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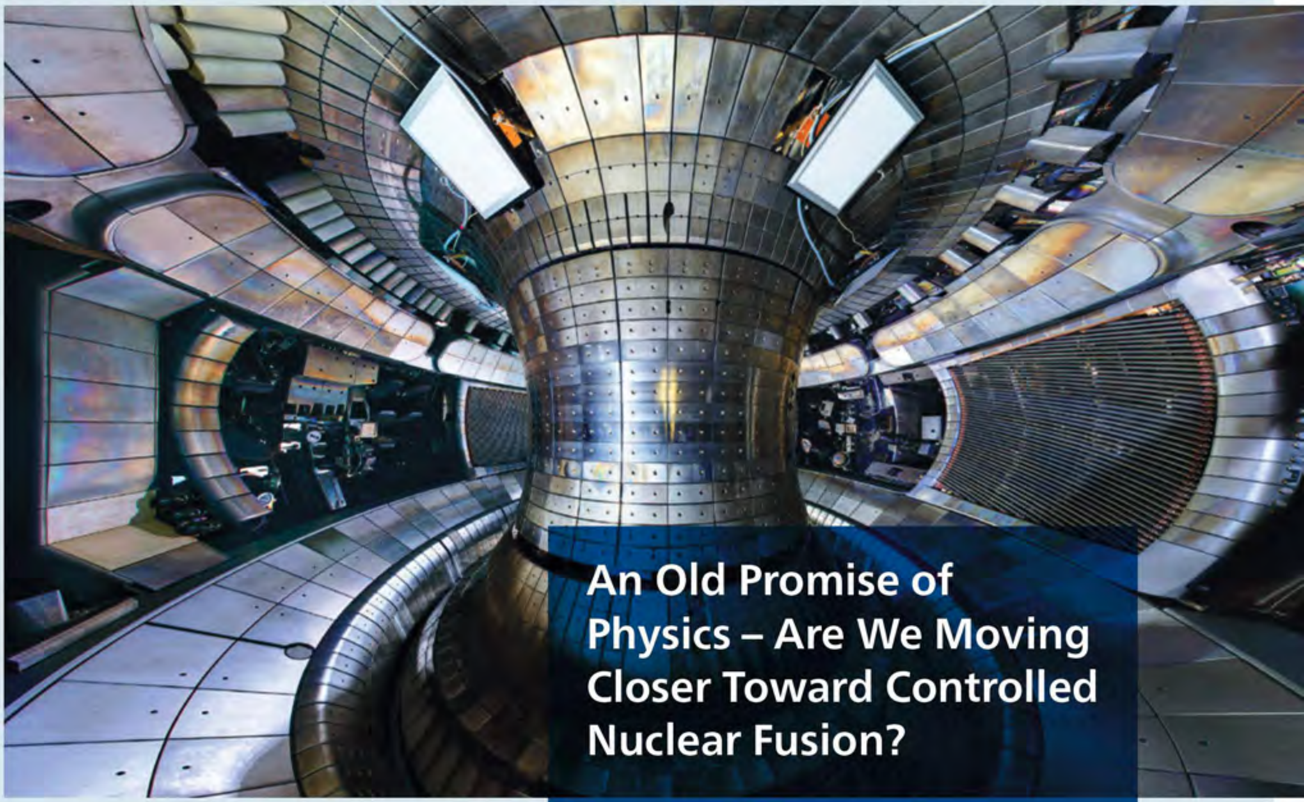

An Old Promise of Physics – Are We Moving Closer Toward Controlled Nuclear Fusion?

Highlights of the World Nuclear Performance Report 2020

The EMPIrE Irradiation Test: Lower-Enriched Fuel for High-Performance Research Reactors

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Contents

Editorial

Inside Nuclear with NucNet

Feature | Major Trends in Energy Policy and Nuclear Power

Serial | Major Trends in Energy Policy and Nuclear Power

Spotlight on Nuclear Law

Energy Policy, Economy and Law

Decommissioning and Waste Management

Fuel

Research and Innovation

Nuclear Today

Insert: Inforum – Seminarprogramm 2021

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G = German
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Feature

Major Trends in Energy Policy and Nuclear Power

Serial | Major Trends in Energy Policy and Nuclear Power

Energy Policy, Economy and Law

Decommissioning and Waste Management

Fuel

Research and Innovation

BioKernSprit

Jochen K. Michels

Planned entry for KERNTECHNIK 2020

Introduction As commendable as all the efforts maybe to supply our society and industry with environmental energy, they will not nearly suffice. This is most easily seen in the quantities of imported primary energy, i.e. gas and oil, and increasingly electricity too. There is an occasional flattening or a dent, but the increase is obvious. Considering the needs for more comfort, communication, mobility, it quickly becomes clear that an increase rather than a decrease is to be expected – despite all efforts to save.

This proposal addresses an important sector: mobility. And here we focus on road-based individual traffic rather than rail-based mass transport or airborne services.

BioKernSprit[1] refers to the project (or proposal) to combine known and proven processes in such a way that they can bridge the coming 30 to 80 years. That is, as long as the scarce and criticized fossil fuel supply will not be fully replaced by other fuels. These processes are associated with the names of Heisenberg, Fischer, Tropsch, Bergius, Pier, Schulten, Kugeler and many others. They are still familiar to many Germans from school and university. All of them have earned merits and fame between 1900 and 2000, but their pertinent developments are not used in Germany currently. Only in China there have been approaches for 15 years to implement at least a part of it into practice. Just recently also the US resume research and implementation projects for this particular flavor of nuclear energy, called “high temperature reactor with pebble fuel”.

Basics

The basic idea is to combine these well proven developments, methods and inventions into one productive and economical process to make mobility ecological and affordable for a long future. It should solve some of the most urgent needs not only in Germany and Europe but also in other countries, even those with limited resources in developing and threshold regions.

The hydrogenation processes of Fischer and Tropsch (FT) as well as Bergius and Pier (BP) synthesized fuel from coal and wood. Also other carbon compounds were tested and proven as input, e.g. wastewood. In Germany 4 billion liter of car fuel were produced in one year (1944) by some 14 factories. This was already 10 percent of today’s consumption of car fuel. The only outstanding detriment was, that almost half of the input feedstock was burned (oxidized) to produce the necessary high temperature for the process. Today this is unthinkable because of the large CO_2 load. The reason is well known with all chemists: if you do not have the optimal catalyst, the hydrogenation can only be reached by massive high temperature heat.

For example: the sun does the same. It converts carbon dioxide from the atmosphere into burnable plants (wood, eatables etc.) by low temperature below 50 degrees Celsius. Chlorophyll is the ideal catalyst and for plants this is acceptable. There is time enough for a slow hydrogenation process and the resulting greens have a rather low energy content per kilogram.

Today’s challenge – and answer

For car fuel we want – and need – faster results and a much higher density of energy. So we require much higher temperature and/or a much more efficient catalyst. This catalyst has not been detected yet. Until better results develop we need for hydrogenation a rather high temperature – about 900 centigrade[2].

We propose to combine the proven – and continuously improvable – synthesis of FT/BP hydrogenation with HTR-heat into an overall economical production line. This complies with business and market constraints, as well as with environmental, social and compliance regulations. Even the German Atomgesetz (nuclear law) does not explicitly forbid this application of nuclear energy. Just electricity is forbidden.

First – the necessary feedstock

Input material must be found and provided in our current natural environment. It seems that about 5 to 10 percent of the national fuel consumption can be gained from today’s bio-waste. Mostly wood, also plastics, blast furnace gas and other feedstocks serve as a source. Lignite and hard coal can be used to increase the initial quantities. Even the “Coal-Exit” can be softened by using coal for hydrogenation. Other sources may be developed as time progresses and experience grows. There is no promise to cover 100 % of our fuel needs in the foreseeable future. We want to make a considerable contribution with minimal economic impact.

With the help of the forest owners’ associations, the above calculation was made. It shows that about 5 percent is already achievable today from wood waste. This can be expanded by using fallow land and special plants without food competition.

The Viessmann company has been showing what is possible for years. There, 1 hectare of rolling forest supplies around 5,000 litres of heating oil or diesel per year.

Second – Sizeable quantities of hydrogen

Since our proposed method does not burn feedstock it needs additional H for input. Currently H is mostly produced by the Linde process from fossil gas and other input. Obviously for ecological reasons and import dependency this cannot be the solution. But with the proposed high temperature heat and nuclear electricity, hydrogen can also be produced by cracking of normal water – a sustainable method, researched and developed in Jülich decades ago. This electrolysis currently is rather expensive because of the electricity needed. But when heat and electricity are provided by a high temperature reactor (HTR) we can overcome this obstacle.

Third – High temperature heat

This necessary heat must be provided without burning fresh or fossil carbonates (wood, plants, and coal). These input materials are too valuable to just burn them. They should be converted completely into highly precious fuel for mobility.

So the necessary heat must come from another source. High temperature gas cooled reactors (HTGCR) offer themselves as an almost ideal

---

[1] BioKernSprit is an acronym for: Synthesized Car fuel from Bio-Waste and Coal by Hydrogenation using high temperature nuclear heat.

[2] Some people claim to do it with lower temperature and optimized catalysts – not proven yet in industrial dimensions.

source of energy. While the usual water reactors with approx. 400 centigrades provide sufficient heat for power turbines, the high temperature reactor provides heat up to approx. 1,000 degrees. This can be increased even further, if and when better alloys for the tubes and valves are developed. There are many concepts and designs of HTGC Reactors since the 1960-es. Some of them are discussed presently in the Gen IV projects. The HTR with pebble bed technology seems to be the optimal choice because its technology:

- obeys all proliferation regulations,
- can be operated decentrally close to residential areas and industries,
- offers continuous operation essential for any ongoing chemical production,
- has fuel elements of tennis ball shape that allow continuous flow through
- allows well controlled cycling of fuel elements from top to bottom and out
- does not need large monocoque structures, but can work as small modular units
- allows small and local operators instead of large concerns
- offers secure repository because the fuel elements themselves are gas tight
- will in emergencies:
  - ☐ cool down without human or technical involvement
  - ☐ return to normal temperature just by the laws of physics
- has been proven in two provoked "meltdowns" in Germany and one in China
- allows that remaining risks can be covered by commercial insurers

There are some more advantages of this technology. Since there is no need for safety gadgets these investments and their maintenance simply do not exist. The result: the total investment will be lower. This leads to lower operating expenses (opex) and lower error susceptibility.

Why is this technology safer than others?

The key lies in the shape and construction of the fuel elements. Also important is the design and construction of the building.

The fuel itself is contained in small particles of under 1 mm in size. These particles are each containing the active heavy metals uranium and/or thorium. Each of them is coated with three layers (TRISO) of gas tight pyrolytic carbon and silicate carbide, very stable layers. Some 20,000 particles are contained in the "pebble" which is very stable too, against shock, abrasion and heat.

Should an emergency occur, such as missing coolant gas helium, they would heat up to about 1.500 centigrades, which results in more neutron capture, so the chain reaction will stop[3]. The residual heat then will be cooled by heat transfer finally to – and out of – the building structure and into the surrounding air. This necessitates a well-designed building structure. Up to now steel pressure vessels have proven optimal for sizes up to about 100 MWe (in Juelich and Tsinghua) and prestressed concrete for sizes above that capacity (in Hamm).

Another fact is, that the low density of energy compared to most current reactors makes the cooling faster and easier. Compared with the absolute safety this is neglectable.

Also the oven (instead of kiln) principle has important safety aspects: never is more fuel in the reactor, than is used at any given moment. This reduces the quantity of radioactive material during the whole process. That this principle also allows to eliminate refilling stops is another advantage, both economical, ecological and from a safety aspect.

Even in case where bombs or other large objects would hit such a reactor and would open the primary cycle, there is only a small quantity of inert helium that can be released to the environment, with very little contamination. Water is not present in the primary cycle of the reactor. Some hot steam out of the secondary cycle of the heat exchanger could get in touch with the helium and the pebbles if worst comes to worst. This will not cause enough oxyhydrogen for a large explosion. Since pebbles and particles are gastight and quite unbreakable, the steam and the environment would have only minimal contamination for some hours or days. The radioactive load will not be much above normal environmental levels.

Two critical points

Final storage is often demanded without specifying its real meaning. Doubtless it does not mean "until the end of the Universe". Rather one thinks of a long time, e.g. 1 Million years.

Much better would be a definition like: "until normal environmental radiation is reached". Now normal radiation varies from about 15 mSv (milliSievert) to more than 100 mSv or the equivalent in Becquerel.

Current calculations of experts in nuclear physics say that about 300 years would be a realistic time for the spent pebbles to reach this level. In Ahaus I saw the Castors with pebbles standing in a hangar for about 40 years without problems. In Jülich the reported situation is comparable. Also research is going on and should be strengthened to partition and/or transmute the radioactive waste. So within those 300 years one might be happy to find the waste in a secure intermediate storage for reuse.

Another topic of endless discussion is the **residual risk** and its insurability. None of about 440 current traditional nuclear power plants is commercially insured. When Fukushima had cooled down, Prime Minister Abe told the world, that each of the three reactors molten down had caused about 50 billion USD in damage, so a total 150 Billion USD was lost. The Japanese nation, the taxpayer had to shoulder this sum. In any comparable accident this will be similar. This risk is commonly understood by "residual risk". And it can happen with all reactors, whose safety depends on either human or mechanical or electronic interaction.

Not so with the pebble bed technology. Because it is inherently safe, this risk simply does not exist. It needs not be covered neither by the society nor by an insurer. The other risks, e.g. building damage, business continuity will be covered by normal industrial insurance.

How about economics?

We have to accept, that there is little knowledge about some important factors, which go into the business case:

1. Nobody can tell us what is the cost of a FT Hydrogenation plant
2. For the cost of a Pebble-Bed Reactor we have some exaggerated figures from Hamm, because of politically influenced tests and delays
3. Operating cost are mainly influenced by the costs for
   a. Personnel
   b. Heavy metal (Uranium, Thorium etc.)
   c. Interest rates

In the following tables some details of the economic calculation are offered. The complete calculation cannot be presented here because of its size, but is available to any interested party by mail.

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[3] This video https://www.youtube.com/watch?v=4A1uoJ1Z5iA shows how the heat steeply degrades after excursion.

Economic calculation for the Pebble Bed Oven		MWth 750
assumed efficiency	0.4000	MWel 300
Capital costs for the investment	**Calculation factors**	**All in Euro**
Construction phase approx 5 years	0.3340	**267,200,000**
Construction costs complete		800,000,000
Provisions for decommissioning, repository, dismantling	0.3000	240,000,000
Building costs as sum of construction and provision		**1,040,000,000**
Construction costs per megawatt electrical		3,466,667
Useful life in years		30
Total investment = sum of construction costs and construction phase		**1,307,200,000**
Depreciation per year (total investment / 30 years)		43,573,333
Annual interest charge	7.50%	49,020,000
Annual capital costs		**92,593,333**
Ongoing operational costs		
Personnel	headcount	100
Annual gross personnel costs	70,000	7,000,000
Material costs		
Market price for yellow cake (U3O8 at 50 USD/pound)	Per ton	101,284
Annual consumption of yellow cake	tons	75
Input energy of uranium (at 20 million KWh per Kg)	kWh per Jahr	13,500,000,000
Fuel Costs for uranium/thorium p.a.		7,596,330
Production of pebbles and coated particles	200 % of fuel costs	15,192,661
Treatment and disposal of elements	200 % of fuel costs	15,192,661
Other costs		5,000,000
Maintenance as a percentage of the construction sum	12.00%	96,000,000
Preheating with lower leve heat form the "oven"		50,000,000
Annual operating costs		**145,981,651**
Total costs – per year		**238,574,985**

Important components and factors:

The goal is to produce about 1 billion liters of ethanol or methanol per year in an industrial complex consisting of a modular pebble-bed reactor and a FT hydrogenation plant:

- Pebble bed reactor, three modules at 100 MWe (approx. 250 MWth) each. The necessary heat exchangers, piping, tubes, the necessary apparatus for control and operation.
- Hydrogenation plant with a capacity of one billion liters of fuel per year.
- 30 years to amortization, 7.5 percent interest
- 180 persons at annual gross personnel costs of 70,000 Euro
- Raw fuel costs (world market) for yellow cake approx. 50 USD per pound
- Hydrogen costs per year of 100 million Euro,
- Coal input per year of 70 million Euros.

The calculation for the pebble-bed reactor assumes construction costs of 800 million, which corresponds to a rate of just under Euro 2,670 per kWel. This is roughly the cost rate of the THTR operated in Hamm, excluding the externally imposed costs – essentially for duplicating unnecessary audits.[4] For the calculation shown here, it is assumed that the learning curve and any development costs are not included in full. The calculation does not refer to a FOAK[5] construction. For the construction phase of 5 years, an additional third of the construction sum is estimated, since this also has to be financed. The same applies to the decommissioning costs. This results in a total rate of 3,470 per kWel. Depreciation is estimated at a 30th per year, because the useful life of the building is expected at least for 30 years. At present, even conventional nuclear power plants abroad are approved for operation for up to 60 years or longer. The relatively high interest rate of 7.5 percent has to be agreed with the lenders in a specific case and is likely to be lower at present. It is deliberately not calculated "on the brim".

The operating costs are based on experience with other power plants. 100 people are probably the upper limit, the average gross personnel cost rate of Euro 70,000 annually includes all qualifications from the management to the gatekeeper as an average value.

The market price for commercial yellow cake uranium usually fluctuates around USD 30 to 40 per pound. The price of USD 50 chosen here is the result of commercial caution. The price of Thorium is even more favorable. The production of coated particles and spheres will be assumed at twice the price of the material until reliable values are available. The same procedure will be followed with the disposal costs, which are not comparable with today's final storage costs due to the "cool down" storage concept. The maintenance with an acceptable 12 percent of the construction costs is also in line with the usual rates in the industry, although due to the lack of maintenance-intensive safety devices, only little effort is to be expected.

Based on these values, an average internal cost price of 0.042 Euro per kWht and total costs of around 95.5 million Euro per year is calcuated for process heat. A further Euro 50 million is added for preheating, i.e. a total of Euro 145.6 million per year, as shown below in the hydrogenation calculation.

With this heat supply the capacity of the reactor is not fully used. The additional energy is available for power generation and district heating. They generate further contribution margins of around 93 million Euros, so that the total costs of 238 million Euros will be recuperated. These rates would have to be increased if internal profits were still to be made.

The economic calculation for the hydrogenation plant is based on a capacity of around 960 million liters of fuel per year. Due to the lower energy content of ethanol or methanol, this quantity corresponds to approximately 672 million liters of petrol (Benzin).

For the construction, including the construction phase, 2.7 billion Euros are assumed here, resulting in annual capital costs of just under 169 million Euros. The operating costs include personnel costs for 80 people of 5.6 million Euros annually and energy costs, as calculated above, of 145.6 million Euros. Added to this are material costs for – in this example – 1.12 million tons of lignite at 67.5 million Euros and gaseous hydrogen of 5 billion liters at 100 million Euros, maintenance 200 million Euros and miscellaneous 50 million Euros. This results in total

---

[4] Prof. Dr. Knizia in atw.

[5] First of a Kind.

Economic efficiency calculation hydrogenation plant (Fischer-Tropsch / Bergius-Pier)		**Liter fuel**	**961,094,746**
Which corresponds to about	0.7000	Liter petrol	672,766,322
Cost of capital for the investment			
	Dimensions and factors		Euro, if not otherwise
Construction phase approx 5 years	0.3340		668,000,000
Building costs complete			2,000,000,000
Useful life	years		30
Total investment = sum of construction costs and construction phase			**2,668,000,000**
Depreciation per year			88,933,333
Interest per year	6.00%		80,040,000
Annual capital costs			**168,973,333**
Ongoing operational costs			
Personnel			80
Annual gross personnel costs	70,000		**5,600,000**
Material costs			
Available energy (high temperature heat from PBR)			
highest temperature heat from the PBR	kWh		2,294,244,000
Medium-temperature heat from the PBR	kWh		1,204,478,100
Total energy supply from the reactor	kWh		3,498,722,100
Costs for this energy supply	Euro		**145,530,741**
possible fuel production with this			
Type of liquid fuel			Ethanol
Energy content per kg	kWh		8.3
Efficiency of the hydrogenation process			90.00 %
Energy content of the generated fuel	kWh		6,297,699,780
Annual quantity of finished product (fuel)	Kilogramm		758,759,010
Special weight of one liter	kg		0.75
Annual quantity of the final product	Liter		1,011,678,680
Input-Material			
Type of available feedstock			Lignite coal
Energy content per kg	kWh		5.6
Required annual quantity by energy content	kWh		6,297,699,780
Required annual quantity by weight	kg		1,124,589,246
Required annual quantity by weight	to		1,124,589
Market price of input material (lignite)	to		60
Input material total costs annually			67,475,355
HT-Energy from the pebble bed oven	see above		145,530,741
Hydrogen supply	Liter		5,000,000,000
Market price of hydrogen	Euro per Liter		0.020
Cost of hydrogen per year			100,000,000
Total material and energy costs			**313,006,095**
Maintenance	10 %		**200,000,000**
Total operating costs			518,606,095
Other / unforeseen			**50,000,000**
Total capital and operating costs			**737,579,429**
Output and price			
Production per year	Liter		1,011,678,680
thereof waste, shrinkage in percent			5.00%
of which waste, shrinkage in liters			50,583,934
Remaining usable quantity (liters of ethanol)			**961,094,746**
Price per liter of ethanol ex plant	Euro/ Liter		**0.7674**

annual costs of approx. 737.5 million Euros.

With an output of 961 million liters as mentioned above, the liter of fuel costs 0.77 Euro ex works. Converted to the liter of petrol, the equivalent price would be 1.1 Euro. Although this price is higher than the current price of petrol ex refinery, a number of government charges can be eliminated because the reasons for them (environment, energy, pension financing) become irrelevant with such sustainable production.

The example quantified above essentially demonstrates the simplicity of such a calculation. Thus, this first scenario, for

Reactor investments of
1,307 million Euros
a hydrogenation plant Investment of
2,000 million Euros
an internal price of 1 kWh of heat
0,042 Euro and
a factory outlet price for one liter of fuel
0.76 Euro

If the parameters are changed, the final results are of course different as follows:

Medium scenario
Reactor investments
2,600 million Euros
Hydrogenation plant Investment
2,000 million Euros
Internal price of 1 kWh heat
0.084 Euro
Factory outlet price for one liter of fuel
1.12 Euro

High scenario
Reactor investments
4,000 million Euros
Hydrogenation plant Investment
2,000 million Euros
Internal price of 1 kWh heat
0.13 Euro
Factory outlet price for one liter of fuel
1.48 Euro

Very high scenario
Reactor investments
6,500 million Euros
Hydrogenation plant Investment
6,000 million Euros
Internal price of 1 kWh heat
0.21 Euro
Factory outlet price for one liter of fuel
2.14 Euro

The price ex-factory therefore varies between 0.75 and 2.14 Euros per liter of fuel. It can be assumed that the reality will result in the lower price range when the FOAK phase is over after 10 years and a sufficient number of such complexes are in operation. In view of the reduced dependence on energy imports and the safeguarding of highly qualified jobs in Germany for a technology with worldwide opportunities, this technology appears worthwhile considering.

Author
Jochen K. Michels
jochen.michels@jomi1.com
Management Consultancy
Konrad-Adenauer-Ring 74
41464 Neuss, Germany

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Robert-Koch-Platz 4, 10115 Berlin, Germany
Phone +49 30 498555-33
E-mail info@nucmag.com
Web www.nucmag.com

Editorial

Christopher Weßelmann
(Editor in Chief)
Phone +49 2324 43977-23
E-mail christopher.wesselmann@nucmag.com

Nicole Koch
(Editor)
Phone +49 163 7772797
E-mail nicole.koch@nucmag.com

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