GEN IV International Forum℠

ASTRID - LESSONS LEARNED

Gilles Rodriguez

CEA

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Meet the presenter

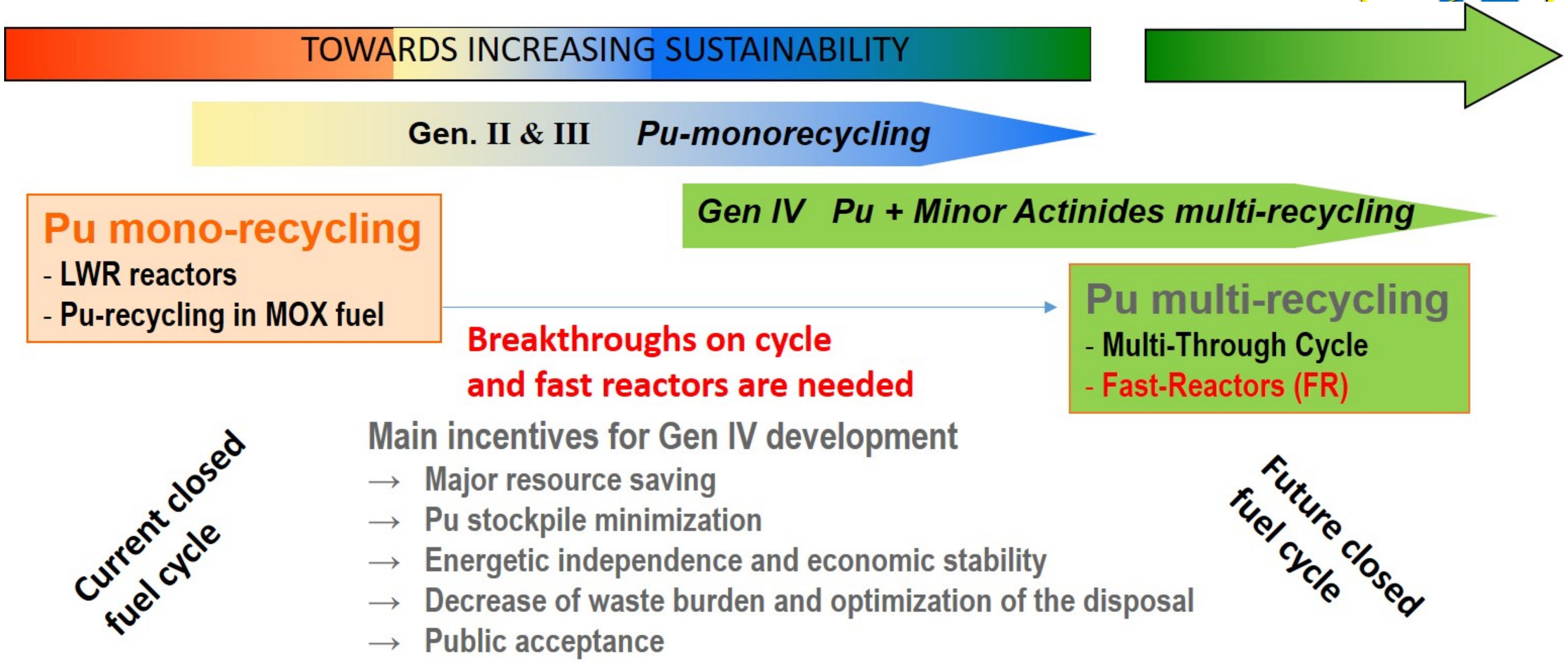
Mr. Gilles Rodriguez is a senior expert engineer at the CEA/CADARACHE (French Atomic Energy Commission/Cadarache center) and has been in the position of deputy head of the ASTRID Project team since 2016. He graduated from the University of Lyon, France in 1990 with an engineering degree in Chemistry and earned a Master of Science in process engineering from the Polytechnic University of Toulouse, France, in 1991. His areas of expertise include fast reactor technology, liquid metal processes, and process engineering. From 2007 to 2013, he was Project Leader of sodium technology and components, within the CEA SFR project organization. In 2013, Mr. Rodriguez joined the CEA project on Sodium Fast Reactor: ASTRID (ASTRID for Advanced Sodium Technological Reactor for Industrial Demonstration), first as responsible of the ASTRID Nuclear Island.

Email: gilles.rodriguez@cea.fr

Outline

- French nuclear policy and its position regarding the several GENIV systems and related coolants
- The advantages and challenges of the SFR concept
- Overview of the ASTRID Program and its related design (main achievements)
- The lessons learned

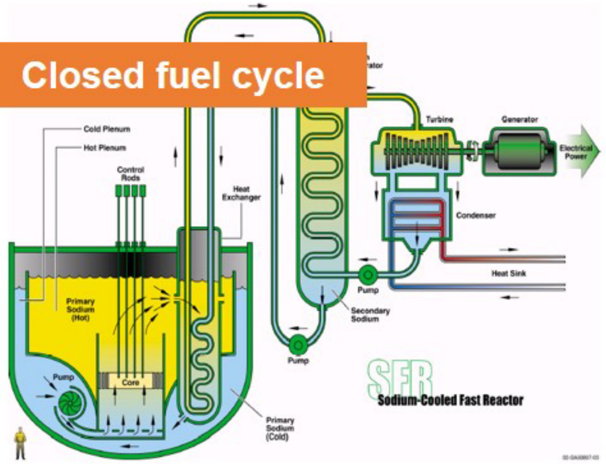
FRENCH NUCLEAR POLICY: THE RATIONALE FOR A CLOSED FUEL CYCLE AND ITS EVOLUTION TOWARDS MORE SUSTAINABILITY



- The French Multi-annual Energy Plan (MEP) is updated every 5 years. An update will be issued at the end of 2018, after the on-going public debate. The governmental document issued to support the public debate on energy has confirmed the closed fuel cycle strategy, as it allows for Pu management and ensures sustainability of nuclear energy.
- Reference of the French roadmap is based on the reprocessing of oxide fuel (hydrometallurgy) and the use of Fast Reactors. Priority is given to Sodium-cooled Fast Reactors (most mature technology). Active survey is performed on other technologies through collaborations.

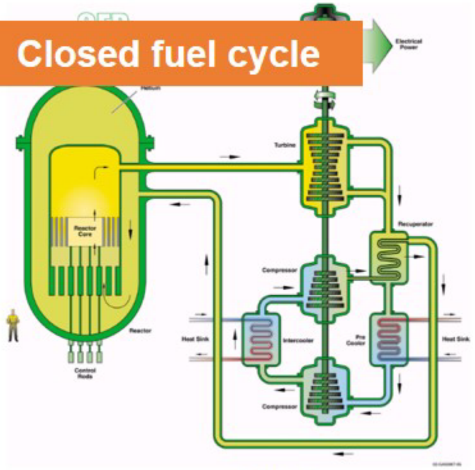
6 Systems Selected by the GEN IV International Forum

Closed fuel cycle



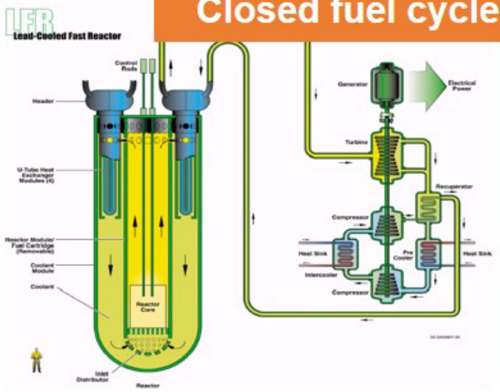
SFR
Sodium-cooled fast reactor

Closed fuel cycle



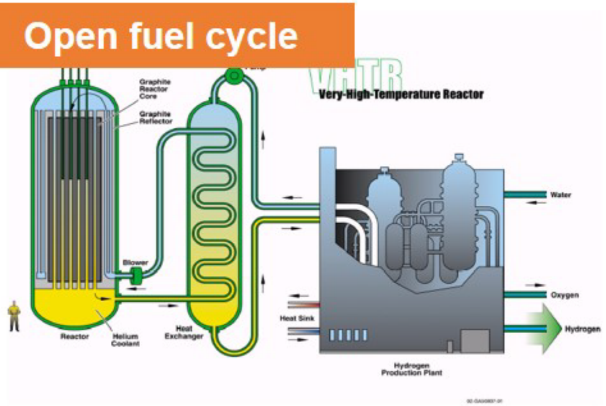
GFR
Gas-cooled fast reactor

Closed fuel cycle



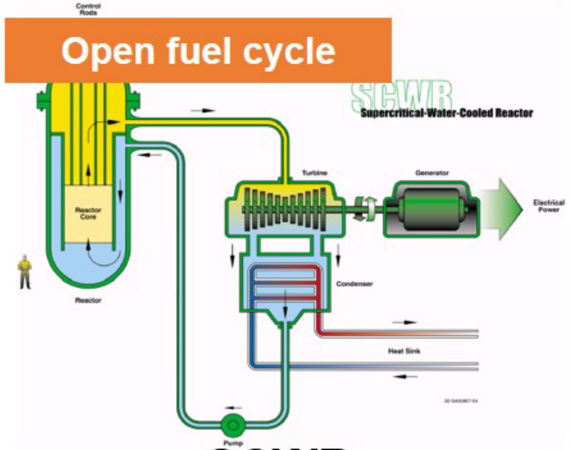
LFR
Lead-cooled fast reactor

Open fuel cycle



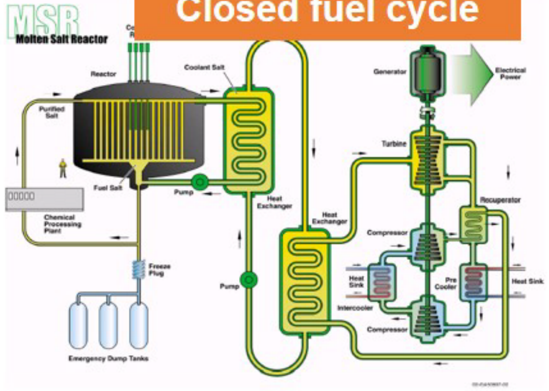
VHTR
Very high temperature reactor

Open fuel cycle



SCWR
Supercritical water-cooled reactor

Closed fuel cycle



MSR
Molten salt reactor

6 Systems Studied Under the Frame of the GEN IV International Forum

GIF systems	Canada	China	France	Japan	South Korea	Russia	Switzer land	US	EU
SFR (SA) ***Fast***		CEFR, CFR-600, CFR-1200	ASTRID (CEA)	JSFR	PGSFR	BN-800, 1200, MBIR		(PRISM), AFR100 TWR (TerraPower)	ESNII/ ESFR
VHTR (SA) ***Thermal***		HTR-10, HTR-PM	Materials, Hydrogen technology	HTTR	NHDD (H_2 prod.)			NGNP, Xe-100	NC2I
GFR (SA) ***Fast***			ALLEGRO (CEA)					EM^2(GA)	ESNII/ ALLEGRO
SCWR (SA) ***Fast/Thermal***	Pressure- tube SCWR	CSR-1000		SCR2000					(HPLWR), NUGENIA/ SCWR-FQT
LFR (MoU) ***Fast***		CLEAR				BREST- OD-300 SVBR-100		SSTAR	ESNII/ ALFRED, MYRRHA
MSR (MoU) ***Fast/thermal***		TMSR (SINAP)	MSFR (CNRS)			MOSART		MCFR (TerraPower) FHR	SAMOFAR

Situation - Septembre 2016

Active contribution   Limited contribution   Observer

CEA Analysis of Different Coolant Technologies on Gen IV Compatible with Fast Neutrons

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➔ Sodium is a consensus

- ✓ High conductivity
- ✓ Liquid from 98°C to 883°C (at 1 bar)
- ✓ Low viscosity
- ✓ Compatible with large variety of steels
- ✓ Industrial fluid
- ✓ Low cost

But reactive with air and water, and opaque

Need a 2ary circuit

➔ Lead is a variant

- ✓ No reactivity with air and water
- ✓ Good coolant

But corrosive, toxic, very dense, opaque (and solid…), high temperature for maintenance (400°C), density (pumping effort, seismic behavior), risk of vapor explosion in primary circuit (secondary circuit)

➔ Helium is an alternative

- ✓ No temperature constraints
- ✓ No phase change
- ✓ Inert
- ✓ Transparent

But low density, high pressure => challenge for a DHR architecture with passive systems

Helium is not such an abundant material on earth

The French Gen IV Program

- French nuclear policy towards a more sustainable nuclear energy ⇒ it requires a cycle based on fast neutrons reactor
- Possibility for a deployment of commercial fast neutrons reactors in the second part of the century ⇒ sodium cooled fast reactor based on a maturity level analysis
  - About 450 years of operation in the world with SFR
  - No implementation of Lead FR, Fast MSR, GFR
- French Fast Reactor program:
  - Priority is given to SFR (reactor and cycle) via the ASTRID project → ASTRID will help to validate breakthroughs on cycle and SFR
  - Active survey on other GenIV fast and thermal neutrons systems through
    - Contribution to projects from EURATOM/H2020, IAEA, OECD/NEA
    - Contribution to GenIV International Forum (systems, working group, task forces…)
    - Specific cooperation frames (for GFR associate member of V4G4, and for MSR cooperation with CNRS)

Fast Reactors Operational data (2018)

Reactor (Country)	Thermal Power	First Criticality	Final Shutdown	Operational period (years)
EBR-I (USA)	1,4	1951	1963	12
BR-5/BR-10 (Russia)	8	1958	2002	44
DFR (UK)	60	1959	1977	18
EBR-II (USA)	62,5	1961	1991	30
EFFBR (USA)	200	1963	1972	9
Rapsodie (France)	40	1967	1983	16
BOR-60 (Russia)	55	1968		50
SEFOR (USA)	20	1969	1972	3
BN-350 (Kazakhstan)	750	1972	1999	27
Phenix (France)	563	1973	2009	36
PFR (UK)	650	1974	1994	20
JOYO (Japan)	50-75/100	1977		41
KNK-II (Germany)	58	1977	1991	14
FFTF (USA)	400	1980	1993	13
BN-600 (Russia)	1470	1980		38
SuperPhenix (France)	3000	1985	1997	12
FBTR (India)	40	1985		33
MONJU (Japan)	714	1994	2016	22
BN-800 (Russia)	2000	2014		4
CEFR (China)	65	2010		8
PFBR (India)	1250	Under commissioning		
Total all fast reactors				450

Projects of SFRs Worldwide

France : *ASTRID*

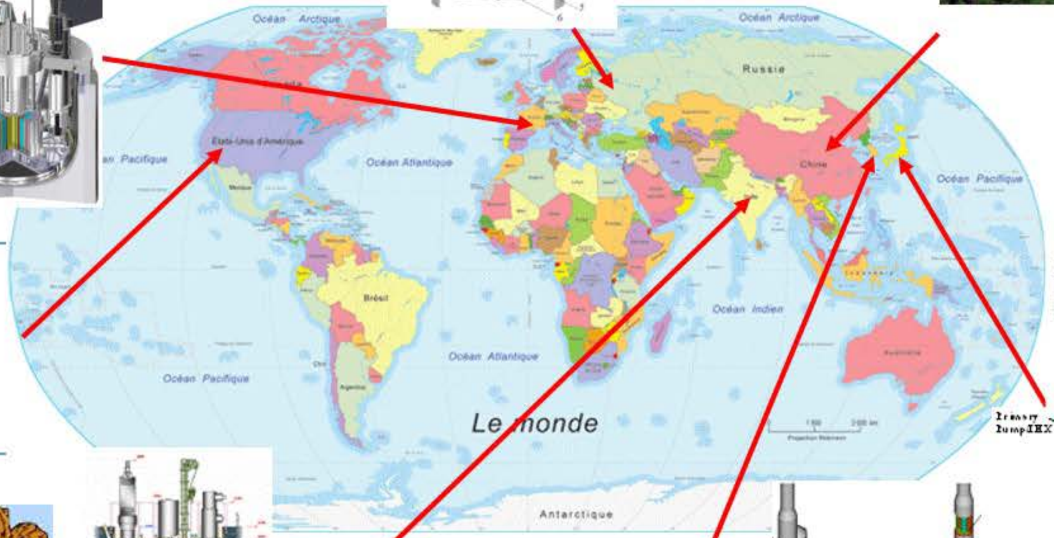
Fuel: MOX-RNR

Russia: BN-800, *MBIR*, *BN 1200*

Fuel: UOX, *MOX-RNR*, *Nitride*

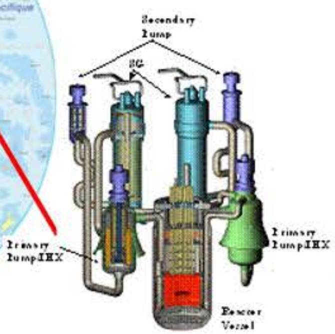
China : CEFR, *CFR600*, *CCFR1000*

Fuel MOX-RNR



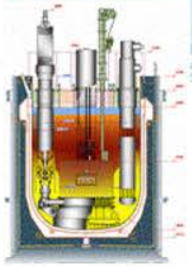
USA : designs of SMR, Terrapower, PRISM, VTR

Collaboration under discussion with the USA



Japan : *prototype JSFR (stand-by)*

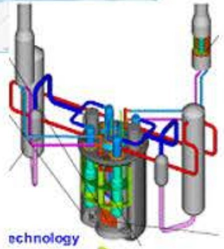
Fuel: MOX-RNR



India: PFBR, *2xFBR (500 MWe)*,

MFDR, MFBR

Fuel: MOX, metallic

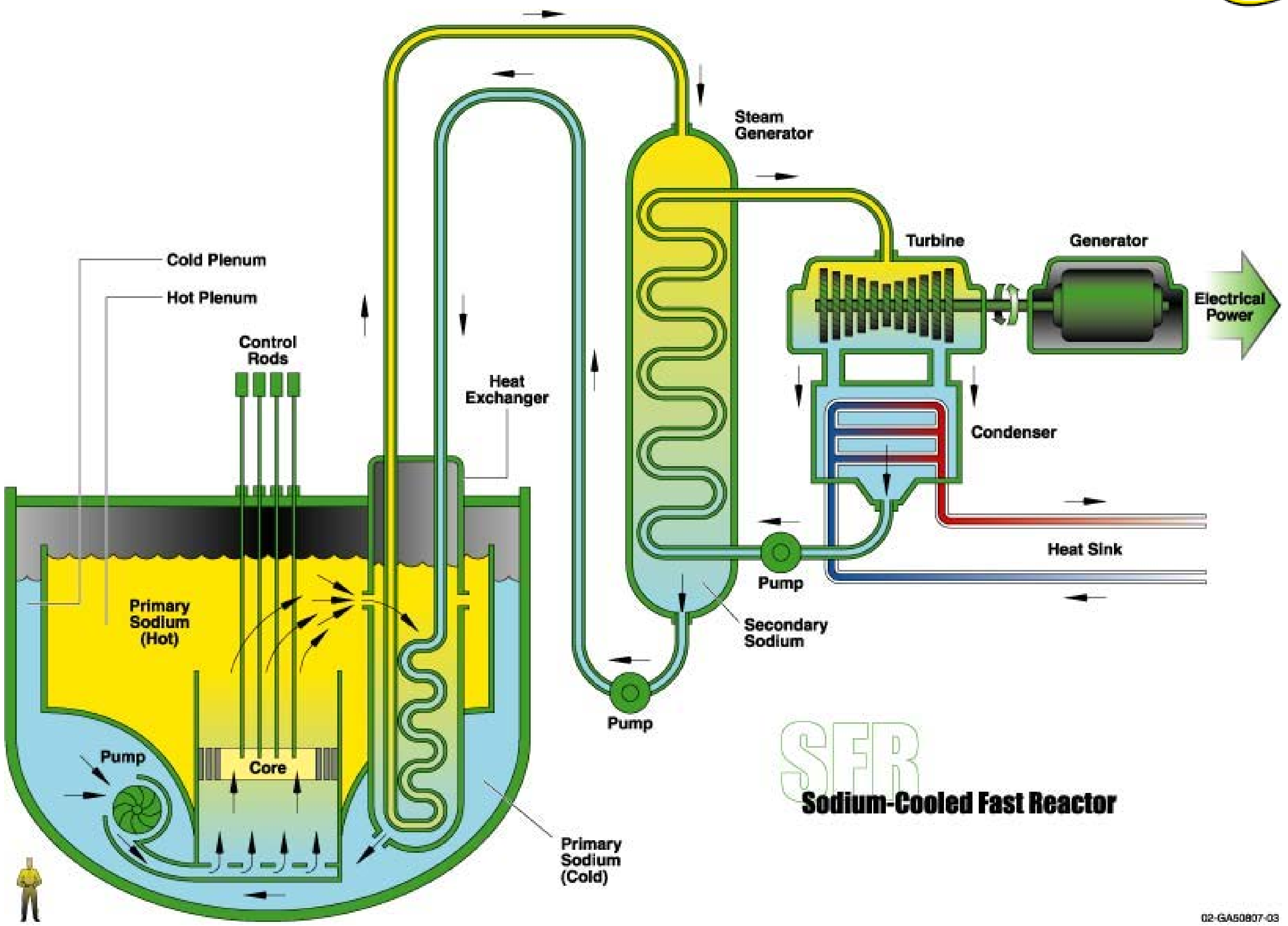


South Korea:

PGSFR (150MWe, 2028)

Fuel: metallic

SFR Design (Basic Principle)

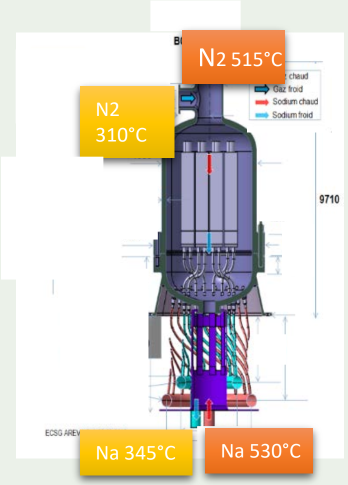


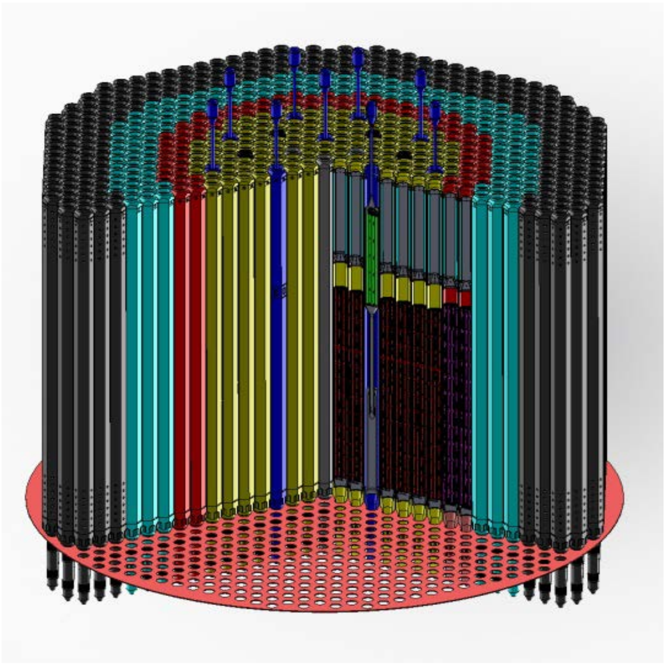
Favorable Features of SFR

- The whole primary circuit is contained is the main vessel, including the core, the intermediate heat exchangers and the primary pumps.
- The primary system is not pressurized.
- The intermediate (or secondary) system transfers the energy to steam generators, thus providing for an extra containment between the primary circuit and the environment.
- Large boiling margin of sodium (>300 K)
- The large quantity of primary coolant provides for a high thermal inertia in case of loss of main heat sink.
- Good natural convection and circulation features allow to design passive, diversified decay heat removal systems.
- Power control by single rod position, no xenon effect, no need of soluble neutron poison.
- Collective dose on a pool type SFR is very low compared to PWR.

Improvements in SFR Design

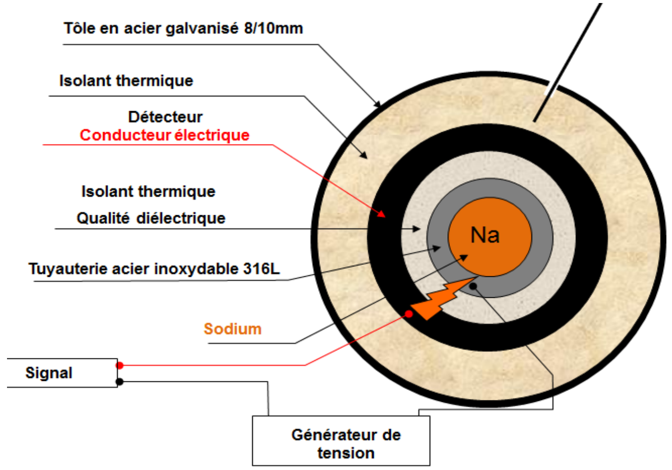
Feedback of previous SFRs	R&D directions	ASTRID Orientations
Core Sodium voiding reactivity **→ Safety**	Optimization of core design to improve natural behavior during abnormal transients. Exploration of heterogeneous cores	CFV core: innovative approach, <u>negative</u> overall <u>sodium voiding reactivity</u> Better natural behavior of the core, for instance in case of loss of flow (e.g. due to loss of supply power). Avoid neutronic power excursion
Sodium-Water interaction **→ Safety - Availability**	Robust steam generators **2 options are studied** Gas Power Conversion System (nitrogen in place of steam/water), *that will allow to physically avoid the sodium-water reaction*	Limitation of total released energy in case of sodium-water interaction, and integrity of the envelop of the steam generator and the secondary loop. Design studies conducted by General Electrics. No show stopper. Design studies on sodium-gas exchanges conducted with FRAMATOME.

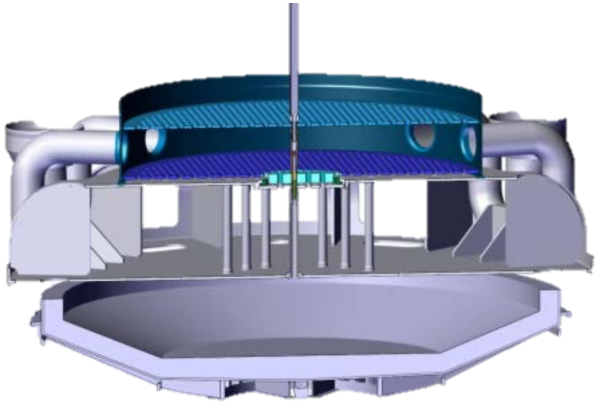




Improvements in SFR Design

Feedback of previous SFRs	R&D directions	ASTRID Orientations
Sodium fire **→ Safety**	Innovative Sodium leak detection systems R&D on Sodium aerosols	Improving detection (Patent of detection system integrated in the heat insulator) Close containment (inert gas + restriction of available oxygen)
Severe accidents **→ Safety**	Core catcher Research on corium and sodium-corium interaction	Core catcher Transfer tubes
Decay heat removal **→ Safety**	Reactor vessel auxiliary cooling system (scaling rules)	Combination of proved Decay Heat Removal systems and Vessel Natural Air draft cooling *with the objective to practically eliminate the long term loss of the function*
In-Service Inspection and Repair **→ Safety – Availability**	ISI&R taken into account from the design stage and Simplification of primary system design Under-sodium viewing: improvement of Signal processing and sensor technologies (ultrasound at high temperature, fission chambers, Optical Fibers, …) Remote handling for inspection or repair	





The ASTRID Program

(Advanced Sodium Technological Reactor for Industrial Demonstration)

- *ASTRID is a technological demonstrator and is not a First of a Kind of a commercial reactor.*
- Based on the feedback experiences of past Sodium-cooled Fast Reactors, ASTRID has the objective to demonstrate at a scale allowing the industrial extrapolation, the relevancy and performances of innovations, in particular in the fields of safety and operability.
- ASTRID with the related R&D facilities will allow:
  - to test and qualify innovative safety design options towards the commercial reactor,
  - to qualify different fuels (transmutation, plutonium burner, …),
  - to obtain the necessary data to justify a useful lifetime of 60 years for future SFR,
  - to confirm performances of innovative components and systems in order to optimize the design of future commercial reactors from a technical and economical points of view,
  - to establish a reference for the SFR cost assessment (building and operation).

The ASTRID Program

(Advanced Sodium Technological Reactor for Industrial Demonstration)

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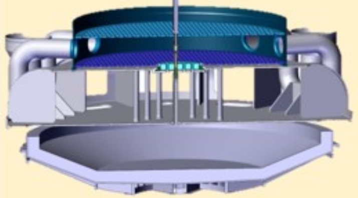
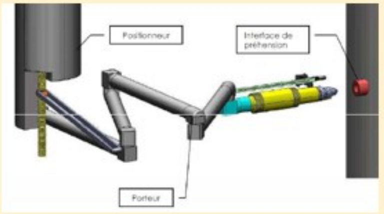
- The technology of ASTRID allows to have a very resilient design to external events (earthquake, flooding, loss of power, airplane crash…)

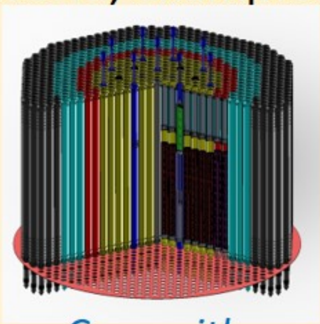
Based on the **feedback experiences of past Sodium-cooled Fast Reactors operated in the world**, examples of **innovations**



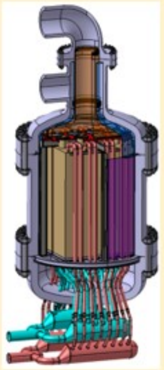
Mitigation devices (core catcher…)



Larger in-service inspection capabilities



Core with an improved intrinsic behavior



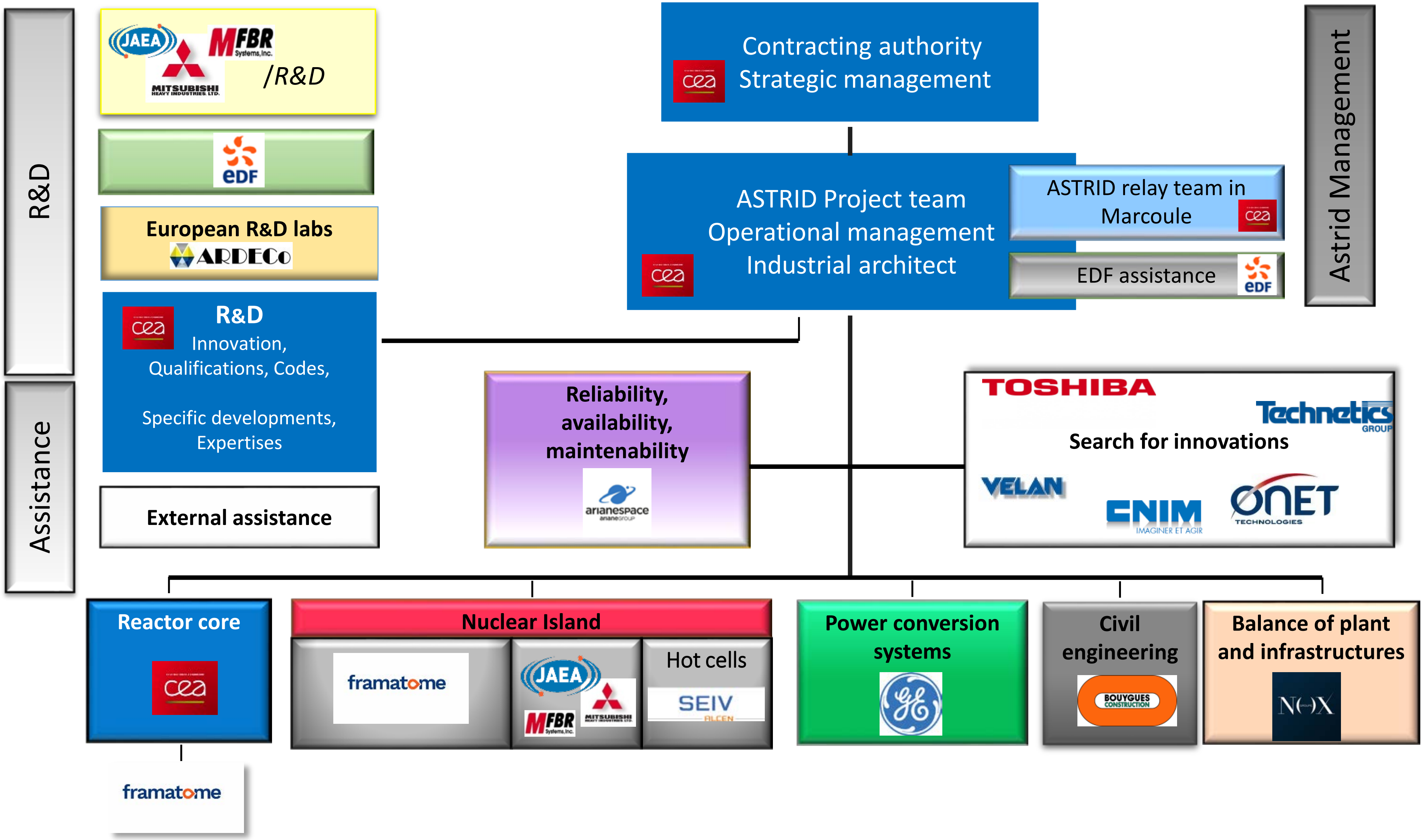
Gas power conversion system

Industrial partners

Leaders in nuclear and high-tech

EDF, framatome, BOUYGUES, GE, JAEA, ENIM, Technetics Group, VELAN, NOX, MFBR Systems, Inc., ONET Technologies, arianespace, SEIV ALCEN, TOSHIBA, MITSUBISHI HEAVY INDUSTRIES, LTD.

ASTRID Project Organisation



ASTRID: Partnerships Organization

GEN IV International Forum

International cooperation

Generic R&D

GEN IV International Forum

EERA European Energy Research Alliance

SNETP Sustainable Nuclear Energy Technology Platform

ESNII European Sustainable Nuclear Industry Initiative

Managed by CEA

cea

ARDECo

EDF R&D, PSI,
Sweden (KTH, Chalmers, Uppsala),
HZDR,
KIT, ENEA, *JRC/ITU, NNL, CIEMAT …*

CNRS (NEEDS), Universities

Industrial partners

arianespace

framatome

EDF

TOSHIBA

ONET TECHNOLOGIES

SEIV ALCEN

LE PÔLE DE L'INDUSTRIE NUCLÉAIRE

BOUYGUES CONSTRUCTION SERVICES NUCLÉAIRES

JAEA

MFBR

MITSUBISHI

VELAN

ENIM IMAGINER ET AGIR

NOX

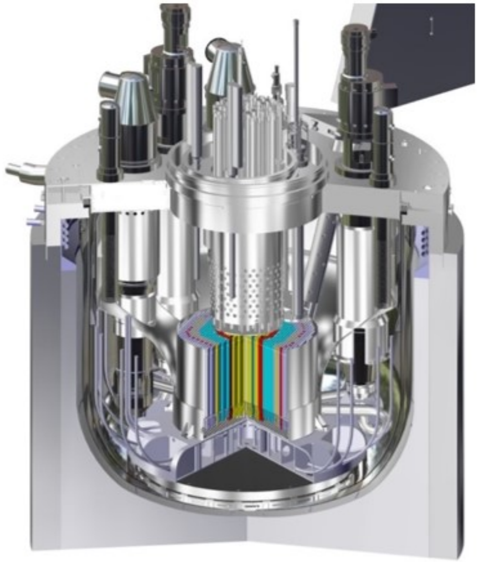
Technetics GROUP

CEA Experimental Platforms

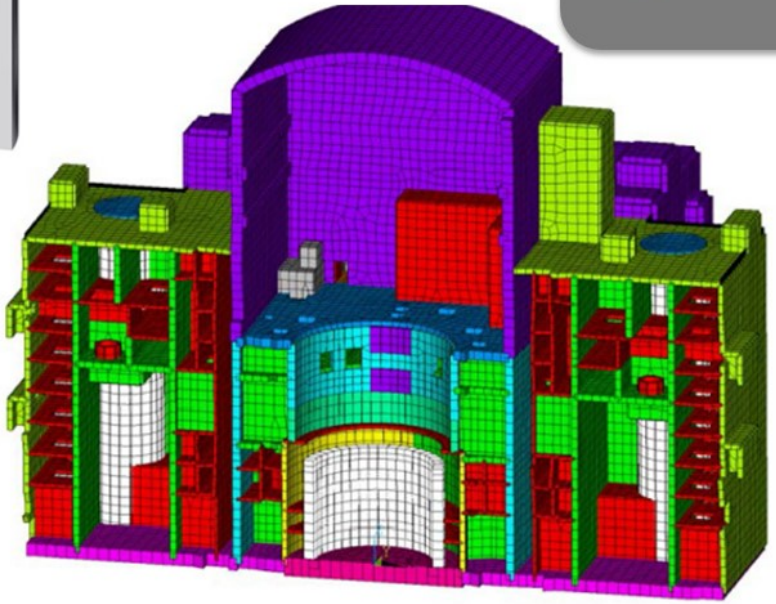
In addition to available foreign experimental platform, CEA is carrying out particular investments

Needs	CEA Platform
Neutronic qualification of innovative core	**MASURCA** : **under reconsideration / International reactors**
Analytical water tests, TH code validation (gas entrainment, hot pool flows), Component qualification (ISIR)	**GISEH** : Acronym for "Group Installations in Surrogate coolant for Hydraulics, thermal-hydraulics, mechanics, fluid-structure interaction" **In operation**
Small Na loop (<3 m^3 Na) TH code validation and Component and technological qualification (under Na viewing)	**PAPIRUS** : Acronym for "Parc of small Installation of R&d for Utilization of Sodium Corrosion test, heat exchanger test, instrumentation… **In operation**
Large Na loop (<100 m^3 Na) Component qualification (close to scale 1 prototypes)	**CHEOPS** : → Sodium-gas heat exchanger or steam generator mock-up, subassembly thermal-hydraulics, Control rods, passive shutdown system qualification, sodium fuel handling, … **Under reconsideration / Jp platform**
Severe Accidents corium behaviour, Qualification of mitigation device (core catcher…)	**PLINIUS-2 :** experimental studies of corium-sodium-interaction and core catcher (100-500 kg of UO2), analytical test **Under design. Decision to build**

Use of Digital in ASTRID Project…



Design and operation of innovative systems

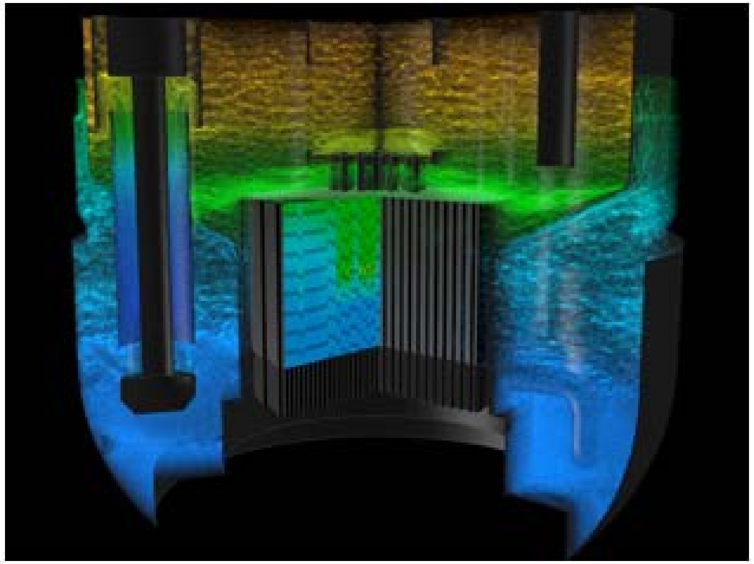


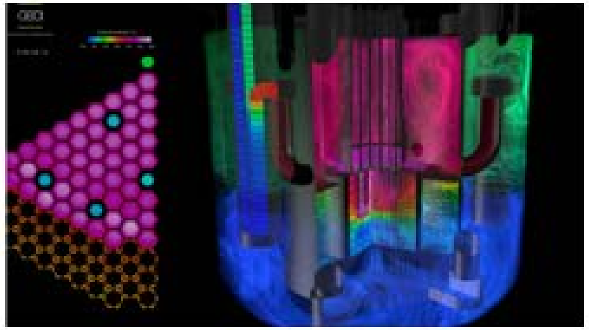
Assessment of performances

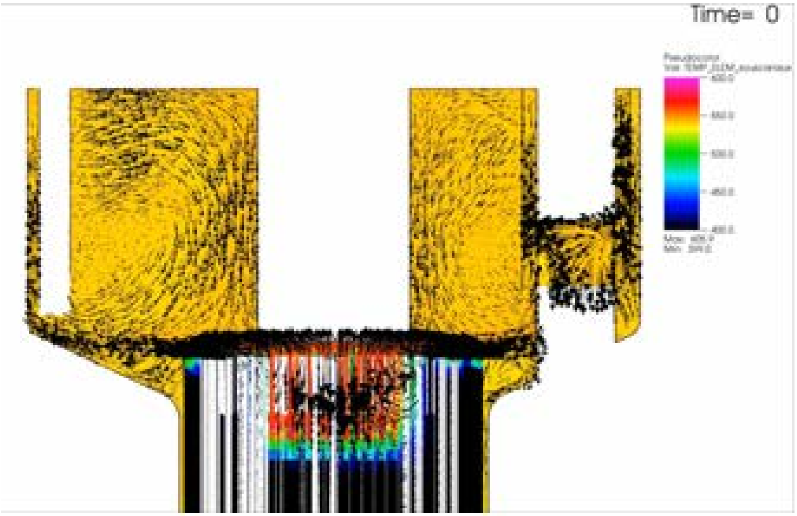
Management of a large & complex project (13 ind. partners, up to over 500 participants)

… Model Complex Phenomena to Consolidate Demonstrations

- Numerical simulation is required to support design studies and safety analysis
- Multi-physics and multiscale modelling





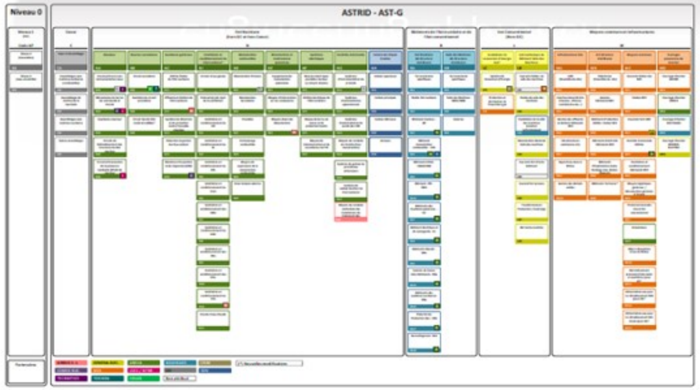


Modelling of an accidental scenario with loss of the primary pump of ASTRID reactor, without control rod protection (ULOF). Natural convection is leading to a stabilised sodium flow in te core allowing core assemblies cooling and avoiding a severe accident situation (no core or fuel melting). CEA/Saclay studies

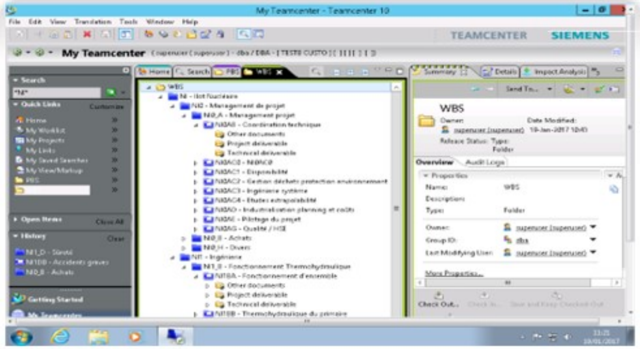
… Management of a Large Complex Project

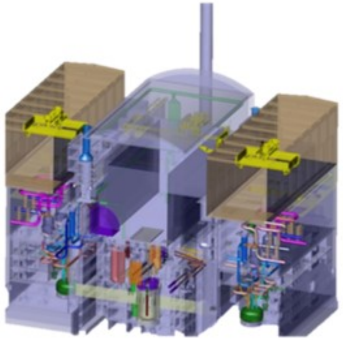
A lot of partners

Organization based on systems engineering approach



Plant Life Management





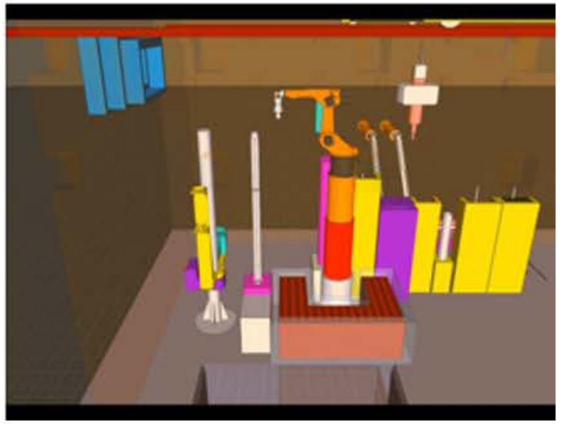
3D numerical model **and configuration management**

- **Model from models provided by 13 partners**
- **15.000 interface data**
- **20 Gigas of data and 200.000 objects in the CAO 3D mockup**

Advantages From the Use of Virtual Reality

Promising deployment of the the use of Virtual Reality

Design	• Large data Treatment • Fusion of 3D PDMS / CATIA models
Review of CAO mock-up	• Technical review realized inside the 3D meeting room
Design-to-Maintenance	• Integration of maintenance and handling operations at the early stage of design
Kinematics studies	• Validation of some complex kinematics



Example of a kinematic of handling processes inside the ASTRID hot cell

SEIV
ALCEN

Main Achievements for 2015, and After…

- A synthesis file was sent to the government mid 2015 :
  - Strategy leading to the choice of Gen IV sodium cooled fast reactor and closed fuel cycle.
- Synthesis file summarizing the conceptual design phase (2010-2015) provided in December 2015
  - Scope statement, with technological choices (including conversion system), issued from Conceptual Design.
  - Workplan for Basic Design, with associated R&D infrastructures.
- Authorization at the end of 2015 from the government to proceed until the end of 2019 (Basic design phase).

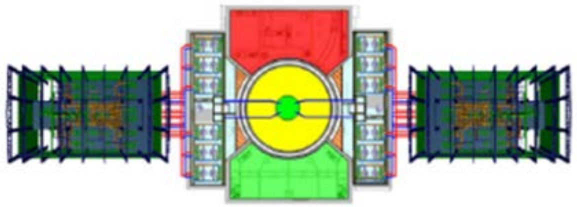

cea
Direction de l'énergie nucléaire

Avancées des recherches
sur la séparation-transmutation
et le multirecyclage du plutonium
dans les réacteurs
à flux de neutrons rapides

Juin 2015

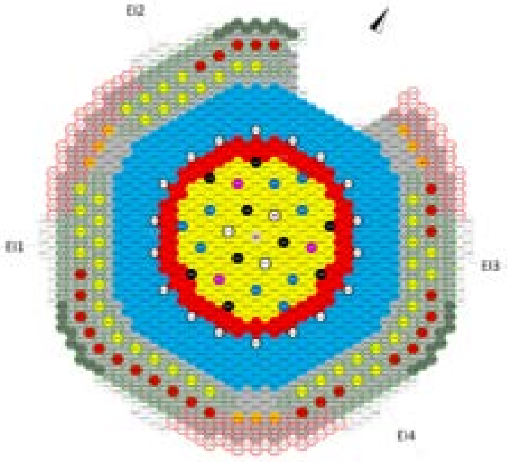
Décret n° 2013-1304 du 27 décembre 2013 pris pour application de l'article L. 542-1-2
du code de l'environnement et établissant les prescriptions du Plan national de gestion
des matières et des déchets radioactifs

(www.cea.fr)

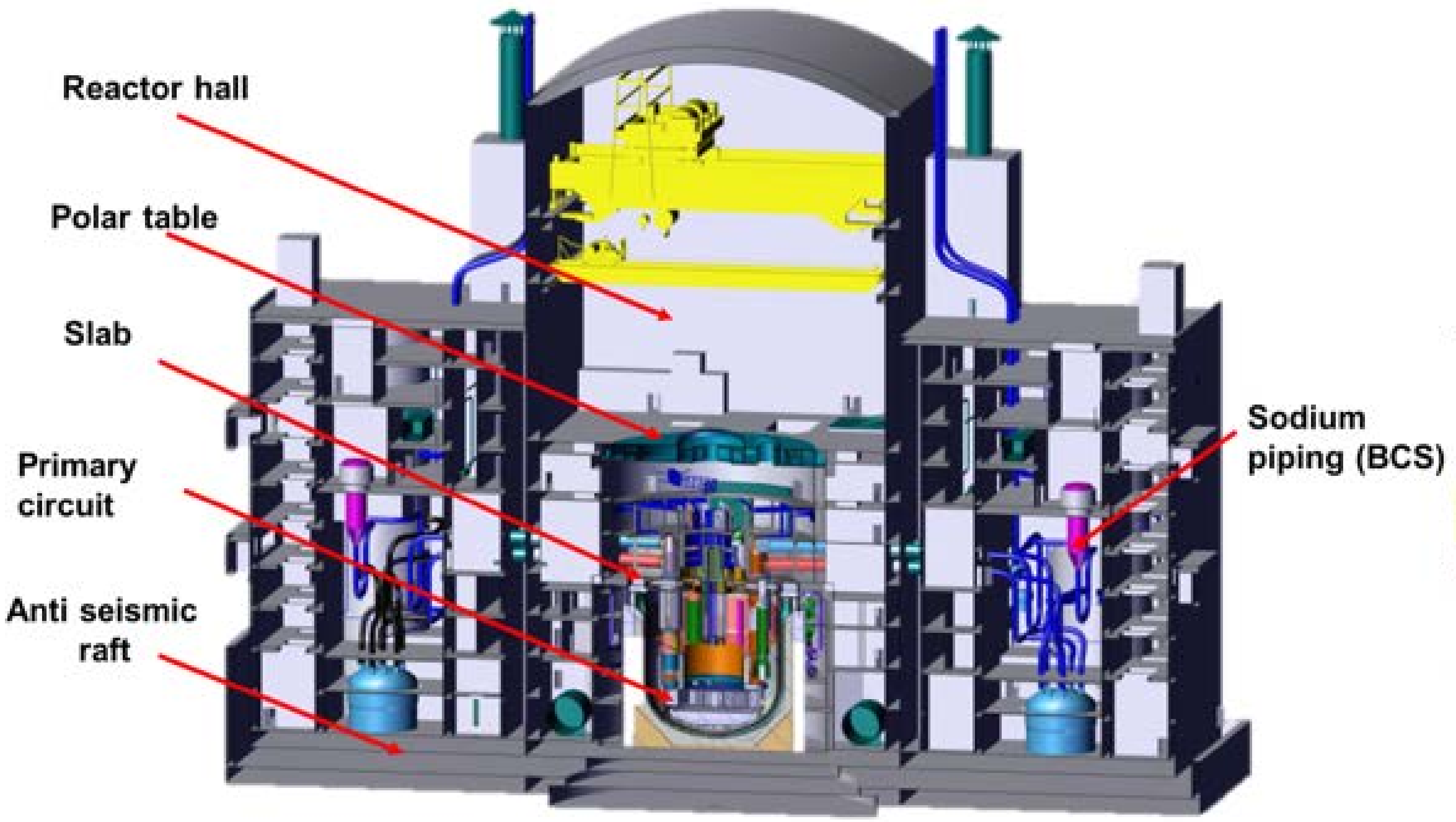


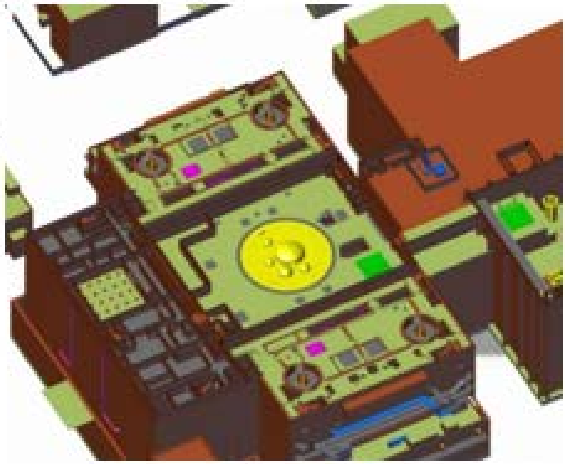
ASTRID Main Technical Choices

- 1500 thMW - ~600 eMW
- Pool type reactor
- With an intermediate sodium circuit
- CFV core (low sodium void worth)
- Oxide fuel UO2-PuO2
- Preliminary strategy for severe accidents (internal core catcher, no large mechanical energy release, …)
- Redundant and diversified decay heat removal systems
- Fuel handling in sodium + combination of internal storage and small external storage (to increase of the availability rate)

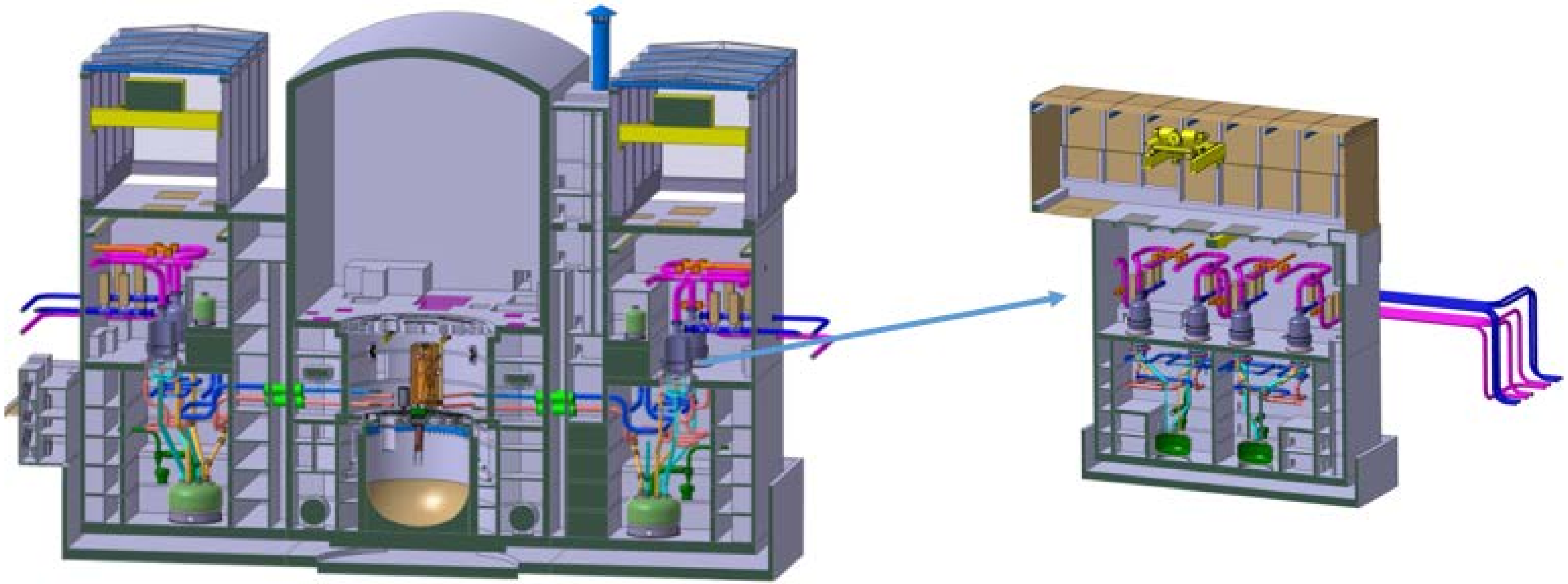


Option with Steam Water Power Conversion System

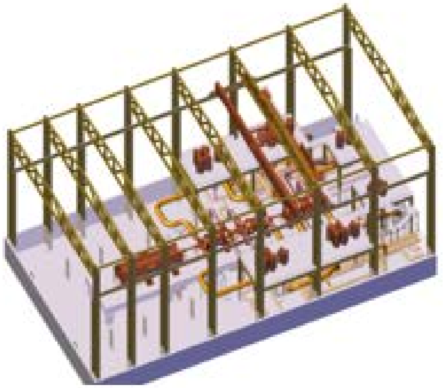


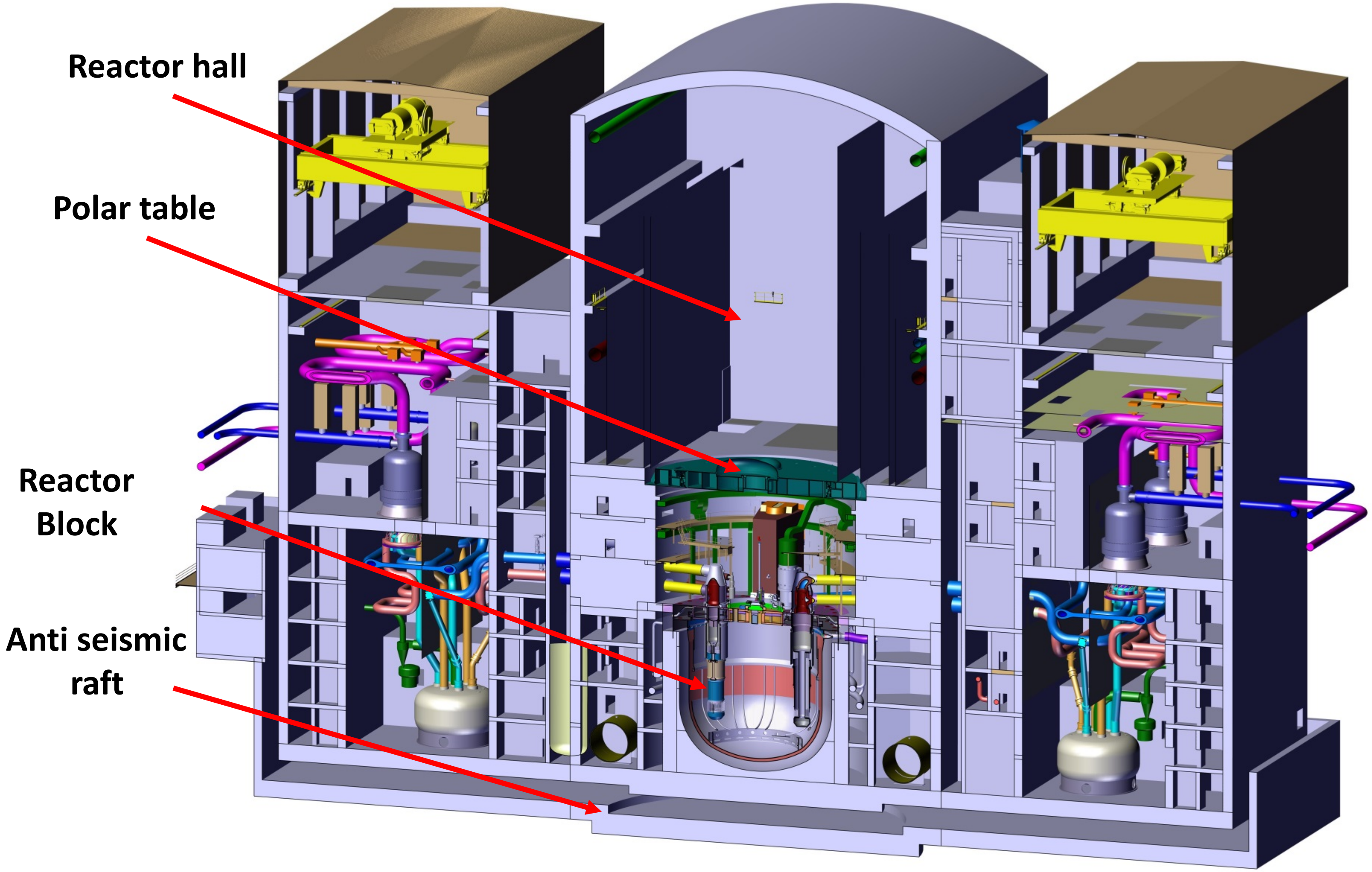


Option with Gas Power Conversion System

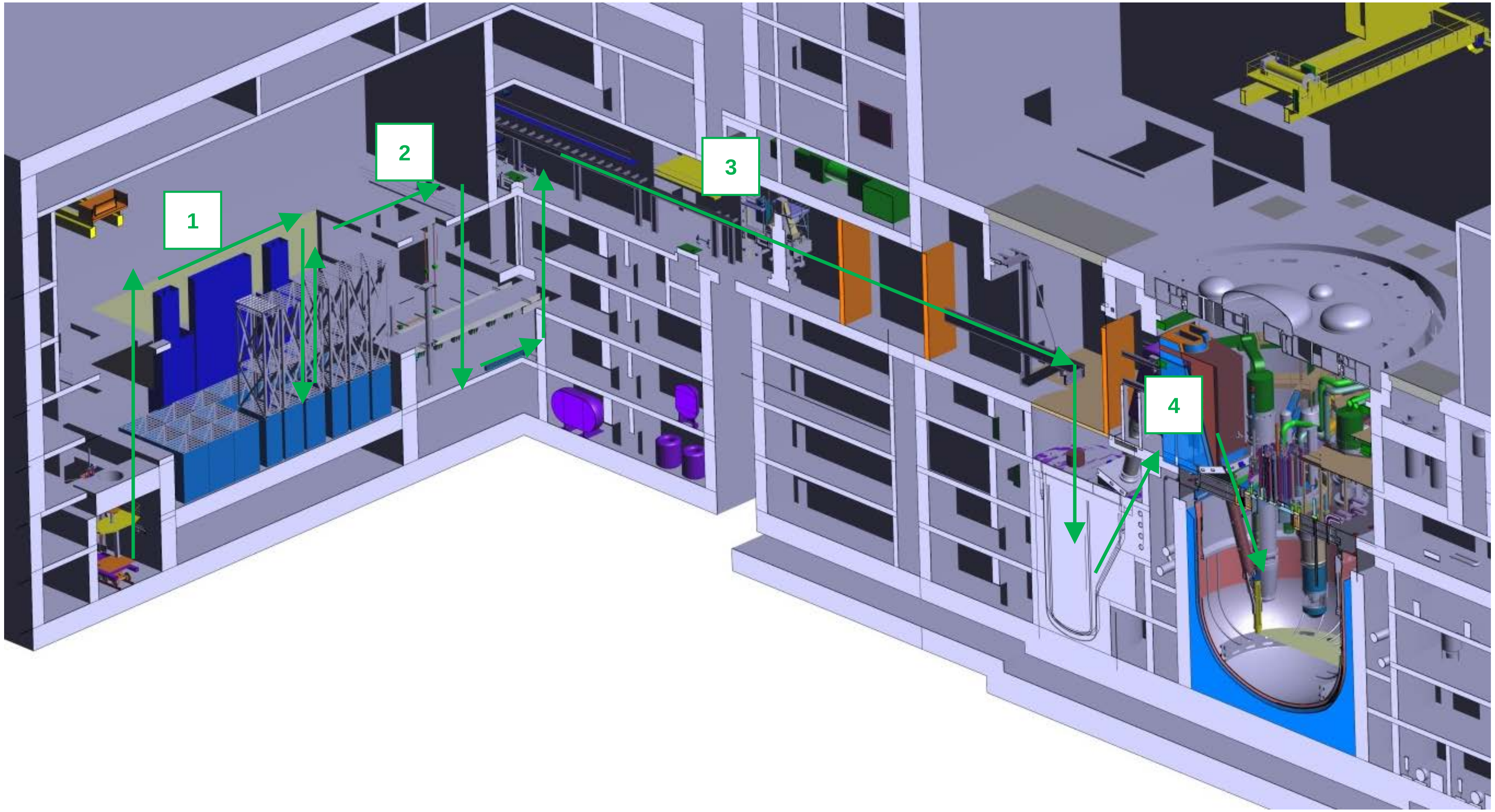


Turbine hall

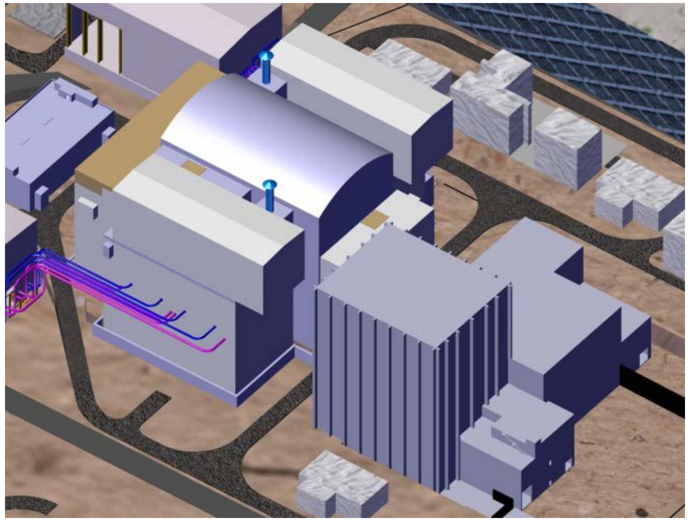


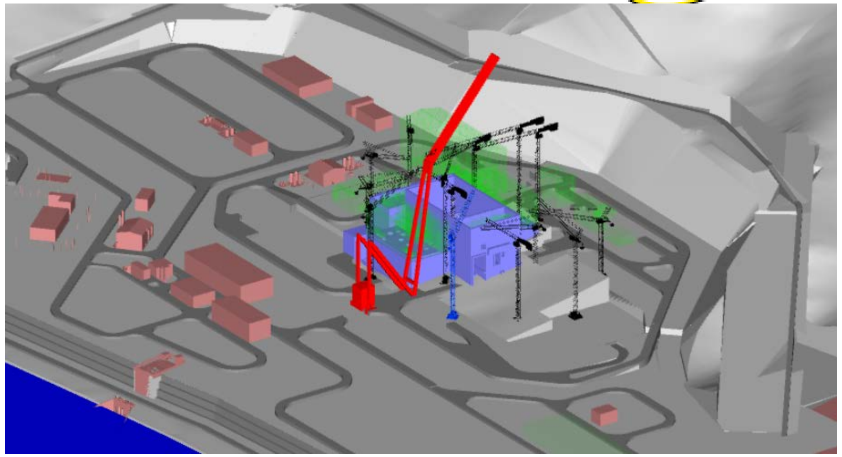

Reactor hall
Polar table
Reactor Block
Anti seismic raft

ASTRID Design: the Fuel Handling Route

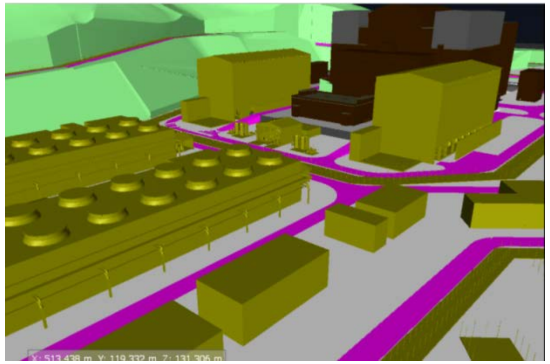


ASTRID Design: BOP & Constructibility



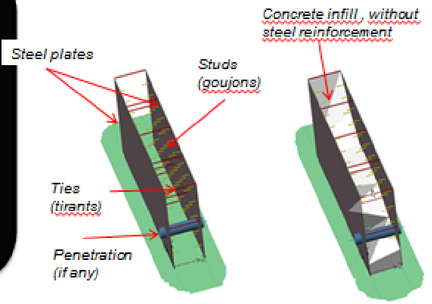


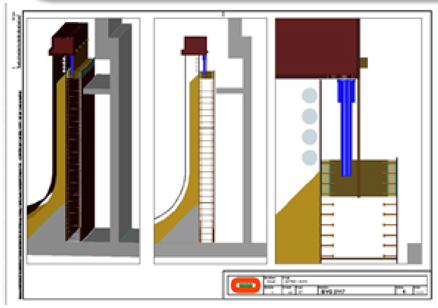
Progress on constructibility operation and Balance of Plant

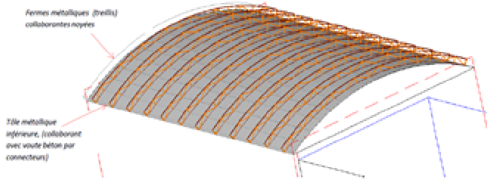


Steel-concrete structure are used for reactor pit and for roof of the reactor building.

- Reactor pit
- Roof of the reactor building
- Gain on planning and consequently on the global cost
- Higher mechanical strength
- Most of abrication of SC modules can be performed in manufactory







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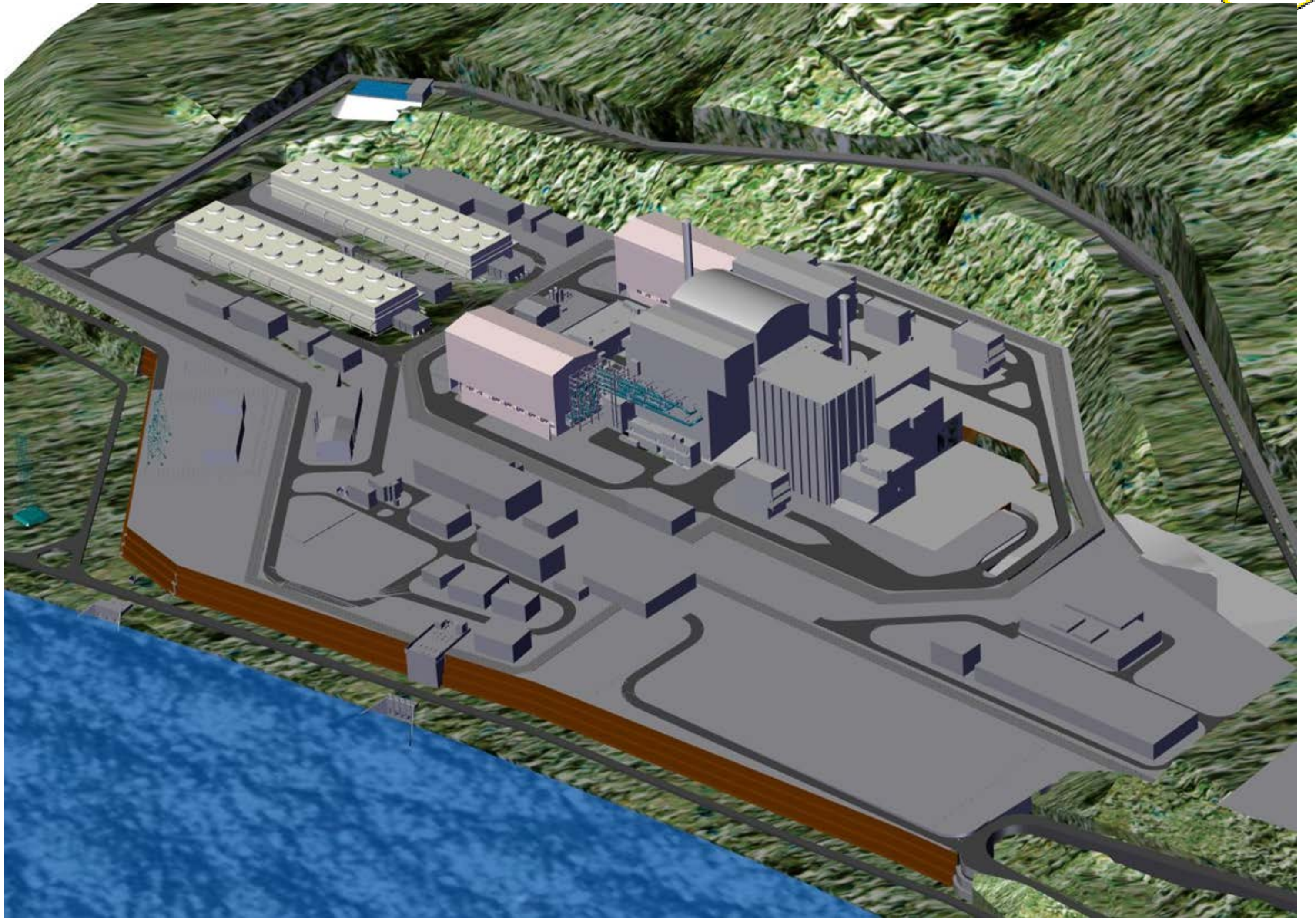
ASTRID - Balance Of Plant



Lessons Learned

- Nuclear energy is a well proven source of large baseload electricity, with no GHG emissions. It will remain one of the pillars of the future French low carbon energy mix.
- The closed fuel cycle associated with FNR will lead to drastic improvement in U resources management, and important reduction in footprint and radiotoxicity of final wastes.
- French program on Generation IV is based on:
  - ASTRID program
  - Basic design phase on-going (2016-2019)
  - Schedule and organization for next phases are under preparation with French government and industrial partners
  - One option could be to review the power of the demonstration reactor. In that option, a large part of works performed from 2010 will be reused (design processes, methodologies (V&V&Q for instance), new generation numerical tools, PLM, lot of innovative design options (maturity level is known…). Efficiency for next works will then be improved and current on-going R&D program is mostly relevant.
  - An active survey on other GenIV fast and thermal neutrons system

Lessons Learned

- SFR is a mature technology because many SFR reactors built from the 50's to the 70's were then operated. But the gap to achieve a GenIV concept is significant because GenIV is requesting improvements mainly in safety, operational and economics aspects; and it is impacting the related design.
- Even if mature, the SFR technology is not obvious and in that field knowledge preservation and transmission to the coming young generation is also a key challenge if you want to keep this key technology available for decades. Thus the use of sodium as coolant – as for the other liquid metal or Helium coolants – needs courses, practice and skills.
- Innovation is the way to design new reactors. It needs to get a close relationships between industry and design teams in one hand and R&D teams on the other hand. The role of the ASTRID Team project is to make them run together.
- SFR reactor design cannot be achieved without international collaboration, mainly to mutualize technological platforms and infrastructures. It is a win-win cost savings approach

Thank you for your attention

Upcoming Webinars

22 August 2018	BREST-300 Lead-Cooled Fast Reactor	Dr. Valery Rachkov, IPPE, Russia
26 September 2018	Advanced Lead Fast reactor European Demonstrator – ALFRED Project	Dr. Alessandro Alemberti, Ansaldo Nucleare, Italy
24 October 2018	Safety of Gen IV Reactors	Dr. Luca Ammirabile, EU