能源的明日之星 – 微小型反應器

淨零碳排的屠龍刀

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大　　綱

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Office of Nuclear Energy

NRC Approves First U.S. Small Modular Reactor Design

SEPTEMBER 2, 2020

Office of Nuclear Energy » NRC Approves First U.S. Small Modular Reactor Design

NUCLEAR MILESTONE

Artist rendition of NuScale Power nuclear power plant.

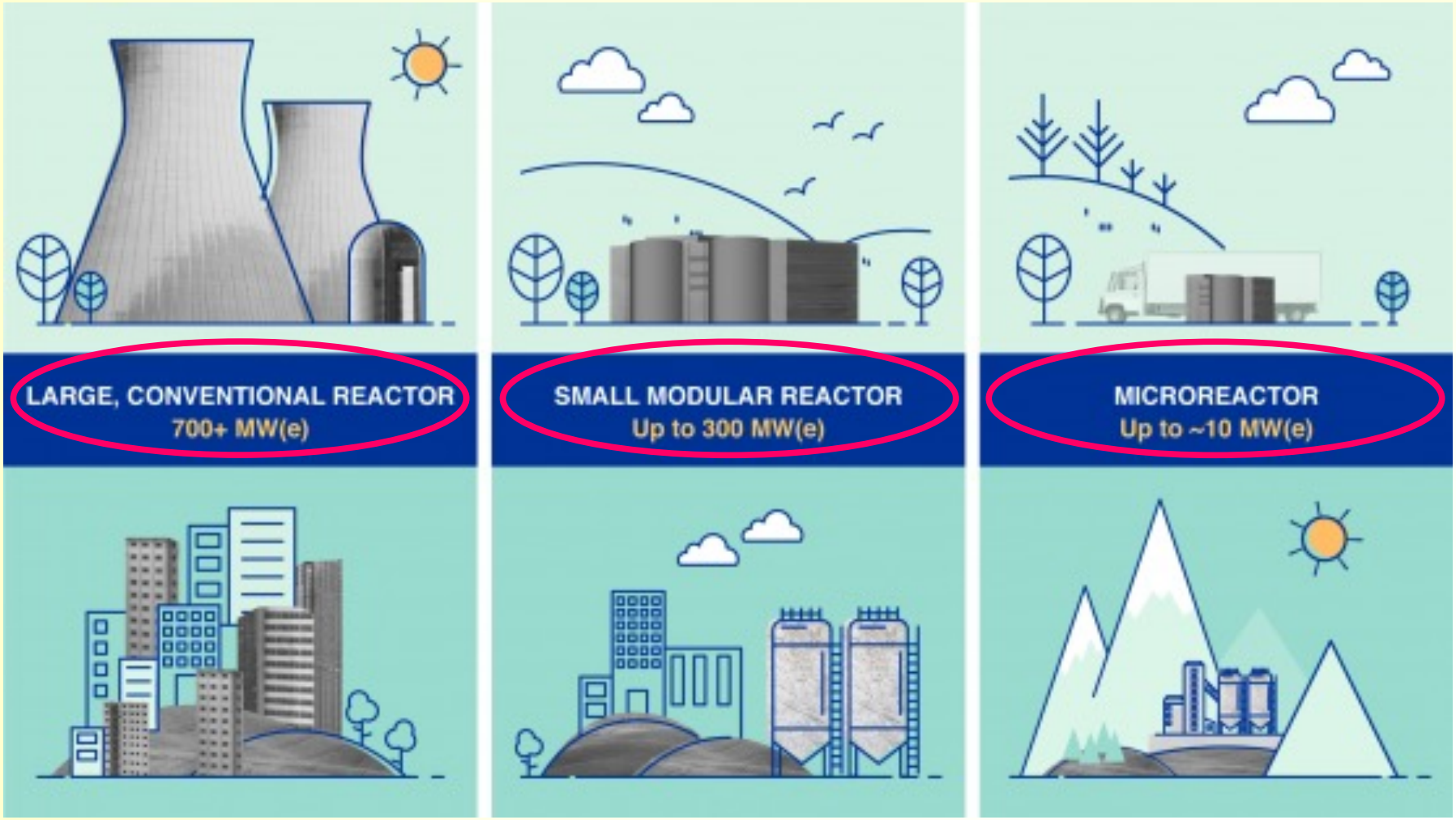
NuScale Power

The U.S. Nuclear Regulatory Commission (NRC) recently issued its final safety evaluation report on NuScale Power's small modular reactor (SMR) design. This accomplishment is the first of its kind

Source: https://www.energy.gov/ne/articles/nrc-approves-first-us-small-modular-reactor-design

1. 微小型反應器分類 (1/2)

◆ IAEA的微小型反應器分類



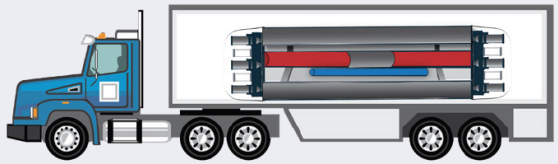
Source: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

1. 微小型反應器分類 (2/2)

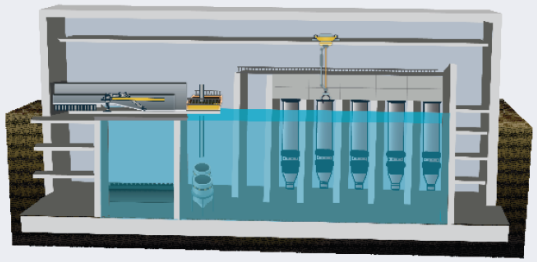
◆ 美國能源部的微小型反應器分類

Advanced Reactor Sizes

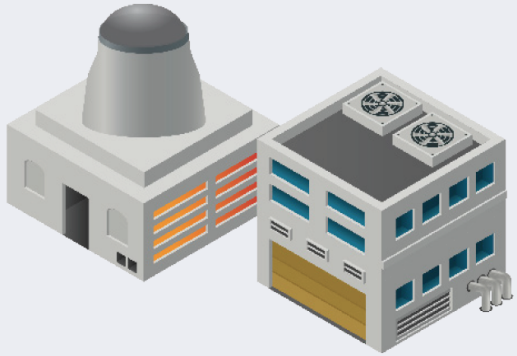
Micro Reactors
Range: 1 MW to 20 MW
Can fit on a flatbed truck, and are mobile and deployable.



Small Modular Reactors
Range: 20 MW to 300 MW
Can be scaled up or down by adding more units.



Full-Size Reactors
Range: 300 MW to 1,000+MW
Can provide reliable, emissions-free baseload power.



https://www.energy.gov/sites/prod/files/2020/01/f70/011620%20Advanced%20Reactor%20Types%20Factsheet.pdf

2. 微小型反應器特色

- 微小型

  傳統反應器大小的百分之一，甚至千分之一不到

- 模組化

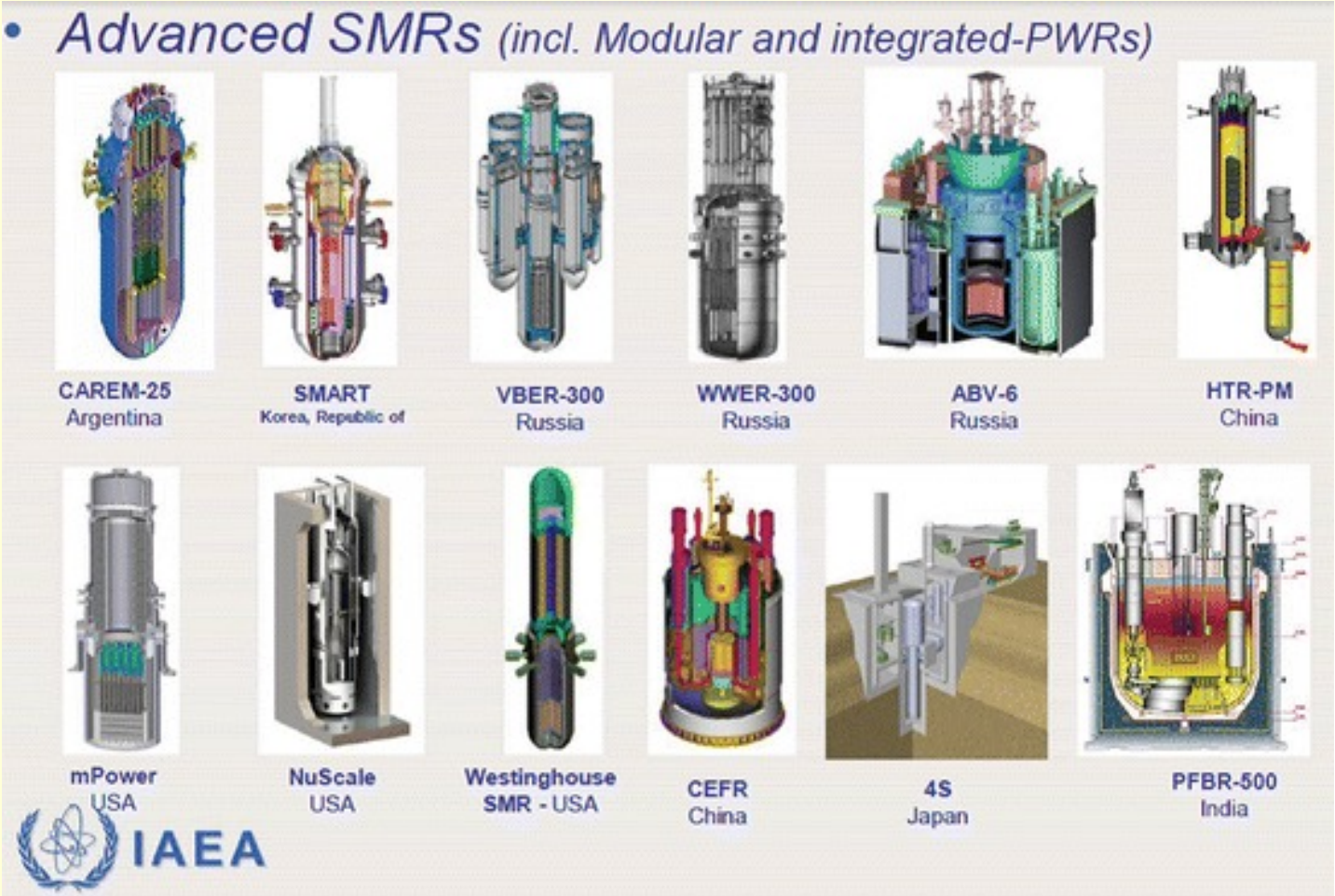
  微型可工廠施作、現地安裝

- 反應器

  輕水式、氣冷式、鈉冷式，快、熱中子誘發核分裂

3. 小型反應器研發現況 (1/5)

◆ 小型模組化反應器 - IAEA



3. 小型反應器研發現況 (2/5)

◆ 小型反應器 – WNA (1/3)

In December 2019 CEZ in the Czech Republic said it was focusing on 11 SMR designs including these seven: Rosatom's RITM-200, GE Hitachi Nuclear Energy's BWRX-300, NuScale Power's SMR, China National Nuclear Corporation's ACP100, Argentina's CAREM, the South Korean SMART, and Holtec International's SMR-160.

Small reactors operating

Name	Capacity	Type	Developer
CNP-300	300 MWe	PWR	SNERDI/CNNC, Pakistan & China
PHWR-220	220 MWe	PHWR	NPCIL, India
EGP-6	11 MWe	LWGR	at Bilibino, Siberia (cogen, soon to retire)
KLT-40S	35 MWe	PWR	OKBM, Russia
RITM-200	50 MWe	Integral PWR, civil marine	OKBM, Russia

Small reactor designs under construction

Name	Capacity	Type	Developer
CAREM25	27 MWe	Integral PWR	CNEA & INVAP, Argentina
HTR-PM	210 MWe	Twin HTR	INET, CNEC & Huaneng, China
ACP100/Linglong One	125 MWe	Integral PWR	CNNC, China
BREST	300 MWe	Lead FNR	RDIPE, Russia

https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

3. 小型反應器研發現況 (3/5)

◆ 小型反應器 – WNA (2/3)

Small reactors for near-term deployment – development well advanced

Name	Capacity	Type	Developer
VBER-300	300 MWe	PWR	OKBM, Russia
NuScale Power Module	77 MWe	Integral PWR	NuScale Power + Fluor, USA
SMR-160	160 MWe	PWR	Holtec, USA + SNC-Lavalin, Canada
SMART	100 MWe	Integral PWR	KAERI, South Korea
BWRX-300	300 MWe	BWR	GE Hitachi, USA
PRISM	311 MWe	Sodium FNR	GE Hitachi, USA
Natrium	345 MWe	Sodium FNR	TerraPower + GE Hitachi, USA
ARC-100	100 MWe	Sodium FNR	ARC with GE Hitachi, USA
Integral MSR	192 MWe	MSR	Terrestrial Energy, Canada
Seaborg CMSR	100 MWe	MSR	Seaborg, Denmark
Hermes prototype	35 MWt	MSR-Triso	Kairos, USA
RITM-200M	50 MWe	Integral PWR	OKBM, Russia
RITM-200N	55 MWe	Integral PWR	OKBM, Russia
BANDI-60S	60 MWe	PWR	Kepco, South Korea
Xe-100	80 MWe	HTR	X-energy, USA
ACPR50S	60 MWe	PWR	CGN, China
Moltex SSR-W	300 MWe	MSR	Moltex, UK

https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

3. 小型反應器研發現況 (4/5)

◆ 小型反應器 – WNA (3/3)

Small reactor designs at earlier stages (or shelved)

Name	Capacity	Type	Developer
EM2	240 MWe	HTR, FNR	General Atomics (USA)
FMR	50 MWe	HTR, FNR	General Atomics + Framatome
VK-300	300 MWe	BWR	NIKIET, Russia
AHWR-300 LEU	300 MWe	PHWR	BARC, India
CAP200 LandStar-V	220 MWe	PWR	SNERDI/SPIC, China
SNP350	350 MWe	PWR	SNERDI, China
ACPR100	140 MWe	Integral PWR	CGN, China
IMR	350 MWe	Integral PWR	Mitsubishi Heavy Ind, Japan*
Westinghouse SMR	225 MWe	Integral PWR	Westinghouse, USA*
mPower	195 MWe	Integral PWR	BWXT, USA*
UK SMR	470 MWe	PWR	Rolls-Royce SMR, UK
PBMR	165 MWe	HTR	PBMR, South Africa*
HTMR-100	35 MWe	HTR	HTMR Ltd, South Africa
MCFR	large?	MSR/FNR	Southern Co, TerraPower, USA
SVBR-100	100 MWe	Lead-Bi FNR	AKME-Engineering, Russia*
Westinghouse LFR	300 MWe	Lead FNR	Westinghouse, USA
TMSR-SF	100 MWt	MSR	SINAP, China
PB-FHR	100 MWe	MSR	UC Berkeley, USA
Moltex SSR-U	150 MWe	MSR/FNR	Moltex, UK
Thorcon TMSR	250 MWe	MSR	Martingale, USA
Leadir-PS100	36 MWe	Lead-cooled	Northern Nuclear, Canada

3. 小型反應器研發現況 (5/5)

◆ 小型模組化反應器 - US

Design	Application Type	Applicant
NuScale	Design Certification	NuScale Power, LLC
NuScale NPM-20	Standard Design Approval (SDA), Pre-Application	NuScale Power, LLC
BWXT mPower™	Pre-Application	BWXT mPower, Inc.
SMR-160	Pre-Application	SMR, LLC, a subsidiary of Holtec International
Clinch River Nuclear Site	Early Site Permit	Tennessee Valley Authority (TVA)
BWRX-300	Pre-Application	GE-Hitachi Nuclear Energy (GEH)

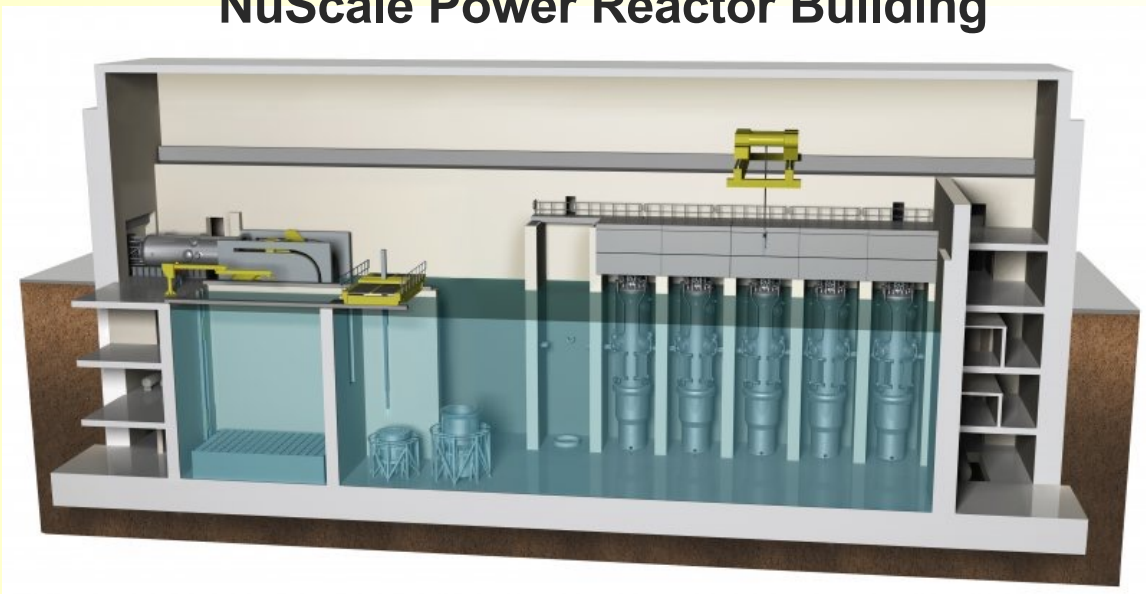
https://www.nrc.gov/reactors/new-reactors/smr.html

4. 小型反應器實例 (1/2)

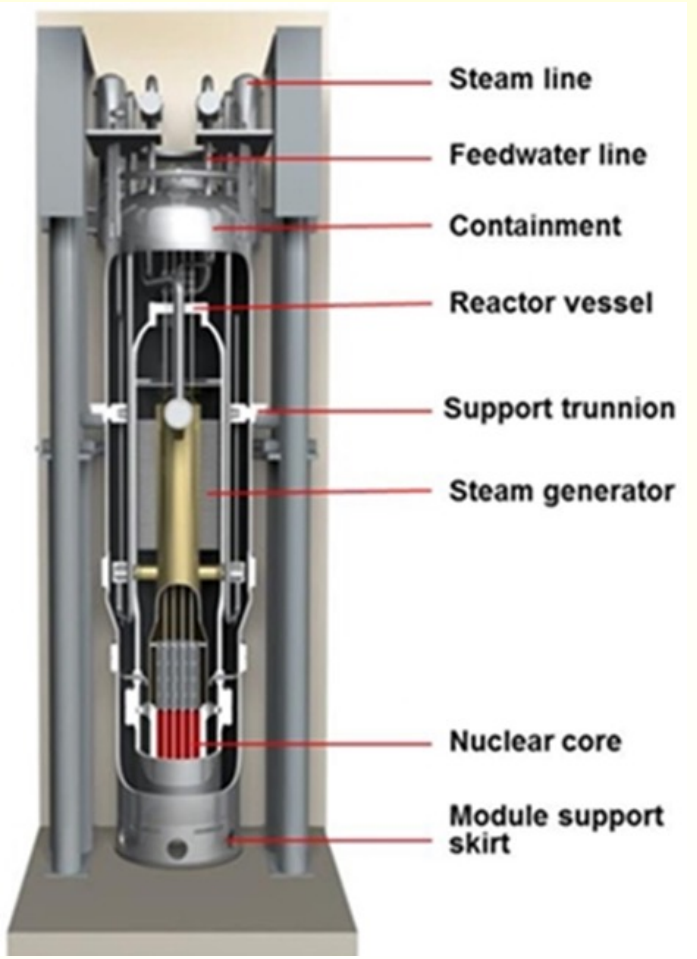
◆ 小型模組化反應器 - US

The NRC refers to light water reactor (LWR) designs generating 300 MWe or less as small modular reactors (SMRs). The NRC has engaged in varying degrees of pre-application activities with several SMR designers over the past several years. In **August of 2020**, the NRC approved a design for an SMR from NuScale Power, LLC.

NuScale Power Reactor Building



NuScale Power Reactors. ©NuScale Power, LLC, All Rights Reserved



https://www.energy.gov/ne/advanced-small-modular-reactors-smrs

4. 小型反應器實例 (2/2)

◆ 小型模組化反應器 - US

NUSCALE

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THE REGULATORY APPROVAL PROCESS AND NUSCALE'S SMR

NuScale's SMR design addressed NRC licensing requirements with two distinct advantages. First, NuScale's SMR is designed with fewer systems and demonstrates singular simplicity. Second, the elegantly simple NuScale VOYGR plants provide greater levels of safety that translate into larger operating margins and more flexible design solutions for support systems.

The NuScale Integral System Test (NIST-2) facility in Corvallis, Oregon was designed and built to assist in the verification and validation of key analytical tools and assumptions. The NIST-2 facility provides nuclear qualified systems data to validate NuScale's cutting-edge thermal hydraulic safety analysis computer codes as needed for NRC design certification, including flow stability, long-term cooling tests, and loss of coolant accident events known as "LOCA" events. NuScale Power also has a main control room simulator that demonstrates the robustness of the NuScale design under transient conditions and will aid in the development of Human Factors analyses and address operational issues. The purpose of the simulator facility is to demonstrate NuScale's concept of operation and plant technology to the NRC and other stakeholders.

NEXT STEPS

NuScale continues to maintain strong program momentum toward commercialization of its SMR technology, including supply chain development, standard plant design, planning of plant delivery activities, and startup and commissioning plans. We are actively engaged with our manufacturing partners and will be ready to deliver the first NuScale Power Modules to a client in 2027. The NuScale SMR design will be incorporated into customers' combined license applications (COLAs).

As part of the Utah Associated Municipal Power Systems (UAMPS) Carbon Free Power Project (CFPP), the first NuScale 6-module VOYGR-6 plant in Idaho is expected to be fully operational by 2030, with the first of 6 modules online by 2029. All NRC laws, rules, and regulations will apply to siting, construction, operation, and decommissioning of the NuScale VOYGR SMR plant for the project, including a full NRC-led review of the COLA. The CFPP COLA will be subject to an environmental review under the National Environmental Policy Act, as well as a safety review of operational issues including water, seismic, transmission, workforce, security, and emergency preparedness.

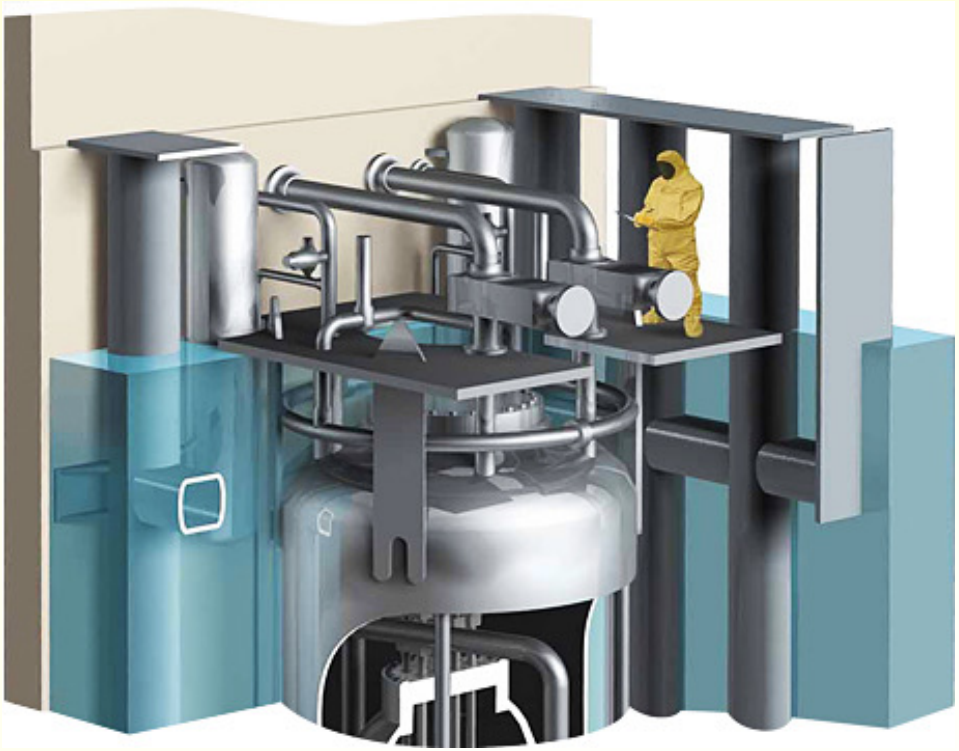
LATEST UPDATES

July 1, 2021: The U.S. NRC is taking public comments on proposed rulemaking for NuScale's SMR standard design certification. The comment period was recently extended to mid-October 2021.

https://www.nuscalepower.com/technology/licensing

5. 小型反應器優勢

- 價格便宜
- 低環境衝擊
- 較高民眾接受度
- 偏鄉供電
- 模組建置
- 工程耗時短
- 管制機關審查時間短
- 事故衝擊低



NuScale Power Module (NuScale)

6. 微型反應器研發現況 (1/4)

◆ 微型反應器 – WNA

Very small reactor designs being developed (up to 25 MWe)

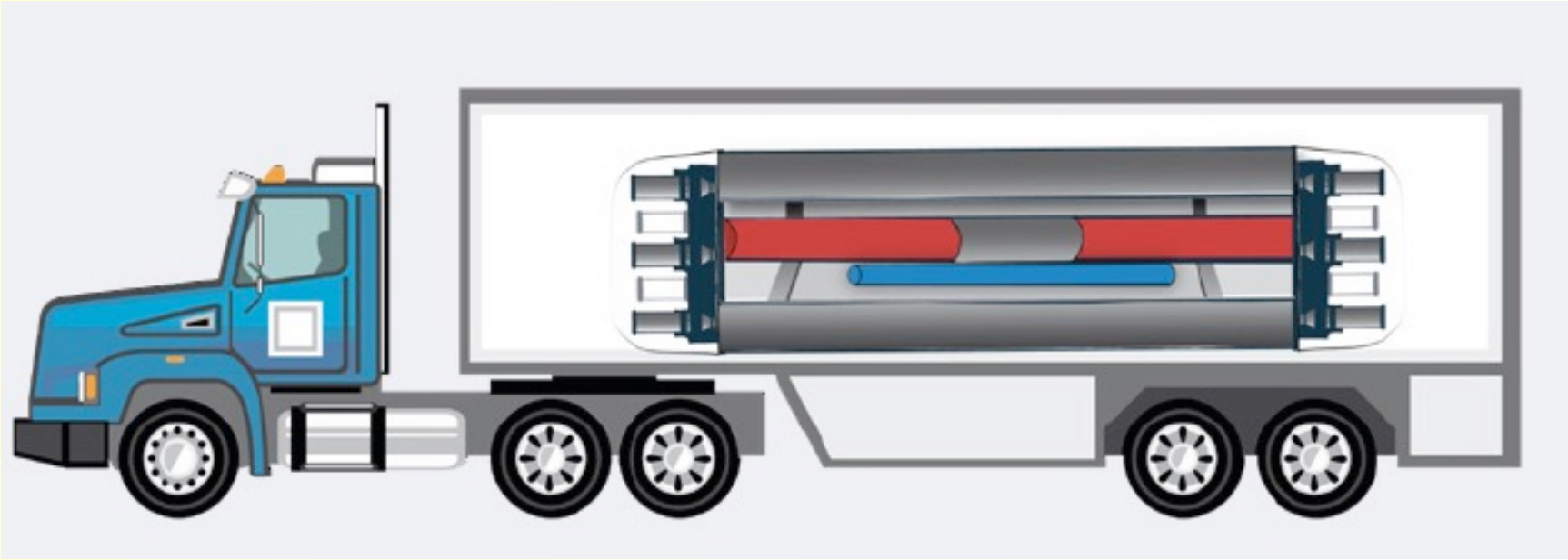
Name	Capacity	Type	Developer
U-battery	4 MWe	HTR	Urenco-led consortium, UK
Starcore	10-20 MWe	HTR	Starcore, Quebec
MMR-5/-10	5 or 10 MWe	HTR	UltraSafe Nuclear, USA
Holos Quad	3-13 MWe	HTR	HolosGen, USA
Gen4 module	25 MWe	Lead-bismuth FNR	Gen4 (Hyperion), USA
Xe-Mobile	1-5 MWe	HTR	X-energy, USA
BANR	50 MWt	HTR	BWXT, USA
Sealer	3-10 MWe	Lead FNR	LeadCold, Sweden
eVinci	0.2-5 MWe	Heatpipe FNR	Westinghouse, USA
Aurora	1.5 MWe	Heatpipe FNR	Oklo, USA
NuScale micro	1-10 MWe	Heatpipe	NuScale, USA

https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

6. 微型反應器研發現況 (2/4)

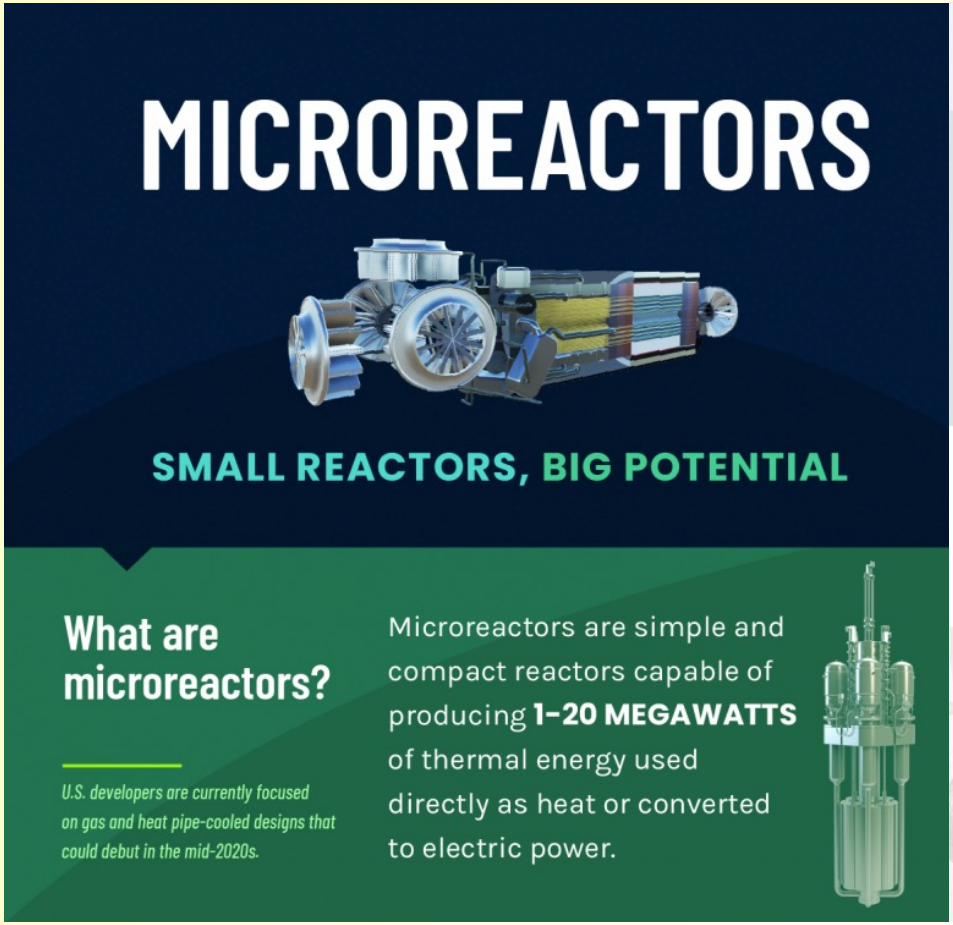
◆ 微型反應器 - US

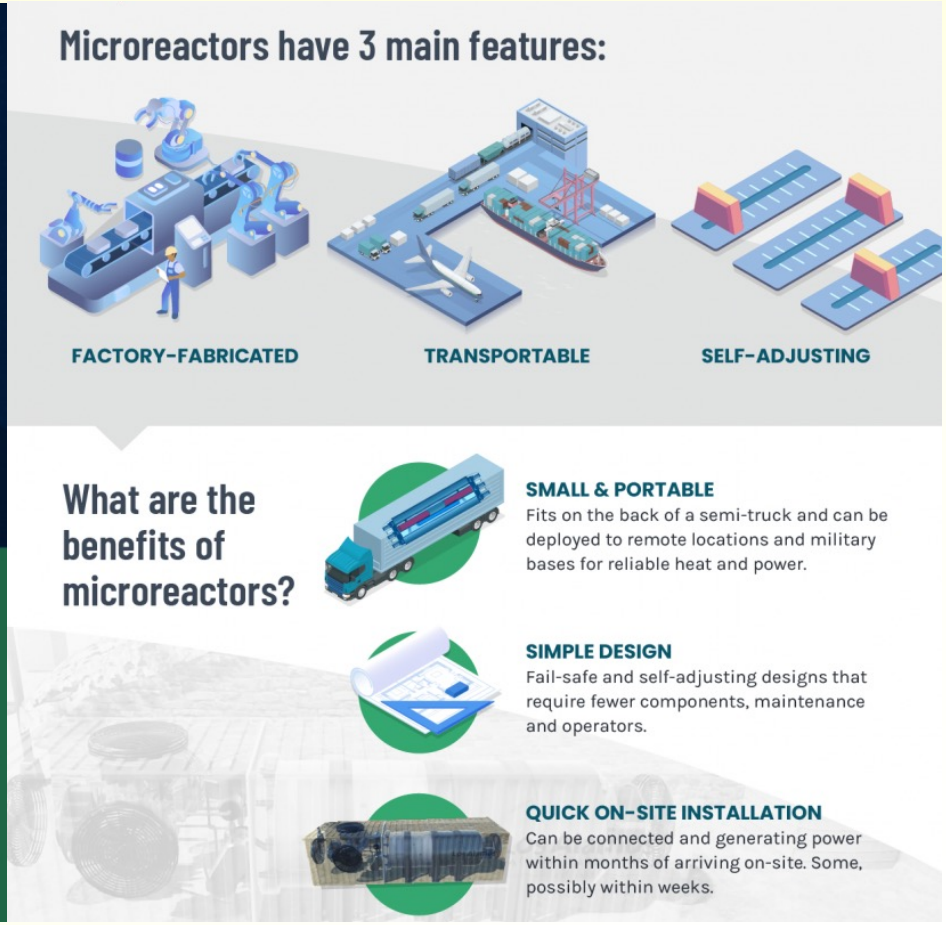
Special Purpose and Micro Reactors				
US Ultra Safe Nuclear Micro Modular Reactor (MMR)	5-10	Fully Ceramic Matrix	Helium	US Ultra Safe Nuclear
eVinci Micro Reactor	0.2-25	Dispersion	Heat Pipe	Westinghouse
Holos Reactor	3-81	TRISO	Helium or CO2	HolosGen, LLC
Oklo	2 MWt	Metal	Heat Pipe	Oklo



https://www.energy.gov/sites/prod/files/2020/01/f70/011620%20Advanced%20Reactor%20Types%20Factsheet.pdf

7. 微型反應器特色 (1/2)





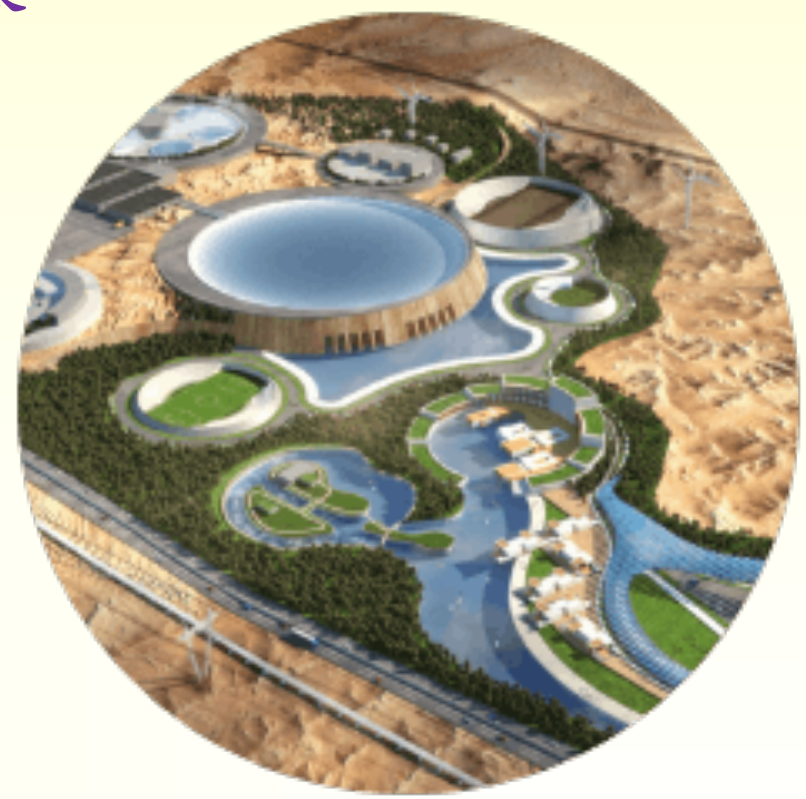
https://www.energy.gov/ne/downloads/infographic-what-nuclear-microreactor-0

7. 微型反應器特色 (2/2)

https://www.keysourceglobal.com/can-small-modular-reactors-solve-nuclears-image-problem/

8. 微型反應器優勢

- 全機組工廠製造後現地安裝
- 運送與移除簡單快速
- 物理定律下的高安全性
- 可靠富彈性的供電模式
- 運轉相對容易
- 數年不須裝填新燃料
- 符合各種型態的用電需求
- 可與其他供電設施整合



9. 微型反應器應用實例

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US Air Force confirms site for first microreactor

26 October 2021

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The US Air Force has confirmed the Eielson base in Alaska as the facility planned to host its first small nuclear power plant. A microreactor of up to 5 MWe could be operational there as soon as 2027, according to Eielson.

Taking off: Will Eielson's microreactor be the first of many? (Image: Jose Miguel T Tamondong/US Air Force)

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TVO applies to start up Olkiluoto EPR

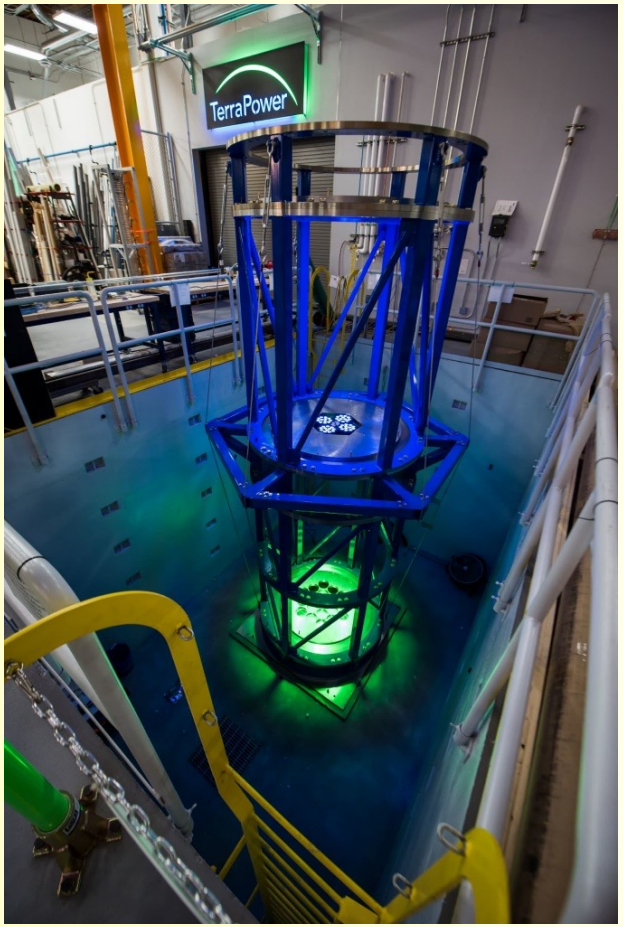
UK selects HTGR for advanced reactor demonstration

Westinghouse signs initial contract for Ukrainian AP1000s

https://world-nuclear-news.org/Articles/US-Air-Force-confirms-site-for-first-microreactor

10. 微型反應器特例 (1/3)

◆ 行波式反應器 – Terra Power



AN INNOVATIVE NUCLEAR TECHNOLOGY

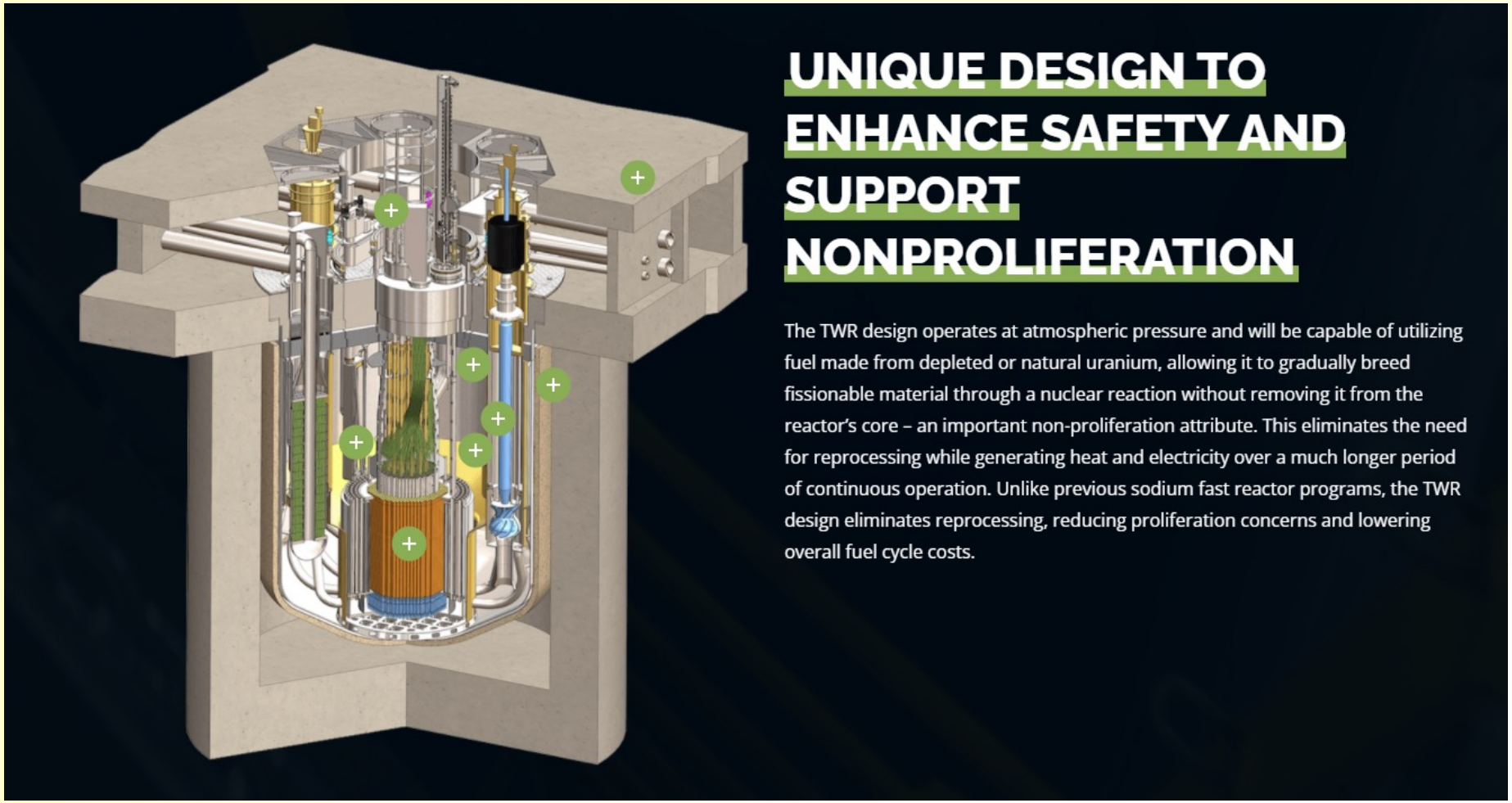
The TWR technology takes leaps forward in cost and safety, while dramatically reducing waste and proliferation concerns. Its innovative design will produce zero carbon emissions while operating with higher thermal efficiency and consuming uranium resources in a more efficient, cleaner and safer manner than current nuclear technology.

The reactor core is the true innovation of the TWR design. In the center of the core sit rods of enriched uranium (U-235), surrounded by rods of depleted or natural uranium (U-238). The U-235 serves as an initiator, kick starting the traveling wave reaction – a slow-moving chain reaction of concentric waves of fission. The traveling wave reaction will then slowly convert the depleted uranium to fissionable plutonium. Periodically, to sustain the fission reaction, the in-vessel fuel handling machine shuffles the fuel, swapping expired fuel rods from the center of the core for fresh fuel rods from the outer edge.

https://www.terrapower.com/our-work/traveling-wave-reactor-technology/

10. 微型反應器特例 (2/3)

◆ 行波式反應器 – Terra Power



https://www.terrapower.com/our-work/traveling-wave-reactor-technology/

10. 微型反應器特例 (3/3)

◆ 行波式反應器主要設施功能 – Terra Power

反應器設置於地表以下

控制棒位於爐心上方

濃化鈾-235位於乏鈾與天然鈾環繞的爐心

燃料控制機自動更新燃料布局，內舊換外新

反應器槽體包封浸沒於液態鈉的爐心，無外管連接

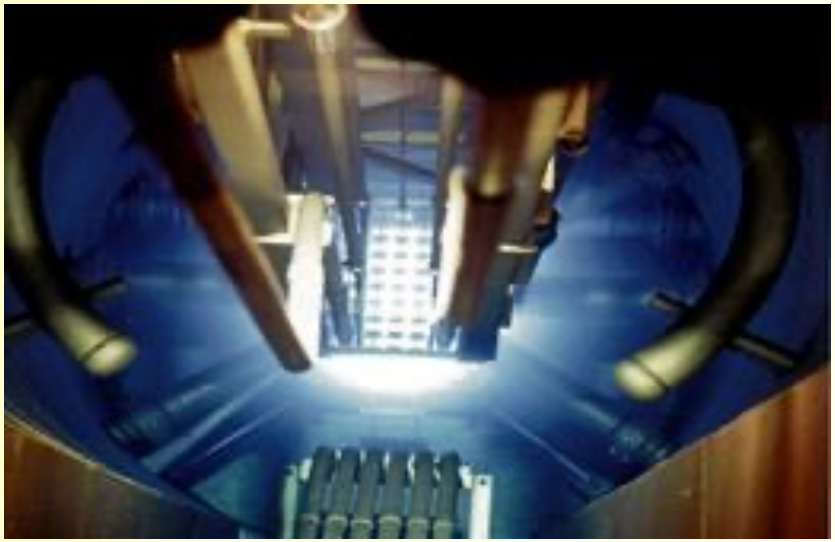
主鈉池環繞爐心，自然物理定律與液態鈉優點提升效能及安全性

主鈉池將爐心能量移轉至次鈉池，透過Rankine蒸汽循環發電

https://www.terrapower.com/our-work/traveling-wave-reactor-technology/

11. 我國的微型反應器

◆ THOR – 2 MW Rated Power



燃料：TRIGA 棒狀燃料 (UZrH1.6-Er)
濃縮度: 20%
臨界質量: 9 kg U-235
爐心冷卻 強迫一次水流與熱交換器之二次水流進行熱交換, 無相位變化,
池水總量: 80,000 加侖
反應度 控制棒本領：12.15%
超溢反應度：4.5%
2 MW 額定供率時之中子通率
平均熱中子通率：2.0 E13 (n·cm-2·sec-1)
平均快中子通率：3.1 E13 (n·cm-2·sec-1)
射線管出口之熱中子通率：1.0E6 - 1.0E9
控制系統 GA 微電腦控制系統

12. 結語

- 微小型反應器是全球核能發展的新趨勢
- 微小型反應器採用被動冷卻，並具有本質安全的特性
- 台灣可建置微小型反應器的腹地：

  核一、二、三、四現址
- 百萬瓦等級的模組化壓水式小型反應器較適合台灣
- 符合2050淨零願景的全球能源發展趨勢 – *核能*

倚天不出、誰與爭鋒！