Safe Nuclear Power: Instrumentation, Human Oversight, and Infrastructure Transition

ECE 4900W – Summer 2025

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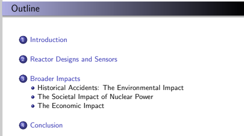
Welcome. This presentation explores the technological, ethical, and infrastructural dimensions of nuclear power in the modern world. We will cover lessons from historic accidents, instrumentation, human-machine interface design, and current innovations. Each story reveals both vulnerability and resilience.

Outline



I will be going through some motivation as to why nuclear power is still safe, explain a little bit about how the fission process works and the instrumentation that is used to control the reaction. I will then go on to emphasize the broader impacts and tell the story as to why nuclear power has not been as widely adopted as it could have been. I will discuss the improvements to human factors engineering because of these, and talk about the economic, environmental, and societal impacts that these accidents have had on the nuclear industry as a whole.

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- Instrumentation plays a critical role in monitoring and control.
- Human oversight is essential for safe operation.

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I've been hearing a lot of misunderstanding when it comes to this photograph taken on july 31, 1964 with the uss enterprise, the uss long beach, and the uss bainbridge. I've heard generally think that the sailors aboard irrelevantly spelled $e = mc^2$. This is just a response out of ignorance however. The formula refers to the fact that as the mass of the fuel increases, the potential for it to create energy is proprotional with that multiplied times the speed of light squared. This was a demonstration of force and showing the world the US Navy's capabilities in the nuclear age. The Enterprise was the first nuclear-powered aircraft carrier with 8 submarine reactors. The uss long beach and uss bainbridge were also powered by dual surface developed reactors.

Motivation

- High energy density and steady base-load power
- Nearly zero emissions, independent of weather
- Risks of failure—catastrophic if unmanaged

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Despite fears, nuclear remains one of the most efficient and clean energy sources. But it requires precision and care at every level.

The Fission Process

$$^{235}\mathsf{U} + ^{1}\mathsf{n} \rightarrow ^{92}\mathsf{Kr} + ^{141}\mathsf{Ba} + 3^{1}\mathsf{n} + \mathsf{Energy} \approx 200\ \mathsf{MeV} \qquad (1)$$

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This is the reaction that drives nuclear power. The energy release is immense, but so is the potential for instability if left uncontrolled.

Reactivity and Control

$$\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}} \tag{2}$$

- k_{eff}: effective neutron multiplication factor
- $\rho > 0$: supercritical (power increases)
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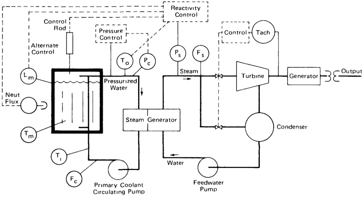
This is our friend Keff. The effective multiplication factor. The effective multiplication factor is just a measure of the average amount of thermal neutrons produced in one neutron lifecycle. The ratio of keff - 1 divided by keff forms a measurement called reactivity. A critical reactor has a keff of 1, a subcritical reactor has a keff of less than 1, and a supercritical reactor has a keff of greater than 1.

Types of Reactors and PWR Instrumentation



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- Advanced Gas-cooled Reactor (AGR)

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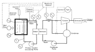

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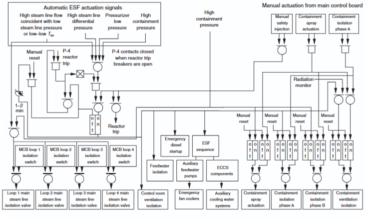
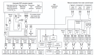
Each design uses different coolants and moderators, which affect safety logic and monitoring strategies.

PWRs are the most common worldwide. Sensors track neutron flux, coolant temperature, rod position, pressure, and flow rate.

Automatic Protection Systems



- Reactor protection systems (RPS): monitor reactivity, temperature, pressure
- Logic interlocks: prevent unsafe configurations
- Hardwired paths with digital backups



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Even the best operator can't always react fast enough. That's where automatic systems step in. SCRAMs instantly insert control rods. Protection logic compares real-time data to safety limits, triggering shutdowns, alarms, or backup actuation.

SL-1: Prompt Critical Accident

- Occurred January 3, 1961 in Idaho Falls.
- A single control rod was withdrawn manually beyond safe limits.
- Caused an instantaneous power excursion and steam explosion.
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Local firefighters arrived in response to a fire alarm and found the facility abandoned. Coffee cups remained warm, and food was left uneaten. As radiation alarms activated on their dosimetry equipment, they realized a serious radiological event had occurred. Two operators were located dead from radiation exposure. The third, Richard Legg, was discovered impaled and pinned to the containment ceiling by a control rod—ejected upward during the reactor's prompt critical event.

Three Mile Island: Partial Core Meltdown

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- Equipment failure: relief valve stuck open.
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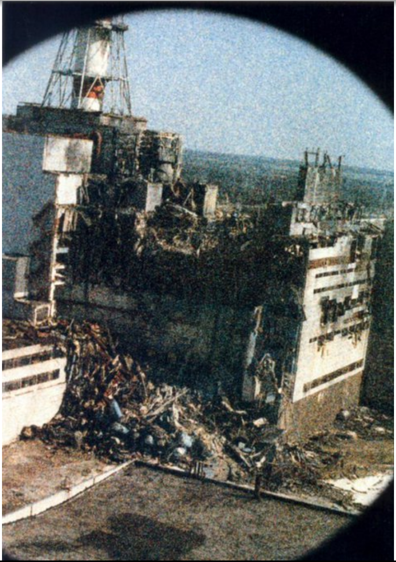
The Three Mile Island Unit 2 (TMI-2) accident occurred on March 28, 1979, near Harrisburg, Pennsylvania, and remains the most serious commercial nuclear accident in the United States. It was precipitated by the failure of a pressure-operated relief valve (PORV) that became stuck open during a minor malfunction. The valve allowed coolant to escape from the pressurizer, but due to inadequate instrumentation, operators believed it had closed properly

Chernobyl: Uncontrolled Power Surge



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- Unsafe test conducted at low power with flawed RBMK reactor.
- Control rods exacerbated the surge due to graphite tips.
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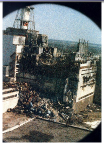

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The test intended to verify whether the rotational inertia of the turbine could temporarily power the emergency coolant pumps in the event of a grid power failure [7]. The RBMK-1000 reactor involved was a Soviet-designed graphite- moderated, water-cooled system—flawed by both design and executionhe core overheated instantly, rupturing fuel channels and vaporizing coolant. A vi- olent steam explosion lifted the reactor's 2,000-ton upper biological shield. A second ex- plosion—possibly from hydrogen or steam—further breached the structure and exposed the graphite moderator, which caught fire. Figure 6 shows the aftermath of the explosion mere hours after the explosion. The fire lofted radioactive particles into the upper atmosphere, affecting much of Europe

The aftermath of Chernobyl catalyzed global reevaluation of nuclear safety, reactor de- sign, and operator training. The international community pushed for increased transparency, safety audits, and enhanced containment strategies. The photograph in Figure 7 famously shows the "Elephant's Foot," a deadly corium formation. The strange visual static in the image is not lightning, but film degradation from intense radiation—testament to the un- precedented radioactive environment at the site

Fukushima Daiichi: Station Blackout

- March 11, 2011 in Japan.
- Magnitude 9.0 earthquake triggered tsunami.
- Backup diesel generators flooded—loss of core cooling.
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The Fukushima-Daiichi Nuclear Power Station, operated by TEPCO, was critically affected. Although the three operating reactors—Units 1, 2, and 3—successfully SCRAMed (shut down automatically), the tsunami flooded the site and disabled both the offsite grid connections and emergency diesel generators [12]. This unprecedented loss of power across all units is illustrated in Figure 8, which shows the reactor buildings after successive hydrogen explosions.

Human Operators: Essential Links

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Human operators are the last line of defense. They interpret complex data, make decisions under pressure, and ensure systems operate safely. The operators in this picutre are in a room named maneuvering. In this tight cramped space, you can see the control panel to control the reactor, and further back the electric plant control panel of a S5W reactor powered ship.

Human Factors Engineering

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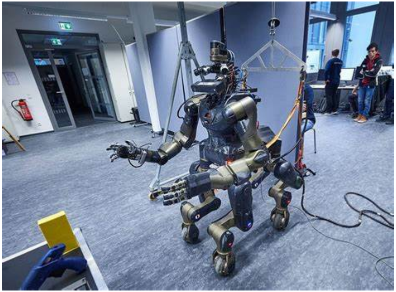
Human-machine interface redesign became essential after TMI. Alarm logic, indicator layout, and system feedback were all reengineered. The need to provide complex and realistic simulation training for operators has increased tenfold since the 1980s.

Ethical Oversight in Automation



- Systems must support—not replace—human oversight.
- Overreliance on automation can erode accountability.
- Ethical design considers failure modes, transparency, and operator input.

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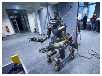

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Designing for ethical oversight means respecting human limits while reinforcing responsibility. The worst outcomes often arise when operators are sidelined.

Why Nuclear Declined

- Each accident—from SL-1 to Fukushima—prompted strict new regulations.
- Longer licensing cycles delayed new builds by decades.
- Public opposition and fear, not technical failure, stalled the industry.
- Skilled labor and supply chains diminished as construction halted.

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The world walked away not because nuclear failed—but because faith in its management eroded. Regulation became slower, and expertise drifted away.

Challenges Today

- Most operating reactors in the U.S. are past mid-life.
- Replacing the aging nuclear workforce is a growing challenge.
- Engineering firms that once supported nuclear have pivoted to renewables.
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Many of the companies and capabilities that built the first generation of plants no longer exist in their original form. As a result, the ability to construct new certified plants has greatly diminished. The nuclear industry is now at a crossroads, where the lessons of the past must inform the future.

Conclusion: A Deliberate Future

- Nuclear power is safe when designed, operated, and overseen with care.
- Instrumentation and human oversight must evolve together.
- Ethical design puts operators in control, not out of the loop.
- The tools are available, what remains is the will to rebuild trust.

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The future of nuclear power depends on our ability to learn from the past, innovate responsibly, and rebuild trust.

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Safe nuclear power isn't an inevitability—it's a discipline. What matters is not just how reactors are built, but how they are overseen.