The SL-1 Accident Consequences

On the night of January 3, 1961, the SL-1 nuclear reactor, a prototype for a military installation to be used in remote Arctic locations, exploded, killing the three-member military crew. The crew had been performing the routine process of re-assembling the reactor control rod drive mechanisms during a reactor outage. The SL-1 was a small 3 Mega-Watt-thermal (MWt) boiling water reactor, complete with a turbine-generator and condenser designed to generate both electric power and building heat. [1]

The SL-1 was designed, constructed and initially operated by Argonne National Laboratory. It was located at the Idaho National Laboratory, then called the National Reactor Testing Station. Combustion Engineering became the operating contractor for the Atomic Energy Commission (now the Department of Energy) for SL-1 on February 5, 1959.

The SL-1 had first gone critical on August 1, 1958 and by July 1, 1959 had accumulated 160 Mega-Watt operating days (MWD). By August 21, 1960, the reactor had accumulated 680 MWD. The boron strips were deteriorating and bowing of the strips made removal of fuel assemblies difficult; therefore, fuel inspections simply ceased. [2]

The SL-1 core contained 14 kg of 93 percent enriched Uranium-235 in 40 aluminum fuel assemblies. The reactor fuel had accumulated 932 Mega-Watt operating days and was nearing end of useful life of the fuel. Fission products had built up inside the fuel as the reactor had operated.

The reactivity control rods at the SL-1 had an extensive history of sticking during withdrawal and during insertion. [3] The rod sticking was worsening as the reactor was operated. The AEC would downplay the severity of the rod sticking problems, despite rod sticking documented for the center control rod near the elevation that this rod would have been positioned during the manual lift of the rod that caused the accident.

Key Things to Remember About SL-1 Accident Consequences:

1. The SL-1's highly enriched fuel had high burnup and had operated for 932 MW-days, building up fission products in the fuel before the accident.
2. The SL-1 condensers were on the top of the building and the reactor was in a ventilated building with no containment.
3. About 30 percent of SL-1's fuel was absent from the reactor vessel after the accident.
4. The AEC claimed that basically only iodine-131 was in the radioactive plume from the accident. This claim, supposedly based on radiological surveys and gamma spectrometry, ignores the cesium-137 which must have been easily monitored. Other alpha and beta emitters are less easily monitored but would have also been in the plume and deposited on soil and vegetation. Radioactive noble gases would have also been emitted.
5. The wind was blowing from the north to the south for 100 hours after the accident. Then the wind pattern resumed the more typical alternating pattern of blowing from the southwest, reversing at night to blow from the northeast.
6. The SL-1 accident radiological airborne release was far larger than officially recognized.

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[1] Various DOE reports released by Freedom of Information Act request about SL-1 are at http://www.id.doe.gov/foia/archive.htm

[2] Atomic Energy Commission report, Idaho Field Office IDO-19300, "SL-1 Reactor Accident on January 3, 1961: Interim Report." Combustion Engineering, May 15, 1961.

[3] IDO-19300, p. 62-63, Table V, p. 62, and Appendix A (half of pages missing in online report as of 12/2014).

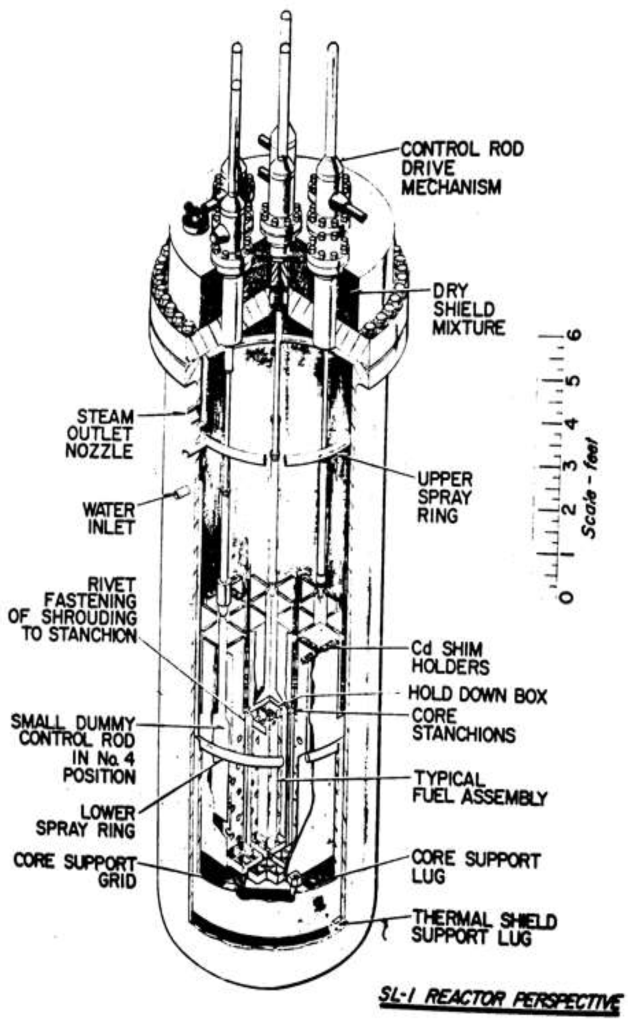

***Figure 1**. SL-1 Reactor perspective from IDO-19311.*

The routine maintenance procedure for the SL-1 to re-connect control rod drives after work above the core, such as installing flux monitoring wires, required manually lifting, twice, each of the 84 lb rods, that included the cadmium control blades, connecting and extension rods and upper-most portion called the rack.

The center control rod would later be found withdrawn 20 inches relative to the normal scram position. [4] Numerous accounts would say it was greater than this distance, including the Department of Energy's "Proving the Principle" which incorrectly states it was manually withdrawn 26 ½ inches. [5] Of the 20 inches it was withdrawn inside the core, it was initially already withdrawn by at least 2 inches and probably by 3 inches. [6] The operator needed only to bend down, clasp the vertical shaft and ease the 84 lb rod up an additional inch or two, wait for his co-worker to remove the C-clamp, and then lower the rod back down.

While the mechanism for the severe explosion was not immediately apparent, it was found that the center control rod (No. 9) had been lifted too high—high enough for the reactor to cause a steam explosion from the "prompt critical" rapid generation of neutrons that heated the reactor fuel, vaporized some of the fuel and flashed the water in the reactor vessel to steam.

[4] Atomic Energy Commission report, Idaho Field Office, IDO-19311, "Final Report of the SL-1 Recovery Operation, General Electric Co., June 27, 1962. partial center rod withdrawal of 20 inches, p. 146.

[5] Susan Stacy, "Proving the Principle – A History of the Idaho National Engineering and Environmental laboratory, 1949-1999," Washington, D.D.: US Department of Energy. p. 148. http://www.inl.gov/publications/ and http://www.inl.gov/proving-the-principle/introduction.pdf

[6] ibid. IDO-19311, p. III-109]

A new core and rod drive mechanism was scheduled to be installed in the spring of 1961.[7] The new rod drive mechanism would have eliminated the need to manually raise a control rod during the coupling operation. Later examination of the core internals would also identify numerous pre-accident weld, corrosion, and material issues in the damaged core. [8]

The Rod Withdrawal Distance for Prompt Criticality Was Unknown

After the accident, reports would state that a reactivity addition of 2.4 percent delta k/k had put the reactor on a 4-millisecond period. While sounding innocent enough, the reactor design allowed manual movement of a single control rod to insert a huge amount of reactivity change rapidly enough to cause the accident. Prior to the accident, no one had computed the prompt criticality rod withdrawal distance. The 4-millisecond neutron population doubling would mean such a rapid increase in neutrons that the heat generated in the fuel could not be transferred to the coolant water before some of the fuel would vaporize from the high temperatures.

The complex and irregular arrangement of burnable boron strips made modeling the SL-1 core particularly difficult. Before the accident, the calculations for predicting normal criticality for reactor operation and the corresponding control rod withdrawal positions for achieving criticality were based on greatly over-simplified computations because of the difficulty in analyzing the complex non-symmetrical geometry of the core. In fact, even studies attempted today find the complex arrangement untenable. The simplified analysis had deviated significantly from the actual observed reactor core control rod positions needed for reaching criticality for normal power operation. [9]

Reactivity shutdown margin is known to change over time with reactor burnup. Very little monitoring to compare predicted to actual reactivity shutdown margins was performed at SL-1. As a prototype, its unproven design should have resulted in more, not less attention than is ordinarily performed at reactor facilities. Such monitoring was hindered by lack of staff and inaccuracies in recorded conditions including errors in accurately zeroing the control rod drives. Post-accident calculations would require tedious and imprecise delving into operating records to try to account for the previous month's operation. [10]

Reactivity shutdown margin and the reactivity worth of each rod are affected by core geometry, individual fuel element history, water temperature, Xenon decay and in the SL-1, also by the status of the deteriorating boron strips. Estimates of reactor shutdown margin and rod position to achieve the "prompt critical" condition that would destroy the reactor would later be extrapolated from non-identical conditions and revised in later, somewhat overlapping SL-1 accident reports. [11]

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[7] ibid. IDO-19300. p. 4.
[8] Atomic Energy Commission report, Idaho Field Office, IDO-19313, "Additional Analysis of the SL-1 Excursion: Final Report of Progress July through October 1962. Flight Propulsion Laboratory Department, General Electric Co., November 1962. p. 147.
[9] ibid. IDO-19300. p. 34-36.
[10] ibid. IDO-19300. p. 49.
[11] ibid IDO-19313.

The core, almost 26 inches high, was a checker board of square shapes but the fuel position approximated a filled cylinder shape. The geometry, looking down on the core, was symmetrical. The power in this core should have been symmetrical, unlike test reactor cores designed for varying power in various lobes in order to simulate higher powers for materials testing such as the Advanced Test Reactor. Maintaining symmetry would have reduced power peaking in different areas of the core, prolonged fuel life and put lower stresses on the fuel during an accident.

The choice to put the cadmium strips in the #2 and 6 tee positions (which can pictorially be thought of as east and west positions, see Figure 2) while providing sorely needed additional shutdown margin had the effect of reducing power on the east and west sides, but of increasing reactor power on the north and south sides of the reactor. After their installation, reactor operating power oscillations had increased. The power levels and fuel damage from the accident are highest in the central area of the core. But fuel plate powers were higher in the north and south than the east and west because of the two rather than four cadmium shim positions used.

Even with the two instead of four cadmium shim locations, one would have expected the north and south fuel assembly powers of the core to be symmetrical: they were not. The effect of mispositioning one of cadmium shims, with its three strips filling the tee slots on the east side of the reactor can be seen in the higher power of the fuel assembly, No. 58 during the accident, next to what I presume is the mispositioned shim. Fuel assembly No. 58 has a higher power, peaking at a higher elevation in the core, than the fuel assembly south of it, fuel assembly No. 60. [12] [13]

By December 21, 1960, the SL-1 had accumulated 932 MWD, and despite the flaking boron strips, the difficulty removing and inspecting fuel assemblies, and frequently sticking control rods, tests were being conducted at higher than rated power, pushing the reactor to the point of power control instability. The tests involved powers of 4.7 MWt in order to test the performance of a newly designed condenser. “The testing was limited since permission had not been granted at that time to operate the reactor at power levels over 3 MW[t].” [14]

“An approach to the limit of the stable operation range and incipient instability of the reactor occurred in November, 1960 during a program to increase the operating power level to 4.7 MW in order to test the recently installed PL type condenser.” [15] At these higher reactor power levels, automatic movement of the center rod was not able to maintain a steady power. Installation of the cadmium strips in the east and west positions had worsened the instability.

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[12] ibid IDO-19311. Figs III-70, III-89 through III-92, Appendix D and E.
[13] ibid IDO-19313. Appendix E- Supplement to IDO-19311.
[14] ibid IDO-19300. p. 72.
[15] ibid IDO-19300. p. 4-5.

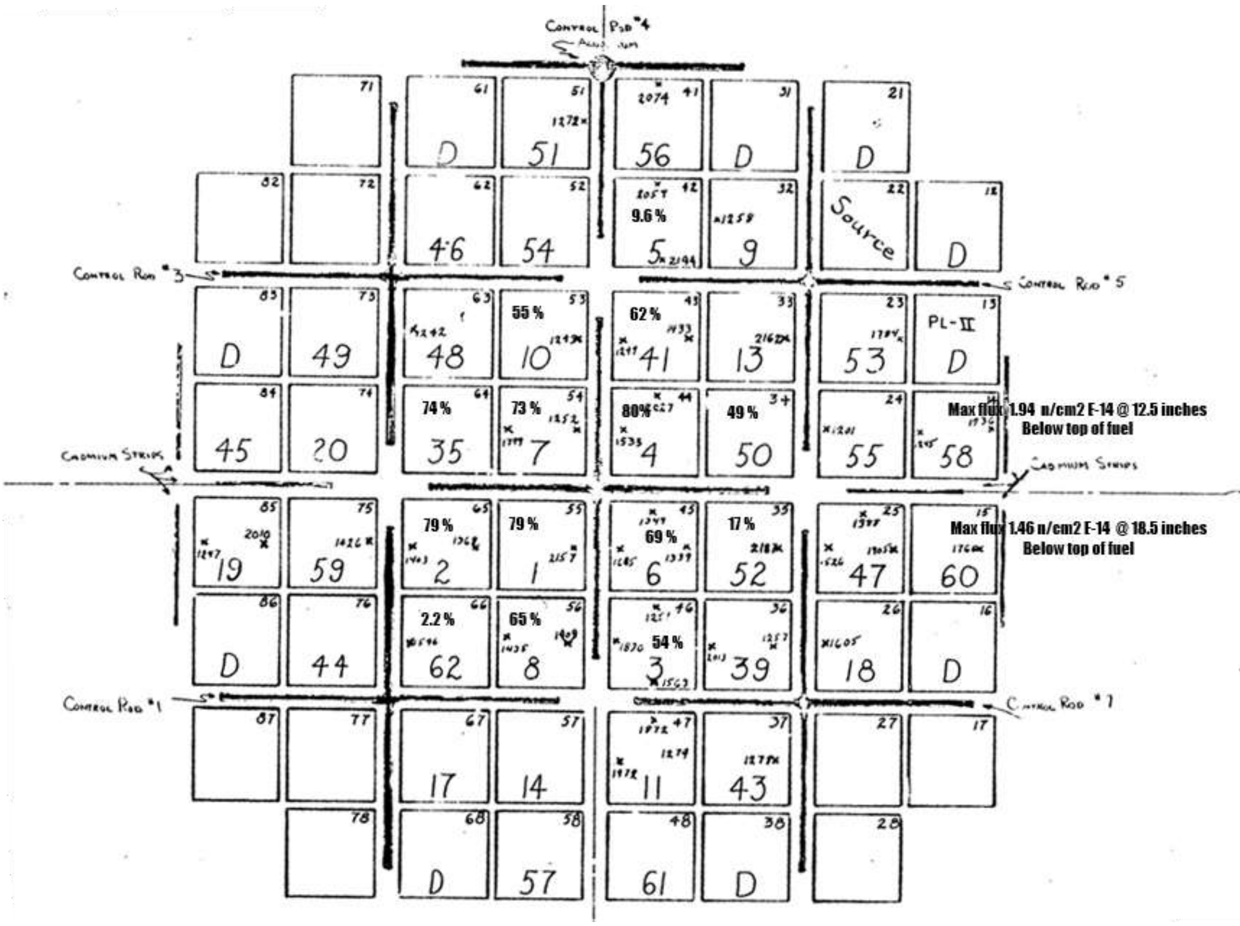

Figure 2. *SL-1 fuel assemblies, core positions, and percent destroyed, i.e. just northwest of center, fuel assembly 7 in position 54 has 73% of the fuel destroyed. Adapted from IDO-19311, figure III-89.*

A reactor scram on overpower had occurred on November 23, 1960. The scram setting was 5.7 MW and the scram was estimated to have occurred between 6 and 8 MW. [16] These reactor power oscillations, known as "boiling noise" were swinging pens off the paper recorder charts and had prompted an automatic scram. This would likely explain the comment remembered later by the spouse of the second victim about his concern that the reactor might blow up.[17]

It would not be discovered until months after the SL-1 accident that not only had the reactor ejected various missile projections, but the vessel had jumped 9 ft, shearing connected piping. Subsequent evaluations determined: "The steam being generated pushed upon the water that was above the level of the core forcing the slug of water upward from the core zone. It was stopped by the vessel head with the resultant water hammer causing peak pressures of about 10,000 psi. While the water was moving upward, the core structure jumped reaching a height of 7 inches

[16] ibid IDO-19300. p. 74.

[17] William McKeown, *Idaho Falls: The Untold Story of America's First Nuclear Accident.* Toronto: ECW Press, 2003. p. 201.

above its supports when the water hammer hit the head. As the water was decelerated upon striking the vessel head, the forces generated collapsed the shield plug guide tube. It also deformed the vessel wall and the vessel head nozzle. Additionally, the momentum of this water as it stuck the vessel head transferred its energy to the reactor vessel imparting a vertical motion to the shield plugs and to the vessel itself. . . The vessel jumped approximately 9 ft shearing the connecting pipes and expelling some of the surrounding thermal insulation. Simultaneously with the vessel lift, the pressure within the vessel expelled the unbolted shield plugs." [18]

A Comparison of the Three Mile Island Unit 2 Fuel Release Fractions to the SL-1 Derived Release Fractions

A report of the 1979 Three Mile Island Unit 2 accident stated that an estimated 10 to 20 curies of radioactive iodine was released from the site relative to 2 to 10 million curies of radioactive gases. [19] The report also stated that the released iodine was in most cases not detectable even by sophisticated modern techniques.

The fuel release fractions from this TMI-2 report which are recognized to not necessarily be bounding provide a perspective on how oddly low the estimated release fractions are for the 1961 Stationary Low-Power Reactor (SL-1) accident.

For the January 3, 1961 accident that vaporized a large portion of the aluminum clad, highly enriched nuclear fuel, the Atomic Energy Commission (AEC), now the Department of Energy, stated that only iodine-131 was detected away from the immediate accident site and that 84 curies of iodine-131 was released.

The AEC claimed that no other fission products were detected other than 0.1 curies of strontium-90 and 0.5 curies of cesium-137 within the perimeter fence of the SL-1. [20] The derived release fractions based on trying to fit the AEC claims to a computer-derived release fraction show that the AEC's claimed low-curie amount releases are fiction. Never before or since has a reactor fuel had such low release fractions! The AEC not only left out many radionuclides, they underestimated the amount of the fission product releases from the accident by a factor of over 22 for iodine-131, 588 for Cs-137 and 277 for Sr-90. And even with the low-balled curie releases, the SL-1 accident was a serious accident.

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[18] *The SL-1 Accident: Phases 1 and 2*. Film produced by the Idaho Operations Office of the US Atomic Energy Commission, *The SL-1 Accident: Phase 3*. Film produced by the Idaho Operations Office of the U.S. Atomic Energy Commission, circa 1963.

[19] Prepared by the Nuclear Safety Analysis Center, Analysis of Three Mile Island - Unit 2 Accident, NSAC-80-1, NSAC-1 Revised, EPRI-NSAC—80-1, March 1980. https://inis.iaea.org/collection/NCLCollectionStore/_Public/13/677/13677904.pdf

[20] Report by Risk Assessment Corporation for Centers for Disease Control and Prevention, Department of Health and Human Services, *Final Report Identification and Prioritization of Radionuclide Releases from the Idaho National Engineering and Environmental Laboratory*, RAC Report No. 3, CDC Task Order S-2000-Final, October 2002, pages 117, 118. https://www.cdc.gov/nceh/radiation/ineel/TO5FinalReport.pdf

Table 1. Core Inventory Release Fractions to Primary Coolant and Auxiliary Building for Various Classes, Three Mile Island Unit 2 accident report.

Class	TMI Release Fraction Estimate (Values more typical but not necessarily conservative for TMI or SL-1)	SL-1 Release Fractions derived by Risk Assessment Corporation, based on the AEC's stated offsite releases
Noble Gases (Helium, Neon, Argon, Krypton, Xenon, Radon)	0.55	
Halogens (Fluorine, Chlorine, Bromine, Iodine, and Astatine)	0.1	0.0044, Iodine-131, derived release fraction
Mo, Y (Molybdenum, Yttrium)	0.01	
Cs, Rb (Cesium, Rubidium)	0.1	0.00017, Cesium-137, derived release fraction
Solubles *	0.01	0.000036, Strontium-90, derived release fraction
Insolubles **	0.001	

Table notes: The TMI-2 report does not specify which radionuclides are solubles or insolubles. Cladding and actinides such as uranium and plutonium may be considered insolubles.

Despite what Risk Assessment Corporation (RAC) writes about prevailing meteorological conditions at the time of the SL-1 accident being characteristic of the typical conditions at the time of year, the conditions were not typical. During the accident, the prevailing winds were from the north to northeast for 100 hours with an extremely strong inversion. Typical conditions are a prevailing wind in the opposite direction during the daytime, with wind reversals at night typical. The SL-1 radionuclide plume blew south toward American Falls and Rupert, Idaho.

The SL-1 reactor fission product inventory consisted of radionuclides produced during the excursion and also radionuclides the had built up in the fuel during previous reactor operations. The operating history of the reactor consisted of 11,000 hours for a total of 932 MW-days. The reactor accident resulted in a total energy release of 133 MW-seconds. Roughly 30 percent of the core's fuel inventory was missing from the vessel, when examined after the accident. [21] [22] [23]

[21] Department of Energy, Idaho National Engineering Laboratory Historical Dose Evaluation, DOE/ID-12119, August 1991. See https://inldigitallibrary.inl.gov

[22] Atomic Energy Commission, "Final Report of the SL-1 Recovery Operation," IDO-19311, June 27, 1962. See p. III-77 regarding fuel damage. https://inldigitallibrary.inl.gov/PRR/163644.pdf

Risk Assessment Corporation used the computer code RSAC to calculated a fission product inventory based on operation of the reactor at a power level of 2.03 MW (mega-watts) for 458 days, followed by a shutdown period of 11 days and the excursion power level of 88,700 MW for a period of 0.015 seconds. The Center for Disease Control did not call out what were obvious discrepancies and which meant that the SL-1 radiological consequences have been grossly understated.

Sage brush samples were collected and according to the AEC, the "gamma spectra of representative samples indicated that the activity was due to iodine-131. (IDO-12021, p. 131)

It was customary for the AEC to monitor jack rabbit thyroids and the iodine-131 levels before the SL-1 accident, for jack rabbit thyroids were typically 100 picocuries per gram. After the SL-1 accident, the levels were as high as 750,000 picocuries per gram at the SL-1, 180,000 picocuries/gram at nearby Atomic City, located south of the SL-1, and 50,000 picocuries per gram at Tabor, a farming community southeast of SL-1 and west of Blackfoot, and 11,200 picocuries at Springfield. These rabbit thyroid results reveal much higher rabbit thyroid iodine-131 levels than produced by the other large episodic and routine releases from the Idaho National Laboratory during the 1950s and 1960s. [24] [25] [26] [27]

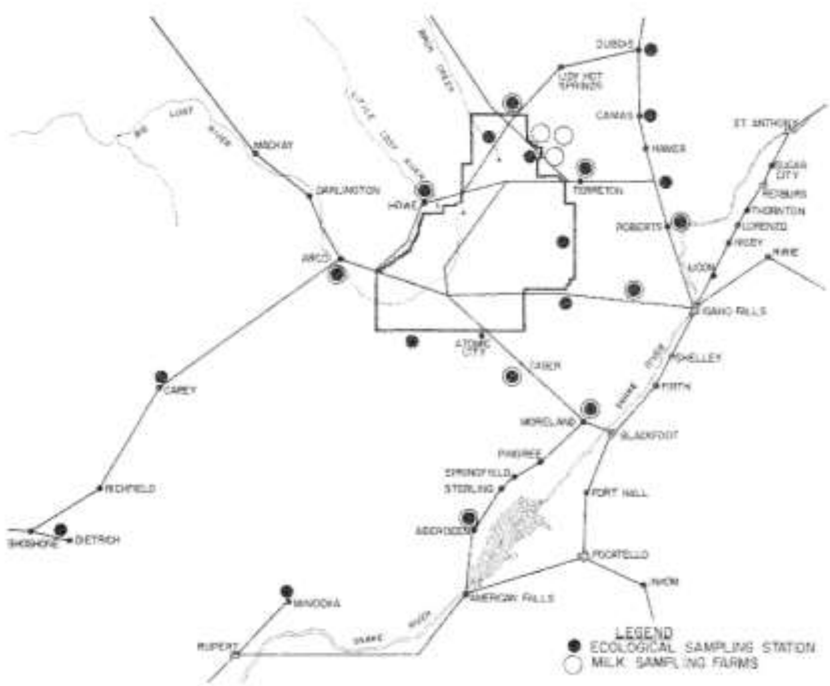

Fig. 51 Perimeter and off-site biological monitoring stations.

[23] Atomic Energy Commission, "Additional Analysis of the SL-1 Excursion Final Report of Progress July through October 1962," IDO-19313, November 21, 1962. See p. 27 Table I-VIII. https://inldigitallibrary.inl.gov/PRR/163644.pdf

[24] Atomic Energy Commission, "1958 Health and Safety Division Annual Report, IDO-12012, See p. 72, 73 for iodine-131 in sage brush and rabbit thyroids. https://inldigitallibrary.inl.gov/PRR/112697.pdf

Figure 51 above and Figure 52 below are from IDO-21021.

U.S. Highway 20, south of and near the SL-1, had hot particles from the SL-1 accident and the AEC estimated the range of individual particle dose rates at 1 inch as 10 milli-rem per hour to 5 rem per hour. On the site roads, farther from the SL-1, the individual particle dose rates at 1 inch were estimated as 10 millirem/hr to 15 rem/hr, according to IDO-12021, the annual report for 1961. Initially during and after the accident, it was assumed that the highways and roadways were not contaminated by the SL-1 accident. Upon further surveys, decontamination efforts of U.S Highway 20 were pursued.

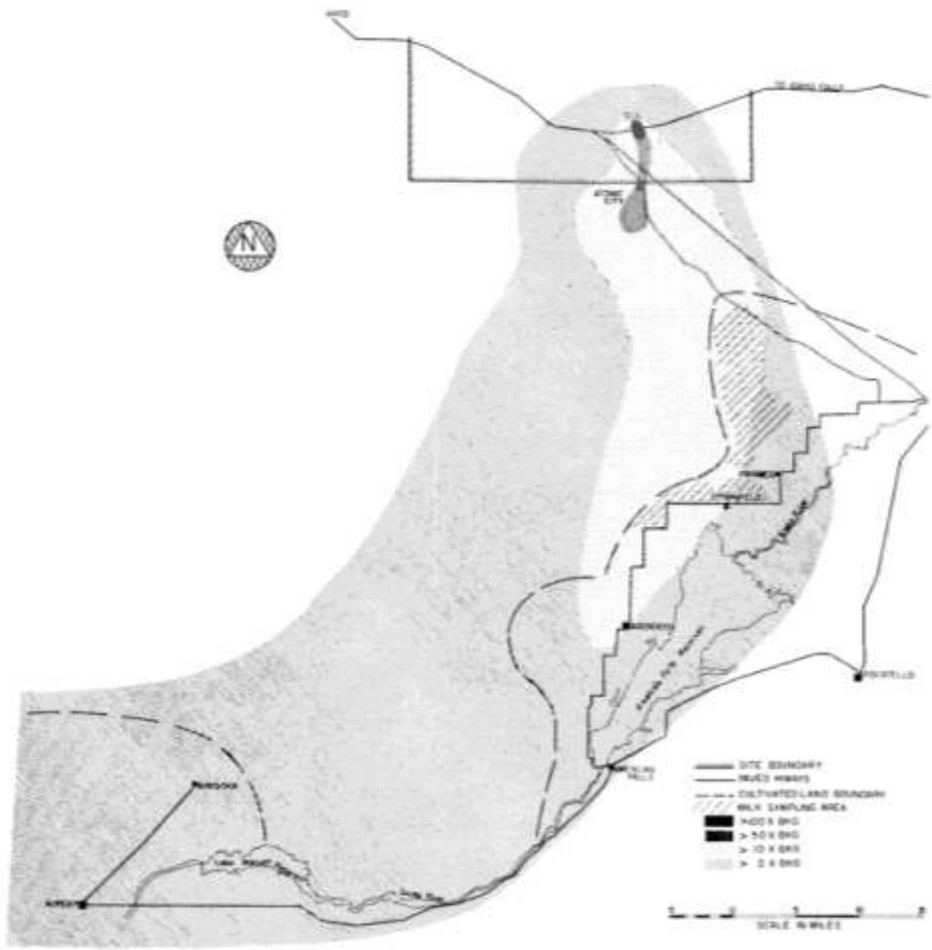

Fig. 52 Iodine-131 deposition on vegetation.

[25] Atomic Energy Commission, "Annual Report of Health and Safety Division, 1959," IDO-12014, See p. 88 for iodine-131 in rabbit thyroids. https://inldigitallibrary.inl.gov/PRR/112700.pdf

[26] Atomic Energy Commission, "Health and Safety Division Annual Report, 1960," IDO-12019, See p. 91 for iodine-131 in rabbit thyroids. https://inldigitallibrary.inl.gov/PRR/90927.pdf

[27] Atomic Energy Commission, "Health and Safety Division Annual Report, 1961," IDO-12021, See p. 128, 133 for iodine-131 in jack rabbit thyroids. https://inldigitallibrary.inl.gov/PRR/163656.pdf

Figure 52, above, depicts the SL-1 radiological plume. The AEC claimed that the radioactive fallout from the SL-1 accident was mainly iodine-131. The AEC's claimed total iodine-131 release from the SL-1 accident would mean that an impossibly low release fraction for the iodine-131 held up the iodine-131 in the fuel. The SL-1 fuel was similar to the Materials Test Reactor fuel, which was not assumed to have low release fractions. The derived low release fractions are predicated on the AEC's stated curie release estimates and the stated curie estimate, along with the AEC's assertion that it was mainly iodine-131 that was released from the SL-1 are simply too good to be true.

A building with offices, adjacent to the SL-1 reactor had been in use for decades after the SL-1 accident, but was deemed too radiologically contaminated to remediate after CERCLA investigations commenced in 1995. I'm not aware of the reasons for the AEC's and later the Department of Energy's flawed radiological monitoring programs ever being revealed. I would suppose that instruments may have been manually calibrated such that, systematically, too much background radiation was subtracted from the monitoring instruments.

At the Idaho National Laboratory, the burial ground for the Stationary Low-Power Reactor No. 1 (SL-1), which includes one trench and two pits 1600 ft east of the SL-1 area, fission and activation products were buried directly in soil below ground level. Radioactive waste from the SL-1 accident was also buried in Pit 1 at the Radioactive Waste Management Complex. The RWMC burial grounds flooded in 1962 and again in 1969 from high levels of precipitation and snow drifts. The CDC fails to point out that later radiological surveys at and near the SL-1 burial ground would also reveal extensive surface or shallow soil contamination that required further remediation under CERCLA cleanup for Waste Area Group WAG 5.

You can read my report about the causes of the SL-1 accident on the Environmental Defense Institute website, *The Truth about the SL-1 Accident – Understanding the Reactor Excursion and Safety Problems at SL-1* at http://environmental-defense-institute.org/publications/SL-1Accident.pdf

Report by Tami Thatcher, former nuclear safety analyst at the Idaho National Laboratory and nuclear safety consultant. She provided safety analysis and probabilistic risk assessment for the Advanced Test Reactor at the INL. The ATR is used to exposure materials to a specified high neutron environment for materials testing. Unlike a commercial nuclear power reactor, at the ATR, core configurations change significantly and often, generally every few weeks. Although she was not a core safety analyst, her perspective has partly been shaped by her association with the reactor operations and engineering organization that monitored core reactivity predictions for normal and off-normal conditions in order to ensure adequate fuel cooling during unplanned reactivity insertions.