Lecture 3 – Case Studies

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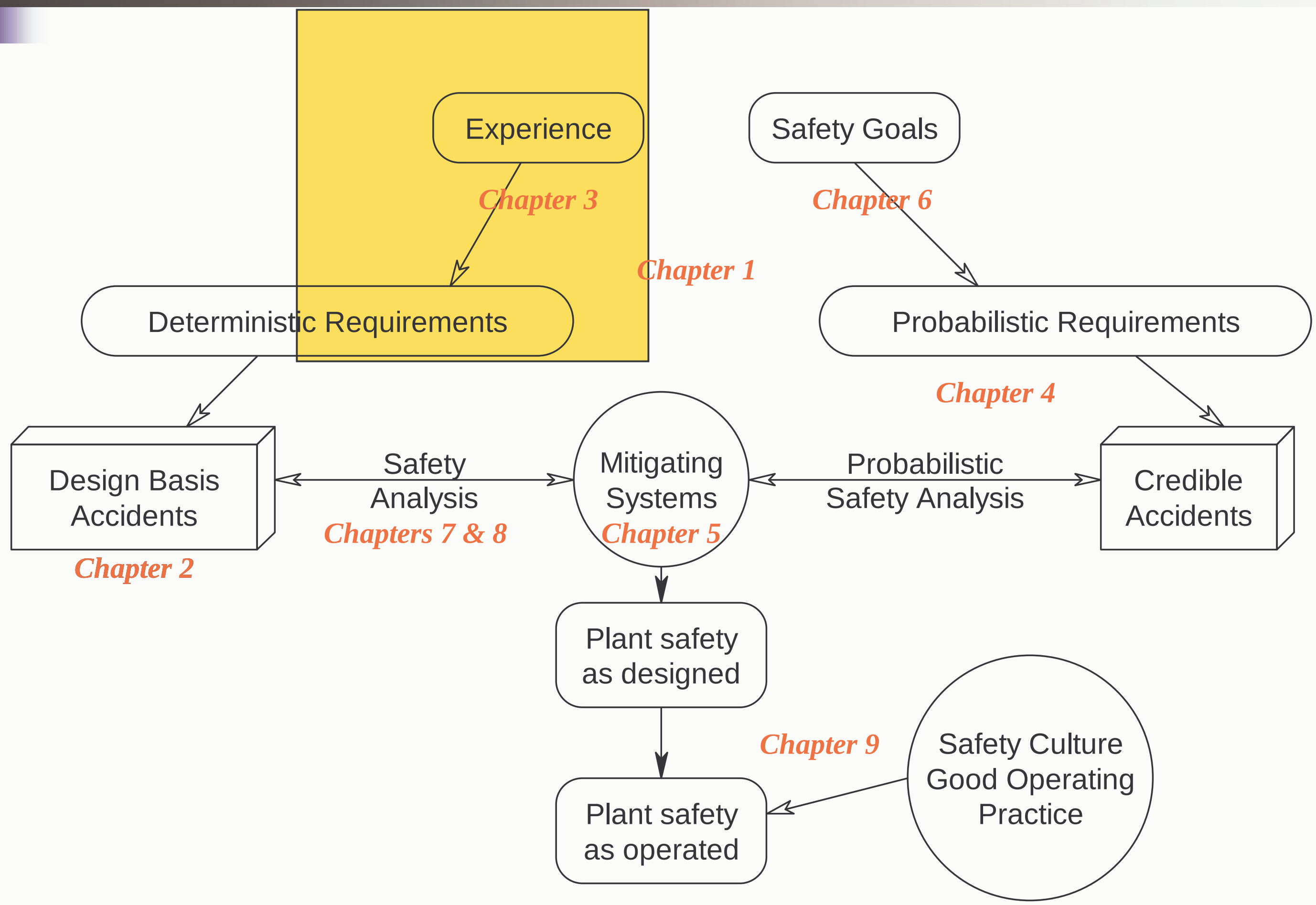
Some material from D. Meneley gratefully acknowledged

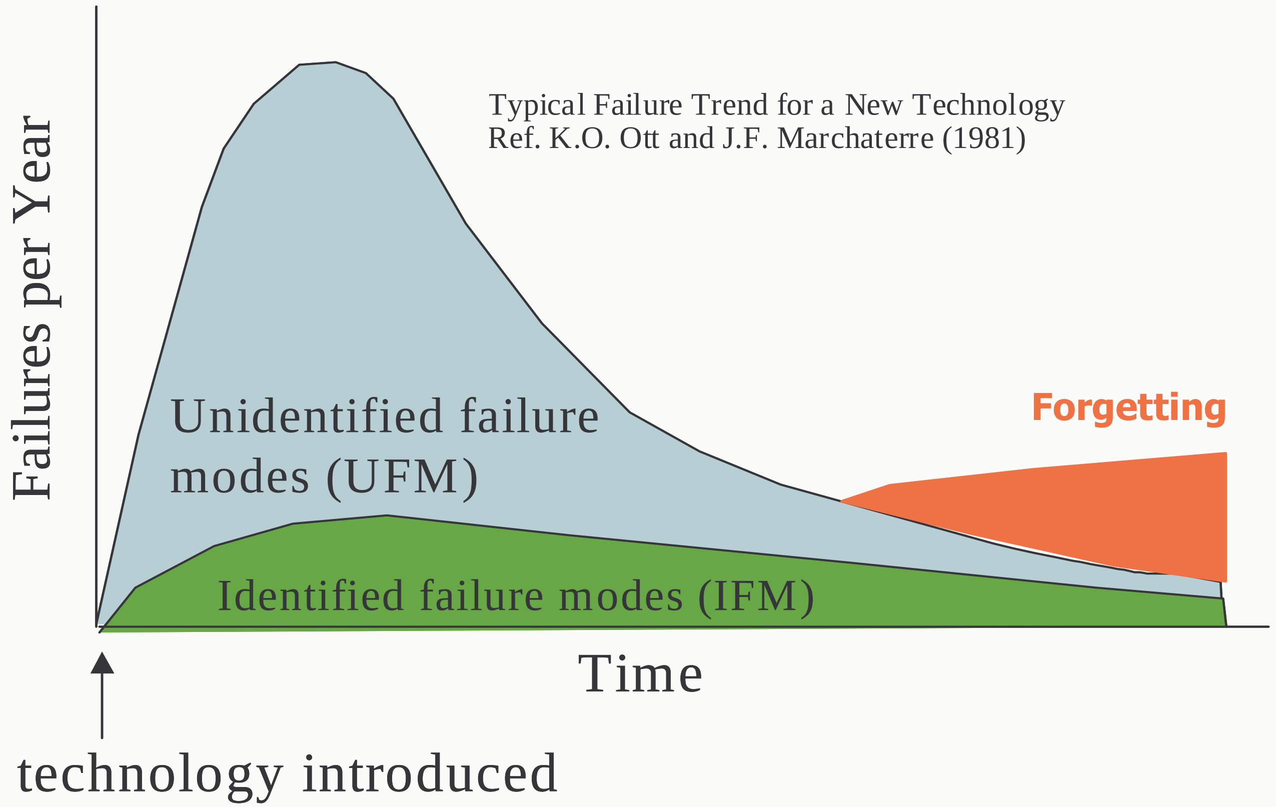
Where We Are


Experience
Safety Goals
Chapter 3
Chapter 6
Chapter 1
Deterministic Requirements
Probabilistic Requirements
Chapter 4
Design Basis Accidents
Safety Analysis
Chapters 7 & 8
Mitigating Systems
Chapter 5
Probabilistic Safety Analysis
Credible Accidents
Chapter 2
Plant safety as designed
Chapter 9
Safety Culture Good Operating Practice
Plant safety as operated

Why Case Studies?

- Accidents are usually highly complex
  - Most designs obey single failure rule
  - High component of human factors
- Lessons learned for future designs
- Humility

Learning and Forgetting



Reactor Kinetics

$$k = \frac{\text{Number of neutrons in generation } i+1}{\text{Number of neutrons in generation } i}$$

Four factor formula - 1

n

Start out with *n* fast neutrons from thermal fission

A fraction ε is added from fast fission

$n\varepsilon$

A fraction $(1-P_{NLf})$ leak out

$n\varepsilon P_{NLf}$

A fraction (1-p) are captured by resonance absorption

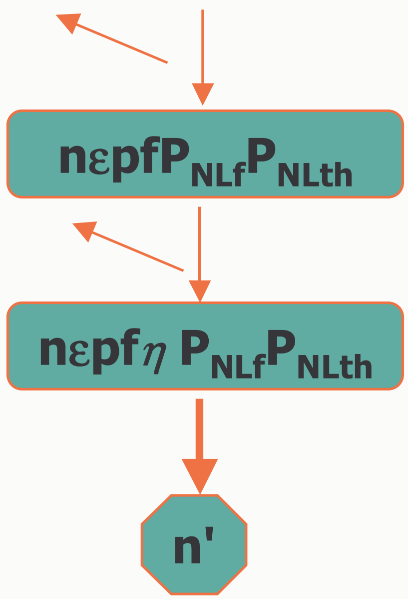
$n\varepsilon p P_{NLf}$

These neutrons make it to thermal energies

A fraction $(1-P_{NLth})$ leak out again

$n\varepsilon p P_{NLf} P_{NLth}$

Four Factor Formula - 2



A fraction (1-f) are captured other than by fuel

These neutrons make it back to the fuel

η neutrons are produced per neutron absorbed

And so begins the next generation

$$k_{eff} = \epsilon p f \eta P_{NLf} P_{NLth}$$

Death of neutrons in CANDU

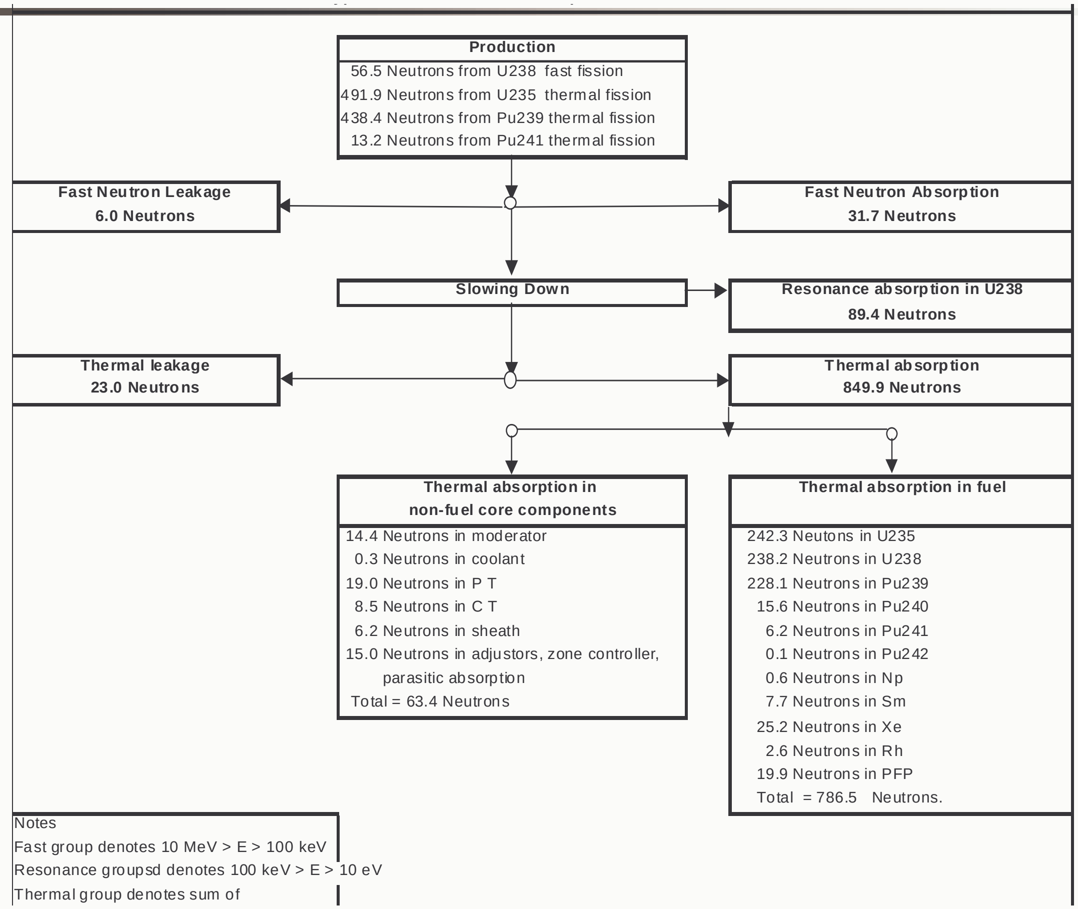


Table 3-1 - How Neutrons are Born and Die in CANDU

Fundamental Concepts

l_p =**prompt neutron lifetime**

= time from birth of prompt neutron to its absorption
= average time between generations of neutrons

$$k_\infty = \frac{N_f(t + l_p)}{N_f(t)}$$

Solve Kinetics Equation

$$\frac{dN_f(t)}{dt} \approx \frac{k_\infty - 1}{l_p} N_f(t)$$

Prompt Neutrons & Reactors

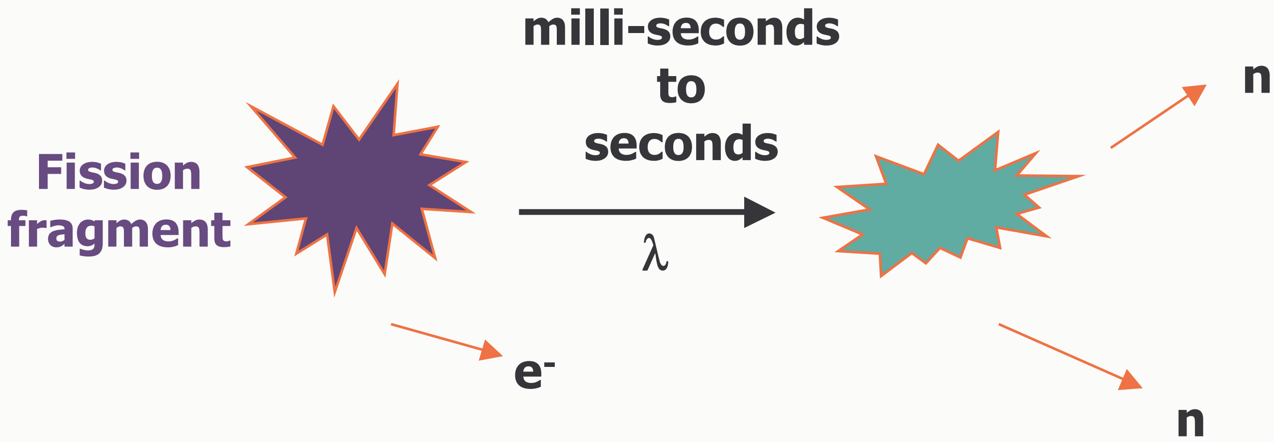
$$N_f(t) = N_f(0)e^{(k_\infty - 1)/l_p t}$$

Period

$$T = \frac{l_p}{k_\infty - 1}$$

Uncontrollable!

Delayed Neutrons



The timescale for ß decay and delayed neutron emission controls the reactor

CANDU delayed neutrons

Group	β (Fraction)	λ (sec^{-1}.) (Decay Constant)
1	0.00029	0.00061
2	0.0012	0.032
3	0.0010	0.12
4	0.0024	0.32
5	0.00078	1.4
6	0.00020	3.8
TOTAL	.0058	
l (sec)*	0.00092	

Kinetics - Delayed Neutrons

For prompt neutrons

$$\frac{dN_f(t)}{dt} = \frac{k_\infty(1-\beta)-1}{l_p} N_f(t) + \sum_{i=1}^{6} \lambda_i C_i$$

For delayed neutrons

$$\frac{dC_i}{dt} = \frac{k_\infty \beta_i N_f(t)}{l_p} - \lambda_i C_i$$

Reactivity

$$\rho = \frac{k_\infty - 1}{k_\infty}$$

= *fractional* increase/decrease in # of neutrons from generation to generation

Units: **milli-k**
$
cents
% Δk

One Delayed Group

$$\frac{dN_f(t)}{dt} = \frac{k_\infty(\rho - \beta)}{l_p} N_f(t) + \lambda C$$

Prompt criticality: $\rho > \beta$

Effect depends on value of l_p

Defences:

- **Limit rate**
- **Inherent negative feedback**

Period vs. Reactivity

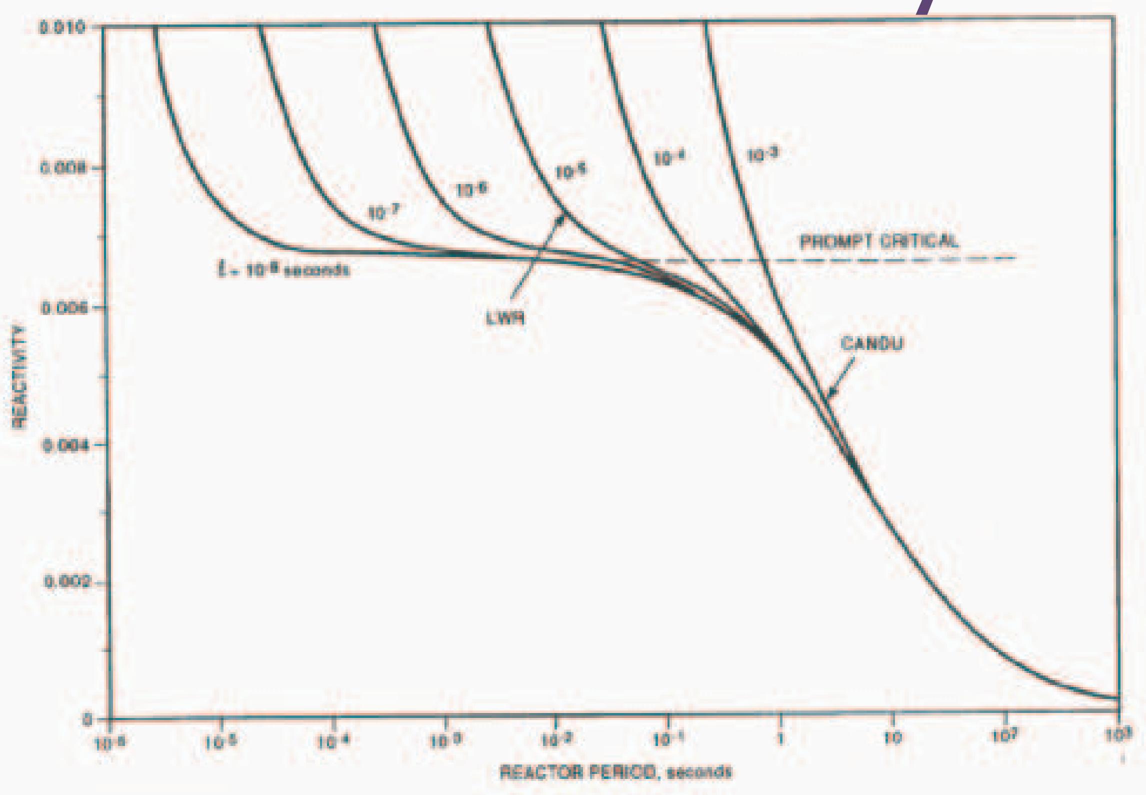
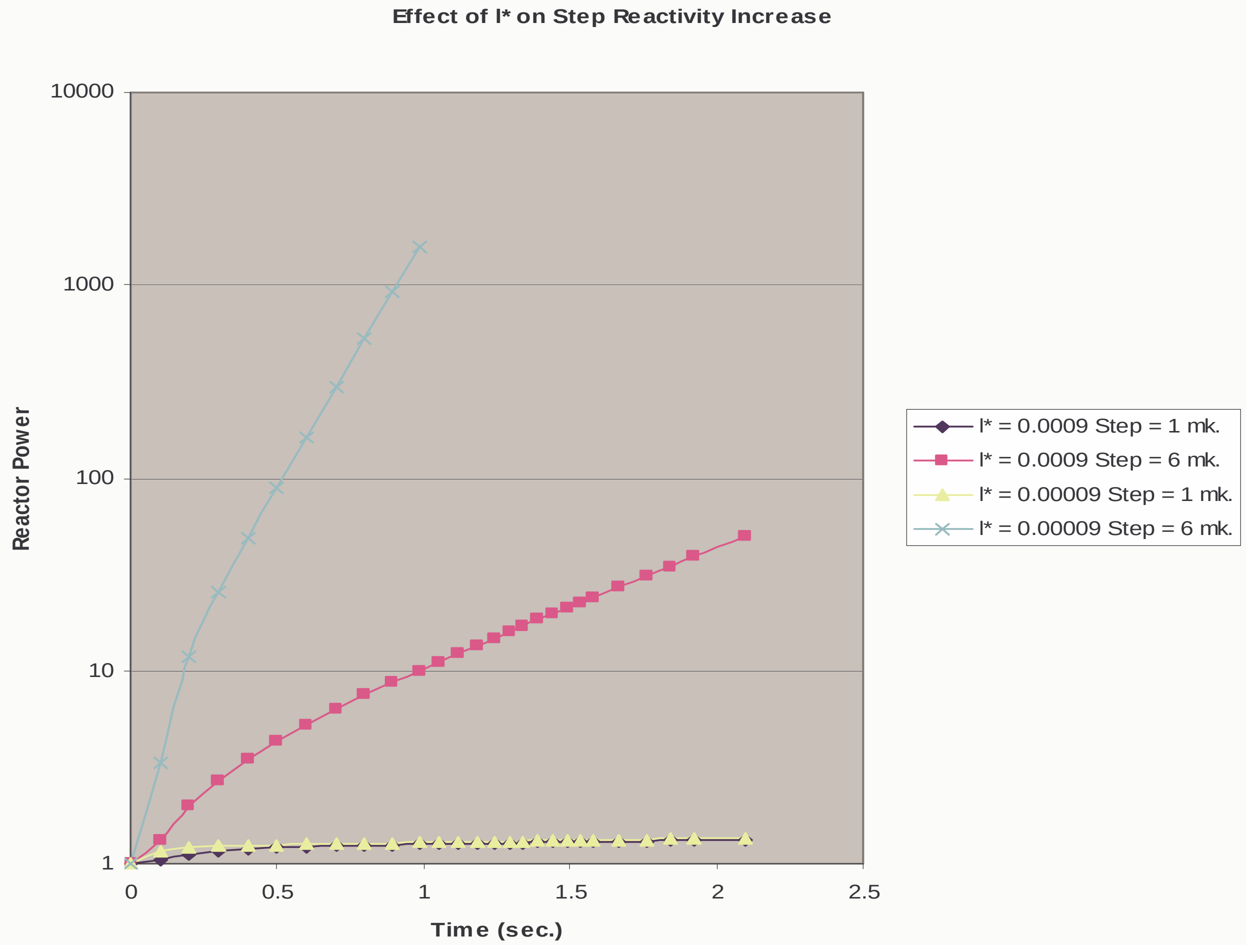


Figure 3-1a Relationship between Reactor Period and Inserted Reactivity for Various Neutron Lifetimes

Transient Behaviour



What Can Go Wrong?

- Fission rate has no inherent upper limit
- Reaction can be stopped or stabilized by:
  - Inherent negative reactivity feedback on e.g. fuel temperature (stabilize)
  - Engineered safety systems (stop)
  - Core disassembly (stop)

Is a Subcritical Reactor Safe?

- Power constant but not actively controlled
- Detectors insensitive
- Margin to criticality not clear
- Shutdown margin controlled by procedure
- Hence: Guaranteed Shutdown State
- Poised safety systems? Or all rods in?
- When to refuel?

$$N_f = \frac{S_e}{-\rho}$$

SL-1

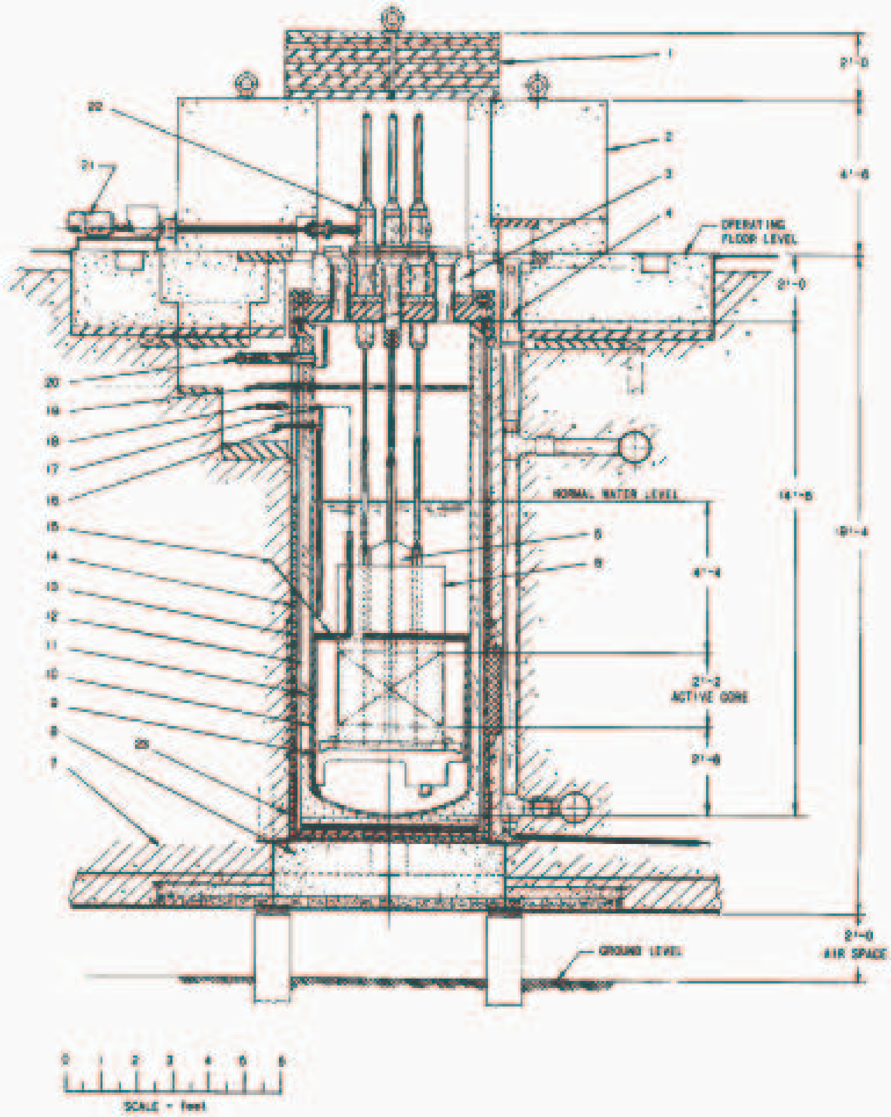


FIG. 3-22 SL-1 reactor installation, vertical section. Numbers indicate principal parts, as follows: 1 – laminated top shield; 2 – concrete shield; 3 – dry shield mixture; 4 – instrument well; 5 – control rod; 6 – core structure; 7 – gravel; 8 – dry shield mixture; 9 – thermal shield; 10 – pressure vessel (4.5 ft outer diam.); 11 – insulation; 12 – air space; 13 – support cylinder; 14 – lead thermal shield and cooling coils; 15 – feedwater spray ring; 16 – separator return line; 17 – purification purge line; 18 – feedwater inlet; 19 – boron spray ring; 20 – steam line; 21 – control rod drive motor; 22 – control rod drive; 23 – Boral shield.

SL-1 Chronology - 1

Chronology of SL-1 Accident	
Time	Event
-500 msec	Central control rod withdrawal starts
-120 msec	Reactor goes critical with rod at 16.7 in. (40.6 cm).
...	Central rod at 20 in. (50.8 cm), period = 3.9 ±0.5 msec, (2.4 ± 0.3)% Δk
0	Peak of power burst. (1.9 ± 0.4) × 10^4 MW.
...	Portion of plates reach vaporization temperature, 2060C (3740F); 5% of centre 16 elements
~2 msec	Prompt nuclear energy release ends; total nuclear energy of excursion = (133±10) MW-sec [+(24 ±10) MW-sec in metal-water reaction]
...	20% of plate area destroyed; centre 16 elements 50% melted; central shroud and control blade ejected from core.
...	Water column above core accelerated by average pressure (500 psi or 35 atm) to velocity 160 ft/sec (49 m/sec).
34 msec	Water slams against lid of vessel.. Maximum pressure ≈ 10,000 psi (~700 atm).

SL-1 Chronology - 2

Chronology of SL-1 Accident	
Time	Event
...	Head shielding ejected. Plugs ejected with velocity of 85 ft/sec (26 m/sec) or less. Vessel rises, shearing connecting pipes. Guide tubes collapse. Nozzles and vessel expand.
160 msec.	First plug hits ceiling.
...	Two-thirds of water expelled. 5-10% fission products expelled.
...	Vessel hits ceiling. Total kinetic energy involved ~1% of total energy released.
...	Insulation ripped from vessel.
2000 - 4000 msec	Vessel comes to rest in support cylinder.

Rod worth = 6 mk / inch

SL-1 Lessons Learned

- Single rod rule
- Limits on rod speed
- Inherent fast feedback
- Human factors / maintenance

NRX

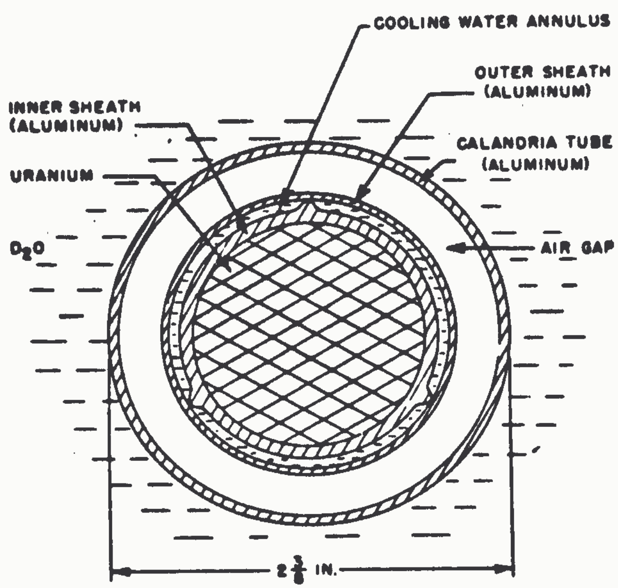
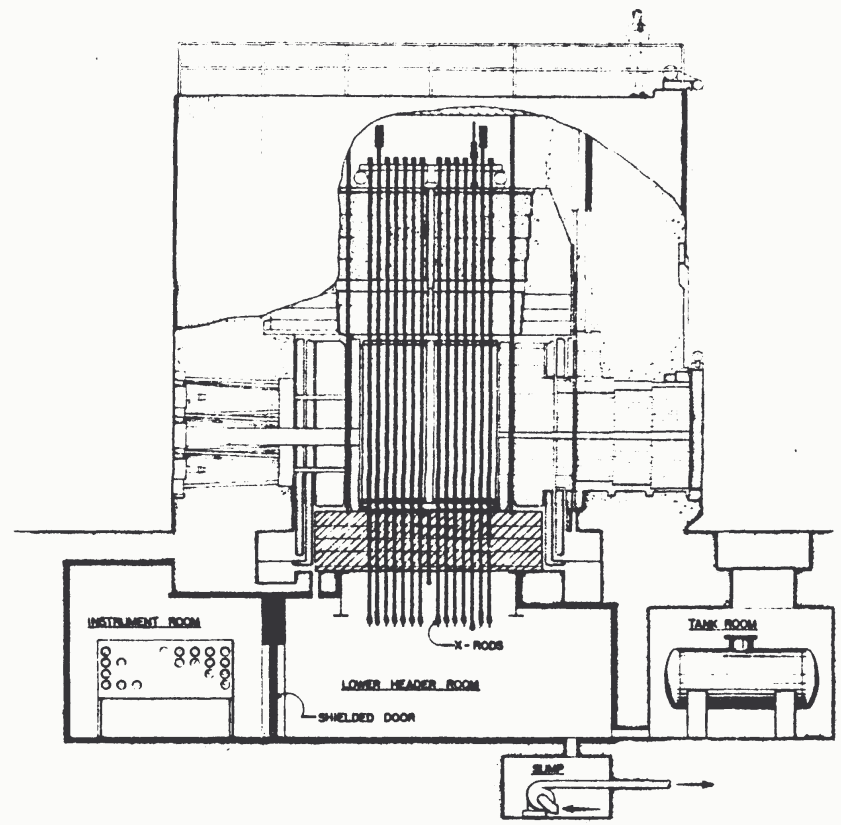
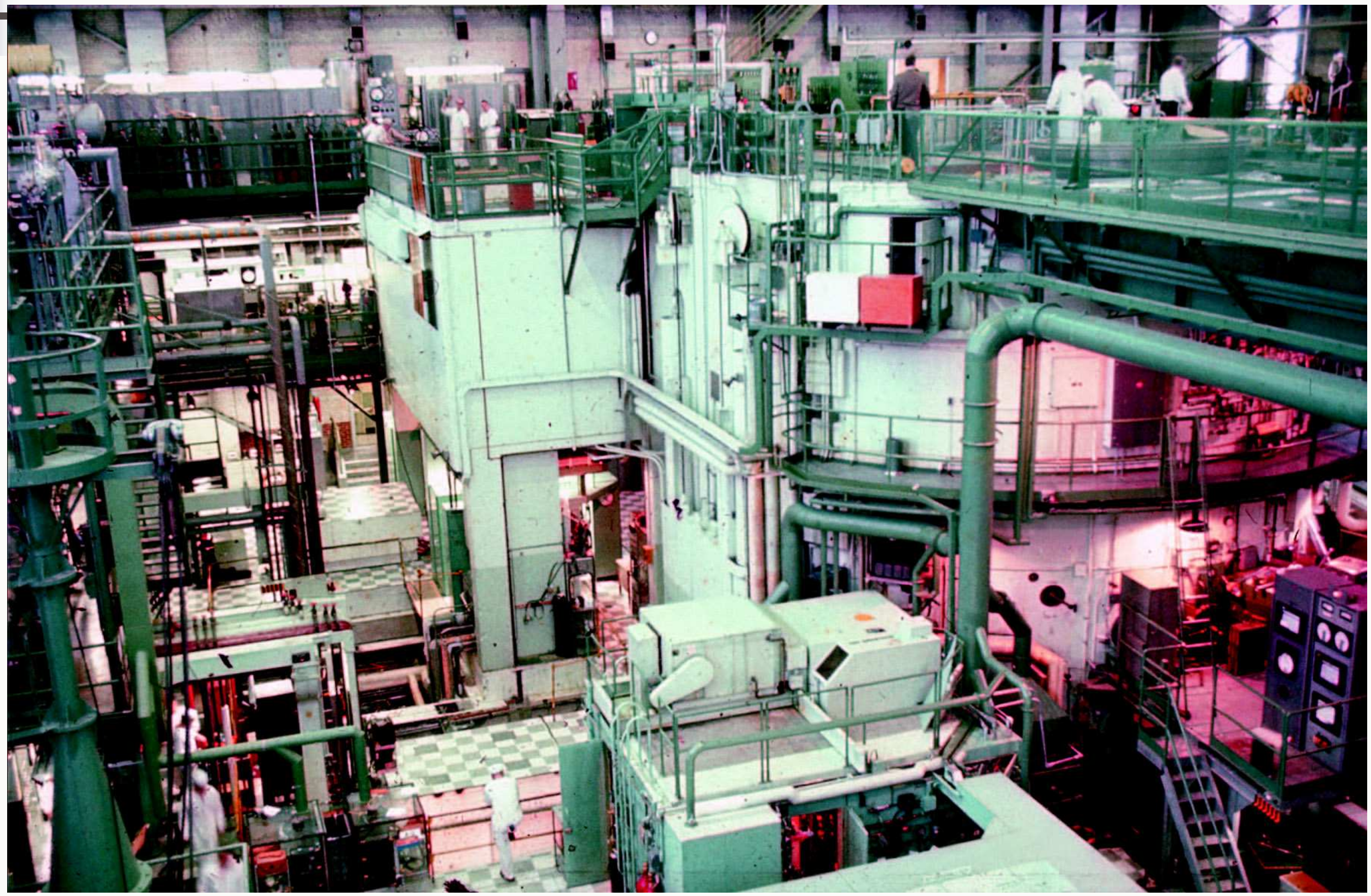


Fig. 1—Cross section of rod structure and calandria tube.



NRX



NRX – Sequence - 1

1.	The reactor had been shut down for a considerable length of time and was quite cold. An experiment was being conducted in which one unirradiated uranium rod was being compared with highly irradiated rods with regard to reactivity. So as to reduce the unknowns, the unirradiated rod was air-cooled at the time. To bring the heavy water up to nearly operating level, six shut-off rods were down. At 260 cm of heavy water the pile was about 1 cm below critical.
2.	It was desired to bring the heavy water up to 277 cm to compare with previous experiments. Therefore it was decided to drop in a seventh rod. To do this the solenoid on the headgear was shorted. The rod dropped in but at the same time a fuse was blown and the pile tripped allowing all the remaining shut-off rods (5) to drop in.

NRX - 2

3.	The first step in going from a trip free condition to seven rods in the reactor and five out was to put all circuits and valves back to the normal operating condition. The electrician re-established the electrical circuits. To re-establish the valves certain ones in the basement had to be opened. Instructions were phoned from the control desk to an operator in the basement to open these valves.
4.	The operator in the basement was either given the wrong instructions or misinterpreted the instructions because he opened the wrong valves. This action caused three to four rods to be raised.
5.	The supervisor in charge saw from the lights on the control console that these rods had been raised and went down to the basement to correct the situation himself. He left the pile physicist in charge of the controls.
6.	On arriving in the basement he closed the valves opened by the operator and opened the proper valves to re-establish normal operating conditions. What he did not realize was the rods raised by the operator's error did not drop back into the reactor.

NRX - 3

7.	**Believing that the pile was now in normal operating condition he instructed the pile physicist by telephone to raise the first bank of rods. In doing this he made an error in the numbers of the push buttons to be pressed.**
8.	**The pile physicist who was not thoroughly trained in the operation of the reactor, pressed the buttons named. As a result he raised the first bank of rods but at the same time released the accelerating air from the headgears. At this stage the pile was above critical and the power started to rise. If all the rods in the pile had been properly water cooled, no accident would have occurred. However, there were a number that had reduced water flow. When the power reached the level sufficient to boil the water out of these rods, the reactivity went out of control and the accident occurred.**
9.	**When the pile physicist realized the pile was critical he pressed the trip switch which should have released the rods that had been raised. However, with no accelerating air the rods did not clear the headgears and remained up. The physicist then contacted the supervisor in the basement who shut off the cooling air in an effort to bring the rods down.**

NRX – 4

10.	**When this did not work the heavy water was dumped. Obviously the dump button was not pressed as soon as it should have been. After a short period in a super-critical condition the reactor shut down, whether due to rods falling into the reactor or the dumping of heavy water is not clear.**

NRX - 5

- Cooling flow to experimental rods reduced; one was air cooled
- Rods raised earlier in error did not drop when error was corrected
- Reactivity reached 6 mk. positive due to removal of safeguard bank; power reached 100kW in 20 sec. and 17 MW at 30 sec.
- Voiding of low-flow channels suddenly added another 2.5 mk
- Moderator dump started at 45 sec.
- Peak power ~80-90 MW at 49 sec. Rapidly decreased to low level at 70 sec

NRX - Consequence

- Several fuel channels damaged
- Some fuel melting
- Heavy contamination in the building
- No worker injuries
- No significant public dose
- Calandria removed, buried, replaced
- NRX operated until April 8, 1994

NRX Human Errors
(from Meneley)

- **Control rod changes were made with the heavy water at a level that permitted the pile to go critical. It would have only required a short time to dump the heavy water to a safe level. This was a mistake in judgment as no instructions had ever been issued against such an operation.**
- **It was realized by both the supervisor and the pile physicist that the operator in the basement was not thoroughly familiar with the pipes and valves. In such a critical hazardous experiment he should have been replaced. (Error in judgment).**
- **Instructions were given over the telephone to change valve settings in a hazardous operation. Contrary to instructions – all such valve changes are to be made on written instruction only.**
- **The physicist had been instructed not to take charge of the control console. This instruction had come from his superintendent and in this case he did not take charge on the request of a supervisor. If he had been fully knowledgeable of the operation of the reactor he would not have made the mistake in buttons even though his instructions were wrong.**

NRX Human Errors - 2

- "Free fall tests" of the safety rods had never been practiced in the reactor. If this had been done it would have been found that the percentage of rod failures due to sticking was high. The clearance in these rods is so small that a bit of dust could cause them to hang up. Also there was some residual magnetism in the headgears that aided the rods in staying up. The reactor had always been operated under the assumption that the rods would fall in without the assistance of the accelerating air. This was never thoroughly tested and, in fact, was not true. (Error in judgment and design.)
- The lights indicating the rods in the down position had not been functioning properly. As a result they were generally ignored. An error in design and judgment. It is interesting to note that these lights were being altered as time permitted with the intent that when alterations were complete the operation of the lights would be a requirement for reactor operation.

NRX – Lessons Learned

- Safeguard bank
- Loss of confidence in rods
- Large clearances, simple design, failsafe
- Separation of control & safety systems
- Eventually, redundant shutdown systems

Exercises

- **Direct cause** (immediate precursors which caused the event)
- **Root cause** (a cause which if prevented would have prevented the event)
- **Contributing cause** (a cause which increased the likelihood of the event)

Draw a time line or an event tree and classify each event as one of the above (or irrelevant).

Exercise 1 – The Lewis Slotin Experiment

Reconstruct-ion of Event

Slotin – Aftermath

Photo of lab after event

Exercise 2 – The Point Lepreau Spurious Douse

- Do a root cause analysis
- Are there any aspects in common with NRX?