~~) In general, two-dimensional materials are described by three elastic constants, one for tensile stiffness in each of two principal directions and one for shear (the modulus matrix may be diagonalized, with only two diagonal elements, but the direction of its principal axes requires a third parameter to describe). This is familiar for woven fabrics with fibers in two orthogonal directions: they are stiff along the fiber directions (in general, with two different stiffnesses if the warp and woof have different numbers of fibers per unit length, or fibers with different properties) but may be very compliant in oblique directions if the fibers readily slide over each other. The tensile strength of carbon fiber reinforced materials in directions oblique to their fibers (even by small angles) may be much reduced by plastic flow or cracking of the matrix and subsequent sliding of the fibers. Because the important parameters are hoop strength and longitudinal stiffness (with the separatory capacity proportional to the 7/4 power of the first and 1/4 power of the second), an optimal layup might be 1/8 longitudinal fibers and 7/8 azimuthal fibers, rather than a helical layup.

(~~U//FOUO~~) Uniaxial tensile strengths up to 45 kbar ("super high tensile" fiber) are reported, but, particularly because when failure occurs it is catastrophic, it is probably appropriate to assume a lesser strength of 30 kbar and modulus of 1 Mbar ("high tensile, low modulus" fiber; definitions and estimated properties from wikipedia). Allowing for the weaker epoxy matrix and the need for fibers in two directions suggests that a conservative assumption would be $\sigma_\theta = 10$ kbar and $E_z = 1$ Mbar. Then, noting a density of 1.8 gm/cm$^3$, the maximum $v = 745$ m/sec and the limit on subcritical length $Z/d < 5.85$. The potential advantage of using carbon fibers to acheive high $v$ is evident, but the technology is not easy, and the complex anisotropic nature (that may depend on manufacturing details) of these composites is unforgiving in such a strength-critical application.

# 5 (U) WHAT ARE THE LONG POLES?

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## 5.1 (U) Precision or exotic machining

(U//~~FOUO~~) As already mentioned, Zippe-derived centrifuges are in most respects artifacts of 1950s machining technology, and can be made in a machine shop of fairly modest proportions. Indeed, Zippe's original paper [2] gives a sense of the scale of the necessary development effort:

> (U//~~FOUO~~) [In 1958,] before any technical work could be started, it was necessary to equip the laboratory in the desired manner. The best space available for the work was an old student cafeteria building recently abandoned by the University. It offered the promise of adequate space but a complete dismantling of the old food-handling equipment and a thorough cleaning were in order before the installation of fixtures and services suitable for

scientific endeavor was possible.

(U/~~/FOUO~~) A small machine shop has been installed in this laboratory building. This was suitable for about 90% of the mechanical work required for the project. The remaining 10%, usually requiring heavier machinery, has been done either in the Physics Department shop or in the main shop of the Research Laboratories for the Engineering Sciences.

(U~~//FOUO~~) A room for the handling of $UF_6$ was added later and a mass spectrometer was installed.

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(U//~~FOUO~~) These are the critical tolerances "to make it work". Virtually all other tolerances need only be good enough "to make it fit". The former require engineering, the latter only craftsmanship.

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### 5.1.1 (U) Stationary magnet holder clips

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### 5.1.2 (U) Spiral grooves on the ball bearing

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## 5.2 (U) Frequency Converters and Motors

(U//~~FOUO~~) Centrifuges require variable-frequency electrical controllers, at power levels ~ 100 W each, and probably less during steady operation; several centrifuges can share a freqnency converter. Frequency converters draw power from the line power and convert the incoming 50-60 Hz AC voltage into the variable AC voltages in the 0.1 - 1 kHz range that are required to drive the hysteresis/synchronous centrifuge motor.

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### 5.2.1 (U) Commodity audio amplifier chips

(U~~//FOUO~~) The drive frequencies required for the motor drive are of order 0.1 to 1 kHz and the output power required for the motor drive is of order 100 W. Both of these requirements can be met by generic audio power amplifiers, such as the TDA 8950 (NXP Semiconductor: Netherlands). When configured as a single-channel bridge-tied load, this class-D audio amplifier can drive 300W into an 8 ohm load with less than 0.5% harmonic distortion. It is available for $4.50 in quantities of 100.

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### 5.2.2 (U) Commodity microcontrollers

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### 5.2.3 (U) Commodity power supplies

(U~~//FOUO~~) The most stressing requirement of the power supply is to provide 100W at ±36 V to the audio amplifier. Several generic power supplies can be used to meet this requirement. One example is the SWS300-36 AC-DC converter (TDK-Lambda: Japan), which provides as much as 8.7 A at 36 V DC derived from the AC power line. These AC-DC converters are available for $121 in quantities of 10.

(U~~//FOUO~~) All other power requirements, such as the 5 V required to drive the microcontroller, are much less stressing. These can either be derived from the 36 V source using a voltage regulator or independently using their own AC-DC converter.

### 5.2.4 (U) Other features

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## 5.3 (U) Rotor Material and Fabrication

(U~~//FOUO~~) Here we discuss both the fabrication of the rotors, and the technology of the maraging steel out of which they are fabricated.

### 5.3.1 (U) Maraging steel

(U~~//FOUO~~) Maraging steel is a martensitic preciptation-hardened very low carbon steel. It is a commodity item for specialized industrial uses, mostly aerospace. Suppliers are easy to locate on the Internet. The word "maraging" is a contraction of "martensite" and "aging", referring to how it is made:

- (U~~//FOUO~~) The desired alloy of iron, nickel, and a particular combination of cobalt, molybdenum, titanium, and/or aluminum (that will precipitate as intermetallics phases) is smelted in a vacuum furnace. The nickel, a component of ordinary stainless steels, does not form an intermetallic precipitate, but contributes to corrosion resistance.

- (U~~//FOUO~~) Cast as a preform, it is annealed at 800°C to austenite.
- (U~~//FOUO~~) The preform is quenched (air cooled) to martensite. This produces a relatively soft material that can be cold worked (e.g., flow formed) as desired.
- (U~~//FOUO~~) When the final hardening is desired, the part is "aged" for 4 hours at 500°C. This causes intermetallic phases to precipitate, giving the steel its hardness.

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(U~~//FOUO~~) Maraging steel can be welded, but must be re-aged after welding to recover its hardness. Possibly the annealing and quenching steps would also need to be repeated before re-aging; a good metallurgist could determine this experimentally in the course of developing any particular welding process step.

(U~~//FOUO~~) Maraging steel tubes must be passivated to protect them from the corrosive effects of $UF_6$. The standard method is to use steam. There is an open literature on the subject (see Slide 39)

### 5.3.2 (U) Flow forming

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### 5.3.3 (U) Final hydroforming

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## 5.4 (U) Bellows

(U~~//FOUO~~) Slender tubes have resonant instabilities that must be passed through on spin-up (see Section 4.6, above, and Slide 16). There are two possible ways to deal with resonances: (1) Always operate subcritically, with rotor speed less than the first resonance, or (2) engineer a method for passing safely through the first one or two resonances.

(U~~//FOUO~~) For any given material, material properties dictate the largest height-to-diameter ratio that will support subcritical operation at its maximum rotational speed. For a nominal maraging steel 350 with $E = 2.1$ Mbar, $\sigma = 350{,}000$ psi $= 23.8$ kbar, $\rho = 8.1$ gm/cm$^3$, $v = 540$ m/s and $Z/d < 5.67$. For aluminum Al-6061-T6, for which $E = 68$ GPa and $\sigma$ is about 2.4 kbar, $Z/d < 7.6$. For the higher strength Al-7075-T6 with $E = 72$ GPa and $\sigma = 4.3$ kbar, $Z/d < 6.65$ at its faster limiting speed.

(U~~//FOUO~~) Zippe introduced bellows (see Slide 17) to reduce the flexural stiffness of the rotor tube for low modes, and thus to move their frequencies to much lower values. At these lower frequences there is not as much rotational energy in the rotor when it passes through resonance, and the passage can be made quickly and safely.

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## 5.5 (U) Centrifuge-Specific Know-How

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### 5.5.1 (U) Upper Suspension Magnets

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5.5.2 (U) Rotor testing and balancing

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~~S//RD~~ (U//~~FOUO~~) [redacted]

(U~~//FOUO~~) Accurate balancing is required to maintain clearance, that might be nominally 1 mm, between the rotor and the molecular pump. The rotor spins about its center of mass (the center of mass of its cross-section if it is accurately cylindrical). If the wall thickness were to vary as one sinusoidal wave around the circumference (a lowest-mode manufacturing imperfection) with amplitude $\delta$, then its center of mass would depart from its geometrical axis by an amount $\Delta = 0.5R\delta/w$, where $R$ is its radius and $w$ its wall thickness. If we demand $\Delta < 0.5$ mm and take $R = 72.5$ mm and $w = 0.35$ mm, then we require $\delta < 5\,\mu$.

~~RD~~ (S/ [redacted]

DOE (b)(1), (b)(3)

DOE (b)(1), (b)(3)

[redacted]

S//RD ~~(U//FOUO)~~ [redacted]

S//RD ~~(U//FOUO)~~ [redacted]

### 5.5.3 (U) Bearing and damping testing

(U~~//FOUO)~~ The natural "tipping" (inverted pendulum) frequency of the rotor about its lower needle/ball support might be measured in the static test stand by an oscilliscope fed by a capacitance gauge. This corresponds to a very low frequency resonance that must be traversed at the beginning of spin-up.

(U~~//FOUO)~~ The restoring horizontal force is determined by the length of the "clips", themselves acting as portions of a compound pendulum. The damping of this oscillation is provided by viscous dissipation in the oil-filled support. The design shows screws that can be used to tune the damping by adjusting the thickness of the viscous oil layer.

~~RD~~ ~~(S/~~/[redacted]

DOE (b)(1), (b)(3)

### 5.5.4 (U) Secondary flow and testing

(U~~//FOUO)~~ Classical (subsonic, uniform-density) flow in the interior of rotating cylinders supports a set of flow-instability modes. Analysis of flow in a centrifuge is further complicated by the large radial density gradient. The high molecular weight (352) and low adiabatic exponent ($\gamma \simeq 1.07$ [4]) of $UF_6$ and its consequent low speed of sound (at 300°K $a_{\mathrm{UF}_6} = 87\,\mathrm{m/s}$ *vs.* $a_{\mathrm{air}} = 347\,\mathrm{m/s}$; *cf.* 400 m/s circumferential speeds) results in supersonic flow with respect to any stationary structures, such as the product and waste scoops, near the rotor. Thus, the flow past the scoops produces shocks, as does a pitot tube in supersonic flow, that generate shear layers from shock curvature and that disturb and can separate boundary layers on impingement with walls. Such effects increase mixing that must be minimized. The upper baffle shields the flow from the top scoop

(U~~//FOUO~~) In the laboratory frame, where non-rotating components live, secondary-flow velocities are much smaller than the azimuthal velocity. To a stationary observer, the flow in the centrifuge interior resembles a tightly wound helix if no additional instabilities develop. In the rotating frame, the flow is as depicted in Slide 15 of the briefing (Appendix A), except for complications arising from Coriolis forces on the radial flow at the ends. The top baffle mitigates and isolates effects from tertiary flows (Ekman spiral) that are likely to result from such forces.

(U~~//FOUO~~) Such flow issues argue against diagnosing and tuning the secondary flow with intrusive means, such as probes, as these will likely cause significant disturbances themselves. The secondary flow could be diagnosed by using surrogates for the corrosive $UF_6$. While no common surrogate matches $UF_6$ exactly (352 mol. wt., vapor pressure 1 atm at 56°C), bracketing at different temperatures or rotation speeds could be obtained by using tetraethyl lead (323 mol. wt., vapor pressure 15 torr at 84°C) or tetramethyl lead (267 mol. wt., vapor pressure 22.5 torr at 20°C).

(U~~//FOUO~~) Zippe used Freon compounds for his preliminary work at the University of Virginia but eventually employed a mass spectrometer (MS) to assay the separative performance of his test centrifuges. This is a real-time process that allows optimization of the secondary flow (for example, by adding heat at the bottom in addition to that provided by the motor drive).

(U~~//FOUO~~) In testing a prototype centrifuge it is necessary to know this "equilibrium time"—the time $t_e$ for the centrifuge enrichment to settle to a new value after a change in parameters. This is the mean residence time for $UF_6$ within the centrifuge and is given by the mass $M_c$ of $UF_6$ contained divided by the feed rate to the centrifuge, $F_r$. We will first calculate $F_r$ and then estimate $M_c$ for a typical centrifuge.

(U//~~FOUO~~) Assume a feed rate $F_r$ grams/second to the centrifuge that produces $F_r/2$ of single-stage enriched product of enhanced in U-235 by a factor $(1+e)$ and $F_r/2$ of single-stage product stripped by a factor $(1-e)$. The separative work $\Delta U$ per unit of feed is $e^2/2$ ([4] Eq A7). For a typical countercurrent centrifuge with enrichment factor 1.05 and stripping factor 0.95, $\Delta U$ is thus $1.25 \times 10^{-3}$ kg-SWU per kg of feed. For a nominal centrifuge with a separative power of 3 kg-SWU/yr, the feed is thus 2400 kg/yr and $F_r$ = 76 mg/s.

(U//~~FOUO~~) For a centrifuge of length $Z = 1$ m and radius $R = 7$ cm, the mass of contained $UF_6$ is the product of the rotor surface area, the density of $UF_6$ at the rotor (at a pressure less than its vapor pressure) and its centrifugal ("gravitational") scale height. Scaling to an operating pressure of 0.1 atmosphere at the rotor wall, we find a density at the wall of 1.57 mg/cm$^3$ and a scale height of about 3.5 mm. Thus $M_c = 2420$ mg.

(U//~~FOUO~~) The settling time $t_e \equiv M_c/F_r = 32$ sec. This is an upper limit to $t_e$ because the separative work output of a centrifuge is independent of gas density; if the machine is operated at lower density, $F_r$ would remain 76 mg/s, but $M_c$ and $t_e$ would be correspondingly smaller.

(U//~~FOUO~~) In a test machine, the feed rate would be determined by a valve setting, and the operating pressure by valves in the product and waste lines to ensure that it remain below the vapor pressure at the operating temperature. The enrichment would be monitored by mass spectrometer, perhaps as frequently as every minute, as the heating is adjusted to optimize the secondary circulation. After optimization, in production centrifuges the valves might be replaced by constrictions in the feed, product and tailing lines. The heating by the waste heat of the motor could be set by a coating with appropriate emissivity on the lower end cap of the rotor.

## 5.6 (U) Manufacturing Scale-Up

S//NF ~~(U//FOUO)~~ [redacted]

DOE (b)(1)

S//NF ~~(U//FOUO)~~ [redacted]

S//NF ~~(U//FOUO)~~ [redacted]

S//NF ~~(U//FOUO)~~ [redacted]

S//NF ~~(U//FOUO)~~ [redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

DOE (b)(1)

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

## 5.7 (U) Human Factors

~~(S)~~ [redacted]

DOE (b)(1)

DOE (b)(1)

[redacted]

~~(S)~~ [redacted]

~~(S)~~ [redacted]

- ~~(S)~~ [redacted]
- ~~(S)~~ [redacted]
- ~~(S)~~ [redacted]

## 5.8 (U) The North Korean Economy

(U//~~FOUO~~) [redacted]

DOE (b)(3)

DOE (b)(3)

[redacted]

DOE (b)(1)

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

(U/~~/FOUO~~) [redacted]

DOE (b)(3)

# 6 (U) ESTIMATED TIMELINES

## 6.1 (U) How Long Does it Take?

DOE (b)(1)

~~(S)~~ [redacted]

1. ~~(S)~~ [redacted]

2. ~~(S)~~ [redacted]

3. ~~(S)~~ [redacted]

4. ~~(S)~~ [redacted]

DOE (b)(1)

[redacted]

5. ~~(S)~~ [redacted]

6. ~~(S)~~ [redacted]

~~(S)~~ [redacted]

~~(S)~~ [redacted]

~~(S)~~ [redacted]

~~(S)~~ [redacted]

(U//~~FOUO~~) [redacted]

DOE (b)(3)

DOE (b)(3)

[redacted]

(U~~//FOUO~~) [redacted]

## 6.2 (U) Where Are They Now?

DOE (b)(3)

(U~~//FOUO~~) [redacted]

DOE (b)(1)

(~~TS~~/[redacted]

(~~TS~~/[redacted]

(~~S~~) [redacted]

# 7 (U) INDICATORS

## 7.1 (U) Making Centrifuges

~~(S)~~ [redacted]

DOE (b)(1)

1. ~~(S)~~ [redacted]
2. ~~(S)~~ [redacted]
3. ~~(S)~~ [redacted]
4. ~~(S)~~ [redacted]
5. ~~(S)~~ [redacted]

DOE (b)(1)

- ~~(S)~~ [redacted]
- ~~(S)~~ [redacted]
- ~~(S)~~ [redacted]

[redacted]

6. ~~(S)~~ [redacted]

7. ~~(S)~~ [redacted]

8. ~~(S)~~ [redacted]

DOE (b)(1)

[redacted]

## 7.2 (U) Operating the Centrifuges

DOE (b)(1)

~~(S)~~ [redacted]

~~(S)~~ [redacted]

DOE (b)(1)

[redacted]

~~(S)~~ [redacted]

~~(S)~~ [redacted]

~~(S)~~ [redacted]

# (U) Appendix A: Briefing Slides and Figures

# NK Capabilities (U)

JSR-09-510 Summer 2009

# North Korea Centrifuge Capabilities (S)

JSR-09-510 Summer 2009

Participants:

[redacted]

[redacted]

DOE (b)(3), (b)(6)

# We thank the government briefers for outstanding, well-organized presentations

- Briefers to JASON
  - [redacted]

DOE (b)(3), (b)(6)

# Summary of what the US knows

DOE (b)(1)

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

Approved for release by ODNI on 6/8/2016, FOIA Case DF-2011-00033.

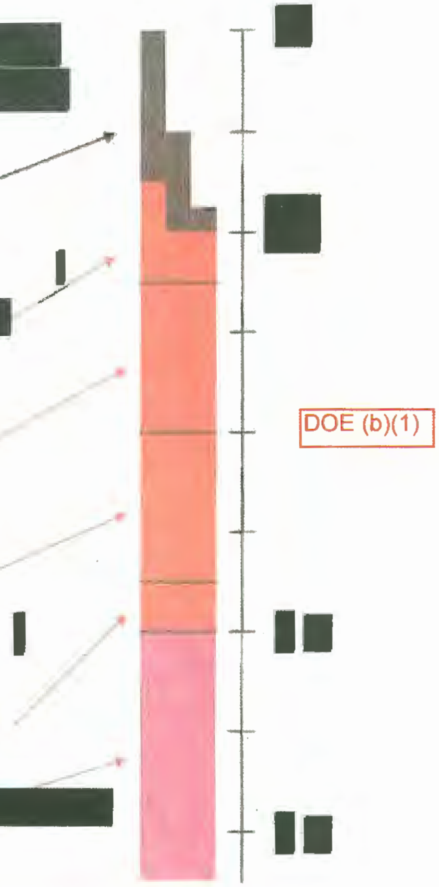
~~SECRET/NOFORN~~//RD

# JASON Task Statement (paraphrase)

DOE (b)(1)

- [redacted]
- [redacted]

[redacted]



# Manufacturing Best Practice in Industrialized Countries

- The fundamental principle is interface control and change control.
- All parts are fully defined in design by their geometry, materials specifications, and tolerances
  - 3D CAD always
  - software verification of fit (e.g., SolidWorks)
  - parts are always interchangeable
- Design and manufacturing are different engineering disciplines
  - train engineers to "design for manufacturability"
  - manufacturer gets to choose the processes while meeting specs
  - manufacturer gets to change technologies with production rate
  - bidding on cost encourages production scalability
- Identical parts can be obtained from different manufacturers
  - ISO 9000, etc.
  - certified processes
  - touch labor and rework are anathemas
- Properly designed and manufactured parts do not need piece-part testing
  - Motorola Six Sigma, etc.

[redacted] DOE (b)(3)

DOE (b)(1)

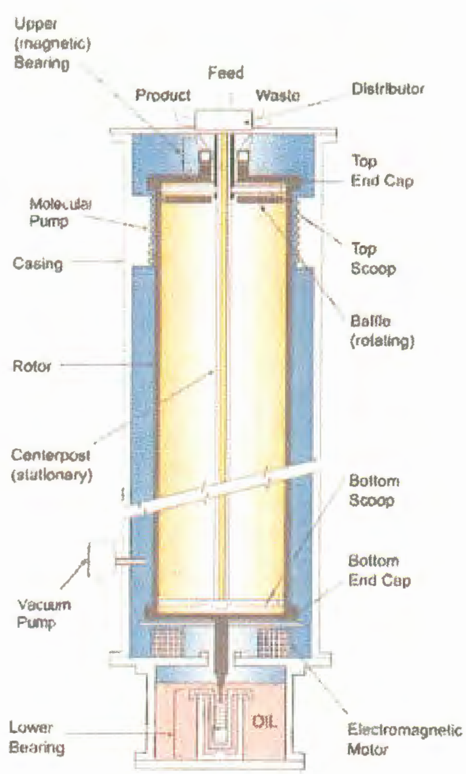
[redacted]

- [redacted]
  - [redacted]
- [redacted]
  - [redacted]
- [redacted]
  - [redacted]
- [redacted]
  - [redacted]
- [redacted]
  - [redacted]
- [redacted]
  - [redacted]

DOE (b)(1)

[redacted]

# The basic ideas (Zippe, 1950s)




- high g-force makes vacuum on axis
  - seals not needed
  - feed on axis
- counter-current creates large bottom-to-top gradient
  - no delicate scooping within a scale height of material
- magnetic bearing naturally allows acceptable wobble without damage
  - and takes load off needle bearing
- "molecular pump" is simply a machined helix in the case
  - no moving parts
- motor uses bottom end cap as its magnetic rotor
- bellows (not shown) allow operation above 1 or 2 resonances
  - move them to low speeds

# The physics is elegant

DOE (b)(3)

[redacted]

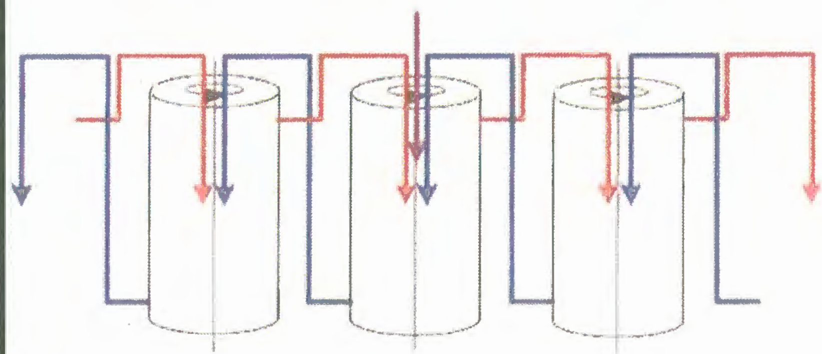
DOE (b)(1)

[redacted]

# The cascade principle is used both within a single centrifuge and in the cascade of multiple centrifuges

DOE (b)(3)

[redacted]



Since the cascade is exponential, its length is approximately a logarithm.
Each stage is an appropriate number of centrifuges in parallel.

$$\text{number of stages} = \ln\left(\frac{1-f_{\text{tail}}}{f_{\text{tail}}}\,\frac{f_{\text{prod}}}{1-f_{\text{prod}}}\right) \Big/ \ln(s)$$

HEU = 92%

$U^{235}$ = 0.71%, tails = 0.4%

$$\approx \frac{\ln[1/0.4\%] + \ln[1/(1-92\%)]}{0.2} \approx 40$$

enrichment per centrifuge

DOE (b)(3)

[redacted]

[redacted]

# Bellows (1)

DOE (b)(3)

[redacted]

[redacted]

DOE (b)(1), (b)(3)

[redacted]



DOE (b)(3)

DOE (b)(1)

[redacted]

[redacted]

DOE (b)(1)

# Required processes add up to machine-shop scale DOE (b)(1),(b)(3)

[redacted]

# Zippe's original paper gives a sense of the scale

[In 1958, ] before any technical work could be started, it was necessary to equip the laboratory in the desired manner. The best space available for the work was an old student cafeteria building recently abandoned by the University. It offered the promise of adequate space but a complete dismantling of the old food-handling equipment and a thorough cleaning were in order before the installation of fixtures and services suitable for scientific endeavor was possible.

A small machine shop has been installed in this laboratory building. This was suitable for about 90% of the mechanical work required for the project. The remaining 10%, usually requiring heavier machinery, has been done either in the Physics Department shop or in the main shop of the Research Laboratories for the Engineering Sciences.

A room for the handling of UF6 was added later and a mass spectrometer was installed.

DOE (b)(1)

[redacted]

DOE (b)(3)

DOE (b)(1)

[redacted]

DOE (b)(1)

[redacted]

DOE (b)(3)

DOE (b)(1)

[redacted]

DOE (b)(3)

DOE (b)(1)

DOE (b)(1)

[redacted]

DOE (b)(3)

[redacted]

# Software workbench for the microcontroller is a commodity item

DOE (b)(3)

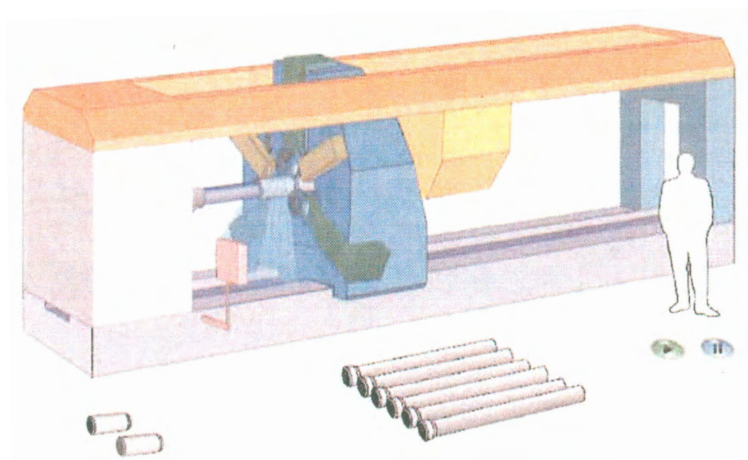
[redacted]

# Rotor material and fabrication?

DOE (b)(1)

DOE (b)(3)

[redacted]



(play movie)

# Maraging steel is a commodity item for specialized industrial uses

DOE (b)(3)

[redacted]

# Maraging steel basics

DOE (b)(3)

[redacted]

DOE (b)(3)

[redacted]

DOE (b)(3)

[redacted]

[redacted]

DOE (b)(1)

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DOE (b)(3)

- [redacted]
  - [redacted]
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- [redacted]
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  - [redacted]
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  - [redacted]
- [redacted]
  - [redacted]

[redacted] DOE (b)(6)

[redacted]

DOE (b)(1)

DOE (b)(1)

[redacted]

[redacted]

DOE (b)(1)

[redacted]

DOE (b)(3)

[redacted]

DOE (b)(3)

[redacted]

DOE (b)(3)

[redacted]

[redacted] DOE (b)(1)

DOE (b)(1)

[redacted]

# Timelines and indicators

[redacted]

DOE (b)(1)

[redacted]

DOE (b)(1)

[redacted]

DOE (b)(1)

[redacted]

DOE (b)(3)

[redacted]

# (U) Appendix B: CHOP

DOE (b)(1)

~~(S/NF)~~ [redacted]

~~(S/NF)~~ [redacted]

~~(S/NF)~~ [redacted]

DOE (b)(1)

[redacted]

~~(S/NF)~~ [redacted]

~~(S/NF)~~ [redacted]

~~(S/NF)~~ [redacted]

~~(S/NF)~~ [redacted]

DOE (b)(1)

[redacted]

# (U) Appendix C: Towards Better Estimates of Program Size

DOE (b)(1)

~~S//NF~~ (U//~~FOUO~~) [redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

[redacted]

~~S//NF~~ ~~(U//FOUO)~~ [redacted]

DOE (b)(1)

~~(TS/~~[redacted]

(U~~//FOUO~~) See [1] for discussion related to this section

# (U) Appendix D: Size of an Enrichment Cascade Facility

S//NF ~~(U//FOUO)~~ [redacted]

DOE (b)(1)

~~S//NF~~ [redacted] DOE (b)(1)

# Appendix E: Motor Windings

DOE (b)(3)

~~C//RD~~ (U) [redacted]

~~C//RD~~ (U) [redacted]

~~C//RD~~ (U) [redacted]

~~C//RD~~ [redacted]

~~C//RD~~ (U) [redacted]

DOE (b)(3)

~~C//RD~~

[redacted]

~~C//RD~~

DOE (b)(3)

[redacted]

~~C//RD~~ (U) [redacted]

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~~C//RD~~ (U) [redacted]

~~C//RD~~ (U) [redacted]

DOE (b)(3)



# References

DOE (b)(3)

~~C//RD~~ [redacted]



DOE (b)(3)