**Polish Project of Research High Temperature Gas-cooled Reactor**

**Mariusz P. Dąbrowski\***, Agnieszka Boettcher, Wojciech Brudek, Wacław Gudowski,

Janusz Malesa, Dominik Muszyński, Sławomir Potempski, Eleonora Skrzypek, Maciej Skrzypek

# National Centre for Nuclear Research

*Andrzeja Sołtana 7, 05-400 Otwock, Poland*

*\*mariusz.dabrowski@ncbj.gov.pl*

Abstract – *Through a series of projects (HTR-PL, Gemini+, GOSPOSTRATEG-HTR) the National Centre for Nuclear Research (NCBJ), Świerk, Poland, got involved into the small-scale High Temperature Gas-cooled Reactor (HTGR) technology. The objective is to replace the existing fossil fueled plants working for chemical and petrochemical industry by the nuclear reactors in order to reduce CO2 emission in Poland and Europe.*

*The task of this paper is to shortly introduce the reader into the HTGR technology – its inherent safety properties, the basic construction components, and an ability of high temperature process heat production. Then, some presentation of the current stage of the work on the concept of the 30 MWth research reactor to be build at the NCBJ site which would also serve a demonstrator of HTGR-SMR technology for Polish industry is given. The reactor’s main technical specifications, its mission, its research, experimental, and utility objectives will be presented. Important steps of the reactor basic design and preliminary safety report preparation performed in collaboration with Japan Atomic Energy Agency – JAEA (the High Temperature Engineering Test Reactor (HTTR) operator) is also briefly presented.*

**Keywords:** decarbonisation, High Temperature Gas-cooled Reactor (HTGR), nuclear cogeneration, reactor design phases.

I. Introduction

High-temperature gas-cooled reactor technology takes its origins almost at the beginning of the nuclear technology with the pebble-bed reactor idea of Farrington Daniels presented already in the 1947. There have been series of reactors working for some period of time worldwide since then. On an experimental side there was DRAGON, UK of 20 MWth(1963-76), Peach Bottom, USA of 200 MWth (1966-74), and AVR, Germany of 46 MWth (1967-88). On the commercial side there was Fort St Vrain of 300 MWe (1976-89) and THTR, Germany of 300 MWe (1986-89). Currently, there are still two acting experimental reactors in Japan (HTTR of 30 MWth opened in 1998) and in China (HTR-10 of 10 MWth opened in 2000). The only commercial reactor which is now operating is the Chinese HTR-PM of 2x106 MWe, but it is still under tests since its commissioning in 2021.

Designs for HTGR test reactors with low-power have also been developed in USA and Canada by the companies USNC (with sites at Canada at the Canadian Nuclear Laboratories in Chalk River, and in the United States at the University of Illinois Urbana-Champaign) and X-Energy. Their licensing process has been pending. Indonesia has prepared its research HTGR design called RDE (Reaktor Daya Eksperimental) planned to be sited at the National Nuclear Energy Agency, BATAN **[1]**.

HTGR reactors are cooled by a chemically inert gas such as helium or carbon dioxide. These reactors harness the fission energy of the uranium 235U nucleus caused by thermal neutrons. Graphite is used as a moderator. The fuel is either uranium dioxide (UO2) or a mixture of uranium oxide and uranium carbides (UCO). Due to high-temperature-resistant materials used in the core (graphite, carbides, and uranium oxides), high coolant temperatures can be achieved (currently between 750 °C and 950°C). In fact, achieving such high coolant parameters at the inlet to the steam generator is not possible in typical water-cooled power reactors and so HTGRs are unique option for chemical industry as a zero-emission source, made with known and safe technology which can successfully replace conventional sources.

HTGR technology has its advantages and they are as follows: 1) high temperature helium at the outlet of the reactor, allowing the heat to be used both in chemical and petrochemical processes and for high-efficiency power generation in typical turbine sets; 2) high level of safety (resistance of fuel and core materials to high temperatures, negative temperature reactivity coefficient - an increase in temperature damps out nuclear reactions, very low penetration of fission products from the fuel into the system); 3) possibility of the load-following operation which is important when accompanying the usage of renewables.

Due to the inherent/natural/passive safety (self-damping of nuclear reactions), the resistance of the fuel to high temperatures, and the low release of fission products from the fuel, it is possible to build HTGR reactors in close proximity to urban concentrations and close to industrial plants.

The inherent safety of HTGR relies on:

● The use of coated fuel particles embedded in a graphite matrix (coating) that retains fission products. The fuel kernel is coated with layers of carbon, pyrolytic graphite (PyC) and silicon carbide (SiC), and therefore has a higher resistance to high temperatures than LWR fuel in conventional cladding made of metal-based alloys. This significantly increases the exceptional durability and creates an additional physical and chemical barrier between the fuel and the environment. Layers of graphite and silicon carbide provide a safety micro-containment.

● Strong negative temperature coefficient of reactivity, which guarantees passive shutdown of the reactor with a relatively small uncontrolled temperature increase above normal operating temperature.

● Very slow reactor temperature change in the event of loss of active (forced) core cooling. This is possible due to the high thermal inertia of the graphite, the core design and the low power density in the core.

● The possibility of passive core cooling. *The core can be configured to have a high surface-to-volume ratio and surface area to power ratio.* This, combined with the low power density, provides the possibility to passively dissipate heat (by thermal radiation, thermal conduction and natural convection) from the core and from the outer surface of the reactor vessel, even under the worst accident conditions. Furthermore, under such conditions, the maximum fuel temperature can be maintained below the integrity limit of the ceramic-coated fuel.

II. Why does Poland need HTGRs?

Poland has a well-defined high-temperature heat market which can be filled in with cogeneration nuclear technologies. According to the report of 2018 **[2],** 13 largest chemical plants in Poland need at least 6.5 GWth of heat at the temperature T=400-550°C  acting in cogeneration i.e. producing electricity and heat. This energy is generated from fossil fuels burning more than 5 mln tons of natural gas or oil, obviously causing CO2 pollution. Besides, there exists about 50 power units of an average size of 200 MWe which both due to the emissions and also due to the expiry of license for exploitation will have to be replaced around 2035 at the latest.

It is vital to say that this is apart from the electricity generating plants capacity of the scale about 1000 MWe which have to be replaced soon due to the same above mentioned reasons. This sector is taken care by the Polish Nuclear Power Program which started in 2010 **[3].** According to this program at least 6 GWe split into 6 or 4 units will be build at mid 2030ies. An agreement with Westinghouse company to build an AP1000 reactor has already been reached and is under progress. All this seems to be an important part of energy market for the country which needs around 30-40 GWe in total.

Poland, as a part of the UE, is obliged to reduce CO2 emissions, and so it is also investing in renewables – mainly solar and wind energy sources **[4]** aiming in the final mix of these sources with nuclear around 2050.

Coming back to an issue of high-temperature heat production, it is more or less clear that the only reasonable nuclear option for that is HTGR. However, at the moment no commercial HTGR reactor (“off-the-shelf’’) is available on the global market (except already mentioned China’s HTR-PM which, in fact, is still a test facility). In view of that and in order to reach the commercial stage, Polish experts reached the conclusion that one first should construct *a research reactor of some smaller power as a technology demonstrator* to convince regulator and the industry about its safety, economy, and practicality. This is a fragile matter anyway, since so far there have been no commercial reactors in Poland, and the only experience is with build in 1974 research light water reactor MARIA which serves radiopharmaceutical production covering about 18% of the global market for this product. The main idea is that a planned HTGR research reactor should possess *as many features of the commercial reactor as possible*, so that one would be able to scale it up to a commercial size with least effort.

III. Polish path to nuclear cogeneration

As it was already mentioned, Poland possesses one of the strongest chemical industries in Europe and it requires some important fraction of heat for the processes. Early academic discussions about implementation of nuclear reactors in this branch of economy appeared around 2012 and they happened to be almost parallel to a recovery of the Polish Nuclear Power Program in 2010. One domestic R&D project called HTR-PL was run throughout 2012-15, but with no political or industrial feedback.

In Poland more acceleration towards implementation of HTGRs happened after the ratification of the Paris Agreement **[5]** in 2015 by the European Union and other countries aiming at reducing the global average temperature on the Earth by decreasing greenhouse gas emissions. In 2019, European Green Deal was formulated which provided a set of policy initiatives with the overarching aim of making Europe climate neutral by 2050 **[6]**. In fact, Poland as one of the strongest emitters of carbon dioxide in Europe had to start thinking about replacement of the current carbon-emitting sources of high-temperature steam into the nuclear.

***III.A. Political support***

In 2016 the Polish Minister of Energy appointed the “Committee for deployment of high-temperature nuclear reactors in Poland”. The Committee presented the report in January 2018 **[2]**. The conclusion was that one should build an industrial HTGR with power 180 MWth, steam temperature T = 540°C, pressure p = 13.4 MPa, and steam flow 230 t/h in order to fit Polish industry demand. In consequence, the Minister took note that deployment of HTGR reactors in Poland is desirable. It was then requested the preparation of further steps for HTGR deployment.

In the meantime the “Strategy for Responsible Development” - the governmental program for Polish economic development – was prepared and adopted in February 2017 **[7]**. It explicitly contained suggestion of deployment of HTGR for industrial heat production in cogeneration. An objective was posed to an HTGR of 200-350 MWth supplying technological heat for industrial installation.

Another important document which included HTGR implementation was a 2020 update of the “Polish Nuclear Power Program” **[3]**. Amazingly, in the recent years 2022-23, there have been a boost of interest in nuclear in Poland and the feature is that Polish private companies started plans to build nuclear reactors of SMR type independently of the governmental plans. Among these reactors there are BWRX-300 and NuScale.

***III.B. Past projects and future action plan***

In view of the governmental interest, NCBJ started some projects in order to get insight into HTGR technology.

The first project of this category was the European GEMINI+ (2017 – 2021) **[8]** devoted to the main design options for HTGR fitting the requirements for cogeneration in Europe. The unit of 180 MWth or its double became the focus for future implementation in agreement with the above mentioned analysis of the “Committee for deployment of HTGRs” in Poland.

Another important step was held within the framework of National Strategy Program GOSPOSTRATEG-HTR (GoHTR) **[9]** co-funded by the National Centre for Research and Development with the grant of about 5 mln euro for joint project of NCBJ, Ministry of Climate and Environment, and the Institute for Chemistry and Nuclear Technology (IChTJ). The project was entitled “Preparation of legal, organizational and technical instruments for the HTR implementation” (2020-2022). Within this project some important steps toward HTGR implementation were made with the final output being the pre-conceptual design of a research reactor **[10]**. One of the deliverables of the project was the preliminary action plan related to HTGR deployment in Poland which is presented in Table I. According to this plan, one will first construct a research reactor of 30 MWth serving as a demonstrator of technology, and then one will build a series of commercial reactors (First-Of-A-Kind (FOAK), Next-Of-A-Kind (NOAK)) of 180 (or 360 as duo-block) MWth power for chemical industry.

*Table I Polish preliminary plan for commercialization of HTGRs* ***[9]*** *(prices of 2020).*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Reactor type | MWth | Units | Cost [bln $] | Time |
| Research | 30 | 1 | 0.35 | 2025-30 |
| Prototype FOAK 1 | 180 | 1 | 0.75 | 2030-33 |
| Prototype FOAK 2-6 | 180  2x180 | 5 | 0.6  < 0.6 | 2034-40 |
| NOAK 7-10 | 180 | 4 | 0.5 | 2040-50 |
| Serial | 180-360 | 10-20 | 0.5-0.75 | 2040-50 |

Within the framework of the GoHTR project, the tasks related to testing HTGR construction materials at NCBJ were also carried out. For this purposes the ISHTAR (Irradiation System for High-Temperature Reactors) thermostatic capsule was designed, manufactured and commissioned **[11]**. Tests were performed in the MARIA research reactor operated at NCBJ.

It is also worth mentioning that the report of the “Committee for deployment of high-temperature nuclear reactors in Poland” also included an opportunity to implement another reactor concept in Poland. It is the Dual Fluid Reactor (DFR) **[12]** which has both fuel (molten salts or uranium-chromium eutectic) and coolant (lead) in the form of fluid. The advantage of such a solution is that it can reach the temperatures above 1000 °C which allow much cheaper production of hydrogen apart from electricity. In fact, NCBJ runs a parallel Ph.D. studies project “New reactor concepts and safety analyses for the Polish nuclear energy program” (phd4gen **[13],** years 2018-2023) financed by the National Centre for Research and Development, under which the students have been working on both HTGR and DFR technologies.

IV. Research HTGR-POLA reactor at NCBJ

***IV.A. The project and its tasks***

The project is held under the contract between NCBJ and the Ministry of Education and Science (MEiN) of Poland. It is entitled “Technical description of the HTGR gas-cooled high-temperature research nuclear reactor” (2021-24). It is intended for the implementation of another batch of design works for an experimental HTGR, being also the technology demonstrator.

The objective of the project worth 14 mln euro is to prepare the main elements of the basic design and the preliminary safety report (PSR) for the research HTGR, which will be the basis for a future application to the National Atomic Energy Agency (PAA) for the licensing of this reactor. The HTGR, planned for construction at the site of NCBJ, is expected to create a development path for the future application of this type of reactors in the Polish chemical and fuel industry.

The project comprises of five subtasks, which fall into two groups.

The first group includes the preparation of the laboratory facilities necessary for the next stage of materials testing required for their licensing in HTGR technology. Multifaceted testing will be carried out on key reactor materials such as graphite and metals and their alloys in terms of their chemical composition, hardness, conductivity and thermal expansion as well as other physical properties.

The second group includes tasks that fall under the preparation of the main elements of the basic design and the PSR. The first element of this group of tasks is the conceptual design of the research HTGR design covering primarily the reactor core and primary cooling system on the basis of simplified calculations of core physics and thermal balance after a basic safety assessment. Neutronic and thermal-hydraulic characterization of the reactor components including fuel, reactor in-vessel components, reactivity control systems and associated instrumentation and control systems are to be prepared. The conceptual design includes a preliminary concept of the secondary loop facilities, together with test plants using steam with fixed parameters in future industrial applications as well as in utility applications (municipal heating) for the NCBJ campus.

This is also investigated by detailed computer simulations based on licensed computational tools for neutron management in the reactor, flows in the primary and secondary systems and technical strength parameters of materials and components. The codes such as SERPENT **[14]** and MCB **[15]** coupled with POKE and CATHARE **[16]** appropriately, are applied. Strong case of the analysis is the use of high-fidelity computational fluid dynamics (CFD) methods **[17]**.

Based on the conceptual design and in collaboration on the intergovernmental agreement **[18]** with JAEA which possesses the detailed technological design of the similar reactor HTTR, the basic design of the nuclear reactor in the nuclear and conventional parts is under development. Elements of the nuclear design include the core, the reactor vessel, the helium cooling system (going beyond water cooling which is a standard method in the Polish law), the reactor control and safety systems, and the refuelling systems. In the conventional part, the turbine, pumps, heat exchangers, reboiler, condenser cooling and heat discharge system to the environment and other structures and equipment components will be designed. Both designs are being integrated into one coherent project at a minimum Level Of Detail (LOD) of minimum 200 **[19]**.

Finally, the most important document required for the initial licensing of the reactor - the Preliminary Safety Report - is being prepared and, together with the basic design, will constitute the main output of the project. This report is being prepared in accordance with the requirements of the “Regulation of the Council of Ministers of 31 August 2012” **[20]**. It covers most of the items sanctioned by Annex 2, including description of the nuclear facility with general design aspects, integrated management system, summary and evaluation of the results of the safety analyses, scope of emergency operations, aspects of the environmental impact of the facility, waste management, as well as the site decommissioning conditions and strategy.

The first element for the preparation of the basic research reactor design was the *creation of a conceptual design*. As it is seen from Table II, this document was finished at the end of 2022 based on the structure regulated by the Regulation **[20]** and exemplary conceptual designs including an early conceptual design for the Fort Saint Vrain commercial reactor **[21]**, the GEMINI+ project [3], and the Japan Atomic Energy Agency (JAEA) materials (e.g. **[22]**). Table II also characterizes further steps of Polish research HTGR projects to be taken.

*Table II Polish research HTGR project progress*

|  |  |  |  |
| --- | --- | --- | --- |
| Phase | Time | Status | Comments |
| Pre-concept **[10]** | ½ y | 30.03.2022 | GoHTR Polish project |
| Concept | 1 y | 31.12.2022 | HTGR-POLA Polish project |
| Basic | 2 y | in progress | Collaboration JAEA, will include PSR |
| Detailed | 2 y | planned | may last longer |
| Licensing | 1 y | planned | may last longer |
| Construction | 4 y | planned | may last longer |

***IV.B. Design philosophy***

The main assumption about the HTGR-POLA reactor is that it should serve building competence (human resources, industry, regulator, etc.), research tasks, and also a *small-scale demonstrator* of HTGR technology for industrial applications. One assumes that the design should *combine* features of the industrial reactor as planned by the GEMINI+ project and proven elements of Japanese HTTR as a test reactor. It should possess a unique core design and a reactor design *matching specific Polish requirements* in research, demonstration and applications. An important objective is that the power of the reactor should be as high as possible (about 30 MWth) in order to *maximize similarity* to an industrial type FOAK 180 MWth reactor design.

The missions of this reactor are as follows: 1) testing industrial applications; 2) performing material research (structural materials and graphite); 3) monitoring and improvement of the safety functions (code validation, support to regulator, etc.); 4) performing TRISO fuel research and tests; 5) competence building (design, licensing, supply chain management, construction, operation - personnel training, inspection etc.); 6) Search for new methods of radiopharmaceutical production – this is related to the fact that currently NCBJ produces radiopharmaceutical in the only existing in Poland reactor MARIA.

The reactor should also possess three important groups of functions: experimental/testing, research, and utility.

As for the experimental function one can enumerate the following: 1) tests of the technological components in small- and micro-scale; 2) tests of efficiency of heat storage and recovery in a special buffer; 3) prospective connection to a hydrogen production plant or other user process; 4) concept development and experiments related to the integration of the reactor with renewables.

The research function should cover the following: 1) passive safety tests; 2) operational safety in normal and simulated accident conditions tests; 3) tests of materials and components in high temperature and strong flux; 4) HTGR specific codes validation; 5) support to Polish regulator (PAA) towards future licensing of the commercial design; 7) fife cycle TRISO fuel research; 8) search for new radiopharmaceutical production methods in HTGR.

Last but not least, the *utility function which is the most important* for the demonstration of cogeneration abilities of HTGR is given by: 1) production of high-temperature heat in the form of steam for industrial plant demonstration technology through coupling with reboiler constituting a physical barrier between HTGR and the plant; 2) electricity production for HTGR's own needs and for NCBJ (e.g. demand for the NCBJ supercomputer centre CIŚ and the research MARIA reactor, etc.); 3) production of heat for NCBJ municipal purposes (domestic hot water, hot water in the heating network) for various process purposes of NCBJ research and production installations (e.g. production of chilled water using compression adsorption units).

***IV.C. Technical details***

In Poland there is a tradition that all the research reactors and even critical assemblies carry the feminine names. The first reactor was EWA (1958-1995) of WWR-S type of 10 MWth power and the flux 8 x 1013 neutrons/cm2 s. It was to honour Eva Curie - the dauther of Maria Skłodowska-Curie – a renowned Polish physicists and a double Nobel Prize winner, who was later honoured in still working reactor MARIA build in 1974 with the neutron flux of 1015 neutrons/cm2 s and the power of 30 MWth. Besides of that there have been some critical assemblies with the names ANNA, AGATA etc.

Within HTGR projects, two research reactor configurations have been prepared now. One was a 40 MWth design of “TeResa” **[9]** (the name which includes two of four letters of HTGR) and another with the name HTGR-POLA which basically stands for POLish Atomic. The two configurations differ with the power (POLA is 30 MWth), and the core size. In fact, POLA has just 19 blocks in a layer while “TeResa” was 31 blocks, so the latter is thicker. The design was determined by the philosophy of safety trying to put stress on the heat removal from the core while in accident situations rather than by its neutronic characteristics. This is why POLA configuration is thin and tall what in terms of numbers is reflected by a large hight-to-diameter ration H/D = 2,169 leading to a large surface-to-volume ratio of the reactor. Such a configuration guarantees passive cooling of the reactor in accident conditions.

The basic characteristics of HTGR-POLA are given in Table III. It is an important issues that the reactor acts in cogeneration producing electricity up to 10 MWe , high temperature heat up to 25 t/h as well as communal heat for own NCBJ purposes up to 16.5 MWth .

*Table III Basic characteristics of HTGR-POLA*

|  |  |
| --- | --- |
| Characteristic | Description |
| Design development, country | National Centre for Nuclear Research (NCBJ), Poland |
| Reactor type | HTGR |
| Core design | Prismatic (hexagonal blocks) |
| Thermal power | 30 MW |
| Fuel enrichment | HALEU (UO2) |
| Fuel type | TRISO in graphite matrix |
| Fuel cycle | Open, spent fuel stored on site |
| Moderator | Graphite |
| Coolant/circulation | Helium/blower induced |
| Coolant pressure | 6 MPa |
| Coolant inlet temp. | 325°C |
| Coolant outlet temp. | 750°C |
| 2nd system coolant | Water/steam |
| 2nd system pressure | 13.8 MPa |
| Reactivity control | Control rods, burnable poisons, reserve neutron absorbing capsules |
| Reactor building | Reinforced concrete construction, design overpressure up to 0.1 Mpa, ventilated building |
| Power output in cogeneration | Electrical power max. 10 MW |
| High temperature heat in steam max. 25 t/h |
| Low temperature thermal power in water max. 16.5 MW |
| Design service life | 60 years |

IV. Conclusions

Polish research HTGR-POLA reactor design is the first step towards the implementation of the high temperature gas-cooled reactors in chemical and petrochemical industry which is the requirement in the challenge of Net-zero 2050 policy of the European Union and the United Nations. Decarbonization has become the priority for the Polish government and the nuclear reactors are planned to be introduced in various fields of energy production.

The National Centre for Nuclear Research which will be siting the research HTGR has already prepared the pre-conceptual design within the GoHTR project (“TeResa") and the conceptual design of HTGR-POLA within the Ministry of Science and Education project - both strongly supported by the results of the Gemini+ project rescaled from 180 MWth commercial reactor to 30-40 MWth research/demo.

The conceptual design, due to its content (detailing the mission and functions of the reactor, the basic characteristics of the core and fuel, the primary cooling cycle as well as the elements of equipment and construction, design of power processing devices, control system and other components and systems with auxiliary devices) and due to the involvement of a strategic partner – Japan Atomic Energy Agency who possesses HTTR technology, made the ground for the further step which is the basic design.

Currently, both parties (NCBJ and JAEA) are working together on the preparation of the basic design and preliminary safety report of HTGR-POLA in order to gain permission for the construction. Further steps which are the detailed design, license, construction, and commissioning are on the way. One of the objectives is the involvement business partners to the tasks.

A breakthrough of the HTGR-POLA project would be the creation of a new boost to the nuclear in Poland after the only Polish working research reactor MARIA constructed nearly 50 years ago.

Acknowledgments

This work was supported under the project “Technical description of the HTGR gas-cooled high-temperature research nuclear reactor” (Contract No 1/HTGR/2021/14) funded by the Ministry of Education and Science (MEiN) of Poland (2021-24). It is partially the result of the studies in the strategic Polish program of scientific research and development work “Social and economic development of Poland in the conditions of globalizing markets GOSPOSTRATEG”, part of “Preparation of legal, organizational and technical instruments for the HTR implementation” co-financed by the National Centre for Research and Development (NCBiR) in Poland (2019-2022).

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