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Present Situation of Small Modular Reactors


Advances in Small Modular Reactor Technology Developments
A Supplement to:
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International Atomic Energy Agency

CURRENT SMRs PROJECTS

- SMRs are newer generation reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises;
- deployable either as a single or multimodule plant;
- reactor lines: water cooled reactors, high temperature gas cooled reactors, liquid-metal, sodium and gas-cooled reactors with fast neutron spectrum, and molten salt reactors;
- the need for flexible power generation;
- envisioned for niche electricity or energy markets where large reactors would not be viable. SMRs could fulfil the need of flexible power generation for a wider range of users and applications, including replacing aging fossil power plants;

CURRENT SMRs PROJECTS

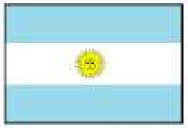
- Though significant advancements have been made in various SMR technologies in recent years, some technical issues still attract considerable attention in the industry. These include for example control room staffing and human factor engineering for multi-module SMR plants, defining the source term for multimodule SMR plants with regards to determining the emergency planning zone, developing new codes and standards, and load-following operability aspects;
- Some potential advantages of SMRs like the elimination of public evacuation during an accident or a single operator for multiple modules are under discussion with regulators. Furthermore, although SMRs have lower upfront capital cost per unit, <u>their generating cost of electricity will probably be substantially higher than that for large reactors</u>.
- Currently there are more than 50 SMR designs under development for different application. Three industrial demonstration SMRs are in advanced stage of construction: in Argentina (CAREM, an integral PWR), in People's Republic of China (HTR-PM, a high temperature gas cooled reactor) and in the Russian Federation (KLT40s, a floating power unit). They are scheduled to start operation between 2019 and 2022. In addition, the Russian Federation have already manufactured six RITM-200 reactors (an integral PWR) with four units already installed in the Sibir and Arktika icebreakers, to be in service in 2020.
- arranged in the order of the different types of coolants, the neutron spectrum adopted, and a sixth part (a new category) on other SMRs that do not make use of the traditional coolants and/or fuel design.

Design	Output MW(e)	Type	Designers	Country	Status
PART 1: WATER COOLED SMALL MODULAR REACTORS (LAND BASED)					
CAREM	30	PWR	CNEA	Argentina	Under construction
ACP100	100	PWR	CNNC	China	Basic Design
CAP200	150/200	PWR	CGNPC	China	Conceptual Design
DHR400	(District Heating)	LWR(pool type)	CNNC	China	Basic Design
IRIS	335	PWR	IRIS Consortium	Multiple Countries	Conceptual Design
DMS	300	BWR	Hitachi GE	Japan	Basic Design
IMR	350	PWR	MHI	Japan	Conceptual Design
SMART	100	PWR	KAERI	Republic of Korea	Certified Design
ELENA	68 kW(e)	PWR	National Research Centre "Kurchatov Institute"	Russian Federation	Conceptual Design
KARAT-45/100	45/100	BWR	NIKIET	Russian Federation	Conceptual Design
RITM-200	50 × 2	PWR	OKBM Afrikantov	Russian Federation	Under Development
RUTA-70	70 MW(t)	PWR	NIKIET	Russian Federation	Conceptual Design
UNITHERM	6.6	PWR	NIKIET	Russian Federation	Conceptual Design
VK-300	250	BWR	NIKIET	Russian Federation	Detailed Design
UK-SMR	443	PWR	Rolls-Royce and Partners	United Kingdom	Mature Concept
mPower	195 × 2	PWR	BWX Technologies	United States of America	Under Development
NuScale	50 × 12	PWR	NuScale Power	United States of America	Under Development
SMR-160	160	PWR	Holtec International	United States of America	Preliminary Design
W-SMR	225	PWR	Westinghouse	United States of America	Conceptual Design

Design	Output MW(e)	Type	Designers	Country	Status
PART 2: WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)					
ACPR50S	60	PWR	CGNPC	China	Preliminary Design
ABV-6E	6-9	Floating PWR	OKBM Afrikantov	Russian Federation	Final design
KLT-40S	70	Floating PWR	OKBM Afrikantov	Russian Federation	Under construction
RITM-200M	50 × 2	Floating PWR	OKBM Afrikantov	Russian Federation	Under Development
SHELF	6.4	Immersed NPP	NIKIET	Russian Federation	Detailed Design
VBER-300	325	Floating NPP	OKBM Afrikantov	Russian Federation	Licensing Stage
PART 3: HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under Construction
GTHTR300	300	HTGR	JAEA	Japan	Basic Design
GT-MHR	285	HTGR	OKBM Afrikantov	Russian Federation	Preliminary Design
MHR-T	205.5x4	HTGR	OKBM Afrikantov	Russian Federation	Conceptual Design
MHR-100	25 – 87	HTGR	OKBM Afrikantov	Russian Federation	Conceptual Design
A-HTR-100	50	HTGR	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design
HTMR-100	35	HTGR	Steenkampskraal Thorium Limited	South Africa	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design
SC-HTGR	272	HTGR	AREVA	United States of America	Conceptual Design
Xe-100	35	HTGR	X-energy LLC	United States of America	Conceptual Design

Design	Output MW(e)	Type	Designers	Country	Status
PART 4: FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
LFR-AS-200	200	LMFR	Hydromine Nuclear Energy	Luxembourg	Preliminary Design
LFR-TL-X	5~20	LMFR	Hydromine Nuclear Energy	Luxembourg	Conceptual Design
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
SVBR-100	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
SEALER	3	Small Lead Cooled	LeadCold	Sweden	Conceptual Design
EM²	265	GMFR	General Atomics	United States of America	Conceptual Design
SUPERSTAR	120	LMFR	Argonne National Laboratory	United States of America	Conceptual Design
WLFR	450	LFR	Westinghouse	United States of America	Conceptual Design
PART 5: MOLTEN SALT SMALL MODULAR REACTORS					
IMSR	190	MSR	Terrestrial Energy	Canada	Basic Design
CMSR	100-115	MSR	Seaborg Technologies	Denmark	Conceptual Design
CA Waste Burner	20	MSR	Copenhagen Atomics	Denmark	Conceptual Design
ThorCon	250	MSR	Martingale	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: ITMSF	Japan	Experimental Phase
Stable Salt Reactor	37.5×8	MSR	Moltex Energy	United Kingdom	Conceptual Design
Stable Salt Reactor	300~900	MSR	Moltex Energy	United Kingdom	Pre-Conceptual Design
LFTR	250	MSR	Flibe Energy	United States of America	Conceptual Design
MkI PB-FHR	100	MSR	University of California, Berkeley	United States of America	Pre-Conceptual Design
MCSFR	50	MSR	Elysium Industries	USA and Canada	Conceptual Design
PART 6: OTHER SMALL MODULAR REACTORS					
eVinci	0.2~15	Small Heat Pipe	Westinghouse	United States of America	Under Development

CAREM (CNEA, Argentina)



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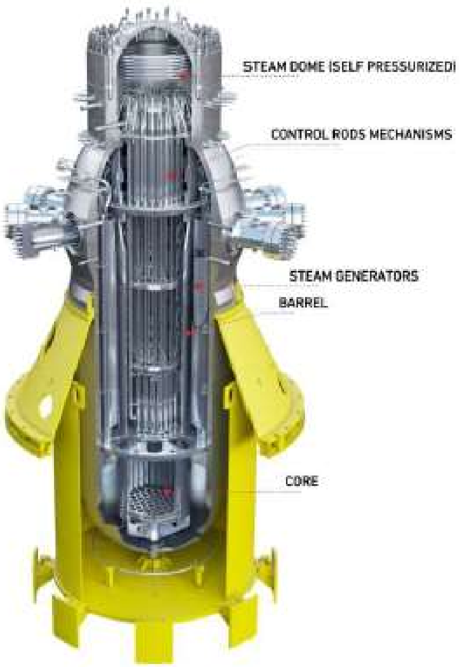
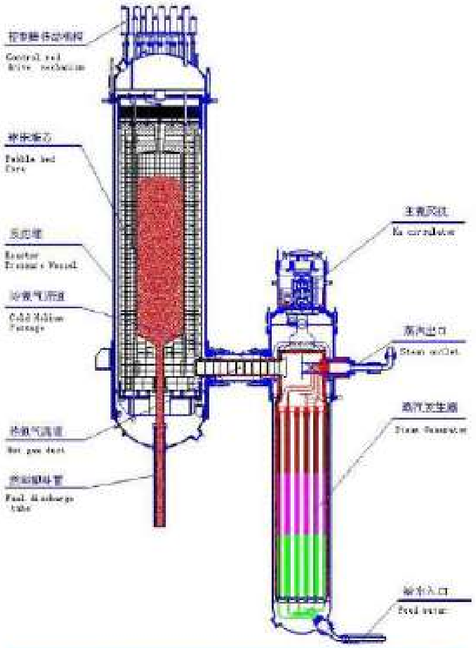


MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	CNEA, Argentina
Reactor type	Integral PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	100/~30
Primary circulation	Natural circulation
System pressure (MPa)	12.25
Core inlet/exit temperatures (°C)	284/326
Fuel type/assembly array	UO_2 pellet/hexagonal
Number of fuel assemblies	61
Fuel enrichment (%)	3.1% (prototype)
Fuel burnup (GWd/ton)	24 (prototype)
Fuel cycle (months)	14 (prototype)
Main reactivity control mechanism	Control rod driving mechanism (CRDM) only
Approach to engineered safety systems	Passive
Design life (years)	40
Plant footprint (m^2)	Not available
RPV height/diameter (m)	11/3.2
RPV, internals and SGs weight (metric ton)	267
Seismic design	0.25
Distinguishing features	Core heat removal by natural circulation, pressure suppression containment
Design status	Under construction (as prototype)

1984	CAREM concept was presented in Lima, Peru, during the IAEA Conference on SMRs and was one of the first of the new generation reactor designs. CNEA officially launched the CAREM project
2001-02	The design was evaluated on generation IV international forum and was selected in the near-term development group
2006	Argentina Nuclear Reactivation Plan listed the CAREM-25 project among priorities of national nuclear development
2009	CNEA submitted its preliminary safety analysis report (PSAR) for CAREM-25 to the ARN. Announcement was made that Formosa province was selected to host the CAREM
2011	Start-up of a high pressure and high temperature loop for testing the innovative hydraulic control rod drive mechanism (CAREM)
2011	Site excavation work began and contracts and agreements between stakeholders are under discussion
2012	Civil engineering works
2014	8 February, formal start of construction
2022	First criticality

HTR-PM (Tsinghua University, China)



MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	INET Tsinghua University, People's Republic of China
Reactor type	Modular pebble bed high temperature gas-cooled reactor
Coolant/moderator	Helium/graphite
Thermal/electrical capacity, MW(t)/MW(e)	2x250/210
Primary circulation	Forced circulation
System pressure (MPa)	7
Core inlet/exit temperatures (°C)	250/750
Fuel type/assembly array	Spherical elements with coated particle fuel
Number of fuel spheres	420,000 (in each reactor module)
Fuel enrichment (%)	8.5
Fuel burnup (GWd/ton)	90
Fuel cycle (months)	On-line refueling
Main reactivity control mechanism	Control rod insertion
Approach to engineered safety systems	Combined active and passive
Design life (years)	40
Plant footprint (m^2)	--
RPV height/diameter (m)	25/5.7(inner)
Seismic design	0.2 (g)
Distinguishing features	Inherent safety, no need for offsite emergency measures
Design status	Under construction

2001	Launch of commercial HTR-PM project
2004	Standard design of HTR-PM started
2006	HTR-PM demonstration power plant approved as one of National Science and Technology Major Projects
2006	Huaneng Shandong Shidaowan Nuclear Power Co., Ltd, the owner of the HTR-PM, established by the China Huaneng Group, the China Nuclear Engineering Group Co. and Tsinghua University
2006-2008	Basic design of HTR-PM completed
2009	Assessment of HTR-PM PSAR completed
2012	First Pour of Concrete of HTR-PM
2013	Fuel plant construction started
2014	Qualification irradiation tests of fuel elements completed
2015	Civil work of reactor building finished
2016	RPV and core barrel etc. delivered, installation of main components ongoing
2017	Fuel plant achieved expected production capacity
2019	First operation expected

KLT-40S (Afrikantov OKBM, Russian Federation)

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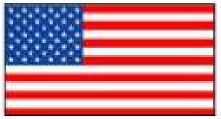
MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	Afrikantov OKBM, Russian Federation
Reactor type	PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	150/35
Primary circulation	Forced circulation
System pressure (MPa)	12.7
Core inlet/exit temperatures (°C)	280/316
Fuel type/assembly array	UO_2 pellet in silumin matrix
Number of fuel assemblies	121
Fuel enrichment (%)	18.6
Fuel burnup (GWd/ton)	45.4
Fuel cycle (months)	30-36
Main reactivity control mechanism	Control rod driving mechanism
Approach to engineered safety systems	Active (partially passive)
Design life (years)	40
Plant footprint (m^2)	--
RPV height/diameter (m)	4.8/2.0
Seismic design	9 point on the MSK scale
Distinguishing features	Floating power unit for cogeneration of heat and electricity, onsite refuelling not required; spent fuel take back to the supplier
Design Status	Under tests, planned commercial start 2019-2020

1998	The first project to build a floating nuclear power plant was established
2002	The environmental impact assessment was approved by the Russian Federation Ministry of Natural Resources
2006	After several delays the project was revived by Minatom (Russian Federation Ministry of Nuclear Energy)
2012	Pevek was selected as the site for the installation of NPPs. JSC "Baltiysky Zavod" undertook charge of construction, installation, testing and commissioning the first FPU
2017	Completion of construction and testing of the floating power unit at the Baltic shipyard
2018	Dock-side trials, fuelling, final tests completion with reactor core, attainment of reactor's first criticality
2019	Transportation of FNU to the town of Pevek
2019-2020	Commercial startup



SMR-160 (Holtec International, USA)

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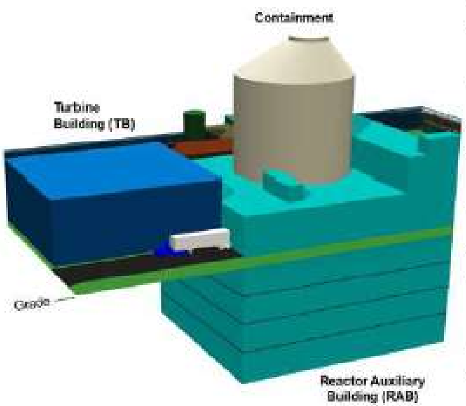
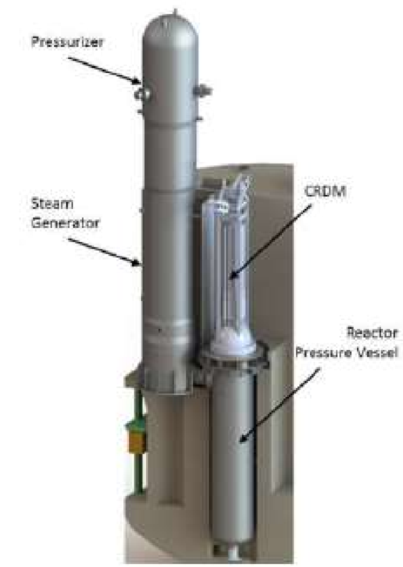


SMR-160 nuclear island



SMR-160 reactor coolant system

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	Holtec International, United States of America (Holtec)
Reactor type	PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	525 / 160
Primary circulation	Natural circulation
System pressure (MPa)	15.5
Core inlet / exit temperatures (°C)	209 / 321
Fuel type/assembly array	UO_2 pellet / square array
Number of fuel assemblies	112
Fuel enrichment (%)	4.95 (maximum)
Fuel burnup (GWd/ton)	45 (maximum, initial design)
Fuel cycle (months)	18 – 24 (flexible)
Main reactivity control mechanism	Fine motion control rod drive mechanism, with control rods
Approach to engineered safety systems	Numerous. Systems utilize diverse phenomena and are entirely passive.
Design life (years)	80
Plant footprint (m^2)	20500
RPV height/diameter (m)	15 / 3
Seismic design	The generic seismic design response spectrum is derived from NRC regulatory guide 1.60 spectra (modified), with a 0.3g PGA.
Distinguishing features	Active non-safety and passive safety cooling systems. Employs very robust protective structures, with critical components below grade. An extremely small source term diminishes the consequences of postulated accidents.
Design status	Preliminary design in progress, supporting commercial project development and pre-licensing engagements.

A Holtec International e a GE Hitachi Nuclear Energy (GEH) estão associadas para o desenvolvimento e comercialização do pequeno reator modular SMR-160 da Holtec (SMR). A cooperação entre as duas empresas incluirá, inicialmente, mecanismos de desenvolvimento de combustível nuclear e mecanismos de controle de barras. De acordo com um memorando de entendimento, a GEH, Global Nuclear Fuel (GNF), Holtec e SMR Inventec estão empenhadas nesse desenvolvimento. A GNF, uma empresa liderada pela GE com a Hitachi e a Toshiba, e é conhecida principalmente por ser fornecedora de combustível de reator de água fervente. A SMR LLC é uma subsidiária integral da Holtec criada em 2011 para gerenciar o desenvolvimento do SMR-160. A cooperação entre as quatro empresas incluirá o desenvolvimento de combustível nuclear suportado pelo GNF e os mecanismos de transmissão de haste de controle projetados pela GEH mas poderão se estender a outras áreas.

O reator modular de 160 MWe da Holtec usa combustível de urânio de baixo teor de enriquecimento. O núcleo do reator foi construído em fábrica e todos os componentes do sistema de fornecimento de vapor nuclear incorpora uma grande variedade de recursos, incluindo um sistema de resfriamento passivo que poderia funcionar indefinidamente após o desligamento. Não são necessários componentes ativos, como bombas, para executar o reator, que não precisa de nenhuma força para desligar e dissipar o calor. O SMR-160 está planejado para operação até 2026.

NuScale (NuScale Power Inc., USA)

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MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	NuScale Power, LLC, USA
Reactor type	Integral PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	160/50
Primary circulation	Natural circulation
System pressure (MPa)	12.8
Core inlet/exit temperatures (°C)	258/314
Fuel type/assembly array	UO_2 pellet/17x17 square
Number of fuel assemblies	37
Fuel enrichment (%)	< 4.95
Fuel burnup (GWd/ton)	> 30
Fuel cycle (months)	24
Main reactivity control mechanism	Control rod drive, boron
Approach to engineered safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	140000
RPV height/diameter (m)	17.8/3.0
Module weight (metric ton)	~700 ton
Seismic design	0.5g peak ground accelerations
Distinguishing features	Unlimited coping time for core cooling without AC or DC power, water addition, or operator action
Design status	Under regulatory review

Primeira usina modular de reatores SMR, que deve estar pronta e funcionando em 2027. A preparação do local em nome do Utah Associated Municipal Power Systems, primeiro cliente da NuScale, deve começar em 2021. A construção no local deverá estar em andamento em 2023. Um dos 12 pequenos reatores modulares para a usina pode estar operacional em 2026 e os outros 11 SMRs estando operacionais em algum momento de 2027. Os cronogramas para plantas futuras, no entanto, podem cair significativamente, já que a primeira instalação é sempre um processo de aprendizado com dicas valiosas para projetos futuros.

A estimativa é que sejam criados 13.500 empregos na cadeia de suprimentos nos Estados Unidos, caso a trajetória de crescimento da empresa seja concretizada. Esse número depende da construção de três usinas de energia de 12 módulos por ano. A NuScale, entretanto, tem feito negociações no Canadá, Jordânia, Romênia e Grã-Bretanha, como clientes ou bases da cadeia de fornecimento para a construção no exterior. Nos Estados Unidos, muitos fornecedores já assinaram um acordo com a empresa.

ACP100 (CNNC, China)

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MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	CNNC(NPIC/CNPE) People's Republic of China
Reactor type	Integral PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	385/125
Primary circulation	Forced circulation
System pressure (MPa)	15
Core inlet/exit temperatures (°C)	286.5/319.5
Fuel type/assembly array	UO_2/17x17 square pitch arrangement
Number of fuel assemblies	57
Fuel enrichment (%)	<4.95
Fuel burnup (GWd/ton)	<52000
Fuel cycle (months)	24
Main reactivity control mechanism	Control rod drive mechanism (CRDM), Gd_2O_3 solid burnable poison and soluble boron acid
Approach to engineered safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	200000
RPV height/diameter (m)	10/3.35
Module weight (metric ton)	300
Seismic design	0.3
Distinguishing features	Integrated reactor with tube-in-tube once through steam generator, nuclear island underground
Design status	Basic design finished

Currently, the East-Asian nation operates 45 nuclear power reactors. Some thirteen more plants (the last to be connected to the Chinese power grid in 2023) are currently under construction and will add another 12.8 GWs to that number. Beijing has 92 "definite" proposed plants (theoretically generating 110 GW's) and 78 "less definite" units in the books for their next Five-Year Plan.

It comes as no surprise, then, that the ACP100 is progressing quickly. Construction of the 125-megawatt electrical (MWe) unit will begin in December of this year with the goal of full operability by May of 2025. When it comes online, the Nimble Dragon is expected to produce enough electricity to power over 100,000 Chinese homes. The projected is a joint-venture, with 51% financed by CNNC and the remainder by China Guodian Corp (CNEPGZ:CH).

Trends for SMR

- There is strong interest in small and simpler units for generating electricity from nuclear power, and for process heat.
- This interest in small and medium nuclear power reactors is driven both by a desire to reduce the impact of capital costs and to provide power away from large grid systems.
- The technologies involved are numerous and very diverse.
- Environmental Issues as Clean energy is helping the development;

Advantages of SMRs

- Portability;
  - ✓Carbon-free power to sparsely populated areas;
  - ✓No grid available;
  - ✓Compensate other sources intermittence
- Expandabillity;
- District application;
  - ✓Desalinization;
  - ✓Industry Processes
- Low capital investment;
- Shorter implementation Timeline
- Complimentarity with renewables
  - ✓Compensate other sources intermittence

Challenges

- Wide commercialization of SMRs faced technical and regulatory challenges for years. (Licensing and Safety Issues);
  - ✓Recent bills by US Senate could accelerate;
  - ✓Safety and Security enhancements;
- Pricing and Scale;
  - ✓Competition with other sources;
  - ✓Among other sources Gas is the stronger competitor. Same features except clean energy
- A tested unit to be commercialized - >> 10 years;

Remarks

- Many international projects;
- Resources are increasing – example of Nuscale, Canada, Russia, China, etc..
- Country Programs in the next 10 years;
- More feasible application when it can be offered by vendors as a product not a joint opportunity for a technology development project;