

小型モジュール炉(SMR)研究開発の概要

概要 / 目的:

原子力発電は、低出力で小型の原型炉・試験炉から始まりましたが、ニーズの高まり、規模の経済、立地可能なサイトの制限により、比較的早い段階から、発電方式は大型炉による発電に代わりました。しかしここ数年は、小型モジュール炉(SMR)への関心が高まっており、50以上の概念が現在検討されています。IAEAでは、個々のモジュールの出力が300MWeまでの先進炉をSMRと定義しています。モジュールは工場で製造でき、プラントサイトに輸送、設置されますが、必要に応じて追加することができます。またSMRは先進技術の全て(水冷却、第4世代システム、超小型炉等)と関連付けられ、**受動安全機能の強化、シンプルな設計及び運転、大量生産による経済性、ハイブリッドシステム及び非電気利用に対する柔軟性も兼ね備えています**。このウェビナーでは、SMRの魅力、課題、開発状況、今後の展開に焦点を当て、紹介します。

講演者紹介:

Mr. Frederik Reitsmaは、ウィーンにある国際原子力機関(IAEA)の原子力技術開発部門(NP)で**SMRのチームリーダー**を務めている。約7年前にIAEAに入局し、この分野のプロジェクトの管理、調整、監督を行っている。加盟国と協力して**将来の主要なトレンドと技術開発のニーズを特定**し、技術的およびプログラムのリーダーシップをとっている。また、以前は、高温ガス冷却炉プロジェクトの責任者を務めていた。多くの技術論文(90以上)を発表し、国際ワークショップや国際会議にスピーカーとして招聘されるほか、国際協力プロジェクト



(OECD/NEAやGIFなど)をリードしてきました。原子炉物理学者でもあり、SMRおよび高温ガス炉の核工学と解析に豊富な経験を持ち、炉心の中性子工学設計と安全性の専門家です。南アフリカのPBMRプロジェクトでは、13年間にわたってさまざまな指導的立場にあり、キャリアの最初の10年間は、OSCARの原子炉計算システムの開発に貢献してきました。

SMRは、導入に伴う経済性、モジュール構造、プラント展開の柔軟性、再生可能エネルギーとの相性などの観点から関心を集めている。

Small Modular Reactors (What is it?)

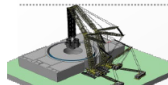
Advanced NPP that produces up to 300 MW(e). Individual modules built in factories and transported to sites for installation as demand arises.

A nuclear option to meet the need for flexible power generation for a wide range of users and applications



Economic

- Lower Upfront capital cost
- Economy of serial production



Modularization

- Multi-module
- Modular Construction



Flexible Application

- Remote regions
- Small grids



Smaller footprint

- Reduced Emergency planning zone



Replacement for aging fossil-fired plants



Potential Hybrid Energy System

Better Affordability

Shorter construction time

Wider range of Users

Site flexibility

Reduced CO₂ production

Integration with Renewables

SMR Designs around the World

Land Based Water Cooled Reactors				Micro Reactors		Fast Reactors		
CAREM	SMART	RUTA-70	DHR400	IHTR	MMR-5	4S	W-LFR	SSTAR LFR
ACP100	UNITHERM	NuScale	RITM-200	IMSBR	MMR-10	BREST-OD-300	SEALER	URANUS
CAP200	VK-300	mPOWER	NUWARD	eVinci	AURORA	SVBR-100	LFR-AS-200	ARC100
IRIS	KARAT-45	W-SMR	BWRX-300	U-Battery	MoveLuX	EM ²	LFR-TL-X	
DMS	KARAT-100	SMR-160	HAPPY200					
IMR	ELENA	UK-SMR	CANDU SMR					

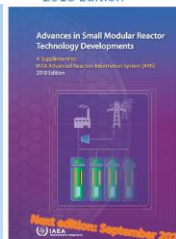
High Temperature Gas-cooled Reactors				Marine Based Water Cooled Reactors		Molten Salt Reactor		
HTR-PM	MHR-100	XE-100	HTTR-30	ACPR50S	VBER-300	IMSR	SSR-WB	CA WB
DPP-200	PBMR-400	A-HTR 100	HTR-10	KLT-40S	ABV-6E	CMSR	SSR-TS	KP-FHR
GT-MHR	HTMR-100	MMR	RDE	RITM-200M	SHELF	THORCON	LFTR REACTOR	MCSFR
MHR-T	SC-HTGR	GTHTR300	StarCore			FUJI ITMSF	MK1 PB-FHR	

IAEAはすでにSMRブックレットを発行しており、ARISデータベースにはSMRのコンセプトが含まれている。

IAEA SMR Booklet

The booklet contains information provided by vendors and designers on their SMRs

2018 Edition



- SMRs are categorized in types based on coolant type/neutron spectrum:
 - Land Based WCRs
 - Marine Based WCRs
 - HTGRs
 - Fast Reactors
 - MSRs
 - Micro reactors
 - Test reactors (to be included with the types above as applicable)

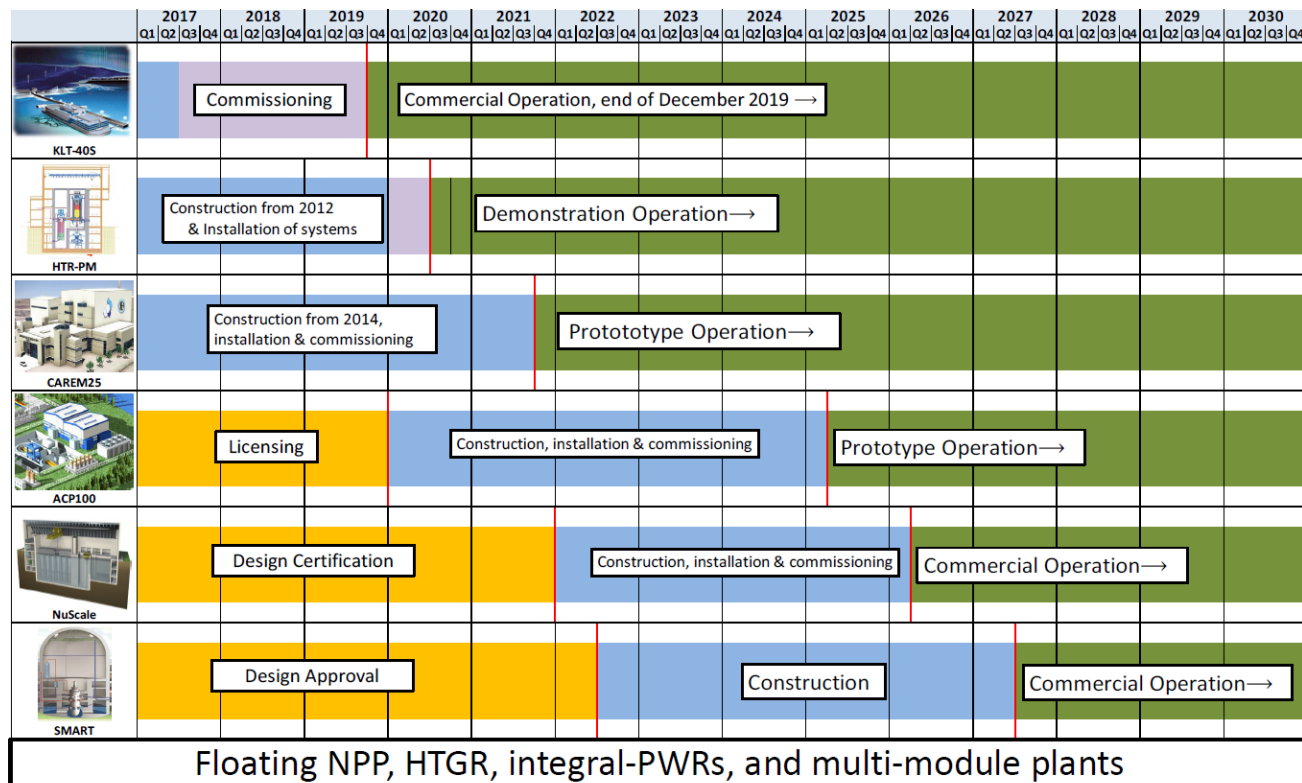
- Design description and main features of ~70 SMR designs being updated (56 in 2018)
- Include information on fuel cycle, decommissioning and final disposal (for the first time)

IAEA ARIS Database Includes SMR Designs



SMRの開発段階は、既にライセンス段階から建設段階へ進んでいる。

Status of Deployment Timeline as of Spring 2020



Land-based SMRs (Examples)

CAREM	ACP100	NUWARD
		
Design Status: Advanced stage of construction in Atucha site, Argentina <ul style="list-style-type: none"> CNEA, Argentina Integral-PWR 	Design Status: Detailed design; received license for construction in July 2019 <ul style="list-style-type: none"> CNNC, China Integral-PWR 	Design Status: Conceptual design; Consortium launched in September 2019 <ul style="list-style-type: none"> EDF led consortium, France Integral-PWR

Marine-based SMRs (Examples)

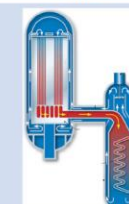

On-Shore Deployment		Off-Shore Deployment	
KLT-40S	RITM-200M	ACPR-50S	SHELF
			
Design Status: Full Commercial Operation since May 2010 in the Akhenskoye community <ul style="list-style-type: none"> 30 MWt / 3.4 MWe Core Outlet Temp: 318°C Enrichment: 19.7% Refuel interval: 120 months Whole core refuelling 	Design Status: 6 prototype reactors were manufactured and installed on land-based test loops, 4 are in the process <ul style="list-style-type: none"> 30 MWt / 3.4 MWe Core Outlet Temp: 318°C Enrichment: 19.7% Refuel interval: 30 months Whole core refuelling 	Design Status: Completion of conceptual / program design, preparation of project design. <ul style="list-style-type: none"> CGNPC, China Integral-PWR 200 MWt / 50 MWe per module Core Outlet Temp: 321.8°C Enrichment: 19.7% Refuel interval: 30 months Whole core refuelling 	Design Status: Detailed design underway <ul style="list-style-type: none"> NIKIET, Russian Federation Integral-PWR 28.4 MWt / 6.6 MWe per module Core Outlet Temp: 310°C Enrichment: 19.7% Refuel interval: 6 years (8 for SHELF-M) on-site refuelling fuel take back

Liquid Metal, Fast-Neutron-Spectrum SMRs (Examples)

4S

Design Status: Detailed design <ul style="list-style-type: none"> Toshiba, Japan Liquid metal cooled fast reactor (pool type) 30 MWt / 10 MWe Forced Circulation Core Outlet Temp: 510°C Enrichment: <20% Refuel interval: N/A

HTGR-type SMRs (Examples)

HTR-PM	SC-HTGR	GTHTR
		
Design Status: Finalizing construction in Shidao Bay for operation by 2021 <ul style="list-style-type: none"> INET Tsinghua University, China Modular pebble-bed HTGR 250 MWt / 210 MWe x 2 	Design Status: Conceptual Design <ul style="list-style-type: none"> Framatome Inc., United States, France Prismatic-bloc HTGR 625 MWt / 272 MWe per module 	Design Status: Pre-Licensing; Basic Design Comp <ul style="list-style-type: none"> JAEA, Japan Prismatic-bloc HTGR 600 MWt / 100 MWe Core Outlet Temp: 850°C

Microreactors (Examples)

ModularX	MMR	eVinci
		
Design Status: Conceptual design <ul style="list-style-type: none"> Toshiba, Japan Fast Reactor 30 MWt / 3.4 MWe Natural circulation Core Outlet Temp: 480-680°C Enrichment: <4.8-5% Refuel interval: Continuous 	Design Status: Preliminary Design, under vendor design review with the Canadian CNEC <ul style="list-style-type: none"> USNC, USA HTGR / micro reactor / nuclear battery 15 MWt / 5 MWe Core Outlet Temp: 600°C Enrichment: <1.2% Refuel interval: N/A 	Design Status: Conceptual Design <ul style="list-style-type: none"> Westinghouse, United States of America Heat Pipe cooled 7.2 MWt / 2.3 MWe per module Core Outlet Temp: 800°C Enrichment: 5-10.7% Refuel interval: 36 months

水冷式だけでなく、液体金属、ガス、溶融塩冷却方式、そして海洋型からマイクロリアクターまで、100近いコンセプトが提案されている。

SMRの設計上の特徴は、モジュール構造、サイト条件との適合性(柔軟性)、物理的セキュリティの確保方法、防護区域(EPZ)であり、それらの特徴の紹介がなされている。また、グレーデッドアプローチ(等級別アプローチ)の適用が想定されている。

SMR Site Specific Considerations

- SMRs promise much smaller sites
 - EPZ can possibly be reduced
 - Located close to population centers / end users
 - Located next to heat users / industries
- The first SMRs currently built / to be deployed has selected existing NPP / nuclear sites (HTR-PM, CAREM, NuScale plan)
- Important factor is physical security (smaller site and close proximity of other buildings / industries will present new challenges)



The HTR-PM - (Two-reactor unit) = 210MWe

The Vogtle 3 and 4 Nuclear power plant USA - 2 units = 2220 MWe

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Progress made in applying a graded approach

- Nuclear Regulatory Commission staff agreed with the Tennessee Valley Authority that scalable emergency planning zones (EPZs) for small modular reactors are feasible

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US regulators discuss smaller SMR emergency zones

28 August 2018

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CLARIFICATION: NRC staff have concluded the TVA methodology can be used in the future to determine if a reduced emergency planning zones is justified, and has not made a decision on EPZ criteria for small modular reactors.

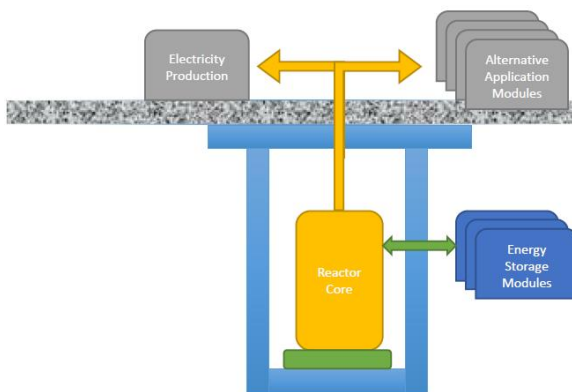
The US Nuclear Regulatory Commission (NRC) has concluded that Tennessee Valley Authority's (TVA's) methodology can be used in the future to determine if a reduced emergency planning zone is justified for small modular reactors, a spokesman for the Commission told *World Nuclear News* today. It has not yet agreed that an EPZ around small modular reactors can be scaled to reflect their reduced risks rather than the mandatory ten-mile EPZ required for the USA's current light-water reactor fleet.



SMRと再エネの相性は良好であるため、コージェネレーションを含むハイブリッド概念に注目が集まっている。

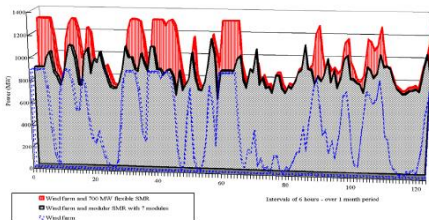
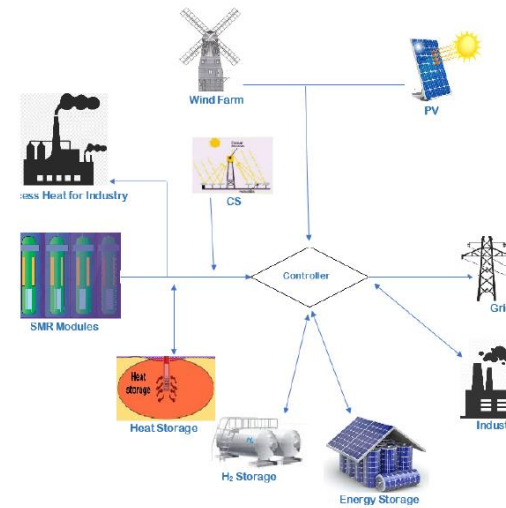
Role of SMRs in Climate Change

SMR Renewables Hybrid Energy System to Reduce GHG Emission



Modules:

- Electricity production
- Process heat
 - Petro-chemical industry
 - Desalination plant
 - Oil and gas reforming
 - Hydrogen production
 - Ammonia production
 - District heating / cooling
 - Waste reforming
- Energy storage
- Load follow capabilities
 - Switch between applications



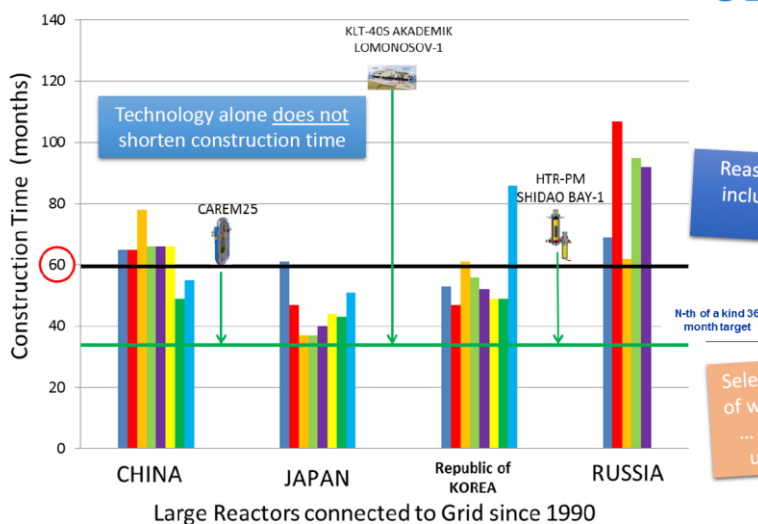
Example of load follow with renewables

TECDOC:

Options to Enhance Energy Supply Security using Hybrid Energy Systems based on SMR; being finalised in 2020

Capital costs for SMRs

Key Topics	Prospects	Impediments
Capital component of levelized cost of power	Potential decrease in case of large scale and serial production	Require large initial order (e.g. 50 – 80 modules)
Comparison of material quantities	Design saving	Standardization of new structure, system, components and materials
Impact of local labour and productivity	<ul style="list-style-type: none"> Reduced construction time for proven design Lesser work force required with modular construction (case by case) 	FOAK deployment of multi-module plant with modular construction technology <u>versus</u> stick-build
Cost of licensing	Based on LWRs technology - easier licensing, but still could take long in established nuclear regulators	First of a kind; Time required for modifying the existing regulatory and legal frameworks
Ensuring all necessary equipment is included in the cost estimate, e.g. there is no 'missing equipment'	<u>Learning curve</u> : the higher the number of SMR built on the same site is, the better the cost effectiveness of construction activities on site	Cost impact by delayed component delivery or defect during shipping
Assurance of reliable estimates of technology holder equipment prices	Similar among vendors	Manufacturing of FOAK components



costs?
(NOAK)
?

We will only know after we build and operate SMRs

これまで経済性評価に影響を及ぼす因子の摘出が行われ、多くの経済性に関する議論が行われている。
ただし、モジュール化の効果については、不確定要素が多く、建設されるまで、その評価は定まらないであろう。

課題と挑戦:

多くのチャレンジすべき課題はあるものの、メリットも多く指摘されており、そのため開発対象として着目されている。

Key Barriers/Challenges to Deployment

- Limited ***near-term commercial availability***
- Technology developers ability to secure investors for design development and deployment: *first domestically, then international markets*
 - *may be an opportunity to cooperate*
- **Economic** competitiveness
 - Need economy of numbers (vs economy of scale) ...
- Regulatory, licensing and **safety issues**.
 - *FOAK, passive features, integrated designs, different technologies*
- Technology Maturity
 - Water cooled SMRs (iPWR and BWRs) based on mature technology
 - HTGR mature technology (with steam generator and Tout < 850 °C)
 - MSR has limited operation experience –some challenges to be solved

NEED GOVERNMENT COMMITMENT TO REALIZE
DEMONSTRATIONS PROJECTS!

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Advantages, Issues & Challenges



Technology aspects

- Shorter construction period (modularization)
- Potential for enhanced safety and reliability
- Design simplicity
- Suitability for non-electric application (desalination, etc.).
- Replacement for aging fossil plants, reducing GHG emissions

Non-Techno aspects

- Fitness for smaller electricity grids
- Options to match demand growth by incremental capacity increase
- Site flexibility
- Reduced emergency planning zone
- Lower upfront capital cost (better affordability)
- Easier financing scheme



Technology issues

- Licensing of FOAK designs, particularly non-LWR technologies
- Prove of operability and maintainability
- Staffing for multi-module plant;
- Supply Chain for multi-modules
- Optimum plant/module size
- Advanced R&D needs

Non-technology issues

- Time from design-to-deployment
- Highly competitive budget source for design development
- Economic competitiveness: affordability & generation cost
- Availability of *off-the-shelf* design for newcomers
- Operating scheme in an integration with renewables