Learning from Engineering Disasters: The SL-1 Reactor Accident

An Online Continuing Education Course for Engineers

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Learning from Engineering Disasters: The SL-1 Reactor Accident

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In the 1950's, the world was still exploring the exciting new possibilities of nuclear power. After an ominous appearance on the world stage in 1945, nuclear fission soon demonstrated an opportunity for high density, long-term energy production. The dynamics involved in the reaction were not yet well understood, and the implications of long-term radioactive waste production were unclear, but the success demonstrated by the US Navy in creating small reactors for submarines encouraged the US Army to join the development efforts already underway.

The US Army and Argonne National Laboratory (ANL) conceived and built a test reactor that could be used to generate electricity and provide space heating at remote military bases without the need of regular fuel deliveries. The reactor was later turned over to Combustion Engineering Inc. (CEI) to supervise development and train crews of Army personnel to safely operate and maintain the reactor. In January of 1961, the Stationary Low-Power Unit 1 (SL-1) reactor located at a remote Idaho test facility underwent routine maintenance on its control rod drive mechanisms after several months of test operations. While reassembling the control system, an accident occurred killing the three night-shift operators, severely damaging the reactor, and releasing both radiation and contaminated particles into the local environment.

At the time, the SL-1 accident was the most severe nuclear accident to have occurred at any power station or test laboratory and the only one involving more than one fatality. It garnered high attention in the military and civilian communities, and the investigative results were considered a high priority considering their potential value to other nuclear power system development programs. After six months, the investigative committee determined the most likely cause of the accident was sudden and unintended prompt criticality while reassembling the control rod drive mechanism on the center control rod. This led to a runaway chain reaction that pushed the reactor far beyond its design power capacity and vaporized the water in the core causing a pressure wave that damaged the reactor and ejected the other control rods.

The details of this event are most useful to nuclear engineers. In fact, the design lessons learned from this accident are now the cornerstones of several nuclear engineering design requirements common to virtually all reactors. But the principles of engineering gleaned from this accident are useful to a much wider audience. This accident was fundamentally driven by competing factors often encountered when new technologies are developed by cooperating organizations. For this reason, the SL-1 accident is a vivid reminder of the care and respect that engineers must cultivate when developing new technology into safe and useful engineered systems.

The objectives of this learning module are

- Understand the basic processes of nuclear fission and reactor control
- Gain a general understanding of the SL-1 Reactor Accident
- Explore underlying causes of the accident prior to the day of the event
- Understand the acute cause of the criticality accident
- Identify common learning points for developing new technology in any field

This course refers to terms introduced in the course “Learning from Engineering Disasters”. Though not required, it is recommended that you consider taking the “Learning from Engineering Disasters” course. Alternately, you can refer to a summary primer of the course in Appendix 1 of this course.

Accident Analysis

Essential Terminology

Nuclear power is complex in its finer details, but only a few main points are needed for a basic understanding. The following terms are used throughout this lesson and will aid the novice nuclear engineer in understanding the SL-1 accident.

Core

The reactor core is the assembly consisting of fuel (uranium-235), the metal sheathe that encases the fuel, and any structural materials that maintain the shape of the fuel per the reactor design. The primary purpose of the core assembly is to hold the fuel in a geometry that is nearly critical, can be controlled by insertion of control rods, and cooled by a liquid or gas coolant flow.

Critical

The status of a nuclear reactor is measured from the critical state. A reactor that is critical creates exactly enough neutrons in each step of the chain reaction to generate the same number of fissions in the next time step as the previous time step. This requires a balance between input (neutrons from fission and decay products) and output (neutrons lost from the reactor as radiation, neutrons absorbed that do not result in fission, and neutrons absorbed in fuel that produce a fission event). For power reactors, the critical state is the most stable state of operation. As a convention for this lesson, we will define the critical reactor as the state where power is constant and reactivity is exactly zero.

Delayed Critical

A reactor that is “delayed critical” requires delayed neutrons to sustain the fission reaction. A reactor operating in this status loses enough prompt neutrons before the next fission step that it cannot balance input (neutrons from fission) with output (neutrons lost from the reactor as radiation, neutrons absorbed that do not result in fission, and neutrons absorbed in fuel that produce a fission event) and is sub-critical on fission neutrons alone. Because delayed neutrons are available to the reaction at a slower rate than fission neutrons, a delayed critical reactor changes power more slowly than a prompt critical reactor, allowing it to be controlled by conventional systems and human operators.

Delayed Neutron

Most neutrons that sustain a fission chain reaction come from the fissions in the previous reaction step. However, some neutrons are developed from the decay of fission products following fission. These neutrons are called “delayed neutrons” because they arrive after a delay (on the order of milliseconds to several seconds) associated with the length of time for decay of the fission product nucleus producing it. Any neutron that is released during the decay of a fission fragment is called a delayed neutron. These neutrons are produced more slowly and have less kinetic energy than fission neutrons. Though they make up a small percentage of all neutrons in the chain reaction, the relatively slow time scale for delayed neutrons to appear makes nuclear fission reactors controllable by outside inputs (coolant flow, control rods, and other operator intervention).

Fission Neutron

A neutron released directly from a fission event is called a fission neutron.

Fission Product or Fragment

When a uranium-235 nucleus splits, it releases energy, a few fission neutrons, and two major fission fragments or fission products. These two terms are interchangeable in referencing the large nuclei that are left over when a larger nucleus is split through nuclear fission.

Half-Life

Unstable atomic nuclei decay to a more stable form by emitting radiation. The amount of time for one half of an unstable material to decay into a new, more stable form is called the half-life.

Moderator

Fission in uranium-235 nuclei requires neutrons at a lower energy state than when the neutron is emitted by fission. Neutrons give up some of their kinetic energy by colliding with other nuclei before combining with a uranium-235 nucleus and causing fission. This process of slowing down fission neutrons so that they are more likely to interact with other uranium-235 nuclei and cause fission is called moderation. Materials that are effective at slowing down neutrons so that they are more likely to fission a uranium-235 nucleus are called moderators. Moderators are most effective when their mass is close to that of a neutron. For this reason, most good moderators contain hydrogen atoms. Carbon is also effective though less so than hydrogen.

Graphite and water are common moderators. Although water is more effective, its density changes with temperature making its effective rate of moderation variable. Water also presents the issue of chemistry control to prevent corrosion. Graphite, though less effective as a moderator, is solid over the normal temperature ranges of most nuclear reactors and is not reactive with other structural components of the reactor. (It is, however, highly reactive with oxygen at high temperature.) This makes the rate of moderation nearly constant for graphite and eliminates the corrosion issue. This trade-off is a fundamental consideration in fission reactor design. Notable water-moderated reactors include SL-1 and most modern US commercial power stations. On the other hand, the Soviet-designed RBMK reactors used at Chernobyl employ graphite moderation.

Nucleus

The center of an atom containing its neutrons and protons is called the nucleus. This is the part of an atom that splits during fission.

Poison

Some materials easily absorb one or more neutrons per atomic nucleus without becoming unstable (as opposed to the neutrons bouncing off or becoming unstable after one or two absorptions). These materials are called poisons because they are very effective at removing neutrons from the fission chain reaction and tend to slow the overall reaction down. Control rods must be made of a poison material because they are used to remove neutrons and either slow or stop the fission reaction. Boron and cadmium are poisons that were used in SL-1.

Some poisons are specifically termed burnable poisons because they absorb a single neutron per atomic nucleus very effectively and then become essentially inert to the fission process. This has the advantage of reducing core reactivity early in life (when fuel load is high) while raising it late in life (after most of the fuel has been used). Boron is a common burnable poison in use in many reactors and was used in SL-1 for this purpose.

Prompt Critical

Remember that a “critical” reactor produces exactly enough total neutrons in each fission step to sustain the same number of fissions in the next reaction step including those from fission fragment decay. A prompt critical reactor, however, produces enough fission neutrons that are immediately available for fission to sustain the chain reaction without delayed neutrons. In a reactor under these circumstances, each fission step occurs very rapidly with delayed neutrons providing excess reactivity to rapidly raise power as they become available in later time steps.

A prompt critical reactor changes power so rapidly that outside intervention—even automatic safety actions—do not change power. The reaction itself will usually terminate after causing rapid depletion of fuel, fuel melting, or an explosion that causes the core to become sub-critical again.

Prompt Neutron
A prompt neutron is a neutron emitted from nuclear fission that is available for the next fission step nearly immediately. Prompt neutrons appear in less than a microsecond after the fission event that created them.

Reactivity
Reactivity is a quantity used to express how some conditions change a reactor's net efficiency at using neutrons for fission. As a convention for this lesson, we will define the critical reactor as the state where power is constant and reactivity is exactly zero.

Anything that increases the number of neutrons available for fission at the end of a single fission time step improves reactor efficiency at using neutrons for fission and adds positive reactivity. Adding positive reactivity pushes reactor state from sub-critical towards critical or from critical to super-critical. Effects that reduce reactor efficiency at using neutrons for fission add negative reactivity and push reactor state from super-critical towards critical or from critical to sub-critical.

Shutdown Margin
The amount of positive reactivity that must be added to restart a cold reactor with its control rods fully inserted is the shutdown margin. A large shutdown margin is often desirable since it means a significant effort must be made to add enough positive reactivity to re-start a reactor. This makes an inadvertent reactor restart or criticality event unlikely.

Sub-critical
A power reactor that produces fewer neutrons on each successive chain reaction step is sub-critical. It has a net negative total reactivity and will exhibit a lowering trend in power. A reactor can become sub-critical by adding sufficient negative reactivity. This is commonly accomplished by inserting control rods, increasing the proportion of neutrons lost as radiation, reducing moderator effectiveness or reducing fuel availability (e.g. from burn-out over long periods of fission).

Super-critical
A power reactor that produces more neutrons on each successive chain reaction step is super-critical. It has a net positive total reactivity and will exhibit a rising trend in power. A reactor can become super-critical by adding positive reactivity. This can occur in various ways including withdrawing control rods, reducing the proportion of neutrons lost to leakage as radiation, or improving the effectiveness of the moderator.

Understanding the System

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infamous dependi … ht together many of the
brightest minds in … t the close of World War II.
The bombs droppe … estructive force of nuclear
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generation. If the re … a highly power dense
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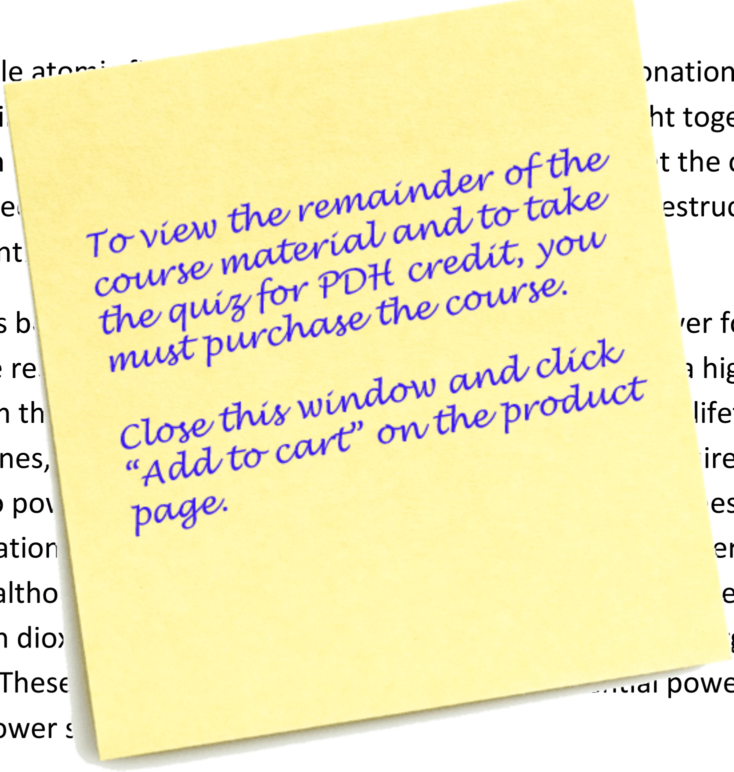

The SL-1 reactor plant was a 3 MWt boiling water nuclear fission reactor with five control rods. By modern standards, it was a very small reactor, but at the time, it was revolutionary in its goal to provide reliable power to remote military outposts virtually independent of a logistics chain. The principles of operation were simple and provide a good case study to introduce non-nuclear engineers to fission power production.

Controlled Nuclear Fission
Nuclear fission is the process by which an atomic nucleus splits into two or more fission fragments. This split releases energy that may be harvested by an engineered system for

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[1] A discussion of the trade-offs between concentrated spent nuclear waste and the disbursed stack products of fossil fuel power plants is beyond the scope of this lesson.