SMRs

Two examples: NuScale in the US, NUWARD in France

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ABSTRACT

In recent years, a new type of reactor has appeared on the world stage, the SMR - Small Modular Reactor. Historically, a number of "small reactors" of very different types have been in operation – small in terms of power compared with the reactors of nuclear power plants currently in operation around the world – notably for use in ship propulsion, such as the nuclear submarines of the pressurized water/enriched uranium type.

The "modular" feature of an SMR is achieved by mass production in a dedicated plant. It would then be transported to the operating site, where it would be connected to the heat or electricity production system to form a "module" and then a "power plant", known as an "SMR". The hope of SMR promoters rests on the hoped-for gain in unit reactor cost due to the series effect, as they are rightly aware that the cost of a site-built model is far too high.

At present, according to the International Atomic Energy Agency (IAEA), there are almost a hundred "candidate" SMR projects/designs, some of them based on existing prototypes ("small" but not "modular"), most of them existing only on paper, of various power ratings, from enriched uranium and pressurized water reactors, a well-known technology, to plutonium fast neutron reactors, thorium or molten salt reactors, etc.

There are no existing SMRs at present.

In addition to a general presentation of the SMR issue and a selection of IAEA projects, this report examines two "SMR candidate" reactor projects in the enriched uranium and pressurized water (PWR) family of reactors: NuScale in the USA and NUWARD in France.

Numerous safety-related questions remain unanswered about the NuSCale model, and the Safety Options File for the NUWARD reactor, studied by the French, Czech and Finnish safety authorities, is not yet available. The technical challenges to be met to guarantee SMR safety are not qualitatively different from those of large reactors.

These challenges are compounded by the uncertainties brought about by the reactor's novel "compact" design, which contains the reactor core (the site of the nuclear fission reaction), the control rods, the steam generator(s) and the pressurizer in a single enclosure.

The SMR gamble is not only risky in terms of the bill, but also in terms of the climate, technical and safety agendas, as well as entailing the negative externalities of nuclear installations such as the risk of nuclear accidents and the production of waste that we are relegating to future generations, at least for the next 100,000 years. These reactors also entail other risks, including proliferation.

INTRODUCTION

In recent years, governments, companies and the media have been buzzing about a new development in the world of nuclear power: the SMR (Small Modular Reactor).
Historically, there have been many "small reactors", with little or very little electrical power output compared with the reactors of the nuclear power plants in operation around the world today.

What's new with the SMR is not so much the reactor's reduced power output as its "modular" characteristic, based on the fact that demand for an SMR of a given type could be sufficiently high (on the order of 50 to 100 units) to allow mass production, in a purpose-built factory, of a reactor that is both compact and not too heavy, so that it can be transported from the factory to its operating site, where it could produce heat or electricity, in this case thanks to a turbo-generator.
It is the combination of a compact reactor and the standardization of its manufacture that enables the promoters and most fervent supporters of SMR to promise acceptable costs for electricity production. Even in such a case, the problems linked to the location and local capacity to manage this new technique are far from negligible, especially in developing countries, the target of many promoters.

At present, according to the International Atomic Energy Agency (IAEA), there are almost a hundred SMR projects, some based on existing prototypes ("small" but not "modular"), most of them existing only on paper, of various power ratings, from enriched uranium and pressurized water reactors, a well-known technology, to plutonium fast neutron reactors, thorium or molten salt reactors, etc.

For the time being, therefore, it must be stressed that while many small reactor models have been developed over the years, and some of them are in operation for specific uses, such as naval propulsion, there is no SMR in existence today whose reactor would have been factory-built and delivered to the site of a "mini-power plant" for civilian use. Clearly, the need to build a factory to manufacture nuclear reactors will lead to the abandonment of many projects, even before the prototype stage, which is obviously very expensive, especially as governments and companies are themselves presenting several projects, and competition is fierce to impose one of their own.

To give the reader a first glimpse into the "SMR galaxy", we have chosen to present in this note two of the easiest-to-understand enriched uranium/pressurized water reactor projects to qualify as SMRs: the NuScale project in the USA and the NUWARD project in France. Chapter 1 presents the historical and operating "small reactors" that are the forerunners of SMRs.Chapter 2 presents the IAEA's selection of candidate SMR reactors. Chapter 3 gives a detailed presentation of the characteristics of the NuScale and NUWARD projects. Chapter 4 analyzes and compares the two projects from a technical, safety and economic point of view.

The International Atomic Energy Agency (IAEA) presents the SMR[1]

« SMRs are advanced reactors with a power capacity of typically up to 300 MW(e) per unit, which is about one third of the generating capacity of traditional nuclear power reactors and whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises. Most of the SMR designs adopt advanced safety features and are deployable either as a single or multi-module plant. SMRs are under development for all principal reactor technology lines: water-cooled reactors, high-temperature gas-cooled reactors, liquid metal-cooled fast neutron spectrum reactors, molten salt reactors, and microreactors ».

« 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 control room staffing and human factor engineering for multi-module SMR plants, applicability of existing codes and standards, manufacturing approach for novel components, and back-end solutions for fuel cycle. Some potential deployment advantages of SMRs such as reduced size of Emergency Planning Zone (EPZ) or single operator monitoring several modules are under discussion by nuclear regulators. Although SMRs are designed for lower upfront capital cost per unit, their economic competitiveness is still to be proven ».

1 //https://aris.iaea.org/Publications/SMR_booklet_2022.pdf

1. LOW-POWER NUCLEAR REACTORS

1.1 SMALL REACTORS WITH NO HOPE OF MODULARITY

Since the 1940s, low-power reactors have been developed, some of which would lead to the construction of more powerful reactors for electricity generation. The first "atomic pile" (Chicago, Enrico Fermi's team, 1942), which demonstrated fission and chain reaction for the first time, with a power close to 0, consisted of natural uranium rods inserted into a 400-ton graphite mass (the "pile"). It was indeed a small reactor, but one that could never become "modular", and was to give rise to the natural uranium graphite gas (UNGG) process, developed notably in France with the low-power G1, G2 and G3 reactors at Marcoule to produce plutonium for military needs, followed by six EDF reactors for electricity generation (Chinon A 1,2,3; Saint-Laurent 1,2; Bugey 1).
The first reactor built in France, the ZOE pile (Z for 0 energy, O for natural uranium oxide, the fuel, and E for heavy water, the moderator), with a thermal power that was later increased to 150 kW, contained 5 tons of heavy water, surrounded by a 90 cm-thick graphite wall and a 1.5 m concrete enclosure. At the same time, reactors using "heavy water" as a moderator were developed in Canada as early as the Second World War, giving rise to the CANDU (CAnada Deuterium, Uranium) line of reactors for electricity production (but also, in India in particular, for the production of plutonium for military use). For their part, small pressurized water and enriched uranium reactors, PWRs, initially developed for military propulsion needs, were to be the forerunners of the nuclear power generation system most widely used in the world today, but far from a "modular" system.

Note
The term "small" can be misleading when it comes to nuclear reactors. A reactor with an electrical output of less than 300 MW may require major infrastructure and have considerable implications in terms of safety, decommissioning or budget. On the other hand, many SMR projects concern mainly thermal applications (district heating, industrial processes, seawater desalination) or cogeneration (electricity + heat). In the case of electricity production, a clear distinction needs to be made between electrical power and thermal power (heat produced in the reactor), which can be 3 to 5 times greater.

1.2 SMALL REACTORS IN THE USA

While during the "Cold War" the two main world powers vied with each other in technical imagination to develop new types of small nuclear reactors, it was in the United States that small reactors were most developed, sometimes with the hope of making them modular[2].

1.2.1 Civil applications

An April 2015 article, "The forgotten history of small modular reactors", provides a historical review of these attempts[3]:
« As it happened, the AEC (predecessor of the U.S. Department of Energy and the Nuclear Regulatory Commission) was keenly interested in small reactors. Starting in the 1950s, a number of small civilian reactors were proposed in the United States, and eventually 17 reactors with power outputs of less than 300 MW were commissioned. None of them are in operation today.

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2 There were many small reactor projects in the USSR, and Russia is still the only country in the world to use on-board reactors on civilian ships (icebreakers, cargo ships). There was even a caterpillar-mounted reactor, the TES-3 (https://nucet.pensoft.net/article/89356), which started up in 1961.

3 M. V. Ramana, The forgotten history of small modular reactors – Economics killed small nuclear power plants in the past – and probably will keep doing so, IEEE Spectrum April 2015 https://spectrum.ieee.org/the-forgotten-history-of-small-nuclear-reactors#toggle-gdpr

Many of these projects were supported by the AEC, which promoted nuclear power to U.S. utilities. Its first round of funding, announced in January 1955, went toward small units that could serve as "prototype reactors that would contribute to the development of large reactors," wrote Wendy Allen in her 1977 report Nuclear Reactors for Generating Electricity: U.S. Development From 1946 to 1963[4].
Of the four proposals submitted, the AEC funded three: the Yankee (not to be confused with the later and much larger Vermont Yankee), Dresden-I, and Fermi-I. Of these, Fermi is the best known, because it suffered a meltdown in 1966, which was colorfully described in John G. Fuller's 1975 book We Almost Lost Detroit [PDF] and Gil Scott-Heron's song of the same title. The other two reactors were relatively successful in meeting the goals they aimed for. The 185-MW Yankee, also known as Yankee Rowe, operated for 31 years; its decommissioning, however, took 16 years and cost $608 million.
As mentioned, the AEC viewed these reactors as prototypes of bigger things to come. It preferred large reactors to small ones for a simple reason: economies of scale. Many of the expenses associated with constructing and operating a reactor do not change in linear proportion to the power generated ».

1.2.2 Installations designed for military purposes

In the United States, the Air Force, Army and Navy all attempted to use small reactors.
In the Air Force, the program pursued from 1946 to 1961 to build a nuclear engine for long-range heavy bombers was recognized as a failure by President J. F. Kennedy.
On the Army side, the small reactors built are the closest to today's projects. The program involved the construction of 8 small reactors. Several of them were located in remote areas and in hostile, isolated conditions where the use of SMRs was in principle favourable: Antarctica, Greenland and remote or isolated military sites.
The following document from 1969 summarizes the results of the experiment, which was not repeated:

« The experience of these sites is not encouraging. The PM-3A plant at McMurdo Station in Antarctica, for example, "experienced several malfunctions, including leaks in its primary system [and] cracks in the containment vessel that had to be welded," according to the program's official history by Lawrence H. Suid. Leaks from the plant (which was owned and operated by the U.S. Navy) resulted in significant contamination, and 14,400 tons of soil were removed and shipped to Port Hueneme, a naval base north of Los Angeles, for disposal.
Unlike the Navy's submarine reactors, the Army's reactors could be replaced by conventional diesel generators, and in 1976 the Army canceled the program. As Suid writes, the Army concluded "that the development of complex, compact nuclear power plants of advanced design was expensive and time consuming... that the development and production costs of such plants are in fact so high that they can only be justified if the reactor has a unique capability and meets a clearly defined purpose supported by the Department of Defense.... [and that] the Army and the Pentagon should be prepared to provide financial support commensurate with the AEC's nuclear development effort". »

On the other hand, the use of small pressurized water and enriched uranium reactors (PWR) or boiling water reactors (BWR) for nuclear submarine and aircraft carrier engines has been a success, enabling submarines in particular to remain at sea for long periods without having to refuel.
Developed in the USA, these nuclear engines now equip similar fleets in the UK, France, Russia, China and India[5].

4 https://www.rand.org/content/dam/rand/pubs/reports/2007/R2116.pdf
5 India remains the only non-signatory to the NPT to have nuclear-powered submarines, with two Arihant-class SSBNs.

In addition to serving as a model for most of the world's current nuclear power reactors, naval propulsion reactors have also inspired several SMR designs, thanks to their compact design. However, as these installations are subject to military secrecy, it is difficult to draw any conclusions from them, since most of the technical difficulties or problems of irradiation of personnel have been kept under wraps. Nevertheless, some experts believe that nuclear problems were involved in the sinking of several American and Soviet atomic submarines.

1.3 Candidate Small nuclear reactors in operation or in construction

1.3.1 In Russia

Two KLT-40S enriched uranium pressurized water reactors, each with an electrical output of 35 MW, have been installed by Rosatom on a barge to form the Akademik Lomonosov "nuclear power plant on a barge".
The power plant is not intended to propel the barge, but to supply electricity and heat to local communities in a remote region, and was connected to the grid in 2019 in Pevek, a town of around 4,000 inhabitants in the Chukotka district, the main port on the East Siberian Sea and Russia's northernmost city. Unit 1 is currently shut down for steam generator replacement. Only unit 2 supplies electricity (20 MW), but its steam generators will also have to be replaced in 2024[6].
Rosatom is working on a more powerful reactor of the same type (VBER-300) for naval and possibly land-based applications. A barge equipped with two reactors would thus achieve a power output of 600 MW.

1.3.2 In China

Construction of a demonstration unit with two HTR-PM reactors (High Temperature Reactor - Pebble bed module) with a power output of 105 MW, i.e. 210 MW of electrical power for the two "modules".
Another more credible candidate for SMR status is the 125 MW, enriched uranium, pressurized water ACP100 (Linlong 1) reactor, based on the ACP 1000. This reactor has been under construction since July 2021 at Changjiang, in the province of Hainan Island, in the far south of China[7], and is scheduled to come on stream in 2025.
In addition, the construction of the first nuclear barge equipped with an ACPR 50 (enriched uranium and pressurized water, 60 MW) and that of a small power (2 MWth) molten-salt-cooled prototype reactor, the TMSR-LF1, have been launched in a Chinese province close to Mongolia (Gansu)[8].

1.3.3 In Argentina

The "Central Argentina de Elementos Modulares (CAREM)" reactor is a prototype of a small integrated pressurized light water reactor currently at an advanced stage of construction in Argentina, near Buenos Aires[9]. It would have a capacity of 27 MW of electrical power. Initially scheduled to start up in 2017, it is now scheduled to go into operation in 2027[10], and a larger version is planned for the future, with a capacity of between 150 and 300 MW.
All primary cooling system components have been incorporated into the reactor vessel.

On October 31, 2023, the developer Nucleoelectrica signed an agreement with the National Atomic Energy Commission (CNEA) for the development of the CAREM project.

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https://www.ifri.org/sites/default/files/atoms/files/ifri_fayet_lozier_propulsion_nucleaire_navale_2023.pdf
6 https://peretok.ru/news/generation/26970/
7 World nuclear news, Core module completed for Chinese SMR, July 2023 https://world-nuclear-news.org/Articles/Core-module-completed-for-Chinese-SMR
8 World nuclear news, Operating permit issued for Chinese molten salt reactor, June 2023 https://world-nuclear-news.org/Articles/Operating-permit-issued-for-Chinese-molten-salt-re
9 https://www.neimagazine.com/news/newsnew-agreement-seeks-to-support-argentinas-carem-smr-11261042
10 https://energynews.pro/en/agreement-in-argentina-for-the-carem-nuclear-project/

2. A SELECTION BY THE IAEA OF SIGNIFICANT PROJECTS

In its aforementioned 2022 report[11], the IAEA identifies 83 small reactor projects worldwide aiming for SMR status, most of which are at the "paper" design stage. On page 14, this document presents the most significant projects, either completed, under construction (see paragraph 1.3 of this note) or under study in countries already equipped with nuclear reactors for electricity generation:

- Thermal neutron reactors (light water moderator), enriched uranium and pressurized water (PWR) or boiling water reactors (BWR): 33 reactors.
- High-Temperature Gas-Cooled Reactors (HTGR): 17 reactors
- Liquid Metal-Cooled Fast Reactors (LMFR): 8 reactors
- Molten Salt Reactors (MSR): 13 reactors
- Microreactors: 12 reactors.

Just over a third of this selection is made up of water-cooled reactors, the majority of which are enriched uranium/pressurized water reactors (PWRs). These PWRs, which are SMR candidates at the project stage, are transposed from nuclear submarine propulsion reactors, making them the most advanced candidates for eventual SMR status.

The other reactors generally do not have satisfactory models in current or past operation, and their access to the SMR candidate stage will most probably require a long period of research and experimentation (prototype) before they can claim SMR candidate status.

In common language, the term SMR is actually used to designate three levels of facilities:

- ***First level: the nuclear reactor*** :
To qualify as an SMR, a nuclear reactor must be mass-produced in a factory and be transportable to the site. By extension, a prototype reactor that qualifies as an SMR is often referred to as an "SMR reactor".

Second level: a "module" :
Known as an SMR module, comprising the reactor and, for power generation, a turbo-alternator. The module is assembled on site using standardized parts. To qualify as an SMR, the module must have a maximum electrical output of 300 MW

- ***Third level: the power or heat generating plant***,
Comprising one or more modules, the complete SMR "power plant" is installed on the site.

In the following tables, the electrical power ("Output" in MW of electrical power expressed in MW(e)) is that of the SMR module.

11 IAEA, Advances in Small Modular Reactor Technology Developments, 2022 edition
https://aris.iaea.org/Publications/SMR_booklet_2022.pdf

Table 1 Design and Status of SMRs included in this Booklet

Design	Output MW(e)	Type	Designer	Country	Status
PART I.1: WATER COOLED SMALL MODULAR REACTORS (LAND BASED)					
CAREM	30	Integral PWR	CNEA	Argentina	Under construction
ACP100	125	Integral PWR	CNNC/NPIC	China	Under construction
CANDU SMR™	300	PHWR	Candu Energy Inc.	Canada	Conceptual Design
CAP200	> 200	PWR	SPIC/SNERDI	China	Basic Design
DHR400	400 MW(t)	PWR (pool type)	CNNC	China	Basic Design
HAPPY200	200 MW(t)	PWR	SPIC	China	Detailed Design
NHR200-II	200 MW(t)	Integral PWR	Tsinghua University and CGN	China	Basic Design
TEPLATOR™	< 150 MW(t)	HWR	UWB Pilsen & CIIRC CTU	Czech Republic	Conceptual Design
NUWARD™	2 × 170	Integral PWR	EDF	France	Conceptual Design
IMR	350	PWR	MHI	Japan	Conceptual Design Completed
i-SMR	170	Integral PWR	KHNP and KAERI	Republic of Korea	Conceptual design
SMART	107	Integral PWR	KAERI and K.A.CARE	Republic of Korea and Saudi Arabia	Detailed Design
RITM-200N	55	Integral PWR	JSC Afrikantov OKBM, Rosatom	Russian Federation	Detailed Design Completed
VK-300	250	BWR	NIKIET	Russian Federation	Detailed Design
KARAT-45	45 – 50	BWR	NIKIET	Russian Federation	Conceptual Design
KARAT-100	100	BWR	NIKIET	Russian Federation	Conceptual Design
RUTA-70	70 MW(t)	PWR (pool type)	NIKIET	Russian Federation	Conceptual Design
STAR	10	LWR (pressure tube)	STAR ENERGY SA	Switzerland	Basic design
Rolls-Royce SMR	470	PWR	Rolls-Royce SMR Ltd.	UK	Detailed Design
VOYGR™	4/6/12 × 77	Integral PWR	NuScale Power Corporation	USA	Equipment Manufacturing in progress
BWRX-300	270 – 290	BWR	GE-Hitachi Nuclear Energy and Hitachi-GE Nuclear Energy	USA and Japan	Detailed Design
SMR-160	160	PWR	Holtec International	USA	Preliminary Design Completed
Westinghouse SMR	> 225	Integral PWR	Westinghouse Electric Company LLC	USA	Conceptual Design Completed
mPower	2 × 195	Integral PWR	BWX Technologies, Inc	USA	Conceptual Design
OPEN20	22	PWR	Last Energy Inc.	USA	Detailed Design
PART I.2: WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)					
KLT-40S	2 × 35	PWR	JSC Afrikantov OKBM	Russian Federation	In Operation
ACPR50S	50	PWR (loop type)	CGNPC	China	Detailed Design
ACP100S	125	Integral PWR	CNNC/NPIC	China	Basic Design
BANDI-60	60	PWR	KEPCO E&C	Republic of Korea	Conceptual Design
ABV-6E	6 – 9	PWR	JSC Afrikantov OKBM, Rosatom	Russian Federation	Final design
RITM-200M	50	Integral PWR	JSC Afrikantov OKBM, Rosatom	Russian Federation	Basic Design Completed
VBER-300	325	Integral PWR	JSC Afrikantov OKBM, Rosatom	Russian Federation	Licensing Stage
SHELF-M	up to 10	Integral PWR	NIKIET	Russian Federation	Basic Design

PART II: HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR (pebble bed)	INET, Tsinghua University	China	In operation
STARCORE	14/20/60	HTGR (prismatic)	StarCore Nuclear	Canada	Pre-Conceptual Design
JIMMY	10 – 20 MW(t)	HTGR (prismatic)	JIMMY ENERGY SAS	France	Detailed Design
GTHTR300	100 – 300	HTGR (prismatic)	JAEA Consortium	Japan	Basic Design
GT-MHR	288	HTGR (prismatic)	JSC Afrikantov OKBM	Russian Federation	Preliminary Design Completed
MHR-T	4 × 205.5	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
MHR-100	25 – 87	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
AHTR-100	50	HTGR (pebble bed)	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design Completed
PBMR-400	165	HTGR (pebble bed)	PBMR SOC Ltd.	South Africa	Preliminary Design Completed
HTMR100	35	HTGR (pebble bed)	STL Nuclear (Pty) Ltd.	South Africa	Basic Design
EM^2	265	GFR	General Atomics	USA	Conceptual Design
FMR	50	GFR	General Atomics	USA	Conceptual Design
Xe-100	82.5	HTGR (pebble bed)	X-Energy LLC	USA	Basic Design
SC-HTGR	272	HTGR (prismatic)	Framatome, Inc.	USA	Preliminary Design
PeLUIt / RDE	40 MW(t)	HTGR (pebble bed)	BRIN	Indonesia	Conceptual Design
HTR-10	2.5	HTGR (pebble bed)	INET, Tsinghua University	China	Operable
HTTR	30 MW(t)	HTGR (prismatic)	JAEA	Japan	In operation

PART III: LIQUID METAL COOLED FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
BREST-OD-300	300	LMFR (pool type)	NIKIET	Russian Federation	Under Construction
ARC-100	100	LMFR (pool type)	ARC Clean Energy	Canada	Preliminary Design
4S	10	LMFR (pool type)	Toshiba Energy Systems & Solutions Corporation	Japan	Detailed Design
MicroURANUS	20	LBE-cooled Reactor	UNIST	Republic of Korea	Conceptual Design
LFR-AS-200	200	LMFR	*new*cleo srl	Italy	Conceptual Design
SVBR	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
SEALER-55	55	LMFR	LeadCold	Sweden	Conceptual Design
Westinghouse LFR	450	LMFR (pool type)	Westinghouse Electric Company, LLC.	USA	Conceptual Design

PART IV: MOLTEN SALT SMALL MODULAR REACTORS					
IMSR400	2 × 195	MSR	Terrestrial Energy Inc.	Canada	Detailed Design
SSR-W	300	MSR (static fuelled)	Moltex Energy	Canada	Conceptual Design
smTMSR-400	168	MSR	CAS/SINAP	China	Pre-Conceptual Design
CMSR	100	MSR	Seaborg Technologies ApS	Denmark	Conceptual Design
Copenhagen Atomics Waste Burner	20 MW(t)	MSR	Copenhagen Atomics	Denmark	Detailed Design
FUJI	200	MSR	ITMSF	Japan	Preliminary Design Completed
THORIZON	40 – 120	MSR	THORIZON	Netherlands	Conceptual Design
SSR-U	16	MSR	Moltex Energy	UK	Basic Design
KP-FHR	140	FHR	KAIROS Power, LLC.	USA	Conceptual Design
Mk1 PB-FHR	100	FHR	UC Berkeley	USA	Pre-Conceptual Design
MCSFR	50 / 200 / 400 / 1200	MSR (fast spectrum)	Elysium Industries	USA	Conceptual Design
LFTR	250	MSR	Flibe Energy, Inc.	USA	Conceptual Design
ThorCon	250	MSR	ThorCon International	USA and Indonesia	Preliminary Design Completed

PART V: MICROREACTORS					
Energy Well	8	FHTR	Centrum výzkumu Řež	Czech Republic	Pre-Conceptual Design
MoveluX	3 – 4	Heat Pipe (sodium)	Toshiba Energy Systems & Solutions Corporation	Japan	Conceptual Design
ELENA	0.068	PWR	National Research Centre "Kurchatov Institute"	Russian Federation	Conceptual Design
UNITHERM	6.6	PWR	NIKIET	Russian Federation	Conceptual Design
AMR	3	HTGR (prismatic)	STL Nuclear (Pty) Ltd.	South Africa	Pre-conceptual design
LFR-TL-30	30	LMFR	*new*cleo Ltd.	UK	Conceptual Design
U-Battery	4	HTGR	Urenco	UK	Conceptual Design
Aurora	1.5 – 50	LMFR	OKLO, Inc.	USA	Detailed Design
HOLOS-QUAD	10	HTGR	HolosGen LLC	USA	Detailed Design
MARVEL	0.015 – 0.027	LMFR	Idaho National Laboratory	USA	Equipment manufacturing in progress
MMR™	> 5 and > 10	HTGR	Ultra Safe Nuclear Corporation	USA	Basic Design
Westinghouse eVinci™	2 – 3.5	Heat Pipe	Westinghouse Electric Company, LLC.	USA	Conceptual Design Completed

Note :
CNEA — National Commission for Atomic Energy (Argentina);
CNNC — China National Nuclear Corporation ;
EDF — French National Electricity company ;
CEA — French Atomic Energy Commission
KAERI — Korea Atomic Energy Research Institute;
K.A.CARE — King Abdullah City for Atomic and Renewable Energy, Saudi Arabia.

3. DESCRIPTION OF TWO SMR CANDIDATE PROJECTS: NUSCALE AND NUWARD

Among the 8 PWR reactors in part I.1 of the previous IAEA selection, we have chosen two PWR SMR projects: the American NuScale, currently the most advanced in terms of approvals, and the French NUWARD, in both cases with a high level of public funding.

3.1 The NuScale project

In January 2017, NuScale submitted its application to the US Nuclear Regulatory Commission (NRC) to build a 12-module power plant, each with an electrical output of 60 MW, to be constructed on the site of a federal research center, the Idaho National Laboratory[12].
On August 2, 2022, NuScale obtained final approval of its concept (design) from the NRC (which is not the authorization to create the plant).
Subsequently, in 2021, the project was modified: the new plant would comprise 6 modules of 77 MW each, on the same site. This new project is called VOYGR[13] .

3.1.1 The NuScale module reactor

The VOYGR module reactor presented by NuScale is a small PWR reactor with a thermal output of 250 MW and a gross electrical output of 77 MW. The fuel is uranium enriched to 4.95%. The average discharge burnup of the fuel assemblies would be of the same order as that of 900 MW PWRs: 33 MWd/t (megawatt.day per ton).
The reactor core is made up of 37 assemblies of 17x17 fuel elements. It is immersed in cooling water that circulates (equivalent to the primary circuit) by natural convection (no pumps) around the helical steam generator.
The secondary loop that transports steam from the steam generators to the turbines requires motor-driven pumps located outside the module.
The pressurizer (several elements inside the reactor) maintains water pressure at 138 bar[14] in the primary circuit (upstream of the steam generator) and 43 bar in the secondary circuit. Control of the chain reaction is ensured by boron in the cooling water and 16 control rod assemblies whose drive system is outside the reactor.
The lower part of the reactor vessel is equipped with flanges located just above the core to enable fuel element assemblies to be unloaded and loaded.
One third of the core is reloaded over an 18-month cycle, according to an "in-out" scheme[15].
During the refueling process, one third of the fuel assemblies are removed from the core and placed in the spent fuel pool.
The pool is connected to the ultimate heat sink and is therefore protected by the reactor building.
The spent fuel storage racks contain enough storage for around 18 years of operation, including five defective fuel assemblies and non-fuel core components such as a control rod assembly.

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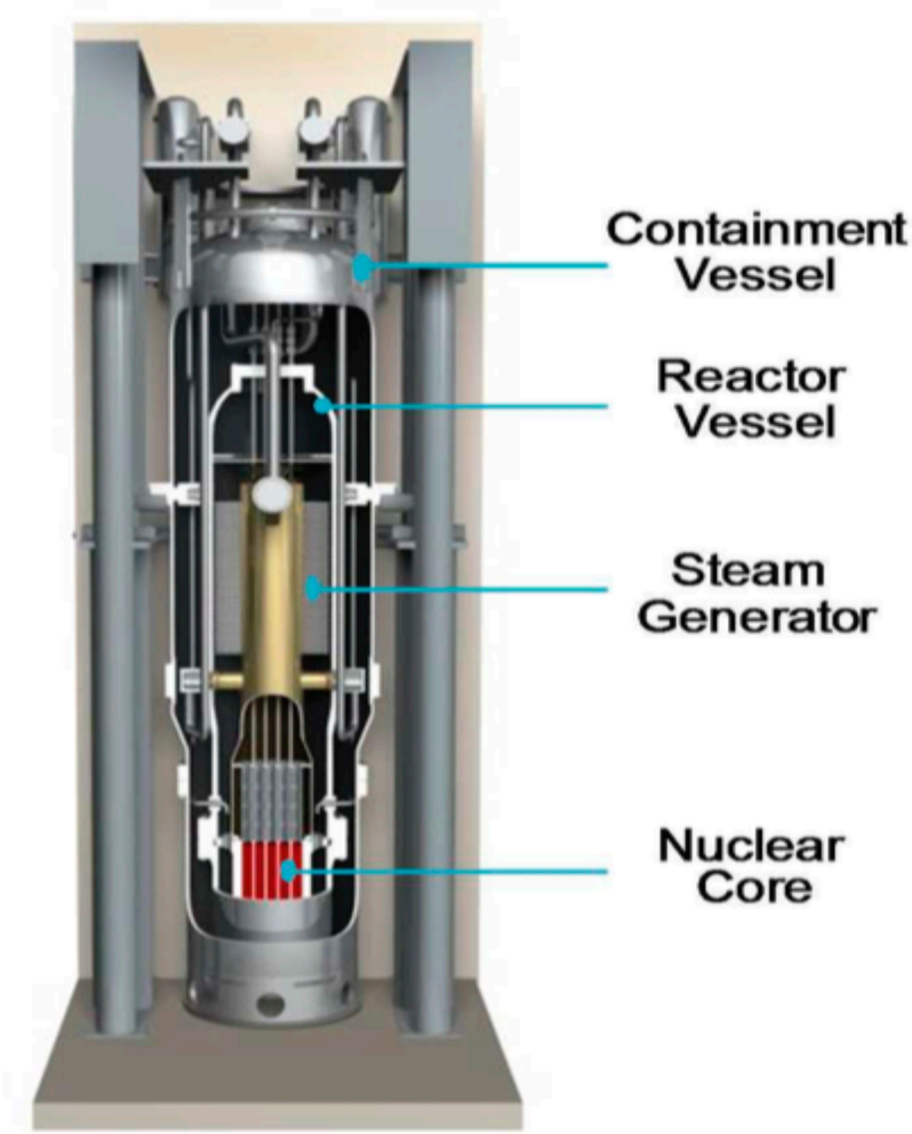
12 IAEA, Advances in Small Modular Reactor Technology Developments, edition 2020
https://aris.iaea.org/Publications/SMR_Book_2020.pdf
13 https://www.nuklearforum.ch/fr/nouvelles/etats-unis-un-soutien-massif-la-poursuite-du-projet-voygr-de-nuscale
14 To be compared to 150 bar in a commercial 900 MW(e) PWR.
15 UARGA – l'expertise des anciens du nucléaire, Les petits réacteurs modulaires (SMR), 2021
https://www.uarga.org/nucleaire/reacteur_SMR.php

The designers claim that emergency cooling in the event of a power failure in the plant would be provided using a series of valves that do not require electrical power to open or close and reach their correct position (Neve system).

Figure 1 shows the reactor from the initial project, before the VOYGR model was proposed.

Figure 1 : The NuSale reactor



Source : AIEA (2020)[16]

Figure 2 simulates the transport of the NuScale SMR reactor from the series production plant (for modular qualification) for on-site integration into the SMR module(s) of the SMR power plant.

16 https://aris.iaea.org/Publications/SMR_Book_2020.pdf, page 89.

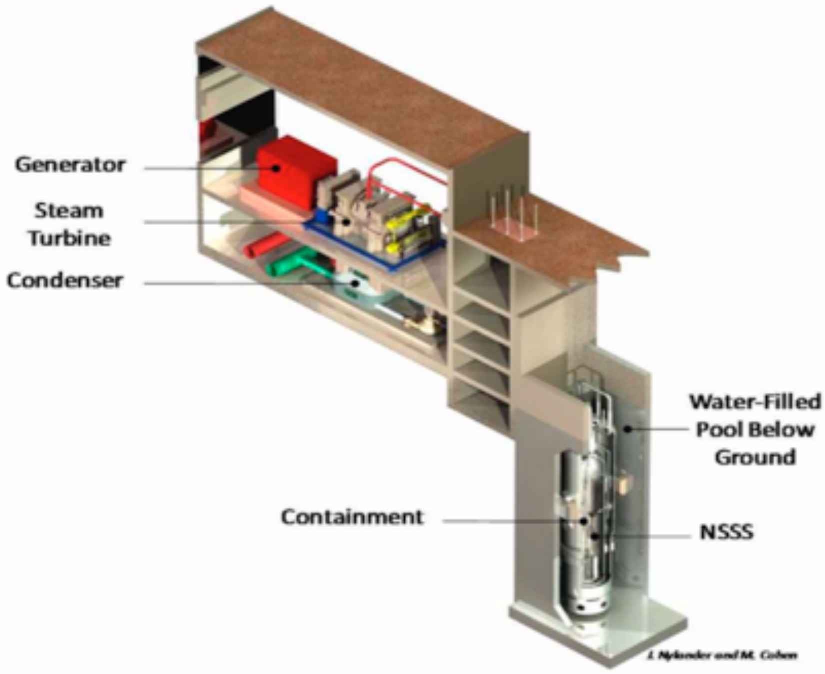
Figure 2 : Simulation of the transportation of the NuScale reactor

Source : NuScale

3.1.2 The NuScale module

Each reactor (nuclear steam supply system) is connected to a turbine and a turbo-alternator, as shown in Figure 3.

Figure 3 : The NuScale module[17]



Source : AIEA (2013)

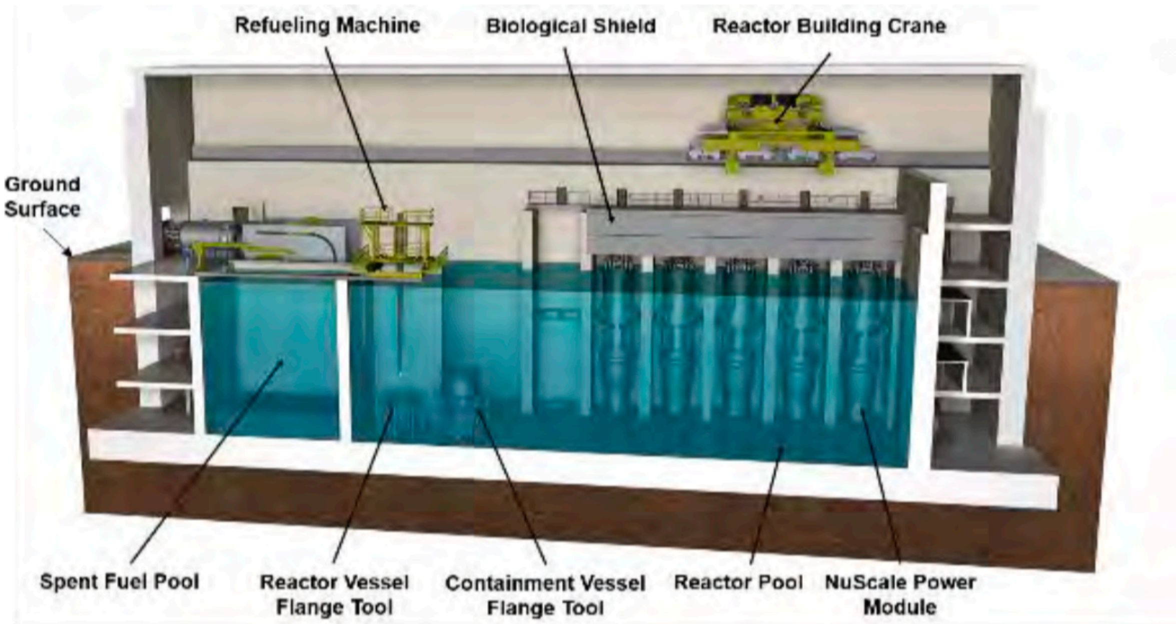
The complete, independent module is made up of the reactor described above, immersed in a vertical underground water basin, that produces steam, and the turbine, coupled to the electricity generator (turbo-alternator). A number of these autonomous modules are then aligned to form the power plant described in the next paragraph.

17 NuScale Power Modular and Scalable Reactor, July 2013 https://aris.iaea.org/PDF/NuScale.pdf

3.1.3 The NuScale power plant

By grouping together 12 independent modules and adding a number of installations required for their operation, we end up with the "NuScale nuclear power plant" shown in Figure 4. Using the same architecture, the new NuScale VOYGR model consists of 6 modules, each with an electrical output of 77 MW(e).

Figure 4: The NuScale SMR nuclear power plant



Source : AIEA (2020)

The modules are contained in a large underground basin filled with borated water (which would provide 72 hours of cooling in the event of loss of external power supply due to an accident).
In fact, the modules share a number of facilities. It's hard to believe that operations could continue normally in the event of a serious problem with one module.

NuScale's VOYGR project for a 462 MW power plant (six 77 MW modules) would be the first power plant in operation to qualify as an "SMR" (figure 5).
This prototype would be located in Idaho Falls (Idaho National Laboratory).The entire facility would occupy a footprint of 140,000 m2.
In May 2023, NuScale announced the manufacture of the first forged parts, in South Korea[18].

18 https://twitter.com/NuScale_Power/status/1653461908383731712

Figure 5 : Simulation of the VOYGR-6 power plant

Source : NuScale

3.2 The NUWARD Project

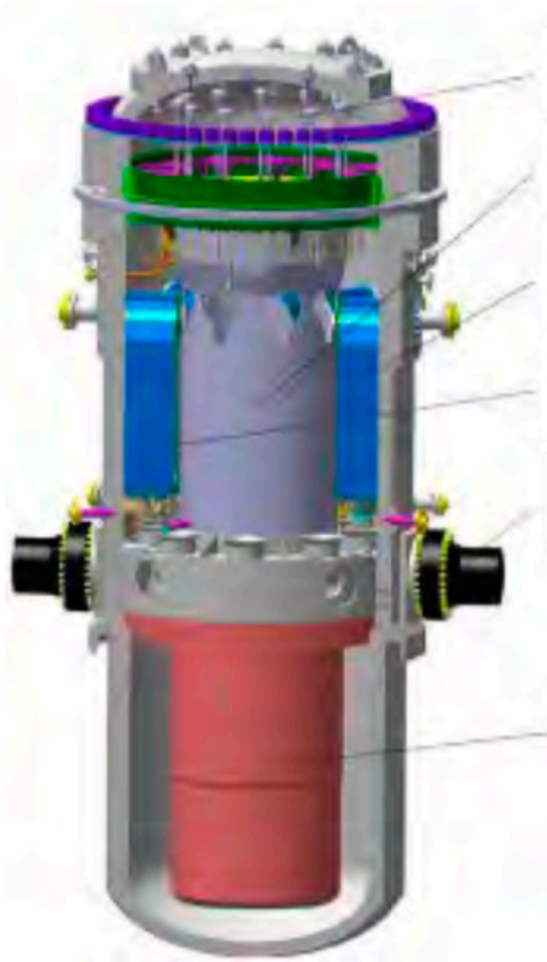
The NUWARD small reactor SMR project is being carried out by the French consortium comprising Electricité de France (EDF), the Commissariat à l'énergie atomique (CEA, civil and military), and the companies TechnicAtome and Naval Group, which have designed and manufactured PWR reactors for the needs of the nuclear-powered navy.

The NUWARD project involves the construction of a 340 MW nuclear power plant consisting of two 170 MW modules - a strange name for a French reactor! NuWard modestly stands for "NUclear ForWARD".

3.2.1 The reactor of a NUWARD module

The NUWARD reactor would be an enriched uranium pressurized water reactor (PWR), "integrated" in the sense that it brings together in the same vessel all the main components: the reactor core in which fissions and chain reactions produce heat, the steam generators, the pressurizer, the control mechanisms and the primary pumps, arranged as shown in figure 6.

Figure 6 : The NUWARD reactor (first vessel)



Source : AIEA 2020[19]

CRDM : control rod drive mechanism

In this project, the various components are:

Reactor core

The reactor core is made up of 76 assemblies of 17x17 enriched uranium fuel elements (less than 5%), similar to those used in conventional PWRs, but shorter.
Core inlet and outlet temperatures are 280/307°C.
Refuelling is carried out in halves every 24 months (15-day shutdown), with one reactor shut down while the other continues to operate.
The reactor is expected to operate for 60 years.
Major innovations have been made in passive safety.

The cooling system and steam generator

Six plate heat exchangers.
Six pumps are mounted horizontally inside the reactor, positioned under the steam generators in the cold branch of the primary circuit (circuit between the condenser return and the reactor core).

The steel enclosure of the integrated assembly "core, pressurizer, steam generators, control rods "

19 https://aris.iaea.org/Publications/SMR_Book_2020.pdf, page 37.

This enclosure is 4 m in diameter and 13.50 m high. By analogy with conventional reactors, this first vessel can be considered the "first vessel" of the reactor.

A second steel vessel, the containment vessel

The first vessel is then housed inside a new metal vessel filled with water, the whole weighing 310 tonnes and forming the NUWARD reactor (figure 7). This second vessel is the equivalent of a conventional reactor containment vessel. Its size and weight could pose problems for transport to and from the plant site.

Figure 7 : The NUWARD reactor (second vessel))

	The integrated assembly (Figure 6) is located inside the reactor containment vessel. Inside this vessel are two steam generators, independent of the six inside the first enclosure shown in Figure 6.

Source : AIEA (2020)

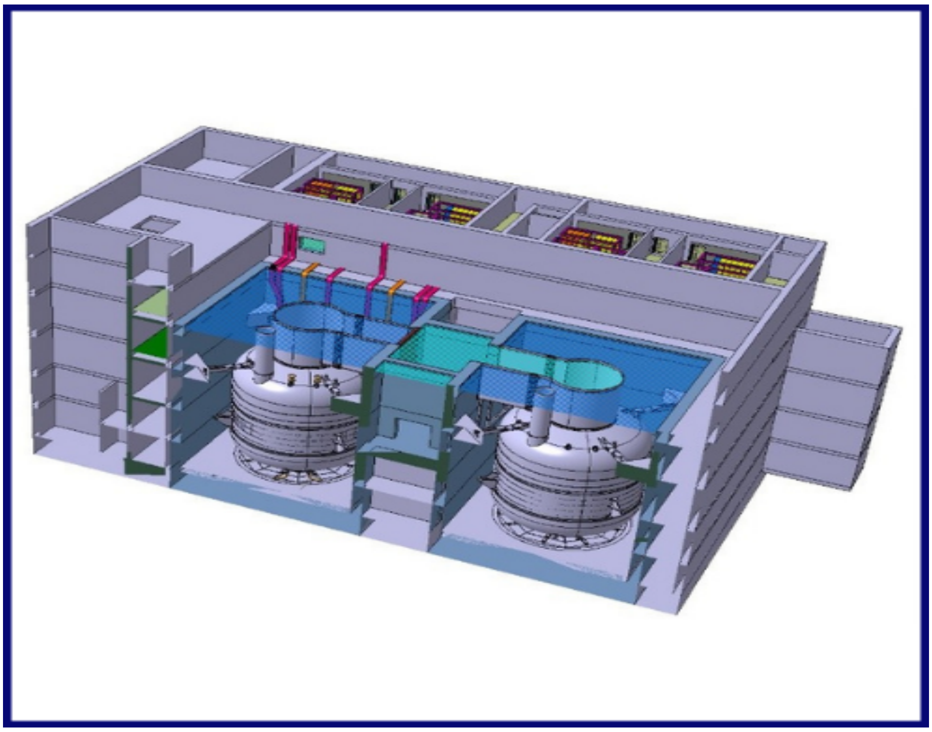
3.2.2 The NUWARD module

The 170 MW NUWARD module comprises the reactor (figure 7), turbine, condenser and alternator, plus a transformer connected to the transmission grid. The reactor would be delivered from its place of manufacture (a plant producing in series in the case of a true SMR). The module and other installations would also be delivered and assembled on site.

3.2.3 The NUWARD power plant

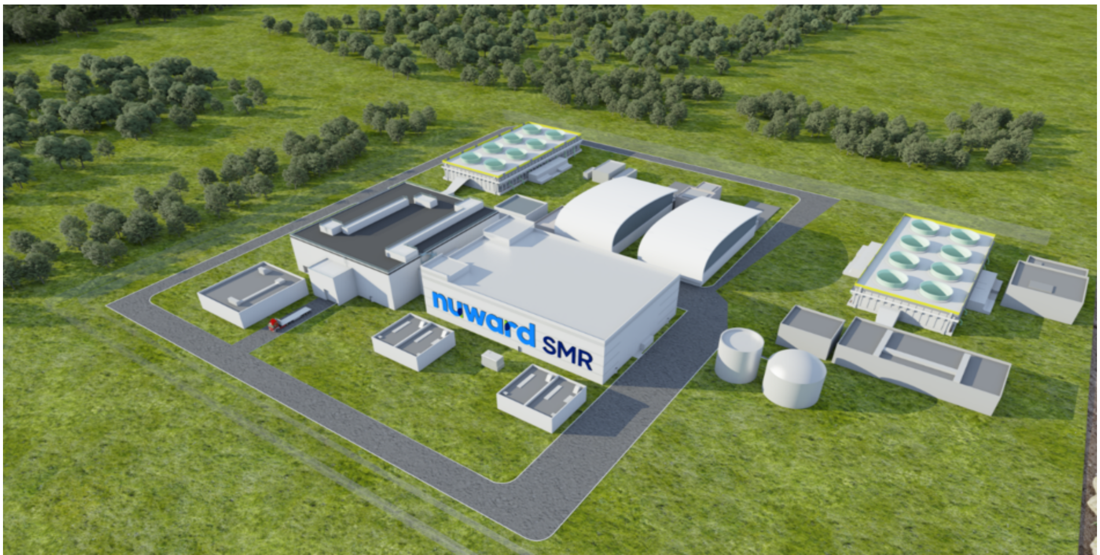
The NUWARD power plant consists of two NUWARD modules joined together (Figure 8).
Each reactor would be immersed in a water basin measuring 25 by 25 metres.
The whole unit would be semi-buried to protect it from external aggression.
Its footprint would be 3500 m2. This is probably the footprint of the installation shown in Figure 8, but the assembly shown in Figure 9 would certainly be much larger.
Figure 8 shows only the juxtaposition of the two modules.
Other installations remain to be planned, notably for the control room, fuel loading and unloading pools, irradiated fuel storage, maintenance workshops, workers' accommodation and living quarters, parking lots and garages, etc.

Figure 8: The NUWARD power plant



Source : Usine Nouvelle

Figure 9 : Model of the future NUWARD power plant



Source : French Embassy in Finland[20].

20 https://fi.ambafrance.org/Le-petit-reacteur-modulaire-francais-NUWARD-SMR-developpe-en-partenariat-avec

4. TECHNICAL, SAFETY AND ECONOMIC ANALYSIS OF THE TWO PROJECTS

The two candidates for SMR status, NuScale and NUWARD, are both enriched uranium and pressurized water reactors (PWRs). This similarity with the reactors that power nuclear submarine engines, and with the majority of reactors used in power plants worldwide, suggests that it should be easier for them to obtain the necessary approvals, and to be deployed on an industrial scale.

But despite these similarities and apparent ease of use, we must realize that these two projects are very different from their "models", and very different from each other, which is what we are going to analyze.

4.1 POWER PLANTS

4.1.1 NuScale

Having received final design approval from the NRC on August 2, 2020, NuScale was aiming for the first start-up of a first 60 MW module in 2029. In December 2021, NuScale proposed a power plant, dubbed VOYGR, comprising six small pressurized water reactors with an electrical output of 77 MW. This new NuScale plant would have a gross electrical output of 462 MW.

As the output - and the number of modules - has varied over time, the project must once again undergo a technical review by the NRC. But other difficulties lie elsewhere: its first customer would be a union of municipalities (UAMPS), some of which have not yet signed electricity sales contracts following the announcement in November 2022 that the cost of the project would be revised upwards.

According to its designers, the advantage of operating with 12 or 6 independent modules is that, should one of the modules fail, it can be isolated and the plant's output reduced by only 8% or 17%. This possibility, widely emphasized by the promoter, is probably guaranteed in the event of a reactor shutdown for checking or maintenance, but most likely disappears in the event of an incident or accident, depending on the severity of one or the other.

The promoter expects the plant to operate for 60 years[21].

4.1.2 NUWARD

The NUWARD power plant is very different in that, consisting of two 170 MW modules, it is expected to have an output of 340 MW. In addition to economic reasons, real or assumed, the decision to install two reactors is intended to ensure continuous operation of at least one of them, when the other would have to be shut down, either due to a lower demand for electricity, refuelling, or some other reason for interrupting operation.

The same question then arises as for NuScale: while this two-reactor configuration may be of real interest at isolated sites to ensure maximum continuity of production, it is hard to see how it could be of interest at sites connected to the interconnected electricity transmission grid.

One question that arises for both NuScale and NUWARD is how many people will be needed to operate the plant, in normal operation and during refuelling, for maintenance work, in the event of an incident or accident, etc. In the case of NUWARD, the project manager recently quoted the figure of 250 people in normal operation.
As for NuScale, the operating life envisaged by the promoter is 60 years.

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21 https://aris.iaea.org/Publications/SMR_Book_2020.pdf

4.2 Modules

In NuScale, the modules are clearly independent, and one can probably be removed if there is a problem. However, in the event of an accident, it may be necessary to shut down all the reactors.
This does not appear to be the case for NUWARD, as shown in the diagram in figure 7.

For either NuScale or NUWARD, the question arises of the external power supply in the event of a failure of the turbine, alternator and condenser system, even if only on one module. Are emergency diesels planned to keep the reactors running, as well as the necessary fuel reserves on site?

Another question: we know that "conventional" PWR reactors, such as those in the French nuclear power fleet[22], experience frequent incidents during normal operation that do not jeopardize reactor safety, but do require the reactor to be shut down for maintenance. It's hard to imagine that this can't happen to these reactors, whether they're prototypes or factory-built SMRs. In the latter case, a fault in the factory would have considerable economic consequences. Should the reactors be "repatriated", as is the case for cars, for example, or repaired on site?
This possibility does not appear to be considered in either project.

4.3 Reactors

A common feature of both projects is the "compact" nature of the reactor, which contains in the same enclosure the reactor core (fuel elements, site of fissions and chain reactions that heat the coolant water), the control rods, the steam generator(s) and the pressurizer. This promiscuity means that neutron fluxes from fissions in the core can damage other equipment.

4.3.1 A major difference in cooling water circulation:

In NuScale, the core is cooled by natural convection for the primary cooling circuit, which transports heat to the steam generators - i.e. without a cooling pump - whereas the secondary circuit, which transports steam from the steam generators to the turbines, requires motor-driven pumps located outside the module. See 3.3.2 for a discussion of the potential problem of powering these pumps, as well as the control rod drive system, which is also located outside the reactor. In NUWARD, the heat transfer system from the core to the plate steam generators is carried out by six pumps mounted horizontally inside the reactor, positioned under the generators in the cold branch of the primary circuit (the circuit between the condenser return line and the reactor core). There must therefore be a power supply inside the reactor, subject to irradiation from the reactor core.

4.3.2 Steam generators

The integration of steam generators in the same confined space as the reactor core calls for compact geometries. This increases the intensity of the radioactive environment in which steam generators have to operate, compared with the situation in large power reactors, which could lead to corrosion rendering them inoperable. We know that under less difficult conditions, steam generators in large power reactors are replaced at least once during their operating life. On the SMR site, such replacement would appear to be impossible: a faulty generator would most likely lead to the permanent shutdown of the module concerned.

22 https://www.global-chance.org/L-accumulation-d-incidents-graves-temoigne-de-l-etat-inquietant-du-parc-electronucleaire

4.3.3 Pressurizer valves

The pressurizer valves can be damaged by neutron flux from the core or by thermal variations (a problem detected on large power reactors).

4.3.4 Impact of fluence on reactor vessel fragility

In nuclear reactor physics, reactor vessel fluence is the integral over a given operating time of the flux of neutrons produced in the reactor core that bombard the vessel wall. Fluence is expressed as the number of neutrons per cm2. The ductile-brittle transition temperature of the reactor vessel steel increases with fluence. Its evolution over time could lead to a shorter operating time for the vessel, and therefore the reactor, than envisaged by the project promoters. This is an essential safety parameter in certain accident scenarios.

4.3.5 Fuel loading and unloading

Fuel for both reactors is conventional: rod assemblies containing enriched uranium pellets, comparable to those used in conventional power reactors, but shorter.

We saw in NuScale that the unloading of irradiated fuel and its replacement with new, whole-core fuel would take place in thirds every 8 months to 2 years.
To achieve this, the reactor of the module concerned, after the chain reaction has been stopped and all external links disconnected, is treated as follows[23]:

a) The reactor is moved, under water, into a first basin of borated water, where the reactor vessel is extracted from the containment (the cover of which is unscrewed to allow this extraction via the flanges provided for this purpose).
b) The vessel is transferred to a second borated-water pool, where it is in turn opened (flanges) to enable the irradiated fuel assemblies to be extracted.
c) The irradiated fuel assemblies are transferred to the spent fuel pool, where the fresh fuel assemblies are also stored.
d) Reverse operations place the new fuel assemblies in the reactor vessel (second pool), then move it into the containment vessel (first pool) and return the reactor to its normal position.

We have no more recent information on this operation.

In the case of NUWARD, according to IAEA 2022[24] , the unloading of irradiated fuel and the loading of new fuel into each reactor would take place by half-core every 24 months. We have no detailed information on the loading and unloading of fuel in the case of NuScale, it is likely that dry storage of irradiated fuel will be used after its stay in the pool, as is the case for existing nuclear power plants in the U.S.

In the case of NUWARD, either the same solution will be used, or, if the policy of reprocessing irradiated fuel is maintained, irradiated fuel will be sent to the reprocessing plant. In this case, as for "conventional" reactors, we come up against the fact that the current La Hague plant is not expected to operate beyond 2040-2050, and that the cost of a new plant would probably be prohibitive.

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23 https://www.nrc.gov/docs/ML0908/ML090850080.pdf. *« Refueling operations report for the NuScale power module »*.
24 https://aris.iaea.org/Publications/SMR_booklet_2022.pdf

4.3.6 Plant decommissioning

There is no information available on the decommissioning of SMRs, whether they are prototypes or full-scale, mass-produced SMRs.
For conventional reactors in today's nuclear power plants, dismantling is carried out entirely on site, with the aim of "returning the reactor site to green field" as soon as possible after definitive closure, removal of all fuel assemblies and sufficient time (several decades) to reduce radioactive emissions from equipment inside the containment.
In the case of a future SMR prototype of the type we are studying here, it is conceivable that the reactor, once all the fuel assemblies have been removed and the reactor's radioactivity has been reduced sufficiently for it to be transported, would be moved to a dedicated site.
For the first NuScale prototype, located on the Idaho National Laboratory (INL) site, dismantling could probably take place on the site itself.
For NUWARD, this could also be the case if the chosen site has the necessary facilities (a CEA center, Marcoule, for example).

In the case of real SMRs, a "dismantling plant" will have to be built, possibly close to the construction plant. Admittedly, the dismantling method can be standardized, but even factory-built reactors may differ in certain respects, notably in the quality of the steels used.

4.4 The safety of the NuScale project

4.4.1 The NuScale project appraisal process

In September 2020, the U.S. Nuclear Regulatory Commission (NRC) approved the application for standard design certification of an integrated plant consisting of 12 small NuScale modular reactors, the "NuScale US600" model[25].
The NRC published the certification of this model in July 2022[26], but NuScale subsequently modified its standard design and proposed the "NuScale US460" model, VOYGR, consisting of 6 modules of 77 MW electrical power, making a 462 MW plant.

In November 2022, the NRC sent NuScale its report assessing NuScale's readiness to apply for approval of the standard design of its SMR project, a document we present in the following paragraph. In early 2023, the NRC announced that it would begin reviewing the bulk of the Standard Design Approval (SDA) application - NuScale Model US460 (VOYGR) for NuScale Power's Small Modular Enhanced Reactor technology, with the remainder of the review suspended until the company provides additional detail on a key safety issue.

4.4.2 The US Nuclear Safety Authority's opinion on the NuScale project

NRC letter to NuScale

NRC letter to NuScaleThe NRC letter to NuScale is attached as Appendix 4.
The process is well explained in the following excerpts:

« The attached comment report presents the NRC staff's observations on NuScale's draft SDA[27] application. The staff observed and acknowledged that NuScale's draft SDAA[28] is a work in progress and that several chapters are incomplete or have not been updated to take into account the US460 model. In addition, several documents referenced in the draft SDAA

25 Design Certification – NuScale US600, United State Nuclear Regulatory Commission
https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/nuscale.html
and : Federal Register/Vol. 88, No. 149 / Friday, August, 2023 / Notices
https://www.govinfo.gov/content/pkg/FR-2023-08-04/pdf/2023-16679.pdf
26 Office of nuclear energy, NRC Certifies first U.S. small modular reactor design, January 2023
https://www.energy.gov/ne/articles/nrc-certifies-first-us-small-modular-reactor-design
27 SDA : Standard design approval
28 SDAA : Standard design approal application

(thematic reports, technical reports, calculations, technical tables, references, information on probabilistic risk analysis, etc.) were not made available to the NRC team during the readiness assessment. As a result, the NRC did not observe the entire SDAA application proposal, and therefore cannot provide a complete assessment of the draft application. In addition, the NRC team's observation report does not include information that NuScale knows is missing or incomplete, and the observations (included) do not predetermine whether the SDA application will be accepted for review. »

...

« Overall, staff identified several difficult and/or important issues that could be areas of focus for SDAA acceptance and/or safety review.
While there has been early engagement on these topics, the team encourages continued engagement on these topics until the SDAA is submitted.
These topics are:

- *Safety classification of the Enhanced Direct Current Supply System (EDAS)*
- *Overall vibration assessment plan and steam generator tube support*
- *Density wave oscillation analysis*
- *Containment vessel and reactor vessel materials*
- *Loss of coolant accident analysis*
- *SDA optimisation. »*

***The NRC report*[29]**

This report is very interesting and deserves to be read carefully. We'd like to highlight a few points:

a) Under the heading "All", covering the entire file, three paragraphs:

« The (NRC) expert team found that the effort to 'optimize' the Standard Design Approval (SDA) application may have removed information necessary to support a reasonable assurance of public health and safety ».

...

« The application makes numerous references to other sections that are not available for the NRC team to review and confirm compliance. For example, the reference to section 9.2.5 for the design of the Spent Fuel Pool (SFP) level gauge, for safe water levels for shielding and cooling, and the thermal assessment of the accident scenario".

...

Partial quote:

"Discussions with NuScale have shown that the SDAA will be a stand-alone application and that much of the documentation made available is under development. During the review of the Chapter 10 system readiness assessment, the NRC team found that there was insufficient system design and operational information to understand the system design and the potential impact of system operation or failure on plant safety or radiological release potential. »

b) Some specific points, by way of example:
- Between the report on the previous model (US600), and the present report on the US460 model, several elements have been deleted, particularly with regard to seismic risk.

- Requests concerning, for example:

29 United States nuclear Regulatory Commission, Preapplication readiness assessment report of the NuScale power, November 2022
https://static.ewg.org/upload/pdf/NRC_readiness_assessment_report_111522.pdf?_gl=1*1i2ys8w*_gcl_au*MjkzMjAzNDU5LjE2OTIyODUxNzA.*_ga*MTc2MTU5NzAwMS4xNjkyMjg1MTcw*_ga_CS21GC49KT*MTY5MjM1MzQ3Ny4yLjAuMTY5MjM1MzQ3Ny4wLjAuMA..&_ga=2.108660288.376542262.1692285170-1761597001.1692285170

- steam generator supports
    - flooding risks
    - protection against missiles and other external hazards
- Lack of information on :
    - calculations concerning the core, control rods, boron injections
    - steel quality (ductility?)
    - equipment ageing
    - welds

We can see that many of the problems that have arisen, and are still arising, for large power reactors can be found in the SMR projects.
Of particular significance is the emphasis placed by the NRC upon security issues (malicious external aggression, terrorism or acts of war), as well as natural external aggression - earthquakes, heat waves, floods - which will inevitably worsen with climate related disruptions.

4.4.3 Union of concerned scientists

We reproduce here extracts from an article in the "Union of concerned scientists" from September 2013[30]. Although relatively old, this article retains its relevance."

« Generally speaking, the technical challenges of ensuring the safety of small modular reactors are not qualitatively different from those of large reactors. Whatever the size of the reactor, systems must be put in place to ensure that the heat generated by the reactor core is removed, under normal conditions and in the event of an accident, at a rate sufficient to prevent the fuel from overheating, being damaged and releasing radioactivity. The effectiveness of these systems depends on the details of their design. Even nuclear fuel in spent fuel pools, which generally have much lower heat loads than reactor cores, can overheat and rupture if adequate cooling is not provided." ...
" Some SMR designs [...] are small enough that cooling by natural convection is sufficient to maintain the core at a safe temperature in the event of a serious accident such as a power failure in the plant". ...

" While there is no doubt that natural circulation cooling could be effective under many conditions for such small reactors, it is not true that these reactors would be intrinsically safe under all accident conditions. In some accident scenarios, heat transfer conditions would not be ideal and natural convection cooling could be impeded. For example, for the NuScale design, a major earthquake could send concrete debris into the pool, obstructing water or air circulation. Indeed, no credible reactor design is totally passive: no design can shut down and cool itself under all circumstances without the need for a natural convection cooling system.
Even passively safe reactors require certain equipment, such as valves, which are designed to operate automatically. But no valve is 100% reliable. ...

" Furthermore [...] accidents affecting more than one small unit can lead to complications that may exceed the ability to cope with multiple failures, outweighing the benefits of reduced heat removal requirements per unit."

We have seen that the passive circulation of cooling water in NuScale was only for the primary loop, and that a pump (with external power supply) was needed for the secondary

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30 , « *Small isn't always beautiful* », Edwin Lyman, September 2013
https://www.ucsusa.org/sites/default/files/2019-10/small-isnt-always-beautiful.pdf

circuit. In NUWARD, the pumps for cooling water circulation are located inside the reactor (powered from inside the reactor)

" The need to reduce the capital costs of SMRs has led to a reduction in the size and robustness of an important passive safety system, the containment structure. None of the PWR models has a containment structure around 1.5 meters around the reactor with sufficient strength and volume to withstand the forces generated by overpressure and hydrogen explosions in the event of severe accidents. SMRs must therefore rely on means to prevent hydrogen from reaching explosive concentrations. However, neither active means (hydrogen igniters) nor passive means (hydrogen recombiners) of hydrogen control are likely to be as reliable as a robust containment system. In addition, smaller containments generally result in greater coupling between the reactor core and the containment, which can have negative safety consequences "....

" Some SMR suppliers are proposing to install their reactors underground, which they see as a major safety advantage. While underground siting enhances protection against certain events, such as aircraft attacks and earthquakes, it can also have disadvantages.

To this must be added the vulnerability of semi-underground installations to flooding. What's more, in the event of a serious accident, emergency crews could find it more difficult to access underground reactors.

*" **Complications linked to the presence of several reactors on the same site** :*
*"Supporters of SMRs often claim that, as with the next generation of large reactors, the probability of core damage may be lower for SMRs than for reactors currently in service. While this is true, it is important to note that these claims refer to the frequency of internal events such as pipe breaks. However, when external events such as earthquakes, floods and fires are added to a probabilistic risk assessment, the Nuclear Energy Institute (NEI) - the nuclear industry's policy organization - has pointed out that "**calculated risk parameters for new reactors are likely to increase and thus be closer to current plants than those presented toda**y" (NEI)." ...*

*" SMR proponents also point out that the risk to the public from smaller reactors is lower than that from larger reactors, due to the fact that there is less radioactive material in the core. While this is certainly true, it is not the most useful comparison.**The relevant factor with regard to societal risk is not risk per unit, but risk per megawatt of electricity generated. By this measure, smaller reactors do not necessarily imply lower risks if there are more of them.**"....*

" For each reactor to remain independent, the number of support staff and the quantity of safety equipment would have to increase with the number of reactors on a site. However, only by significantly sharing systems and personnel between several units could the resulting increase in costs be moderated. This is why SMR suppliers are keen to reduce the number of control rooms and certified operators that the NRC would normally require for a number of units. For example, in the NuScale design, a single control room operator could be responsible for 12 units, the feasibility of which would have to be verified by performance tests."

4.4.4 A recent study for the "Environmental Working Group

We quote significant excerpts concerning nuclear safety from a very comprehensive article by A. Makhijani and M.V. Ramana dated April 9, 2023, which we recommend reading in full:

"Questions for NuScale VOYGR Reactor Certification: When will it be done? And then, will it be safe?[31]

"Of the projects currently scheduled for deployment, the NuScale 77-megawatt pressurized water reactor concept (named VOYGR) is the one for which the U.S. Nuclear Regulatory Commission (NRC) certification process is most advanced for small modular reactors (SMRs). But it's unclear how the process will proceed; it will probably be delayed yet again due to safety issues surrounding this model. The NuScale saga once again suggests that the SMR boom will take a long time, if ever. ...

I. Problems with the NuScale 50 MW model

"The Nuclear Regulatory Commission's (NRC) final decision identified "three unresolved issues". The NRC stated that it did not have sufficient information "regarding (1) the design of the barrier wall in certain areas of the plant, (2) the potential for leakage from the fuel gas monitoring system containment, and (3) the ability of the steam generator tubes to maintain their structural integrity and tightness during density wave oscillations in the secondary circuit." We elaborate on the third issue below, which we consider particularly important for the design of the 50 MW model, and even more so for the 77 MW version.

i. Steam generators

A major concern that emerged during the certification process for the 50 MW model concerned steam generator stability, and was identified in a March 2020 letter from the NRC Advisory Committee on Nuclear Safety (ACRS). The ACRS letter noted that "steam generator design and performance [had] not yet been sufficiently validated". No civil nuclear power plant uses the steam generator design proposed by NuScale; the ACRS pointed out that it "introduces various failure modes".

The NRC confirmed the ACRS findings, echoing the ACRS conclusion that "steam generator design and performance have not yet been sufficiently validated due to uncertainties associated with unstable density wave oscillations (DWO) on the secondary side of the steam generator".

Steam generator integrity is a major safety issue. In pressurized water reactors in operation, the primary circuit water circulates through a large number of U-shaped bent tubes; it never boils. Secondary circuit water flows vertically through these tubes and boils; steam accumulates at the top to be sent to feed the turbine-generator set where electricity is produced. (A simplified diagram on the NRC website can help visualize this process: https://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html). The steam generator is located outside the reactor vessel, but inside the secondary containment. Replacing this massive component is not easy, but it can be done and has been done in many pressurized water reactors.

The NuScale concept is different. Under its "passive design", primary circuit water flows vertically upwards from the reactor to the steam generator, which is located inside the reactor vessel. The secondary circuit water circulates through helical tubes, where it boils, capturing heat as the primary water flows between the tubes. Two design-related problems played a major role in the steam generator's non-approval. The first was premature wear of the steam generator tubes. The second, related to the first, concerned vibrations known as "density wave oscillations". The circulation of water and the intense boiling inside the spiral tube subject the tubes to mechanical forces that differ from those of current pressurized water reactor designs. These have been studied in depth because "thermally induced oscillations in system flow and pressure are undesirable"; such oscillations "can cause mechanical

31 A. Makhijani et M.V. Ramana, Questions for NuScale VOYGR Reactor Certification : When will it be done ? And then, will it be safe ?, 9 avril 2023 https://static.ewg.org/upload/pdf/FINAL_NuScale_analysis_for_EWG.pdf

vibrations, thermal fatigue, circuit control problems and, in extreme circumstances, disrupt the heat transfer characteristics of the circuit".

II. Pre-application issues for the 77 MW Nuscale model

"As noted above, in the November 2022 communication, the NRC identified 99 "significant" observations and six "difficult and/or significant issues" that will need to be resolved for the safety review. Some of these are included in this brief report.

ii. Suppressed information

*An overall NRC conclusion was that NuScale appears to have "**suppressed information necessary to make a decision with reasonable assurance regarding public health and safety**" in its application documents. The NRC communication did not describe in detail what had been deleted, but suggested that it might be related to the large increase in power, indicating that the deletions "may have been" related to the effort "to optimize" the application for Standard Design Approval. [...]*

iii. Severe accident assessment

*The NRC identified a **specific concern regarding the power increase and its impact on accident assessment**: the NRC experts stated that "the power increase from 160 MWth to 250 MWth [i.e., from 50 MW electrical to 77 MW electrical] and other design changes are expected to impact all stages of severe accident assessment, from identified accident sequences, derived source terms, to radiological consequence analyses". Yet, the experts noted, it "appears [that] all... 'severe accident progression' analyses have remained identical in NuScale's certification pre-application documents." This is clearly one of the areas where the "new elements" mentioned by NuScale in January 2022 should have been added. With a 50% increase in power, the consequences of accidents can be expected to be more severe. It therefore seems unjustified to leave the accident analysis "as is". Was NuScale's intention to check whether NRC staff actually read the documents? If so, the good news for the public is that the answer seems to be "yes".*

iv. Steam generators

Despite more than two years having passed since the steam generator issues were raised - and the clear dissenting opinion regarding the granting of certification to the 50 MW reactor model - the NRC once again determined that a "comprehensive vibration assessment plan and support for steam generator tubes" and a "density wave oscillation analysis" remained among the challenges to be overcome for the 77 MW Nuscale model. In other words, NuScale has apparently made little progress over the past two years in addressing one of the fundamental safety issues associated with its reactor concept. Because the NuScale steam generator is located inside the reactor vessel, its replacement, in the event of failure, will require the reactor vessel to be opened, with potential risks of greater damage to the vessel as well as to external structures. The situation is further complicated by the fact that the reactors would be underwater: their positioning in a pool is part of the design".

4.5 Safety instruction for the Nuward project

4.5.1 The NUWARD Safety Option File

As the future operator of the potential first NUWARD SMR power plant in France, EDF submitted its Safety Options File (DOS) to the ASN on July 19, 2023, in accordance with the project schedule, based on the elements prepared by the NUWARD teams and its partners.

The Safety Options File is a document presenting the safety objectives, overall design features and essential operating and risk management principles of the NUWARD SMR. According to French legislation, the assessment of safety options is the first stage in the authorization procedure for a nuclear facility project: "*This stage will enable us to obtain an early opinion* *from the French Nuclear Safety Authority (ASN) before submitting the application for authorization to build (DAC), a prerequisite for starting construction of the first power plant in France*".

We currently have no access to this Safety Options File. In the case of the NuScale reactor, thousands of pages of documentation are provided for consultation on Design Certification[32].

4.5.2 First information from French Safety Authority (ASN)

In Annex 2, you will find the text of the ASN information note of July 4, 2022 on the: "Development of small modular reactors in collaboration with the Finnish and Czech safety authorities, ASN initiates an unprecedented joint preliminary examination of the NUWARD reactor project", of which: "*On June 10, 2022, the French (ASN), Finnish (STUK) and Czech (SUJB) safety authorities initiated, with their respective technical support, the preliminary examination of the main safety options of the NUWARD™ small modular reactor project carried by EDF*."

On this subject, the IRSN produced a note in the "Savoir et comprendre" section on April 5, 2023, presented in Appendix 3.

4.5.3 An international review of the NUWARD project.

The ASN published a new information note[33] on small modular reactors on September 26, 2023, announcing the publication of the "*lessons learned from the review conducted jointly with its counterparts STUK and SUJB on the safety options for the NUWARD SMR reactor project developed by an EDF subsidiary*".

This publication, entitled "*NUWARD SMR, Joint Early Review, Pilot Phase Closure Report*", was also published by the three safety authorities in September 2023[34]. This succinct report (29 pages) is essentially devoted to the concern to achieve homogenization of the practices and methods of the nuclear safety authorities of the three countries, with an initial application to the NUWARD SMR project, led by EDF as project leader.

In the case of SMRs, harmonization of the requirements of the national safety authorities is particularly crucial, insofar as reactor standardization plays a central role in the economic competitiveness of this model.

Presentation of the project

The project itself is briefly presented in paragraph 2.2, with a very positive assessment and the announcement of first construction in France from 2030:

"NUWARD SMR is a 340MWe SMR plant with two independent reactors (170MWe each). Each reactor is a compact integrated Gen III+ Pressurized Water Reactor (PWR), with full integration of the primary circuit (including primary pumps, pressurizer and compact steam generators) within the reactor pressure vessel. Both reactors are immersed and housed in a single nuclear building, which also houses a shared spent fuel pool. To support the inherent safety of its SMR project, EDF puts notably forward NUWARD SMR's autonomy, as no

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32 United State Nuclear Regulatory Commission, Application Documents for the NuScale US600 Design https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/nuscale/documents.html

33 https://www.french-nuclear-safety.fr/asn-informs/news-releases/a-joint-review-has-been-carried-out-by-3-european-regulators-on-the-safety-options-of-a-smr

34 ASN, STUK, SUJB, Nuward SMR Joint Early Review, Pilot Phase Closure Report, Septembre 2023 https://french-nuclear-safety.fr/content/download/192690/file/NUWARD%20SMR%20Joint%20Early%20Review_Closure%20Report_Final_Version%20sign%C3%A9e_vf.pdf

system nor resource (including heat sink) outside the nuclear island is required to ensure the safe-state for at least 3 days.

Indeed, it is claimed that the nuclear island is self-reliant for at least this period due to the adoption of a pool (named "water-wall") in which each 3rd barrier, the steel containment vessels, are immersed. This autonomy is key as EDF claims that all DBC scenarios can be passively managed, with no need of operator's action, external heat sink, boron injection or external electrical power supply for at least 3 days.

Although PWRs are a technology with which both EDF and the regulators in the Joint Early Review have strong experience, the NUWARD SMR presents ***innovative features on which there is no operating experience.***
According to EDF plans, the construction of a first of a kind is expected to start in 2030 in France. NUWARD SMR is being designed to target replacement of fossil fuel power plants around the world, as well as supply energy-intensive industrial sites. In addition, NUWARD SMR is developed to support cogeneration of electricity and either heat (for industry or district heating), hydrogen production or water desalination"

International group work program
Paragraph 2. 3 presents a work program on the main nuclear safety issues, to be carried out over a period of six months, which appears to be very "accelerated".
This interesting work program is presented in Appendix 5.
Paragraph 2.4 describes the working method of the three safety authorities.

It appears that EDF is involved in a very concrete way in this work.
In fact, paragraph 3.2 states that the working group's joint summary of the NUWARD SMR project provides its conclusions. In particular, this summary compares the guides and practices of the nuclear safety authorities in the three countries concerned, particularly in their possible handling of the NUWRD SMR project. Some "high-level" examples highlighted by their analysis are presented, but at EDF's request, this summary is not made public because of industrial property issues.

There is a clear sense of an operation seeking international recognition, or at least from certain European countries, of the interest of the NUWARD SMR project led by a French consortium dominated by EDF.

5. COSTS

The question of costs is obviously essential if we are to have an opinion on the merits of developing the SMR models we have presented.

Let's say straight away that we have not found any information on the cost of NUWARD, whether for an initial prototype or for a real SMR whose reactor would be mass-produced in a factory before being transferred to the plant site.
All we know is that the project's promoters believe that "the development of the NUWARD SMR project will require favorable financial, institutional and regulatory conditions", so we will present what we currently know about the projected costs of the NuScale model.

5.1 THE COST OF BUILDING THE FIRST NUSCALE POWER PLANT

The simplest thing to understand is the cost of building the first NuScale prototype.
This is a very concrete project: in February 2023, the electric utility of a group of Utah municipalities, Utah Association Municipal Power Systems (UAMPS), decided to continue its commitment to purchase the output of the 6-module, 77 MW NuScale power plant planned for construction at the federal research center "Idaho National Laboratory" (see Figure 4).

The reference above provides the following cost figures:

- Development and construction costs, including financial charges: \$9.3 billion
- Total federal subsidies (Cost Share Award) and other aid: \$4.2 billion
- Net cost to UAMPS: \$5.1 billion.

It explains the contractual terms of this project:
"*The overall project consists of six of NuScale's 77 MW power modules to generate 462 MW of electricity. UAMPS member utilities "subscribe" for the quantities of electricity they wish to purchase from the six SMRs. If too many of them withdraw, the project will not be built, or at least not under current financial conditions. UAMPS will have the option of terminating the project and being reimbursed if the total of all subscriptions to member utilities does not reach 370 MW (out of 462 MW available) by the end of 2023*".

Many commentators consider that the actual costs will be higher, in view of the experience gained on the construction of large power reactors, even in so-called well-known fields (Westinghouse's AP-1000 and France's EPR).

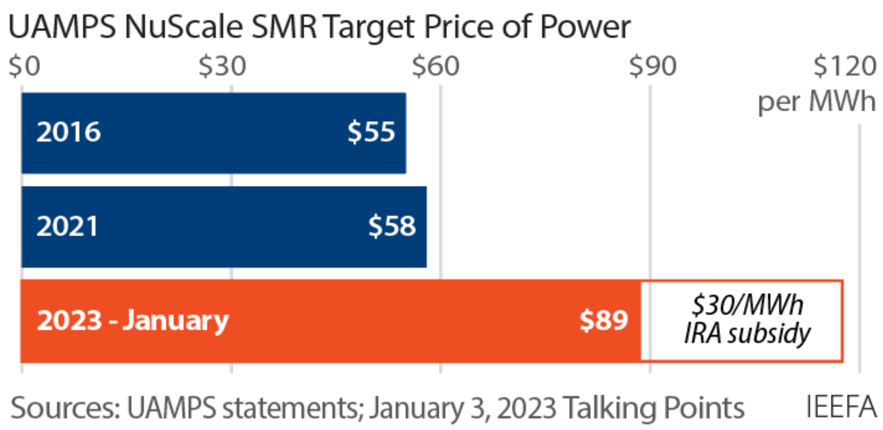
5.2 THE SOLD PRICE PER MWH

5.2.1 Institute for Energy Economics and Financial Analysis (IEEFA)

In "Spectacular new cost estimates for NuScale's small modular reactor", we read:
« Last week, NuScale and Utah Associated Municipal Power Systems (UAMPS) announced what many have long expected. Construction cost and target price estimates for the 462 megawatt (MW) Small Modular Reactor (SMR) are up, way up. »
...
« From 2016 to 2020, the target electricity price was \$55 per megawatt-hour (MWh). This price was then increased to \$58/MWh[35] when the project was scaled back from 12 to 6 reactor modules (from 924 MW to 462 MW). Today, after preparing a new, much more detailed cost estimate, the target price for electricity generated by the proposed SMR has soared to \$89/MWh . »
...

35 US dollars of 2020.

« Target price for electricity generated by the UAMPS NuScale reactor virtually stabilized until 2021 at $55 and then $58, the announced price per MWh is $89 in January 2023 and would be $119 if various subsidies, notably federal, are included. »



Virtually stabilized until 2021 at $55 and then $58, the announced price per MWh is $89 in January 2023, and would be $119 if we include the various subsidies, notably federal.

« It should be noted that the new electricity price of $89/MWh would be much higher if it weren't for the more than $4 billion in subsidies that NuScale and UAMPS hope to obtain from US taxpayers thanks to a $1.4 billion contribution from the Department of Energy and the estimated $30/MWh subsidy under the Inflation Reduction Act (IRA).
It's also important to remember that the $89/MWh target price is expressed in 2022 dollars, and significantly underestimates what utilities and their ratepayers will actually pay if the SMR is completed. For example, assuming a modest inflation rate of 2% through 2030, utilities and ratepayers would pay $102 for each MWh of electricity generated by SMR, not the $89 that NuScale and UAMPS want them to believe they will pay.
The 53% increase in the target price of electricity generated by SMR since 2021 is due to a dramatic 75% increase in the estimated cost of building the project, from $5.3 billion to $9.3 billion. This new estimate makes the NuScale SMR reactor about as expensive ($20,139 per kilowatt) as the two-reactor VOGTLE nuclear project currently under construction in Georgia, undermining the claim that SMR reactors will be inexpensive to build.

NuScale and UAMPS attribute the rise in construction costs to inflationary pressure on the energy supply chain, in particular the rising prices of raw materials that will be used in the construction of nuclear power plants.
For example, UAMPS reports that increases in the Producer Price Index over the past two years have pushed up the cost of:
- *fabricated steel plate, by 54%;*
- *carbon steel piping, by 106%; - electrical equipment, by 25%;*
- *fabricated structural steel, by 70%;*
- *copper wire and cable, by 32%.*

In addition, UAMPS notes that the interest rate used to model project costs has increased by around 200 basis points since July 2020. The higher interest rate increases the cost of financing the project, which increases the total cost of construction.

Assuming that the raw material price increases cited by NuScale and UAMPS are accurate, the construction prices of all the SMRs NuScale is marketing - and, indeed, of all the SMR *models currently marketed by any company - **will be much higher than acknowledged**, and the prices of the electricity generated by these SMRs will be much higher.*

Finally, as we have already said, no one should be fooled into believing that this cost increase will be the last for the NuScale/UAMPS reactor. The project still needs further design work, authorization from the U.S. Nuclear Regulatory Commission, construction and pre-operational testing. Experience with other reactors has repeatedly shown that further significant cost increases and schedule delays are to be expected at all stages of the project's development.

The cost increase announced last week makes it even more imperative that UAMPS, the utilities and the communities involved in the project issue RFPs to find out if there are other resources capable of delivering the same power, energy and reliability as SMR, but at lower cost and financial risk. David Schlissel is director of resource planning analysis at IEEFA.

5.2.2 Environmental Working Group (EWG)

Extract from an article by A. Makhijani and M.V. Ramana[36]: "Questions for NuScale VOYGR Reactor Certification: when will it be done? And then, will it be safe?
« On January 2, 2023, UAMPS[37] published a "matters of interest" document revealing a new cost estimate for the NuScale project, which would increase it from the previously projected $5.32 billion to $9.3 billion. » »

Note:
Recent information casts legal and financial doubt on the NuScale project: on October 19, 2023, Iceberg Research published a short-sale report entitled « NuScale Power ($SMR): « False customer and major contract at risk cast doubt on NuScale's viability"[38]. »

5.3 The doubtful future of the NuScale project

5.3.1 Failure of the present NuScale project

Recent news reports have cast doubt on the NuScale project in both legal and financial terms.

On November 14, the magazine "Nuclear Engineering International" published the article **"UAMPS and NuScale cancel plan to build SMRs at Idaho National Laboratory (INL)"**[39].

In its first paragraph, the article writes :

« Utah Associated Municipal Power Systems (UAMPS) and Oregon-based NuScale Power have mutually agreed to terminate the Carbon Free Power Project (CFPP). The project envisaged construction of six small modular reactors (SMRs) at the US Department of Energy's (DOE's) Idaho National Laboratory (INL). "Despite significant efforts by both parties to advance the CFPP, it appears unlikely that the project will have enough subscription to continue toward deployment." A joint statement said. "Therefore, UAMPS

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36 https://static.ewg.org/upload/pdf/FINAL_NuScale_analysis_for_EWG.pdf
37 UAMPS : Utah Associated Municipal Power Systems
38 Peter Judge, Lawyers circle nuclear startup NuScale overclaims a 24-reactor SMR deal xwill fail, October 2023. https://www.datacenterdynamics.com/en/news/lawyers-circle-nuclear-startup-nuscale-over-claims-a-24-reactor-deal-will-fail/
39 https://www.neimagazine.com/news/newsuamps-and-nuscale-cancel-plans-to-build-smrs-at-inl-11297083

and NuScale have mutually determined that ending the project is the most prudent decision for both parties. »

Then, the article reminds us the various steps of the NuScale project and deliver a devastating information :

*« However, earlier this month, the company came under pressure after a lengthy report by Iceberg Research entitled "**NuScale Power ($SMR): A fake customer and a major contract in peril cast doubt on NuScale's viability**". Iceberg alleged that NuScale had sold 24 reactors to a "fake customer". This referenced a deal NuScale had announced in October to supply Standard Power with 1,848 MWe of power provided by 24 SMRs to power two US data centre sites. Iceberg predicted that Standard Power would be unable to support the contract. NuScale, in response said the Iceberg allegations were "riddled with speculative statements with no basis in fact and demonstrates a limited understanding of small modular nuclear reactors (SMRs) and the nuclear power industry. »*

and :

« The collapse of the project is raising questions in other countries with SMR plans. Commenting on the situation, Canada-based The Energy Mix said.
The failure of the US project "is shining a light on public subsidies that might keep similar technology under development in Canada, even if it's prone to the same cost overruns that scuttled NuScale Power Corporation's Carbon Free Power Project (CFPP) in Utah".
The publication quoted Gordon Edwards, President of the Canadian Coalition for Nuclear Responsibility, as saying: "Private investors in Utah forced NuScale to divulge financial information regarding the cost of electricity from its proposed nuclear plant," and "cost became the deal-breaker". He added: "Publicly-owned utilities in Canada are not similarly accountable. The public has little opportunity to 'hold their feet to the fire' and determine just how much electricity is going to cost, coming from these first-of-a-kind new nuclear reactors."
Similarly, Romanian Insider noted: "The small nuclear reactor (SMR) technology and the SMR project in Romania came under scrutiny after NuScale dropped one of his projects in the US because of the excessive costs that increased by 53% and made it economically inefficient." In Romania, NuScale is developing a similar SMR project at Doicesti. NuScale now has four projects under development in the US, one in Canada, three in Asia, one in the Middle East and three in Europe (Poland, Bulgaria and Romania).

5.3.2 Toward a new project

On 21 November 2023, World Nuclear News (WNN) published the following article :
« NuScale, ORNL to assess SMR use by industry[40] »

Quotations :

« NuScale Power and the US Department of Energy's Oak Ridge National Laboratory (ORNL) are to collaborate on a techno-economic assessment (TEA), studying a NuScale small modular reactor's ability to implement a cost-effective steam heat augmentation design.»

[40] https://www.world-nuclear-news.org/Articles/NuScale,-ORNL-to-assess-SMR-use-by-industry#:~:text=NuScale%20Power%20and%20the%20US,effective%20steam%20heat%20augmentation%20design.

« The study will be based on process data from a US chemical facility to help the plant meet its electric power and process steam requirements with NuScale's small modular reactor (SMR) technology.
The TEA will evaluate the viability of NuScale's SMR technology with steam heat augmentation for use in a chemical system, including examination of steam reliability, operational costs and system stability. It will also study SMR siting suitability. »
…
The TEA is receiving funding through an award granted by the Department of Energy's Gateway for Accelerated Innovation in Nuclear (GAIN) initiative, which connects industry with the US national laboratories to accelerate the development and commercialisation of advanced nuclear technologies. Funding for the project was announced in September, in the fourth round of GAIN Vouchers awarded in fiscal year 2023. »

One must note that this new initiative is far from the commercial approach of the first NuScale proposal. It is now a techno-economic assessment receiving funds from the Department of Energy.

CONCLUSIONS

1. There's a long way to go

Small nuclear reactors, to qualify as SMRs, have to be mass-produced in factories, essentially for the economic advantages hoped for by a series effect, and then transported to the power plant site where they are connected to the turbo-alternator and condenser enabling the steam they produce to be transformed into electricity.
It is this "transportability" that leads to the "compact" nature of these reactors, in which the reactor core containing the fuel assemblies and control rods, the steam generators and the pressurizer are housed in a single steel shell.
This configuration, which is the "trademark" of an SMR, means that these models are new reactors, far removed from their conventional counterparts of the same type, whose design and construction must be examined and controlled with the utmost vigilance.

We have presented two models, NuScale and NUWARD, of "nuclear power plants", candidates for SMR status. These plants are made up of "modules", each equipped with a low- or medium-power nuclear reactor which, being of the enriched uranium and pressurized ordinary water (PWR) type, well known for both civil and military reactors, should be the first, or among the first, likely to receive all the necessary authorizations to start construction.

We have been able to follow the evolution of the NuScale model, which is older than NUWARD in its development. Despite its advance, the NuScale plant is still a long way from receiving construction authorization, given all the questions and requests from the US Nuclear Safety Authority (NRC). It's hard to imagine construction starting before the end of the 2020s, and it's only a prototype whose location has been carefully chosen: a Federal Nuclear, Energy and Defense Research Center (INL). This model is already being challenged, particularly from an economic and financial point of view.

For its part, the NUWARD project, which has been studied in relative secrecy for several years and is led by a consortium around EDF, is currently under examination of its unpublished safety options file (DOS) by the safety authorities of three European Union countries, including France. Today, NUWARD is the subject of a considerable communication-propaganda offensive, of mediocre quality and full of untruths.

Although a number of prototypes will undoubtedly emerge with the support of public subsidies, it's another matter altogether to move on to the next level: the SMR.
The first condition is to have enough firm orders to launch the construction of a plant capable of mass-producing "compact" reactors on the basis of the experience acquired with the prototype(s). The hope of SMR promoters, rightly aware of the excessively high cost of a site-built model, rests on the hoped-for gain in unit cost due to the series effect.
However, the history of the French nuclear fleet has also shown that, in the event of a generic defect, standardization could result in significant economic losses.

Such a plant has yet to be invented. We already have experience of this in the automotive and aviation industries. Will the same apply to the construction of equipment designed to contain highly radioactive fuels, notably plutonium, in which a design or construction fault could lead to serious accidents?
Of course, standardization can lead to improvements in equipment quality, but experience shows that a serious or major accident occurs as a result of the juxtaposition of several factors, including equipment ageing, lack of maintenance, external aggression (natural or deliberate), operating error and failure to comply with safety standards.

The quality of control and operating personnel is a fundamental factor.
Finally, all attention is currently focused on so-called SMR reactors, and little or no information is provided on the fuel "cycle", radioactive waste and the dismantling of these facilities.

2. What's the point of an SMR?

It's easy to see why small reactors should be installed in isolated areas, far from any electricity grid, such as in the Far North, as is already the case.
So who needs an SMR?
Let's take the example of the NuScale US460 model with six reactors, each with an electrical output of 77 MW, for a total output of 462 MW.
It's true that a number of local authorities have agreed to purchase the electricity generated by the planned prototype, at a price that is already high but far from reality, thanks to various subsidies.
What's more, it's not certain that all the communes currently applying would maintain their commitment if the project were delayed and costs were to rise further (which is likely).
It's hard to see why an SMR would be of interest in an interconnected region that can call on other sources, notably renewable electricity production (particularly photovoltaic and wind power), the costs of which are falling rapidly while those of nuclear power are rising.

Poland is also often cited as an example of a country that would be interested in SMRs to replace 300 to 600 MW coal-fired power plants, in a country with an electricity grid covering the entire country, including, of course, the coal-fired plants to be replaced.
Beyond the possible construction of a prototype, probably financed in part by the seller and international organizations, many questions arise for real SMRs:

- Is there a factory manufacturing SMRs in Poland? Unlikely.
- Would there be one in Europe? Perhaps, but with which SMR?
- Would SMRs be imported? Numerous legal problems concerning liability and costs (excluding the prototype, which would most probably benefit from various subsidies).

Generally speaking, exporting an SMR would run up against enormous difficulties, concerning the respective responsibilities in terms of insurance, the question of fuel and waste, etc.

As for indiscriminate export, it would be very unlikely. As for the "all-out" export advocated by some SMR promoters, particularly in poor so-called "developing" countries, it would be extremely dangerous without a high degree of local expertise, independent nuclear safety authorities and security forces, not to mention the deployment of IAEA controls on proliferation risks.

3. SMR and climate

Greenhouse gas emissions caused by nuclear power generation are far from negligible: CO2 emissions from uranium mining, reactor and fuel plant construction and operation, radioactive waste management, as well as emissions of other greenhouse gases (SF6, for example).
Most of these emissions occur during the construction phase of the facilities (steel, concrete, building sites), which can be estimated, and in the uranium mines (excavation, transport), in practically unknown quantities.
The value of emissions per kWh produced used is the ratio of the estimated value of total emissions from the "nuclear system" that enables this production, divided by the electricity production of the nuclear power plant in question (in France, for example) over the assumed 60-year lifespan of the reactors.

This method of calculation calls for two comments. The first is that a reactor construction program planned from around 2030 onwards, which would be that of SMR development, would emit a significant quantity of greenhouse gases precisely at a time when every effort must be made to bring greenhouse gas emissions to 0 by 2050. A negative effect.

The second point is that, if we envisage the construction of new nuclear reactors from around 2030 onwards, whether SMR or "conventional" (the French government is planning to build several EPR2s from that date), these reactors, designed to operate for 60 years, would have to operate under conditions of considerable stress due to the climatic upheavals we are already suffering the rigors of today, announced ages ago by the IPCC and superbly "ignored" to date by most States, major fossil fuel companies and international organizations, despite the commitments made.
Everywhere, and particularly in Europe and France, we are going to experience drastic temperature rises, heat waves, fires, floods, drought, rising sea levels and the destruction of coastlines.
Nuclear reactors consume water for their construction and operation, they heat up the water in rivers and streams whose flow is tending to diminish (reactors have already been shut down in France for this reason) or are located, in many cases, on flood-prone coastlines. Not to mention the evolution of seismic and geopolitical risks, all of which are set to increase year after year.

How can we accept decisions to build reactors that are expected to operate beyond 2100 and continue business as usual?

It is unlikely that true SMRs, i.e. "modular" reactors, will ever operate. If they did, it would be a dangerous and ruinous solution.

APPENDIX 1 : A NEW PRO-SMR TENTATIVE IN THE UNITED STATES IN 1955

… With these arguments, and eager to extend nuclear power to regions that couldn't accommodate large reactors, the AEC announced a second round of funding in September 1955. This time, small reactors were the objective, not a means to an end. The Commission received seven proposals and funded two: a 22 MW reactor at Elk River, Minnesota, about 50 kilometers northwest of Minneapolis, and a 12 MW reactor near the town of Piqua, Ohio. Two other reactors were subsequently added to the program: the Boiling Nuclear Superheater (Bonus) in Punta Higuera, Puerto Rico, and the La Crosse boiling water reactor in Genoa, Wisconsin.

Elk River was billed by its operator as "rural America's first atomic power plant". Like the SMRs envisioned today, it consisted of prefabricated components, and its reactor vessel was compact enough to be transported to the site in a standard railroad flatcar. The reactor design was a variant of the boiling water reactor, which is the second most common reactor type today. But its fuel was unusual, consisting of a mixture of highly enriched uranium (which contained more of the isotope 235 of chain-reacting uranium than the usual nuclear fuel) and thorium. Many experts saw thorium as the hope of nuclear power in the long term, partly because they feared that uranium would run out; even today, some believe that thorium is the answer to all nuclear power's problems.

During Congressional hearings on the demonstration program, O.N. Gravgaard, president of the Rural Cooperative Power Association, which was building the plant, said: "In rural power, we started from scratch, out of necessity. There was no electricity several years ago...

Construction of Elk River began in January 1959, and the reactor reached criticality in November 1962. However, it was not declared commercially operational until July 1964, three and a half years behind schedule. This long delay was due to various technical problems, including cracks in certain components. According to Congressional hearings in 1967, the cost of building Elk River more than doubled, from $6.2 million to $16 million. Certainly, other reactors built at the time and subsequently ended up costing at least three times as much as originally estimated; by comparison, Elk River looked pretty good.

For a reactor that took over five years to build, Elk River had a remarkably short lifespan: just three and a half years. The reactor was shut down permanently in February 1968 after cracks appeared in the cooling system piping. Faced with repair costs estimated at one million dollars, the cooperative chose not to repair them. A spokesman for the co-op told the Chicago Tribune that the group "didn't feel like spending the money, especially since the reactor hasn't been very economical because it's too small", adding that the reactor had produced electricity at twice the cost of electricity produced by coal-fired plants.

As nuclear physicist Walt Patterson noted in his book Nuclear Power (1976), Elk River became the first demonstration reactor to be decommissioned. As the reactor vessel was highly radioactive, new underwater torches had to be developed and remotely operated to cut through the thick steel structure. The process took three years and cost $6.15 million, almost the same amount as the original estimate for construction.
Processing the spent uranium-thorium fuel also proved difficult. Finally, the spent fuel was shipped to a reprocessing plant in southern Italy.

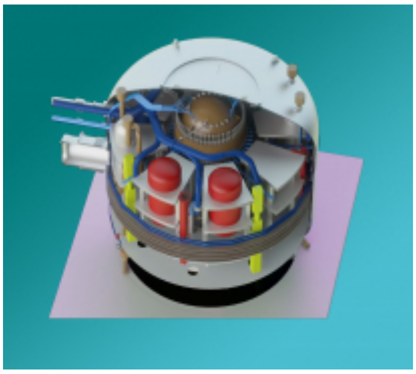
In 1968, the same year as Elk River's closure, the last of the Atomic Energy Commission's small reactors was connected to the grid: the 50 MW La Crosse boiling water reactor. This plant operated for 18 years; at the end, its electricity cost three times as much as that of the neighboring coal-fired plant, according to a 2012 article on the plant's spent fuel disposal. In that article, a former plant manager is quoted as saying that the La Crosse plant "was very well designed. The only problem was that it was too small ».

Since then, no small reactors have been commissioned in the USA. In fact, the size of reactors in the U.S. exploded, reaching 800 to 1,300 MW by the mid-1970s.

The only exception to this growth trend was an experimental 330 MW high-temperature gas-cooled reactor, the Fort St. Vrain plant in Platteville, Colorado. It was commissioned in 1976, with a design promoted as ultra-safe. But the reactor was a failure. A New York Times article on the 1988 decision to shut it down captured the essence of the problem: "The safest reactor shuts down because it rarely works." Data from the International Atomic Energy Agency showed that the plant produced around 15% of the electricity it should have if it had been operating at full capacity.

APPENDIX 2 : ASN INFORMATION NOTE OF JULY 4, 2022[41]

NUWARD™ small modular reactor project



For the first time, a joint review has been carried out by three European safety regulators on the safety options of a small modular reactor project.

ASN publishes the lessons learned from the review conducted jointly with its Finnish (STUK) and Czech (SUJB) counterparts regarding the safety options of the NUWARD SMR [1] reactor project, developed by a subsidiary of EDF.

This joint review, performed at the initiative of ASN, was a European first. Its aim was to examine the safety options of certain topics proposed for the design of the NUWARD reactor, notably the safety approach and objectives, the use of passive systems and the inclusion of two reactors within the same facility.

By means of a concrete example, this review identified the safety advantages of small modular reactors, along with the questions to which they could give rise. It also compared the various requirements, practices and experiences of the three regulators involved and identified the opportunities for changes to national regulations and practices. Following this review, NUWARD now has data allowing the development of a more standardised design.

The closing report from this multilateral cooperation presents the programme and the working method adopted, along with the main lessons learned.

This initiative confirms ASN's position regarding the benefits to be gained from multilateral cooperation when reviewing sufficiently mature reactor projects, in an international context of standardisation.

Discussions are under way for continuation of the joint review of the NUWARD reactor project, addressing new topics and expanding the programme to include other European safety regulators.

[1] The NUWARD SMR project is an electricity production unit concept consisting of two pressurised water nuclear reactors of 170 MWe each. This project falls within the Small Modular Reactor (SMR) category.

[41] https://www.french-nuclear-safety.fr/asn-informs/news-releases/a-joint-review-has-been-carried-out-by-3-european-regulators-on-the-safety-options-of-a-smr

Appendix 3 : IRSN, « Savoir et comprendre « sur les SMR

April 5, 2023

Small Modular Reactors (SMRs) are small modular reactors with an electrical output of less than 300 MW. Some concepts offer an architecture that allows the installation of several independent modules to reach a higher overall power (of the order of 600 - 800 MW).

Promoters have put forward a number of different applications for SMRs in response to the current context:
- They provide a means of generating electricity that can meet a variety of needs, exploit cogeneration and lend itself to non-electric applications (industrial heat, fresh water production, etc.)
- They are a suitable solution for isolated regions or those with limited infrastructure
- They offer enhanced safety performance thanks to intrinsic and passive safety features. In the event of an incident or accident, reactors can be brought to and maintained in a safe shutdown state for several days without human intervention.
- Due to their low power and small size, SMRs allow a variety of design choices, some of which may indeed be favorable to safety.

There are over 80 concepts based on different reactor technologies (light water, high-temperature, gas, molten metal, etc.).

To find out more:
- Information note on the safety of Small Modular Reactors
- Small Modular Reactor (SMR) Regulators Forum
- PASTIS Program (PAssive Systems Thermalhydraulic Investigations for Safety)

Appendix 4 : NRC letter to NuScale

Ms. Carrie A. Fosaaen
Director, Regulatory Affairs NuScale Power, LLC
1100 Circle Boulevard, Suite 200 Corvallis, OR 97330

November 15, 2022

SUBJECT: PREAPPLICATION READINESS ASSESSMENT REPORT OF THE NUSCALE, POWER, LLC STANDARD DESIGN APPROVAL DRAFT APPLICATION

Dear Ms. Fosaaen:

On October 21, 2022, members of the staff of the U.S. Nuclear Regulatory Commission (NRC) staff completed a preapplication Readiness Assessment (hereinafter "Readiness Assessment") of the draft application and supporting documentation that NuScale Power, LLC (NuScale), intends to submit as part of its Standard Design Approval Application (SDAA). NuScale's letter requesting the Readiness Assessment can be found at Agencywide Documents Access and Management System (ADAMS) Accession No. ML22145A460. NuScale requested the Readiness Assessment in order to (1) identify any required information that is missing from the proposed SDAA and (2) identify technical or regulatory issues that may complicate the acceptance or technical reviews of the SDAA. The staff's readiness assessment plan used to conduct the review of NuScale's proposed SDAA can be found at ML22178A254.

The staff conducted the readiness assessment via NuScale's Electronic Reading Room in accordance with NRC's Office Instruction LIC-116, "Pre-application Readiness Assessment" (ML20104B698). The readiness assessment is not part of the NRC's official acceptance review process; however, the staff performed the Readiness Assessment as part of an approved preapplication activity that allowed the staff to gain an understanding of any significant issues or information gaps between the draft application and the technical content required to be included in the final application submitted to the NRC.

The enclosed Observation Report provides the NRC staff observations of NuScale's SDA draft application. The staff observed and recognized that the NuScale draft SDAA is a work in progress and several chapters are incomplete or have not been updated to reflect the US460 design. Additionally, there were several documents referenced by the draft SDAA (i.e., Topical Reports, Technical Reports, calculations, technical tables, references, probabilistic risk analysis information, etc.) that were not made available to the staff during the Readiness Assessment. As such, the NRC has not observed the entirety of the proposed SDAA application and thus cannot provide a complete assessment of the draft application. Further, the staff's Observation Report does not include the information known to NuScale as missing or incomplete and the observations (included) do not predetermine whether the SDA application will be accepted for review.

In conducting the Readiness Assessment, the staff used a phased approach with groupings of relevant chapters and sections. The collection of observations in the report is organized by chapter and any chapters that did not have observations are absent from the report. Overall, the staff has identified several challenging and/or significant issues that could be focus areas for the SDAA acceptance and/or safety review. While there has been some early engagement on these topics, the staff would encourage continued engagement on these topics until the SDAA's submittal. These topics include:

- Augmented Direct Current (DC) Power System (EDAS) Safety Classification
- Comprehensive Vibration Assessment Plan and Steam Generator Tube Support
- Density Wave Oscillation Analysis
- Containment Vessel Material/Reactor Vessel Material

- Loss-of-Coolant Accident Analysis
- SDA “Optimization”

Enclosed are two Observation reports – non-proprietary version (Enclosure 1) and proprietary version (Enclosure 2). The complete ADAMS package can be found under ML22305A518. The observations included are those that the staff considered to be significant. Additional less significant observations were identified and communicated to NuScale throughout the review. The staff recommends that NuScale consider the entirety of the observations while finalizing the application and application submission date based on your evaluation of the time needed to address the observations.

If you have any questions, please contact Getachew Tesfaye, Senior Project Manager, at (301) 415-8013 or Getachew.Tesfaye@nrc.gov.

Docket No. 99902078

Enclosures:
1. Observations Report
2. Observation Report, Proprietary

cc: w/encl.: DC NuScale Power LLC Listserv

Sincerely,

Brian Smith, Division Director
Division of New and Renewed Licenses Office of Nuclear Reactor Regulation

C. Fosaaen 3

SUBJECT: PREAPPLICATION READINESS ASSESSMENT REPORT OF THE NUSCALE, POWER, LLC STANDARD DESIGN APPROVAL DRAFT APPLICATION NOVEMBER 15, 2022

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ADAMS Accession Nos.:
PKG: ML22305A518
PUBLIC: ML22305A520
PROP: ML22305A519 (Enclosure 2 Proprietary Summary) *via email NRR-106

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APPENDIX 5 : NUWARD SMR WORK PROGRAM

Presentation of the Joint Early ReviewNUWARD SMR Joint Early Review - Pilot Phase Closure Report - September 2023

Before the beginning of the initiative, the working group agreed on a working process and a program of work. The scope of the program of work was limited to the most important topics, as it was considered not feasible nor "cost-effective" to review the whole design at this stage, especially using an innovative form of international collaboration.

The program of work was initially composed of 5 topics. These topics were selected because they fulfilled at least one of the conditions below:

1. it is a topic which brings answers on the level of safety that could be expected, and on the approach to meet this level;
2. it is a topic with SMR specificity on which there is no or very few safety requirements, recommendations or guidance, or significant information and experience feedback;
3. it is an important feature of the safety demonstration which requires a lot of time to be developed and assessed, due to its complexity or novelty. Starting the review of this topic as early as possible could help reducing the timeframe of the licensing process;
4. it is a key topic for the NUWARD SMR design, in a way that a late change on this topic would have an important impact on the design or the safety demonstration. Providing feedback as early as possible can enable the vendor to meet regulators' expectations more easily and timely.

In addition, one key condition to consider a topic in the program of work was that the topic was mature enough and the related documentation was available.
Finally, it was possible to add an additional topic during the initiative, if it fulfilled the conditions above, had limited impact on the timeframe of the initiative, and was agreed by consensus within the working group.
Based on these conditions, a proposition of list of topics was proposed, discussed and agreed.

The initial program of work consisted in the following topics:

-Topic 1: definition of safety objectives. This topic covered general safety goals, main safety requirements and approach, the implementation of the defense in depth into the design, and the study rules for "Design Basis Conditions" (DBC) and "Design Extension Conditions" (DEC). This topic fulfills conditions 1), 2) and 4);

- Topic 2: identification of DBC. In this topic, a preliminary list of DBC, the general process for DBC identification and the way the list of DBC would be consolidated throughout the project were presented. Also, the overall approaches for DEC conditions and practical elimination were presented. This topic fulfills conditions 1), 3) and 4);

- Topic 3: use of cooling passive systems. In this topic, EDF presented the cooling strategy for the reactor and the spent fuel pool. Safety classification approach was also presented, as it could help understanding some aspects of this topic. This topic fulfills conditions 1), 2), 3) and 4);

- Topic 4: development plan of scientific computing tools. In this topic, EDF presented the list of major scientific calculation tools expected to be used in support of the NUWARD SMR design and transient studies, and the associated validation program. This topic fulfills conditions 2) and 3);

- Topic 5: twin modules integration. This topic covered the safety approach regarding the risk of interactions between the two reactors units, as well as the spent fuel pool, as they are all located in the same building. Some examples of shared systems were also presented. This topic fulfills conditions 2) and 4).

During the technical meeting on the safety objectives, it was observed that Probabilistic Safety Assessment (PSA) should be discussed. Hence, and considering that this topic fulfills conditions 1), 2) and 3), this topic has been added to the program of work (topic 6). In this topic, EDF presented how PSA would be used to support the design process, and the methods and tools for PSA development.

The review was based on preliminary extracts from the safety options file. This level of details corresponds to the beginning of the basic design phase. The technical meeting provided additional information through presentations and discussions between experts.