A CANDU-TYPE SMALL/MEDIUM POWER REACTOR

by

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THE CANDU SMR STORY

- "If you want a smaller fire, just use fewer logs"

  -- John Foster, former president of AECL

- In the beginning, there was NPD
- Back to the future?
  - Now, we need a small power reactor for remote sites
  - NPD produced 22 Mwe (gross) - about the right size
  - Site needs and modern knowledge -- to be added

THE SMALL MEDIUM-OR-MODULAR REACTOR

- Small may be beautiful, but big is cheap
  - Given the same project criteria, this is <u>always</u> true
  - Changing the rules can make the statement false
- Niche market or strange financing conditions
  - Small demand – remote, off-grid location
  - Aberrant rules for charging costs into the rate base
- Large units carry obsolescent reference designs
  - Too big for the market?
  - Too many frills – a touch of Byzantium?

DYNAMICS OF REACTOR DEVELOPMENT

- Some difficult project objectives
  - Ideal – a brand new design with an operating record
  - Ideal – solves old operating problems but opens no new licensing questions
  - Ideal – it is accepted as safe by a majority of people
  - Ideal – privately owned, but government funded
  - Ideal – much cheaper than those that came before

A PRACTICAL CASE – CDN. REMOTE POWER CORP

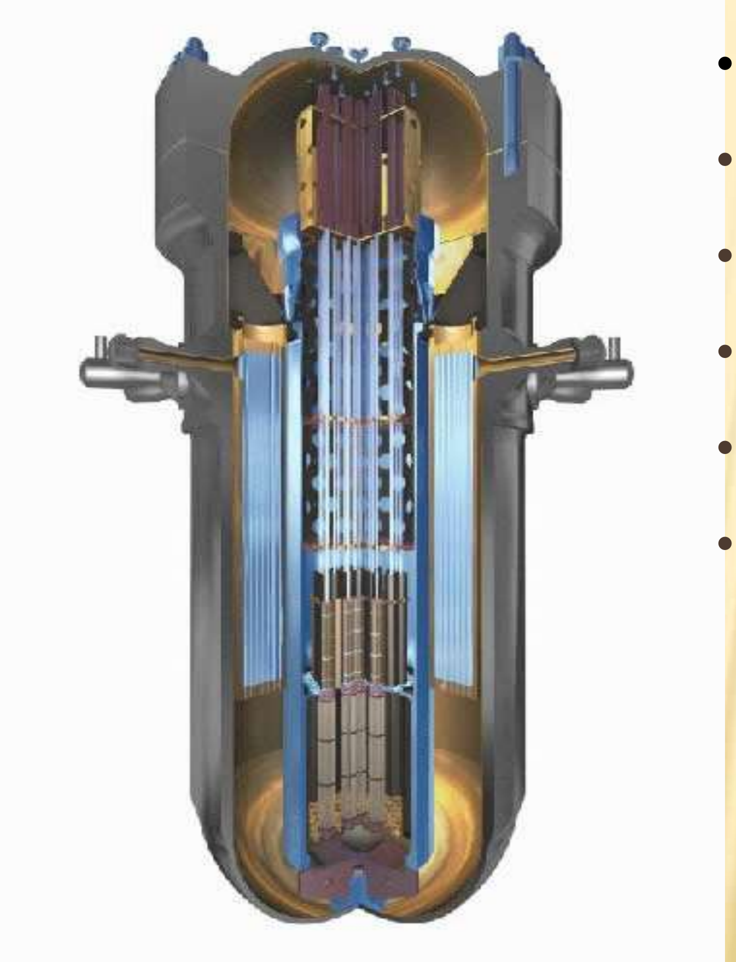
- Reliable, economic, energy needed for projects communities, bases at remote Northern sites.
  - Fuel oil is expensive
  - Grid connections are non-existent
- Company is interested in 25 Mwe units
  - Delivery schedule "as soon as possible"
- NPD ran successfully for 25 years
  - The "all Canadian" solution

REACTOR DESIGN OPTIONS

- Argentina – CAREM
- The all-Canadian option - CANDU
- Sub Critical Assembly (SCA)

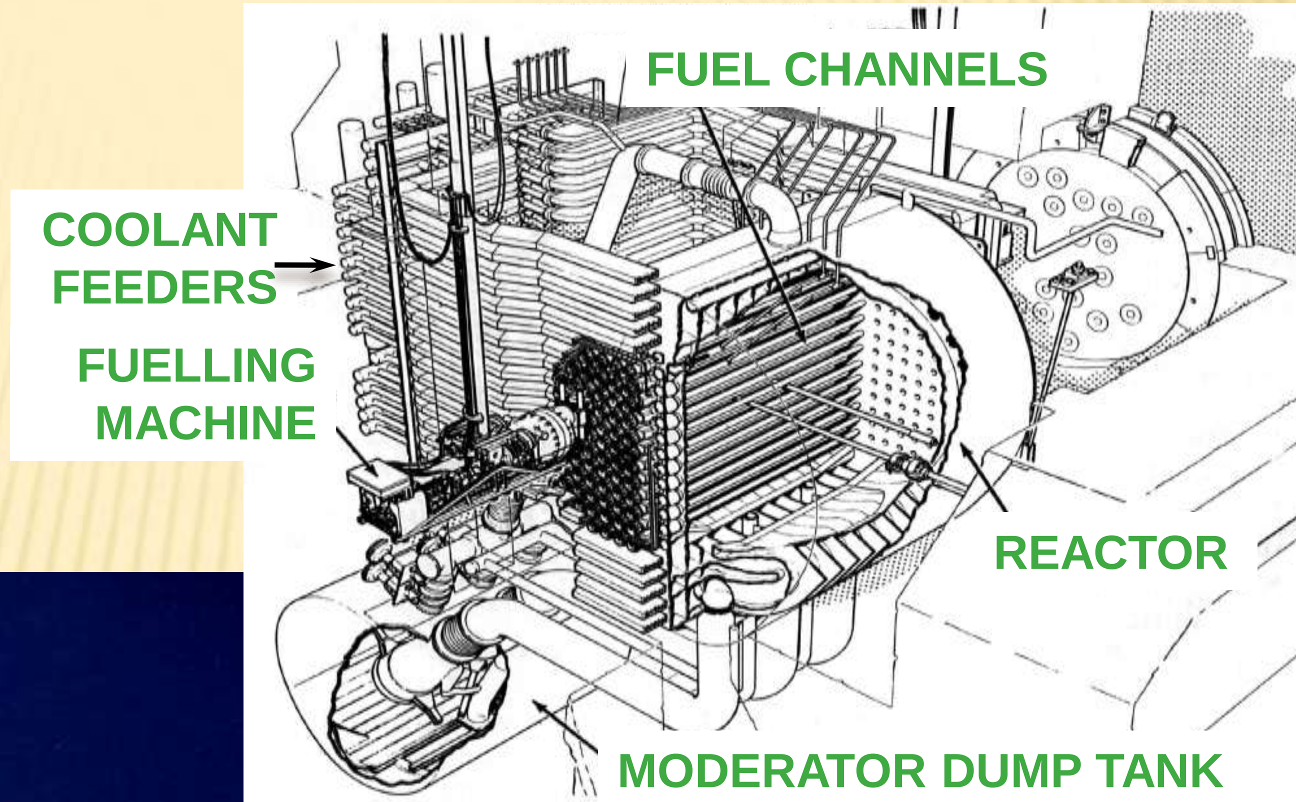
- Candidates eliminated:
  - Toshiba 4S General Atomics TRIGA
  - Hyperion NuScale
  - Babcock & Wilcox IRIS
  - Russian ABV-6M

CAREM – ARGENTINA



- 27 MWe integral PWR – IRIS Type
- Compact, relatively portable
- Natural circulation in primary circuit
- Prototype already committed (FOAK)
- Could be operational in 2016
- Weaknesses:
  - licensing process unfamiliar to CNSC
  - lack of power maneuvering capability
  - pressure vessel is large
  - capital cost estimate is high

A SUCCESSFUL FIRST TRY – NPD-2



TRY IT AGAIN?

NOT A BIG DEAL

CANADIAN REMOTE POWER CORP - SUMMARY

- Favorable Economics – a good business case
- Canadian Expertise – global recognition
- Remote power is needed in Canada
- Favorable regulatory climate
- Imperative of carbon emissions reduction
- Market not limited to remote sites, once proven
- Useful as a starting point for future designs

- Project suspended – site economics have changed

THE CANDU 80 CONCEPT – HART, 1996

- 100 Mwe
- True SMR concept – for remote sites, oil sands
- Applicable for countries new to nuclear energy
- Low power density, large operating margins
- Proven technology throughout
- Low specific capital cost, low operating cost
- Short project cycle

CANDU SMR - 50 MW OPTION

- Made in Canada
- CNSC Personnel understand the technology
- 25 years of successful operation of NPD-2
- Expected “nth” capital cost – About $150 M
  - ≈ $3000 - 4000 per kWe
- Marginal Economics for “nth” installation in Canada

CANDU-SMR CONCEPT & MAJOR FEATURES

- Basic design principles
  - Evolution of reference design begins from an earlier concept design – CANDU 80*
  - Primary objective is electricity and process heat production
- Major operational features
  - On-power refueling
  - Remote fueling from fresh to used fuel bay
  - Energy storage capability for load levelling
- Operating concept
  - Day to day (limited) intervention by local trained staff
  - Monitoring and visits by expert staff (annual?)

* R.S. Hart, "CANDU 80 Technical Outline", AECL, (Feb. 1996)

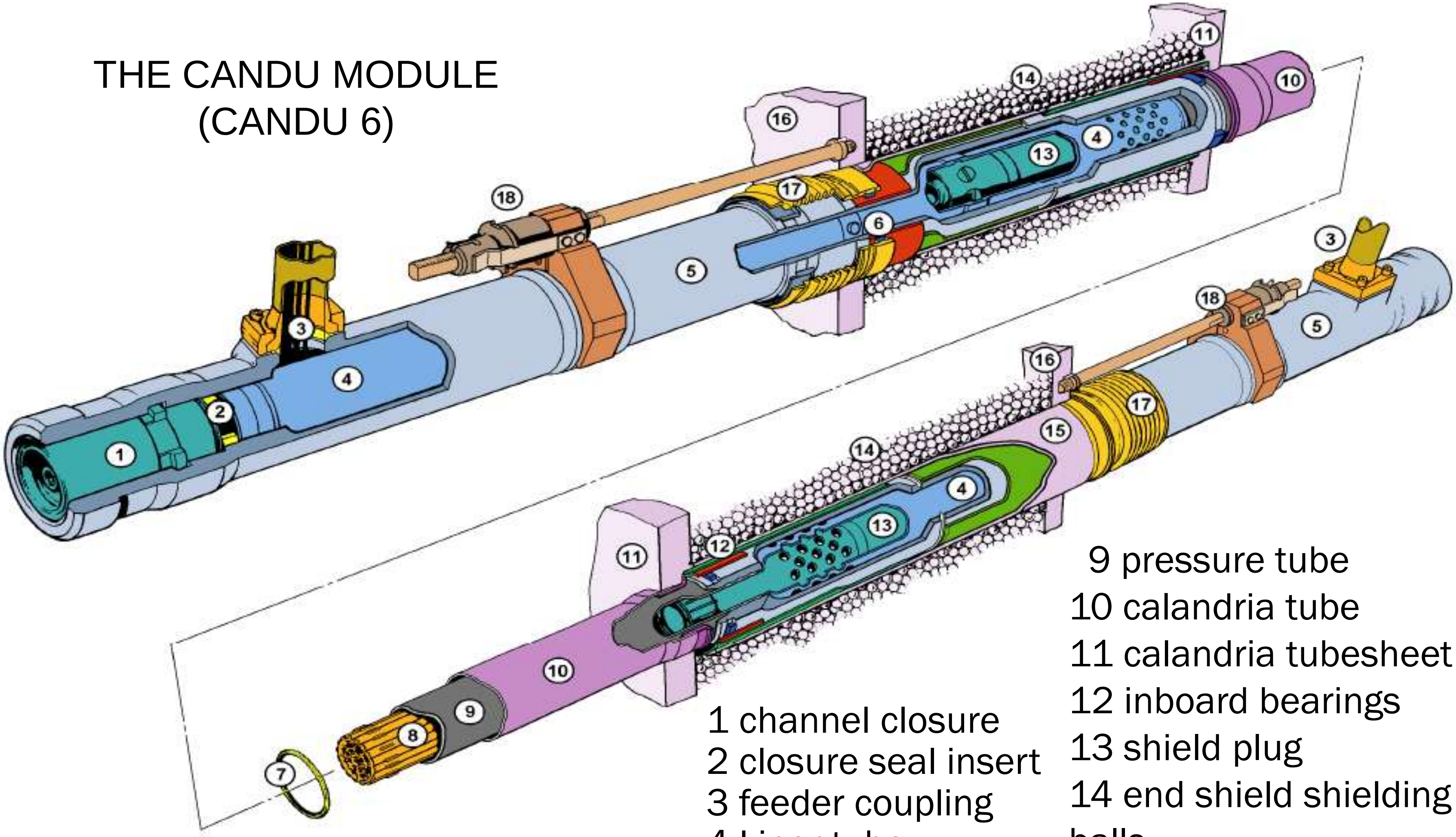
MAJOR SYSTEM PERFORMANCE SPECS

- Cost-competitive with petroleum for heating and electricity
- Licensable in Canada, under small-reactor licensing guidelines
- 100% availability (including backup)
- “No-freeze” systems via underground placement
- Portable in segments, both new and as a used facility
- Full range load following –seconds to days, with energy storage
- Computer controlled operation plus remote safety intervention
- Daily fuel changing at power
- Infrequent fuel restocking – minimum one-year at full power

FUEL SUPPLY

- Small, inexpensive LEU fuel assemblies
  - Easily transported, both as new and when used
  - Useless for unauthorized diversion
- Automated fuel movement
- Use Gentilly-1 type of fuel system – fuel strings
  - Automate fuelling from fresh store to used fuel bay
  - On-site staff only to monitor operation
    - Annual visit by expert staff to replenish fuel string supply and remove used fuel bundles

THE CANDU MODULE (CANDU 6)



1 channel closure
2 closure seal insert
3 feeder coupling
4 Liner tube
5 End fitting body
6 outboard bearings
7 annulus spacer
8 fuel bundle

9 pressure tube
10 calandria tube
11 calandria tubesheet
12 inboard bearings
13 shield plug
14 end shield shielding balls
15 end shield lattice tube
16 fuelling tubesheet
17 channel annulus bellows
18 positioning assembly

TWO PLANT CONFIGURATIONS

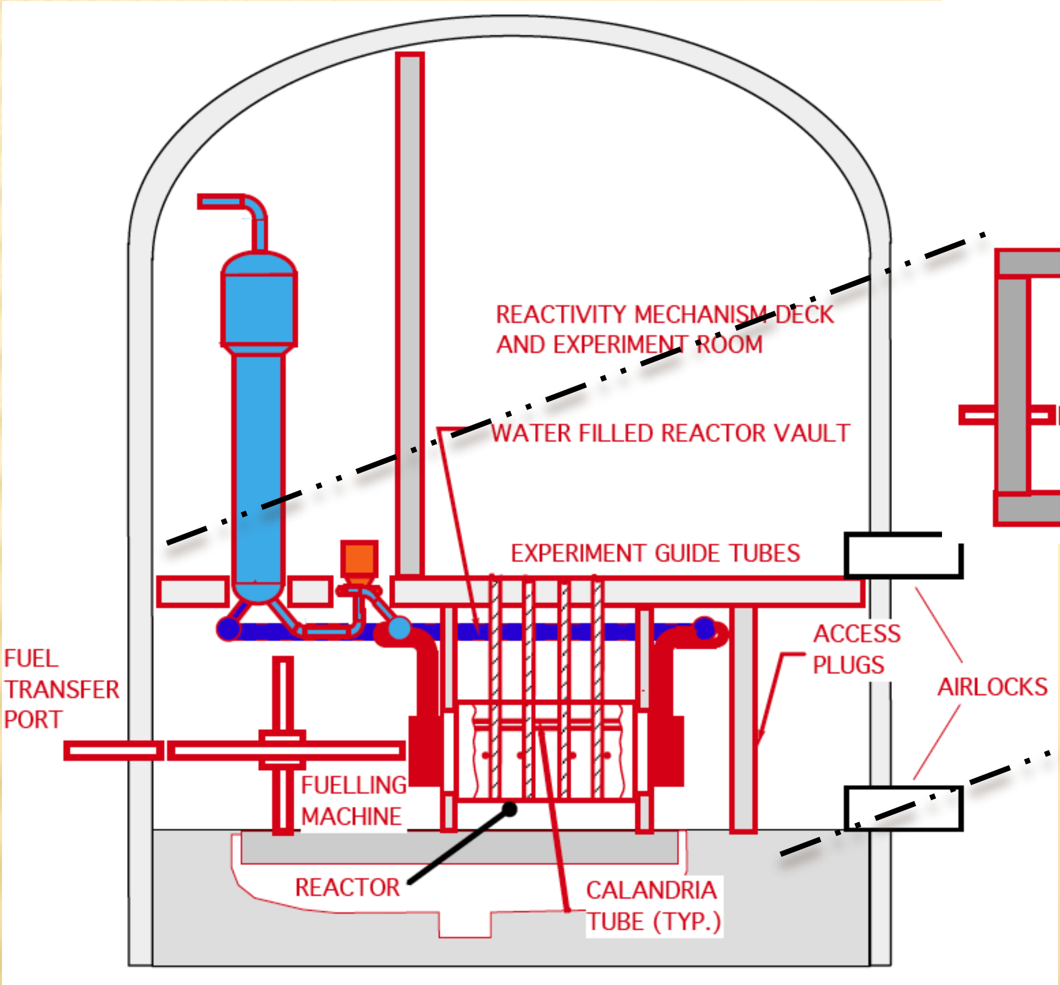


Figure 2(a) – The CANDU ETR

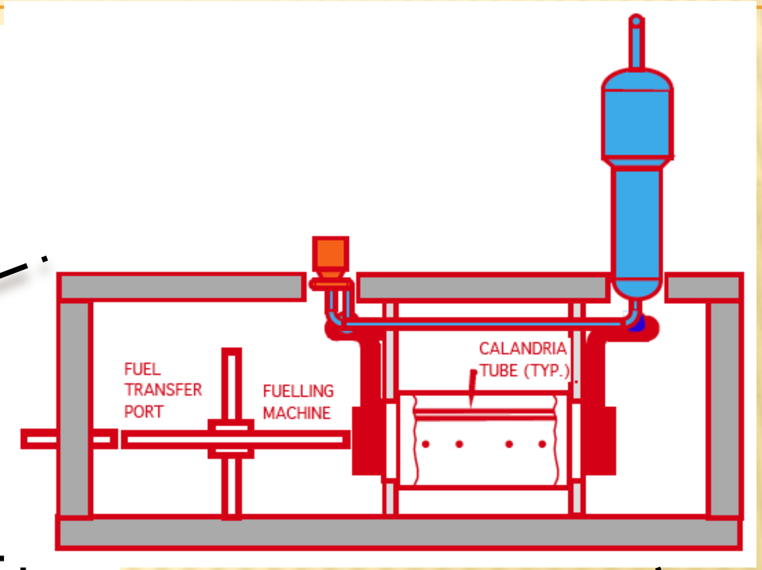
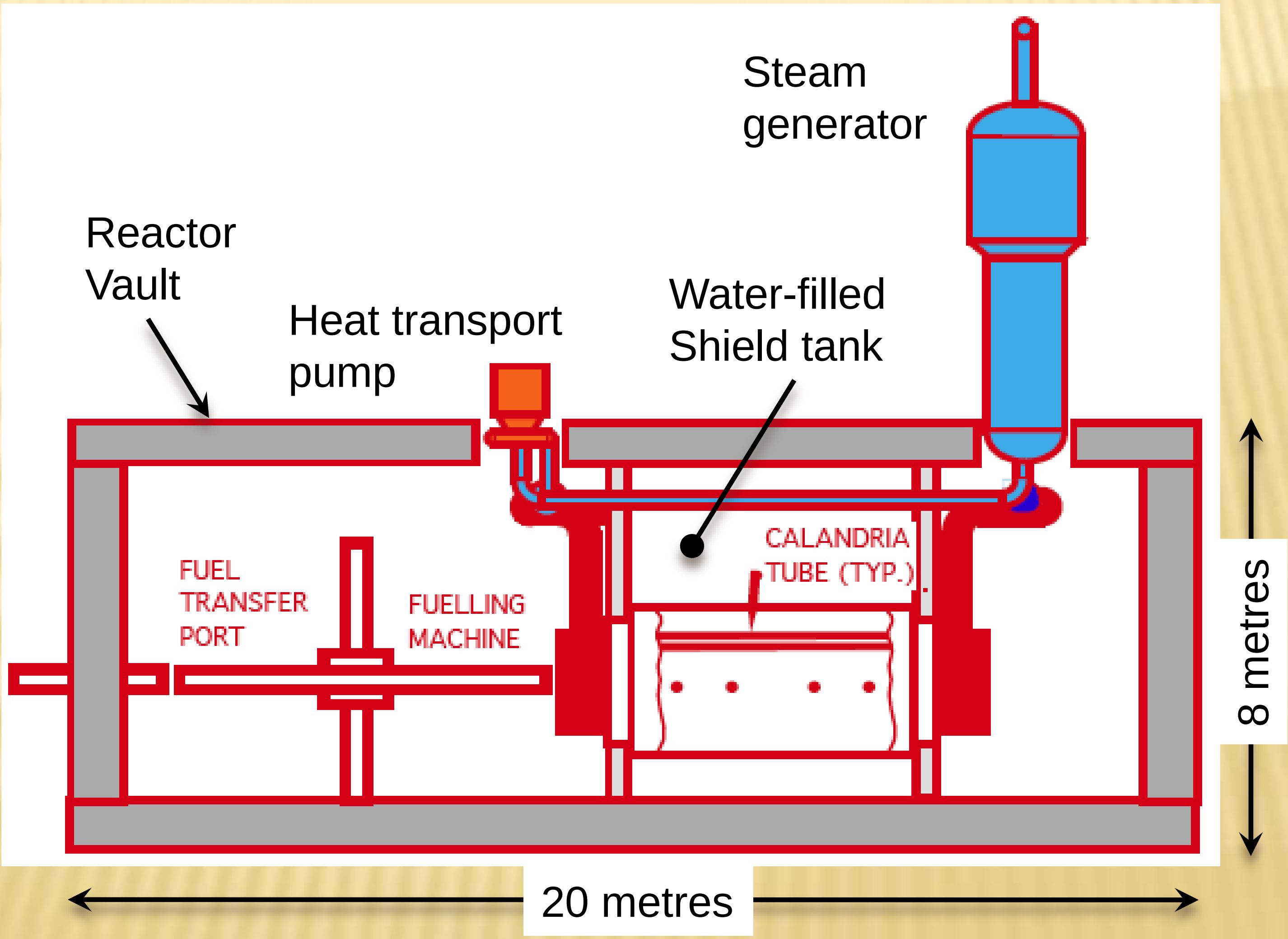
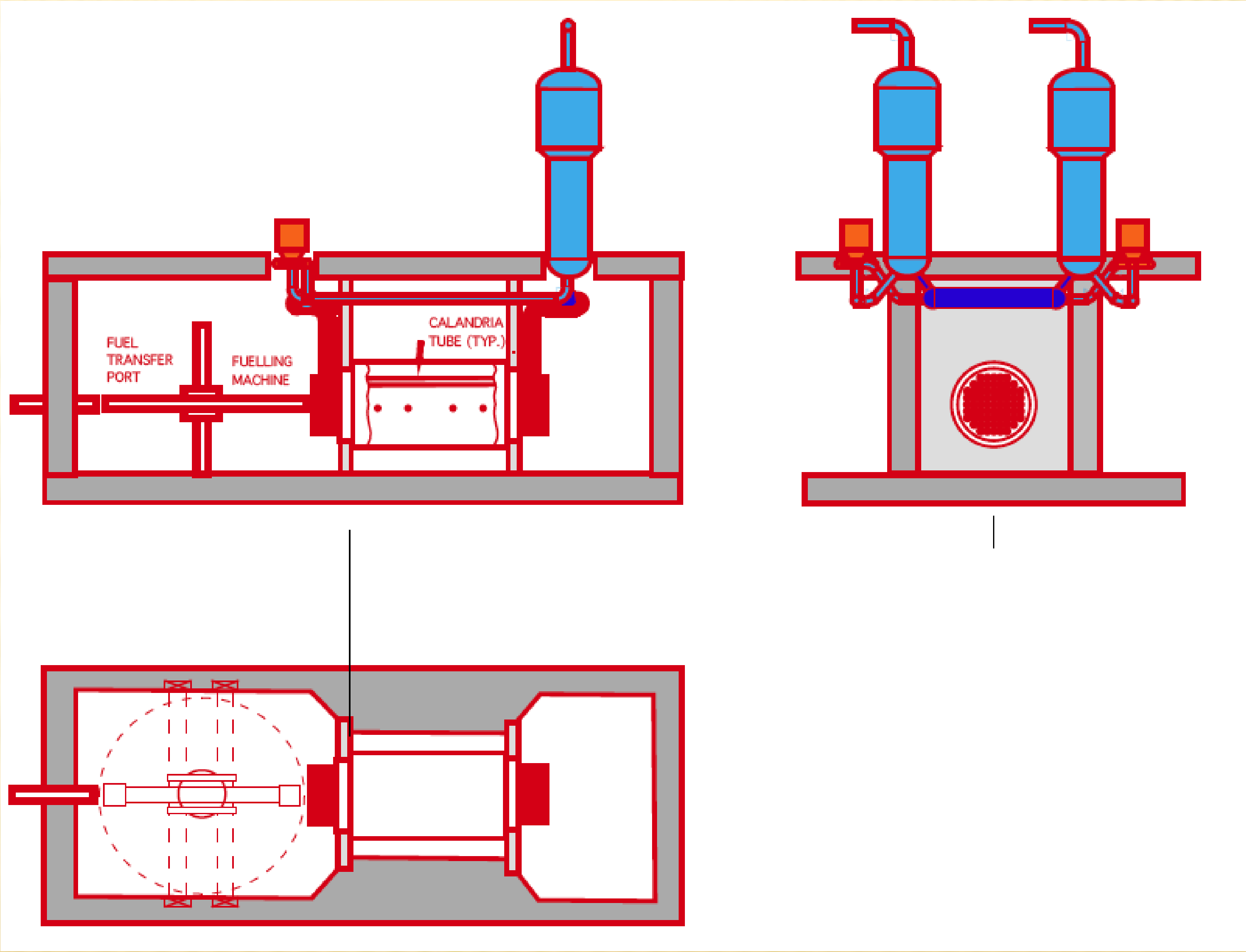


Figure 2(b) – The CANDU SMR

CANDU - SMR CONCEPT



PRELIMINARY SKETCHES – CANDU SMR



DESIGN DECISIONS TO MAKE

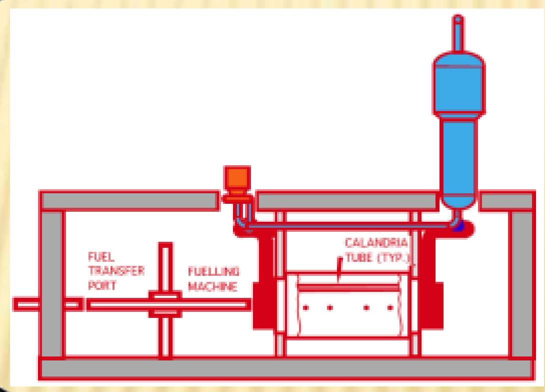
Operating policies/principles

Staffing

Licensing

Energy storage

Turbine/generator



Steam generators

Fresh fuel handling

S/G feed water

Used fuel handling

Site grade elevation

Containment

Control systems

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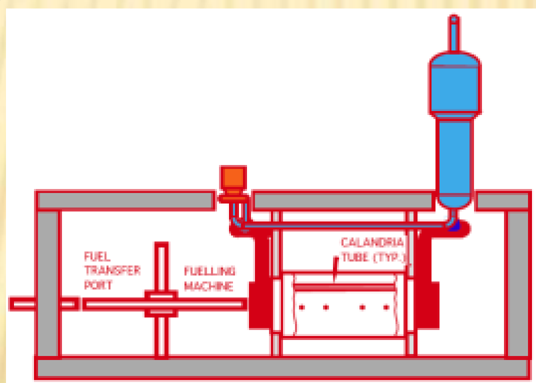

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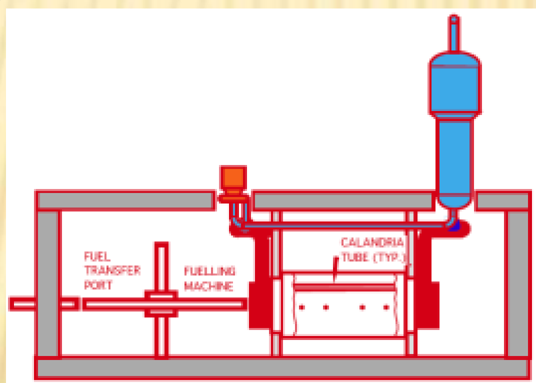

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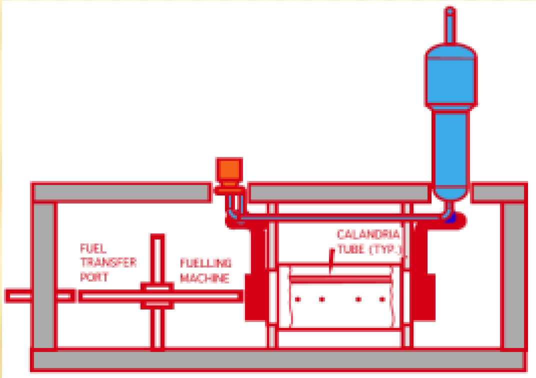

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ENERGY STORAGE

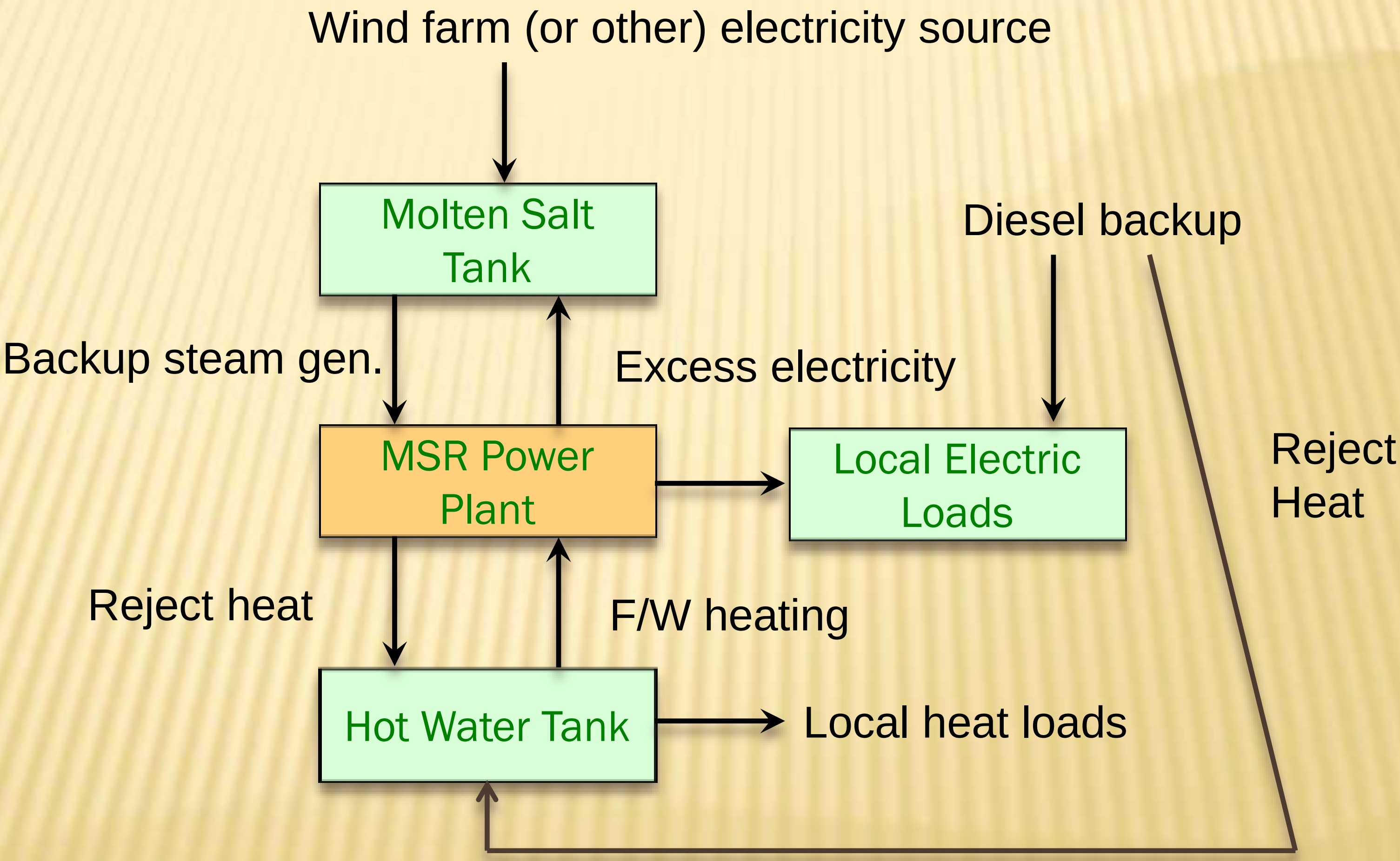
- Desirable due to highly variable load profile
- Site loads include large thermal requirement
- Molten salt tank – heated by excess electricity
  - Possibly using on-site wind and/or diesel-electric
- Water tank – excess thermal output of SMR
  - Possibly using back-pressure turbine

SYNTHETIC OIL PRODUCTION

- See Charles Forsberg – "**Nuclear Beyond Base-load Electricity: Variable Electricity and Liquid Fuels**"

  http://canes.mit.edu/sites/default/files/pdf/NES-115.pdf
- Consider the balance between small reactors for local service or larger units with regional distribution of liquid fuels

ON-SITE TANK STORAGE CONCEPTS



CANDU SMALL/MEDIUM POWER REACTOR

- Next steps
  - Get the cost down – simplify & refine the concept
  - Confirm the two-step fuelling frequency
  - Minimize operator intervention tasks at local level
  - Find at least one customer
  - Initiate communication/discussion with CNSC
  - Conduct preliminary and detailed design
  - Build/maintain a computer-based design package
  - Refine the cost estimate

SUMMARY

- Energy supply in the High Arctic is a challenge
  - Social acceptance is a major factor
  - There are additional technical challenges
  - Commercial competition will be fierce
  - First-of-a-kind risks may be large
  - Licensing is a big question – as always