Safer Nuclear Energy for the Future

Lecture 4 -- The Long Term

by

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This lecture attempts to look forward about 50 -100 years.

This long time schedule is typical of energy systems, and a necessary horizon for serious engineering concept studies.

As we go further into the future uncertainties become larger and larger. What actually transpires may be entirely different than what is expected – but being prepared for alternate futures is still important. Some obvious near-term events (such as the depletion of North American natural gas supplies) will have profound impacts on our future, regardless of other unknown factors.

Some longer-term uncertain trends (such as global warming) should be matters for early planning and some degree of implementation, because of the huge potential magnitude of their impacts on society.

But recall the old saying "We are very good at predicting nearly everything, except the future."

Principal Needs for Future Nuclear Plants

- Competent, dedicated and ‘mindful’ operating staff
- Competitive economics
- Assurance of good reliability and protection from plant damage
- Robust, safe plant -- simple to operate, ’packaged’ complexity
- Sustainable Fuel Supply -- major system growth in next 50 years
- Adequate protection of public -- ‘No Evacuation’ criterion?
- Mature and effective materials safeguard systems

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These needs could be used as the basis of conceptual design for future plants. We need some of them now, and some can wait in line for a little while.

The term “Mindful” is taken from the book “Managing the Unexpected” by Weick and Sutcliffe. It has substantially the same operational meaning as “Safety Culture” but is more specific to some aspects of human behaviour.

Competitive economics is the “entry requirement” for nuclear energy. However, economics should be defined properly to include sustainability and minimum downside risk of loss and environmental damage.

Protection from plant damage contributes criteria for both public safety and owner’s economics

Robust plant design – more akin to a “Gravel Truck’ than to a “Formula 1 Racer’

Packaged complexity simplifies operations by reducing mental and temporal demands on the plant operators to understand such a wide variety of technical issues while operating the plant.

Sustainable fuel supply likely is the most demanding need, if we assume that fossil fuel supplies will dwindle and their costs will increase over the next few decades.

Adequate protection of the public in the presence of thousands of operating nuclear plants is the main underlying need in the context of this lecture.

Nuclear fuels always will be potential source materials for explosive weapons – the best defence is to have no need for such weapons, and second-best is to prevent access to them. This subject is beyond the scope of these lectures.

Take Care of the People First

- The first, major, task is to earn the trust of the people
  - Staff competence and mindfulness
  - Make sure that the plant is a “Good Neighbor”
  - Be prepared to wait years for progress
- What do the People Worry About?
  - It may be the rare, big accident – pay special attention to the lessons of the “Normal Accident” model
  - It may be waste management – demonstrate that you can do this job
  - Listen and respond to concerns
- Participate in International Programs
  - Trust comes from an understanding that you know what you are doing
  - Looking at different countries’ programs gives a broader and balanced perspective than does relying only on internal practices.

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The best way to earn the trust of the people is to deserve it.

A power plant should be a learning center for staff – this makes the job more interesting, and more productive for the owner.

Researchers should be encouraged to spend time at one or more operating plants – in the future, many of the most important research and development programs will originate there.

Operating staff should be encouraged to communicate with staff in other plants, to learn more about the technology and about things that break down, and how to keep the plant running well.

Understanding of how things are done safely in other industries (chemical production, airline operations) can help to develop sound safety ideas in the nuclear energy industry, and can increase public confidence.

Search for Designs that Limit Complexity and Coupling

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Finally, we come to the direct engineering task.

When looking for new designs applicable in the long term it is good practice to first "open all the doors" and look very broadly at the whole design task, including safety of course, but also the many other aspects of a plant. Only a few of these will be examined here.

Adopting the idea of "normal accidents", we look for changes that will reduce complexity as well as inter-system coupling.

Adopting this idea in no way accepts the notion, implicit in Perrow's work, that nuclear energy is too dangerous to use. Adopting the idea is very similar to adopting the need for "Accident Management", a concept that does not rely on the low frequency of occurrence, but requires preparations in spite of that low frequency.

As in normal US practice accident management is applied beyond the "design basis" set of accidents (a concept that has unique meaning only within a specific body of law). No specific cutoff accident frequency is stated or implied; the plant condition is assumed to occur and facilities are installed to cope with that condition.

Changing Perspectives

- Since today’s nuclear plant designs are highly optimized toward minimizing either the capital cost or the levelized unit energy cost, searching for simpler, less tightly coupled designs implies a cost increase.
- At least some of this cost increase can be offset by explicitly considering the downside financial risk to the plant owner that arises from the lifetime risk of plant damage.
- This additional influence factor, if added into the decision-making processes of a plant design group, can itself help to improve the safety of future plant designs.

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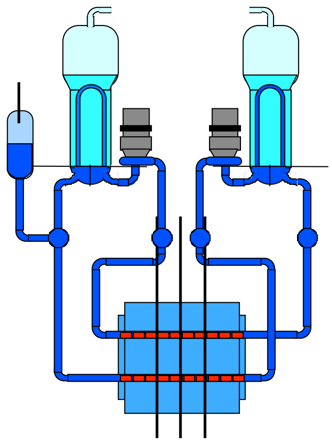
It is necessary to first change one’s outlook for starting a multi-parameter search for improvement.

It is common to produce a levelized lifetime plant cost by adding capital plus operation and maintenance costs, and combining them to recognize the time value f money. Recently, most assessments include the cost of fuel disposal and plant decommissioning.

(Occasionally, one sees the cost of major plant refurbishment added into the total.)

It is rare to include the downside risk of accidental plant damage in these costs. (See the article by Chauncey Starr some years ago – early 1980’s -, in the periodical Nuclear Safety.)

Example: Steam Generator Design



- Objective: Reduce coupling between primary and secondary cooling circuits
- Increase secondary side water inventory to improve maneuverability
- Increase heat transfer area, narrow pinch point
- Horizontal steam generators?

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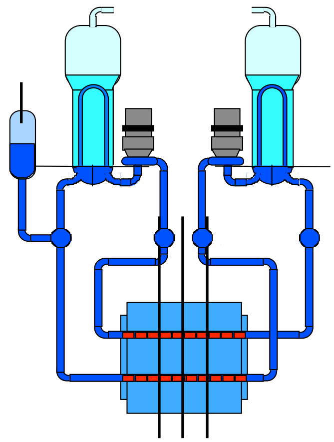
Vertical steam generators were essential for nuclear-powered submarines, but a horizontal arrangement offers potential advantages.

Larger heat transfer area adds margin for tube plugging, etc.

Larger steam separator area (larger water inventory) improves plant maneuverability

Example -- Primary Heat Transport System



- Objective: Increase operating margins
- Reduce fuel channel power, add more fuel channels
- Reduce primary coolant flow velocity, system pressure drop, pumping power
- R&D to reduce production cost of heavy water

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This option is suggested as a means to "back away" from the constraints related to performance and safety limits, and to design for a 'low, slow, and lazy' operating condition.

Underlying this design direction is an assumption that it is more important to sustain a very high level of steady plant output than to push the plant design as near as possible to material and other constraints.

To some degree this approach discounts plant capital cost in the design process.

Packaging the Complexity

- Increase operating margins to reduce chances for plant damage
- Put critical, high-speed operations in a box – use computers to monitor ‘system health’, and take protective action when needed
- Create highly detailed computer-based model of plant and use it for design, manufacturing, construction, operations, and maintenance
- Link system health monitors to computerized operations/maintenance model
- Simplify the operator’s job and reduce his work load

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The overall goal is to simplify the external system (the one seen by the human operator).

Operator is fully informed of plant state – thereby simplifying the decision to take safety-protective action

Implement a computer-driven model of the plant, then “duplicate and operate” that model forward into the future to find the best operating choices for the real plant that follows, in real time. Use the model for training.

Existing Designs Evolve Toward Better Safety in Sequential Build Projects

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Considerable improvement can be achieved simply through evolution of an existing design.

Designers must select advisors on a new-plant project from among the senior operating staff of a similar plant.

Specific Changes to Wolsong 2,3&4 & Qinshan 1&2

- Meet Canadian *and* Korean / Chinese requirements for siting
- Level 2 PSA with external events, performed by Korea
- First application of AECB Consultative Document C-6 on a CANDU 6
- Comprehensive dual parameter trip coverage
- Technical Support Centre
- Critical Safety Parameter Monitoring System

Wolsong 1, 2, 3, & 4

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Wolsong station has four units. Last two units benefited from experience gained on the earlier two units.

Improved safety should result from refinement of design and more detailed understanding of the system

Detailed computer model of the plant provides efficient framework for maintenance and training.

Specific Changes to Wolsong 2,3&4 & Qinshan 1&2 - continued

- Tornado protection of key safety related systems on Qinshan site – dictated by site characteristics
- Seismically qualified fire protection system in addition to existing two-group design approach
- Comprehensive, 3-D CADDS model coupled with construction and project control systems

Qinshan Phase 3 - Units 1& 2

(Projected appearance - Unit 1 in service)

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More changes introduced on Qinshan project

Further improvement in plant models, operations management systems

Detailed CADDS model, inventory, and configuration management system in use for operation, maintenance, and training

Design Options in Current Generation of Reactors

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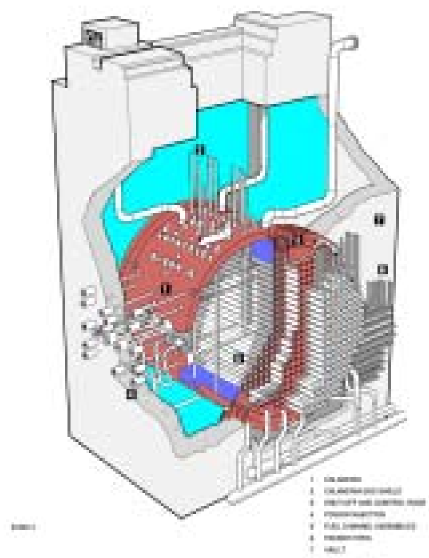
Looking a bit further forward, we can see opportunities for relatively small design changes that add to the depth of safe defence, especially for the larger, less frequent events.

Shield Tank as Core Catcher

- Large source of water surrounding the calandria
- In severe core damage accidents such as LOCA + loss of ECC + loss of moderator heat removal, the shield tank can keep the damaged core material inside the calandria by providing water on the outside of the calandria shell
- Inherent “core catcher” for debris retention and cooling
- Challenge to containment is much reduced



This reactor type features a very large amount of cool, low pressure water surrounding the fuel.

Minor adjustments of the design can markedly improve severe accident performance.

Severe Accident -- Core on the Floor

- Loss of primary and emergency heat removal in LWRs leads to
  - melting of reactor fuel (e.g. TMI)
  - penetration of reactor pressure vessel
  - eventual penetration of containment base-mat or overpressure of containment building
- The most likely outcome:
  - no prompt deaths
  - inferred delayed cancer cases which cannot be detected due to “natural” cancers
- The same accident in CANDU - moderator and shield tank prevent and delay core melt

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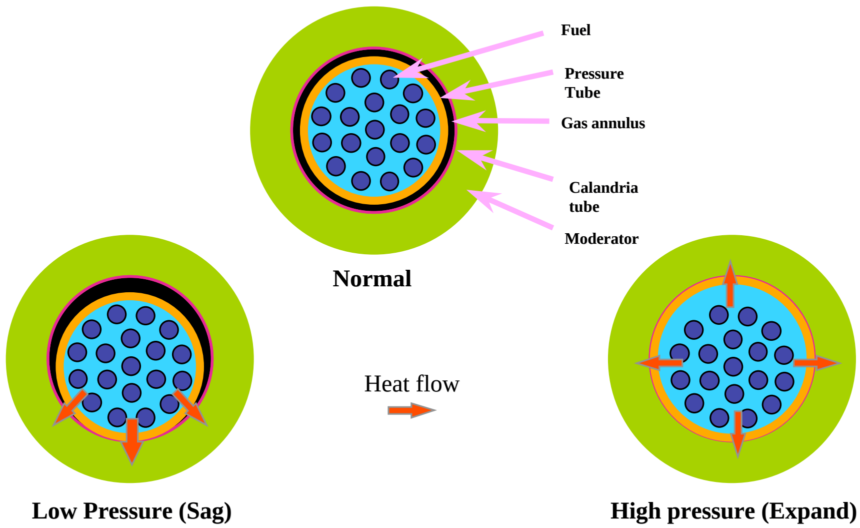
In the TMI-2 accident, fuel melting did not begin until two hours after shutdown, when poor cooling was intitiated by operators who did not understand the situation.

In a similar accident in a modern CANDU, IF the emergency coolant system was completely disabled there would be no fuel melting, even though the fuel channels would be destroyed. Then, IF moderator cooling also failed, and IF shield tank cooling also failed, then the core would collapse to the containment floor WITH NO MELTING.

Heat Rejection to Moderator in Severe Accident



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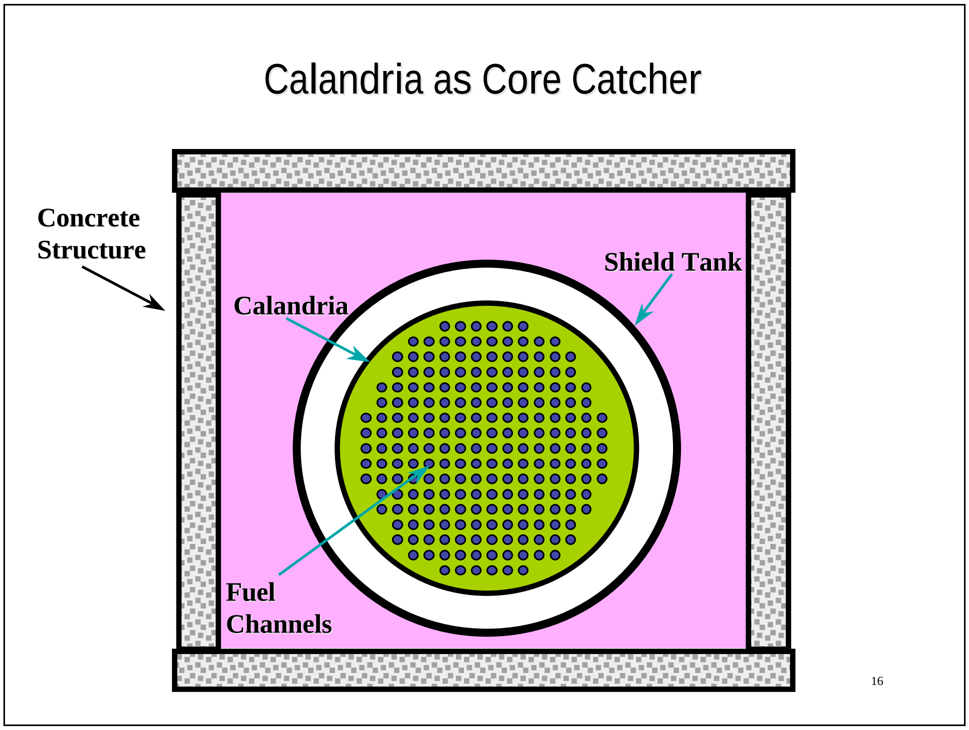
This heat transfer process is very simple – the pressure tube contacts the calandria tube, and fuel decay heat is transferred by conduction to the moderator water.

Cooling of fuel below its melting temperature is independent of the presence or absence of emergency cooling water in the channel

Experiments were conducted to prove the sufficiency of this heat transfer mode under severe accident conditions



If the moderator cooling is interrupted, fuel channels eventually slump into a debris pile at the bottom of the calandria, and fuel cooling continues via the shield tank cooling system.

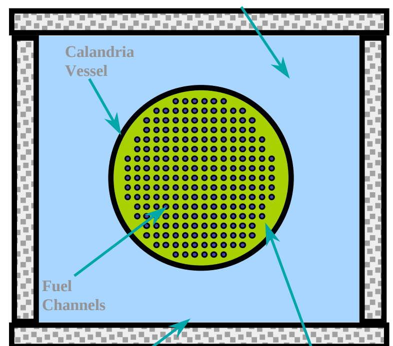
If the shield tank cooling system also fails, core slumping eventually continues to the floor of the concrete structure.

This structure includes the base slab of the containment.

Fuel cooling continues via evaporation and condensation of the large water pool, with heat removal via building air coolers and containment walls.

No fuel melting occurs.

Shield Tank as Heat Sink



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Calandria water boiloff requires at least five hours.

Shield tank water boiloff requires at least 20 hours, but in reality would not occur due to continuing condensation.

The system remains stable.

The reactor is destroyed, but the containment is not breached.

Toward Safer Designs...

- Current evolutionary designs
  - ensure a water covering over the damaged “core on the floor” & remove heat from containment
- Passive designs:
  - passive: a component or system which does not need any external input to operate (e.g., electrical power)
  - usually uses gravitational forces to supply water, natural convection to transport heat, capability to store heat
  - sometimes requires active valves, signals
- Passive designs allow more time to arrest an accident before core damage and are believed to be simpler

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Two alternatives are being considered.

The current evolutionary design, designated ACR, can accommodate either option.

Toward Advanced Designs...

- For the long term, it will be essential to adopt a method of generating new fissile material
- Current FBR designs (IFR in particular) can be designed for high breeding ratio, but are handicapped by the high first-core fissile material demand
- Molten-salt systems and gas-cooled systems offer some advantages in terms of safety – but require large new investments
- Potential for accelerator production of fuels should be investigated once again

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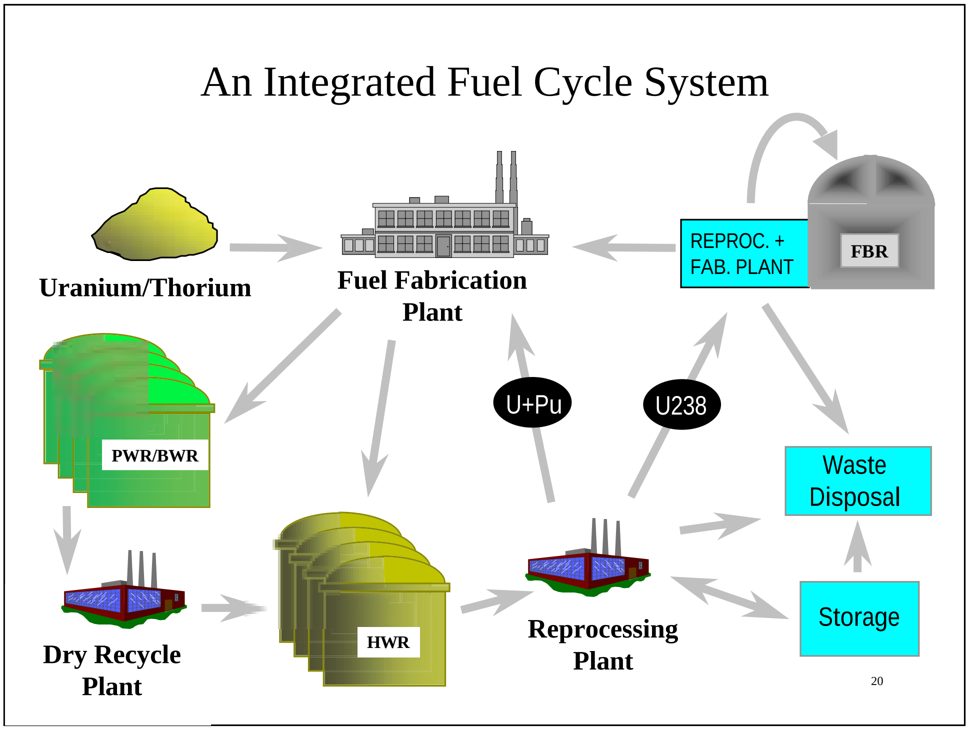
"Long Term" in this context includes the time period up to and beyond 100 years into the future. At some time, a new energy supply system may be found. If it is not, fission energy can supply a large fraction of the world's needs into the indefinite future.

Safety requirements will continue, of course, in the long term. The most likely candidates for long-term designs are some sort of fuel breeding system – either critical or accelerator-driven.

Safety of current FBR designs (in particular the IFR concept) is very well assured, by theory and experiment.

Research on the accelerator-breeder concept continues at a low level.



This illustrates one possible integrated power system in the long term. All components are located on one site, including waste disposal. The site is isolated, most likely on an island.

Safety is enhanced through the presence of a large technical-skills base on the site.

Specifically, it would be feasible to locate FBR reactors (along with associated enrichment, reprocessing, and fuel fabrication facilities) or accelerator breeding facilities at very few central sites in the world. Input to these sites would be in the form of natural uranium, thorium, and used fuel bundles from LWR and BWR units in the contributing region of the world.

The product of such a system could include electricity, transportation fuels, fresh water, fertilizer, and a large array of industrial products whose production process requires heat, electricity and/orvarious industrial chemicals that also are produced on the site.

Storage of separated fissile materials would be restricted to these sites, and would be under international control – preferably by the IAEA.

[Note: A similar proposal (but one also completely within the control of an international agency) was created first by the Lillienthal Committee in the US.