Design of a U-Battery®

Delft, November 2011

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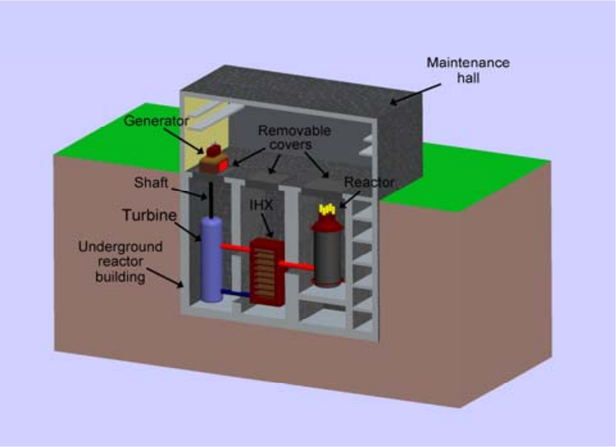

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A study sponsored by Urenco, and Koopman and Witteveen.

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1. Introduction

In the past fifty years, the size of nuclear reactors has grown from 200 MW_{th} to more than 4.500 MW_{th} in order to make full use of economy of scale. Because large-size nuclear reactors usually require high capital investment and heavily rely on the infrastructure of the nuclear sites, this has motivated designers to develop small modular reactors, especially for developing countries and remote areas off main power grids. Major drawback of most of these small modular reactor designs is that new technology is introduced, which has to be developed and licensed. This will normally take decades in a nuclear environment.

To be economically feasible a small modular reactor should work like a battery. The reactor and the energy conversion system are brought to the purchaser's site as modules, the electricity is hooked up and the reactor will run for 5 years or more with a minimum of operational personnel. This allows the modules to be manufactured in series and transported to the purchaser's site by rail, barge, truck, etc. After operation of 5-10 years, the reactor can be brought back to the factory for refueling or can be directly replaced by a new module. This modular and standardized approach will, with increasing sales, result in significant cost reduction by economy of number. On top of this a user in an industrialized area will save the yearly cost of the power grid infrastructure.

This report presents a feasibility study for the design of an intrinsically safe modular nuclear power generation system that combines quick-developed till commercial design using proven technology with the basic features to profit from economy of number. The investigation shows that the proposed 10MW_{th} U-Battery® design is very promising to fulfill all the above requirements.

The study is executed by the Delft University of Technology together with the University of Manchester and is sponsored by URENCO and Koopman & Witteveen.

2. Core design

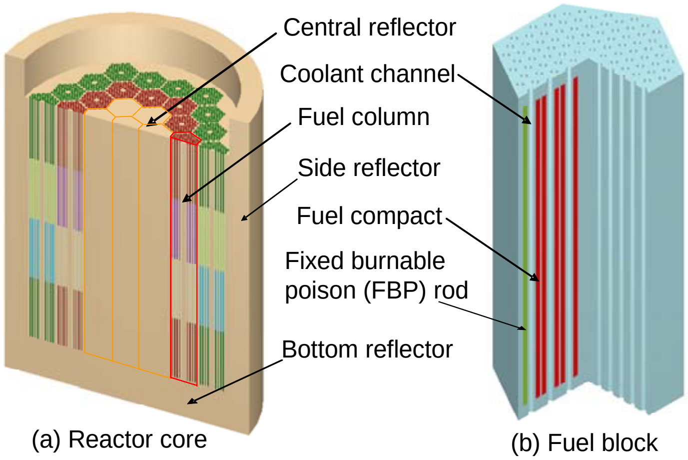
Different reactor core configurations and thermal power levels of the U-Battery® have been investigated for various diameters of the reactor pressure vessels (RPVs). The RPV diameter is one of the important parameters affecting the transportability of the U-Battery®.

2.1 Graphite moderated 20 MW_{th} Design

Since the main ideas behind the U-Battery® are inherent safety, modularity and near-term utilization, the U-Battery® has been developed based on currently mature High Temperature Reactor (HTR) fuel blocks utilizing standard TRISO particles as fuel. The reactor core of the U-Battery® is composed of hexagonal fuel blocks with reflectors as shown in Fig. 2.1.

The calculations show that the 20 MW_{th} U-Battery® can achieve a fuel lifetime of 10 Effective Full Power Years (EFPYs). The annular reactor core Layout 30*4 (meaning a reactor core of 30 fuel blocks per layer and 4 layers on top of each other), as shown in Fig. 2.1, is the recommended configurations for the 20 MW_{th} design.

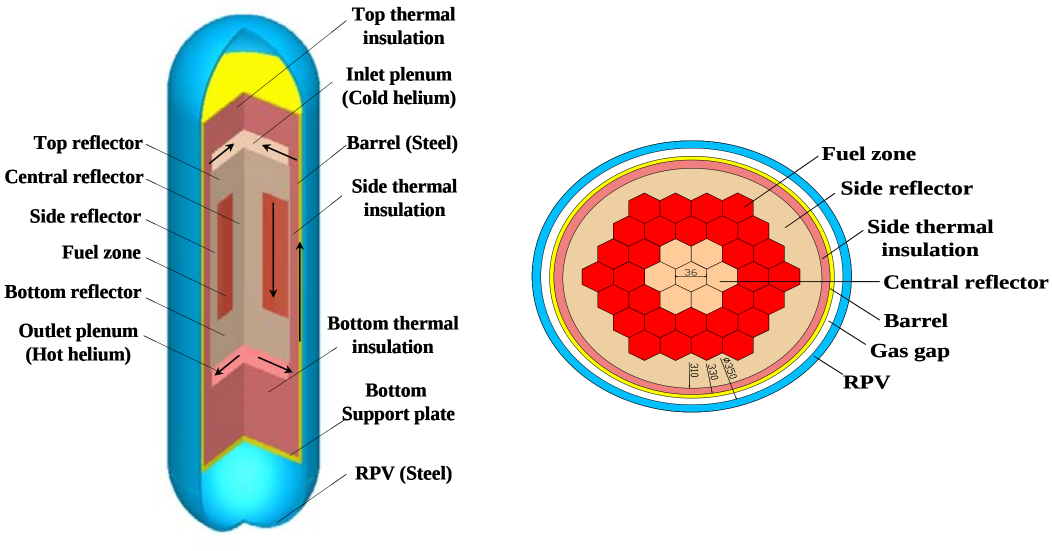
The cylindrical reactor core Layout 37*4 is a good alternative for comparison. The main difference between the two Layouts is the presence of 28 graphite blocks in the center of the core of Layout 30*4 while these are replaced by fuel blocks in layout 37*4, as shown in Fig. 2.1. The annular reactor core has a longer lifetime than the cylindrical one, because of the extra neutron moderation by the central graphite blocks. The burn up of Layouts 37*4 and 30*4 are 70 and 57 MWd/kgHM, respectively.



(a) Reactor core

(b) Fuel block

Fig. 2.1: 3D figure of the annular core (Layout 30*4) and fuel block (right); for clarity the top and bottom reflectors have been removed in the core as well as the fuel handling hole in the block.



(a) 3D reactor configuration

(b) Horizontal cross section

Fig. 2.2: The schematic diagram of Layout 30*4. The coolant channels in the blocks and the auxiliary structures in the reactor have been removed to make the main components of the reactor better visible.

The core configuration and horizontal cross section of Layout 30*4 are shown in Fig. 2.2. The thermal-hydraulic design calculations show that this Layout has preference from thermal-hydraulic point of view. Although it faces slightly higher temperatures for the barrel and RPV, the maximum temperature is 230 °C lower than for Layout 37*4. In conclusion, Layout 30*4 not only decreases fuel cost, but also increases the safety of the U-Battery®.

2.2 Graphite moderated 10 MW_{th} Design

If the thermal power of the U-Battery® decreases from 20 MW_{th} to 10 MW_{th} the inner diameter of the RPV reduces from 3.5 m to 1.8. Using a 25-cm-thick graphite reflector, the fuel lifetime reaches 2 EFPYs. If the side reflector is made of 20-cm-thick Beryllium oxide (BeO), the annular core Layout 6*4, as shown in Fig. 2.3, can achieve a lifetime of 5 EFPYs.

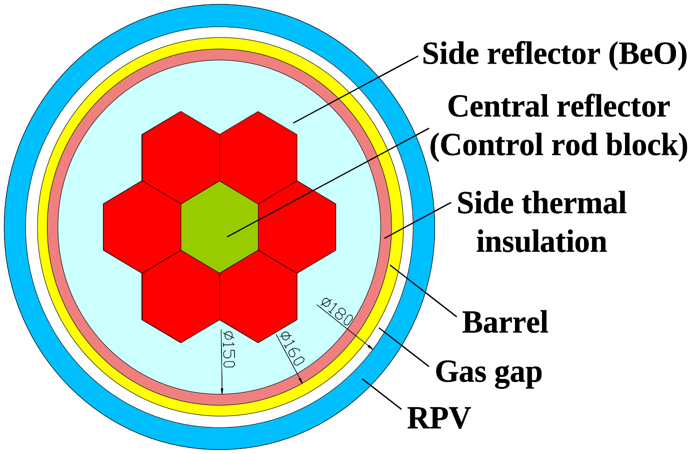


Fig. 2.3: Horizontal cross section of Layout 6*4

2.3 Excess reactivity control method

The geometric parameters of the B_4C fixed burnable poisons (FBP), as shown in Fig. 2.1b, have been optimized to reduce the reactivity swing of the cylindrical core Layout 37*4. Although the reactivity penalty (this is the higher enrichment of uranium needed to compensate for the remaining poison at the end-of-cycle) increases, the use of fixed burnable poisons can be beneficial, because the cost of control rods and driver mechanisms may be higher than the extra fuel costs.

2.4 Thorium-fueled fuel block

Seed-and-blanket (S&B) fuel blocks, as shown in Fig. 2.4, have been investigated for a Thorium-fueled U-Battery® with the aim to reduce the fuel cost of the U-Battery® and to control the reactivity swing without the reactivity penalty inherent to using fixed burnable poisons in a Uranium-fueled U- Battery®.

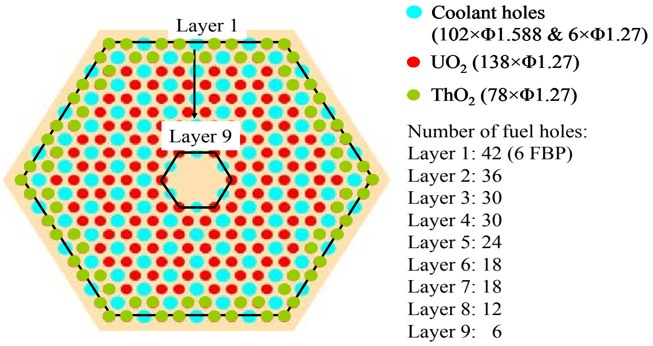


FIG. 2.4: Seed-and-blanket (S&B) fuel block with ThO_2

For fuel blocks with 36, 54 and 78 UO_2 fuel rods in the central regions, the reactivity swing is only 0.1 Δk during 10 EFPYs. The excess reactivity of 0.1 Δk is so small that no fixed burnable poison is needed. Moreover, when thorium is equally expensive as uranium, the S&B fuel block may be about one-third cheaper than that of LEU fuel block.

3. Safety characteristics

3.1 Graphite moderated 20 MW_{th} design

Due to neutronic feedback mechanisms and the thermal-hydraulic performance of the reactor core, the 20 MW_{th} U-Battery® is inherently safe.

The negative reactivity feedback coefficients, as shown in Table 3.1, guarantee the automatic shut-down of the reactor when the temperature increases. The values of the reactivity coefficients of the U-Battery® are very similar to those of the HTR-10, which has been used to demonstrate this effect.

Table 3.1: Reactivity temperature coefficients of the U-Battery®.

Configurations	Time [Years]	Fuel [pcm/K]	Moderator [pcm/K]	Reflector [pcm/K]
Layout 30*4	0.0	-3.8	-1.6	+0.5
	5.0	-5.4	-3.1	+0.1
	10.0	-5.3	-3.8	+0.8
Layout 37*4	0.0	-5.4	-2.9	+1.2
	5.0	-7.5	-3.4	+0.4
	10.0	-7.2	-4.1	+0.2

Besides the automatic shut down of the reactor, removing decay heat passively out of the reactor without any fuel damage is an important safety characteristic. When using TRISO fuel particles, the maximum temperature should stay below 1600 °C under all circumstances. The thermal hydraulics analyses show that for loss of forced-cooling scenarios, both pressurized and depressurized, the U-Battery® fulfill these requirements.

Under the assumption that the control rods shut down the reactor two scenarios were investigated:

- A pressurized loss of forced-cooling (**PLOFC**), In this case, the U-Battery® loses forced-cooling possibly caused by mechanical problems or a loss of power, but the reactor system remains intact, so it does not lose system pressure.
- If the reactor system loses pressure at the same time, for example, because of a broken hot gas duct which connects the reactor pressure vessel with the power conversion system, a depressurized loss of forced-cooling (**DLOFC**) incident happens.

Both situations are investigated for the cylindrical and annular core configurations. The calculations show that the fuel temperature is higher for a DLOFC incident, because the decay heat can only be removed by conduction and not by natural convection. The maximum temperature of the reactor core (Layout 37*4 and Layout 30*4) decreases immediately, as show in Fig. 3.1, without any violation of the temperature limits. This favorable characteristic is due to the low power density and the large heat capacity of the core.

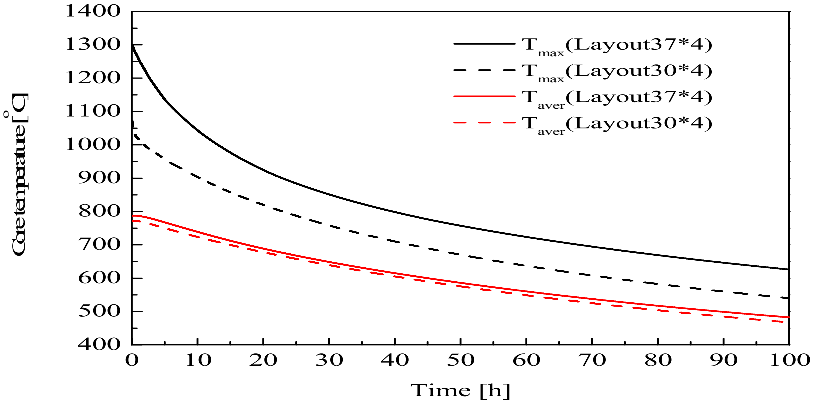


Fig. 3.1: Maximum and volume-averaged temperatures of the fuel zone of the annular (Layout 30*4) and cylindrical (Layout 37*4) core configurations during DLOFC incident.

3.2 Graphite moderated 10 MW_{th} BeO reflector design

Although the 10 MW_{th} U-Battery® with BeO reflector was only investigated neutronically, its safety characteristics can be estimated based on the 20 MW_{th} U-Battery® design and other large prismatic High Temperature Reactors (HTR), like the USA prototype GT-MHR.

Because the same fuel blocks are used for the 10 and 20 MW_{th} U-Battery®, the first probably has negative reactivity temperature coefficients as well. Although the power density is higher in the 10 MW_{th} design, which is a challenge for the PLOFC and DLOFC scenarios, it is still one-third lower than for large prismatic HTRs like GT-MHR. This is a strong indication that the decay heat of the 10 MW_{th} U-Battery® might be removed by passive means without any violation of the temperature limits. Moreover, the thermal-hydraulic calculation of a 100 MW_{th} U-Battery® with an annular core configuration, which has a 50% higher power density than the 10 MW_{th} design, shows a maximum fuel temperature is far below 1600 ^{o}C.

3.3 Beyond design-basis scenarios

Besides design-basis scenarios, the U-Battery® faces some beyond design-basis scenarios, such as PLOFC and DLOFC without SCRAM (i.e., control rods cannot be inserted into reactors) and control rods withdraw without SCRAM. As shown in Fig. 3.2, tests executed in AVR and HTR-10 showed, that these reactors

- can be shut down immediately by the negative temperature feedback coefficients even if the control rods are not inserted into the cores;
- get re-critical only at a very low power level.

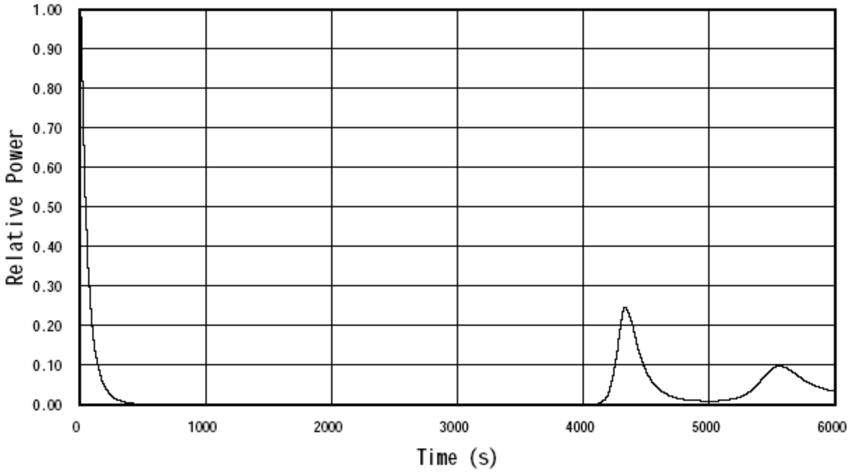


Fig. 3.2: Experimental curve of fission power during PLOFC without scram for the HTR-10 at 3 MWth.

Since the U-Battery® has similar values for the temperature coefficients as the Chinese prototype HTR-10, it will also shut down automatically. After the reactor has shut down, the U-Battery® can passively remove the decay heat out of the core without violating the fuel temperature limit, as analyzed in Sec. 3.1.

4. Core Structural Design and Fuel Design

Originally the U-Battery® was to be designed to operate in a carbon-dioxide coolant based on the excellent thermal properties of high pressure CO_2. However, investigation, both analytical and experimental demonstrated that this was not practicable due to thermal and radiolytic oxidation. Therefore the design was changed to an inert, high pressure helium system which precludes both radiolytic and thermal oxidation under all normal operation conditions. The design will be such to preclude the accidental ingress of water or air in the system under normal operation and design faults.

The structural designs for two cores is outlined below, the first is a 20 MW_{th} graphite moderated design the second design is a 10 MW_{th} reactor also graphite moderated, but also included a BeO reflector.

4.1 Graphite Moderated 20 MW_{th} Design

The reactor is housed in a steel Reactor Pressure Vessel (RPV) about 100 mm thick designed for a working pressure of 40 bar at 300 °C and a maximum transient temperature about 50 °C higher than the limiting temperature of 395°C during several hours. Transients above this temperature will cause the RPV to vent into the secondary containment (confinement). The RPV design is such that a single main inlet/outlet is situated towards the bottom of the reactor to prevent the "chimney effect" in case of a main inlet/outlet duct failure. The RPV is provided with a removable (bolted) lid that can be removed for refueling. The lid has proved openings to which the control rods mechanisms can be bolted to. All bolted joints are to be "helium tight".

The design will be such that when the reactor lid is removed for refuelling, the control rods will remain secure in the core.

Inside the vessel a core support structure rests on the bottom of the vessel. The structure provides support for the lower core support plates and the core barrel. The lower core support and core barrel is to be kept as close to the reactor inlet temperature as possible during normal operation.

On top of the core support plates layers of insulation and graphite form the lower inlet/outlet plenums, the detail of which is for further design study but will be based on experience gained at Fort St. Vrain (FSV) and HTTR. The purpose of the lower plenum structure is to direct "cool" inlet gas upwards between the core barrel and RPV and to keep the return "cool" inlet and "hot" return gas separate and direct it outwards to the heat exchanger in the primary circuit.

The lower plenum also supports the main reactor core structure. This consists of a hexagonal array of fuel elements of FSV design, interspersed with other hexagonal blocks with larger holes through which the control and safety shutdown rods can freely pass. The core is four elements high of annular design with outer rings of 18 and 12 elements of fuel elements and a central rings of 6 and 1 hexagonal graphite elements, see Figure 2.1.

The reasoning behind the choice of the FSV fuel block design is that this design of fuel block proved itself in operation for a number of years.

The core is surrounded by an inner (removable) graphite reflector which is surrounded by insulation material. At each fuel block height, tubular "Calder" type restraint bands will be located. These will be designed to facilitate side restraint and will expand/contract with temperature with the same expansion coefficient as graphite ensuring that no "gaps" will appear between reflector and fuel blocks to prevent coolant gas bi-pass and neutron streaming.

Above the core there will be a hexagonal array of tightly clamped graphite reflector bricks, with holes to direct coolant flow downwards from the upper plenum and for control/shutdown rods to pass. The upper core plenum is to be insulated and designed directing the “cool” gas that flows upwards from the lower inlet plenum up between the RPV and core barrel back down through the core (Figure 4.1).

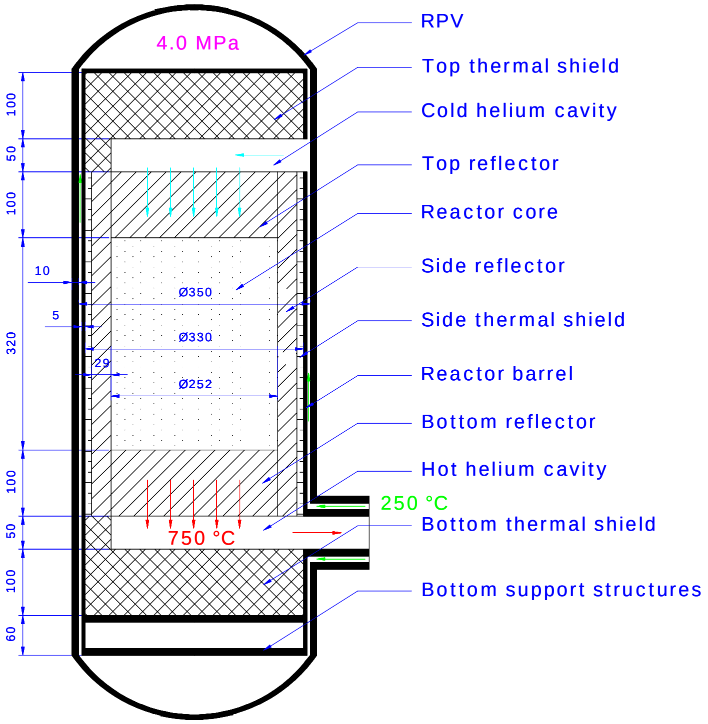


Figure 4.1: Reactor Pressure Vessel and Core Internals - Dimensions

Nuclear graphite property changes will be based on published Material Test Reactor (MTR) data for medium grained graphite obtained over many years. Although there are uncertainties in this data this tends to be the greatest at high fluence and mostly associated with the effect of radiolytic oxidation. The maximum irradiation fluence it is expected that the graphite would experience in the 20 MW_{th} design would be significantly less than one third that AGR would experience in 30 years.

The design will account for:

- Differential thermal expansion between graphite, insulation and steel;
- Differential thermal expansion due to radial and axial thermal gradients;
- Graphite shrinkage.

4.2 Graphite Moderated 10 MW_{th} Design

This design is similar, but physically smaller to that described above. In this case there is one ring of six hexagonal fuel elements by four with a central graphite column by four elements high. However, in this case the active core is surrounded by a beryllium oxide reflector, see Figure 2.3.

Beryllium oxide (BeO) is an excellent neutron reflector. It has very low neutron absorption cross-section, is excellent at moderating fast flux (both due to low mass of Beryllium and the inelastic scattering by oxygen, see Table 4.1).

BeO has a high temperature capability (2840 K). BeO actually improves upon the moderating capabilities of Beryllium alone having a higher neutron scattering cross section and lower absorption cross section at the expense of higher density (~3.01 g/cm^3 c.f. 1.85 g/cm^3). It also has a high thermal conductivity ~275 W/m/K. The toxicity of BeO make it difficult to handle, however, it has been and still is used in many research reactors and for space applications and there is a significant amount of data concerning the use of beryllium in the nuclear industry.

Table 4.1 Scattering and Absorption Cross Sections for 2200 m/s neutrons (Units barns)

Element	Scattering X-Section	Absorption X-Section
Beryllium	7.63	0.0076
Carbon	5.551	0.0035
Oxygen	4.232	0.00019

It is envisage if this option were chosen that two 10 MW$_{th}$ units would supply one power unit.

The layout of the whole plant 20 MW$_{th}$ is given in Figures 4.3 - 4.5.

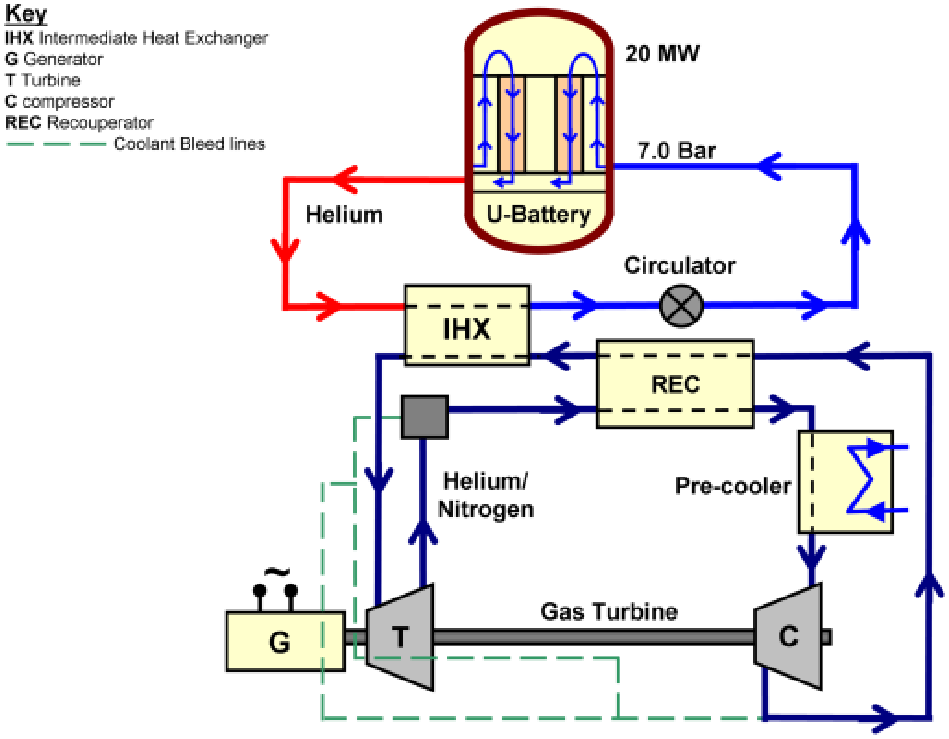


Figure 4.3: Layout of the primary circuit of the 20 MW$_{th}$ U-Battery®.

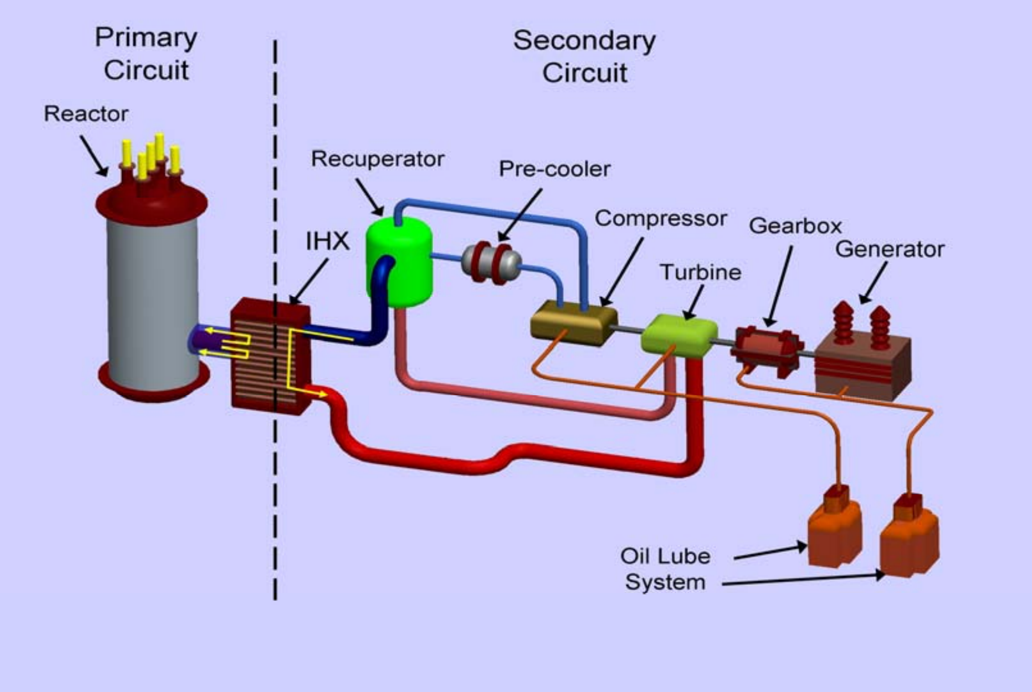


Figure 4.4: Layout of the secondary circuit of the 20 MW_{th} U-Battery®.

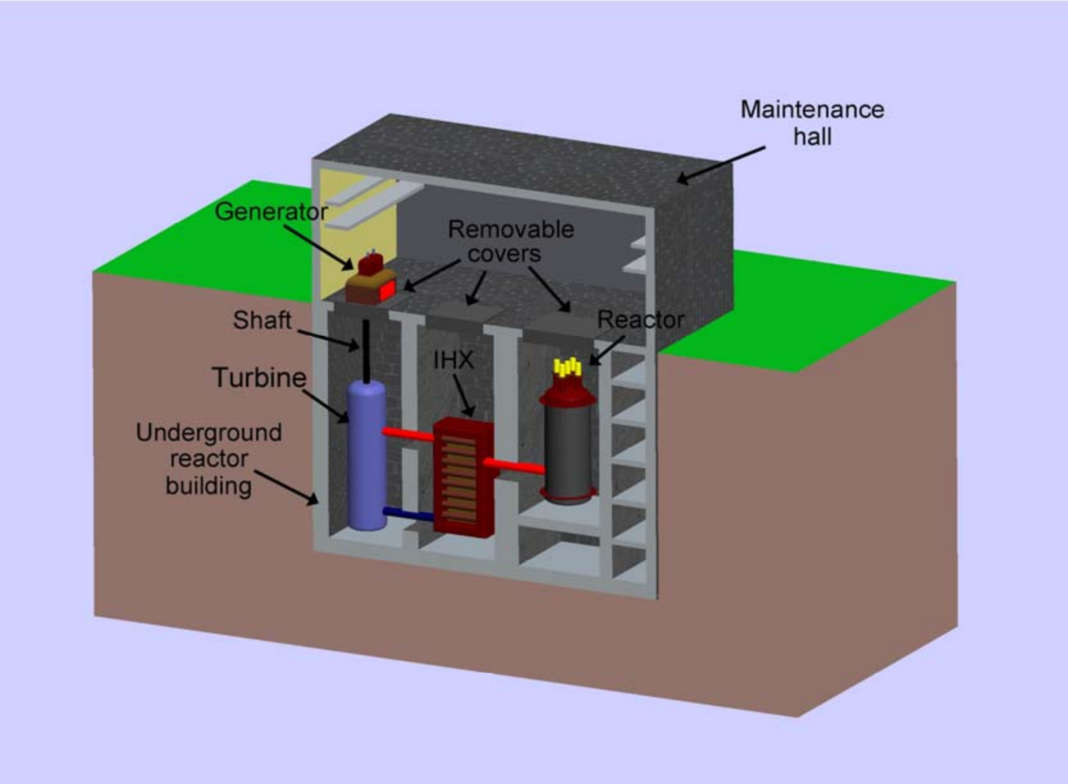


Figure 4.5: Layout of the reactor building of the 20 MW_{th} U-Battery®.

5. Plant Layout and Operation

The original concept for the U-Battery® envisaged a simple and robust plant design in which both the reactor and power conversion system would place few constraints on transport, and would require minimal routine maintenance. A long-life core was envisaged that would be capable of being refueled as a single unit and transported away from site immediately after use, requiring very little permanent on-site refueling equipment or fuel storage capacity.

The work conducted over the last two years of the project suggests that whilst some of these objectives can be met, others are not compatible with the current U-Battery® concept. A power conversion module based on the concept of an indirect cycle employing a He-N_2 turbine seems feasible, and Rolls-Royce has been identified as a potential supplier of such a system. A plant layout has been developed based on a below-ground reactor cavity and adjacent spent core storage facility, both served by an overhead crane and co-located with the power conversion module in a vented confinement building.

There are no precedents for transporting intact an entire unirradiated reactor core, and regulatory requirements may preclude this option, although transportation of a small number of sub-sections may be possible. In any case the current reference core geometry of the 20 MW_{th} Layout is likely to be too large to allow transportation of an intact irradiated core without developing and licensing a new spent fuel transport container.

5.1 Fuel Handling System

The current reference design for the 20 MW_{th} U-Battery® core and fuel elements seems incompatible with a single cartridge-type core module, largely because the dimensions of the active core plus the radial reflector and shielding/packaging requirements may exceed the maximum permissible width for European road transportation.

Currently, all spent fuel shipments take place by rail and/or sea, with very short road transport to the nearest rail head or port facility. The Excellox transport flask is internationally accepted for this purpose, but would impose a limit of 1.8 m on the diameter of the cartridge, and weighs 110 t, making road transport difficult except over very short distances. One of the Sellafield Waste Transport Containers, the SWTC25, has a gross weight of 25 t and may simplify road transport, but in this case the cartridge diameter would be limited to 1.2 m, which is too small to support a feasible core design for the current reference power output.

For these reasons, the current design employs individual fuel elements, which greatly simplifies the transport of fresh and irradiated fuel, but requires the provision of handling equipment suitable for both fresh and irradiated fuel. Fuel handling machines have been developed for previous designs of prismatic HTRs, and these have been reviewed for applicability to the U-Battery® design. The simplified single-element design produced by GA for the MHTGR project appears to be well suited to the U-Battery®.

5.2 Energy Conversion System

The reference concept for the U-Battery® is an electricity-generating module, capable of producing around 20 MW_{th}. Several different options have been explored for the energy conversion system, including: an indirect steam (Rankine) cycle with and without reheat; a direct CO_2 turbine; and an indirect gas-turbine, as well as more novel systems such as direct thermal-to-electrical conversion, and an Alkali Metal Thermal-to-Electrical

Converter (AMTEC). Of these, the novel systems and the CO_2 turbine were rejected because they were incompatible with the requirement to employ demonstrated, highly-reliable technologies, and because of their generally poor efficiencies.

A steam cycle with reheat requires a significant increase in the complexity of the steam circuit piping, and the provision of economizers and other additional components, and the small gain in overall efficiency was also considered to be incompatible with the over-riding requirements for plant simplicity and low maintenance. The two preferred options were therefore a steam (Rankine) cycle without reheat, and an indirect-cycle gas turbine. The steam cycle employs proven technology and is reliable and reasonably efficient, but it will require regular maintenance and frequent condition monitoring, for example to ensure an acceptable water chemistry is maintained.

An indirect gas-turbine would require a reasonably large heat exchanger, but avoids the potential safety concern associated with a steam ingress into the primary circuit, and could employ a relatively inert working fluid, minimizing the need for careful control of the secondary coolant chemistry. Rolls-Royce have published a concept for a power conversion module based on their well-established air turbine designs, but employing a He-N_2 mixture which combines the proven aspects of their air turbines with the advantageous thermal properties of helium, allowing a smaller heat exchanger to be used. Moreover, it is possible that Rolls-Royce could design the power conversion module as a separate unit. This would simplify the U-Battery® design process and remove a substantial item of risk from the program, as well as offering the potential for some novel financing options. The U-Battery® investors plan to hold discussions with Rolls-Royce in the near future.

5.3 Control System Design

The control system for the U-Battery® will be based on existing high-integrity control systems available from established vendors such as Siemens. However, it is anticipated that the control requirements for the U-Battery® will be considerably simpler than for corresponding LWRs, allowing a substantial reduction in control system cost.

5.4 General Plant Layout

The layout of the primary circuit and power conversion module fluid systems has already been described in Section 4 (Core Structural Design). A preliminary design for the U-Battery® plant layout is provided in Figure 5.1 below.

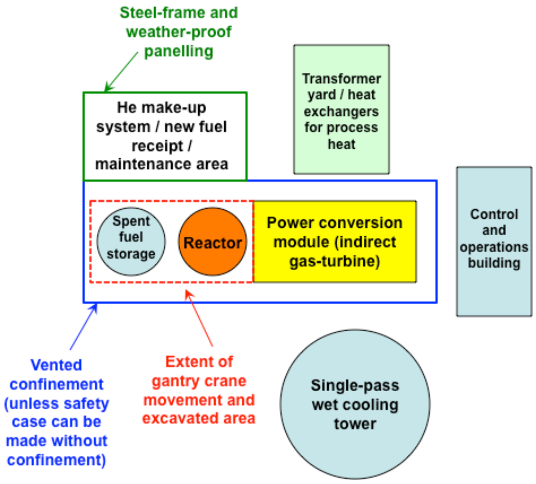


Fig. 5.1: U-Battery® plant layout schematic

The main features are the provision of two adjacent excavated cavities housing the RPV and the spent core storage facility. Locating these major plant items below ground level will assist in radiation shielding and will limit the height of the U-Battery® structure. The power conversion unit is located adjacent to the reactor, sharing the same containment, but at ground level to facilitate access for maintenance. For costing purposes it is assumed that a sealed containment building will be required. However, it is likely that a vented confinement could be justified (similar to the Pebble Bed Modular Reactor concept), with a consequent reduction in cost. The mechanical annex, housing facilities for fuel receipt, maintenance, and He make-up, is also located adjacent to the reactor, but does not need to be accommodated within the containment because it does not house safety-critical systems. It is anticipated that the civil structures outside of the containment can be of steel-frame and weather-proof panel construction to minimize cost.

5.5 Fuel Transport

The original U-Battery® concept envisaged the core being replaced as a single "battery" unit. However, a review of European road transportation regulations has shown that the physical size of the reference U-Battery® core would preclude transport as a single module in a standard ISO freight container package. Moreover, it is considered unlikely that regulatory authorities would accept the transport of an intact reactor core. Instead, it is proposed to transport individual fuel elements, and to build the core structure on site, following conventional practice. Although this approach lacks the simplicity of a single "battery" module, the infrequency of refueling ensures that any additional time taken to refuel the reactor will be inconsequential compared with the regulatory difficulties associated with shipping an intact core. Several existing transport containers are likely to be suitable for U-Battery® fuel elements with only minor modifications, including the current containers for UK Advanced Gas Cooled Reactors. Fresh fuel transport is therefore considered to be feasible with the existing transport infrastructure, and no new development is anticipated.

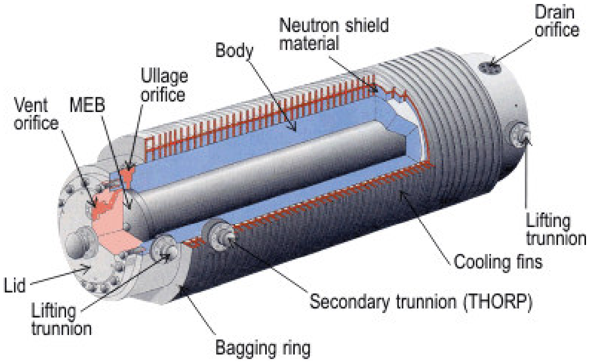


Figure 5.2: Excellox spent fuel transport flask

Spent fuel transport for the reference design is simplified by the use of individual fuel elements, avoiding the need to transport an intact core. For this purpose, several existing spent fuel transport casks already exist.

However, for the 10 MW_{th} design, it may be possible to transport an intact fresh/spent core using an Excellox transport flask, shown in Figure 5.2. Design details for the Excellox-7 flask have been requested from Sellafield Sites Ltd.

6. Economic Analysis

So far, most reactors have been built with economies of scale by increasing the power of the reactor, as the leading principle. The purpose of the U-Battery design however has been to devise an economically feasible micro reactor (<=20MWth) that can be justified by the economics of number. Besides this aspect major cost saving aspects compared to large-scale reactor design have been achieved by the intrinsic safe reactor design with virtually no operating or maintenance expenses and the built in capability for modular design.

Based on the Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, a top-down cost calculation approach is adopted. The analysis consists of an input-throughput-output model to assess the economic parameters of a 20 MWth U-Battery compared with a 2*10 MWth U-Battery. A South African 100MWth HTR case is used as a cost calculation reference.

6.1 Cost of Major Equipment

Starting point of the analysis are the costs of the following equipment, which serves as a base for both cases to be compared (see table 1):

- Reactor Pressure Vessel
    - Vessel (SA-508 steel @ 30€/kg)
    - Reflector material (Graphite @ 65€/kg and BeO @ 230€/kg)
    - Control Rods (scaled down from AP600-CRDM)
- Power Conversion Module (preliminary estimate from Rolls-Royce)
- Miscellaneous Equipment

6.2 Markups for direct, indirect costs and contingencies

Markups on top of the major equipment costs are used for direct field costs, indirect cost and contingencies. For the direct field costs (mechanical, electrical, civil, and instrumentation) the markup is 100% on the cost of major equipment. The markup for indirect cost (engineering, procurement, construction, management) is 50% on top of the sum of cost of major equipment and direct field costs. With the markup for contingency at 30% over the total costs, the total fixed capital expenditures amounts to 76 M€ for the 20 MWth case and 63 M€ for the 2*10 MWth case (see table 6.1).

6.3 Working Capital

Fuel, fuel-handling Costs

At 17% Uranium enrichment for the 20 MWth case and a price (excl. final disposition) per 1,000 kg set at 15,800$ the cost will be 11.5 M€. Adding handling cost for 0.5 M€ this amounts to 12 M€ for the 20 MWth case for a batch with a lifetime of 10 years. Costs are calculated on 2011 Uranium and fuel enrichment data. long the same line of reasoning we arrive for the 2*10 MWth case at 6.1 M€ (20% enrichment, 208 kg). This batch will have a lifetime of 5 years.

Construction installation manpower Costs

For both cases the labor costs during construction are set at 4 M€.

Decommissioning Costs

Based upon detailed calculations for the decommissioning of the RID reactor at Delft we estimated that for both U-Battery cases a NPV (Net Present Value) of 10.3 M€ is needed.

6.4 Resulting total investment

Adding up all parts of the capital expenditure we arrive at a cash outflow of 102,4M€ for the 20 MWth U-Battery and 83,2 M€ for the 2*10 MWth:

Table 6.1 Calculation of Total Investment, NPV (both in M€), ROI and PBP

	20 MWth	**2*10 MWth**
Vessel	2,2	1,1
Reflector Material	5,6	3,0
Control Rods	2,3	2,6
Power Conversion Module	2,9	2,9
Miscellaneous Equipment	6,5	6,5
Cost of Major Equipment	**19,5**	**16,1**
Markup for other Direct Costs	19,5	16,1
Direct Costs	**39,0**	**32,2**
Markup for Indirect Field Cost	**19,5**	**16,1**
Markup for Contingencies	**17,6**	**14,5**
Initial Fuel Core Load	12,0	6,1
Labour during Construction	4,0	4,0
Decommissioning Costs	10,3	10,3
Working Capital	**26,3**	**20,4**
Total Investment (TI)	**102,4**	**83,2**
Net Present Value (NPV)	**7**	**23**
Return on Investment (NPV/TI)	**7%**	**28%**
Pay Back Period (in years)	**18**	**16**

6.5 Running costs

The revenues of both cases are dependent on the availability of the U-Battery, the efficiency and of course the selling price per KWh of the generated electricity. At 96% availability and 40% efficiency, the battery produces 7.7 MW. At a selling price of 0.10 €/KWh and 8.766 hours /year this gives a cash inflow of 6.9 M€.

The cash outflow consists of direct labor 15 FTE (e.g. Operating, Maintenance and Security) and direct materials 350 K€/ year (3% of replacement asset value) which totals 1.4 M€.

These cash flows occur for each year in the lifetime of the U-Battery (set at 60 years) and are accrued with the inflation rate of 2%/year.

6.6 Results

In order to assess both cases, we selected the Net Present Value (NPV), the total Investment (TI), the ROI (defined as the NPV/TI) and the Pay-Back Period (PBP) as measures. The firms cost of capital was set at 5.6%: assuming an equity/debt ratio of 20/80, a return on equity of 12% and the cost of debt at 4%. This results in a NPV of resp. +7 M€ and +23 M€ as shown in table 6.2.

Table 6.2: Resulting measures.

M€	NPV	Investment	ROI	PBP
20 MWth	7	-102	7%	18
2*10 MWth	23	-83	28%	16

In both cases the investment per KWh is approx. 2 euro cent. The total U-Battery electricity producing of 20 MWth would be enough for a community of 20.000 families, consisting of an average of 2.3 persons per family and using on average 3500 KWh per family.

6.7 Sensitivity Analysis

By changing the variables between -100% and +100% we were able to discover the impact of each variable in the end result. Most sensitive for the end result is the price at which a KWh is sold, in our case set at 10 euro cent. This is the lower limit with a positive margin for the 20 MWth U-Battery. A price of 9 euro cent would result in a loss of -9% ROI in the steady state. However the 2*10 MWth U-Battery 9 cent/KWh seems to be still feasible but is the lower limit with a positive margin of 8% ROI.

6.8 Conclusions

This comparison shows that the U-Battery is economically feasible from a KWh price of 9 cent. This result shows that there are opportunities in designing tailor made reactors for large industries or (small) towns. These opportunities lie in modularity and standardization, simple design, serial fabrication of components and building multiple units at one site.

6.9 Still to be addressed: sharing the economic risk

Operating a U-Battery consists of roughly two parts: monitoring the reactor for security reasons and changing the fuel after each 5 or 10-year period. The cost of the monitoring part is dependent on the design of the U-Battery and the deployment of the battery by the end-user. In an industrial environment there might be opportunities to share these tasks either with other companies in the vicinity or within e.g. a production company with similar tasks thereby further improving the economic viability of the case.

The frequent necessity of RPV transport to the producer and changing of the fuel could be heavily reduced when performed by a specialized company that benefits by standardizing this task.

Though the capital investment for a U-Battery is much lower compared to the expenditure for a large reactor; there is still a timing difference between the manufacturing of the battery - up front, and the cash inflows - during the lifetime of 60 years. This would be a problem for a stand-alone situation, in which one or a relatively small number of batteries are produced. By applying serial production the producer can divert part of this economic risk. Alternatively, the timing difference could be a smaller problem for an end-user buying a secure energy solution at a fixed price for the next 60 years. The economic risk of building U-Batteries can thus be shared between producer and end-user.

ANNEX: Main Parameters of the U-Battery®

	10 MW$_{th}$	**20 MW$_{th}$**
Reactor Core		
Reflector composition	BeO	Graphite
Control rods (#)	4	6
Fuel Blocks (#)	6*4	30*4
Enrichment (%)	20	17
Fuel life time (a)	5	10
Fuel block dimension (cm)	36*80	36*80
Fuel mass (kg)	208	1.040
Burn-up (MWd/kg HM)	88	70
Radial dimensions		
Outer diameter (cm)	180	370
Vessel thickness (mm)	<100	100
Reactor core diameter (cm)	108	252
Reflector thickness (cm)	20 (BeO)	29
Insulation thickness (cm)	5 (SiC fiber)	10 (SiC fiber)
Barrel thickness (cm)	2	2
Gap thickness (cm)	5	5
Axial dimensions		
Core Height (cm)	320	320
Top reflector (cm)	20 (BeO)	50
Bottom reflector (cm)	20 (BeO)	50
Top plenum (cm)	20	20
Bottom plenum (cm)	50	50
Top insulation (cm)	30	30
Bottom insulation (cm)	60	60
Core support plate (cm)	10	15
Support structure (cm)	60	60
Vessel height (cm)	590	655
Reflector/Moderator		
BeO mass (kg)	7.900	0
Graphite mass (kg)	8.100	~ 70.000 (incl. Ins.)
Excellox Flasc		
Flask inner diam (cm)	180	
Flask inner height (cm)	>500	