DEVELOPMENT AND STATUS OF GAS CENTRIFUGE TECHNOLOGY

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Abstract

Start of lightweight gas-centrifuges in the former USSR. Short subcritical and long supercritical flexible thin-walled aluminum-rotors. Development in Sukhumi. Results. Transfer to Leningrad. Decisive improvements on gas dynamics. Results 1954.

1957, International Symposium on Isotopseparation in Amsterdam. 1958-1960, Cooperation Germany - USA. 1960, Classification to prevent spread of nuclear weapons. Development in Germany: supercritical centrifuge-rotors, cascading, better rotor-materials. 1970 Treaty of Almelo for peaceful use of gas-centrifuge technology. Production plants in Almelo (Holland), Capenhurst (England), Gronau (Germany). Failure in USA. Enrichment plants in USSR, Japan, China, and Pakistan. Nuclear-weapons equilibrium in East and West prevents the use of nuclear weapons during the Cold War.

Advantage of gas-centrifuges for uranium enrichment compared to other methods like Gaseous diffusion, Nozzle-plants, Mass-spectrometer, and Laser. Application for production of stable and radioactive isotopes for medical and metallurgical use. Removing of impurities in gas-mixtures. Multicomponent-separation in special centrifuge-clusters.

Comparison of short subcritical and long flexible supercritical centrifuge rotors. Subcritical centrifuge machines for separation of liquids in uninterrupted runs. Biological centrifuges for separating viruses or bacteria. New superconducting magnetic material seems to be suitable for an improved bearing design

Keywords:
Gas-Centrifuges, Uranium- Isotope- Multicomponent- Separation, Comparison with other methods, Development, Status.

The 20th century of nationalism and dictatorships with horrible consequences for the suffering peoples during World War II is now finished.

Let us hope that the new time of global cooperation and peaceful competition to find the best solutions for the benefit of all mankind is on the horizon.

Gas-centrifuges for uranium-enrichment is an example of such a global cooperation and made an important contribution to the fact of Cold War between East and West came to an end without a nuclear holocaust.

As soon as the World war II had ended, the victors used the industrial complex of the former enemy as well as the brainpower of able persons for their own purposes.

For instance, the Soviets had transferred the private laboratory of Manfred von Ardenne in West Berlin to Suchumi at the Black-Sea including the whole staff and their families.

After the of Hiroshima and Nagasaki in Japan Ardenne was summoned to marshal Beria into a session of governing persons and was told: "Such a bomb you have to make now for us!" After a few seconds of consideration Ardenne answered:

"The nuclear bomb requires two different parts. The easier one is the bomb itself. The difficult part is the enrichment of the uranium isotope 235 in the natural isotopic mixture. This part, I propose, we will make for you. The explosive itself should be your work."

Beria agreed and gave Ardenne a list of persons somehow already in soviet disposal and said: "Select whom you can use for the project and start to work immediately!"

My name was on this list, I was selected and quickly transferred from Moscow to Suchumi, because I had finished my doctor degree at the Radium Research Institution of the University in Vienna, Austria. The Institution was a forerunner for atomic students.

In Suchumi at the Black-Sea in a former sanatorium and in nearby Agudseri, several important scientists were already assembled: Nobelprice-winner Gustav Hertz, a specialist on diffusion isotope separation, professor Peter Thiessen, former head of the famous Kaiser Wilhelm Research Institution in Berlin and doctor Max Steenbeck, a former director of a big Siemens-factory.

It was their unanimous opinion, that the only way to avoid further use of nuclear weapons would be a so-called "nuclear balance". Only if both sides, the West and also the East would have a necessary arsenal of nuclear weapons, an actual use would be useless, because it would make no sense to govern over a completely destroyed and radioactive contaminated world. Even not for people who would have the possibility to survive for a lot of time in safe shelters.

I was assigned as a co-worker to doctor Steenbeck, who had a double duty. As a well-known expert on plasma physics in Germany, Professor Artsimovich as his Soviet counterpart, had Steenbeck taken out of the concentration camp in Posnan to work with uranium enrichment on his mass-spectrometer.

Secondly he has a duty to think about others than already known methods of uranium isotope separation. He was a brilliant theorist in physics and mathematics as well as an experienced manager of his factory of the well-known Siemens-company.

At the end of 1946 we started working on the development of gas-centrifuges. After a few basic experiments with a thick-walled rubber house, fixed on the axle of an electric motor with variable rotating speed, Steenbeck did theoretical calculations on gas dynamics inside of rotating cylinders. Then he made a proposal to a technical soviet in Moscow. He proposed to use 10 meters long, thin-walled gas-centrifuges with peripheral speed of about 250 meters per second as a device to separate uranium isotope 235 in one step from the natural mixture to nuclear bomb quality.

Despite the fact that such a device had never been realized anywhere in the world, it is remarkable that the technical soviet agreed to try out this kind of gas centrifuge proposal by Steenbeck.

The scientists and engineers in Suchumi did not believe in Steenbeck's idea of the "rotating chimneys" as they called it. It was clear that these long tubings had to pass many critical rotational frequencies before reaching operational speed.

I personally had no specific opinion on that matter. For me it was the only way to survive imprisonment. I decided to do my best as an experimenter to find out a solution.

At that time Steenbeck spent most of his time with Artsimovich in Moscow and left to me most of the experimental development on rotor-dynamics in Suchumi.

Dr. Steudel, an experienced co-worker coming from A E G, a known big German firm, had joined our team and introduced many good ideas in our project. He started to built an apparatus for uranium isotope separation with a fully magnetically suspended centrifuge-rotor. The rotor of about 30-mm in diameter and 30 cm length was partly made out of aluminum and steel. The whole housing and the tubes for introducing uranium hexafluoride as well as the cooling devices for extracting the light and heavy fractions were made out of glass.

Fig.1: Magnetically suspended centrifuge

It was Steenbeck proposal to stabilize the long centrifuges by a chain of dampers inside the rotating tubes. Such a device was included in this experiment, connected to little wholes in the rotor covers by especially wound flexible springs around the central wire.

On March 1, 1948, Steenbeck came back from Moscow with the message: if we cannot show a successful experiment on uranium separation before April 1, the centrifuge development would be finished.

At that time Dr. Steudel with his co-workers was already working for more than one year to built his apparatus. There have been many doubts if Dr. Steudel would be able to show the desired within this short time limits. So I proposed to Steenbeck to built a simple device, using all my so far accumulated knowledge, to meet the required goal. Together with three engaged co-workers, we showed with our very simple machine on March 21, 1948 the

successful separation of uranium 235 with a separation factor of 8% between the upper and lower end of the rotor. At the same day, Dr. Steudel also succeeded with a separation experiment with equal results.

Fig.2: Simple separating device on the needle tip.

The successful experiments of uranium isotope separation with two different devices with uninterrupted flow of the process gas uraniumhexafluorid gave a boost of support to the project. Manpower in laboratory and working hours in the mechanical workshop was increased.

Supercritical centrifuges

The next goal was to learn how to run long supercritical rotors. I designed a simple device with a flat rotor-disc and fixed an axle a few millimeters out of its center. So I was able to mark on it's blackened surface the turning point of the spinning top. The lower end of the axle was held in a bearing of a non-rotating disc. This non-rotating disc was centered by three springs and could move freely in an oil-pool. Beginning from the point at the fixed axle, the turning point of the spinning top moves with increasing rotational speed to the center of the top's mass. The path of the turning point is a more or less complicated curvature. It depends on the rotational mass of the spinning top, the non-rotating mass of the supporting disc, the viscosity of the damping oil and the spring forces of the rotor axle and the forces of the centering springs.

Steenbeck quickly found a mathematical solution of this unknown behavior - unknown at least to us - and extended his calculations later for handling the long supercritical rotors to be developed. From this moment on we were able to handle the movement at any critical resonance frequency for all possible combinations of springs, masses and the forces of spinning centrifuge tubes by bearings with optimized spring-forces and damping.

Fig.3: Critical resonances of spinning tubes

At the end of six years of development in Suchumi in 1952, we had learned the trick to combined short subcritical centrifuges with flexible bellows and to design super-critical rotors. We had demonstrated a group of six three meter long centrifuges containing 10 short tubes of 58 millimeter diameter and 9 flexible bellows, in more than 1000 hours endurance tests. The running speed was 1200 cycles or 1400 cycles per second depending on the available aluminum alloy of the centrifuge tubing. The corresponding peripheral speed was 220 to 240 meters per second. In separation tests using uranium hexafluoride with these sort of rotors, we obtained a separation factor of 3 between the ends. The material losses in one run were only 0.15% of hexafluoride in the collecting ampoules. The efficiency of the separative work was about 50% of the theoretical maximum.

Selection of gas centrifuges for industrial application

Steenbeck was informed by Artsimovich on the stage of development of all the attempts in the Soviet Union to produce highly enriched uranium 235 for nuclear explosives. The goal was to get 1kg highly enriched U-235 (higher than 90%) every day in a industrial producing factory. For this purpose, we calculated that an overall length of centrifuge tubings of 20

kilometers would be necessary and the energy requirement to run the factory would be of about three Megawatts. The mass-spectrometer method would require more steel for the magnets than was used to build the complete soviet navy. The diffusion method had a factory running but suffered such heavy losses by corrosion inside the separating devices that the required enrichment was not obtained.

Evaluating the situation, Steenbeck decided to write directly to the head of the Soviet nuclear enterprise, to marshal Beria. He proposed to built a centrifuge enrichment - factory on top of a diffusion plant to get the necessary enrichment. After having delivered a second urgent letter to marshal Beria, Steenbeck was summoned to an audience. There, it was decided to transfer centrifuge work from Suchumi to Leningrad.

In this dramatic audience, Steenbeck asked Beria to send his family back home as soon as possible. For his co-workers hi asked for a written contract determining the end of their work and a date for returning home.

Beria agreed and I got a contract to be sent home a half a year after having finished my work on centrifuges in the laboratory stage. It was signed on November 29, 1950.

Transfer to Leningrad

In 1952 the chief-constructor of the Kirov-factory, Sinjov, came to Suchumi to select the equipment and the staff for continuing the work in Leningrad. Steenbeck confirmed in written form that I had successfully finished my work, I remained in Suchumi while the selected staff and the equipment were moved to Leningrad.

It took about a half a year until the transferred equipment was again in operation. Disregarding my signed contract, I was ordered to join the centrifuge group in Leningrad on January 1953.

In the laboratory, a big vessel for six 3 meters long supercritical centrifuges was already waiting for the machines to be inserted. If one of the six centrifuges would fail, all the others would be destroyed immediately. I felt very sorry to see the end of my work in an uncertain future.

Return to subcritical, short centrifuges

At that time the Russian co-workers came up with important propositions:

to use Pitot tubes inside the centrifuges for extracting the separated fractions and

to use Holweck-molelar pumps to maintain the necessary vacuum around the spinning rotor.

Together with tube like Alnico- magnets for use at the centrifuge top as touchless bearings, I immediately realized: that must be the fastest way to succeed.

I refused to lose a single working hour on those supercritical centrifuge vessels an .Ud proposed all efforts to put in the new direction. I was sure to finish the task using subcritical centrifuges within a half of a year.

The Soviets agreed and Steenbeck started calculating suitable form of tubes for the gas handling and optimal grooves for the molecular pumps around the rotor.

The Soviets told us: "Show 15% efficiency of the theoretical separative capability in the collecting ampoules and we will let you go home".

The subcritical rotors of 58 mm in diameter and about 45 cm length run with a peripheral speed of 350 meters per second instead of 240 meters per second as the supercritical rotors had done because of the larger diameter of the connecting bellows. The separative capability for the equal length therefore increased about 4-fold.

The first separation experiments resulted in an efficiency of 30% in the collecting ampoules.

With these prospects for a quick end of task, I signed a new contract on October 12, 1953 containing a fixed date for the end of my duty on January 1, 1954.

The last design that I worked with the Soviet Union was a rotor having 100mm in diameter and 50cm length. We called this machine SSZ-100, Self-Stabilizing Centrifuge with 100mm diameter of the rotor tube.

Fig.4: Subcritical centrifuge SSZ-100

It was also the time when the corrosion problem in their plants was solved. So it was my opinion: well, they do not need us any more, they have now their highly enriched uranium produced by diffusion plants and let us go.

This opinion was completely wrong. Three years after we had finished in Leningrad, the first centrifuge plant was in operation. The gaseous diffusion method was gradually phased out. The Soviet-Union was able to keep it secret for 30 years until the Cold War had ended, that the highly enriched U-235 for their arsenal of ten thousands warheads was made in four big enrichment plants with millions of simple subcritical gas centrifuges.

Having finishing our presence in the laboratory of the Kirov-factory we were transferred to Kiev for a so-called "cooling off time". It was a decision of the government to keep the foreigners for a time of 2 or 3 years in the Soviet Union after finishing their work in secret fields. During this time it was offered to work in a non-secret project. After this time and returning back to any country, there should be no further restrictions about the former secret engagement.

On July 28, 1956, two and a half years after leaving the laboratory in Leningrad, Steenbeck and his secretary, Sheffel with his family and myself were sent home. We agreed to conclude a contract about determining our rights on the common gas-centrifuge development in the Soviet-Union.

This contract, signed in July 1958 and also acknowledged as binding for the firm DEGUSSA in Frankfurt/Germany, gave all the patents and other rights of exploitation in the western world to Scheffel and myself, while Steenbeck kept the same privileges in all the eastern block countries.

In April 1957 I attended an international conference on isotope-separation in Amsterdam, organized by professor Kistemaker. I realized that our gas centrifuges developed in the Soviet-Union far exceeded the presented achievements on uranium isotope separation. The low energy requirement compared with gaseous diffusion was a striking advantage. I decided not to leave my knowledge buried in the Soviet Union but to introduce the gas-centrifuge for uranium enrichment into the western world.

In January 1958, I had a meeting with the soviet representative for atomic energy, professor Emelianov, in Vienna. He invited me to come back to the Soviet Union to work on the intercontinental rockets. I did not want to go again to the East, but I asked Emelianov for permission to introduce my centrifuge knowledge into the western world and I got it. He offered even support if I would need some protocols and I have a telephone consultation about his permission fixed on tape recorder.

Scheffel and I started working in a Degussa laboratory in Frankfurt. All my patents filed in Austria with the help of Steenbeck were transferred to the Degussa and a fair share was agreed in case of success. The Degussa confirmed in the contract to use the centrifuges for peaceful purposes only.

In July 1958, I went to the grandfather of the gas-centrifuge enrichment, professor Jesse W. Beams, at the University of Virginia in Charlottesville, USA. It was an agreed cooperation with full exchange of information between the firm Degussa and the University of Virginia as well as between the US-Atomic Energy Commission and the German Ministry for Atomic Energy.

It was my intention to find out whether our new enrichment process would be compatible to the American diffusion. I demonstrated in the course of two years endurance tests and separation tests with short bowl gas-centrifuges. Again, I obtained an efficiency of the separative work of 30%.

Several times I returned for a few days back to the Degussa laboratory in Frankfurt, Germany to help Scheffel who was working to repeat the last soviet centrifuge model SSZ-100.

After two years the US-Atomic Energy commission decided not to continue the cooperation with Germany. I wrote a final report about my results known as USAEC-report ORO-315. It is the last detailed unclassified publication. My visa was cancelled and I wend back to Degussa in Germany.

Further development of gas-centrifuges world-wide

The further course of events in the United States in America is known. President Carter started a new enterprise with 15m long centrifuge rotors on the basis of earlier machines developed at the University of Virginia in Charlottesville. It was very heavy machinery. After

having invested 3.5 billion dollars in development and three industrial enrichment plants, they gave up and decided to develop Laser enrichment instead.

On August 1,1960 all the gas-centrifuge work in Germany was classified upon American request. The Degussa-board decided to turn the gas-centrifuges over to the government.

In 1964, the whole laboratory and a part of the staff were moved from Frankfurt to Juelich in the neighborhood of the big Center for Nuclear Research. The goal was to demonstrate within 5 years whether the centrifuge process was capable to compete with other enrichment processes and to close the gap in the cycle to produce nuclear fuel for power stations.

We demonstrated an ideal cascade arrangement containing 21 machines of the SSZ-100 type. The peripheral speed of the rotors was 400m per second. The output of this cascade was about 5kg low enriched uranium per year.

Even the best aluminum alloy is creeping at that peripheral speed. We tried all sorts of fiber with little success at that time. The solution for an industrial application we found at a firm making thin walled tubes for small rockets in mass production out of maraging steel.

Several firms, ERNO, DORNIER, INTERATOM and M.A.N. delegated a small staff to our laboratory in Juelich to learn how to work with centrifuges and to gain experience for transfer into mass-production.

Larger cascades were designed and put in operation around 1967. The best diameter for the rotor tubes was found to be a flat optimum between 100 and 200mm. All this work was accomplished with subcritical centrifuges.

Transition to supercritical centrifuges

Now I started to fight for supercritical machines. Nobody believed in the possibility to built and run such devices. Finally I made the necessary joints out of maraging steel on a lathe in our mechanical shop by myself.

Fig.6: Patent for supercritical centrifuges

The first separation experiment with uranium-hexafluoride with a supercritical centrifuge combined two subcritical tubes. The result, doubling the output, was convincing.

The firm M.A.N, Mashinenfabrik Augsburg Nuernburg, immediately switched all its efforts to supercritical centrifuges and won the competition between the bidding firms to produce the centrifuges for the first industrial cascades and later on for the plants.

URENCO gas-centrifuges in Europe

In 1969, the Netherlands and Great Britain decided to join Germany to exploit the gas-centrifuges process to produce low enriched uranium. All three countries ratified the well-known "Almelo - Treaty" in 1970.

A common enterprise was founded, the URENCO, and at Almelo in Holland, at Capenhurst in England and later at Gronau in Germany started industrial production of low enrichment uranium.

In Capenhurst, it was decided to stop the diffusion plant and to construct a centrifuge enrichment factory instead.

Fig.7: Diffusion and centrifuge plants in Capenhurst

The overall capacity of the URENCO plants in about 4000 tons separative work per year and further extension is planned. The financial situation is no problem because the centrifuge plants only about two percents of electricity necessary for diffusion plants at t the same capability. The failure rate of the machines is less than a tenth of a percent per year.

Fig.8: Supercritical centrifuges in the Gronau-Plant.

Gas centrifuges in Japan

In 1973 the PNC, the Power Reactor and Nuclear Fuel Development Corporation invited me to come to Japan. A decision was to be made whether to built a diffusion plant or develop gas-centrifuges for fueling the nuclear power stations. I was able to convince the PNC that centrifuges would be the better way compared to the energy hungry diffusion.

At present time research and production facilities are in operation to supply about 1/3 of the necessary fuel for the Japanese nuclear power stations.

Gas centrifuges in Russia

The millions of subcritical centrifuges running in the former Soviet-Union had replaced the enrichment of uranium 235 by diffusion. The production of highly enriched material for ten thousands nuclear warheads was the reason for a nuclear equilibrium in East and West. It prevented the use of atomic weapons to solve conflicts. The Cold War of superpowers ended without and overall nuclear destruction of the world.

Fig.9: Subcritical, short centrifuges in Russia.

Gas centrifuges in China

Besides national research in a small scale, China acquired enrichment plants from Russia for the nuclear program.

Gas-centrifuges in Pakistan

Based on the principle of URENCO centrifuges, Pakistan produced uranium-enrichment for nuclear explosives.

Gas centrifuges in Iraq

The Iraqi attempt to net nuclear weapons by using URENCO type gas-centrifuges has been stopped after the Gulf War by assistance and inspection of the International Atomic Energy Agency, IAEA, in Vienna, Austria.

Gas centrifuges in Brazil

Brazil has a long tradition using gas-centrifuges for uranium-enrichment. After an agreement with Argentina to refrain from nuclear armament, centrifuge of Brazilian design are developed and installed in industrial enrichment-plants. In 1970s a plant based on nozzle-elements was built but never finished.

Conclusions

No challenge for economical competitive industrial plants for uranium-enrichment with gas-centrifuges is to be expected in the near future. Even Laser-enrichment has been stopped in the United States of America for that purpose.

The development of gas-centrifuges shifted to purification and multicomponent-separation of gas-mixtures. Isotopes for medical or metallurgical use like tungsten, iron, xenon, krypton, sulphur, molybdenum and others have been separated.

Subcritical short centrifuges, based on similar bearing-technology, are on market to handle liquids in uninterrupted operation, to separate viruses, bacteria or vaccines.

Worldwide experience on different sorts of tubular centrifuges arranged in different clusters is available to be selected for special purposes.

I want to draw the attention to newly developed touchless magnetic bearings based on superconducting material operational at the temperature of liquid nitrogen. With these bearings support of the rotor and damping is provided without any electronic guidance.

Let us see what else on new developments and separation methods will be presented in the following workshop.

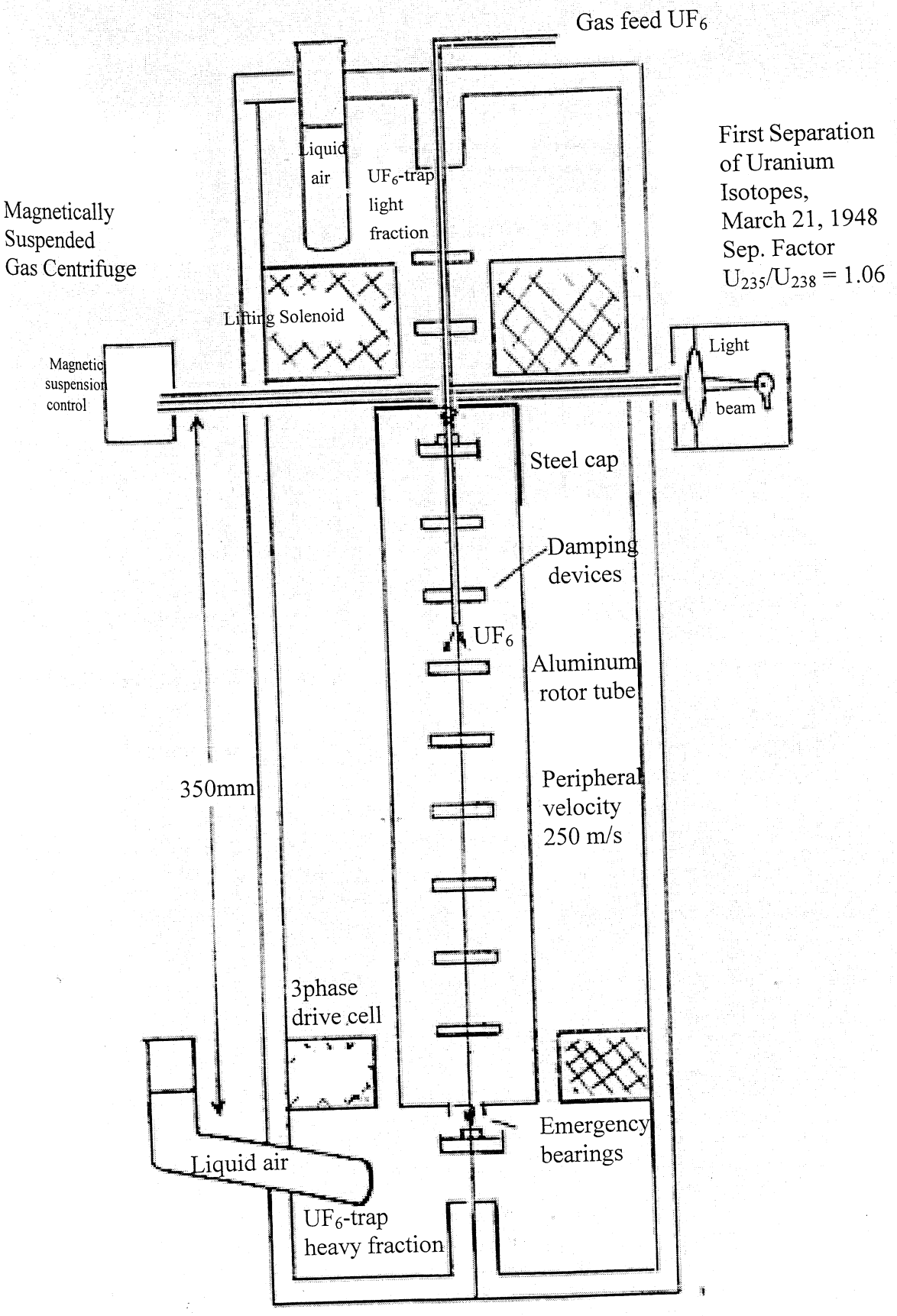


Fig.1: Magnetically suspended centrifuge

First Separation
of Uranium Isotopes
March 21, 1948,
Sep. Factor
$U_{235}/U_{238} = 1.08$

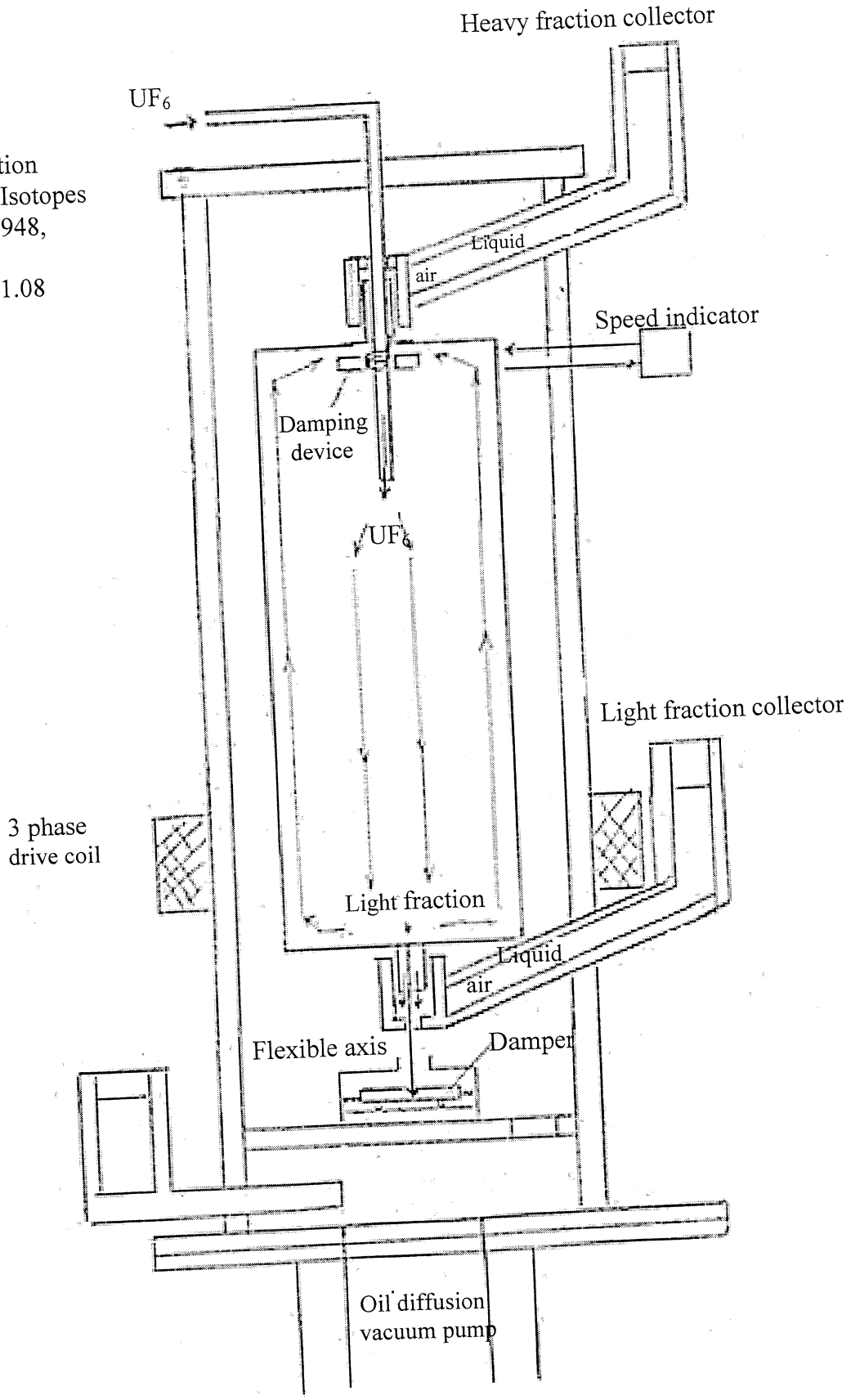
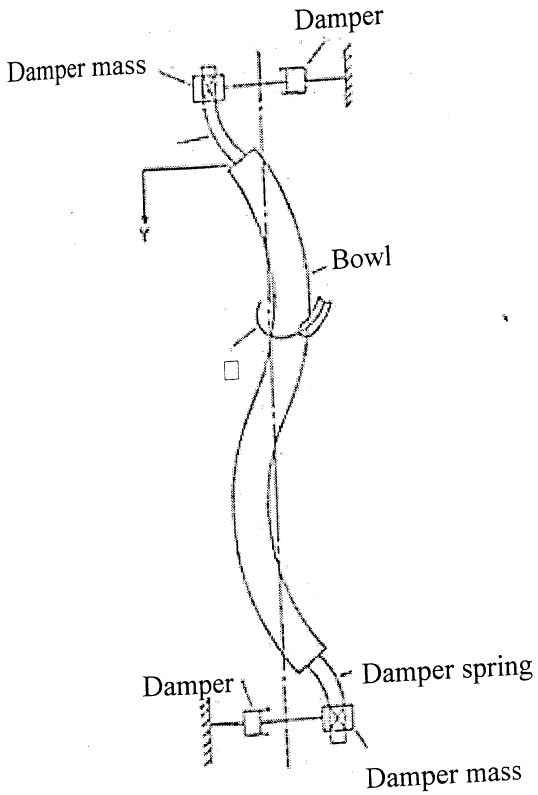


Fig.2: Simple separating device on the needle-tip



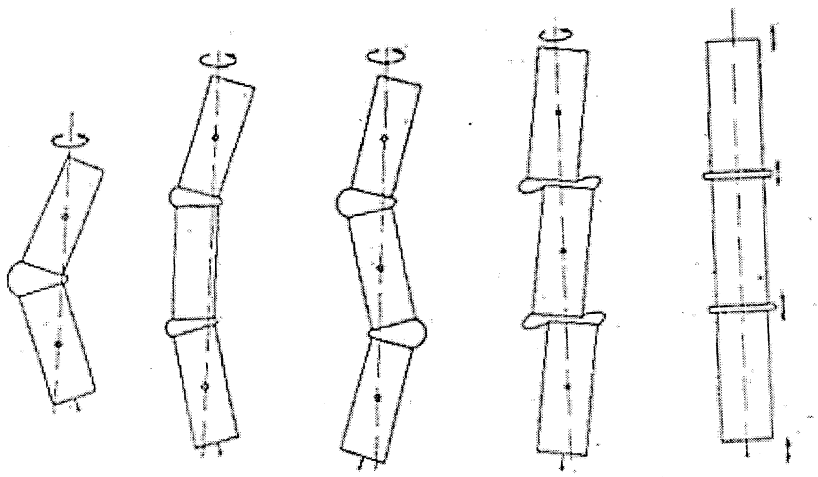


Fig.3: Critical resonances of spinning tubes

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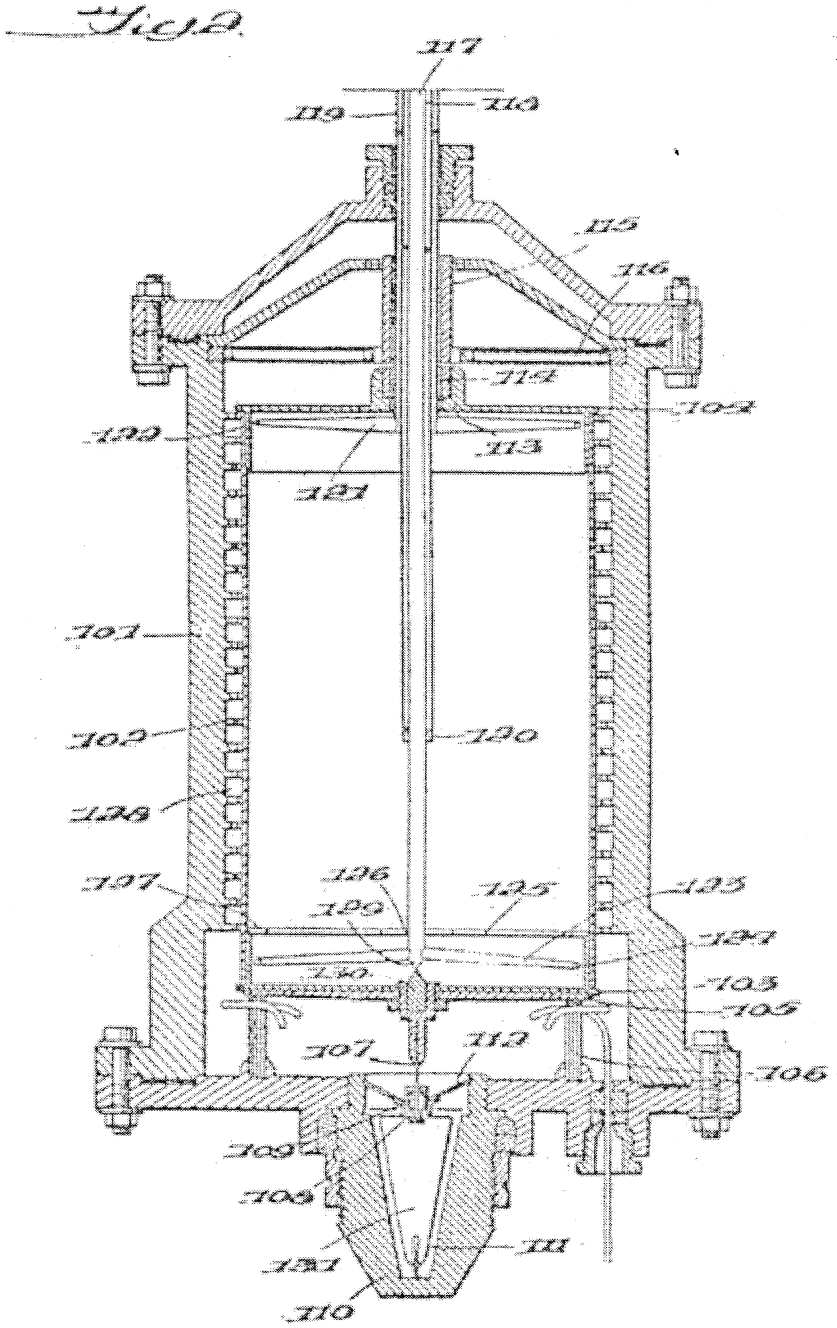

INVENTORS
Gernot Zippe
Rudolf Scheffel
Max Steenbeck

Fig.4: Subcritical centrifuge SSZ-100

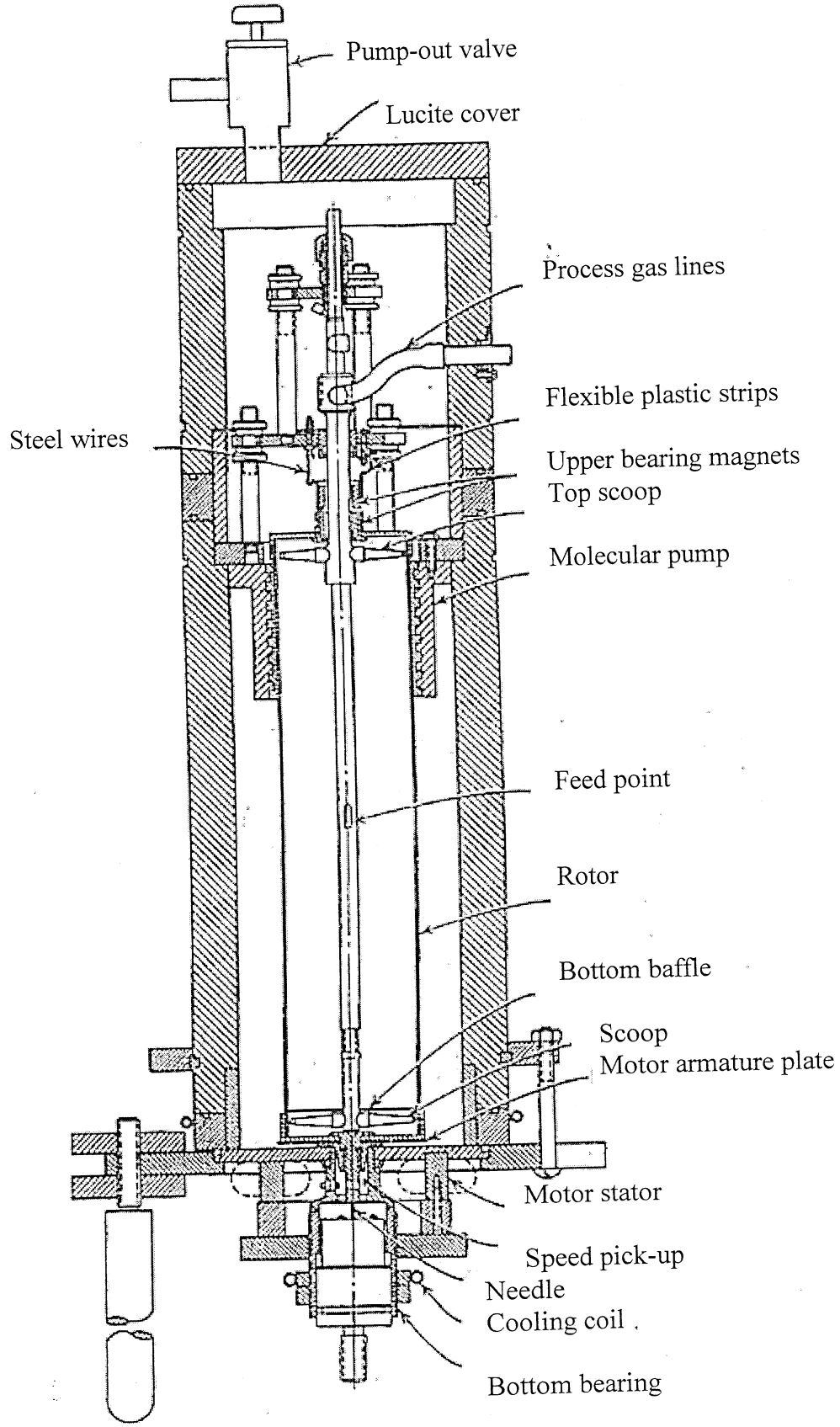

Fig.5: The Zippe centrifuge, Virginia model

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Fig. 1.

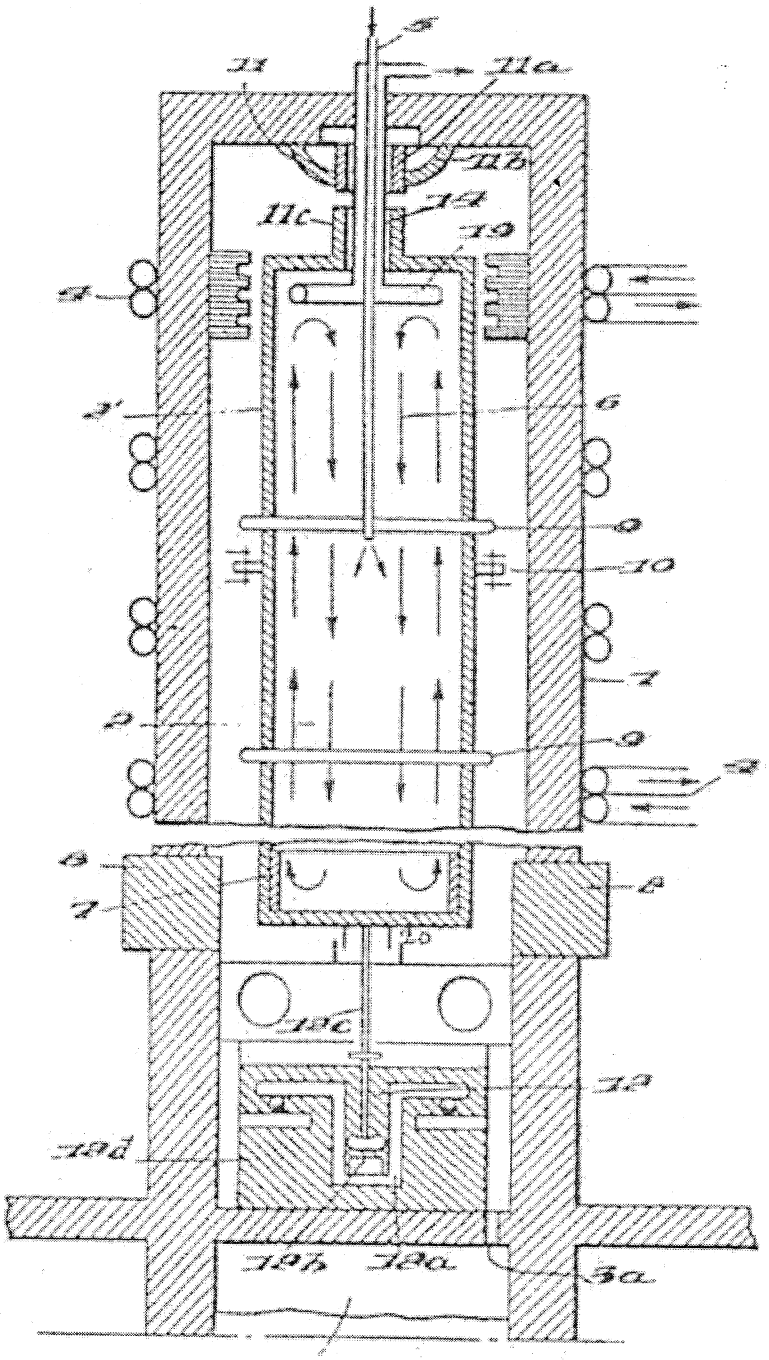

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Fig.6: Patent for supercritical centrifuges

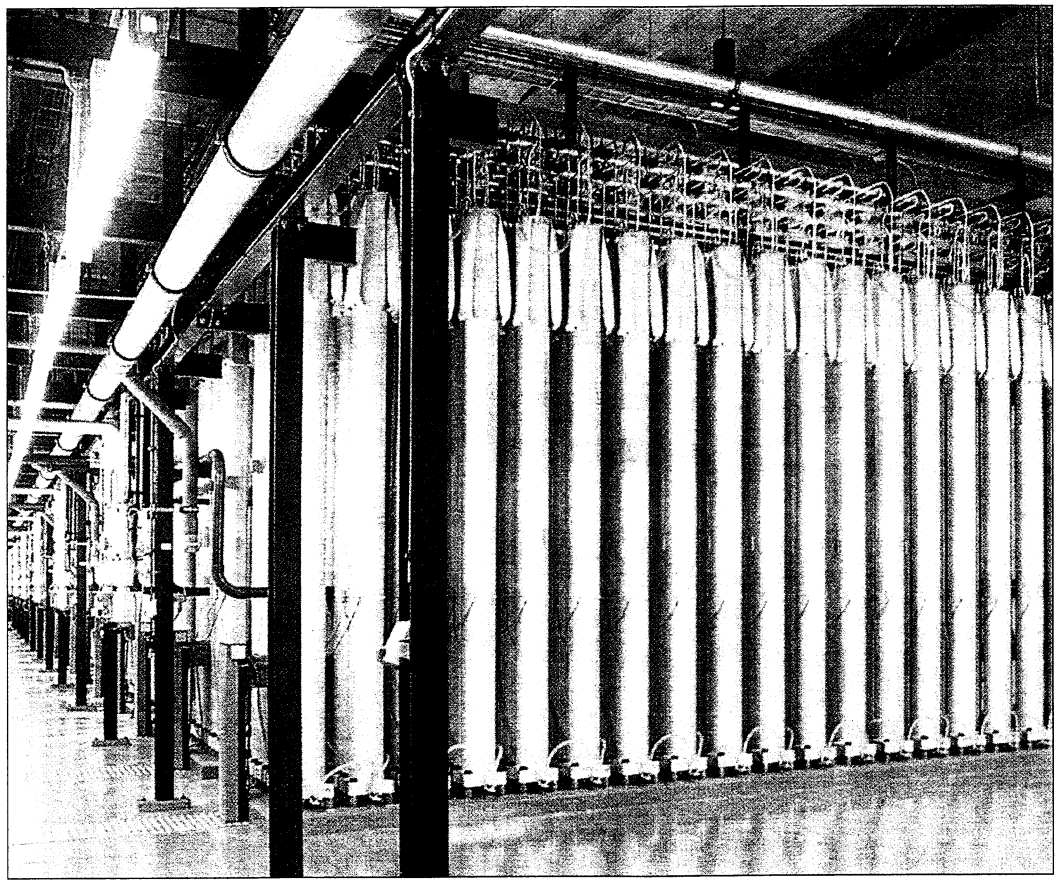

Fig. 8: Supercritical Centrifuges in the Gronau-plant

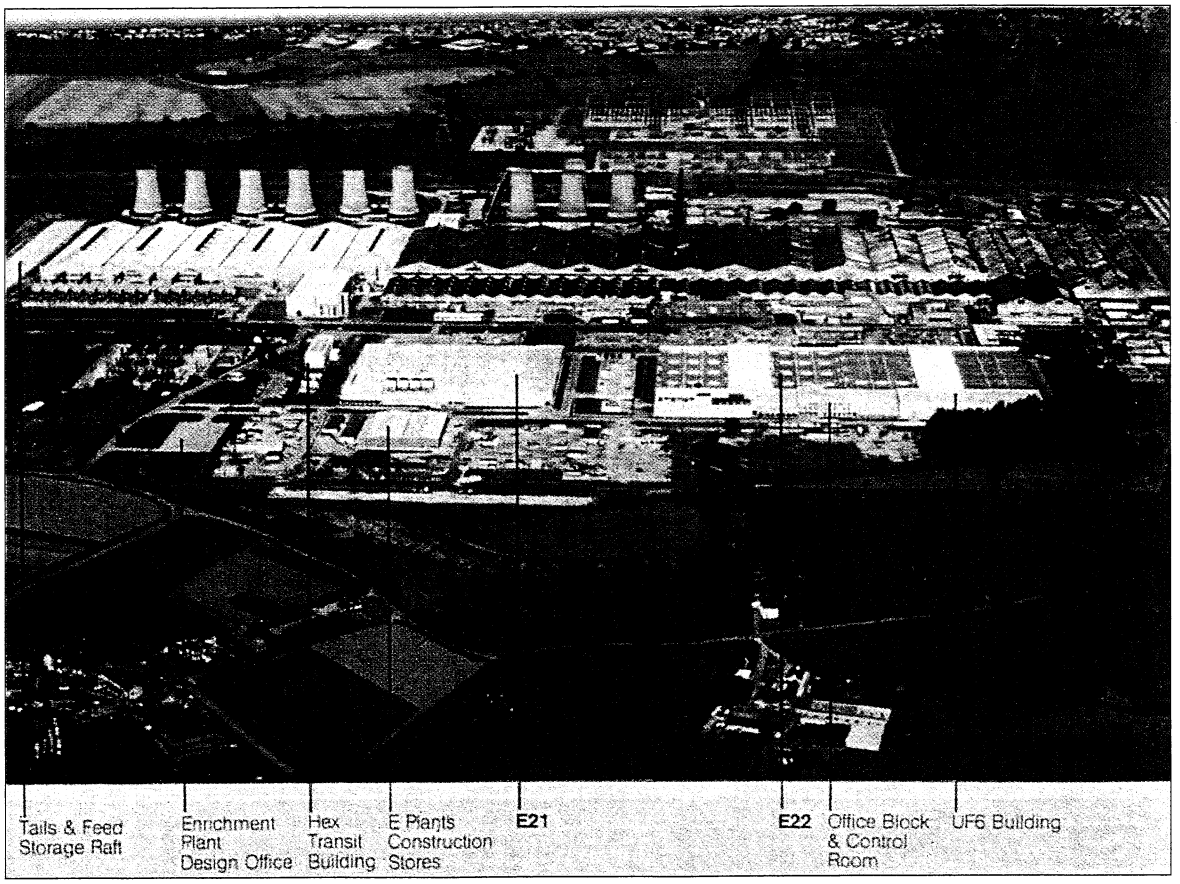

Fig. 7: Diffusion and Centrifuge Plants E21 E22 in Capenhurst

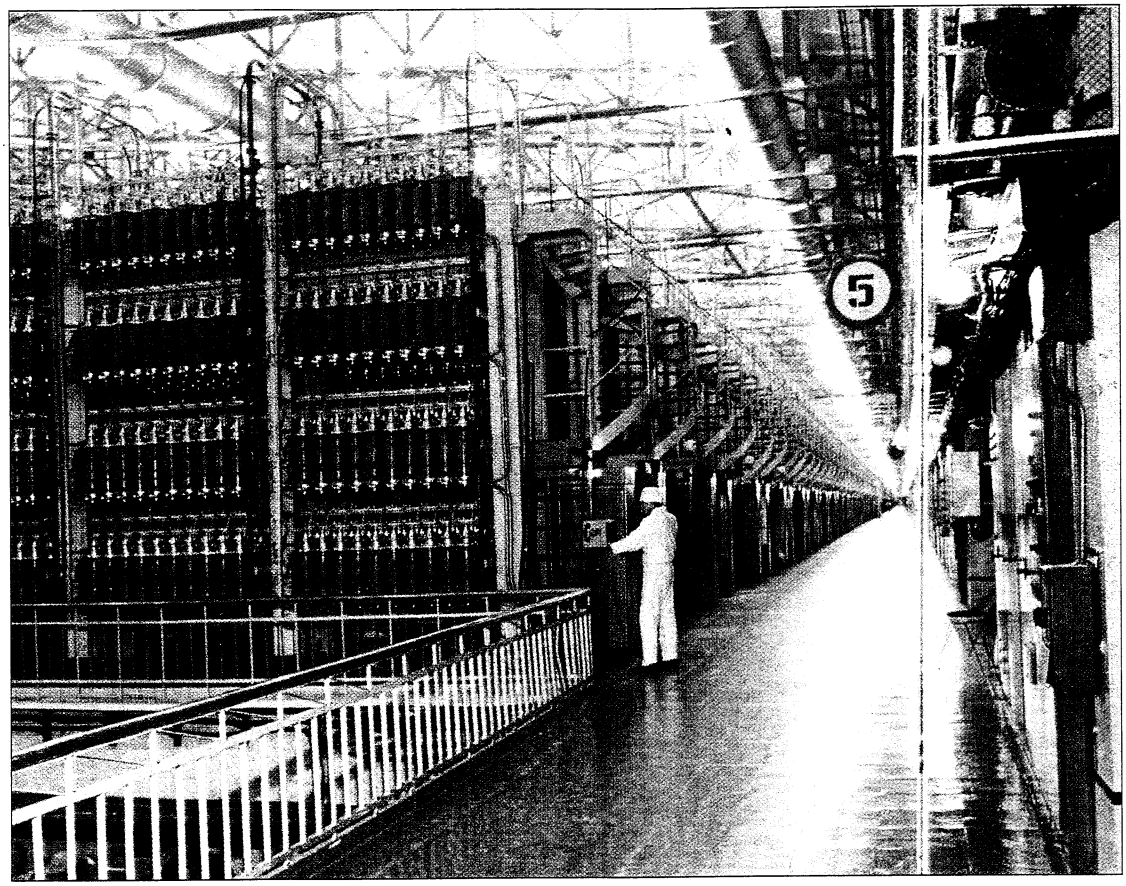

Fig. 9: Subcritical, Short Centrifuges in Russia