SODIUM-GRAPHITE REACTOR EXPERIMENT, SRE INCIDENT

11/19/2018

INTRODUCTION

The Sodium Reactor Experiment, SRE reactor is a graphite-moderated and sodium-cooled experimental reactor that was brought to criticality on April 25, 1957. It reached a power level of 5.8 MWe and 20 MWth for an overall thermal efficiency of 5.8 / 20 = 0.29 or 29 percent. The electric power was fed into the Southern California Edison grid which delivered electricity to the town of Moorpark, California.

The experimental reactor was located at the Santa Susana Field Laboratory, SSFL owned by NASA and the Boeing Company's Rocketdyne / Atomics International division at Ventura, California. It was meant to explore the possibility of power production and the use of a fuel mixture of low enriched U^{235} and Th^{232} for breeding U^{233} in a thermal spectrum. The operational low pressure of the system was thought to preclude radionuclides release. The reactor was primarily an experimental reactor with the power generation as a secondary consideration.

The reactor was situated on 2,900 acres in the Simi Hills above Chatsworth, West Hills and Simi Valley. The field laboratory was established in the 1940s to develop rocket engines such as the rocket for the Apollo-11 moon mission, and nuclear reactors for space applications for NASA and for electricity production. The laboratory owner, then Rocketdyne, conducted contract work for the USA Atomic Energy Commission, USAEC, which was superseded by the USA Department of Energy, USDOE

Figure 1. The Sodium Reactor Experiment, SRE, was a Na-cooled, graphite moderated thermal neutron spectrum reactor experiment producing 5.8 MWe of electrical power.

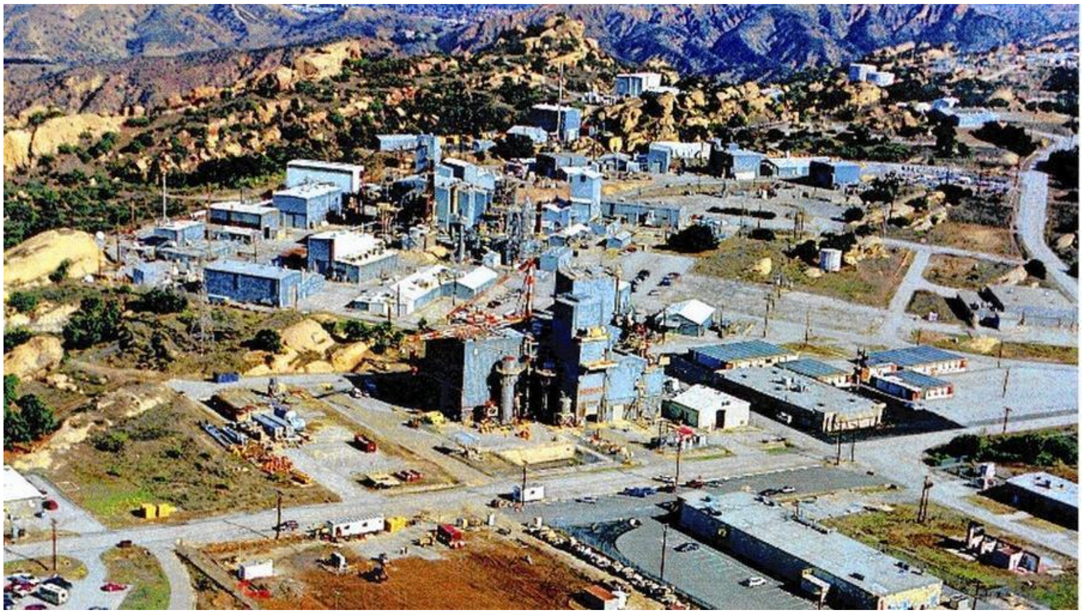


Figure 2. Santa Susana Field Laboratory.

Figure 3. Sodium Reactor Experiment building.

Figure 4. Location of Santa Susana Field Laboratory.

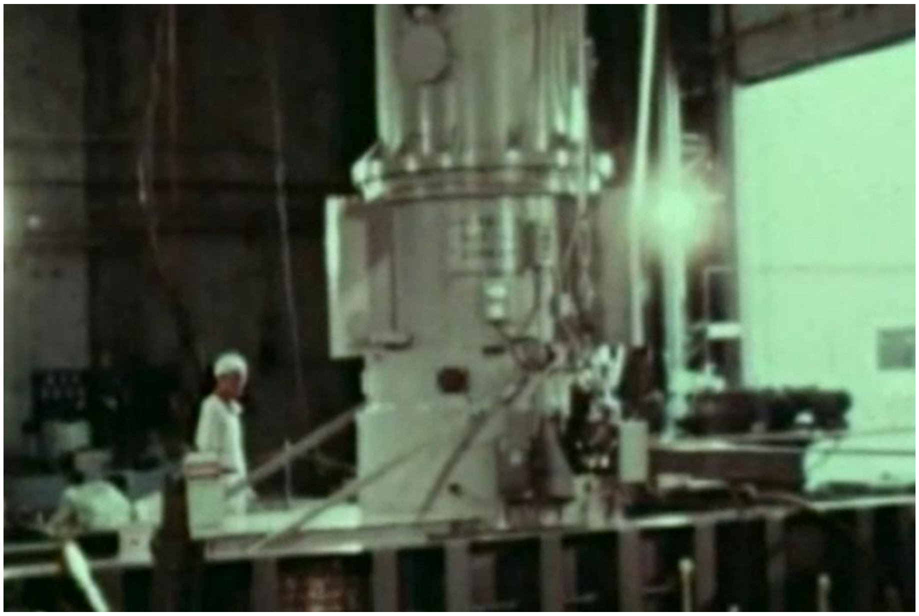


Figure 5. SRE core vessel under repair.

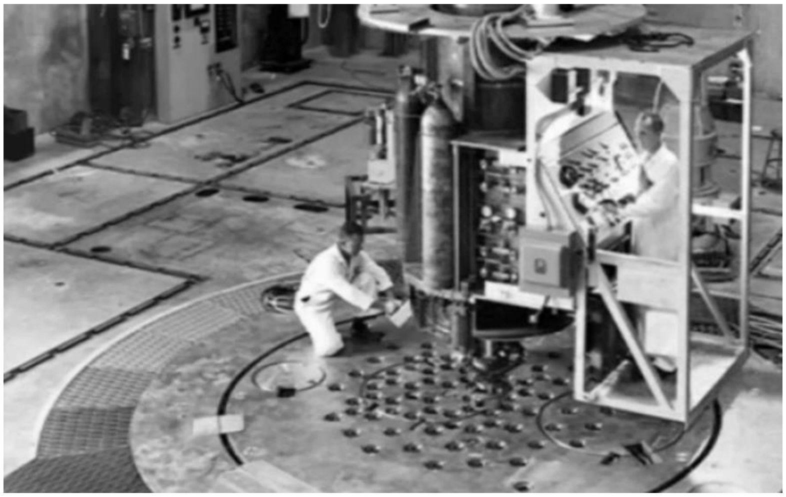


Figure 6. SRE core monitoring and refueling machine.

Figure 7. Top of SRE vessel.

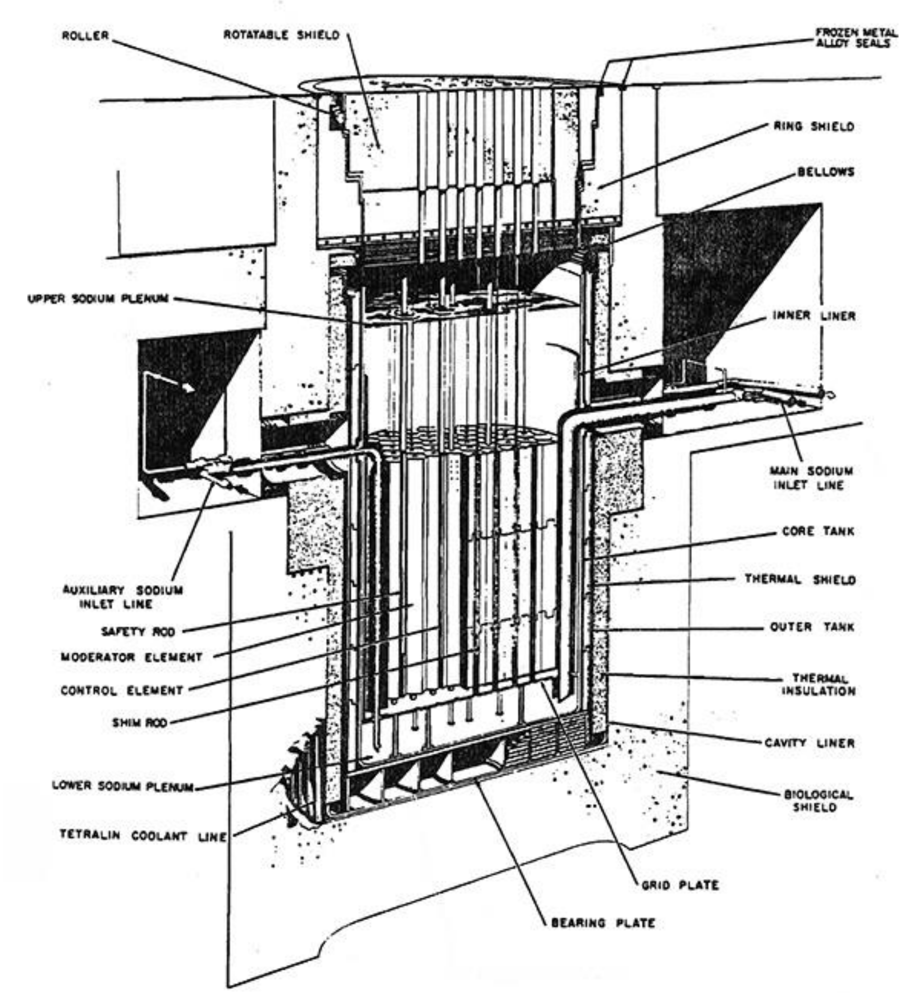


Figure 8. Sodium Reactor Experiment, SRE cutout. Sodium was used as a coolant and graphite as a moderator. Bellow rings were used to allow for the vertical expansion of the core.

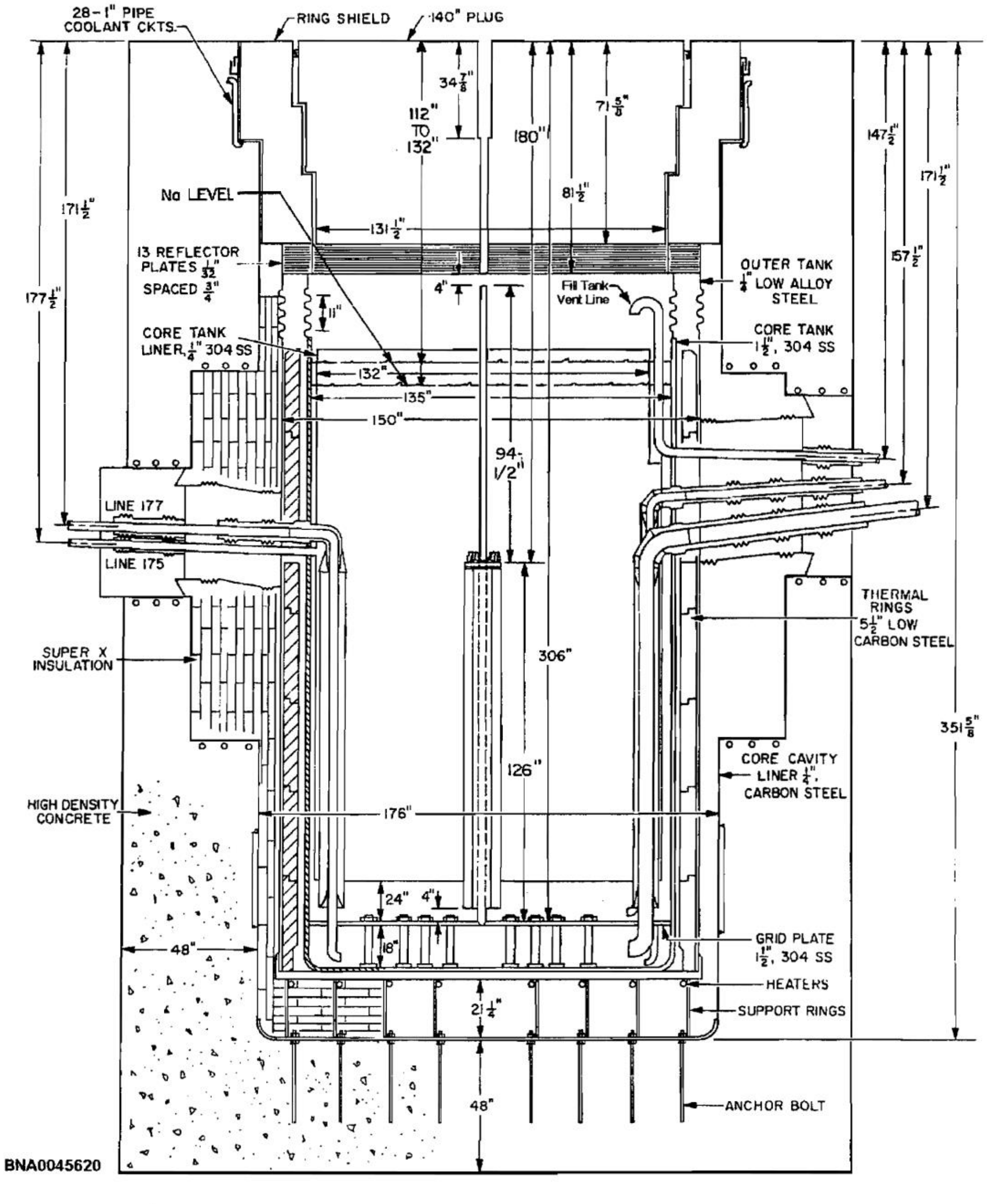


Figure 9. SRE Reactor sectional view showing the bellows allowing the vertical expansion of the core.

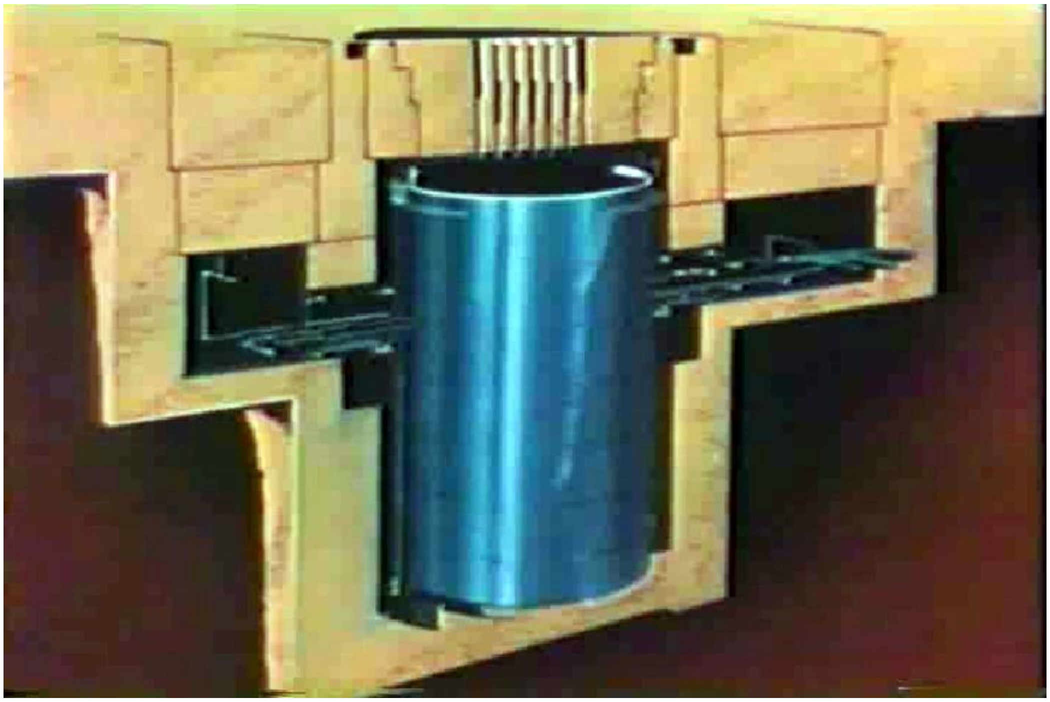


Figure 10. Sodium Reactor Experiment, SRE layout showing thermal shield around reactor vessel and Na coolant inlet and outlet piping.

REACTOR DESIGN CONCEPT

The reactor concept uses graphite as a moderator and reflector, Na as a coolant and low enrichment uranium metal as a fuel. The moderator region is 6 ft in diameter by 6 feet in height, and the reflector region is 2 ft in thickness. The graphite is formed into hexagonal prisms contained in thin-walled zirconium cladding to form the moderator and reflector regions.

The Na coolant is pumped into a plenum chamber at the bottom of a stainless steel tank and flows through the coolant channels to a free-surface pool. An inert atmosphere of nitrogen is used to cover the Na pool.

The fuel assemblies are suspended in the coolant channels by hanger tubes that extend from shield plugs to the top of a cluster of fuel rods. The individual rods are made of stainless steel tubes containing cylindrical slugs of low-enriched uranium. A NaK heat transfer bond fills the tubes.

Control rods are driven vertically by a ball-nut mechanism located in the shield section of the thimble. Safety rods are released for a gravity drop by a latch mechanism at the bottom of the rod and picked up by a ball-nut mechanism.

Heat is removed by primary Na pumps to a secondary Na loop and then to a steam generator.

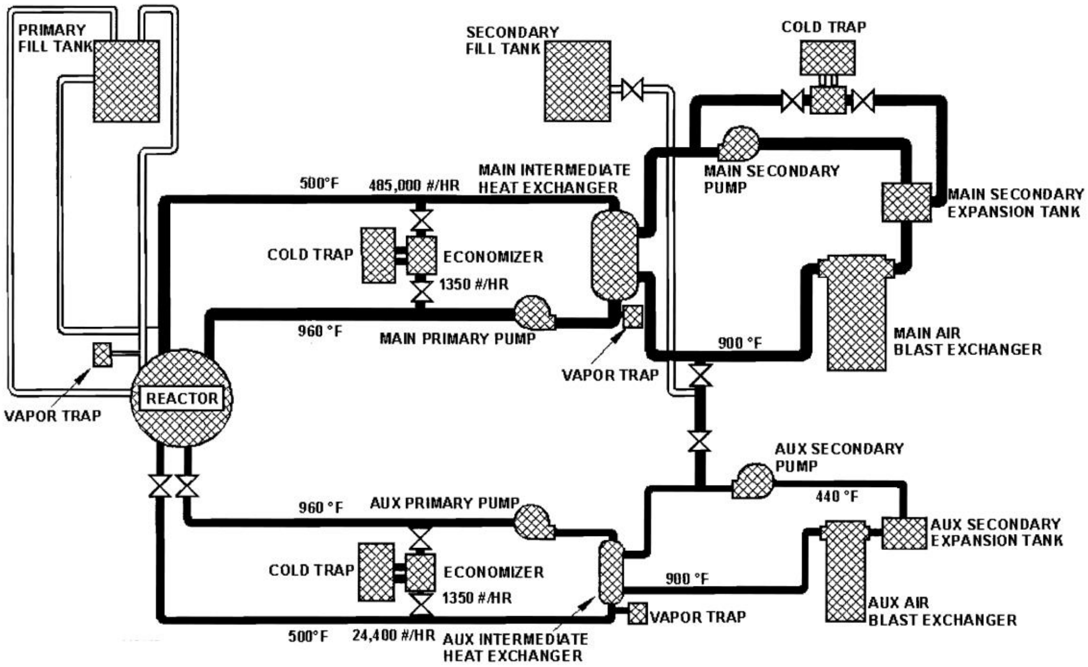


Figure 11. SRE's power cycle diagram. As an experiment, it could either produce power for delivery to the grid, or just reject the produced heat through air blast heat exchangers.

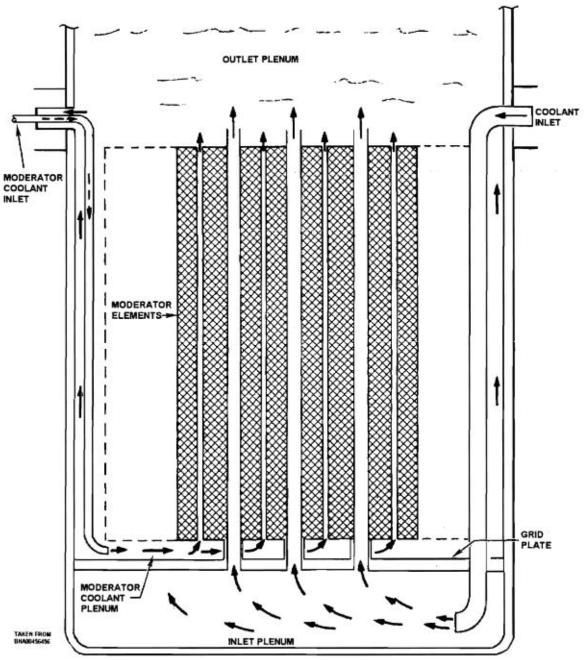


Figure 12. Core coolant flow in the SRE.

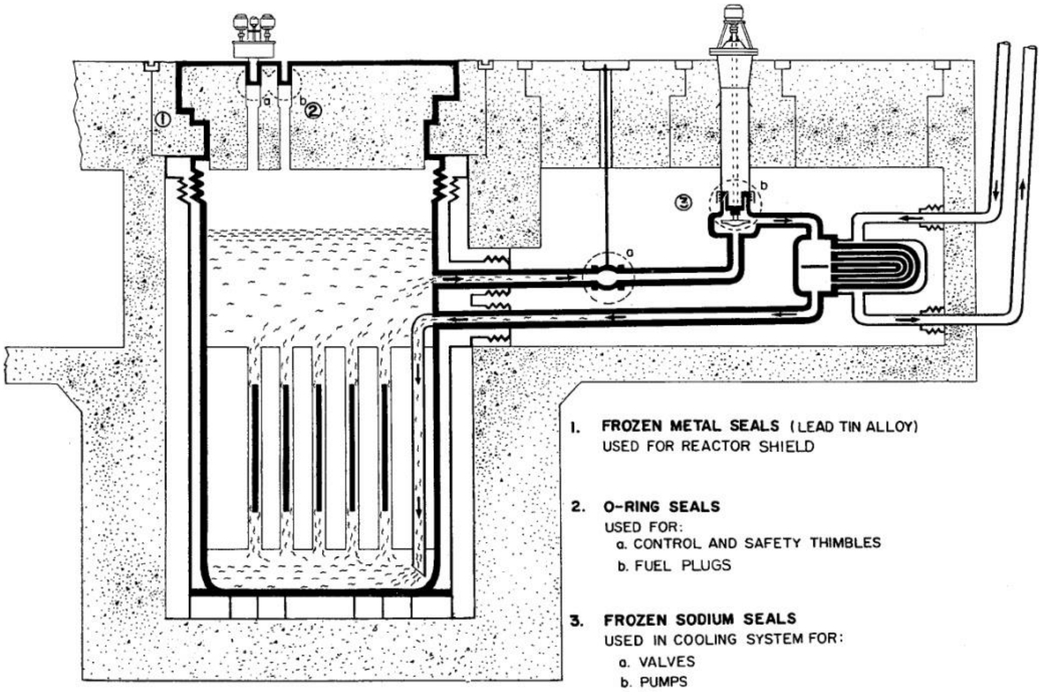


Figure 13. Flow diagram of the SRE, showing the seal system to prevent sodium interaction with air.

SAFETY FEATURES

Graphite is used as a moderator to reduce the neutrons energy to the thermal region of the spectrum, providing a longer response time for control compared with a fast neutron spectrum system.

Graphite is favored since has a large thermal inertia and heat capacity, minimizing temperature transients.

Sodium is used to remove the heat energy at high temperature assuring a high thermal efficiency, yet operating at low pressure compared with light water reactor systems.

The thermal capacity of a heat machine compared with its power output is a good figure of merit of the time available for the control systems to correct power transients. In such systems, it is desirable for the fuel to have a comparatively low heat capacity compared with the coolant and moderator.

Table 1. Heat capacity of fuel, Na and graphite in the SRE at 68 x 10^6 BTU/hr.

	Heat capacity C_p [BTU]	Temperature °F	Response time at full power [Min]
Fuel elements to melting temperature of uranium	0.3 x 10^6	2,070	0.3

Sodium to boiling point	12.0×10^6	1,620	11.0
Graphite to 1,620 °F operating temperature	23.0×10^6	1,620	20.0

Operation at near atmospheric pressure eliminates the hazard potential of operating liquids and gases at high pressure. A sudden depressurization would lose the coolant as it flashes into steam in the case of light water reactor designs.

Compatibility between the materials used provides inherent safety. There are no reactions between uranium, Na, NaK, steel, Zr and graphite.

Another safety feature is the negative temperature coefficient of reactivity. Under normal operation this stabilizes the power level, and in the case of failures that lead to temperature increases, would keep in check any power rise.

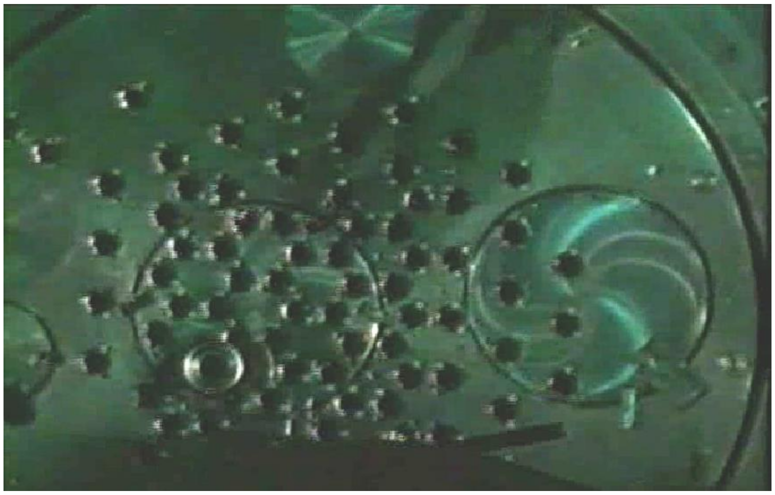


Figure 14. Top of core shield plug with access to core for loading and unloading experimental fuel configurations.

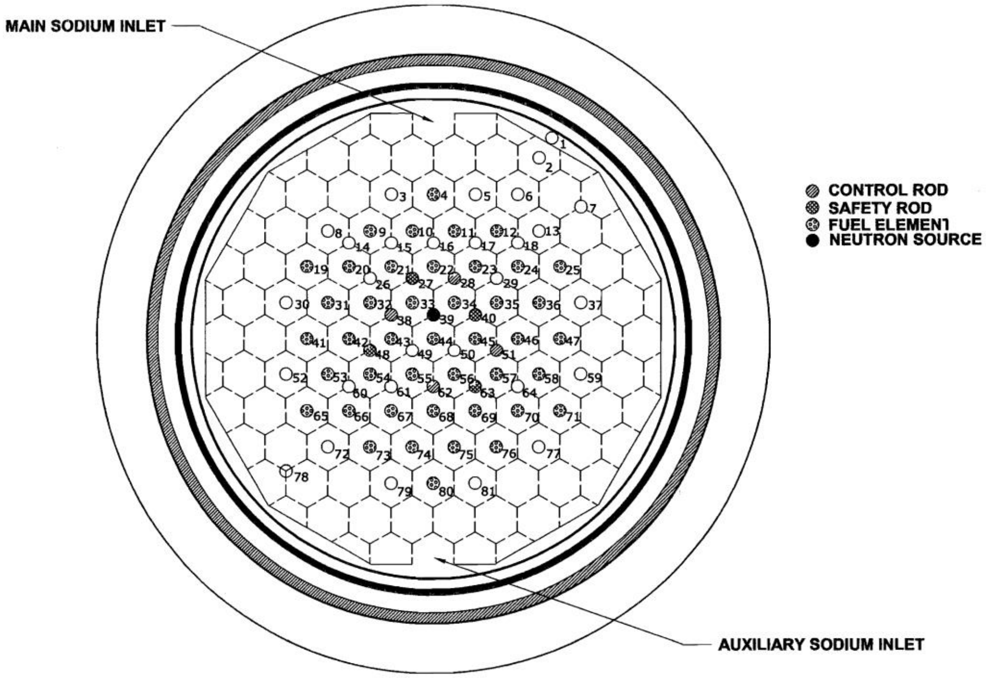


Figure 15. Core configuration of SRE.

One disadvantage of systems that use separate coolants and moderators is that the coolant, be it Na or H_2O, acts as a neutron absorber, whereas the moderating action is carried out by graphite (STR, RBMK-1000) or D_2O (SGHWR, CANDU-BLW). Local boiling of the coolant in this case leads to a positive reactivity addition, and results in a positive power coefficient of reactivity; an unstable configuration.

CHARACTERISTICS OF SODIUM AS A COOLANT

The neutron capture cross section in Na is relatively high leading to the activation of the primary coolant:

$${}_{11}Na^{23} + {}_{0}n^{1} \rightarrow {}_{11}Na^{24} + \gamma \tag{1}$$

The resulting Na^{24} is a negative beta emitter which has a 14.959 hr half life and emits energetic 2.754 and 1.3687 MeV gamma photons.

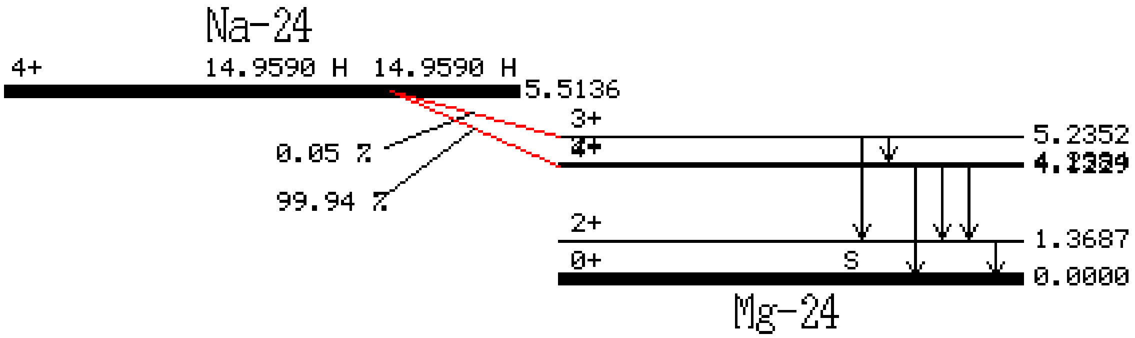


Figure 16. Decay diagram of Na^{24}.

The neutron capture rate reaches an equilibrium level of 0.3 Ci / cm^3. In the SRE a total of 8 x 10^6 Ci existed in the primary Na coolant loop. This necessitates the use of thick shields, nitrogen inert atmospheres, special leakage seals, double-walled heat exchangers and a secondary Na coolant loop

Sodium is reactive with air, steam and water. It must be isolated from these other fluids by a series of seals and barriers.

GRAPHITE AS A MODERATOR

Neutron irradiation and the creation of interstitial atoms in the graphite matrix results in the storage of energy known as the Wigner Energy. This energy must be released by the process of annealing. A graphite reactor is usually operated within a temperature range of 600-1,000 ^{o}F that promotes annealing.

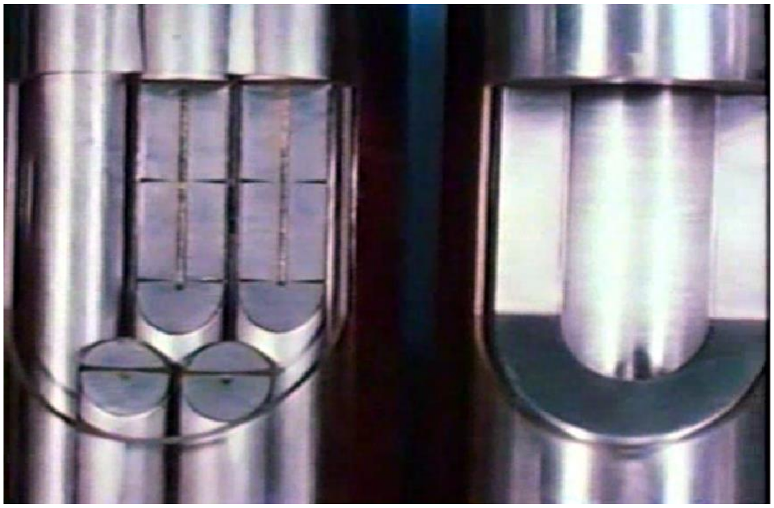


Figure 17. Experimental fuel assemblies each containing 7 fuel elements configurations including slightly enriched U^{235} and Th^{232} fuel mixtures in Stainless Steel cladding, were tested in the SRE.

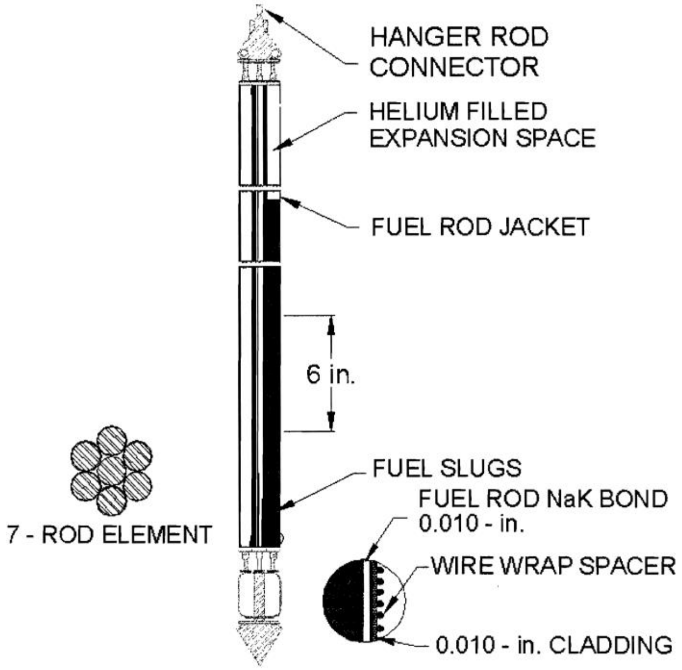


Figure 18. Fuel element geometry in the SRE.

INCIDENT DESCRIPTION

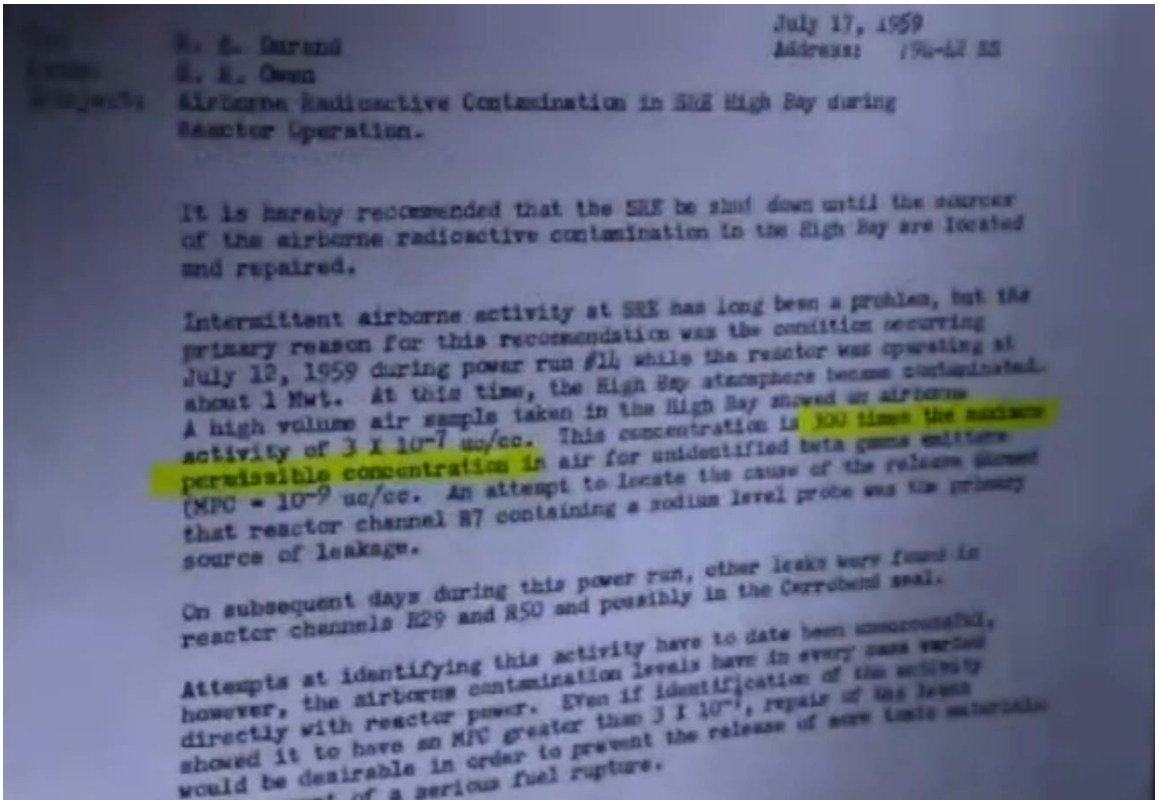
During operation of a test cycle or “run” over the period of July 14-26, 1959, the reactor experienced several excursions and showed signs of overheating.

On July 26, 1959, the operators shut the reactor down, and noticed that 4 fuel elements were “stuck.” Upon further inspection it was noticed that 13 of its 43 fuel elements had partially melted with a possible release of I^{131} and Cs^{137} within the reactor containment system.

Upon removal of the fuel elements from the reactor, some were found to be partially melted. Pieces of the damaged fuel elements fell to the bottom of the reactor.

The cause of the accident has been attributed to a faulty design in the used Na coolant pumps which were an adoption of the technology used to pump hot oil in petroleum refineries. The pumps used to move the Na coolant were impeller pumps. A fluid called “Tetralin” was used to cool the pump seals along the pump shaft. The Tetralin is thought to have seeped into the primary coolant system through a pump seal, decomposed into a black residue under the effect of the high temperature coolant, and clogged several of the Na cooling channels, resulting in local overheating and damage to the stainless steel cladding of the fuel.

An alternative to avoid such a problem with the impeller pumps would be to use Magneto-Hydro-Dynamic, MHD pumps that would involve no moving parts in pumping the liquid metal fluid.



July 17, 1959
Address: 196-42 BS

To: R. A. Durand
From: E. R. Owen
Subject: Airborne Radioactive Contamination in SRE High Bay during Reactor Operation.

It is hereby recommended that the SRE be shut down until the sources of the airborne radioactive contamination in the High Bay are located and repaired.

Intermittent airborne activity at SRE has long been a problem, but the primary reason for this recommendation was the condition occurring July 12, 1959 during power run #14 while the reactor was operating at about 1 Mwt. At this time, the High Bay atmosphere became contaminated. A high volume air sample taken in the High Bay showed an airborne activity of 3 X 10^{-7} uc/cc. This concentration is 300 times the maximum permissible concentration in air for unidentified beta gamma emitters (MPC = 10^{-9} uc/cc. An attempt to locate the cause of the release showed that reactor channel R7 containing a sodium level probe was the primary source of leakage.

On subsequent days during this power run, other leaks were found in reactor channels R29 and R50 and possibly in the Cerrobend seal.

Attempts at identifying this activity have to date been unsuccessful, however, the airborne contamination levels have in every case varied directly with reactor power. Even if identification of the activity showed it to have an MPC greater than 3 X 10^{-7}, repair of the leaks would be desirable in order to prevent the release of more toxic materials in the event of a serious fuel rupture.

Figure 19. Accident report dated July 17, 1969.

CAUSES OF ACCIDENT

Two modes of cladding failure were identified:

1. Thermal cycling through the U α-β transformation temperature which caused the fuel to expand until the cladding burst,
2. The formation and melting of Fe-U alloys of near-eutectic compositions. The U diffused into the 304 stainless steel cladding to form the low-melting alloys.

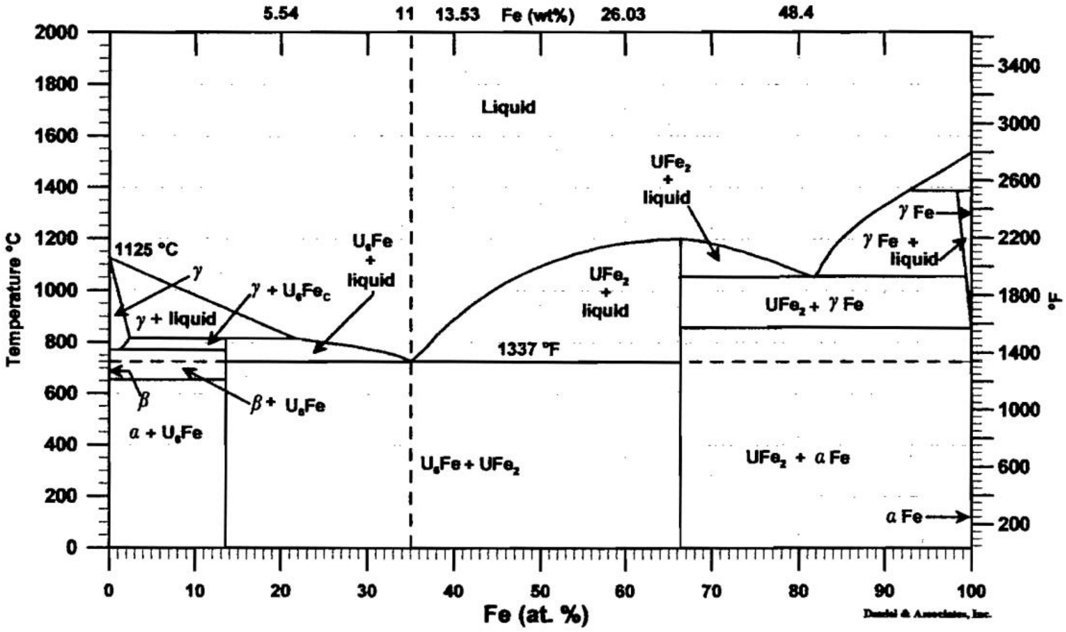


Figure 20. The Fe-U phase diagram.

Both modes of failure were caused by the presence of plugging material in the coolant passages of the fuel elements which caused a partial blockage of the coolant channels by the Tetralin decomposition products.

The reactor excursion is explained by the expulsion of Na from several of the partially blocked fuel channels. Since Na acts in this system as an absorber, its expulsion results in a positive reactivity insertion in a system that has a positive power coefficient of reactivity. The lesson was not learned when the same situation repeated itself, with water as a coolant and graphite as a moderator, in the RBMK-1000 reactor involved in the Chernobyl accident later on.

A 1.2 percent loss in reactivity resulted from the penetration of Na into two of the graphite moderator assemblies.

Carburization and nitriding of the stainless steel in the primary system were negligible. Some hydriding of the Zr moderator cans occurred. The probability of cans failures may have increased as a result of the hydriding.

Despite the cladding failure of 13 out of 43 fuel elements and the release to the primary coolant of several thousand curies of fission product activity, no radiological hazard was presented to the reactor environs.

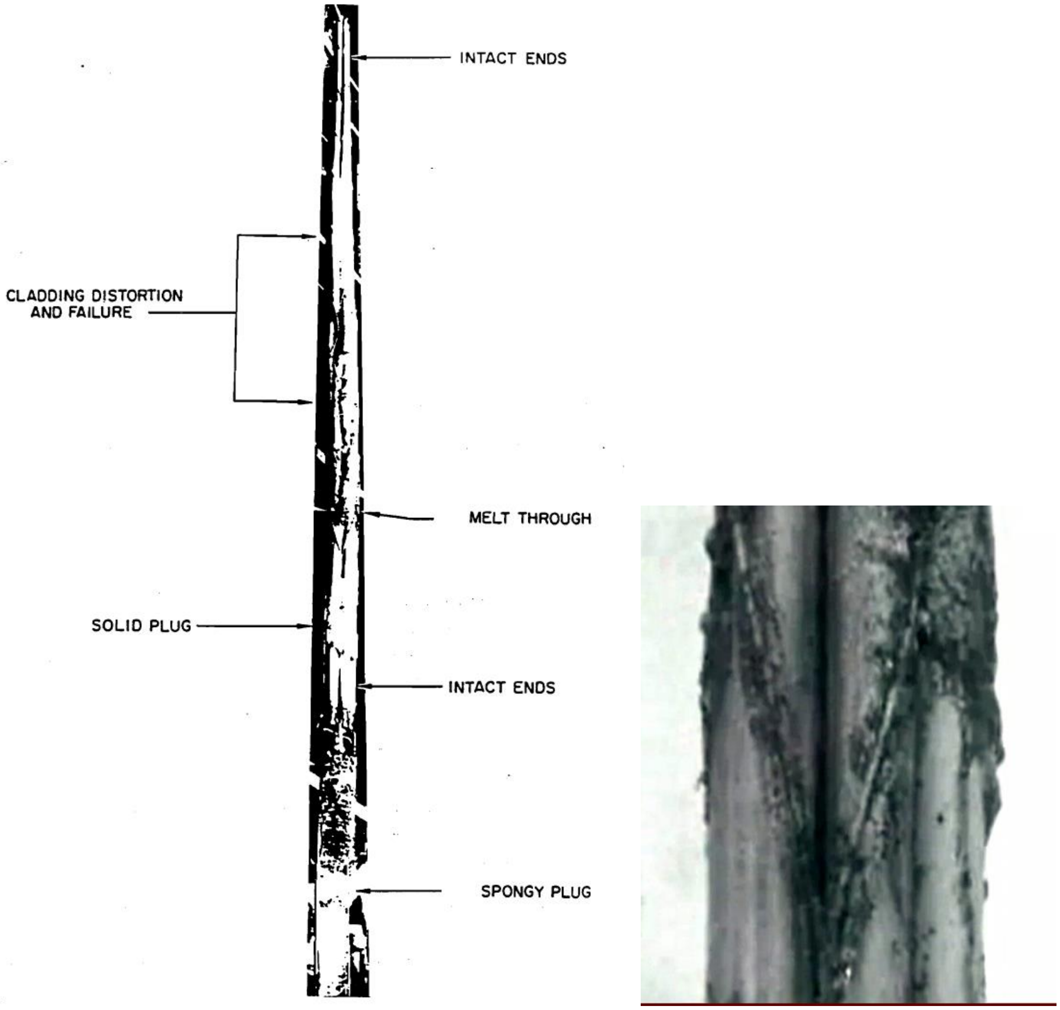


Figure 21. Structure of fuel damage.

EUTECTIC FORMATION

Metal alloys are formed with various amounts of two or more elements. Their properties are described by their phase diagrams. The “eutectic” is a temperature that represents the lowest temperature at which any liquid in the alloy can exist.

For the damaged fuel of the SRE, the formed alloy was about 11 w/o Fe and 89 w/o U. At this composition, the eutectic temperature is 1,337 ^{o}F. Above the eutectic temperature, a mixture of U_6Fe would exist until the temperature becomes high enough for a complete liquid phase. Below 1,337 ^{o}F, a solid mixture of Fe and U exists.

When the eutectic temperature is reached, the uranium diffuses into the Fe since the U has the lower phase change temperature at this composition.

RADIONUCLIDES RELEASE

In 2004, the Boeing Company and the USDOE held a public meeting in Simi Valley to detail what happened during and after the SRE accident. They maintained that most of the radioactive material from the melted fuel rods was trapped in the Na coolant and never left the containment structure. The I^{131} would have interacted with the Na coolant forming sodium iodide, NaI.

They suggested that almost all the radiation was contained inside the reactor and that the only radioactive material to escape through the reactor's stack after allowing it to decay in holding tanks was 28 curies of inert gases such as Kr^{85} and Xe^{133} that posed no major health risk. The release followed the relevant federal regulations.

In comparison, the 1979 Three Mile Island accident in Pennsylvania released 17 curies of I^{131} and no Cs^{137}.

They estimated that the closest resident living in the Santa Susana Knolls in July 1959 would have been exposed to an effective dose of 0.018 millirem, or about (0.018 / 300) x 100 = 0.006 percent of the 300 mrem the average person is exposed to in a year from natural and man-made sources of radiation.

SANTA SUSANNA FIELD LABORATORY (SSFL) WOOLSEY FIRE, NOVEMBER 2018, OVERHEAD POWER LINES OPERATIONAL FAILURES

The Pacific Gas and Electric (PG&E) Company in California experienced a power outage on a remote line in northern California immediately before the Camp Fire that devastated northern California in November 2018 ignited. The utility company told the California Public Utilities Commission that it experienced an outage on the 115-kV Caribou-Palermo line in Butte County. According to the California Department of Forestry and Fire Protection (Cal Fire), the blaze started at 6:29 a.m. on Thursday, November 8, 2018 in a spot near that where the fault was reported. The Jarbo Gap had a wind gust to 51 mph due to the canyon effect associated with the Santa Anna Winds. The Jarbo Gap site is about 5.5 miles to the S-SW of the failure site, and located on a ridge. Winds were from the northeast there, with gusts around 50 mph for several hours before the power line failed. The accident location was within a canyon or gap, which was oriented to the northeast upstream from the accident site. The terrain features would have blocked the flow and thus the winds could have been substantially accelerated at the location of the failure. The lines were sparking a full day in advance of the fire. It must be noted that sometimes lightning strikes in storms can ignite the fires. In the Redding area fire, there were reports of a car with brakes that caught fire alongside the freeway. Fire creates its own wind and ounce it gets hot enough, becomes all but impossible to stop.

PG&E sent a plane to inspect the fault and noticed damage to a transmission tower on the affected line and noticed damage to a transmission tower on the affected line. The tower is about a mile from Pulga, one of several small towns in the region affected by the Camp Fire. That day, PG&E announced it would not turn off power in eight Northern California counties, as it had previously warned it might do in response to dangerous weather conditions. In October 2018, PG&E cut off power to 60,000 customers in 12 counties as a preventive measure.

The utility has historically resisted such measures, saying power cutoffs pose other risks for residents and first responders, such as shutting down hospitals and fire stations. But in December 2017 it began considering adopting shut-offs as part of its wildfire response, and in March 2018, it made switching off power lines part of a formal plan.

The Camp fire was the most destructive in state history, and has destroyed more than six thousand homes and other buildings, killed 42 people and spread to more than 90,000 acres. The company already faces billions in potential liability in connection with previous wildfires in the state. The question of PG&E's liability has hung over the company since devastating fires broke out in 2017 in the Wine Country and other parts of Northern California served by the utility.

State investigators previously said PG&E equipment flaws led to at least 16 fires in Northern California. Investigators said the company violated state safety laws in 11 of the fires. The cause of the Tubbs Fire, which ravaged Santa Rosa and was the state's most destructive fire in history. PG&E plans to invest $6 billion to install 1,300 weather stations and 600 cameras over four years in response to wildfires.

The utility company has been criticized in the past year by residents and state officials after a bevy of wildfires tied to downed power lines swept through the state in October 2017. Investigative reports in May and June from the California Department of Forestry and Fire Protection linked PG&E to 16 fires in 2017 that killed 18 people and destroyed thousands of homes and other buildings.

The PG&E service area covers much of Northern and Central California, and includes 18,000 miles of power lines. It spends up to $70 million per year to clear vegetation near those lines. In three cases, Cal Fire contends PG&E violated state codes by failing to get rid of trees and vegetation near the power lines. The utility has been increasing its efforts: "in response to the increased risk of fire danger brought on by climate change and drought, we are doing more to ensure PG&E facilities are safe and reliable." PG&E paradoxically also has come under fire for cutting down trees near power lines as a safety precaution.

Winds would tend to be channeled and strengthened in the Canyon downing the overhead powerlines. One would not think that such winds would take down big high-tension power lines. These could be replaced by insulated wires or placed underground like in European countries in association with HVDC instead of HVAC transmission, at least in sensitive locations.

PG&E aging infrastructure was blamed in 13 Northern California fires in 2017. Utility company Southern California Edison invested $582 million to replace nearly 600 miles of power line in high-risk areas as well as installing fire-resistant poles.

Under a PG&E policy, the utility can preemptively shut off power to areas facing extreme fire-threat, including 54,000 homes and businesses in Santa Cruz County. PG&E put the policy to practice October 14, 2017, shutting off power to nearly 60,000 Northern California customers as high winds and dry fuel threatened to fuel a spark.

Clearing away vegetation and trees 15 feet back from power lines could lead to the loss of critical habitat, erosion and allow encroachment of invasive species. And shutting off power to remote rural areas is seen as a risk to elderly and infirm residents who may rely on the power for their medical needs. Investigators found the deadly Cascade

The Fire in Yuba County was sparked by two sagging PG&E power lines driven together by high winds. Cal Fire investigators have found PG&E's equipment to blame for igniting 13 Northern California wildfires in 2017, for which PG&E expects to pay at least $2.5 billion in damages. In eight of those cases, investigators said they found evidence state or federal law had been violated.

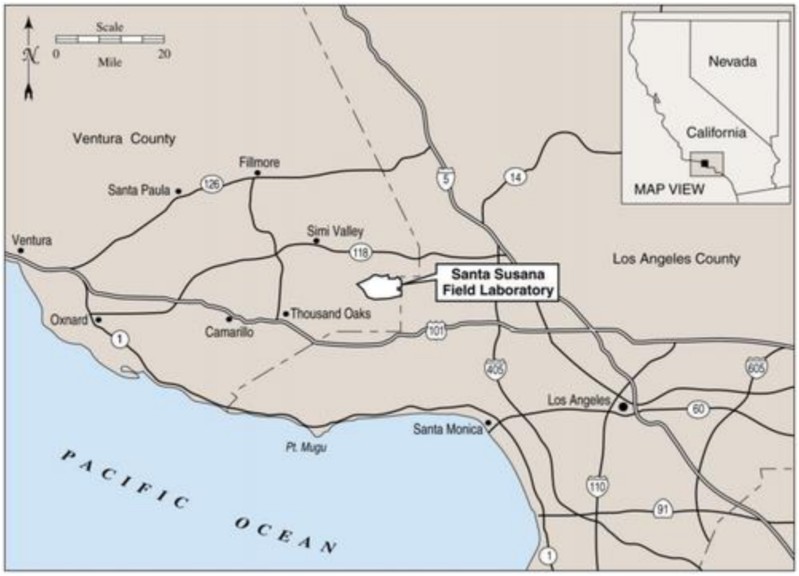


Figure 22. Santa Susana Field Laboratory Location.

Figure 23. GOES-16 Weather satellite view of the Woolsey fire, November 2018. Source: NASA.

The 95,000 acre Woolsey fire in November 2018 which has coated Southern California with an apocalyptic orange glow may have released radioactive particles and toxic chemicals into the air, after scorching the land on the closed-down government weapons testing facility in Simi Hills known to be contaminated from decades of experiments.

Commencing operation in 1947 for Rockwell's Rocketdyne Division, a government contractor for the Atomic Energy Commission (AEC), the Santa Susana Field Lab (SSFL) has a history of nuclear and chemical releases. In 1959, facility operators vented nuclear material from the site’s “Sodium Reactor Experiment” to prevent it from overheating.

The lab property, now owned by the Boeing Company, stretches for 2,800 acres in the Simi Hills, and remains contaminated with toxic materials. Thousands of people live within two miles of the site, and roughly half a million live within 10 miles, northwest of Los Angeles.

Robert Dodge, a physician and president of Physicians for Social Responsibility Los Angeles, suggests that highly toxic materials embedded in SSFL's soil and vegetation may have been spewed into the air by the Woolsey fire: "We know what substances are on the site and how hazardous they are. We are talking about incredibly dangerous radionuclides and toxic chemicals such a trichloroethylene, perchlorate, dioxins and heavy metals. These toxic materials are in SSFL’s soil and vegetation, and when it burns and becomes airborne in smoke and ash, there is real possibility of heightened exposure for area residents."

California officials with the state's Department of Toxic Substances Control said that as of Friday, November 9, 2018, an area of the SSFL site that was scorched by the Woolsey fire posed no danger, stating: "Our scientists and toxicologists have reviewed information about the fire’s location and do not believe the fire has caused any releases of hazardous materials that would pose a risk to people exposed to the smoke."

Satellite imagery tells a similarly two-sided story. These images show that the fires did spread to the compound, but they did not take down structures. With near-infrared (NIR) imagery, dense vegetation appears red while burn scars from the Woolsey fire contrast as dark brown. According to a Draft environmental statement from the Energy department, Santa Susana Field Laboratory and its adjoining Northern Buffer Zone has never been fully decontaminated.

Left: Planet Labs, Right: Planet Labs

Figure 24. Burn scars from Woolsey fire around Santa Susana field laboratory.

Figure 25. Downed overhead power lines constitute a sparking fire hazard in addition to their electrocution hazard.

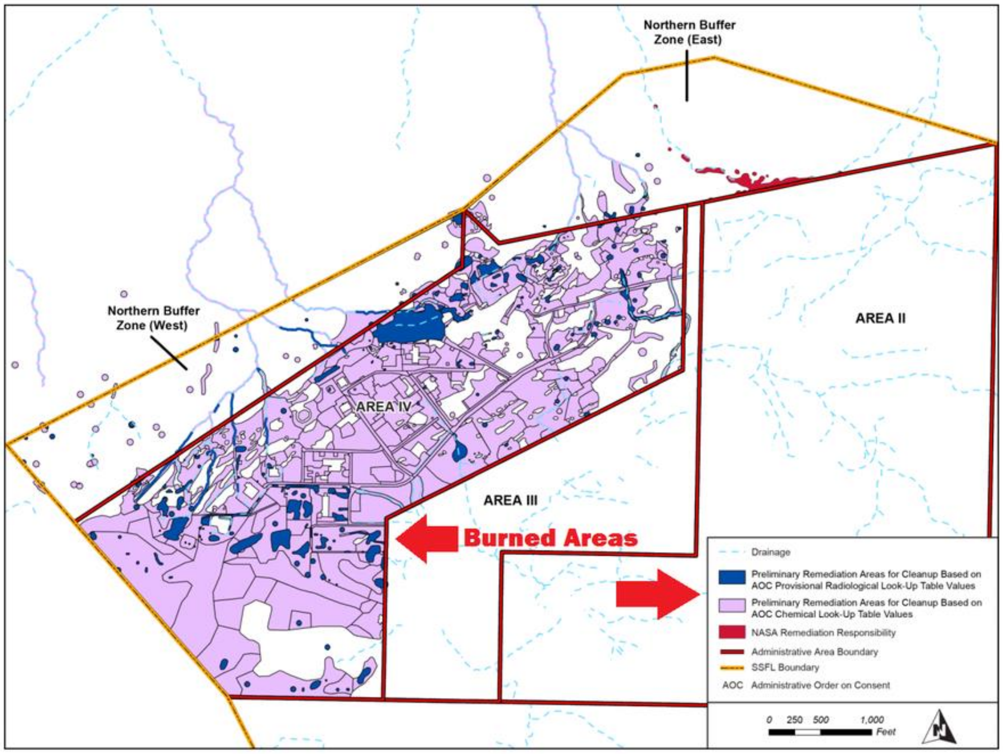


Figure S–4 Extent of Radiological and Chemical Constituents Above AOC Look-Up Table Values

Figure 26. Burned areas around Santa Susana field Laboratory.

Figure 27. Totally destroyed city of Paradise, November 2018. California's Camp Fire claimed 63 lives and destroyed at least 9,844 homes, 336 commercial and 2,076 other buildings.

Figure 28. Tree removal around overhead power lines. Santa Cruz, California.

AFTERMATH

In the following months, the Atomics International personnel eliminated the use of Tetralin, removed all of the stuck fuel elements, retrieved the pieces of dropped fuel elements, cleaned the Na system, improved the design of liquid metal pump seals and installed a new reactor core.

The Sodium Reactor Experiment, SRE was restarted on September 7, 1960, 14 months after the incident and operated until February 15, 1964 without a similar incident.

The site ultimately hosted several facilities that handled radioactive materials and 10 reactors, including the Sodium Reactor Experiment, SRE.

In 2007, the Environmental Protection Agency, EPA proclaimed the site as a superfund site because of additional chemical toxicity at the site from the testing of rocket propellants.

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