SMRs – Concepts and R&D axes

André Bergeron
CEA/ISAS/DES/DM2S/STMF/LMSF

Cea-Saclay
GdR MaNu – 25 October 2023 – Le Croisic

Outline

SMR – What are we speaking of

- SMR
  - **S**mall **M**odular **R**eactors
- Small reactors
  - New trend in Nuclear development since 90s
  - Electricity power below 300 Mwe
    - Sub-class AMR below 10 Me,
  - **Not new in the history of nuclear power**
    - During 50s and 60s development of small nuclear reactors
      - Experimental reactors all over the world (CEA small reactors in 50s, 60s, OSIRIS) , TRIGA reactors all around the world…and son on
      - Very small reactor for military bases (at least 9 reactors in US)
      - Spatial reactors
      - Marine applications (sub-marine, ice-breakers …)
      - A step in the development of larged water cooled reactors for civil electricity with the "from small to great" strategy
        - Shippingport reactor of *60 Mwe* first PWR up to EPR **1500 Me**
- Modular
  - Many elements of SMRs must be built in factories and put together on the nuclear site.
    - Large production of many identical pieces
    - Reduced costs
  - Constraints on the vessels dimensions in order to be transportable on roads ….
  - Modularity is already used in others industries such as high power electricity, oil installations
- **Small power and Modularity are not fully new but …..**

SMRs – What are we speaking of

- The deployment of nuclear power plants made of small size modular nuclear cores positionned side by side that can be easily adapted to **the small and large electricty and heat grids**.
  - This approach allows :
    - To drasticaly reduce the initial financial investment compared with large scale nuclear power while being really adapted to local electricity and heat needs
    - Decarbonization of electricity production by 2050
      - For example replacement of fossil-plants in Islands and distant territories and so on
      - Replacement of fossil electricty and heat for heavy industries such steel industries, H2 production, electrochimy and so on
    - Allows the capability to extent easily the power production by adding modules that are easily built in dedicated factories and transported on sites.

- **The ambition of SMRs is to replace carbon-based industry with improved safety small size reactors**

SMR – The motion

- Ideas of SMRs since the beginning of 1990
    - Research activities in USA, China, Japan, Russia,Korea…
    - Due to reduced power SMR can increase safety using passive emergency cooling that are difficult to design or demonstrate for large reactor but with existing concepts (AP600, AP1000, ESBWR …)
- Russia and China first in the run for industrial applications
    - In Russia we **have heard** of the floating Nuclear power plants in Siberia for supplying electricity to 2 small on sea small towns
    - In China there are already SMRs in production and a lot of projects have been undertaken
- US has recently set-up a large program of SMR designs with investigation of
    - Historical nuclear reactors vendors
    - Start-ups
    - National laboratories
    - Lot of designs are under licensing in the NRC or already licensed as NuScale
- In France activities are quickly increasing
    - NUWARD led by EDF
    - Start-ups whose number is increasing each year
    - Two from CEA, Stellaria and Hexana, Jimmy, Sparta, Renaissance Fusion, Naarea,….
    - A dedicated program in CEA , in CNRS
    - Increasing participation of FRAMATOME, ORANO to SMRs designing
    - Greater involvement of ASN and IRSN with a **new SMRs dedicated service**

SMRs – A large amount of designs

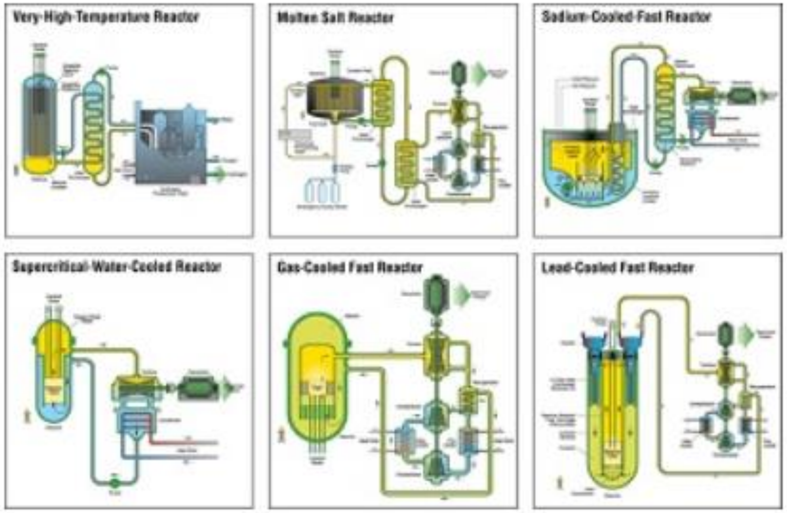
- **Currently about 80 SMRs** are under design or running or on the market
- **Two kinds of SMRS**
  - **PWR and BWR like** :
    - Decreasing the power and size of Pressurized Water Reactor (PWR) and Boiling Water Reactors (BWR)
    - Use of the very large experience and well known components of PWRs and BWRs with capabilities of passive emergency cooling at least
      - In some designs Free cooling at nominal operation is proposed
    - About 20 SMRs in this category all around the world
    - Examples are NUWARD in Fance, NuScale in USA, SMART in Korea, RITM-20 in Russia, CAREM in Argentina …
  - **In the spirit of Generation IV Forum**
    - Generation IV International Forum (GIF)
    - https://www.gen-4.org/gif/
  - In research journals and conferences as of 23/10/23
    - Keyword : Small Modular Reactor

Web of Science	**1641**
Scopus	**2647**

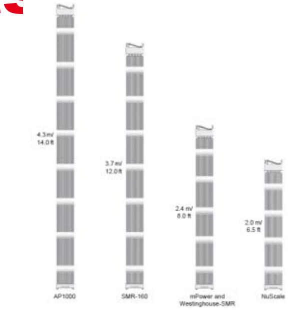
Generation IV concept goals

- **GENERATION IV requirements**
  - Launched at the beginning of the 21^{th} century
    - Improved safety
    - Reduce nuclear proliferation (as the Plutonium stocks)
    - Reduce nuclear waste
    - Reduce the use of natural stocks such as air and water for cooling, footprints and so on
    - Reduce initial building costs and maintenance costs,
    - Enable others productions than electricty such asf heat, desalination and so on
  - The idea behind Generation IV is to have reactors managing their wastes and using increased passive safety

- **Six selected concepts in 2002**
  - Supercritical water reactors (SCWR)
  - Gas cooled reactors (GFR)
  - Sodium cooled reactors (SFR)
  - Molten salt reactors (MSR)
  - Lead-cooled fast reactors (LFR)
  - Very High Temperature reactors (VHTR)



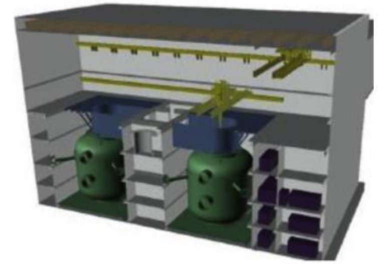
SMR – PWR and BWR like concepts



- Around 20 SMRs use PWR or BWR Concepts
- Water cooling reactors have a **very strong** feedback
- These reactors use shorten PWR fuel
- While high power PWR and BWR use a core vessel and primary loops to extract heat many water cooled SMR adopt the integral type core
- The core vessel , pressurizer and steam generator, pumps (in case of), control rods are all in the same small size Reactor Pressure vessel (RPV). Only steam pipes go out the vessel.
- No LOCA accident, no rod ejection accident
- This integrated vessel may be plunged into a large pool
- Reduced sizes of steam generator (SG) in PWR lead to advanced compact steam generators
- Systematic use of passive safety
- In integral design free convection within the RPV that serves as containment

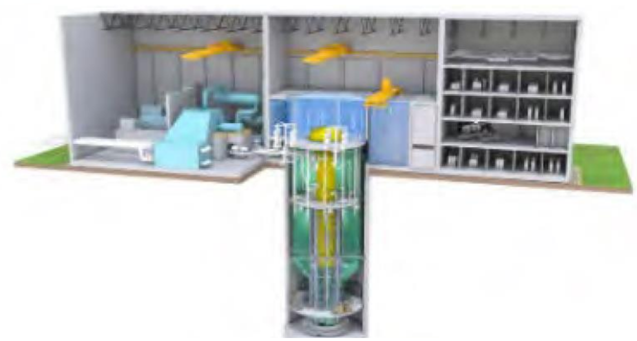
SMR PWR and BWR like

Carem	Argentine
ACPR50S	Chine
ACP-100	Chine
SMART	Corée
UKSMR	England
RoyleRoyce SMR	England
Nuward	France
RITM-200 M	Russe
KLT-400S	Russe
KLT405	Russe
RITME-200N	Russe
RITME-2005	Russe
ABV-6	Russie
PWR-20	USA
SMR-160	USA
AP300	USA
Nuscale	USA
BWRX-300	USA et Japon
And so on	



NUWARD

Nuscale



VK300	Russe
BWRX-300	USA et Japon
VVER300	Russe

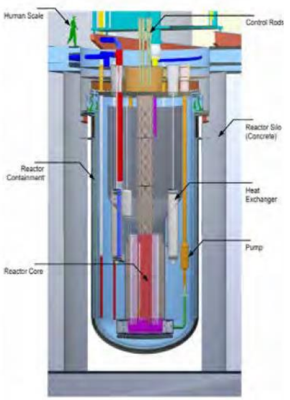
BWRX-300

SMRs – PWR

- Integral concepts
  - Both free or forced convection may be used
    - NUWARD is forced and CAREM, Nuscale are free.
      - Challenge of size for integration of all components in a vessel (core or core vessel, Steam generator, pumps, pressurizer) that has a limited radial size.
      - In case of free convection for **normal operations**
        - No pumps but apropriate channelling of the fluid
        - Demonstration that the free convection is real
    - To reduce the size new design of steam generators
      - Compact steam generators that need important R&D specifically for chemical, building, efficiency aspects
    - Reduce size of containment
      - In case of vapor leak in the vessel, condensation on the vessel walls with non-condensable (such as H2) gas that reduce the condensation rate
        - Challenging and to be demonstrated
      - On the contrary of large PWR, the containment and reactor cooling system phenomena must be investigated together
      - In case of diving in polls, the vessel see a water wall and large Rayleigh number in free convection
        - To be demonstrated
  - All passive safety features to be **computed and demonstrated** in dedicated thermalhydraulic experiment
  - Shorter core thus novel critical heat flux correlations to be eleborated
    - Expensive experimental results
    - Small experiments and full thermalhydraulic loop representative of phenomena (scaling)
  - In case of free-boron managing of the core, demonstration of the availibility of control rods to perform the job
  - Half or fully buried in the ground ?
  - Plutonium refueling capabilities ?
  - Example of recent investigations : Investigation of enhanced passive safety with heat pipes ongoing for some projects
  - ….

Sodium Reactors

- Sodium cooled reactors are fast reactors with avalibilities for refueling the Plutonium and burn some high-life actinide thus reducing long-time dangerous wastes
- Limites feedback (Phenix, Superphenix in France, Monju in Japan with an accident, BN-600/800 in Russia, India, China)
- A renewal of activities around sodium SMRs
- Positive features
  - Fast reactors
  - Capabilities for burning plutonium and actinide thus dedicated to the nuclear cycle
  - High boiling temperature thus no pressurization
  - High thermal conductivity
  - High outlet temperature thus good output
  - Concepts with many years cycle without re-fueling
- Problematic features
  - Sodium reacts with air and water
  - Some void effect (neutronic)
  - Opacity
- R&D activities
  - Extensive research and experience of design, computer codes avalibilties, with some feedbacks of experimental reactors
  - Development of specific instrumentations for sodium leakage
  - Material for high temperatures
  - Passive features for removing for a long time decay heat power
  - Association with power storage (molten salt ….)
  - Heat pipe technology



ARC-100

4S	Japon
ARC-100	Canada
Aurora	USA
Natrium	USA
eVinci	USA
Hexana	France
..	..

Lead and lead-Bisthmut Reactors

- Lead reactors have been used for a long time by Russian in their sub-marines
- Despite some problems solved by Russians, Lead has many advantages. Russians continue to develop reactors and have an extensive experience but they are not alone

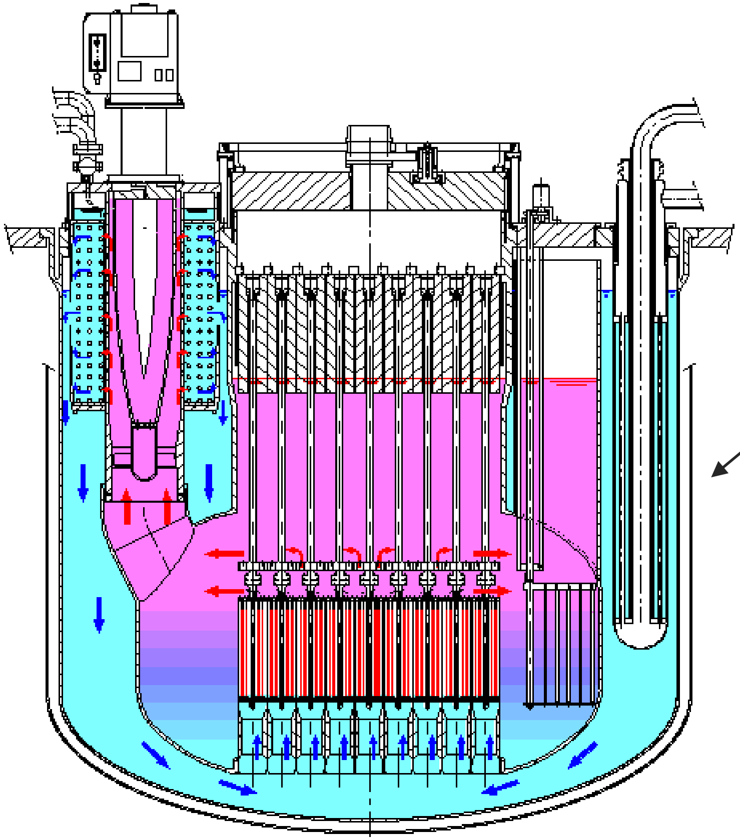
Interesting features

- Fast reactors
- Lead has a very high boiling temperature (1737°C) allowing **high efficiency** and **atmospheric pressure** in the core and **no void problem** as in sodium
- The core can be freezed in the lead
- Lead is chemical inertness (no interaction with air and sodium). No **intermediate loop** as for sodium
- High thermal conductivity
- High heat capacity thus large inertial effect in case of accident
- High **retention capability** for radionucleide thus lead is an additional barrier.
- Less interaction with neutron than in sodium **so greater distance between rods and reduced friction loss** that is good for free convection
- Long cycle without refueling capabilities

- **Major problem**
  - **Corrosion**
    - Control O_2 concentration
    - Velocity limited to 2 to 3 m/s
    - **Material reasearch activity**
- For SMRs the pool configuration with integrated pump and heat exchanger is preferred

LFRAS20	Italie
BREST-OD-300	Russe
Westinghouse LFR	USA
SEALER-55	Suede
SVBR100	Russe
newcleo	Italie
DF300	Canada
Sparta	France

Lead Reactors



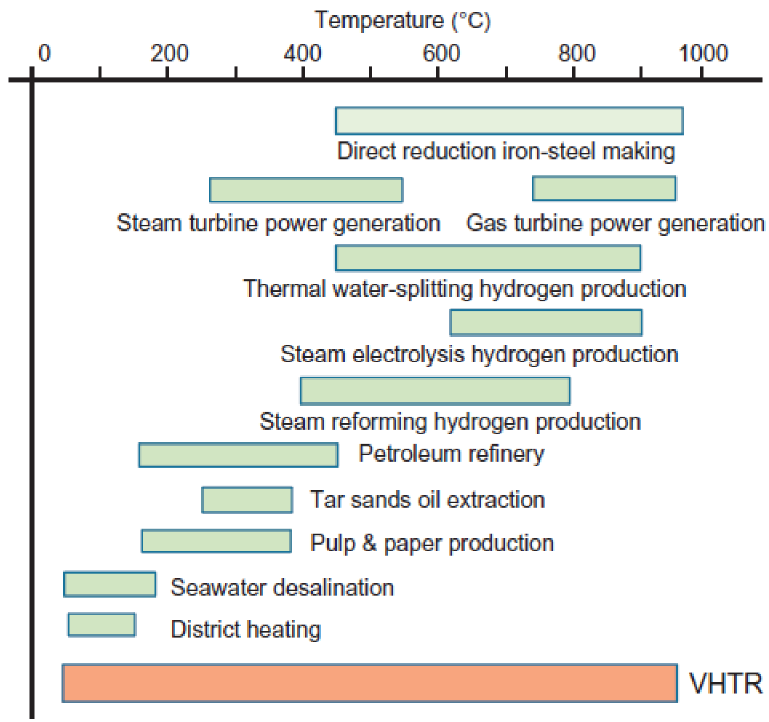
LFRAS20	Italie
BREST-OD-300	Russe
Westinghouse LFR	USA
SEALER-55	Suede
SVBR100	Russe
newcleo	Italie
LFR-AS-200	Luxembourg
DF300	Canada
Sparta	France

Gas cooled reactors – High Temperature reactors

- Gas cooled reactors : Active R&D since the **dawn of nuclear reactors**
    - Experimental reactors past and present in China, Japan, Germany, ….
- Fast or thermal, great potential for burning and breeding
    - Harder spectra in fast reactors than sodium and lead
- High retention of fission products in TRISO fuel
- Lot of gas possibilities
- Good efficiency (for example 48 %)
- High power density and **no intermediate loop possibility**
- High outlet temperature (850 °C for example), possibility of heat desalinazation, heat production
- But **pressurization needed** (70 bar He and 20 bar in CO_2) due to low heat capacity of gas
- Despite a large amount of effort no GFR **concept has been brought to industrial applications**
    - No scientific barriers but engineering barriers with long times R&D programs
        - Essentialy material (ceramics for high temperatures) and safety barriers
        - No intermediate circuit to turbines, Investigations of Brayton cycle
        - Fuel design (pebble bed or prismatic)
        - Long effort of R&D, specially safety, on past and present GFR experimental reactors
- Hope in GFR SMRs design with low power and **possibility of passive safety**
    - Already under operation in China and **Japan for experimental investigations related to safety**

Very High Temperature Reactors

- Gas cooled reactors but with very high core temperature outlet (up to1200 °C)
- High efficiency and large amount of applications beyond electricity

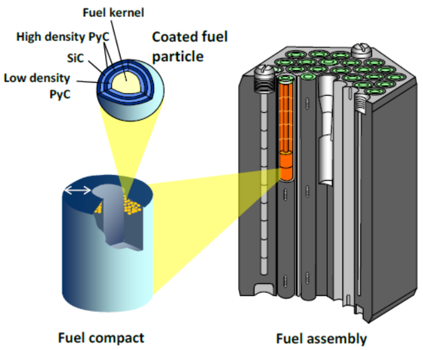


- **Same R&D as for Gas cooled reactor but increased constraint on material and safety**
- **R&D on thermodynamic cycles for distributing heat**

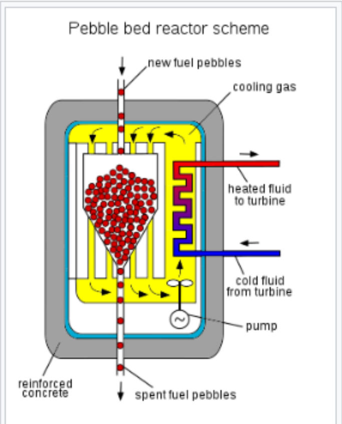
Gas cooled reactors – High Temperature reactors and Very High temperature Reactors

Jimmy	France
EM2	USA
KALEIDOS	
Project PELE	USA
BANR SMR	USA
MMR	USA
GTHTR300	Japon
MMR	USA-Canada
XE-100	USA
MHR	Russie
MHR-T	Russie
HTR-PM	Chine
U-Battery	England

Hexa



Pebble bed



Sketch of a pebble-bed reactor.

Molten salt reactors

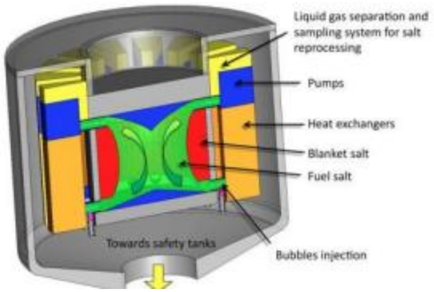
- Molten salt reactors have been studied in the 50/60s in USA at the beginning for plane propulsion
- Two reactors have been built (ARE and MSRE) that operated very well. The program has been stopped by the US government

- Molten salt reactors have been investigated for 20 years now.
- Today there are about **20 start-ups** working in this topic and increasing work in large institutions and companies
  - Programs in CEA and CNRS
  - 3 collabarative programs in France (CEA,ORANO,FRAMATOME,EDF…)

CMSR	Danois
IMSR	Canada
TMSR-500	USA
Energy Well	Tcheque
TMSR-LF1	Chine
MCRE	USA
Stellarium	France
X-	France
SSRW	England
MCSFR	USA

Molten salt reactors

- **Advantages**.
    - Fast or thermal
    - The fuel is liquid and mixed with a liquid salt (such Nacl !!).
        - **No more problems of molten solid fuels during accident**
    - Relatively high boiling point thus **no pressure**
    - The reactor present inherent safety.
        - **Increase in salt temperaturre automaticaly decreases the power.**
    - On-line refueling is possible
    - On-line extraction of fission gaz possible. On-line extraction fission product possible. On-line refueling possible
    - When there is a leak, **the salt freezes closing the break**,
    - Cheminal inertness.
    - Can burn Pu and transuranics
- **Main problems**
    - **High corrosion rate**
        - **Without any protections some materials may be completly corroded in 2 weeks**
        - **Very Intensive research activities in CNRS and CEA on the subject**
        - Lot of ideas in laboratories. Challenges for **extending to industrial applications** Redox control, polarization, materials and so on…
    - **High coupling between the flow and neutronic.**
        - Power oscillations observed in the USA reactors;
        - Currently under investigation in CEA and CNRS
            - Problem of the great cavity in Fast concepts
        - In 1 D some preliminary works in CEA of **analytical N-Th coupling**.



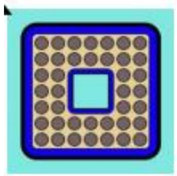
MSFR – CNRS

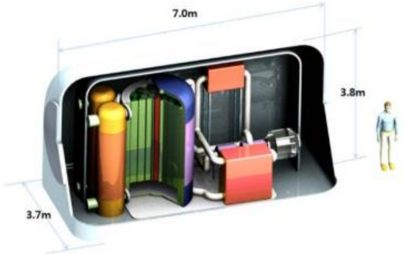
SMR – Supercritical

- Studies of SCWR SMRs are rather limited
- Success of coal and oil thermal supercritical power station
- The Canada has investigated the topic for 20 years. Investigated also in China and Korea
- **Advantages**
    - Fast and thermal
    - Water cooled or CO_2 with high liquid temperature thus good efficiency,
    - Fuel design close to BWR fuel design (closed assemblies)
- **Problems**
    - In water very high problems of corrosion
    - As in BWR thermalhydraulic instabilities may occur
- Supercritical SMRs
    - Not the same enthusiasm as for others Generation 4 concepts
    - Limited number of concepts and papers
    - Some projects seem to have disappeared

- A Korean concept of 32 MwTh with supercritical CO_2 transportable on a truck with direct Brayton cycle, 20 years without refueling

- Ongoing ECC-SMART, Canada/China project with supercritical water-cooled


Cross-section of fuel assembly



Advanced computing tools for SMRs

- SMRs are small so even if experiments are needed to assess computations tools we can
  - Compute a core with Monte-Carlo methods in neutronic
  - Compute a core in thermalhydraulic with CFD at least with RANS and even LES for MSRs
  - Imagine a complete numerical twin of the reactor at design
  - Design a core with complete neutronic/thermalhydraulic/chemical coupling at system, component and CFD scales.
  - ….
- The SMRs development is a good opportunity to promote and urge new physical computing tools in the design process such as :
  - Molecular dynamic (CNRS, CEA and start-ups) for computing molten-salt thermophysic properties
  - Ab-initio computing of material properties
  - Ab-initio computing of material dislocations specially under irradiation
  - Fine two-phase flow computing methods
  - ……
  - …..

Summary and conclusion

- SMRs developments are growing fast with
  - the involment of large traditional nuclear industries and institutions
  - the emergence of start-ups
- Large choice of designs ranging from **classical PWR and BWR** like reactors but reduced in size and power and adopting passive safety features to **all Generation-IV** designs
  - A strong opportunity to increase the knowledge on the physic of Generation-IV reactors
  - Due to low power an opportunity to really build reactors with passive safety, burner and breeder capabilities to close the nuclear cycle.
  - A gate to motivate research in materials, ab-initio methods, multiphysic tools, production optimization and so on
  - Very attractive subjects for young recent graduates