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Amory Lovins Explains How Investment in Nuclear Energy Hinders Implementing Solutions to Climate Change

Amory Lovins explains why the high cost and long construction time of new nuclear power plants makes nuclear a horrible choice if you care about climate change. He expects that the cost of new nuclear power isn't likely to be reduced and will continue to rise. New nuclear power plants are estimated to cost more than new gas, coal, and far more than solar or offshore wind.

Renewable costs continue to fall as nuclear build costs continue to rise. **And importantly, new nuclear plants will save much less carbon per dollar.**

And these nuclear cost estimates for construction and operation don't include all the costs of nuclear energy because no one knows what the cost will be to manage, store and dispose of the nuclear waste over the millennia that the waste is toxic. Neither are the cost of nuclear disasters factored in. And neither are the cost of increased cancers and illnesses near nuclear plants from routine operation, less alone unplanned radiological releases from reactor accidents.

Lovins points out that replacing a closed nuclear plant with efficiency or renewables takes only 1 to 3 years. The long construction times for nuclear, as well as their high cost, mean nuclear power isn't a good choice if you care about protecting the climate.

He points out the arguments from the nuclear boosters claiming that climate change will be combatted faster with new nuclear build <u>have no basis in fact</u>.

In the U.S., the nuclear industry's immense lobbying power is aimed at harming its competitors and slowing climate protection while claiming to increase it, all while charging the most money to taxpayers and rate payers.

His full article "Does Nuclear Power Slow Or Speed Climate Change?" is worth a careful read. [1] This comes as the Spanish environment minister Teresa Ribera, whose country will host climate talks in December has said, "We have to do more in less time." [2]

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[1] Amory B. Lovins, *Forbes*, "Does Nuclear Power Slow Or Speed Climate Change?" November 18, 2019, https://www.forbes.com/sites/amorylovins/2019/11/18/does-nuclear-power-slow-or-speed-climate-change/#d4c446f506b4

[2] Aritz Parra and Frank Jordans, AP, *Idaho Falls Post Register*, "We have to do more in less time," December 1, 2019.

Fascinating Study of the Explosions Caused During the Chernobyl Nuclear Disaster

In 2017, a new investigation was published by Swedish researchers of the explosions at the Chernobyl Unit 4 nuclear reactor, more than 30 years after the accident. Sweden suffered heavy radiological fallout from the Chernobyl nuclear disaster. The research makes use of the detection of fresh xenon fission products detected at Cherepovets, 1000 km north of the reactor, soon after the April 1986 accident. [3] The detection capability at Cherepovets was unplanned but occurred by the filling of cylinders at an industrial use gas complex in the days following the accident.

With now available high-resolution weather data and state-of-the-art meteorological dispersion calculations, the fresh xenon ratios observed at Cherepovets was found only to be possible if these fission products were injected to a far higher altitude than the bulk of the fission products released from the core. This is thought to be possible by the nuclear explosions in a small number of fuel channels that formed upward jets of debris, shaped by the vertical, 88 mm diameter fuel channels. The maximum concentration of radionuclides released from the nuclear plasma injected high into the atmosphere was at an altitude of 2.5 to 3 km. However, the radiological debris extended to 8 km in altitude, according to Figure 6 of the study.

The investigators think that **nuclear explosions** happened in perhaps one to three fuel channels with the maximum operational power. They created high temperature streams or jets of plasma reaching high into the atmosphere while the channels were relatively intact.

A subsequent explosion tossed the 500-ton upper biological shield into the air and removed the building structure that had been over the reactor, exposing the core. This last explosion happened **after** the few channel explosions that created high temperature plasma jets of debris that was detected at Cherepovets.

The Chernobyl reactor was a boiling water, graphite moderated RMBK-1000, 1000 MW electric reactor, with 1661 fuel channels. RBMK stands for Reaktor Bolshoy Moshchnosty Kanalny. The vertical fuel channels have an 88 mm diameter and extended through the 23 ft high reactor core. Each fuel channel contained about 115 kg uranium, 2 percent enriched in U-235, and 13.6 mm in diameter. Each vertical fuel channel had a maximum channel power of about 3 MW (thermal). The RBMK reactors were designed to allow opening a channel from the main floor above the reactor to extract the fuel in a channel while the reactor was operating. The low-enriched fuel that could be extracted without shutting down the reactor was originally designed for plutonium production.

The 1986 Chernobyl nuclear accident involved the rapid reactivity insertion and uncontrolled nuclear power surge of at least 100 times the design power of 3,200 MW (thermal) for a few seconds. The accident occurred during a test of turbine-generator coast-down, and this test had

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[3] Lars-Erik De Geer et al., *Nuclear Technology*, "A Nuclear Jet at Chernobyl Around 21:23:45 UTC on April 25, 1986," Received May 18, 2017. https://www.tandfonline.com/doi/full/10.1080/00295450.2017.1384269

been performed before at a similar reactor. According to Zhores Medvedev in his book *The Legacy of Chernobyl*, the RBMK reactors had been licensed despite failure to meet stated requirements during a station-wide loss of electrical power. It had already been *assumed* that the turbine generator coastdown electricity would adequately bridge the roughly 50 seconds needed to start a diesel generator. But previous testing had shown that the 50 second gap in electrical power was not provided by turbine generator coastdown.

The test was not deemed to involve nuclear safety risks and because the test was delayed that day, personnel who were not expecting to run the test found themselves in the position of trying to comprehend hand-written procedure changes for the test. When reactor power fell excessively before the test, the nuclear operator was pressured by a supervisor to raise power, which required the withdrawal of an excessive number of control rods to overcome xenon poisoning of the core. Even with so many control rods withdrawn, the operators were only able to attain 200 MWthermal (or MWt). The test was supposed to be run at 700 to 1000 MWt. But the lower power level with so many control rods withdrawn created reactivity control vulnerabilities that the operating crew didn't understand. The requirements for keeping a minimum number of rods in the core had been violated before, without adverse consequences. With emergency core cooling disabled, the throttle valve to the turbine that energized the coolant pumps was closed. Overheating and steam voiding would have the effect of reducing reactor power in a water-moderated reactor with a negative void coefficient. **But the graphite moderated RBMK had a large positive void coefficient (from 2 to 5 Beta) and so boiling and steam formation in the core increased reactor power.** With the large positive void coefficient and positive temperature coefficient, power started increasing and the operators likely actuated the control rods insertion to shut down the reactor upon noting power increasing. But the effect of inserting the graphite-tipped control rods added an additional 0.5 Beta to an already high level of positive reactivity.

The control rods only partially inserted into the core. Steam formation in the fuel channels had grown to the extent that the 350 kg shield blocks over the vertical fuel channels were dancing up and down.

Soon after the partial insertion of the control rods, several explosions were witnessed during the Chernobyl accident. The final explosion resulted in tossing the 500-ton upper biological shield into the air and removing the building over the reactor. [4] [5] There have been many theories about the explosions witnessed during the April 26, 1986 Chernobyl accident. The first explosion was widely believed to be a steam explosion and the explosion a few seconds later has been described as a hydrogen explosion resulting from the melted zirconium in the fuel cladding and channel tubing.

The Swedish investigation finds evidence that the first explosion (which was actually two explosions, one lower and one higher in the core) consisted of thermal neutron mediated nuclear explosions in one or rather a few fuel channels, which caused a jet of plasma that reached an

[4] Grigori Medvedev, *The Truth About Chernobyl*, 1989, Basic Books, ISBN 2-226-04031-5.
[5] Zhores A. Medvedev, *The Legacy of Chernobyl*, 1990, W. W. Norton and Company, ISBN 0-393-30814-6.

altitude of exceeding 3 km. They conclude that the second explosion would then have been a steam explosion.

The timing and energy of the explosions is corroborated by seismic measurements recorded some 100 km west of the reactor.

What was the Radiological Release from the Chernobyl Nuclear Disaster?

Now over thirty years after the 1986 Chernobyl Unit 4 reactor disaster, there is still no consensus on how many curies were released during the accident.

In order to understand the harm posed by a radiological release, it is necessary not only to know the total curies released, it is necessary to know which radionuclides were released and in what curie amounts. Each radionuclide has a unique half-life and unique impact on the body when inhaled or ingested.

There was motivation for the Soviets to understate the radiological release. They also focused on **external radiation dose** when the internal dose from inhalation and ingestion, such as for iodine-131 that contaminates milk, was far more important.

The core inventory of fuel, fission products and transuranic radionuclides at the beginning of the accident can be known by knowing the type of nuclear fuel and how many days the reactor had operated. The nuclear excursion would have added to the core inventory, but not significantly in relation to the relatively large buildup of fission products from operation of the reactor for 22,300 MWd/metric ton.

The Soviets provided data for a 1986 INSAG report which listed various radionuclides that were present in the reactor when the accident began. [6] I have provided data from that report in Table 1 below. The 1986 INSAG report of core inventories and estimated release fractions from the Chernobyl accident is the basis for the often cited “80 million curies were released from the Chernobyl accident.”

The gaseous radionuclides xenon and krypton are assumed to be entirely released from the fuel and this is reasonable. But the assumption that only 20 percent of the iodine was released appears to be an underestimate. The highly volatile iodine-131 can be released from fuel when the fuel has exceeded fairly low temperatures even if the fuel hasn’t melted. Very high temperatures occurred throughout the core.

[6] Primary source is INSAG-1 Report (*Summary report on the post-accident review meeting on the Chernobyl accident*, Vienna, International Atomic Energy Agency Safety Series, 1986), p. 34, as provided in Zhores A. Medvedev, *The Legacy of Chernobyl*, 1990, W. W. Norton and Company, ISBN 0-393-30814-6.

Table 1. The 1986 INSAG report of core inventories and estimated releases from the Chernobyl accident in becquerels and curies.

Element (Note 1)	**Half-life, day (years) (Note 2)**	**INSAG Report Inventory, Bq (Curies)**	**INSAG Report, Estimate of Percent released, according to the Soviets in 1986 (Note 3)**	**My suggested estimate of percent released (Note 4)**
Krypton-85	3,930 days (10.76 years)	3.3E16 Bq (0.89 E6 Ci)	~100	~100
Xenon-133	5.27 days	1.7E18 Bq (46 E6 Ci)	~100	~100
Iodine-131	8.05 days	1.3E18 (35 E6 Ci)	20	~100, given the high temperature of the fuel
Tellurium-132	3.25 days	3.2E17 Bq (8.6 E6 Ci)	15	~50
Cesium-134	750 days (2.046 years)	1.9E17 Bq (5.1 E6 Ci)	10	~50
Cesium-137	1.1E4 days (30.0 years)	2.9E17 Bq (7.8 E6 Ci)	13	~50
Molybdenum-99	2.8 days	4.8E18 Bq (130 E6 Ci)	2.3	~50
Zirconium-95	65.5 days	4.4E18 Bq (119 E6 Ci)	3.2	~50
Ruthenium-103	39.5 days	4.1E18 Bq (111 E6 Ci)	2.9	~50
Ruthenium-106	368 days	2.0E18 Bq (54 E6 Ci)	2.9	~50
Barium-140	12.8 days	2.9E18 Bq (78 E6 Ci)	5.6	~50
Cerium-141	32.5 days	4.4E18 Bq (119 E6 Ci)	2.3	~50
Cerium-144	284 days	3.2E18 Bq (86 E6 Ci)	2.8	~50
Strontium-89	53 days	2.0E18 Bq (54 E6 Ci)	4.0	~50

Element (Note 1)	Half-life, day (years) (Note 2)	INSAG Report Inventory, Bq (Curies)	INSAG Report, Estimate of Percent released, according to the Soviets in 1986 (Note 3)	My suggested estimate of percent released (Note 4)
Strontium-90	1.02E4 days (27.7 years)	2.0E17 Bq (5.4 E6 Ci)	4.0	~50
Neptunium-239	2.35 days	1.4E17 Bq (3.4 E6 Ci)	3.0	~50
Plutonium-238	3.15E4 days (86.4 years)	1.0E15 Bq (0.027 E6 Ci)	3.0	~50
Plutonium-239	8.9E6 days (24,390 years)	8.5E14 Bq (0.023 E6 Ci)	3.0	~50
Plutonium-240	2.4E6 days (6,580 years)	1.2E15 Bq (0.032 E6 Ci	3.0	~50
Plutonium-241	4,800 days (13.2 years)	1.7E17 Bq (4.6 E6 Ci)	3.0	~50
Curium-242	164 days	2.6E16 Bq (0.7 E6 Ci)	3.0	~50
	Total activity	3.22E19 Bq (870 E6 Ci) ***Partial Inventory:*** ***870 million Ci***	2.98E18 Bq (80 E6 Ci) ***Soviet estimated release:*** ***80 million Ci***	1.76E19 Bq (470 E6 Ci) ***Partial inventory and higher release fractions:*** ***476 million curies***
	Note: The total inventory was probably closer to 9 billion curies, not 870 million curies. Therefore, the total release was probably above 3 billion curies.			

Table notes: Primary source is INSAG-1 Report (*Summary report on the post-accident review meeting on the Chernobyl accident*, Vienna, International Atomic Energy Agency Safety Series, 1986), p. 34, as provided in Zhores A. Medvedev, *The Legacy of Chernobyl*, 1990, W. W. Norton and Company, ISBN 0-393-30814-6. These figures were decay corrected to May 6, 1986 and calculated as by Soviet experts for the inventory and percentage released to the Soviet Union. Note 1. Many radionuclides are left out: nonvolatile rare earths and others; uranium and other actinides would add substantially to the curie level released when compared to two-thirds of the expected release from a 1000 MWe reactor. Note 2. For the half-life of neptunium, plutonium and curium, it must be remembered that the decay proceeds through many decay progeny that are also radioactive. Note 3. The percent release in this column is the INSAG-1 Report figure estimated by the Soviets and the release fractions appear grossly low.

The Soviets INSAG data and the basis for saying Chernobyl released 80 million curies assumes that the total inventory before the accident was less than one billion cures. In fact, at 22,300 MW-days per metric ton of burnup, the Chernobyl Unit 4 should have had on the order of 9 billion curies in initial inventory. [7] A comparison of the INSAG estimated initial inventory of cesium-137, strontium-90, and plutonium-239 to the expected inventory for a 1000 MWe plant, assuming two-thirds of the burnup used in Nero's Table 3-1 does compare rather well. This means that if a reasonable release fraction is assumed, then the initial total inventory provided in the INSAG data can provide a reasonable release estimate for the specific radionuclides listed in the INSAG table.

But the often-cited radiological release figure of 80 million curies isn't just low because of the low stated inventory, it is also low because most of the low fractional releases aren't defendable. The Chernobyl release was probably on the order of 100 percent of the xenon, krypton and iodine-131 and at probably at least 50 percent of the rest of the inventory.

The Chernobyl release was likely on the order of at least 3 to 6 billion curies. In 1996, Argonne National Laboratory was estimating 30 percent of the core's total inventory of 9 billion curies was released (or about 3 billion curies), and scientists at Lawrence Livermore National Laboratory were estimating that about 80 percent of the core, or 7 billion curies, had been released. [8] [9]

In a 1987 report on the Chernobyl accident, NUREG-1250, [10] the NRC only repeats what the Soviet experts have presented as the radiological release. The NRC quotes the Soviets as saying that an estimated total of about 50 million curies of noble gases (approximately 100 percent of the core inventory) and a total of about 50 million curies of other radionuclides (approximately 3 to 4 percent of the core inventory) were released to the environment over a period of 10 days (from April 26 to May 6). This statement adds 20 million curies to the 80 million curies estimated to be released in the INSAG table. Then the NRC report repeats the same INSAG table of total inventory and release fractions from the Soviets that I have provided above.

The adjustments in the INSAG data for decay time to May 6, 1986 lower the curie level for short-lived radionuclides probably by a few million curies, but the omission of rare earth and other fission products and leaving out the uranium isotopes and various transuranics lowered the release by several billion curies. What's a few billion curies among friends? Why didn't the

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[7] Anthony Nero, Jr. A Guidebook to Nuclear Reactors, University of California Press, 1979. See Table 3.1, the radionuclide inventory for a 1000 MWe uranium-fueled light water reactor with 33,000 MWd/metric ton operation would have an inventory of about 15,500,000 curies or 15.5 billion curies.

[8] John M. LaForge, Ratical.org, Chernobyl at Ten: Half-lives and Half Truths, (cerca 1996). https://ratical.org/radiation/Chernobyl/Chernobyl@10p2.html#fn8

[9] World Information Service on Energy, Nuclear Monitor Issue #641, How Much Radiation Was Released by Chernobyl? January 27, 2006. https://www.wiseinternational.org/nuclear-monitor/641/how-much-radiation-was-released-chernobyl

[10] U.S. Nuclear Regulatory Commission, Washington, DC, Joint Agency Report, *Report on the Accident at the Chernobyl Nuclear Power Station*, NUREG-1250, January 1987. https://www.nrc.gov/docs/ML0716/ML071690245.pdf

multi-agency report published by the U.S. NRC, NUREG-1250, point out these differences? Maybe because the nuclear industry likes to pretend that alpha emitters don't matter and that uranium is natural even though these radionuclides and their decay progeny are proven to harm health.

Can a Nuclear Reactor Explode Like a Nuclear Bomb?

I have heard many times that a nuclear reactor cannot explode like a nuclear weapon. In an Argonne National Laboratory webpage, they explain that it is a myth that a nuclear reactor can explode like a bomb. They state: "It is impossible for a reactor to explode like a nuclear weapon; these weapons contain very special materials in very particular configurations, neither of which are present in a nuclear reactor." [11]

I agree that in terms of capability to demolish structures over a wide area, nuclear weapons are designed to provide far more explosive force than an explosion or even multiple explosions at a nuclear reactor.

But despite the reduced capability to demolish structures over a wide area and instantly kill thousands of people, the release of fission products from a single 1000 MW nuclear reactor can force the evacuation of several hundred thousand people, ruin millions of dollars worth of agricultural products, and ruin the economy of a nation as happened with the Chernobyl nuclear accident. These consequences are horrible enough even without considering the health harm from the billions of curies released by Chernobyl that spread across many countries.

But as devastating as the Chernobyl and Fukushima nuclear accidents were, the nuclear industry doesn't want the public to understand the costs and consequences of these accidents.

And something never discussed is the fact that each of these accidents, that in fact Chernobyl and Fukushima, could have been far worse. Releasing the fission products in spent fuel pools, accumulated from years of operating the nuclear reactors at a plant, would have been far worse.

While a nuclear weapon is designed to destroy buildings, structures and human life of a chosen enemy, an accident at a nuclear reactor causes harm to not only the people near the reactor but as with the Chernobyl accident, adversely impacts the lives of people living in other countries. With Fukushima, we had nuclear fallout in the U.S. and we all suffer from the harm to ocean life.

The fact is that nuclear weapons are usually made from plutonium-239, and usually include uranium-238 or uranium-235 as well. The mining, enrichment, manufacturing, material storage and disposal for nuclear materials, whether for weapons or for nuclear reactors are highly environmentally polluting. And no matter how loud the nuclear industry shouts that disposal of nuclear waste just isn't a problem — it's a problem they have not solved in 70 years and the fact

[11] Argonne National Laboratory, "10 myths about nuclear energy," September 9, 2013, originally an American Nuclear Society article. https://www.anl.gov/article/10-myths-about-nuclear-energy The deceptions in this "feature story" are typical of the nuclear industry.

is that there are not known methods of containing the radionuclides over the millennia that they will be toxic.

In fact, the only thing the nuclear promotors are good at is public deception.

Nuclear excursions are rapid increases in neutron population growth, and hence, reactor power, to levels that can far exceed the design value for the reactor. While there are higher temperatures and fission yields possible in nuclear weapons than in a nuclear reactor accident, explosive energy generation from the rapid increase of fission is a ***nuclear explosion*** rather some other kind of explosion such as a steam explosion or metal-water reaction that releases hydrogen and may explode.

The small diameter channels in the RBMK provided the geometry to produce a jet of plasma from the nuclear explosion. But despite less explosive yield from nuclear reactor accidents compared to nuclear weapons, nuclear excursions that melt fuel or vaporize fuel release fission products to the environment in quantities that, depending on fuel burnup prior to the excursion, can release far more fission products into the environment than a nuclear weapon.

INL Wrong When They Said That a Wife Visiting a Dying Chernobyl Radiation Victim Could Not Have Been Harmed

At the Idaho National Laboratory's Fact-Light public meetings [12] to downplay the consequences of the 1986 Chernobyl nuclear reactor accident, the INL said that the hospital patient could be infected by a visitor but no way could a woman and her unborn child have been harmed by a Chernobyl fire fighter dying in a radiation clinic.

It is documented that some Chernobyl radiation victims required lead-lined casks and that some funeral workers sustained radiation burns.

If it doesn't seem possible, read the autopsy report for the three crewmen who died at the SL-1 nuclear reactor accident in 1961. [13] The general radiation level of the man who lived about two hours was generally 10 rem/hr, with some parts of their bodies reading 200 rem/hr. One victim's head was over 500 rem/hr. Although the men died from the blunt force trauma from the explosion, they had received fatal gamma radiation doses and also fatal neutron doses from the accident.

There were various attempts to decontaminate the bodies: various detergents, ethylenediamine tetraacetate (EDTA, and citric acid were tried, along with vigorous scrubbing with long-handled brushes and flushing with water. Even on unbroken skin, the washing and scrubbing was only effective to a limited extent, according to the SL-1 autopsy report.

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[12] Idaho National Laboratory, Chernobyl Talks – Just the Facts, four public talks held in October 2019.

[13] C. C. Lushbaugh et al., Los Alamos Scientific Laboratory of the University of California, *The SL-1 Reactor Accident Autopsy Procedures and Results*, LAMS-2550, May 1961. https://inldigitallibrary.inl.gov/PRR/163773.pdf

The doctors performing the autopsy used lead shielding, cranes, and various precautions to limit their radiation dose, but still received over 3 rem.

Even after undressing, soaking, and scrubbing, two of the men required 1/8-in. thick lead lined caskets to limit the radiation field to 450 millirem/hr and one of the men required a ¾-in. thick lead lined casket, even after removing his head and limbs, to limit the radiation field to 650 millirem/hr.

Since it is known that as little as 500 millirem dose to an unborn child can double the child's risk of cancer or leukemia, an hour spent near a radiation victim having a 5 rem/hr radiation field would not be benign to an unborn child. And for various reasons, including the contamination spread of radionuclides, radiation victims were turned away from hospitals and radiation clinics near Chernobyl. The radiation clinics, of course, became contaminated and required extensive radiological decontamination.

Radiation victims exposed to fine airborne particulate fission products can absorb the radionuclides into the skin. And radiation workers who've ever sweated on the job know that radionuclides can wick through anti-contamination clothing resulting in skin contamination.

The propaganda the Idaho National Laboratory put on in their public meetings in a number of instances didn't just downplay the Chernobyl, at times the INL gave completely false information. For more about these talks, see the Environmental Defense Institute November 2019 newsletter.

Radiation Worker Reproductive Health Issues Indicated by SL-1 Victim Sperm Damage

An important detail is included in the SL-1 autopsy report that reveals excessive worker radiation exposure prior to the January 3, 1961 SL-1 accident at what is now called the Idaho National Laboratory. [14]

For one of the accident victims, "Only sections of the testis were made. The other organs were extensively damaged by blast, and dissection beyond that required for identification and considered unwarranted because of the radiation hazard."

The section of testis showed "preserved mitotic figures, spireme in the spermatocytes, and, in general, normal cytology of all cells except the spermatogonia, which were almost all densely pyknotic. The cells of Leydig were all autolyzed and not recognizable."

The spermatogonia become spermatocytes. The observation that the victim's spermatogonia was "densely pyknotic" likely means that gamma radiation exposure within weeks of the

[14] C. C. Lushbaugh et al., Los Alamos Scientific Laboratory of the University of California, *The SL-1 Reactor Accident Autopsy Procedures and Results*, LAMS-2550, May 1961. https://inldigitallibrary.inl.gov/PRR/163773.pdf

accident was causing cell degeneration. Leydig cells are radiosensitive [15] but the damage to the Leydig cells could also been because of death. The extent that the high radiation fields were preserving the corpses was noted in the autopsy report, but whether the Leydig cells were damaged prior to the accident isn't stated in the report.

When I worked at the Idaho National Laboratory, I knew of quite a few men who were concerned about the effects of radiation exposure on their reproductive health. These men knew that they were on their own to try to understand the potential for reproductive harm and try to protect themselves. And not only that — it was obvious that management at the INL frowned on men even asking questions about the potential for harm to reproductive health — their ability to conceive children and potential genetic harm to their future children.

The Department of Energy's radiation protection program shied away from discussing possible issues or possible underestimation of gonad radiation doses, especially important for men who worked with the high radiation fields of spent fuel beneath them while their radiation badges were required to be worn near their neck on the lapel or chest pocket. In the U.S., the official radiation protection training sticks to the lie that no genetic effects have been observed in humans. And while studies of the effect of radiation on men's fertility have been conducted, radiation worker protection training isn't likely to discuss the issue.

The radiation worker protections now, and as they were in 1961, were not necessarily protecting the men's reproductive health during routine work at nuclear reactor and spent fuel facilities nor were they warning men of the risks. Studies of reproductive health are not conducted for radiation workers at nuclear facilities.

The only reproductive health policy for radiation workers is limited to female radiation workers being required to report when they are pregnant. The allowed radiation exposure is then reduced from 5 rem per year to 0.5 rem while the woman is pregnant. Even then, radiation protection standards allow excessively high radiation exposure to the unborn child.

Men's reproductive health may be adversely affected not only by external radiation exposure, but also by inhalation or ingestion of radionuclides such as plutonium which may be disproportionately stored in the gonads. In addition, failure to accurately monitor neutron dose can be an issue where fissile nuclear materials, such as uranium-235 or plutonium-239 unirradiated fuel, are handled.

All of the victim's wives eventually separately won compensation because of the deaths caused by the SL-1 accident. Combustion Engineering and Argonne National Laboratory's University of Chicago paid one million dollars for the death of Richard Legg, the man who was lifting control rod No. 9. [16] Acceptance of the unsafe design and inadequate safety oversight by

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[15] Michael A. Izard, Radiotherapy and Oncology, "Leydig cell function and radiation: a review of the literature," May 22, 1994. https://www.thegreenjournal.com/article/0167-8140(94)01501-S/fulltext

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

the Idaho Operations Office was the responsibility of the Atomic Energy Commission, now the Department of Energy.

Interesting Similarities Between the SL-1 and the Chernobyl Nuclear Accidents

As I found myself reviewing both of these nuclear excursion accidents, trying to understand the language used to describe the reactivity insertions, I found that there are some interesting similarities between the 1961 SL-1 accident and the 1986 Chernobyl accident in the Ukraine.

For those of you who have heard of the January 3, 1961 accident at the Stationary Low-Power Reactor (SL-1) in Idaho, the small 3 MW (thermal) reactor that exploded during shutdown when a control rod was manually lifted to reassemble the control rod drives, you are probably wondering how the SL-1 accident could possibly be comparable to the 1986 Chernobyl accident at a 3200 MW (thermal) RBMK nuclear reactor. Of course, there is no doubt that the human catastrophe caused by the Chernobyl nuclear disaster and its release of billions of curies of radionuclides far exceeds the consequences of the SL-1 accident.

But in reviewing these two accidents, there are some similarities in the causes and the responses to the accidents. I've taken the design information for Chernobyl from two reports [17] [18] and the design information for the SL-1 from several 1961 Idaho Operations Office Atomic Energy Commission reports. [19] [20] [21]

First, here's some of the ways that these two reactors were opposites:

- SL-1 used 93 percent enriched uranium and Chernobyl used 2 percent enriched uranium
- SL-1 had 40 fuel elements and Chernobyl had 1661 fuel channels
- SL-1 had 14 kg uranium (mostly U-235) and Chernobyl had roughly 200,000 kg uranium (mostly U-238)
- SL-1 used water as a moderator (to slow neutrons) and Chernobyl used graphite
- SL-1's core was 25.8 inches high and 31.5 inches in diameter and Chernobyl's core was 23 ft high and 39 ft in diameter.

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[17] Makhail V. Malko, Joint Institute of Power and Nuclear Research, National Academy of Sciences of Belarus, *The Chernobyl Reactor: Design Features and Reasons for Accident*, https://www.rri.kyoto-u.ac.jp/NSRG/reports/kr79/kr79pdf/Malko1.pdf

[18] F. Motte, The Chernobyl-4 Reactor and the Possible Causes of the Accident, INIS-f—10945, Presented at the Seminar THE CHERNOBYL ACCIDENT AND ITS IMPACT organized by SCK/CEN at Mol on October 7, 1986. https://inis.iaea.org/collection/NCLCollectionStore/_Public/18/082/18082425.pdf?r=1&r=1

[19] Atomic Energy Commission report, Idaho Field Office IDO-19300, "SL-1 Reactor Accident on January 3, 1961: Interim Report." Combustion Engineering, May 15, 1961. https://inldigitallibrary.inl.gov/PRR/114443.pdf

[20] 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. https://inldigitallibrary.inl.gov/PRR/163645.pdf

[21] Atomic Energy Commission report, Idaho Field Office, "Additional Analysis of the SL-1 Excursion: Final Report of Progress July through October 1962," IDO-19313, November 21, 1962. https://inldigitallibrary.inl.gov/PRR/163644.pdf

- SL-1 fuel was aluminum-nickel clad and Chernobyl fuel was Zirconium-Niobium clad
- SL-1 had 5 control rods and Chernobyl had 179.
- SL-1 could insert control rods to shutdown the reactor, in less than 2 seconds and it took Chernobyl about 20 seconds to insert control rods the 23 ft height of the core
- SL-1 had a negative steam void coefficient and Chernobyl had a positive void coefficient, meaning that when water turned to steam in the Chernobyl reactor, it caused more neutrons to fission and power to increase.

Both reactors were boiling water reactors cooled by light water but the Chernobyl Unit 4 reactor, a Soviet RMBK reactor was graphite moderated.

Now here are some of the interesting similarities about the accidents:

- Both reactor accidents were "nuclear excursions" caused by the rapid insertion of reactivity, which causes the rapid growth of the number of fissions in the core
- The government owner and regulator for each reactor would place the blame on the reactor accidents on the operating personnel, rather than management or designers
- The causes of the accidents were a mystery, even to the experts
- The type of explosion(s) and forces involved were a mystery as investigations were conducted. (For Chernobyl accident, the determining the nature of the explosions continues to be a puzzle.)
- Managers closely associated with each facility could not believe that a reactor accident had taken place. For SL-1, one manager insisted that a chemical explosive must have been placed in the reactor and this was thoroughly disproven.
- The magnitude of the radiological release and the radionuclides released would be deliberately misrepresented to understate the amount of the radiological release.
- Neither reactor facility had adequate radiation monitoring equipment for response to the accident
- Fire fighters would respond to the event without knowledge of the radiological hazard
- Environmental monitoring of the plume and fallout would show unpredicted patterns.
- Citizens exposed to the radiological fallout along highways, at their homes, and while consuming food and water — were unaware of the invisible radioactive contamination they were exposed to, inhaling and ingesting. And the environmental monitoring controlled by the government was designed to not inform citizens of the exposures and radiological contamination.

Here are some additional similarities pertaining to conditions prior to the accidents:

- Neither reactor had a containment
- The safety analysis for each facility was inadequate, it would later be determined
- The procedures for each facility did not explain the safety importance of specific procedural steps
- The focus was on testing and operational objects far more than on safety
- Indications from the control room instrumentation did not help prevent the accident

- The failure to manage and monitor non-symmetrical or uneven power distributions in the core worsened the accident
- There was a failure to closely track and manage changing core rod reactivity worth in all operating regimes
- There was a lack of proper training and procedural as well as design controls to limit reactivity insertions during all phases of operation

Now, a comparison of the nuclear excursion for each reactor accident is provided in Table 2.

Table 2. Comparison of SL-1 and Chernobyl nuclear excursions.

Parameter	SL-1 Accident	Chernobyl Accident
Rated Maximum Power	3 MW (thermal)	3200 MW (thermal) Each fuel channel 3 MWt maximum
Initial power before the accident	0 MW	200 MW t
Peak power during the accident	19,000 MW t	320,000 MWt
Total energy of the reactivity excursion	130 MW-sec	~3000 MW-sec
Void coefficient	Negative 1.3 to 2 percent deltaK/K or nearly negative 3 Beta	Positive 2 to 4 Beta, up to 5 Beta (Note 1)
Reactivity insertion	2.4 % delta K/K	0.99 % delta K/K
Reactivity insertion in units of dollars	3.69 $	1.5 $
Neutron Period, the time it takes to double the number of fissions	~ 4 milliseconds	Reactivity ramp for about 2 seconds
Peak plate energy	500 cal/gram (IDO-19311, page IV-21)	Above 300 cal/gram (Motte, p. 67)
Steam explosion	Caused 9 ft vessel jump	Thought to have caused great destruction
Metal-Water Reaction	Aluminum-water reaction contributed 24 MW-sec (IDO-19311, page IV-22)	Zirconium-water reaction, hydrogen explosion unknown
Nuclear plasma jet	Vaporized fuel just blew in the wind	Nuclear jets from 3 MW channels to up to 8 km above the reactor

Table notes: Note 1. The void coefficient for Chernobyl was positive and increasingly positive with a high number of rods withdrawn. For a discussion of the various reactivity coefficients and how they vary depending on moderator temperature, presence of plutonium-239 in the fuel, and other factors can be found in Risley M. Hyland, *Europhysics News*, "Reactivity Coefficients in Nuclear Reactors," November/December 1987, Volume 18, Number 11/12. https://www.europhysicsnews.org/articles/epn/pdf/1987/11/epn19871811p133.pdf

The table above shows that the small SL-1 reactor had a whopper of a reactivity insertion: 3.69 reactivity dollars. It only takes 1 dollar of reactivity to bring a reactor to "prompt critical."

About half of the fuel from the center part of the SL-1 core was missing — the fuel had vaporized. Fuel plate vaporization was predicted to occur at 2060 C, while melting would occur at 640 C (see IDO-19311, page IV-13). The reactivity insertion reactor period was estimated by knowing that only part of the fuel had vaporized. Had the reactor period been 3 millisecond, more of the fuel would have vaporized. Had the reactor period been 5 millisecond, less fuel damage would have occurred (see IDO-19311, Page IV-12). Aluminum-water reaction in the SL-1 excursion added energy to the accident, about one-fifth of the energy released by the nuclear energy release (IDO-19311, page IV-22).

The AEC would claim that only iodine-131 was released from the SL-1 accident. But a look at the list of fission products for Chernobyl in Table 1 above shows the gamut of fission products that would have been released by vaporizing part of the fuel in addition to the fuel (even though the list in Table 1 is incomplete). The AEC underestimated the iodine-131 release and denied that other fission products were released from the immediate vicinity of the SL-1. The high-enriched uranium-235 does create more plutonium-238 and less plutonium-239 and there are other differences in the proportion of fission products created. The estimated releases from the SL-1 accident are provided in Table 3. The AEC grossly understated the SL-1 radiological release and the Department of Energy continues the deception which would have otherwise dominated all historical INL radiological releases.

Table 3. SL-1 radiological release estimates.

Element	**Inventory (Ci)**	**AEC Release Fraction, percent (Note 1)**	**INEL HDE Release Estimate (Ci) (Note 2)**	**More Probable Release Fraction**	**More Probable Release (Ci)**
Iodine-131	18,182 Ci	0.44 percent	80 Ci	30 to 100 percent	5455 to 18,182 Ci
Cesium-137	2,941 Ci	0.017 percent	0.5 Ci	30 percent	882 Ci
Strontium-90	2,778 Ci	0.0036 percent	0.1 Ci	30 percent	833 Ci

Table Notes 1 and 2. See *Idaho National Engineering Laboratory Historical Dose Evaluation*, DOE-ID-12119, August 1991. US Department of Energy Idaho Operations Office, Volumes 1 and 2 (and Table A-41 with SL-1 release estimates) at https://www.iaea.org/inis/inis-collection/index.html or see https://inldigitallibrary.inl.gov

The reactivity insertion that caused the Chernobyl accident was less than the SL-1's but with more destructive results to the building. The ports of the SL-1 reactor top were open and the building ceiling vents were large. The tall vertical channels of the Chernobyl reactor provided the shape and structure to keep the fissioning fuel together after reaching very high temperatures, whereas the SL-1 reactor had allowed the vaporized fuel to disperse more readily within the vessel and more easily escape the vessel. The Chernobyl radiological release was far larger than the SL-1's because of the size of the RBMK 1000 MWe reactor and the large inventory of fission products that had built up during many months of reactor operation. The buildup of fission products (and transuranics) over time, the burnup, can outweigh those released during the reactor excursion because of the short duration of the extreme high-power levels.

Understanding Reactivity Insertions – And Why You Should Never Insert a Dollar…

Being "prompt critical" means that the reactor is critical on prompt neutrons alone, without any contribution from "delayed neutrons." "Delayed neutrons" arise from neutrons emitted during the radioactive decay process of certain fission products. In order to control a nuclear reactor, usually the reactivity needs to stay below 50 cents or 0.5 Beta. When the reactivity insertion is at or above 1 dollar (or 1 Beta), reactor power will increase rapidly, usually until the fuel melts or vaporizes, reducing the density of the fuel so that the loss of neutrons no longer support fission.

People often confuse the term "supercritical." Every reactor goes supercritical in the normal course of raising the power. Being supercritical with the reliance on prompt and delayed neutrons is fine.

Supercritical without the need for delayed neutrons — now that's a problem. That is called "prompt supercritial." With either "prompt critical" or above prompt critical at "prompt supercritical," the power increases so rapidly, and the neutron population is doubling so rapidly that nuclear reactors are not designed to withstand these conditions. And besides melting fuel and releasing radionuclides, the thing might have a steam explosion, metal-water reaction, hydrogen explosion, or it just might have the geometry to create a nuclear jet of high temperature plasma. That the nuclear industry emphasis on stating that a nuclear reactor can't explode like a nuclear weapon doesn't seem like much consolation….

There is a joke among folks who provide the analysis of the reactivity in a nuclear reactor and the control rod movements to control a nuclear reactor. Whenever anybody is standing near a candy machine, they smile and walk by saying "don't insert a dollar" and they laugh because they get the joke.

When it comes to nuclear reactors — really, don't insert a dollar. Actually, don't insert anything over 50 cents! And unless you want to vaporize the fuel, don't insert more than a dollar! Next, I going to explain what a dollar of reactivity means.

I have provided Table 4 below for general information to give a perspective on reactivity terminology. It can be especially confusing because reactivity can be expressed in a variety of units. The neutron multiplication factor, K-effective, defines the level of reactivity. Reactivity is commonly expressed in percent or in dollars or in multiples of Beta. Beta is the fraction of neutrons that are delayed neutrons and the value of Beta depends on fuel composition and may vary with burnup, for example. For Chernobyl, the delayed neutron fraction, Beta, decreases with reactor fuel burnup, from 0.00715 to 0.00478, according to a report, *Multidimensional Analysis of the Chernobyl Accident*. [22]

Table 4. A relative comparison of reactivity to reactor period and flux.

K effective	Reactivity, ρ (reactivity in percent) (Note 1)	Reactivity in Multiple of Beta, β (reactivity dollars) (Note 2)	Reactor period, T, seconds (Note 3)	Neutron flux(0+1 second)/Neutron flux (0) (Note 4)
1.001	0.001 (0.1 percent)	0.156 β (15.6 cents)	57	
1.006	0.0064 (0.64 percent)	1.0 β (1 dollar which when reactivity equals Beta and corresponds to "Prompt critical")	0.83	3
1.010	0.0099 (0.99 percent)	1.5 β (1.5 dollar) Prompt super critical whenever reactivity is greater than Beta.	0.28	34
1.015	0.0148 (1.48 percent)	2.3 β (2.31 dollar) Prompt super critical	0.12	5000
1.020	0.0196 (1.96 percent)	3 β (3 dollar) Prompt super critical	0.074	700,000
1.024	0.024 (2.4 percent)	3.75 β (3.75 dollar) (Note 6) Prompt super critical	0.055	79,000,000

Table notes. This table is inspired by the report by F. Motte, figure 27 on page 66. [23]
Note 1. Reactivity, ρ = (keff -1)/keff or "delta Keff/Keff" where Keff is the neutron multiplication factor.
Note 2. Beta is the delayed neutron fraction. β is assumed to equal 0.0064 in this example. (Various values of β are possible, depending on fuel composition of U-235, U-238, etc.)
Note 3. Reactor period, T = (prompt neutron lifetime/keff) * [1/(ρ - β)].
Note 4. Neutron flux at time t is equal to neutron flux at time 0 multiplied by $e^{t/T}$.
Note 5. Prompt neutron lifetime assumed in this example to be 1.0E-3 seconds; however, the value varies.

[22] P.S. W. Chan et al., Atomic Energy of Canada, Limited and B. Chexal, Electric Power Research Institute, Multidimensional Analysis of the Chernobyl Accident, January 1988. https://inis.iaea.org/collection/NCLCollectionStore/_Public/22/069/22069564.pdf

[23] F. Motte, The Chernobyl-4 Reactor and the Possible Causes of the Accident, INIS-f—10945, Presented at the Seminar THE CHERNOBYL ACCIDENT AND ITS IMPACT organized by SCK/CEN at Mol on October 7, 1986. https://inis.iaea.org/collection/NCLCollectionStore/_Public/18/082/18082425.pdf?r=1&r=1

Table notes continued: Note 6. For the SL-1 accident, the reactivity insertion of 2.4 % delta K/K, beta was assumed to be 0.0065, prompt neutron lifetime was assumed to be 6.1E-5 seconds rather than 1.0E-3 seconds, which yields a reactor period of 3.4 milliseconds rather than 5.5 milliseconds.
Note 6. For a useful online source of reactor reactivity definitions, see https://www.nuclear-power.net/nuclear-power/reactor-physics/nuclear-fission-chain-reaction/neutron-generation-neutron-population/

The prompt neutron lifetime for the fuel along with the reactivity define the reactor period, in seconds, which is the length of time for the neutron population to double. When the neutron population doubles, the reactor power doubles. The table shows the neutron flux for 1 second, a time frame that is arbitrary and that doesn't apply to either the SL-1 or Chernobyl accident.

In Table 4 above, you can see that at K-effective of 1.001, the reactivity is 0.001, or 0.1 percent. This reactivity is less than Beta, the fraction of neutrons resulting from neutron emission from fission products. Beta is assumed to be 0.0064 in Table 4. At 0.156 multiplied by Beta, the reactor period is 57 seconds, which may be enough time to insert control rods to shut down the reactor. **But any reactivity insertion above Beta, or 1 dollar, or more means you probably can't control the nuclear reactor.** And the high energy releases by the high amount of fissioning means the fuel assembly may overheat, depending on its design and the ability to transfer heat to a coolant. And the higher the reactivity insertion, the shorter the reactor period, the faster the neutron doubling, and the higher the level of energy generated by fissioning before the accident melts, vaporizes, or creates a high-temperature plasma from the nuclear fuel.

Just Some of the Lies Told About SL-1 Accident to Coverup the Accident Cause and Consequence

In 1961, the first AEC report, right off the bat, hid the data on the rod involved in the SL-1 accident. In Appendix A or the AEC report on the SL-1 accident, IDO-19300, [24] the SL-1 Control Rod Operational History is provided for only four of the five control rods.

Data is provided for Rod 1, 3, 5 and 7 but not for Rod 9, the control rod that was withdrawn and caused the accident.

The AEC report IDO-19300 has the following deceptions that suggest to me that the AEC knew full well that rod sticking caused the SL-1 accident:

1. IDO-19300 states on page 61 that "A listing of all rod sticking incidents that took place since CEND has been operating the SL-1 facility is included in Appendix A." ***But, in fact, no control rod incidents for Rod No. 9 are provided in Appendix A.***
2. IDO-19300 admits that rod sticking increased markedly in the one-month period prior to the shutdown, from November 18 to December 23, 1960 and it gives a summary of

[24] Atomic Energy Commission report, Idaho Field Office IDO-19300, "SL-1 Reactor Accident on January 3, 1961: Interim Report." Combustion Engineering, May 15, 1961. https://inldigitallibrary.inl.gov/PRR/114443.pdf

the rod sticking incidents in Table V. But Table V emphasizes scram and rod drop tests while providing minimal information about Rod No. 9 pertaining to sticking during rod withdrawal. The control rods involved with sticking incidents during rod withdrawal are not identified in Table V. In fact, Rod No. 9 had stuck during withdrawal on July 5, 1960 and it stuck so severely that the aluminum shear pin failed. ***There is no mention that Rod No. 9 had failed during withdrawal as the rod sticking incidents for withdrawal are tallied in Table V.*** And neither does there appear adequate explanation of why Rod No. 9 and other rods had stuck during rod withdrawal from the zero position. For the remaining four rods, there were 12 rod withdrawal sticking events where the rod was noted stuck at a variety of lift heights between zero and 3 inches withdrawn.

3. IDO-19300 on page 63 then states ***"It can be seen from control rod sticking history that of all of the rods, the central rod No. 9, had the best operational performance record even though it was operated more frequently than any of the other rods."*** While the control rod sticking history of Rod No. 9 did have fewer Type I problems for failure to meet drop time requirements for scram and rod drop tests compared to the other four rods, Rod No. 9 had poor performance for Type II and III faults. **In reality, Rod No. 9 had poor performance for Type II sticking faults where the rod is so stuck it requires power assist to move it and Type III sticking faults where drive failures make it impossible to move the control rod.** The IDO-19300 report gives incomplete and misleading statements about Rod No. 9 sticking when it states that Rod No. 9 performed better than the other rods. And with the very high number of sticking events for the other rods, even if it had modestly performed better than the other rods, it would still indicate very unreliable performance.
4. The SL-1 accident was caused by rod sticking from withdrawal not sticking during rod drops, so it is rod sticking during withdrawal that should have been emphasized in the AEC's investigation. Two of the rods had no rod withdrawal sticking events, while Rod No. 9 had one event and Rod No.1 had 3 and Rod No. 5 had 6 events. So, despite Rod No. 9's better operational performance record for drop times during scram tests, **Rod No. 9 was worse than two of the other rods for sticking during rod withdrawal.**

The operational history of Rod No. 9 while excluded from the IDO-19300 report was included in Combustion Engineering document SL-1 Annual Operating Report, February 1960-January 3, 1961, CEND-1009, 1961, on page 63, available on osti.gov.

In addition to control rod sticking being downplayed, the degree to which the AEC was inviting disaster is also downplayed by the AEC. The Congressionally appointed review board provides some insight on page 96 of its report by providing Operations Log History of Rod No. 9 from October 7 through November 27, 1960. [25] While the Rod No. 9 hung up momentarily before insertion there are many rod control problems noted. **These problems include Rod No. 9**

[25] Joint Committee on Atomic Energy, SL-1 Accident Atomic Energy Commission Investigation Board Report, U.S. Government Printing Office, Washington, June 1961 available at INLDigitalLibrary.inl.gov

spuriously automatically driving out during reactor operation, which inserts positive reactivity. The operators would have to manually take the rod out of automatic mode.

In addition to control rod sticking, the fuel elements had gotten so difficult to remove from the core that the lifting of fuel elements to inspect them simply ceased in August of 1960. The shutdown margin of the SL-1 had so markedly reduced due to flaking off of boron strips on the fuel elements that cadmium strips were added to two positions in the core in order to increase the shutdown margin.

So, with no fuel inspections being conducted, the control rods of the SL-1 being prone to sticking and not inserting rapidly and reliably to shut down the reactor, and the use of Rod No. 9 as a regulating rod in automatic mode which was glitchy — prone to insert positive reactivity when not needed — here was the verbal agreement from the AEC to allow Combustion Engineering to operate the SL-1 above its rated power level of 3 MWt and all without conducting any formal safety review or involving the reactor licensing division of the AEC.

Combustion Engineering wanted to test a new condenser design and needed higher power levels, 4.7 MWt, from the SL-1 reactor. The AEC provided the verbal OK. With the higher power levels came far greater reactor instability from "boiling noise" as steam voiding reduced power and the absence of voids increased power. The power instability worsened after cadmium strips were inserted in only two instead of four positions in the core. The power oscillations were as high as 1 MWt and diverging. On November 23, 1960, the reactor scrammed on over-power, and should have scrammed at 5.7 MWt but scrammed between 6 and 8 MWt. And power flux non-symmetries go unnoticed which means some of the fuel plates are more vulnerable to overheating during a reactor transient.

Movement of four outer rods together, the rod bank was worth about 0.55% deltaK/K per inch of motion near the critical position. Saying this another way, once the reactor was nearly critical or at critical, a movement of the bank of rods by an amount less than an inch could bring the reactor to an uncontrollably rapid increase in neutron population, doubling faster than control rods could control.

Prior to adding the cadmium strips in November 1960, the critical position was only 14.3 inches. In IDO-19300, page 3, the predicted Rod No. 9 positions at shutdown, 83 F, with all other rods inserted for critical, prompt critical and 1.8% deltaK/K supercritical are 17.3 inches; 19.5 inches; and 24.3 inches, respectively. But later AEC reports would issue a revised estimate that reduced the height that the SL-1 would become critical at lower rod withdrawal lift height, critical at 16.7 inches, prompt critical at 17.6 inches, and the 20-inch position was worth 2.4% deltaK/K (on page III-107).

When the AEC report **gives a photo of a man performing a simulation and lifting the rod 30 inches**, in IDO-19300, Figure 101, when the 20 inches of rod withdrawal only required lifting about 17 inches because the rod was already raised about 3 inches and held by a c-clamp for reassembly when the fatal lift was commenced. It appears that the AEC was deliberately trying to imply that the over lift could not happen by accident.

Basically, before the accident, the lift height that would bring the reactor to critical was not accurately known and the procedure that called for lifting a rod provided no warning as to the dire consequences of over-lifting a stuck rod. Nor was control room instrumentation used to monitor for reactivity increases while core changes were conducted. While there would not have been time to respond in this over lift of Rod No. 9, there are other circumstances where monitoring neutron flux could have signaled a problem.

The SL-1 was a reactor with unsafe design, poor fabrication and material choices, deteriorating shutdown margin, unreliable control rod performance and there are virtually no meaningful safety reviews being conducted as the rated power is roughly doubled on verbal agreement by the AEC.

Only after the SL-1 accident was it concluded that having so much excess reactivity in a single control rod was a horrible idea. Despite the AEC blaming the SL-1 accident on operator error or implying a deliberate act as the Department of Energy does in “Proving the Principal,” [26] it seems no one ever wanted to build an SL-1 reactor again.

The rapid reactivity insertion accident risks for the SL-1 were not limited to the vulnerability of raising a single rod during shutdown. The control rod scram and power regulation glitches posed to risk of a reactivity accident during reactor power operations. Depending on the level of Xenon poisoning during power operation and other factors, once the reactor was critical, movement of a rod of about an inch could bring the reactor to prompt critical or super prompt critical.

There were a multitude of design problems with the SL-1 reactor. The SL-1 accident brought to light many problems at the facility and within the AEC, including the need for better emergency response and accident investigation. [27] But perhaps the biggest mistake was for the Army to have trusted the AEC and Argonne National Laboratory to provide the SL-1 reactor design in the first place.

Articles by Tami Thatcher for December 2019.

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[26] 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

[27] Joint Committee on Atomic Energy, SL-1 Accident Atomic Energy Commission Investigation Board Report, U.S. Government Printing Office, Washington, June 1961 available at INLDigitalLibrary.inl.gov