RUDOLF SCHULTEN'S HIGH TEMPERATURE REACTOR

A Technology Ready for Today

by Dr. Urban Cleve

Dr. Cleve addressing the EIR seminar in Frankfurt.

EIRNS

Editor's note: This is an edited transcript of a talk Dr. Cleve gave to an Executive Intelligence Review *seminar, Sept. 28, 2010, in Frankfurt, Germany.*

Dr. Cleve was the head of the engineering department of BrownBoveri/Krupp Reaktorbau GmbH, where he was responsible for the engineering, design, building, testing, and putting into operation of the AVR high temperature reactor. Later he worked in management for companies that built large plants for energy and environment. He retired in 1992, and is now the last living member of the BBC/Krupp leading crew.

His presentation was translated from the German by Vyron Lymberopoulos.

The AVR experimental high temperature reactor. Dr. Cleve headed the engineering team that designed and built the nuclear reactor.

In its first issue of 2010, the German-language *Fusion* magazine reprinted a most interesting contribution by Dr. Rudolf Schulten, "Old and New Ways in Nuclear Technology," which was initially published in 1990. Today, more than 20 years after that first publication, it is exciting to give a lecture in which I can substantiate fully that High Temperature Reactor technology is still up to date, and I will provide the evidence that the thoughts and considerations which Dr. Schulten had as a young engineer during the 1950s, have been, and are still correct and trend-setting.

As a young engineer, I was excited about the task of collaborating on the reactor concept invented by Professor Schulten, the AVR Reactor in Jülich. At 33, I was in a leading position as head of the department for complete engineering and responsible for design, erection, testing, and commissioning of the complete reactor, up to its handover to the customer.

I have never lost this excitement, and therefore I am happy to give this presentation. I will begin with some basic considerations from the viewpoint of the energy policy of Germany at that time.

The German economy after the war was based on:

(1) The most inexpensive and as cheap as possible power supply for industry and households for electricity production. It was believed that an excessively expensive price of electricity is antisocial, and by and large, that it would hinder the growth of the national economy.

(2) Security of supply.

(3) Optimum use of available fuel and capabilities for electricity and power production, both for households and transportation.

For this purpose, we had available solid fuel (coal and lignite), and liquid fuel (oil and natural gas). All these primary energy sources are suitable for electric power generation in power plants. To date, only liquid fuel is technically sound and economically useful for households and transportation.

In electricity production, the objective was then primarily to use coal and lignite. The noble energies, oil and gas, should only be used in large power plants in special cases of great benefit to the economy. Back then, the popular belief was that these fuels would only be available for a limited period of time, perhaps up to the turn of the 20th Century. This turned out to be too pessimistic. Today, nobody knows how long these reserves will truly last, with a constant increase in the use of energy and a constant rising world population. Furthermore, the fact is that oil and gas are limited and becoming steadily more expensive. That surely does not need further discussion.

Germany is one of the poorest nations in oil and natural gas. Only coal is widely available. To counteract, at an early stage, an expected worldwide power shortage to come, and to avoid its effects, nuclear power plants were already being developed and built worldwide during the 1950s. The same shortage problem remains today, but in addition to nuclear plants, the so-called renewables—wind and solar power—are now considered alternatives. Some words on that later.

Dr. Rudolf Schulten, who developed the concept of the pebble bed high temperature nuclear reactor.

By the 1950s, Professor Schulten already had the idea of building very high temperature reactors, which would not only burn uranium-235 (of which there are relatively limited deposits in nature), but also breed thorium as nuclear fuel and then burn it as uranium-233. His deliberations for a technical solution were based on the following reactor fundamentals:

• Sphere-shaped fuel elements, because of their superior flow and heat transfer characteristics. During reactor operation, these fuel balls can be circulated, replaced, removed, and stored; and burn-up measurements of the fuel can be made.

• Graphite as a basic material for fuel elements and the reactor core, which would serve as a moderator for neutron radiation and is suitable in particular for very high operating temperatures.

• Helium as coolant, because of its very high heat-transfer coefficient.

• An integrated, self-contained primary circuit reactor concept, to obtain the highest safety standards

• Uranium-235 and thorium-232 as fuel, with the objective of breeding new fuel from the thorium, which decays to U-233.

• High operating temperatures for electricity production with the highest thermodynamic efficiency, for optimum utilization of the nuclear fuel.

• Use of the high heat made possible by the high temperatures of the nuclear reaction, transferred by the helium gas, for the engineering and chemical processes of gasification of coal, lignite, turf, and other biomass. Thus, nuclear fuel would be used to produce liquid fuels for households and transportation.

• Inherent reactor safety. A Maximum Credible Accident or MCA scenario can not occur, even during complete failure of the cooling system.

These were the visionary considerations that led to the success of this technology then, and today, 60 years later, all these considerations are still valid, with no exceptions. In his field, Professor Schulten was ahead of his time, and in this respect, actually only comparable to space scientist Wernher von Braun.

The development pursued in Germany with the high temperature reactor is a big achievement, even though environmentalists do not want to acknowledge this and politicians have not yet recognized this. By the end of the 1990s, when the experimental AVR and the THTR (Thorium High Temperature Reactor) were decommissioned because of political pressure, Germany had a leading position in this technology worldwide, almost a monopoly.

Technical Challenges

The implementation of these ideas posed extreme demands on engineering technology. Helium gas constituted one of the largest problems. It is a very thin and dry gas, which had not been used to this extent before.

All the reactor components had to be constructed from scratch, without any prior examples and without previous experience. These components were tried and tested under normal conditions in test facilities, and most failed when installed in the reactor and operated under helium conditions. This inevitably led to constant schedule delays and cost increases.

As an executive, the pressure on me was enormous. From the top, it was once put forward to me: “You build everything two times.” My answer was short: “Yes, that is nearly true, but nothing three times.”

Testing and trying until ultimate reliability is achieved and all problems are identified and solved, is the decisive foundation for successful development. One time I angrily said, “What shall I do—avoid costs and keep deadlines, or build an installation that works; you can’t have both?” I was young enough to assert myself.

It is beyond the scope here, to explain all the technical problems and point out the solutions. Nevertheless, to the engineers, one development, and one can say the deciding one, was very beneficial. This was the development of fuel elements with so-called “coated particles.” Without this development under wide international cooperation, success of the AVR would have become vastly more difficult. The new graphite fuel pebbles, embedded with coated uranium particles, were developed—and this should be emphasized—in cooperation with: The AVR in Germany; the Dragon project in the United Kingdom; Gulf General Atomics in the United States; the Jülich nuclear research center in Germany; the Institut Laue-Langevin nuclear research center in Grenoble, France; the Austrian nuclear research center at Seibersdorf; the Petten reactor center in the Netherlands; the Atomic Energy Agency in the United Kingdom; the Union Carbide Corp. in the United States; and Nukem, together with Hobeg in Germany.

The successor to the AVR: The 300-megawatt Thorium High Temperature Reactor (THTR) operated for three years, until it was shut down for political, not technical, reasons.

This unique international cooperation was mainly co-financed by the Federal Ministry of Research and Education, which contributed a decisive share. The success of this development is best represented when one looks at the original design of the helium cooling system, in the AVR reactor. Initially, the radioactivity was calculated at 10^7 curie. Subsequently, the actual radioactivity measured amounted to 360 curie only.

AVR: An Unparalleled Success

The AVR first went critical on August 28, 1966, after successfully passing all the test runs of different components, and nuclear physical measurements to verify the calculations.

On December 18, 1966, for the first time the steam turbine was connected to the grid, with an output of 6 megawatts. Thereafter the reactor was in operation for 22 years, until December 31, 1988.

The reactor was shut down in 1988 solely for political reasons. There were no technical doubts, and certainly no doubts of technical safety were present. For 22 years of operation, a technical safety upgrade was not necessary, no insolvable problems emerged, and no significant technical modifications were necessary. Everything was well thought out from the start.

One event, however, is of foremost importance. In 1967, for the first time, we tested a Maximum Credible Accident, which is one where the fuel elements lose their coolant and all reactor safety devices fail. This was a test of the reactor’s inherent safety concept, devised by Dr. Schulten, which ruled out the possibility of such an MCA. This exciting experiment took place privately, and was barely noticed outside of the plant.

Hans Weingartz

Political pressure shut down Germany’s high-temperature reactors. Above: An anti-nuclear protest in Bonn, after the Three Mile Island accident in 1979. Right: Green terrorists in the 1980s attack a German nuclear plant.

The reactor was driven to the maximum power of 15 megawatts-electric and a predetermined operating temperature of 850° Celsius. Next, all safety devices were disabled, and the cooling gas fans were switched off. As we had calculated, the reactor cooled down by itself over a few days, dissipating the residual heat from the core to the outside.

Worldwide, this was the first planned MCA in a nuclear power plant. Nobody outside noticed anything, no radiation penetrated

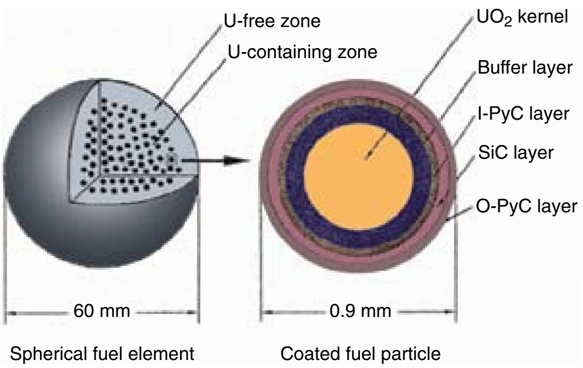


Figure 1
TRISO FUEL ELEMENTS
The unique design for the pebble bed fuel has a kernel of uranium oxide surrounded by layers of pyrolitic carbon, silicon carbon, and graphite. These fuel elements are then embedded in a "containment" structure the size of a tennis ball.

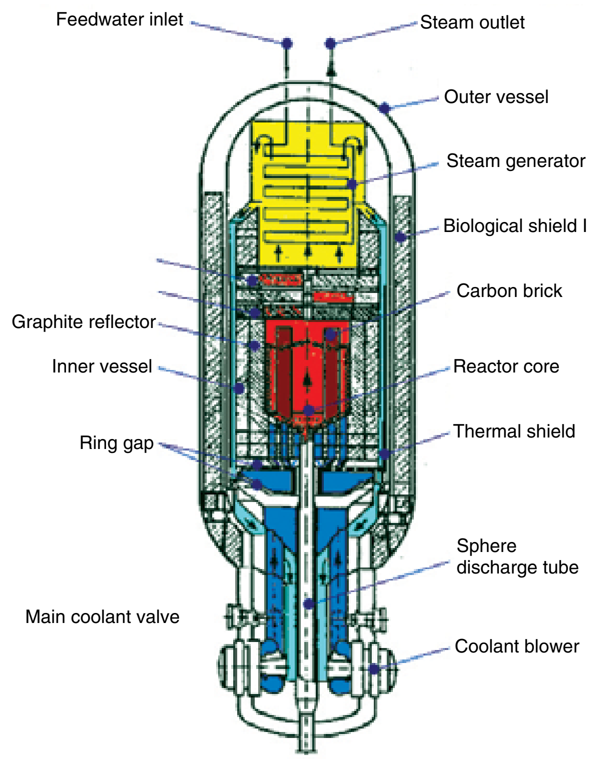


Figure 2
CROSS-SECTION OF THE AVR PRIMARY CIRCUIT

outside the reactor core, and from the control room the operational staff could observe the course of the experiment unmolested. This MCA experiment was repeated in 1979, this time, however, with detailed recordings and measurements of the entire sequence.

Chernobyl took place later, in 1986; it was not the first MCA. The terrible backlash of the Chernobyl disaster, a completely different reactor construction, weighs heavily upon any safety discussion of nuclear power plants even today. At present, the HTR is the only reactor concept, in which such an accident is ruled out, on the basis of nuclear physics.

Keeping anything under wraps in politics and public opinion is incomprehensible to every nuclear specialist. And so, when we discuss failures, we should mention one serious failure in the AVR steam generator. The steam generator is considered a critical unit, because, if it leaks, water could permeate the helium system, requiring a total shutdown of operation.

Several hundred thousand AVR weld seams had been examined during construction, and all available testing methods were applied, even those newly developed. All inspections and pressure tests were passed without complaint. Obviously, the effects of water penetration in the system had been calculated in many computations and probes. All indicated that an alarming nuclear failure could not occur. But, sure enough, this failure did occur, although it was not related to safety. According to the international seven-stage assessment scale for incidents and accidents in nuclear installations, this failure can be categorized as a level 1—simply an anomaly.

Nevertheless, the stoppage of several months, to repair the damage, was unfavorable from an operational standpoint. Practically all other reactor components operated without flaws. Partly worn-out components and small defects could be fixed during ongoing operation, making use of

Figure 3
INNER GRAPHITE CORE OF THE AVR

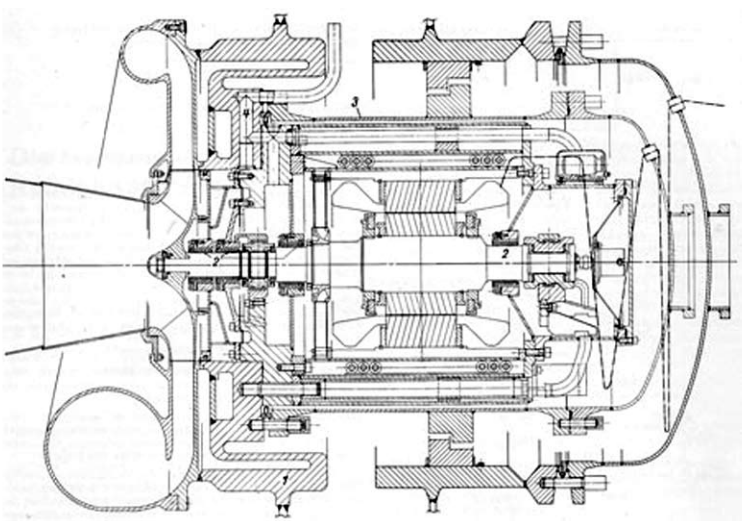


Figure 4
DIAGRAM OF AVR GAS COOLING BLOWERS

disassembly technology that was specially developed for such events, without exposing staff to excessive irradiation.

As a prototype, the operation of the AVR was an unparalleled success story. Not a single radiation accident occurred. During 22 years of operation, not a single employee was exposed to an excessively high radiation dose. The release of radioactive substances to the atmosphere was insubstantial; the exceeding of permissible doses did not occur even once. With the exception of the steam generator, all operational failures that were not 100 percent preventable can be classified as "0" on the assessment scale—having no or insubstantial safety related concern.

The utilization factor, the percentage of reactor online operation time over 22 years, was 66.4 percent. As an experimental reactor, particularly for testing various fuel elements, under the international development program mentioned above, the down time for this work is included. The highest operational availability was reached in 1976, at 92 percent. Although international statistics were not kept, certainly this was a world record for a technology developed from scratch.

The THTR Is Conceived As a Follow-up

Already in 1966, the basic concept for a follow-up reactor was developed. Output was specified at 300 megawatts-electric. Without previous operational experience, surely it was a giant leap from an 15-MWe experimental reactor to a demonstration reactor of 300 MW. After weighing all arguments, pro and con, it was a courageous decision to proceed with the larger reactor, and an appropriate one for today.

With respect to the AVR technology, we had to accomplish substantial construction alterations for the larger reactor:

• The steel pressure vessel had to be replaced. A prestressed concrete pressure vessel was designed, a completely new design, globally.

• The limited activity of helium permitted us to do without pressure-tight containment. Therefore, only an unpressurized steel casing was designed.

• Because of its increased performance, the gaseous helium coolant had to flow through the reactor from top to bottom; otherwise the fuel elements would withdraw to the upper layers.

• A new mechanism was incorporated as the trigger for the fuel elements. Once this concept was well advanced during design, the reactor physicists found that the diameter of the pebble bed was so large, it was no longer practically possible to guide the shutdown and control rods in the outer graphite reflector without mechanical stress. Therefore, the reactor would not be able to shut down completely.

During a roundtable meeting with all staff members, this extremely difficult problem was discussed. After it became clear that damage endangering the staff, and above all, the environment, could not occur, it was decided to drive the shutdown rods directly into the pebble bed. This resulted in a very complicated construction of these rods, and the possible danger of the destruction of fuel elements.

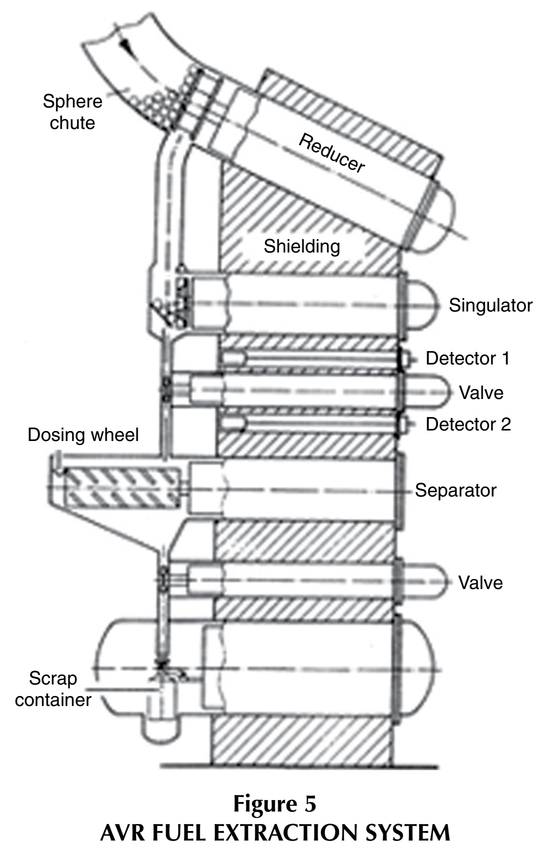


Figure 5
AVR FUEL EXTRACTION SYSTEM

far too high. The sole causes of this high rate were the shutdown rods and the new trigger mechanism. All other components performed flawlessly.

The THTR operated for three years (1986-1989), accumulating 16,000 hours. This time of operation was sufficient to obtain sufficient understanding and experience to build additional reactors. A finding of major importance was the trouble-free operation of steam generation, with the highest thermodynamic efficiency, including intermediate super heating. The startup, shutdown, and routine operation of the THTR installation had operating results that were fully comparable to conventional power plants. As with the AVR, not a single relevant technical failure occurred. Despite problems that occurred, the operating staff was never overexposed to radiation.

The essential findings and experience with the THTR-300 can be summarized as follows:

- According to guidelines of load distribution, HTR power plants can be utilized for the supply grid; control characteristics, also with regard to maintaining frequency, are perfect. When idle, even when repairing open primary components, the staff is not excessively exposed to radiation.
- The radioactivity of the primary gas helium did not rise when the pebble fracture occurred; the coated particles are so small and strong that they can not break.
- All newly designed components, and the entire installation, except for the above-described problem with excessive pebble fractures, functioned flawlessly.
- As demonstrated by unequivocal evidence, the safety technology is so advanced that no risk exists to the operators and the population. Because of the very low radioactive contamination of the helium, an evacuation of the population is not necessary in case of a worst conceivable accident.

Despite its short operating time, the demonstration reactor

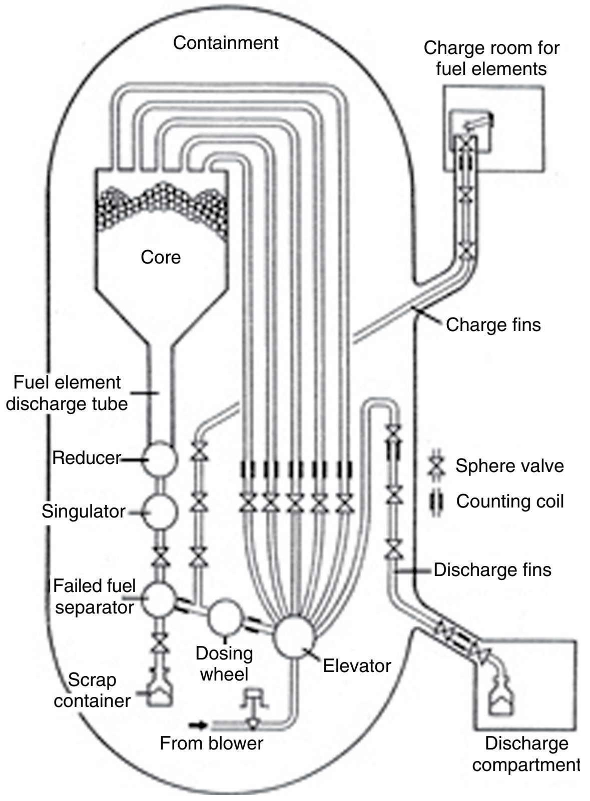


Figure 6
BASIC DIAGRAM OF THE AVR FUEL CYCLE

It was acknowledged that, in order to learn if this proposed construction was at all technically feasible, a reactor of 300-MW size had to be built. The alternative would have been a conventional ring core design, although without longstanding knowledge of operational behavior of the AVR's graphite interior, the construction risk for this design appeared even greater. Twenty-three years later, after the shutdown of the AVR, this decision proved to have been a mistake, because we found that after 22 years of operation the graphite interior of the AVR was as if brand new. Not a single block had shifted even 1 millimeter!

Unfortunately the decision was in favor of driving shutdown rods into the pebble bed. Operational experience with the demonstration reactor had to be postponed in order to make the final decision at a later stage. During commissioning, regrettably, the feared difficulties actually happened. The conditional difficulties were controlled during operation of the reactor, but nevertheless, the reactor operated for three years.

Comparing the failure rate between the AVR and the THTR shows the problem. The failure rate per circulated fuel element of the AVR was 0.0092 percent, compared with the THTR at 0.6 percent. Naturally that was

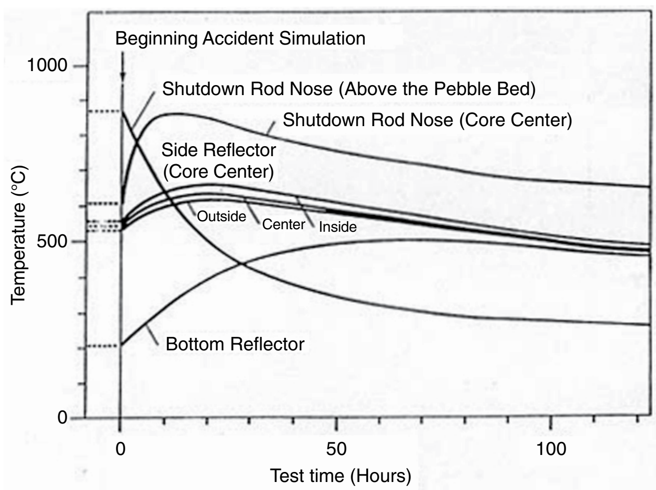


Figure 7
LOSS-OF-COOLANT SIMULATED ACCIDENT TEST RESULTS
The AVR shut down and cooled down as designed, when operators forced a loss-of-coolant situation.

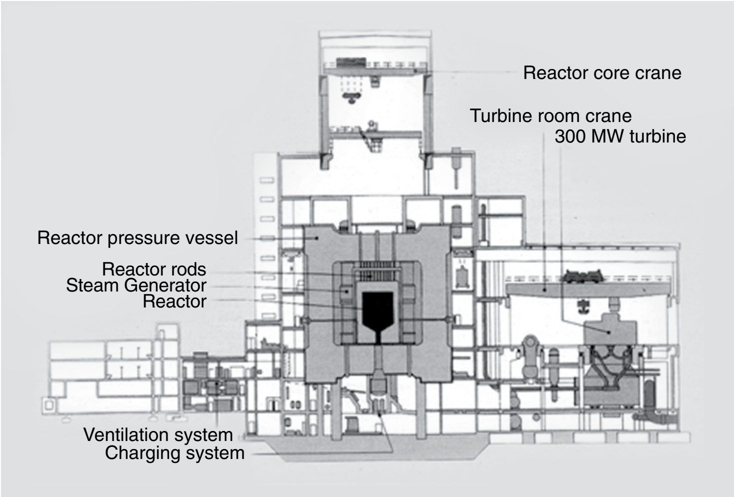


Figure 8
SCHEMATIC OF THE 300-MW THTR POWER STATION

has yielded all the necessary knowledge and experience required to build new HTR power plants safely. Although little known publicly, the decommissioned reactor provides the evidence that its prestressed concrete pressure vessel is the safest storage repository for radiating components. There is nothing more safe than this from a technical engineering standpoint. No radiation can be detected on the outside of the prestressed concrete pressure vessel. A nice restaurant built on the roof, with splendid views over the Münsterland would certainly be an excellent use for the site!

HTR Decommissioning Lessons

The results of the combined operational experience with the AVR and THTR show that, without further development, it is possible to apply this technology on a large scale. Here are some of my conclusions, from my experience:

To maximize safety is by far the most important criterion with a future very high temperature reactor. Furthermore, the question of final storage of radioactive materials, after decommissioning such an installation, should be planned from the start. The technology I describe, has to be understood as an integrated concept of self-contained Nuclear High Temperature Technology (NHTT). The following design principles are the centerpiece of NHTT:

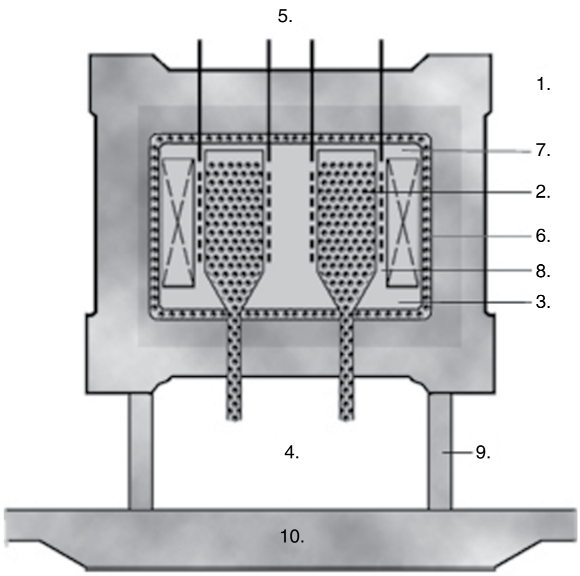
• Earthquake resistance up to magnitude 6, which for our region here is the highest imaginable seismic security. This is achieved through an extensive, strong concrete foundation, which forms a large base area and enables a stable, gas-tight concrete substructure. All activities which could be associated with exposure to radiation are carried out in the space below the actual reactor. This, for example, includes performing repairs on components, decontamination of the components, and, eventually, permanent storage in confined spaces. Also it would be the final repository for spent fuel. The aim should be that no component that has been exposed to radiation must leave the premises. Therefore, no "spent fuel transports" to other nuclear sites are required. Experience with the THTR-300, has shown this is possible without any problems.

• A meltdown, a maximum credible accident, is ruled out from the standpoint of nuclear physics—the inherent passive safety system of the reactor.

• The spherical-shaped fuel elements proved to be the best nuclear fuel. To a large degree, the fissionable material in the fuel particles, with a diameter of only 0.5 mm, is kept inside the core of the coated particles by high density gas-tight covers of pyrolytic carbon (PyC) and silicon carbide (SiC). These layers comprise the first barrier to prevent the escape of fission products to the helium coolant gas.

Further, compared to all other designs, the spherical fuel elements have the advantage that they are very compact and easy to handle. Therefore, after many years of operation, the necessary space for intermediate storage or disposal, is very small, and can easily be accommodated in the concrete substructure.

• In terms of safety, the prestressed concrete pressure vessel proved best; it is the important second barrier against the es-



1. Prestressed concrete pressure vessel
2. Ring pebble bed reactor core
3. Graphite structure
4. Fuel chamber
5. Regulation and shutdown rods
6. Liner with insulation and water cooling system
7. Helium heat exchanger inlet
8. Helium heat exchanger outlet
9. Concrete support for prestressed pressure vessel and biological shield
10. Concrete foundation

Figure 9
RING CORE DESIGN FOR A PEBBLE BED

cape of radioactivity.

• An unpressurized containment surrounding the entire installation, constitutes the third barrier. The volume of this structure is so large, that it can trap and contain all the helium primary gas in the cooling system, without any leakage to the outside.

• Instead of a central fuel-element trigger mechanism with a centered pebble bed core, a ring core is built with multiple trigger devices. With the same basic concept, it enables a building of medium size to equal the high performance installations at optimal circulation of the fuel elements. The shutdown and control rods are installed in the graphite reflectors without mechanical stress.

• A double helium-helium cycle prevents the transfer of fission products, including graphite dust, to the exterior. The primary part of the reactor is also safe against "foreign object invasion" from the outside.

• This concept allows a simple means of control of the whereabouts of nuclear material.

• The pressure vessel's 5- to 6-meter-thick walls of prestressed concrete provide safety against all kinds of terrorist threats, including aircraft crashes. These walls even stand up against targetted missile attacks.

To this extent, these advantages of technological safety could not be reached by any other known nuclear power plant.

"When there is no man-made CO_2 produced at all in Germany, and the nation would have ceased to exist, this reduction would account for 0.00004712 percent of total CO_2 emissions produced on our planet worldwide."

High Temperature Economics

Now, in summary, here is a brief assessment of the economics of HTR technology:

• The spherical fuel elements are the safest nuclear fuel. Operationally, they are most easy to handle and most safe to store permanently because of their low volume of radioactivity. Moreover, they allow change of fuel elements during operation and without shutting down the installation. This is a major advantage from the standpoint of operational economy.

• The high primary gas temperature allows the highest thermodynamic efficiency, hence the best utilization of nuclear fuel.

• In addition to generating electricity, the high-temperature heat can be used for various industrial processes; for example, for the production of liquid or gaseous fuels.

• The use of thorium-232 enables the breeding of fissile uranium-233 as new fuel. Therefore, the available reserves of uranium U-235, in combination with thorium-232 will suffice indefinitely.

The Carbon Dioxide Myth

Finally, a word on the question of carbon dioxide in the atmosphere. Without CO_2, the planet Earth is uninhabitable. Those who claim that CO_2 is a "harmful gas" or "toxic gas," and who aim for a zero CO_2 target for planet Earth, show an incomprehensibly low level of minimal, most elementary basic knowledge, and lack of general education. Accurate scientific evidence of the CO_2 influence on the climate of our planet Earth does not exist. On the contrary, for millennia the climate of our Earth has been changing, even without human beings. Nature, not man, but also the universe, with the Sun, Moon, and stars, govern our climate.

Dr. S. Fred Singer comprehensively described this in his book *Nature, Not Human Activity, Determines the Climate*. With the exception of Germany and some European states, all states are acting accordingly worldwide, especially the United States and China. Therefore, the planned emissions trade for power plants is complete and utter nonsense. Nuclear power plant operators should not emphasize the advantage of zero CO_2 emissions, only the economic supremacy of the nuclear technology.

In all nuclear power plants, electricity is generated at a cost factor 6 to 30 times lower than is possible in installations with renewable energy, now and in the long run. Electricity costs comprise a crucial share of the burden on the population, and high electricity prices are extremely antisocial. Above all, energy-intensive industry, which today makes millions of secure jobs available, would have decisive disadvantages compared with foreign competition if Germany persists with so-called renewables. Germany is weakened, and possibly will be destroyed by the high cost of "renewable energy." This most certainly will lead to a decisive weakening in all sectors of our economy, with the result that there will be no money available for our social programs.

Only an energy mix by the most inexpensive production plants is an economically sound energy mix. As I explained at the start, this was true in the postwar years, and still is true today. In a letter to the editor of the daily *Frankfurter Allgemeine Zeitung,* on July 19, 2010, Dr. Jürgen Grossmann described the situation as follows: "It is all about a brutal industrial policy." Whoever does not acknowledge this, and act accordingly, commits a sin against the German economy.

How absurd are the efforts by our government and the opposition parties, attempting to gain worldwide leadership in "renewable energy" so as to prevent CO_2 emissions and thereby protect the climate, is demonstrated by a simple calculation, which appeared in a letter to the editor of the *Frankfurter Allgemeine Zeitung,* of January 14, 2010, (and which brought me tremendous support):

"When there is no man-made CO_2 produced at all in Germany, and the nation would have ceased to exist, this reduction would account for 0.00004712 percent of total CO_2 emissions produced on our planet worldwide. Those who still pursue this zero CO_2 target, therefore, must have succumbed to an unbelievable delusion of grandeur."*

---

* For more detailed explanations of this presentation, see www.buerger-for-technik.de, nuclear engineering 2009 and 2010; www.eike-klima-energie.eu/news-anzeige/ umwelt-klima-energie.

More comprehensive articles about the CO_2 theme, written by thousands of scientists around the world, and not yet understood or read by German politicians, can be found at www.eike-air-energie.eu and www.buerger-for-technik.de. I also recommend the book cited by Dr. S. Fred Singer.