Status Report – MoveluX (Toshiba Energy Systems & Solutions) Japan (2019/9/30)

This reactor design is a new concept with a projected earliest deployment (start of construction) time of 2030s.

The reference plant has a net power output of or 10 MWth.

INTRODUCTION

Indicate which booklet(s): [ ] Large WCR [X] SMR [ ] FR

MoveluX stands for Mobile-Very-small reactor for Local Utility in X-mark. It is a 10-MWth class multi-purpose micro reactor that uses heat-pipes for its primary core cooling and sodium as the working coolant. The heat-pipe provides passive safety features as well as system simplification. MoveluX uses low enriched uranium fuel of less than 4.99 wt% that complies with nuclear security and non-proliferation measures. As a multi-purpose micro reactor, high temperature operation is crucial. To achieve the purpose of minimizing the core size, , calcium-hydride (CaH_2) capable of operating at up to 800ºC is adopted as the moderator material. The MoveluX reactor system is designed with inherent passive safety based on the natural principle, i.e. reactor shut down by moderator material property decay heat removal from the surface of the reactor vessel by natural circulation of air.

Development Milestones

2015	Initiate a fundamental study based on the space reactor design
2017	Decision was made on reactor type
2019	Initiate conceptual design of MoveluX
2025	Complete concept design and component demonstration
2028	Complete reactor system demonstration – without nuclear fuel
2030s	Demonstration of the FOAK-plant of MoveLuX

Design organization or vendor company (**e-mail contact**): rei.kimura@toshiba.co.jp

Links (https://www.toshiba.co.jp/worldwide/index.html) to designer/vendor homepage:

Detailed Design Description: N/A

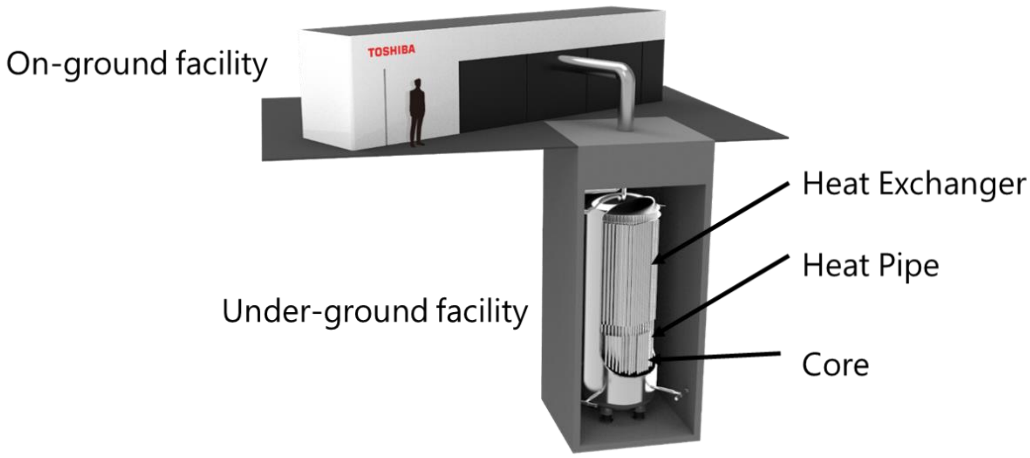

On-ground facility
TOSHIBA
Heat Exchanger
Heat Pipe
Under-ground facility
Core

Table 1: ARIS Category Fields (see also Spreadsheet "Categories") for Booklet

ARIS Category	Input	Select from
Current/Intended Purpose	Commercial – both for Electric and Non-electric	Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Non-electric (process heat, hydrogen)	Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Off-grid/Remote	On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)	Single Unit or more	Single Unit, Dual Unit, Multiple Unit (# units)
Reactor Core Size (1 core)	Small (10 MWth)	Small (<1000 MWth), Medium (1000-3000 MWth), Large (>3000 MWth)
Reactor Type	Other	PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Core Coolant	Na	H_2O, D_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Neutron Moderator	Calcium hydride (CaH_2)	H_2O, D_2O, Graphite, None, (Other-specify)
NSSS Layout		Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Natural	Forced (# pumps), Natural
Thermodynamic Cycle	Brayton	Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid	He or N_2	H_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Prismatic	Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Hexagonal	Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle	n/a	#, n/a
Fuel Material Type	Silicide	Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Conceptual	Conceptual, Detailed, Final (with secure suppliers)
Licensing Status	Not started	DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)

Table 2: ARIS Parameter Fields (see also Spreadsheet "Data") for Booklet

ARIS Parameter	Value	Units or Examples
Plant Infrastructure		
Design Life	10 - 15	years
Lifetime Capacity Factor	90%	%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages		# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources	/	# Staff in Operation / Maintenance Crew during Normal Operation
Reference Site Design		n Units/Modules
Capacity to Electric Grid	3 - 4	MWe (net to grid)
Non-electric Capacity	10	e.g. MWth heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption		MWe
Plant Footprint	100	m^2 (rectangular building envelope)
Site Footprint		m^2 (fenced area)
Emergency Planning Zone	TBD	km (radius)
Releases during Normal Operation	/ /	TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed	- 100	x – 100%, % per minute
Seismic Design (SSE)	0.3	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary/secondary)	0.1/0.3	MPa(abs), i.e. MPa(g)+0.1, at core/secondary outlets
Primary Coolant Inventory (incl. pressurizer)		kg
Nominal Coolant Flow Rate (primary/secondary)	/	kg/s
Core Inlet / Outlet Coolant Temperature	680 / 685	ºC / ºC
Available Temperature as Process Heat Source	680	ºC
NSSS Largest Component	Heat exchanger	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- dimensions	6.0 / 2.5 / TBE (reactor vessel)	m (length) / m (diameter) / kg (transport weight)
Reactor Vessel Material		e.g. SS304, SS316, SA508, 800H, Hastelloy N

ARIS Parameter	Value	Units or Examples
Steam Generator Design		e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow
Secondary Coolant Inventory		kg
Pressurizer Design		e.g. separate vessel, integral, steam or gas pressurized, etc.
Pressurizer Volume	/	m^3 / m^3 (total / liquid)
Containment Type and Total Volume	/	Dry (single/double), Dry/Wet Well, Inerted, etc. / m^3
Spent Fuel Pool Capacity and Total Volume		years of full-power operation / m^3
Fuel/Core		
Single Core Thermal Power	10	MWth
Refuelling Cycle	continuous	months or "continuous"
Fuel Material	U_3Si_2	e.g. UO_2, MOX, UF_4, UCO
Enrichment (avg./max.)	4.8 / 5.0	%
Average Neutron Energy		eV
Fuel Cladding Material	TBD	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel "Units"	177	specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit		kg
Total Fissile Loading (initial)		kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation		applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge		%
Core Discharge Burnup	5	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)		MWd/kgHM
Breeding Ratio		Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing		e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Lithium Expansion Module	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber		e.g. Gd_2O_3,
Core Volume (active)		m^3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary		N/m^2-s

ARIS Parameter	Value	Units or Examples
Max. Fast Neutron Flux		N/m^2-s
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	Active/Passive	/
- core injection	n/a	/
- decay heat removal	Passive	/
- containment isolation and cooling	Passive	/
- emergency AC supply (e.g. diesels)	Not required	/
DC Power Capacity (e.g. batteries)		hours
Events in which ***Immediate Operator Action*** is required		e.g. any internal/external initiating events, none
Limiting (shortest) ***Subsequent Operator Action*** Time	/	hours (that are assumed when following EOPs)
Severe Accident Core Provisions		e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)	To be evaluated	x / reactor-year (based on reference site and location)
Severe Accident Containment Provisions		e.g. H_2 ignitors, PARs, filtered venting, etc.
Large Release Frequency (LRF)		x / reactor-year (based on reference site and location)
Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)		
Construction Time (nth of a kind)		months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort		person-years (PY) [DP&P]
Construction and Commissioning Effort		PY [C&C]
Material and Equipment Overnight Capital Cost		Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C] / %[M&E]	
- Site Development before first concrete	/	(e.g. 25 / 10) (30 / 40) (20 / 25) (20 / 10) (5 / 15) (-----------) (to add up to 100 / 100)
- Nuclear Island (NSSS)	/	
- Conventional Island (Turbine and Cooling)	/	
- Balance of Plant (BOP)	/	
- Commissioning and First Fuel Loading	/	

ARIS Parameter	Value	Units or Examples
Factory / On-Site split in [C&C] effort	/	% / % of total [C&C] effort in PY (e.g. 60 / 40)

1. *Plant Layout, Site Environment and Grid Integration*

SUMMARY FOR BOOKLET

The MoveluX reactor system is designed for a small footprint of two-container size. The final heat-sink is atmospheric air, thus restrictions of site locations can be relaxed compared to that of conventional reactors. MoveluX is a multipurpose energy source that can be used to produce electricity, hydrogen and high temperature heat. Due to its small size, MoveluX can provide process heat to chemical plants and steel mills located in remote places. A MoveluX power plant can generate 3-4 MW(e) base-load electricity in off-grid location in synergy with renewable energy source.

1.1. Site Requirements during Construction

Siting requirements for constructing MoveluX reactor system are not many, because it is designed for small footprint at remote places. In this regard, road accessibility by trailer is one of the few requirements for construction MoveluX, in the current design. The MoveluX reactor system consist of on-the-ground and under-ground facilities as shown in Fig. 1. The on-the-ground facility include power generator and/or other applications (heat utilization, hydrogen production and so on). On the other hand, the under-ground facility contains the reactor primary system (the core, heat-pipe and heat exchanger).

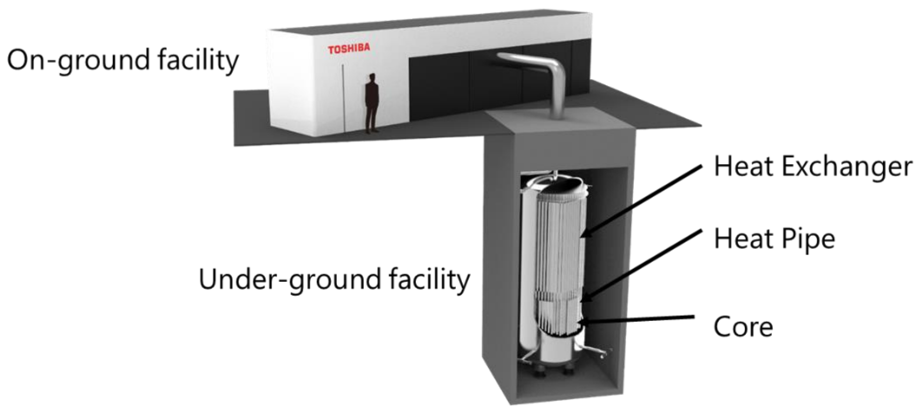


Fig. 1. Schematic view of the MoveluX reactor system

1.2. Site Considerations during Operation

Because the ultimate heat sink is atmospheric air, MoveluX reactor system does not need access to a bulk body of water for operation. The operation of MoveLux reactor system is automatic using passive control devices based on the natural principle, thus minimizes the manpower to operate the reactor. MoveluX has also the option of remote monitoring and operation to reduce engineering and operation cost. The MoveluX reactor system aims to reduce maintenance by simplification of the systems. In particularly for the primary system, the adoption of heat-pipe for primary core cooling, eliminates the need of movable parts. This design simplification enhances also reliability.

In case of emergency, there is no release of radioactive from the reactor vessel, because the decay heat is removed from the surface of reactor vessel by natural circulation of air. This feature may reduce the size of emergency planning zone close to zero if it is addressed in the regulation.

1.3. Grid Integration

The MoveluX reactor system is designed for multi-purpose energy source that include off-grid and micro-grid electricity supply, high temperature heat source, hydrogen production and so forth. This reactor produces 10 MW thermal power and generates 3-4 MWe if it is used for electricity production. In this regard, MoveluX reactor system is suitable for connection with small and micro grids. Load follow operation in a small or micro grid is made possible by passive reactivity control system.

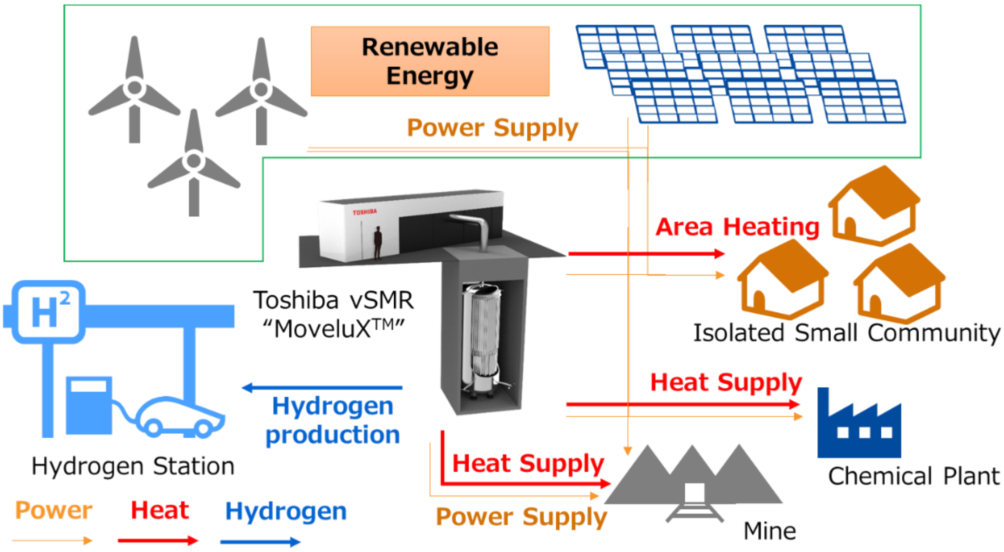


Fig. 2 The MoveluX reactor system for the multi-purpose energy source

Reference

1) R. Kimura, et al, "The Conceptual Design of Heat-Pipe Cooled and Calcium Hydride Moderated vSMR", Proc. ICAPP2019, Juan-les-pins, France, May 12-15, 083, ICAPP2019 (2019)
2) R. Kimura, et al, "Hydride moderated heat-pipe cooled very small modular reactor MoveluX (1): Overview of reactor system and core concept", Proc. AESJ 2019 Annual Meeting, Mito, Japan, Mar. 20-22, 2019, Atomic Energy Society of Japan (2019). [in Japanese]

2. Technical NSSS/Power Conversion System Design

SUMMARY FOR BOOKLET

- Primary Circuit

The primary circuit of the MoveluX reactor system is heat-pipe which is one of passive cooling devices. Therefore, the primary circuit does not have recirculation pump and other forced circuit devices. In the current design, sodium is selected as the working fluid for the heat-pipe considering its high operating temperature and heat transportability.

- Reactor Core and Fuel

The core of MoveluX consist of the fuel, moderator, heat-pipe and control devices. In this core, uranium silicide and calcium-hydride are used as fuel and moderator materials. The maximum fuel enrichment is set as 4.99 wt% to satisfy the economics and non-proliferation objectives. The core reactivity is controlled by passive reactivity control device, such as the Lithium Expansion Module (LEM).

- Fuel Handling
  Fuel components are installed in the core during the fabrication line. Furthermore, this fuel will not be extracted from the core during its lifetime. Hence, fuel handling is not required during operation.
- Reactor Protection
  In the case of emergency, the core is shut down by material property of calcium-hydride as the moderator. The calcium-hydride decomposes in high temperature environment. When the core temperature increases due to abnormal occurrences, the hydrogen in the moderator is released by material property. This hydrogen release adds a negative reactivity to the core. After the core shut down, the decay heat is passively removed from surface of the reactor vessel by natural circulation of the air.
- Secondary Side
  In the current design, helium gas is adopted for the secondary side of the MoveluX reactor system. This He system can provide high temperature around 700°C. Therefore, the secondary side can be used for cogeneration of electric power generation, heat supply and hydrogen.
- Containment/Confinement
  Fuel material is contained in the reactor vessel. The fuel material is separated from primary cooling system by heat-pipe. Therefore, radionuclide is confined in the reactor vessel unless the reactor vessel leaks or breaks. The reactor vessel and fuel components are also protected by inherent passive safety system in the case of emergency.
- Electrical, I&C and Human Interface
  Few I&C devices are installed to the MoveluX reactor system for the reactor start-up, monitoring and active control. Technically, manned operation is not required during nominal operation in current design concept.
- Unique Technical Design Features (if any)
  The heat-exchanger is very important component of the MoveluX reactor system, because, it is strongly required to improve the heat exchange density. To realize this goal, a two-phase micro channel heat-exchanger will be developed. The liquid/vapour sodium flows in the primary side while the helium gas flows in the secondary side. The primary side can use condensed-sodium, thus, the density of heat exchanger can improve.

2.1. Primary Circuit

Figure 3 shows the diagram of MoveluX reactor system. For the primary cooling circuit, MoveluX reactor system adopts heat-pipe, which is a passive cooling device, to eliminate the need of recirculation pump or other forced circuit devices. In the current design, sodium is selected as the working fluid of the heat-pipe considering its high operating temperature and heat transportability.

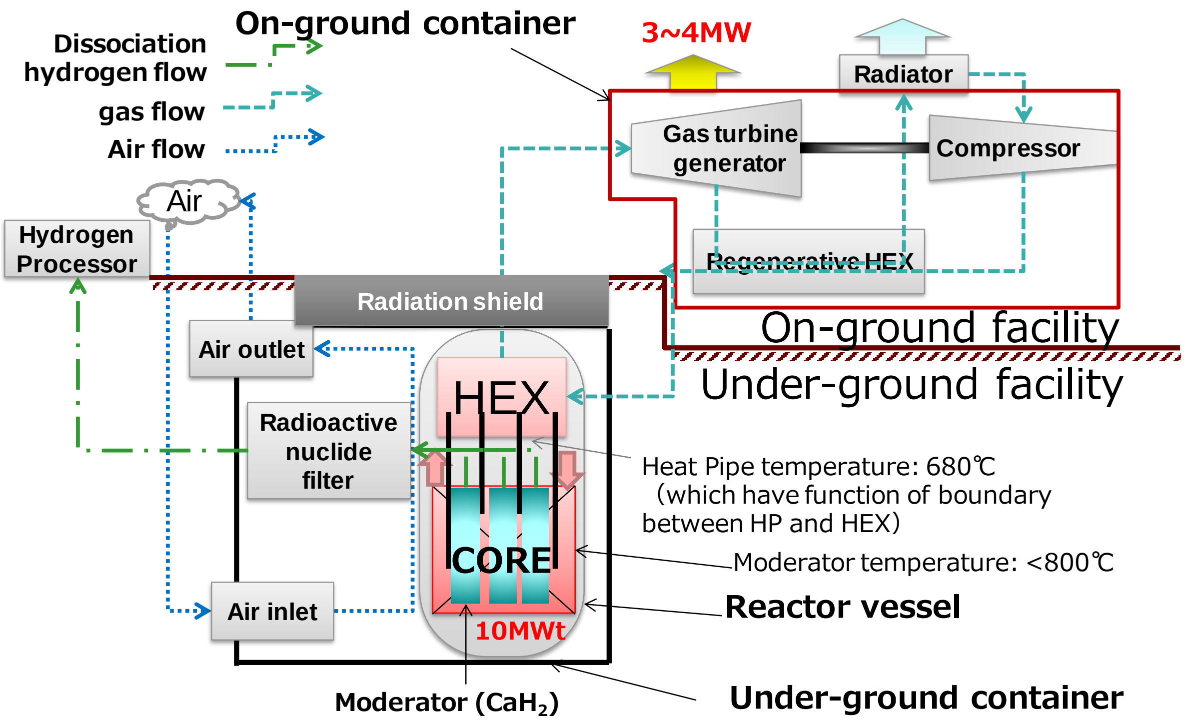


Fig. 3 System diagram of MoveluX reactor system

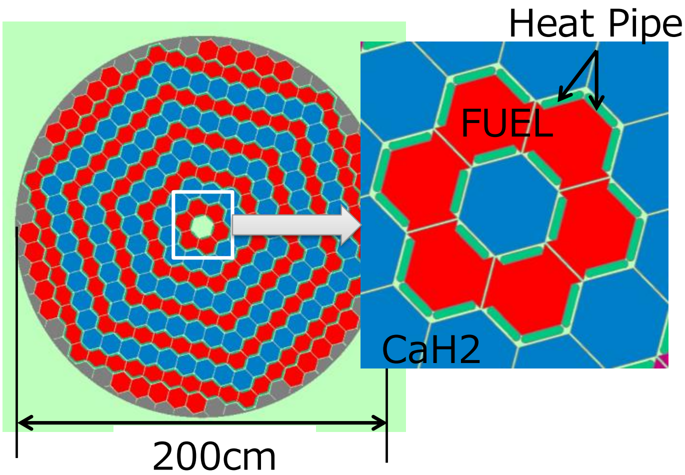
2.2. Reactor Core and Fuel

The MoveluX core consist of fuel, moderator, heat-pipe and control devices. In this core, uranium silicide and calcium-hydride are used as the fuel and moderator materials. The maximum fuel enrichment is set as 5 wt% to assure workable procurement of fuel material. Furthermore, the low enrichment facilitates compliance for nuclear security and non-proliferation measures.

The fuel and moderator has 10 cm wide-hexagonal shape as shown in Fig. 3, however, a side of fuel components is cut off for heat-pipe installation.

A safety-rod is placed at the center of the core for criticality safety and reactor start-up. Reactivity during nominal operation is controlled by passive reactivity control devices, such as the Lithium Expansion Module (LEM) developed by Kambe. This reactivity control device implementation will be examined in 2019.

Additionally, as shown in Fig. 3, the gap between fuel/heat-pipe/moderator exists. This gap is filled by Pb-Sn liquid metal with the purpose to reduce the contact thermal resistance. This liquid metal works as heat transport medium to inner surface of reactor vessel in the case of emergency.



○

○ Fig. 3 Horizontal cross section of MoveluX core

2.3. Fuel Handling

Fuel components are installed into the core during the fabrication phase. Furthermore, this fuel will not be removed from the core during its lifetime. Hence, fuel handling is not required during operation.

2.4. Reactor Protection

In the case of emergency, the core is shut down by material property of calcium-hydride as the moderator. The calcium-hydride decomposes in high temperature environment above 1000^{o}C. Furthermore, hydrogen dissociation will only start at 800^{o}C by building up pressure inside the cladding. When core temperature increases due to heat-pipe fracture, reactivity incident, or other abnormal behaviour, then hydrogen in the moderator is released by material property. This hydrogen release adds a negative reactivity to the core. After the core shut down, the decay heat is passively removed from surface of the reactor vessel by natural circulation of air. The reactor vessel is installed underground for reactor protection and radiation shielding. The radiation shielding on the top of the reactor protects the reactor from external physical attacks. For natural hazards, the MoveluX reactor protects the core by inherent safety based on natural principle.

2.5. Secondary Side

Helium gas is used for the secondary side of MoveluX reactor system. This He gas system provides high temperature around 700^{o}C. With this high temperature, the secondary side is capable to perform cogeneration of electric power, process heat and hydrogen. If the secondary system is used for electricity production, the gas-turbine Brayton cycle is adopted. Atmospheric air is used for the ultimate heat sink. MoveluX reactor system aims to utilize air cooler as radiator. This design approach is intended to alleviate restrictions during siting.

2.6. Containment/Confinement

Fuel material is contained in the reactor vessel. The fuel material is separated from primary cooling system, because, heat-pipe is closed heat transportation device. Additionally, the heat-exchanger between heat-pipe and secondary circuit functions as one of the boundaries. Therefore, radionuclide is confined in the reactor vessel unless the reactor vessel breaks as shown in Fig. 3.

Furthermore, reactor vessel and fuel components are protected by inherent passive safety system in the case of emergency as the decay heat is removed from the surface of reactor vessel. Pressure in the primary system can be set near the atmospheric pressure, because the system does not utilize pump for primary fluid circulation. Therefore, the risk of large emission of radioisotopes can be reduced.

2.7. Electrical, I&C and Human Interface

Few I&C devices are installed to the MoveluX reactor system for the reactor start-up, monitoring and active control. Technically, manned operation is not required during nominal operation in the current design concept due to the adoption passive reactivity control system.

2.8. Unique Technical Design Features (if any)

The heat-exchanger is an important component of the MoveluX reactor system, because, it is strongly required to improve the heat exchange density. To realize this goal, two-phase micro channel heat-exchanger will be developed. The liquid/vapour sodium flows in the primary side, while helium gas flows in the secondary side. The primary side can use a condensed-sodium, thus, heat exchanger density can be improved.

Reference

1) R. Kimura, et al, “The Conceptual Design of Heat-Pipe Cooled and Calcium Hydride Moderated vSMR”, Proc. ICAPP2019, Juan-les-pins, France, May 12-15, 083, ICAPP2019 (2019)
2) R. Kimura, et al, “Hydride moderated heat-pipe cooled very small modular reactor MoveluX (1): Overview of reactor system and core concept”, Proc. AESJ 2019 Annual Meeting, Mito, Japan, Mar. 20-22, 2019, Atomic Energy Society of Japan (2019). [in Japanese]
3) R. Kimura and S. Wada, “Temperature Reactivity Control of Calcium-Hydride-Moderated Small Reactor Core with Poison Nuclides”, Nucl. Sci. and Eng., 193, 1013-1022 (2019)
4) R. KIMURA, et al., “Small CaH2 Moderated Thermal Reactor for Surface Power Generation I: Conceptual Design” Summary. ANS 2016 winter meeting, Las Vegas, NV, Nov. 6-10, American Nuclear Society (2016)
5) S. WADA, et al., “Small CaH2 Moderated Thermal Reactor for Surface Power Generation II: Core Neutronics Design” Summary. ANS 2016 winter meeting, Las Vegas, NV, Nov. 6-10, American Nuclear Society (2016)

3. Technology Maturity/Readiness

SUMMARY FOR BOOKLET

MoveluX is now at the conceptual design stage. Feasibility study of the core is performed in the current work. For designing the core, nuclear data of thermal scattering low (S(α,β)) and material property of calcium-hydride are should be measured. Additionally, sodium boiling and condensation characteristics are required for heat-pipe and heat-exchanger design. The target year of FOAK construction is 2035.

3.1. Deployed Reactors

N/A

3.2. Reactors under Licensing Review

N/A

3.3. Reactors in the Design Stage

3.4. MoveluX is now at the conceptual design stage. Feasibility study of the core is performed in the current work. For designing the core, nuclear data of thermal scattering low (S(α,β)) and material property of calcium-hydride are should be measured. Additionally, sodium boiling and condensation characteristics are required for heat-pipe and heat-exchanger design. The target year of FOAK construction is 2035.

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4. Safety Concept

Passive control is the main approach for the MoveluX reactor safety system. In the case of emergency, the core will be shut down autonomously by material property of calcium-hydride, if safety rod insertion fails. Specifically, calcium-hydride losses neutron moderation power with increasing temperature, because hydrogen dissociates in high temperature environment above 800^{o}C. Therefore, proposed core has inherent safety for criticality in emergency based on the material property.
The decay heat after reactor shut down is removed by passive means. If heat-pipe and secondary circuit perform their function, the decay heat is removed as nominal operation. In the case of loss of cooling capability of heat-pipe, the decay heat is removed from surface of reactor vessel by air natural circulation. Furthermore, in the reactor vessel, the heat is transported from the center to the peripheral of the core by natural circulation and thermal conduction of liquid Pb-Sn in the gap between fuel, heat-pipe and moderator. This decay heat removal system not required a power for system driven, therefore, proposed system can realize infinite grace period. Consequently, risk of core meltdown is expected to be very small value. Additionally, the heat-exchanger between heat-pipe and secondary circuit is functioning as one of the boundaries. Therefore, radionuclide will be confined in the reactor vessel.

SUMMARY FOR BOOKLET

4.1. Safety Philosophy and Implementation

Passive control is the main approach for the MoveluX reactor safety system. Fig. 4 shows the passive safety systems of the MoveluX. In the case of emergency such as loss of cooling ability and/or reactivity insertion accident (RIA), the core will shut down autonomously by material property of calcium-hydride if safety rod insertion fails. Specifically, calcium-hydride loss neutron moderation power with increasing temperature because hydrogen dissociates in high temperature environment above 800 ^{o}C. Therefore, proposed core has inherent safety for criticality in emergency based on the material property. If hydrogen pressure increases due to dissociation, hydrogen will be processed at the hydrogen processor. However, this issue will be further examined.

The decay heat after reactor shut down is removed passively. If heat-pipe and secondary circuit performs their intended function, decay heat is removed as the nominal operation. In the case of loss of cooling ability of heat-pipe, the decay heat is removed from surface of reactor vessel by natural circulation of air. Furthermore, in the reactor vessel, the heat is transported from the center to peripheral of the core by natural circulation and thermal conduction of liquid Pb-Sn in the gap between fuel, heat-pipe and moderator. This decay heat removal system not required a power for system driven, therefore, proposed system can realize infinite grace period. Consequently, risk of core meltdown is expected to be very small.

Additionally, the heat-exchanger between heat-pipe and secondary circuit is functioning as one of the boundaries. Therefore, radionuclide will be confined in the reactor vessel.

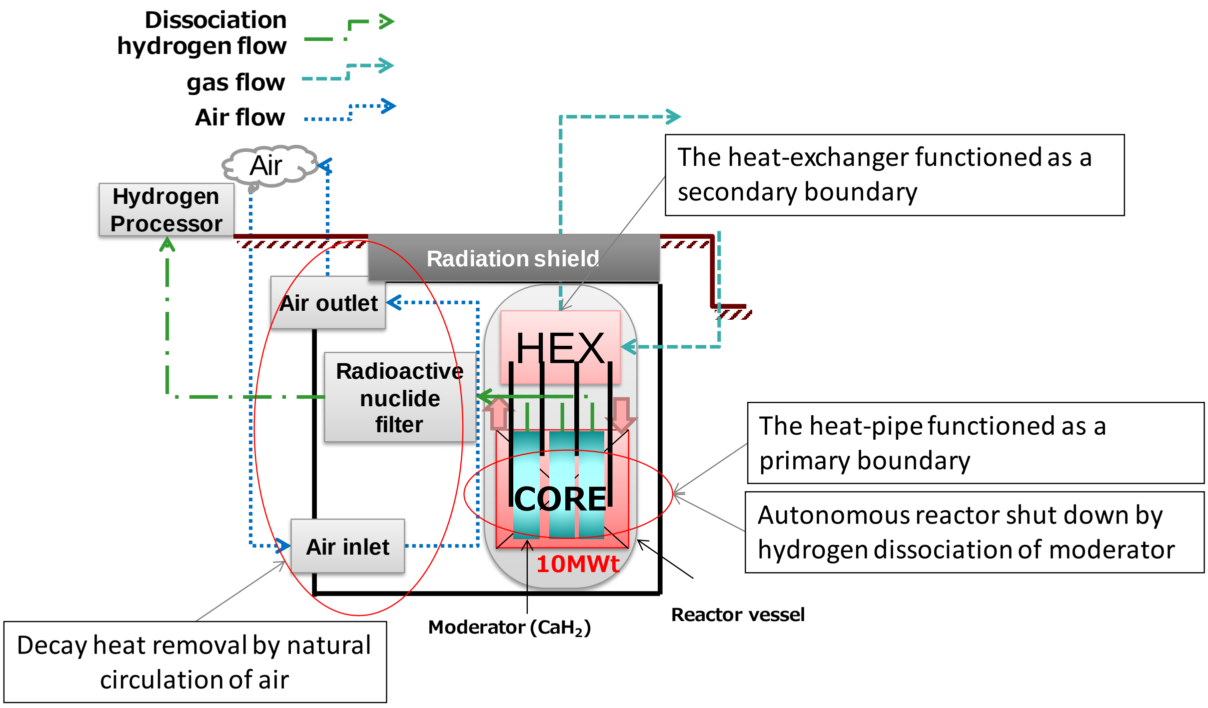

Fig. 4 Passive safety systems of the MoveluX

4.2. Transient/Accident Behaviour

The loss of cooling ability and/or the RIA can be assumed as transient/accident mode. When the core temperature increases, the moderator (CaH_2) temperature also increases. Hydrogen in the moderator will begin to dissociate when the temperature reaches 800°C. Above this temperature, the CaH_2 is losing its moderating ability due to the hydrogen dissociation. Consequently, the core autonomously shutdowns due to the material property of the moderator.

The decay heat after reactor shut down is removed passively. If heat-pipe and secondary circuit can keep their intended functions, the decay heat is removed in the same way as that in nominal operation. In the case of loss of cooling ability of heat-pipe, the decay heat is removed from the surface of reactor vessel by natural circulation of air.

Reference

1) R. Kimura, et al, “The Conceptual Design of Heat-Pipe Cooled and Calcium Hydride Moderated vSMR”, Proc. ICAPP2019, Juan-les-pins, France, May 12-15, 083, ICAPP2019 (2019)

5. *Fuel and Fuel Cycle*

SUMMARY FOR BOOKLET (optional)

The MoveluX reactor can adopt either once-through fuel cycle scheme or closed fuel cycle scheme. It mainly depends on user country's fuel cycle policy. In the case of once-through fuel cycle scheme, spent fuel is cooled in the reactor vessel for one year and temporary stored. Then, it is eventually shipped to a permanent repository. In the case of closed fuel cycle scheme, spent fuel can be economically reprocessed and is re-fabricated as fresh fuel for recycling use in LWR or FR.

5.1. Fuel Cycle Options

The MoveluX reactor can adopt either once-through or closed fuel cycle scheme. In both schemes, reactor vessel contains the spent fuels. These spent fuels will be stored together with reactor vessel in a temporary storage site. After that, treatment of the spent fuel depends on the country's fuel cycle policy. In the once-through scheme, spent fuel is extracted from the core at the facility, then, spent fuel is stored to the cask for disposal. In the closed fuel cycle scheme, spent fuel is re-processed and re-fabricated as fresh MOX fuel for recycling use in LWR or FR.

5.2. Resource Use Optimization

The major provisions of the MoveluX reactor for resource use optimization are as follows.

- Simplified plant design contributes to wastes reduction during operation and decommissioning.
- Low maintenance requirement by using no-moving parts component that contributes also to low maintenance costs/labours and low waste amount.
- Reduced size of emergency planning zone contributes to reduced burden in accident management and/or cost such as for evacuation.

6. *Safeguards and Physical Security*

SUMMARY FOR BOOKLET (optional)

The containment confirmation of SNM is realized by reactor vessel seal after fabrication. Fuel of the MoveluX reactor is installed in fabrication phase, besides, this fuel is not removed from the reactor vessel during the lifetime of the reactor. Therefore, containment of SNM can be confirmed. In addition, new on-line validation technique for distributed vSMR in remote places such as muon tomography is required. To satisfy nuclear security, the MoveluX reactor system utilizes low enriched uranium of less than 4.99 wt% to reduce the attractiveness of SNM. Additionally, packaged core in the reactor vessel and radiation shield provide an ability of physical protection.

6.1. Safeguards

Fuel of the MovleuX reactor is installed during fabrication phase. Furthermore, this fuel is not extracted during lifetime of the reactor. Thus, as long as the reactor vessel seal is intact, containment integrity is assured from the viewpoint of safeguards.

In addition, validation of special nuclear materials (SNM) is important for distributed small modular reactor such as very small modular reactor (vSMR), because, SNM will be distributed to remote places by micro reactor installing. In those places, the cost of inspection is expensive, therefore, on-line validation technique is required such as muon tomography.

6.2. Security

Nuclear security is one of the important issues in deployment of distributed very-small SMR. To comply with nuclear security measures, the MoveluX core utilizes low enriched uranium of less than 5 wt%.

The distributed vSMR is designed to be transportable from the fabrication facility to the construction and installation in remote places. During transportation, SNM has high attractiveness due to its low radioactivity. On the other hand, distributed vSMR in remote places require long response time of security forces by distance from the base. Hence, risk of theft of SNM may arise in both phases. Due to these considerations, the MoveluX core applies minimized enrichment level possible to minimize attractiveness.

Moreover, the packaged core in the reactor vessel aims to better ensure physical protection. The MoveluX reactor system does not have spent fuel pool at the site. Thus, all of the SNM is contained in the reactor vessel. Demolition of the reactor vessel is required for theft of SNM to occur. However, before the reactor vessel can be demolished, the heavy radiation shielding above of the reactor vessel should first be removed.

The internal and external threats such as terrorist attacks would need too much time for these process, thereby, security forces can secure enough time to response.

Reference

1) Haruo Miyadera; Konstantin N. Borozdin; Steve J. Greene; Zarija Lukić2; Koji Masuda; Edward C. Milner; Christopher L. Morris; John O. Perry (2013). "Imaging Fukushima Daiichi reactors with muons". *AIP Advances*. 3 (5): 052133

7. *Project Delivery and Economics*

SUMMARY FOR BOOKLET (optional)

To be a viable option for power generation in remote areas, the MoveluX is designed to offer a competitive cost of electric power. The target plant construction cost is $4,000/kWe. The target construction cost will be achieved by design simplification, standardization, shop fabrication, modular construction to enable short construction time, and mass production.

7.1. Project Preparation and Negotiation

To be a viable option for power generation in remote areas, the MoveluX is designed to offer a competitive cost of electric power. The target plant construction cost is $4,000/kWe. The target construction cost will be achieved by design simplification, standardization, shop fabrication, modular construction to enable short construction time, and mass production..