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Innovation and Creativity

ADVANCED CONTROL OF NUCLEAR POWER PLANTS: PRESENT STATUS AND FUTURE TRENDS

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OUTLINE

- FUNDAMENTALS OF NUCLEAR POWER
- REACTOR DYNAMICS
- REACTOR CONTROL
- STEAM GENERATOR CONTROL
- SEISMIC RESPONSE CONTROL
- FUTURE OUTLOOKS

FUNDAMENTALS OF NUCLEAR POWER

- To generate heat from nuclear reactions, we can either:
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  - Most reactors use neutrons to split fissile atoms
  - Fission reactions generate other neutrons that continue the fission process
- Nuclear fusion has not yet produced one self-sustaining reactor and is still experimental; control of future plants is only speculation (however interesting), so it will not be discussed here

NUCLEAR FISSION

- The most common fissile atom is by far ^{235}U:
    - Many reactions are possible to split ^{235}U, one is:
    - $\mathrm{n} + {}^{235}\mathrm{U} \longrightarrow {}^{147}\mathrm{La} + {}^{87}\mathrm{Br} + 2\,\mathrm{n}$
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  - About 200 MeV per split atom of ^{235}U (≈ 19.3 TJ/mol; Norway's yearly total energy consumption is ≈ 1.5 EJ)
- Reaction products are usually unstable:
  - Some decay rapidly and contribute to heat and neutron production
  - Some take much longer to decay and become nuclear waste
  - Some can take neutrons from the reaction (reaction poisons)

NEUTRON INTERACTIONS

— There are three ways a nucleus can interact with a neutron:

SCATTERING	Neutron and nucleus “bump” into each other
CAPTURE	The neutron becomes part of the nucleus
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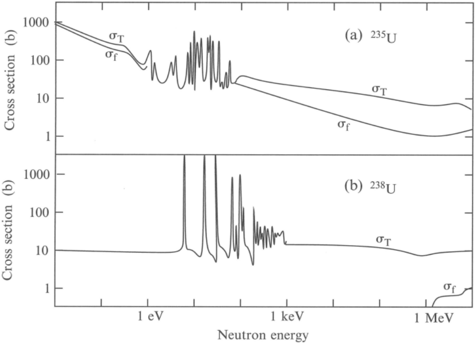
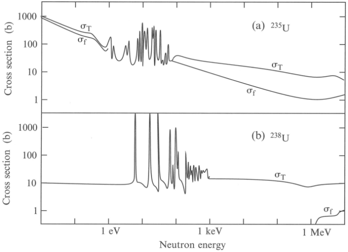
- The total neutron *cross section* σ_T is the sum of these (σ_s, σ_c, σ_f)
- Cross sections are *very* dependent on neutron energy
- To split ^{235}U, we need low-energy (*slow*) neutrons



THERMAL NEUTRONS



- The fissile isotope ^{235}U is only 0.7 % of natural uranium
- Slow neutrons are much more selective towards fission of ^{235}U, rather than being captured by ^{238}U
- We seek therefore to *thermalise* neutrons, so that their velocity (energy) is in equilibrium with surrounding temperature ($\approx 25\,\text{meV}$)

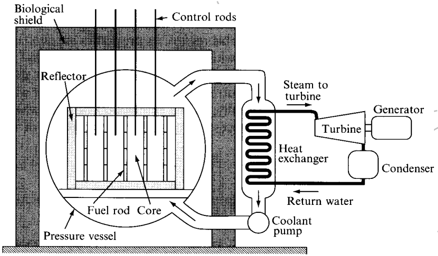
NEUTRON MODERATION

- A neutron *moderator* has a high scattering cross-section for neutrons
- The scattering takes energy away from the neutron, thermalising it

Moderator	σ_s	$\sigma_f + \sigma_c$	Issues
H_2O	49.2	0.66	Requires enriched U
D_2O	10.6	0.001	Expensive
Graphite	4.7	0.0045	Černobyl

A Typical Nuclear Power Plant

- Heat is produced it the reactor core
- Coolant brings heat to exchanger
- A steam cycle generates electricity



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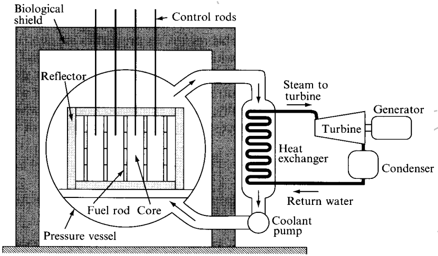

Control loops:

- Fission rate is set using the control rods
- Coolant temperature is controlled with the coolant pump
- Steam to the turbine is throttled to maintain boiler pressure
- Boiler water level is kept constant with the return-water pump

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  - $1 - l$ Fraction of neutrons that do not leak outside the reactor
- The reaction will be in equilibrium ("critical") when $k = \eta\, p\, f\, (1 - l) = 1$

DYNAMIC EQUATION

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- In general, we change δk to maintain the reactor at criticality: this system is *unstable* and *nonlinear*
- Feedback is necessary to control the reactor. However, Λ is very small ($\approx 1\,\text{ms}$), and requires an unreasonably large bandwidth requirement on sensor, controller and actuator

PROMPT AND DELAYED NEUTRONS

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— The dynamic equation has now become:

$$\begin{cases} \dfrac{\mathrm{d}\, n}{\mathrm{d}\, t} = \dfrac{\delta k - \sum_i \beta_i}{\Lambda} n + \displaystyle\sum_i \lambda_i C_i \\ \dfrac{\mathrm{d}\, C_i}{\mathrm{d}\, t} = \dfrac{\beta_i}{\Lambda} n - \lambda_i C_i \end{cases}$$

— Most detailed models assume six groups of delayed neutrons; assuming only one, we have a new dynamics with $\tau \approx 12.5\,\mathrm{s}$

PROMPT CRITICALITY

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- The system is *still unstable*, but we have now a manageable bandwidth
- If k ever reaches 1.0076, prompt neutrons will be able to escalate the reaction unassisted by delayed neutrons. This is a situation of *prompt criticality* which must be avoided, as it can lead to meltdowns
- For this reason, a common control requirement on δk is to limit its transients in a band of $\pm 6\,\mathrm{mk}$

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DEPLETION	Obviously the amount of fissile material will decrease. This is also mathematically stabilising
VOID	If a liquid is used in the core, its evaporation will leave a "void" for neutron interactions: this is stabilising if the liquid is the moderator (PWR, PBR) and destabilising if it is only absorbing neutrons (RBMK, Černobyl)

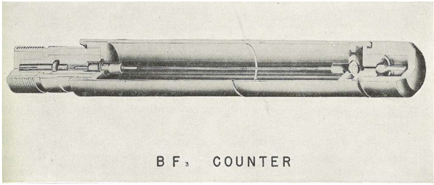
The Control Rods

- Control rods are highly neutron-absorbing material (cadmium, boron)
- When they are inserted, neutrons are removed from the reaction
- There are three main types of control rods:

Regulator	a few, used to fine-tune the reactor's activity
Shim	to compensate for long-term reactivity changes (xenon poisoning, uranium depletion)
Scram	emergency rods to be inserted in case of loss of control

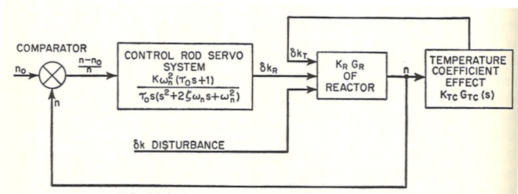
- Rods are usually placed so that moving the regulators completely out will not exceed the limit of $\pm 6\,\mathrm{mk}$

Measurement of Reactor Power Output



- Neutron flux is a good measurement of heat generation
- Placing neutron sensors is a design issue
- Measuring the coolant temperature and flow is also possible, but it has a too large lag to be useful
- Measurements are much slower at low power: operation at low power can be dangerous

CLASSIC CONTROL



- Control strategy by Schultz (1955) for a generic reactor
- Error signal given as $\frac{n_0-n}{n}$ to compensate for nonlinearity
- It ignores the increased measurement lag at low powers

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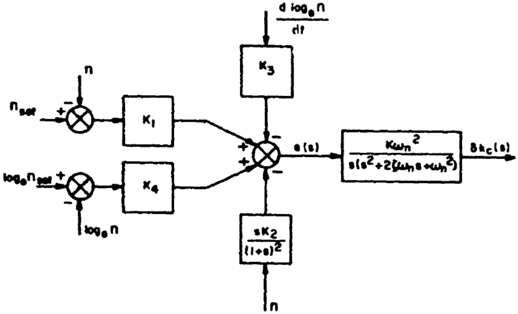

- Controller for a CANDU reactor, 1975 paper (Mehta) from Whiteshell Laboratories: probably used in actual practice
- Seems to have been synthesised by trial and error
- The logarithm is probably to slow down low-power operation

OPTIMAL CONTROL

- Interest for $\mathcal{H}_2$ control in ’70 and early ’80
- Most approaches were of the full-state feedback type
- Kalman filtering is necessary for all six species of delayed neutrons, ^{135}Xe, ^{135}I; only neutron flux is measurable

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- Kalman filtering is necessary for all six species of delayed neutrons, ^{135}Xe, ^{135}I; only neutron flux is measurable
- Not many practical applications:
  - Neophobia?
  - Safety has priority over performance
  - Nuclear plants are usually in base-load mode, not load-following
  - “Slower is safer”

RECENT APPROACHES

- Most new work uses fuzzy logic and/or neural networks
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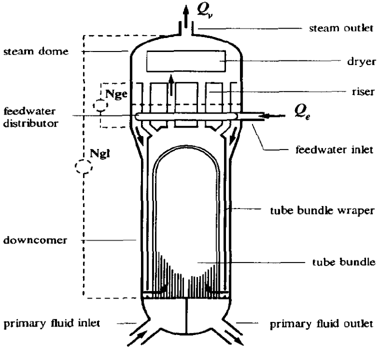
  - No first-principle modelling required
  - Training of the network is however necessary
- A fuzzy or neural-network controller will be no smarter than the trainer
- Performance is usually compared to PID control, no more advanced techniques (loop shaping, $\mathcal{H}_\infty$, nonlinear control…)

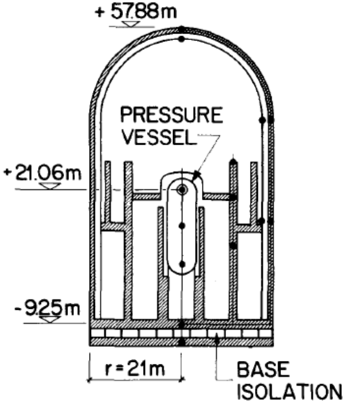
Steam Generator Control

- Many reactors transfer heat from the (primary) cooling cycle to the (secondary) turbine cycle
- Bad control of steam generators causes 25 % of reactor stops
- Inverse response in water level when steam flow is changed due to “swell-and-shrink” behaviour
- New approaches include adaptive, linear parameter-varying and model-predictive control



SEISMIC RESPONSE CONTROL

- Interest especially in Japan
- *Active* compensation of earthquakes has been studied since the '80s
- High requirements in power and bandwidth for actuators



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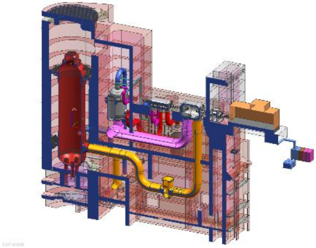
- Is one solution going to cause many problems?
- The Pebble-bed reactor is often touted to be *inherently* safe:
    - Reactivity decreases rapidly with escalating temperature
    - The core has very low power density, making natural dissipation possible
    - The graphite cannot burn with the coolant (helium)

PEBBLE-BED REACTORS

But. . .

- “Natural dissipation” means the core will be cooled by atmospheric air
- Therefore, no meaningful containment building will be present
- Helium will be run through a compressor: surge problems may be catastrophic
- Surge control will be of critical importance



CONCLUSIONS

- Nuclear plants are operated with a “play-it-safe” philosophy, no fancy control unless necessary
- As fossil sources become more expensive, nuclear power may be used for load following
- Performance requirements, and with it advanced control, may become more important
- New reactor types may introduce new types of control issues

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Thank you for your attention!