South Africa moves ahead with high-temperature reactor project

by Jonathan Tennenbaum

Since the early 1990s, the South African electricity company ESKOM has been actively pursuing the possibility of applying the technology of the high-temperature gas-cooled reactor (HTR) as a nuclear alternative to coal power in meeting the rapidly expanding electricity requirements of the country. After favorable initial evaluations, ESKOM has now drawn up plans for an ambitious program to develop and produce small, standardized high-temperature reactor modules both for domestic use and for export. Detailed design is projected to be completed around the end of this year, with the first module to go into operation by the year 2005. Eventually, ESKOM intends to produce as many as 30 modules per year.

The South African project derives special importance from the fact, that the modular HTR has unique features that make it ideal for use as a power source for economic development around the world, and particularly in the developing sector. These include small size, low cost, and high efficiency; robust and inherently safe design; simplicity of operation; and potential application as a heat source for desalination, the chemical industry, and other industrial processes as well as cheap generation of electricity. For this reason, the HTR figures prominently in the Eurasian Land-Bridge development concept promoted by Lyndon LaRouche and his collaborators (see "The Eurasian Land-Bridge: The 'New Silk Road'—Locomotive for Worldwide Economic Development," *EIR Special Report,* January 1997).

Although the basic HTR design employed in the South African project is the so-called "pebble-bed" reactor developed in Germany, the South Africans are not simply taking over existing technology, but are carrying out ambitious new technological developments of their own. This includes development of a helium turbine for direct-cycle generation of electricity. In fact, the South African HTR project is an excellent means to make highly productive use of highly qualified scientific and technical manpower and industrial infrastructure, which already exists in that nation, especially in military-related areas. In addition, as a developing country itself, South Africa is in an excellent position to act as a springboard for the HTR technology to the entire developing sector.

South Africa's requirements

South Africa currently accounts for over half of the electricity consumed on the entire African continent. Thanks to a major electrification program, according to ESKOM, access to electricity has risen from only 30% of the South African population in the early 1990s, to more than 60% today. At present, more than 93% of South Africa's electricity comes from coal, and is mainly produced by large-scale coal-burning plants built near two large coal fields located far inland on the northeast of the country, far away from the coastal centers of electricity consumption. The prospect of avoiding the enormous costs of transport of large amounts of coal, or of electricity, over distances of 1,000 kilometers, is a major factor favoring the use of nuclear energy.

South Africa, which is rich in uranium, has a single Pressurized Water Reactor located near Capetown, which produces 4.5% of the country's electricity. However, for various reasons ESKOM has decided against constructing more large-scale nuclear plants. Instead, ESKOM has pursued the concept of much smaller modular reactors, based on the "pebble-bed" High-Temperature Reactor technology originally developed in Germany. The term "pebble-bed" derives from the fact, that the reactor core in this reactor type consists of a pile of spherical fuel elements ("pebbles"), about the size of tennis balls, instead of the familiar fuel rods of standard light water reactors. Accordingly, the South Africans call their new reactor the Pebble-Bed Modular Reactor (PMBR).

Background of the High-Temperature Reactor

The High-Temperature (Gas-Cooled) Reactor (HTR, or HTGR) is an alternative line of nuclear reactor technology, which differs in important respects from the light water reactor (LWR) and heavy water reactor (HWR) technologies which are used in nearly all commercial nuclear power generation in the world today. Early experience included the DRAGON reactor in Great Britain, the Peach Botto and Fort St. Vrain reactors in the United States, and the AVR Reactor in Jülich, Germany. The latter reactor demonstrated the "pebble-bed" concept invented by the late Prof. Rudolf Schulten. It operated successfully from 1967 to 1988 at outlet temperatures of 900-950°C (compared to typical outlet temperatures of 280-330°C in LWR reactors). Development work on the Jülich reactor demonstrated the feasibility not only of "inherently safe" operation (see below), but also the potential to use the HTR as a heat source for a variety of industrial processes, including: generation of synthesis gas; coal gasification and production of synthetic fuels, including hydrogen; oil refining and heavy oil recovery; bauxite processing; ammonia production; and desalination and cogeneration of district heat.

In the mid-1980s, a large-scale, 500 megawatt HTR power plant was operated for several years, only to be shut down for political reasons. Significant development work continued, however, both in Germany and in the United States, where the HTR technology was pioneered by the General Atomics Company.

Despite the remarkable successes of the Jülich HTR in particular, the HTR technology has so far failed to establish itself in commercial power generation. Apart from various technical hurdles, which have largely been overcome, the "back-seat" status of the HTR is not least of all connected to the opposition of sections of the nuclear power industry who fear competition to the established LWR technology, as well as to the efforts of the anti-nuclear lobby generally. During the 1990s, however, the prospects for HTR technology have dramatically improved, thanks to a wave of new projects in several countries:

1. A 10 MW experimental HTR module, based on the German pebble-bed concept, has been built in China by Qinghua University's Institute of Nuclear Energy Technology outside Beijing. This reactor is scheduled to go critical later this year.

2. A 30 MW High-Temperature Test Reactor, built by the Japan Atomic Energy Research Institute (JAERI), is now operating at JAERI's Oarai Research Establishment. This reactor, using prism-shaped fuel blocks, will be used (among other things) to test process-heat applications of the HTR.

3. A cooperative program is now running among the U.S. General Atomics Company, France's Framatom, Japan's Fuji Electric Co., and Russia's Minatom, to develop a 600 MW modular plant which would be used to burn up weapons plutonium and produce cheap electricity at the same time.

4. Last but not least, is the ambitious Pebble-Bed Modular Reactor (PBMR) program launched by South Africa's ESKOM, which promises a near-term breakthrough of the HTR technology into commercial electricity production.

The ESKOM PBMR concept

A key feature of ESKOM's strategy is the flexible use of small (114 MW electric) series-produced modular reactor units, rather than the giant (1,000 MWe or more) reactor blocks commonly used in commercial LWR and HWR nuclear power stations up to now. To reach higher powers, ESKOM plans to install as many as 10 HTR modules at a single site, with a common control room.

This approach replaces the economies of scale, exploited until now by the nuclear industry in realization of individual reactors of very large capacity, by the economy of mass-production of a large number of standardized smaller units. A big additional advantage, especially for developing-sector countries which should become a major export market for South Africa's new HTR industry, is the flexibility inherent in the low cost and small size of the individual modules. Thereby, the intrinsic advantages of nuclear energy will become available to nations and regions having limited long-term capital, and where existing electricity grids are far too small for the huge LWR plants built in industrial countries. With the modular HTR system, a power station could first be set up with just one or a few modules; further modules would then be added, gradually, as the grid capacity and electricity demand grow.

Small size and standardized design will permit greatly reduced construction times. Once the production infrastructure has been set up and the first few modules are in operation, ESKOM calculates a mere two years for completion of an HTR module. (Naturally, construction and installation of modules can be carried out in parallel.)

ESKOM expects to reach a production level of about 30 HTR units per year by the end of this decade, of which 10 would be destined for domestic use, and 20 for export. ESKOM counts mainland China and Taiwan, South Korea, India, and other Asian nations among the most promising potential buyers of the HTR modules.

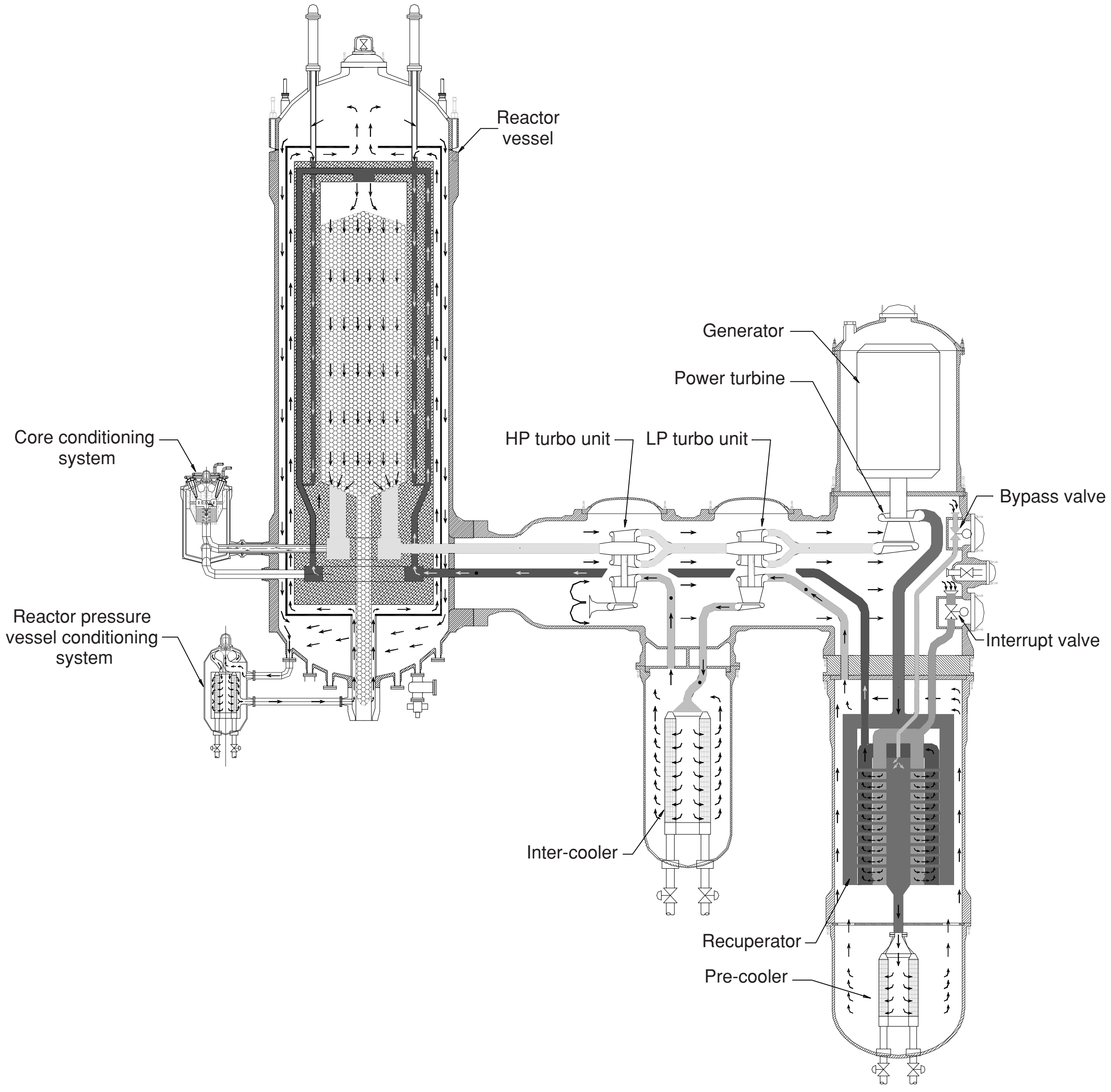
According to ESKOM, the development costs for the first reactor units will be about $72 million. The construction cost for the first unit should be about $100 million, with the unit price subsequently going down to about $90 million for each of the next 10 blocks.

Taking into account the economies achieved by series production of standardized HTR modules, it is estimated that the total cost of generated electricity can be brought down to below 1.6¢ per kilowatt-hour—a very competitive level, indeed!

Basics of the pebble-bed HTR technology

The German High-Temperature Reactor development very early adopted the goal, to create "from scratch" (i.e., not as an adaptation of a pre-existing design) a basic reactor type which would be not only *inherently safe,* but highly economical at the same time. The idea was to realize a form of nuclear

ESKOM's pebble-bed modular nuclear reactor design

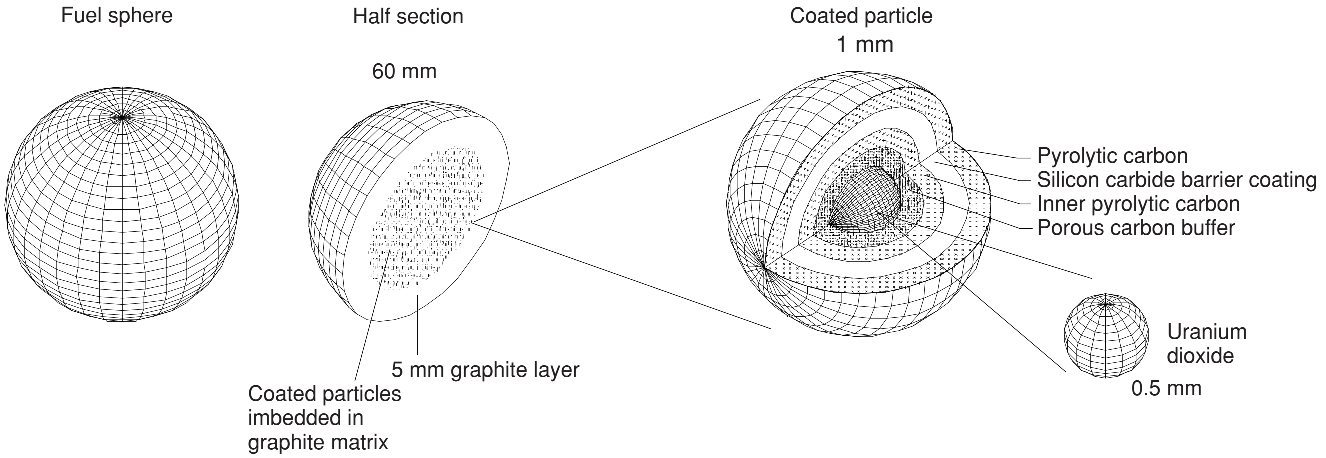


A cutaway of the South African PBMR module. On the left is the reactor vessel, on the right is the helium turbine, and in between is the housing for turbopumps which circulate the helium gas coolant. The core of the reactor is made up of several hundred thousand spherical fuel elements ("pebbles"). While spent fuel balls are withdrawn at the funnel-shaped bottom, new fuel balls are introduced at the top in a continuous fueling process. Each tennis-ball-size spherical fuel element contains thousands of tiny "coated particles" of uranium fuel encapsulated in special high-temperature ceramic materials, embedded in a graphite matrix.

energy that would not only be good for generating electricity, but could also be used as a heat source for a wide range of chemical and other industrial processes; a reactor which could be realized in a variety of sizes and would be simple, robust, and safe enough to be built and operated in industrial and population centers anywhere in the world, including the developing nations. The result, reached after decades of work, is the German pebble-bed HTR, which is the immediate basis for the South African PBMR and a smaller test reactor in China; and two related designs with somewhat different, prism-shaped fuel elements, developed in the United States and Japan.

Key to many of the inherent safety and many other advantages of these reactors, is a U.S. invention called "coated particles." Instead of arranging the uranium fuel in the form of cylindrical pellets stacked inside metallic rods

The fuel pellet of ESKOM's pebble-bed nuclear reactor



(“fuel rods”), the HTR fuel elements are built from tiny, sand-corn-sized uranium “particles” which are encapsulated in concentric layers of temperature-resistant materials, including especially silicium carbide. A major advantage of these coated particles, is that nearly all the radioactive fission products, created by the fission of the uranium in the particle, remain trapped inside the particle, even at very high temperatures.

In the German pebble-bed design, the actual fuel elements are spheres (“pebbles”) the size of tennis balls, in which thousands of coated particles are embedded in a graphite matrix. If desired, further outside coatings can be added to the fuel “pebbles,” reducing diffusion even more and rendering the pebbles impervious to oxidation and corrosion. (The latter is also relevant for the option, pointed out by Schulten, for using water instead of helium as a coolant for lower-temperature pebble-bed reactors.)

The core of a pebble-bed reactor consists basically of a pile of some hundreds of thousands of spherical fuel elements, filling a cylindrical vessel with a funnel-shapped conical lower end. In full operation, each fuel “pebble” typically generates about 500 watts of heat. Unlike the large light water reactors, which have to be shut down for several weeks for refueling, the pebble-bed HTR is *continuously refueled:* Fuel balls are withdrawn at the end of the funnel at the bottom of the reactor, and replacement balls are introduced at the top. By a combination of introducing fresh balls and recycling partially “burnt” old ones, the reactivity of the core is maintained at relatively constant level—generally speaking, only as is required to maintain the chain reaction.

The South African PBMR, with an 18-meter-long pressure vessel, will operate with 310,000 fuel balls plus an additional 130,000 graphite balls for additional moderation. In the course of the continuous refueling, a total of 10 to 15 fuel loads will be consumed during the design lifetime of the reactor. The level of enrichment of the uranium fuel will be initially 4% for the start-up, and afterwards 8% for equilibrium operation. Each fuel ball will contain about nine grams of uranium.

Through continual testing and development, the release of radioactive products from HTR fuel elements was brought down to extremely low levels—far lower than LWRs in normal operation at much lower temperatures. The encapsulation of radioactive fission products within the HTR fuel elements is ensured up to temperatures of 1,600°C. Thus, HTR fuel elements easily withstand temperatures at which the normal metallic fuels rods of LWRs would already weaken and fail, releasing large amounts of radioactive substances. The level of radioactivity released to the coolant gas (helium) in the 500 MW pebble-bed reactor in Schmeehausen, Germany, for example, was so low, that a person could theoretically inhale it without risking dangerous radioactive exposure. This translates into much lower radiation doses to the personnel, than in conventional nuclear power plants.

In fact, the “cleanness” of HTRs can now be improved even further, thanks to a breakthrough by Schulten and his coworkers, in creating the advanced silicium-carbide-based ceramic material Siamant. With Siamant, it becomes feasible to construct fuel “pebbles” in such a way, that essentially no radioactivity at all is released—up to temperatures in excess of the maximum which could be reached in any conceivable accident, through an error, or even by the deliberate mishandling of the reactor (see discussion of “inherent safety” below).

The drastic reduction of radioactivity release from fuel elements under all conditions permits major simplifications in the design and maintenance of pebble-bed HTRs. In particular, the option of direct-cycle generation of electricity—

by placing a turbine directly in the reactor cooling cycles—becomes far simpler, for example, than is realized in the standard boiling water reactors, where the significant level of radioactivity in the coolant water necessitates special measures for containment and maintenance.

The helium turbine

The South African PBMR will include a major innovation vis-à-vis earlier HTR designs: exploitation of direct-cycle generation of electricity by a helium turbine, which will be used for the first time in commercial power production. Here the South Africans make use of some of their experience both in aircraft technology, and in the ultracentrifuge bearing technology developed in South Africa's former military nuclear program.

The PBMR operates with a single helium gas coolant cycle without the costly heat exchangers and secondary cycles used in commonplace light water reactors. Helium gas is heated in the reactor core to a temperature of 900°C, and passes directly to a turbine where its thermal expansion is transformed into rotational motion for electricity generation. The expanded helium is then recycled into the reactor core by means of two turbocompressors, entering at an inlet temperature of 569°C. With its higher operating temperature, the South African HTR realizes a net efficiency of 45% (compared to 30-35% for standard LWRs).

Waste heat can be removed either by water or air cooling, thus providing important additional flexibility in the choice of sites. (Use of air cooling was demonstrated on the 500 MW HTR in Germany.)

The small size and simplicity of the helium turbine add to the attractiveness of the PBMR, which promises to become a "work horse reactor" for widespread use around the world in the coming 20 years.

Achieving 'inherent safety'

A very important feature of the South African PBMR is its inherent safety, which at the same time permits unique economies in construction and operation. To appreciate the significance of this feature, one must take a brief look at the two basic approaches to the nuclear safety problem, which have emerged in the course of the development of nuclear energy.

One approach, which has been the one followed in the development and design of nearly all the commercial reactors now operating around the world, is to reduce the estimated probability of an accident involving a dangerous release of radioactivity to the outside, to such a low level, that it is judged "acceptable," or even practically insignificant, in comparison with the countless other risks of industrial society, and the average risks which any reasonable person accepts in their daily life. According to this approach, the designers do not attempt to completely eliminate the possibility of a major accident—indeed, this is nearly impossible with the LWR technology—but only to render it extremely unlikely. This goal is achieved with the help of high redundancy of crucial components and an extensive safety system.

The second approach, followed in the German development of the HTR and adopted by the South African PBMR, is to design the reactor in such a way, that a major accident involving a dangerous release of radioactivity is excluded under all imaginable conditions, by the *physical characteristics* of the reactor itself—without depending on additional safety systems.

Obviously, common sense would naturally prefer the second approach. However, for various reasons, connected in part with the specific history of the development of nuclear energy, the first approach has predominated. This is connected with the fact, that inherent safety is very difficult or even impossible to achieve, at economically acceptable cost, for the light water reactors which have dominated commercial nuclear energy generation until now.

The basic physical characteristics of the standard, large unit-size LWRs now in use are such, that two basic sorts of serious accidents are in principle possible: 1) a *reactivity* accident—an uncontrolled, "runaway" chain reaction, resulting, for example, from a failure of control systems, improper operation, sabotage, and so on, and 2) an overheating or even "meltdown" of the reactor core, with rupture of fuel elements and large-scale release of radioactive substances from the core, which could conceivably occur as a result of failure of cooling systems, or their inadvertent or deliberate switching-off.

In fact, a serious accident of the first sort did occur once, namely, in Chernobyl, leading also to an explosion and fire with massive release of radioactivity to a large area. A relatively serious accident of the second type occurred at Three Mile Island. In the latter case, the dangerous levels of radioactivity were successfully confined to within the reactor building, and there was no significant health danger to the population outside the plant. The plant itself, however, had to be permanently shut down and dismantled at great expense.

The first type of problem is complicated by the fact, that the LWRs are refueled only from time to time, rather than continuously; thus, a new "charge" of fuel rods must have a sufficiently large excess of reactivity, to maintain the criticality of the reactor for many months in spite of a substantial amount of "burn-up" up to the next scheduled refueling. In the event all the control rods were for some reason suddenly withdrawn from the reactor, the chain reaction would rapidly grow out of control, with possibly disastrous consequences. In practice, the likelihood of a "runaway" reaction is rendered extremely remote, by a combination of automatic control, emergency shutdown, and other safety systems.

The second problem is exacerbated by the fact, that during normal operation, a fission reactor accumulates a large inventory of heat-generating radioactive fission products. As a result, even following a successful shutdown of a reactor (i.e., ending the chain reaction), the radioactive substances in the core continue to produce large amounts of heat. In the case of modern LWRs, this amount of heat is so large, that reactor components would be severely damaged, and eventually melt, unless the heat-buildup were speedily removed by active cooling systems. To prevent such an eventuality, modern LWRs are built with several backup cooling systems, so that the likelihood of a simultaneous failure of all of them is extremely remote.

There is little doubt, that state-of-the-art LWRs are extremely safe. However, that safety is ensured at the expense of complex safety and control systems, as well as special quality standards of manufacture of components ("nuclear grade"), which together account for a significant percentage (of the order of 30-50%) of the cost of a nuclear power plant. Furthermore, the modern plants are extremely complex, requiring very high skill levels in construction and in operation, which alone has tended to restrict their use mainly to advanced industrial nations.

There do exist designs for LWRs, in which the possibility

PBMR promises good power source for desalination

Freshwater through nuclear desalination: The PBMR could become an ideal power source for large-scale desalination of seawater, which is a life-and-death issue in the Middle East and other areas of the world lacking necessary freshwater supply.

At present, the conflict over water resources is a leading underlying cause of the tension and danger of war between Israel and its Arab neighbors—a conflict that could be defused by opening up alternative supplies by the well-established technology of desalination. This problem was addressed by Lyndon LaRouche's "Oasis Plan," put forward in the 1980s, which foresaw the large-scale application of nuclear energy together with desalination, together with other modern transport, water, energy, and communications infrastructure, to lay the basis for peace through economic development in the region. This concept was picked up again in the context of the 1993 Oslo Agreement by Israel's then-Foreign Minister Shimon Peres, who among other things proposed building a nuclear-powered desalination plant to be jointly operated by Israelis and Palestinians. Once again, just recently, the issue of freshwater supply and desalination has been raised in the context of continuing negotiations for peace in the region.

The PBMR holds the promise of becoming a highly economical source of both electricity and heat for desalination plants. Using electricity to power a reverse osmosis plant, for example, a single "dedicated" PBMR module would provide enough power to produce 370,000 cubic meters of freshwater per day—corresponding to the average domestic (household) water consumption of 2.5 million people at modern standards. Fifteen dedicated PBMR modules, coupled with reverse osmosis plants, would be enough to provide for the *entire* freshwater consumption of Israel today, including agriculture and industry as well as household consumption. Alternatively, PBMR "waste heat" (at 90°C) can be used to power distillation-desalination processes, while supplying electricity to the grid. Studies of these possibilities have been going on in cooperation with the International Atomic Energy Agency, with Morocco being one of the interested nations.

of the two major types of accidents, indicated above, is virtually eliminated without depending on complex active cooling and safety systems. This can be done by reducing the amount of excess reactivity, and placing reservoirs of coolant water *above* the reactor core, so that a sufficient flow of coolant is ensured by gravity alone. However, these designs are very far removed from the present commercial LWRs and have been practically rejected on the grounds of too high costs. The principal difficulty lies in the physical basics of the LWR technology, which was originally developed for military use (U.S. nuclear submarines), under circumstances where safety considerations were much less stringent than for commercial nuclear power today.

The HTR, and particularly the pebble-bed design, is conceived from very early on with a view toward inherent safety via basic physical principles, without the need for any special safety systems or exotic design features. Rather than contributing to increased costs, the inherent safety features greatly improve the economic viability of the reactor.

Two basic features are key to the "inherent safety" realized by modular pebble-bed reactors of the type now being realized in South Africa:

First, the HTRs are generally characterized by a *strongly negative temperature coefficient*. This means that the efficiency of the chain reaction—the average number of fission reactions triggered by a given neutron in the reactor—decreases very rapidly with increased temperature. This is achieved by the choice of core geometry and the moderator material (mainly graphite). As a result, a significant increase of temperature above the designed operating temperature (ca. 900°C) immediately causes the reactor to become subcritical, i.e., the chain reaction stops by itself, without any intervention from the outside. This "automatic shutdown," which occurs within fractions of a second by a natural physical process, was demonstrated repeatedly on the AVR test reactor in Jülich. For example, at maximum power the control rods were suddenly withdrawn and the cooling systems turned off—a suicidal act in a normal reactor. But with the AVR, nothing happened; the chain reaction immediately ceased, and the reactor temperature remained within the tolerance of the fuel elements.

Second, the dimensions of the PBMR reactor and the relatively low power density are chosen so that the natural diffusion of heat through the reactor vessel provides sufficient "passive cooling" to keep maximum core temperature following a shutdown of the reactor well within the 1,600°C tolerances of the fuel elements.

As a result of these two main properties, a reactivity accident or the release of significant amounts of radioactivity is excluded under *all* conditions, including deliberate sabotage of the reactor. *No special safety systems* are required! This means an enormous cost reduction, as well as major simplifications in the design, construction, and operation of the reactor.