Nuclear Power in Startup Mode:
How can Startups contribute to new reactor design?

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STELLARIA

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Introduction

Me

- training + PhD in physics (ENS Paris, 2005-2013)
- research engineer in thermalhydraulics (CEA, 2013-2024) :
  - ASTRID (Sodium Fast Reactor, 2013-2019)
  - NUWARD (Small Modular Reactor, 2020-2024)
  - ARAMIS/Stellaria (Molten Salt Reactors, 2020-)
- Associate professor (PCC) at X (2019-)
- Member of the Framatome Scientific Council (2019-)
- Deputy CTO of Stellaria (2024 -)

Disclaimer

- this presentation only contains information from public sources...
- ...and only reflects my personal opinion!
- no fusion, sorry :-(

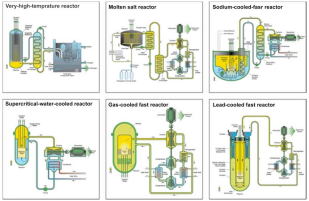
Introduction

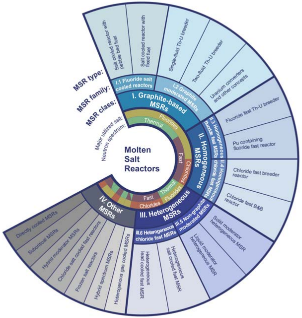
Contents

- some features ("the rules") of new reactor development :
  - design space and tradeoffs
  - "design-to-safety"
  - project phases and their time/cost
- how this has played out in the past in France :
  - recent projects
  - older projects (and some current ones)
- how startups can change that... potentially :
  - their advantages and limitations
  - what kind of projects can they contribute to?
  - and how far can they go?

→ with some feedback from the US + the current French situation

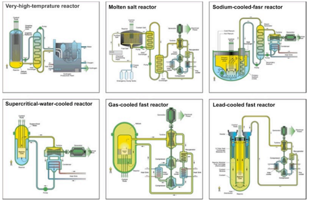
Reactor development

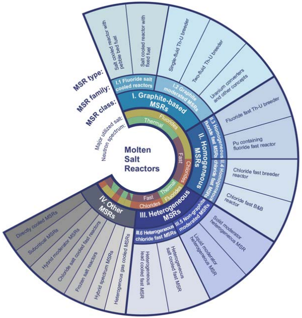




- the design space for a nuclear (fission) reactor is huge
  → only two basic requirements :
  - maintain the chain reaction in the core :
    fissile ($^{233/235}$U/Pu) $\xrightarrow{\text{1 neutron / 2.xx}}$ fissile
  - remove the heat during normal operation…
    … and in all possible accidents (decay heat)
  - avoid radioactive releases in all cases
- but then the branches start:
  - slow down the neutrons before the next fission?
    → if so, with what?
  - solid or liquid fuel?
    → if solid, what coolant?
  - materials? can they withstand the neutrons?
  - use naturally-occuring ^{235}U or synthetize ^{233}U/Pu
    → isogeneration / breeding?

Reactor development





Phase space

- Energy-producing reactors are currently classified in generations :
  - Gen 1 : early reactors (1950s-1960s)
    → often adaptations of non-power designs (ex.: UNGG)
  - Gen 2 : commercial reactors (1970s-1980s)
    → evolutions of Gen1 (PWR) + new (BWR, CANDU)
  - Gen3 : evolutions of Gen2 (1990s-)
  - Gen4 : 6 new designs (left)
- even this is a restriction! Some examples :
  - liquid plutonium (LAMPRE, 1961-1964)
  - solid-fuel reactor cooled by molten salt (Kairos, 2016-)
- and some categories are very wide! (see left for MSRs)

Reactor development

Path effects

- some aspects of a new design can be estimated fast :
  - neutronics
  - thermalhydraulics

→ enough to obtain a "paper reactor" (pending confirmation)

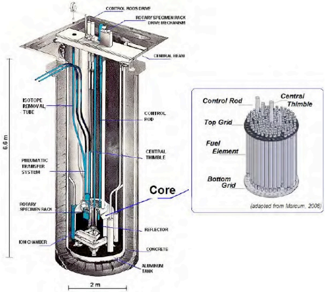
- but some take much longer / add uncertainty :
  - material behavior: corrosion (short / long term), mechanical properties... ... including under irradiation → already need a reactor!
  - fuel fabrication... and reprocessing?

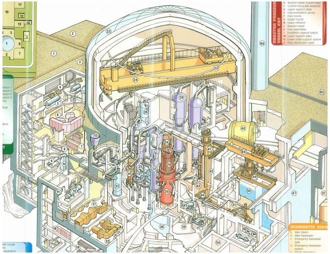
⇒ very strong incentive to follow exising paths :

- graphite / ^{nat}U: CP-1 (1942) → ... → UNGG/Magnox → AGR
- Sodium Fast Reactor: EBR-1 (1951) → .. → SUPERPHENIX → ASTRID
- Pressurized Water Reactor : S1W (1953) → ... → EPR / NUWARD

→ all recent French projects are grounded in 1940s/50s technology!

Reactor development





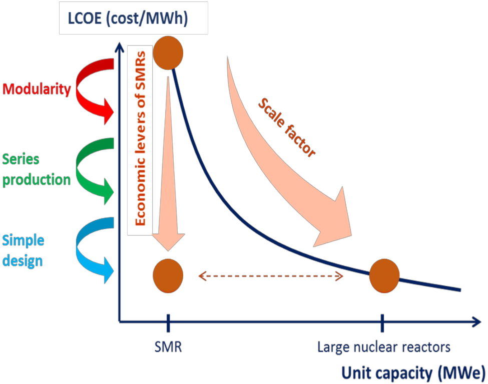
Tradeoffs

- on the left:
  - TRIGA: "is safe even in the hands of a young graduate student" (E. Teller) $\rightarrow$ but $<$3MW at 30°C
  - EPR: 4.5GW at 325°C but quite more complex...
- on paper, larger reactors are always more efficient $\rightarrow$ but this comes at the cost of extra complexity
- some (but not all!) of this complexity comes from safety requirements

$\Rightarrow$ because these have increased over time, evolutionary designs tend to add systems :
N4 $\rightarrow$ EPR : 3$\rightarrow$ 4 emergency diesels
SPX $\rightarrow$ ASTRID : 2/4 $\rightarrow$ 5 emergency cooling systems

- this does not help...

Reactor development



Tradeoffs → reactor size

- "paper" scale factor balanced with:
  - complexity → time/cost
  - lack of series/learning effect
  - more in-place fabrication → time/cost

→ interest in smaller sizes (<300 MWe) :
  - with existing technology (PWR/BWR): Small Modular Reactor
  - with new technology (Gen4): Advanced Modular Reactor

- also opens new markets:
  - heat production (low/high temp)
  - industrial customers
  - small grids
  - ...

Reactor development

Phases

The development process follows a series of phases :

1. Conceptual design / pré-avant projet sommaire:
   - formulate an initial concept (with only the main systems)
   - perform lab-scale experiments where needed (<100 K€): *how long does this material last in a molten salt at 500° C*?

   → at this stage, frequent changes are very likely!
2. Basic design / avant-projet sommaire:
   - specify all the systems and arrange them in a reactor building
   - perform small-scale experiments that are closer to reactor conditions (<1 M€): *does this material last in a loop with the actual temperature gradient*?

   → at this stage, large changes are still possible, but complete pivots become difficult

Reactor development

Phases

The development process follows a series of phases :

3. Detailed design / avant projet détaillé:
   - design each subsystem separately
   - perform large-scale experiments to test them (<10 M€, sometimes 10-100 M€): *design/operate a 1:10 model of a molten salt with the same components*

   → at this stage, overall design changes are very difficult/costly (in practice → "return" to basic design)
4. Construction :
   - start pouring concrete, order parts, etc.
   - at this stage, design changes are very costly!

Reactor development

Phases / Safety

In France, these phases are coupled with interactions with the safety authority (ASN) :

1. conceptual design → Safety Orientations Report (DOrS):
   in this reactor, how do I intend to manage each type of accident?
2. basic design → Safety Options Report (DOS):
   for each accident, what systems are used and what are the consequences?

⇒ these documents can be sent/studied by ASN/IRSN, but are not mandatory!

Reactor development

Phases / Safety

In France, these phases are coupled with interactions with the safety authority (ASN) :

3. detailed design → Preliminary Safety Report (RPrS):
   analyses of each accident + experiments to justify them
   needed for the request for a new nuclear installation (Demande de DAC) sent to ASN
   → process in three phases:
   - initial analysis ("recevabilité"): 6 months → questions from ASN(/IRSN)
   - after these questions are answered: instruction (18 months)
   - public inquiry (12 months)

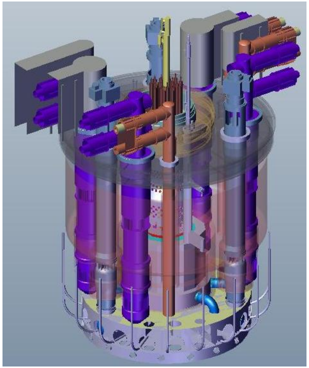
   → "Décret d'Autorisation de Création" → construction can start!
4. during construction→ Final Safety Report (RPS):
   necessary for ASN to authorize divergence

Reactor development

Phases / Remarks

- these phases have increasing cost and duration
  → for new reactors, this is mainly driven by experiments
- are only superficially interlocked with the safety process
- the actual criterion for moving from one phase to the next is the risk of going backwards
- in particular if only part of the work is done when moving to the next phase:
  EPR FA3 → 2 Mh engineering done at first concrete (2007)
  out of 5 Mh (2007 estimate) / 20 Mh (actual)
  [Folz]

Past Experience / ASTRID



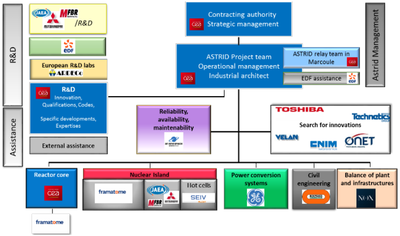
Context

- 2006 French law on nuclear waste:
  "CEA shall build a prototype reactor for waste incineration by 2020"
  ⇒ restart of sodium reactor R&D (slowed after 1997)
- funding: "Plan d'Investissement d'Avenir" (2009)
- initially: reactor to demonstrate transmutation
  → but reoriented to a power-production demonstrator: Advanced Sodium Technology Reactor for Industrial Demonstration

→ somewhat large reactor (600 MWe / 1500 MWth)
half a SUPERPHENIX!

Past Experience / ASTRID

Organization

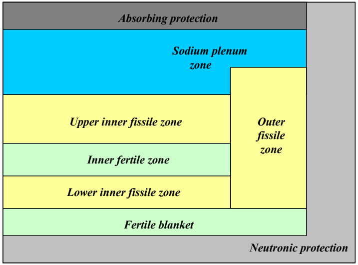


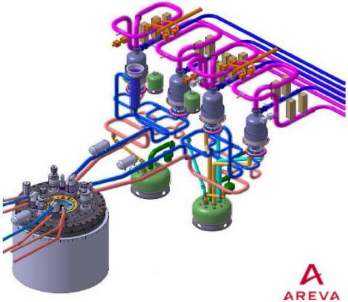
[F. Varaine, 2020]

- 2006-2009: design exploration by a small team at CEA
- after 2010: project team (with no technical autonomy) + contracting
  - core design: internally within CEA (!)
  - reactor design: with Framatome
  - + other industrial partners

⇒ consequences:
  - very long reaction times (1 year!)
    → especially a problem for experiments
  - settling on conservative design choices: “SUPERPHENIX (EFR) + some innovations”

Past Experience / ASTRID





Innovations

Two main innovations, related to safety properties:

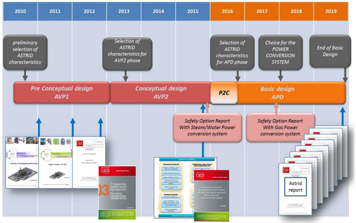
1. core design → eliminate the positive void coefficient:
   - objective: avoid power excursion + core meltdown if the sodium boils → CFV core (drawback : larger / more costly core/reactor)
   - calculations (2015-16): no power excursion, but... ... meltdown still possible!

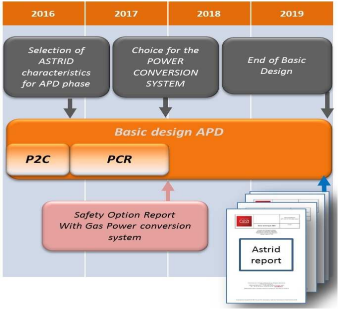
   but design already fixed, so...
   ⇒ decision: keep the core + add more control rods

2. power conversion system → replace H_2O with N_2 → to avoid sodium-water reactions
   - need to develop a new heat exchanger/turbine
   - lower efficiency (41 → 38%)
   - considered as unnecessary by EDF

   ⇒ decision: switch to N_2

Past Experience / ASTRID

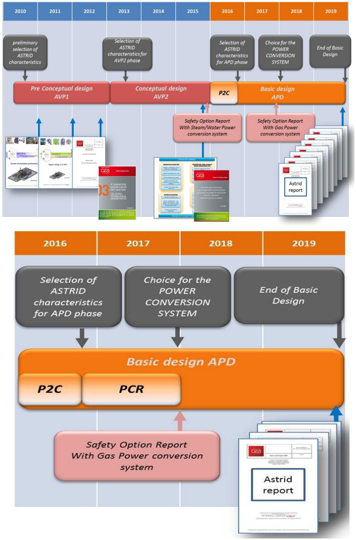




Phases

- initially → all OK:
  conceptual design → DOrS (2012)
  basic design → DOS (2015)
- but no funding to enter the next phase...
  - PIA → too costly
    large reactor → large experiments!
  - EDF → not interested (too early)
- 2016-2017: holding pattern in basic design
  → second DOS (2017, 537p)

Past Experience / ASTRID



Phases

- 2018-19 → pivot to smaller power (1500 MWth → 400 MWth)
- but costs still high because of conservative design: vessel diameter 16m → 12m!
- EDF still not interested, design still expensive

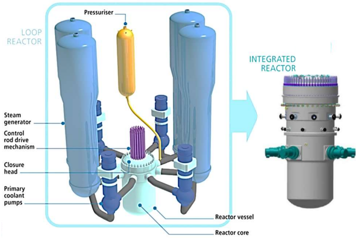
⇒ cancellation in 2019

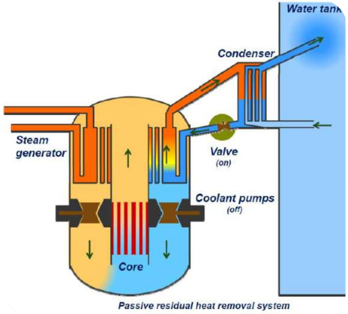
Past experience / ASTRID

Remarks

- Path effects tend to produce a "worst of both worlds" scenario:
  - most of the design is conservative → low flexibility
  - but some innovations are needed ("need to do something different")
    → they need a long/costly development program
- the contracting-based project organization makes everything worse:
  - no technical autonomy in the project team
    → cannot make decisions without...
  - long/difficult communications
  - pivoting is very difficult (and may involve contract changes)
- ASTRID was a single project → (project) risk-taking was impossible: "all eggs in one basket"

Past experience / NUWARD





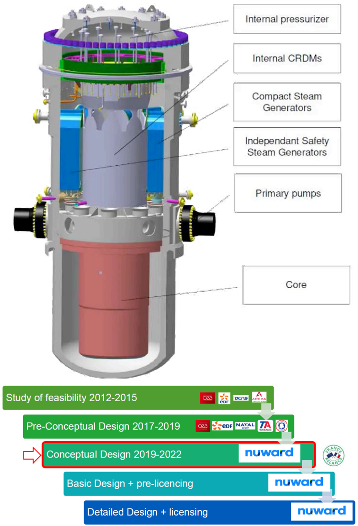
Context

- regroup all the components of a typical PWR in a single vessel
  → largest possible leak reduced from 70cm to 3cm
  → eliminate high/low pressure emergency pumps :
- remove decay heat with a passive loop to a large water tank

⇒ large simplifications at the cost of:

- low power (540 MWth / 170 MWe) : SMR
- some major innovations:
  - compact steam generators
  - integrated pressurizer
  - ...

Past experience / NUWARD



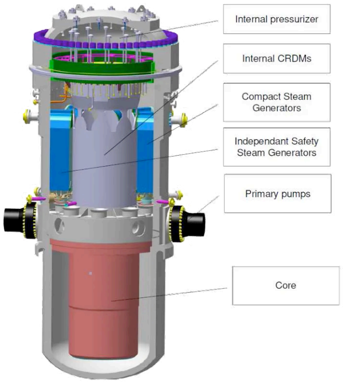
Organization

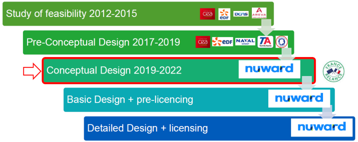
- contracting (again!) but with more institutes: EDF → NUWARD SA (project team) → CEA/TA/FRA/Naval Group/EDF

Phases

- initially slow (without EDF) : conceptual design (2012-2019)
- then EDF interest + France Relance/2030 support: basic design (2020-2023) → DOS in 2023
- start of detailed design in 2023...

Past experience / NUWARD





Phases

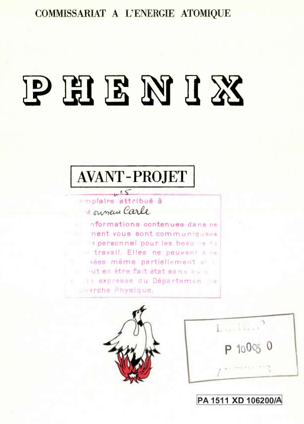
- … but unexpected difficulties in 2024
  + large time/costs expected to validate innovations
  (large risk with a 2030 construction start)

⇒ pivot in 07/2024 to a traditional PWR

Remarks

- “worst-of-both worlds”again:
  apparently conservative/proven design,
  but critical/risky innovations in practice

Past experience / PHENIX

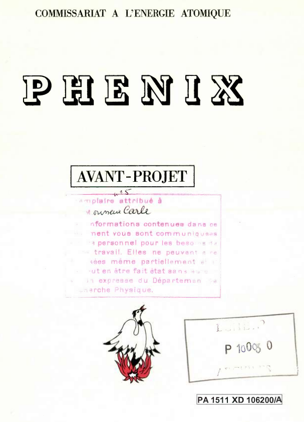


Timeline

- Development of the first two sodium reactors in France:
  - RAPSODIE (11 → 40 MWth):
    - 1957: first studies
    - 1958: conceptual/basic design
    - 1960: detailed design
    - 1962: construction start
    - 1967: divergence
  - PHENIX (560 MWth / 250 MWe):
    - 196x: basic design
    - 1966: detailed design
    - 1968: construction start
    - 1973: divergence

  ⇒ much faster!

Past experience / PHENIX


COMMISSARIAT A L'ENERGIE ATOMIQUE

PHENIX

AVANT-PROJET

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PA 1511 XD 106200/A

Remarks

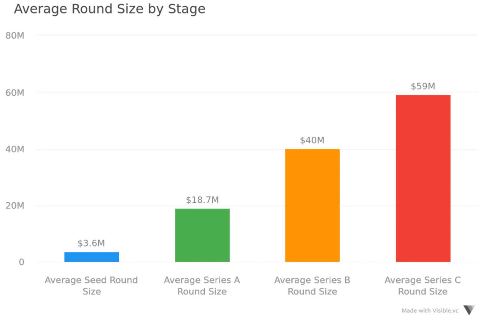
- Different safety requirements than today...
- but also very different organization:
  - design team: small and integrated
    → around 20 people for the PHENIX basic design!
  - with all participants
    for PHENIX : CEA / EDF / GAAA
- the advantages of such an organization seem obvious
  → could it be reproduced today?

Startups

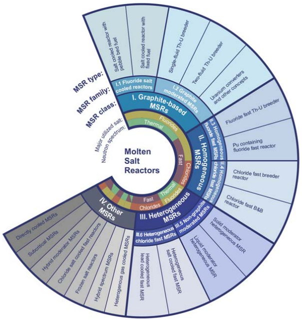
Main features

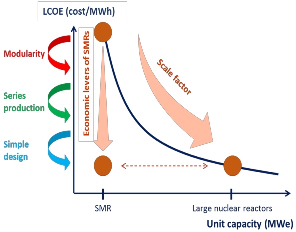
especially: deep-tech startups (ex.: space, pharma, etc.)

- funded in stages : seed → Series A → Series B → Series C
- organized in small teams at the beginning, then grow
- need to provide a return to their investors with a deadline (typically 10 years)
- and... numerous!



Startups





Advantages/Drawbacks

- can explore the design space faster than a single project
- but without the same depth
  → can only work for simple designs:
  - reduce power → SMR/AMR
  - reduce complexity : added → intrinsic safety

  ⇒ this should also reduce costs!
- must "listen to their customer"
- can take risks compared to a single project...
  ... and pivot if necessary (in the early stages)
- may not be able to follow the conplete course of a project
  → but should be able to produce a basic/detailed design

Advantages/Drawbacks: Simplification

Loss of function supporting	General slowdown of the primary pumps	OS2
	General acceleration of the primary pumps	OS2
	Seizure or shaft failure of one primary pump	OS3
	Connection failure between a primary pump and diagrid	OS4
	Unprotected general slowdown of the primary pumps	PS
Defect of sub-assembly cooling	Partial blockage of a fissile sub-assembly	OS3
	Partial blockage of an absorbent sub-assembly	OS3
	Progressive melting of a sub-assembly owing to a blockage	PS
Defect of primary circuit cooling	One or several secondary pump trips	OS2
	Unintentional draining of secondary loops	OS3
	Unintentional closure of isolation valve on secondary loops	OS4
Defect of secondary and tertiary circuits cooling	Station BlackOut shorter than 2 h	OS2
	Station BlackOut longer than 2 h	OS3
	Generalized under-voltage shorter than 3 days	OS4
	Unprotected Station BlackOut shorter than 2 h	OS4
Reactivity variation	Unintentional rising of a control rod	OS2
	Unintentional drop of a control rod	OS2
	Unintentional automatic reactor shut-down	OS2
	Unintentional fast reactor shut-down	OS2

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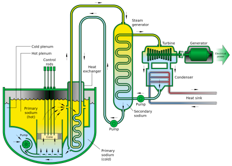
Startups

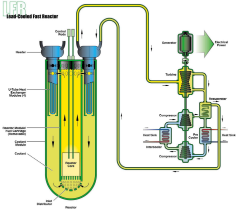
France 2030

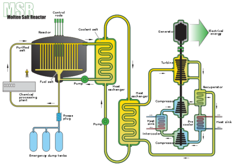
- New interest in nuclear in 2021 (“Discours de Belfort”, CPN...)
- several programs in the post-Covid France Relance and France 2030 :
  - R&D projects (ISAC, MOSARWASTE...)
  - NUWARD support
- ... and an “Innovative Reactors” call:
  - only newcomers → startups!
  - 50% public funding
  - support in three rounds :
    - phase 1 : ∼10x10 M€: conceptual design
    - phase 2 : ∼4x40 M€: basic design
    - phase 3 : 1x300 M€: detailed design

  \+ public support: CEA, CNRS,...

Startups





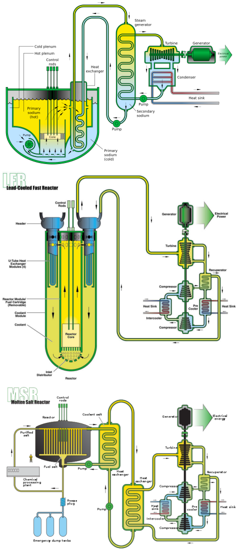


Panorama

6 fission startups in phase 1 + 2 in phase 2:

- Sodium-cooled reactors:
  - HEXANA ← closest to ASTRID
  - OTRERA
  - Blue Capsule ← sodium, but with graphite blocks ⇒ moderated reactor!
- Lead-cooled reactors:
  - Newcleo
- Molten salt reactors:
  - NAAREA
  - Thorizon
  - Stellaria
- Gaz-cooled reactors: Jimmy Energy

Startups

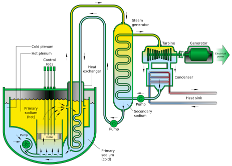


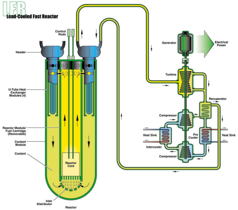
Remarks

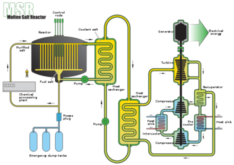
- most startups have asked for R&D support from CEA:
  - materials research
  - sodium knowledge (for Na startups)
  - ...
- Stellaria and Thorizon formed a consortium with ORANO:
  - start work on fuel supply
  - work on future reprocessing

⇒ the smaller startups can function as small design teams, while leveraging the capabilities of the large institutes

Startups





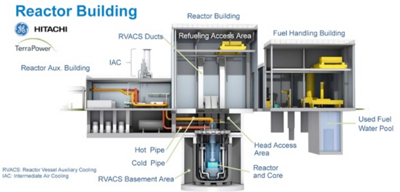


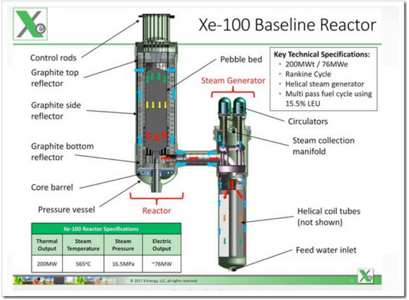
Remarks

- from past experience, startups should be more efficient than the “institutes + contracting” process
- most importantly: not all eggs are in one basket!

⇒ how many of them will succeed?

Startups





The US experience

- the nuclear startup phenomenon emerged in the US in the 2010s!
  → three AMR startups are in the application phase
- two commercial reactors:
  - Terrapower: Natrium (Na-cooled, 345 MWe)
  - X-Energy: Xe-100 (gas-cooled, 4x80 MWe)
- two experimental reactors:
  - Terrapower: MCRE (chloride MSR)
  - Kairos: Hermes (fluoride-cooled HTR)

→ ~20% success rate among "serious" startups!

Conclusion

- Compared to the past, recent projects in innovative reactors have suffered because of safety-induced complexities, but also from other causes:
  - organizational challenges
  - "worst-of-both-worlds" : conservative design + a few innovations
  - "all eggs in one basket" → impossible to take risks
- in comparison, startups:
  - can function like the integrated design teams of previous projects
  - will need to find simplicity
  - can pivot until they do...
  - ... or fail otherwise

→ from the US experience, it is likely that at least a few will succeed

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