Santa Susana Field Laboratory
Energy Technology Engineering Center

Sodium Reactor Experiment Accident
July 1959

August 29, 2009

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Sandia National Laboratories

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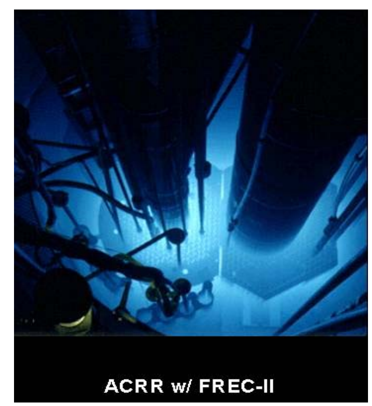

Nuclear Energy Safety Research

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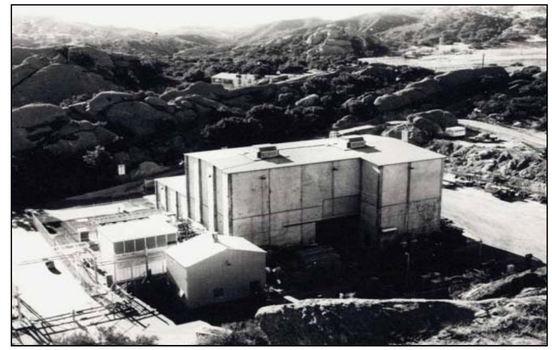
Presentation Purpose and Approach

- **Purpose:**
  - **Overview of nuclear reactor technology relevant to the Sodium Reactor Experiment (SRE)**
  - **Description of the cause and progression of the accident and fuel damage that occurred in July 1959**



SRE Facility (1957)

- **Approach:**
  - **Reviewed available information on SRE design and July 1959 reactor accident**
  - **Review focused on accident causes and resulting fuel damage**
  - **Review covered only 2 weeks of operations at the site and did not include subsequent recovery activities or other Area IV operations**

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Presentation Outline

SRE Facility (1958)

- **Background – early nuclear reactor technology**
- **Description of SRE reactor**
- **July 1959 sequence of events**
- **Reactor fuel damage**
- **Fission products* release mechanisms**
- **Comments and observations**

** Fission products are the atomic fragments left after a large nucleus fissions*

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Early Nuclear Power Reactor Development
Water and Sodium Cooled Systems

- **Early nuclear power reactor development focused primarily on Light Water cooled Reactors (LWR)**
  - **Water cooled reactors were selected for Naval applications**
  - **Water cooled reactors were already being commercialized**
  - **LWRs have limited efficiency (~33%) due to low temperature operation (~350^o C, 660^o F)**
  - **LWRs operate at high pressures (~2200 psi)**
- **Sodium (liquid metal) cooled reactors with graphite moderators were considered promising options for achieving higher efficiencies**
- **Sodium cooled reactors could operate at**
  - **Higher temperatures, higher efficiencies**
  - **But still operate at lower pressures**

Shippingport Pressure Vessel
Operational – 1957
(60 megawatt-electric)

Overview of Area IV Reactor Operations

- **Area IV – research focused on development of new types of nuclear power reactors**
- **SRE was the largest of the 10 reactors operated in Area IV**

Reactors Operated within Area IV (1956 – 1980)

Facility Name	Power, kW_t	Operating Period
Kinetics Experiment Water Boiler	1	07/56 -11/66
L-85 Nuclear Experiment Reactor	3	11/56 - 02/80
Sodium Reactor Experiment	20,000	04/57 - 02/64
S8ER Test Facility	50	09/59 - 12/60
SNAP Environmental Test Facility	65	04/61 - 12/62
Shield Test Irradiation Facility	50	12/61 - 07/64
S8ER Test Facility	600	05/63 - 04/65
Shield Test Irradiation Facility	1	08/64 - 06/73
SNAP Environmental Test Facility	37	01/65 - 03/66
SNAP Ground Prototype Test Facility	619	05/68 - 12/69

kW_t = kilowatt-thermal SNAP = Systems Nuclear Auxiliary Power

<u>Sodium as a Coolant</u>

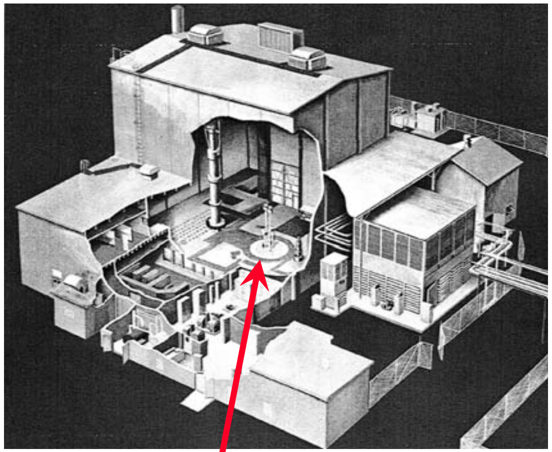
- ***Low pressure operation (boiling point of 883º C, 1621º F)***
- ***Excellent heat removal***
- ***Flammable in air***
- ***Can become radioactive***
- ***Melting point of 98º C, 208º F***

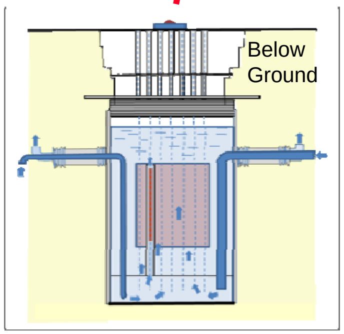
Sodium Reactor Experiment Description

Overview of
Sodium Reactor Experiment (SRE)

- The SRE was a 20 megawatt-thermal (MW_t), low pressure sodium cooled nuclear reactor
- Purpose of the SRE was to investigate different nuclear fuel materials and the use of sodium as a coolant
- SRE was operational from 1957 to 1964
- SRE did not operate on a continuous basis - each experiment (or run) lasted up to a few weeks
- Experiments were conducted under varying operating conditions in order to test designs and components, which required frequent startups and shutdowns, and refueling operations
- During Core I operations involving uranium metal fuel; 14 experimental runs were conducted between 1957 and July 1959

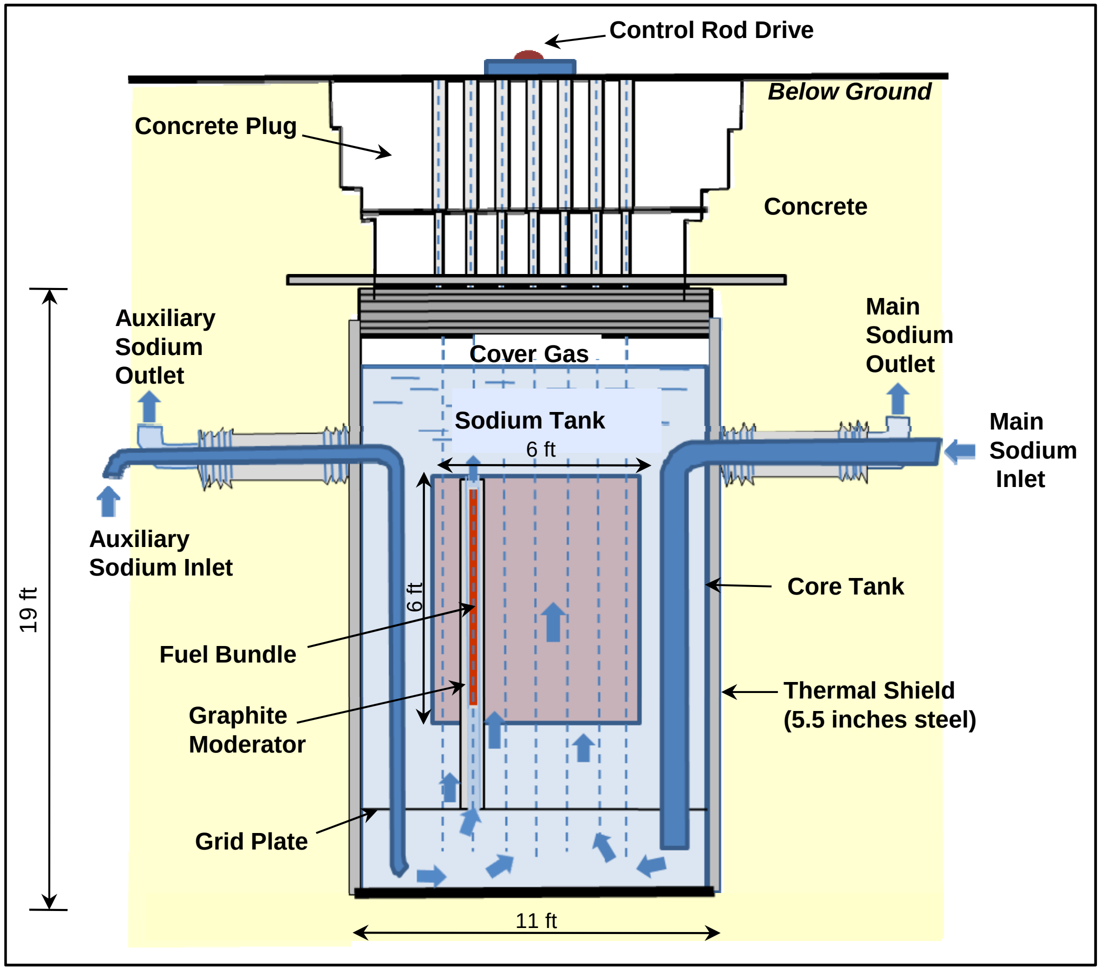
Design Rendition of SRE Facility (1957)





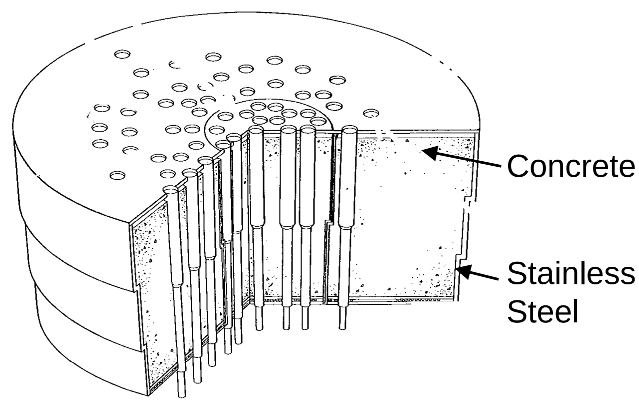
SRE Core and Vessel

SRE Core and Vessels



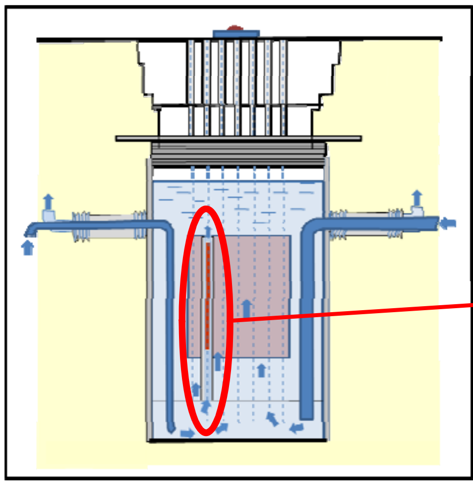
Vertical Section of SRE Reactor

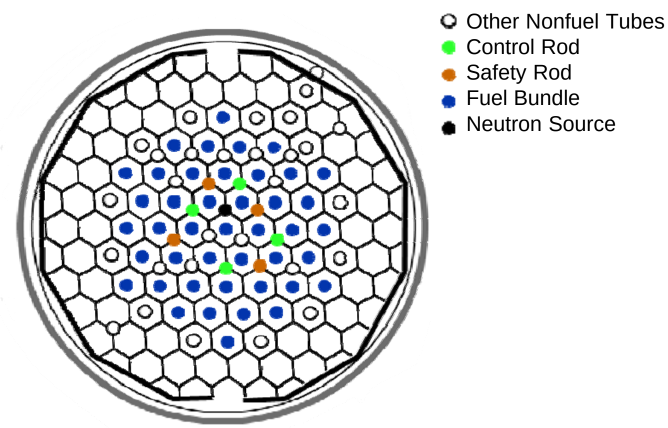
Handling of Upper Concrete Plug



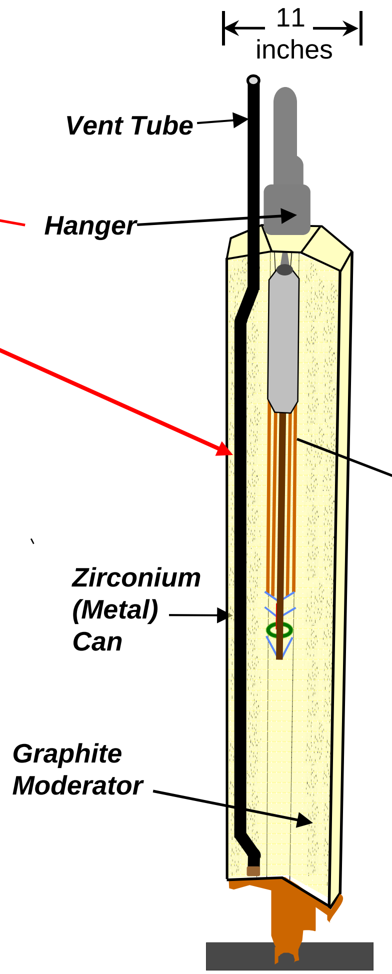
SRE Upper Concrete Plug

SRE Fuel Bundle and Moderator Can

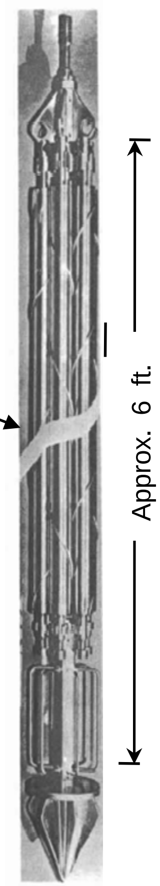




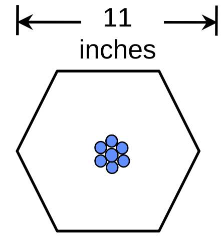
Hexagonal Moderator Cans Containing Fuel Bundles (Top View)



Moderator Can Assembly



Fuel Bundle

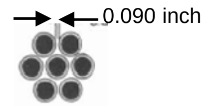


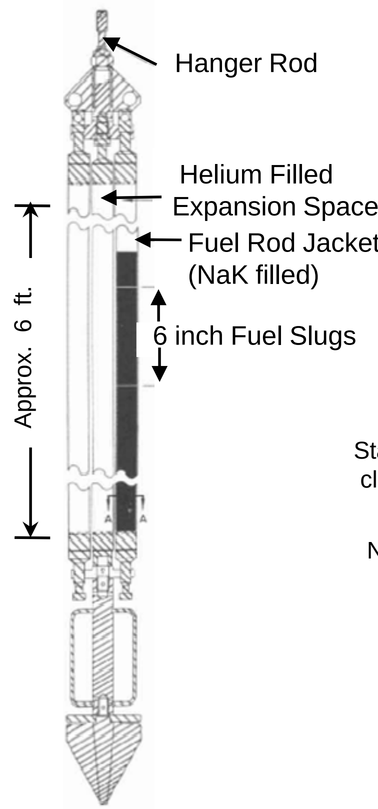
Cross-section of moderator can containing fuel bundle comprised of 7 fuel rods

SRE Fuel Bundle

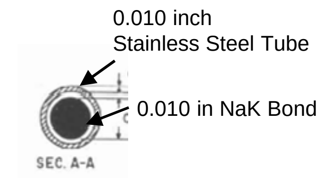
- **Uranium metal fuel**
- **2.7% U-235 enrichment (natural uranium is 0.7% U-235)**
- **Fuel slugs are 0.75 inch diameter and 6 inches in length**
- **Clad in stainless steel tubes**
- **Sodium-potassium (NaK) bonding between fuel and cladding**
- **Wire wrap around fuel bundles**

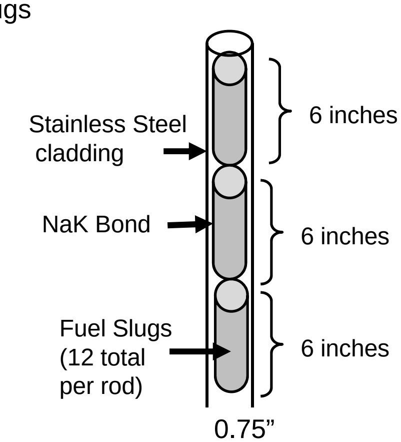
0.75 inch Diameter Fuel Slugs





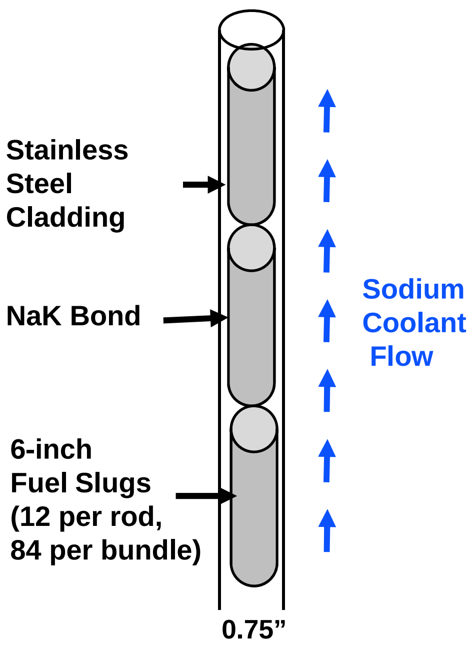
7-Rod Fuel Bundle

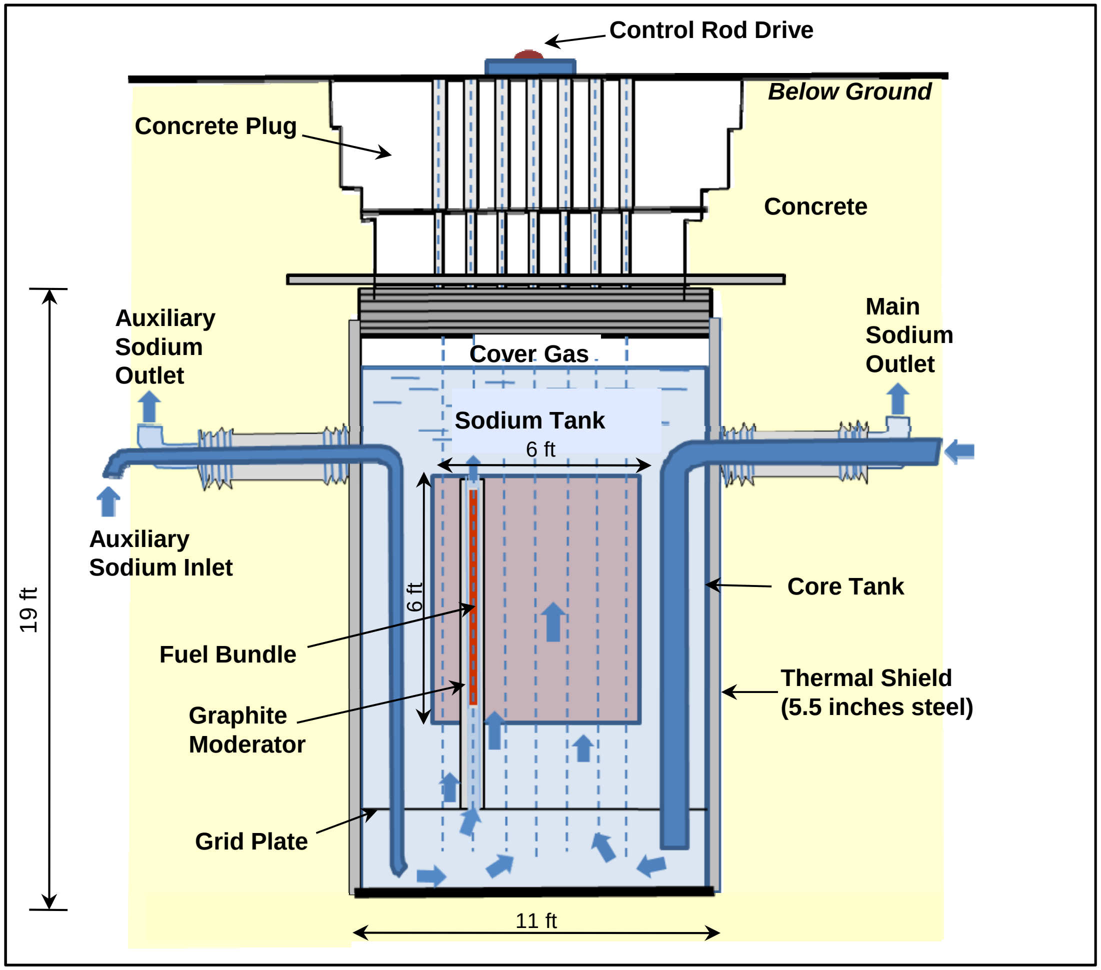




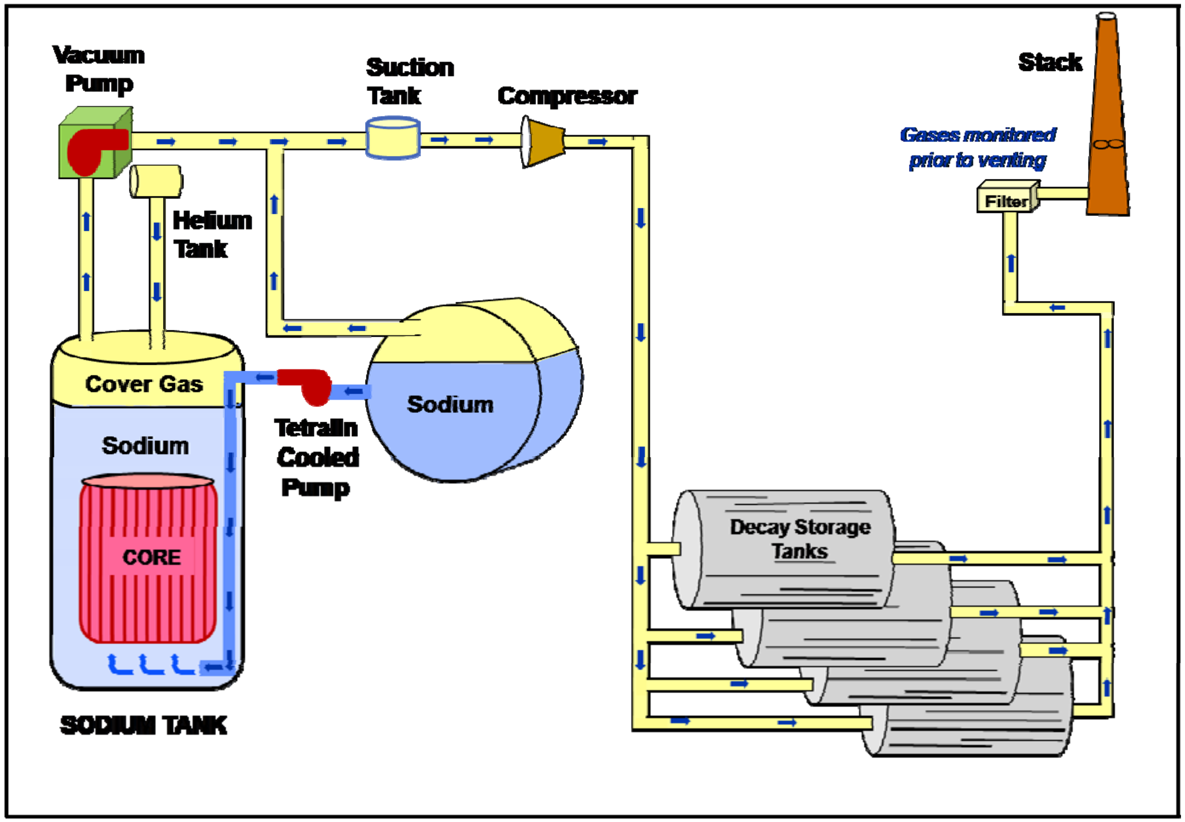
Fuel Rod

SRE Fuel Bundle Cooling





SRE Cover Gas and Venting System Under Normal Operations



- **Gaseous activation products* produced during normal operations would collect in the cover gas**
- **Cover gas was pumped to storage tanks to allow activation products to decay**
- **After decay to acceptable release levels, storage tanks were vented to atmosphere through a HEPA filter and stack**
- **Stack was monitored with radiation alarms and automatic shut-off valves to prevent release of activation products exceeding acceptable levels**

** Activation products are materials made radioactive by neutron activation*

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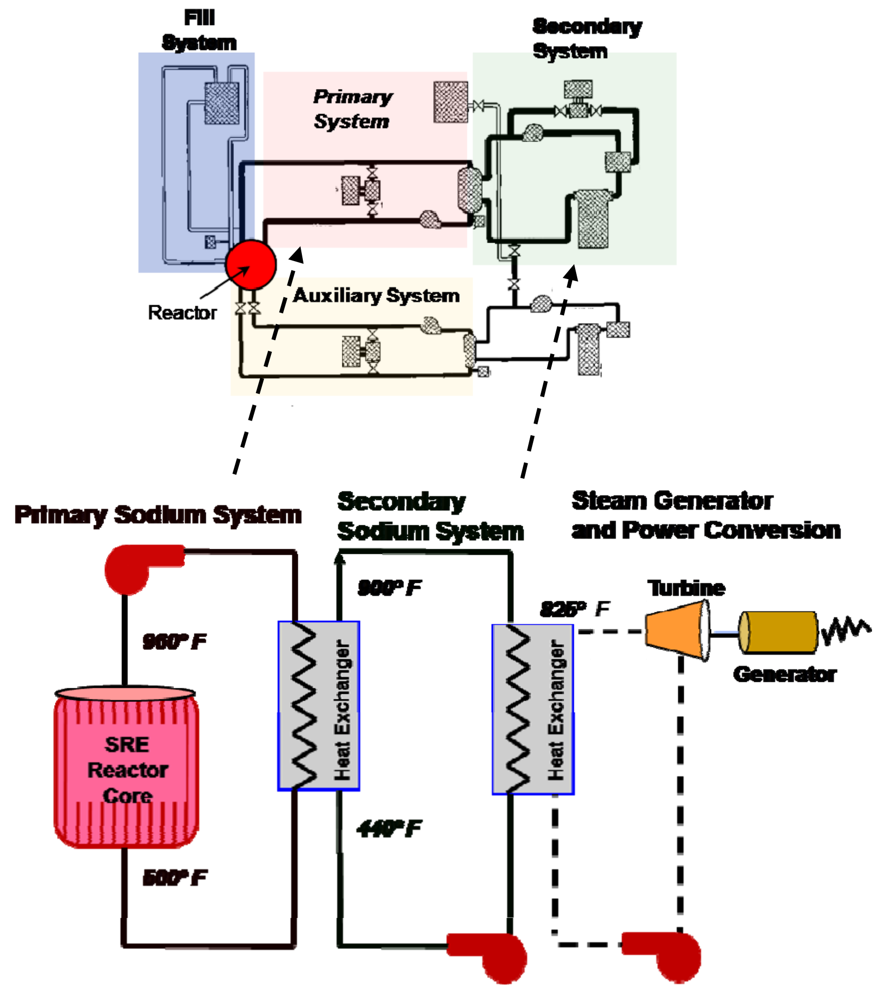
SRE Cooling Systems

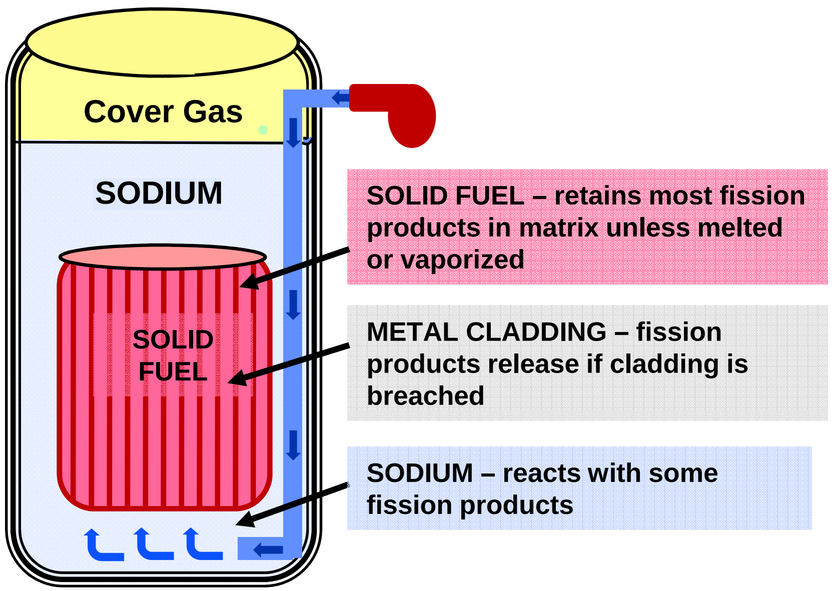
SRE Cooling System Features

- SRE core could produce up to 20 MW_t of power
- Primary sodium cooling loop removed heat to an intermediate heat exchanger
- Secondary sodium loop isolated core and radioactive coolant from power generation system
- Numerous other pumps and valves existed to startup and control system operations



Barriers to Release of Fission Products under Accident Conditions

- Multiple barriers were used to minimize release of radioactive materials
  - fuel
  - cladding
  - coolant
  - vessels
- Physical and chemical characteristics of different fission products affected the probability of release from fuel or coolant in an accident



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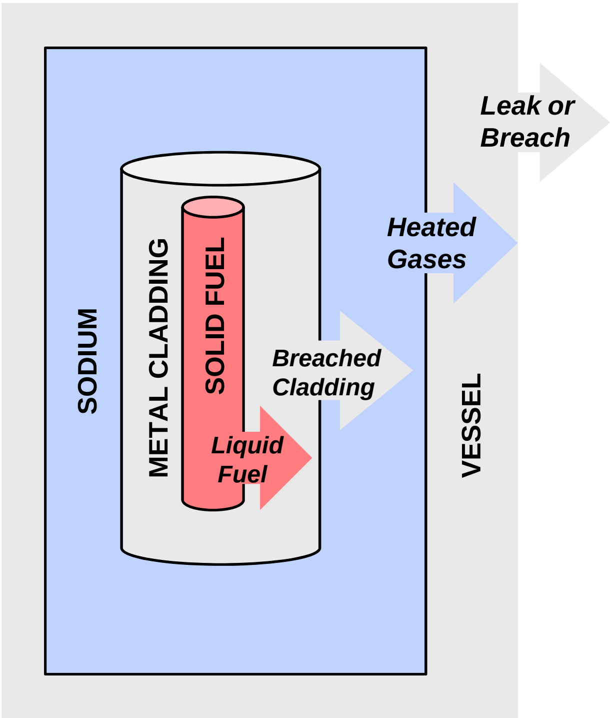
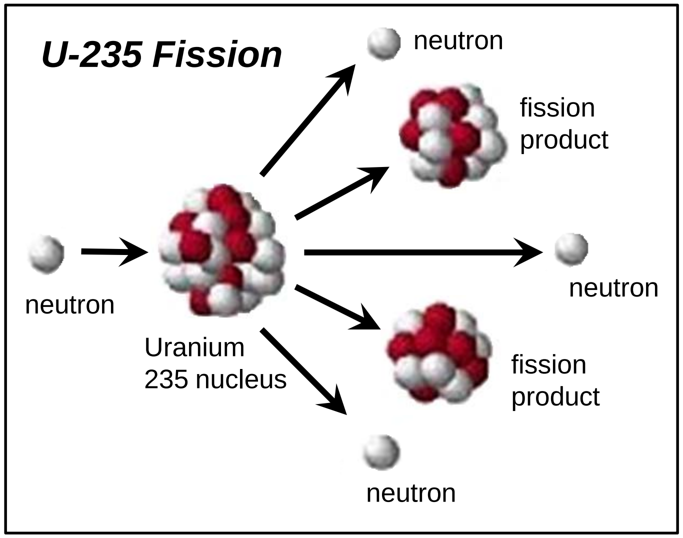
General Types of Fission Products

- **Inert gaseous species** (Xe, Kr) are non-reactive; readily released from the fuel
- **Volatile species** (I, Cs, …) have higher vapor pressures; generally reactive; released at higher temperatures
- **Non-volatile species** (Mo, Zr …) have low vapor pressure elements that generally remain with the fuel; less likely to be released



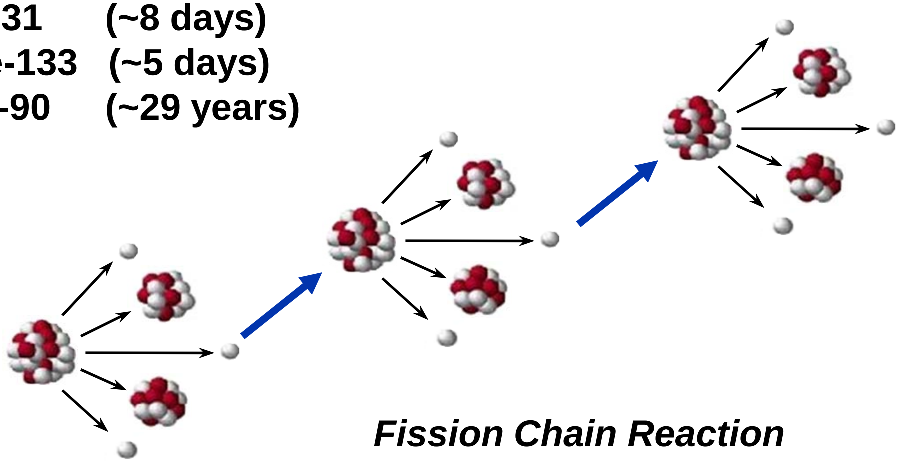
Barriers to Fission Products Release

Nuclear Fission of U-235



- U-235 “fissions” into two lighter nuclei (fission products)
- Fission products include most elements in varying percentages
- Radioactive with a range of half lives:

I-131 (~8 days)
Xe-133 (~5 days)
Sr-90 (~29 years)



Fission Chain Reaction

- On average, the fission of U-235 also produces about 2.4 neutrons
- One neutron is recaptured in U-235 to sustain the fission process
- Remaining neutrons escape out of system (or are absorbed into other materials)

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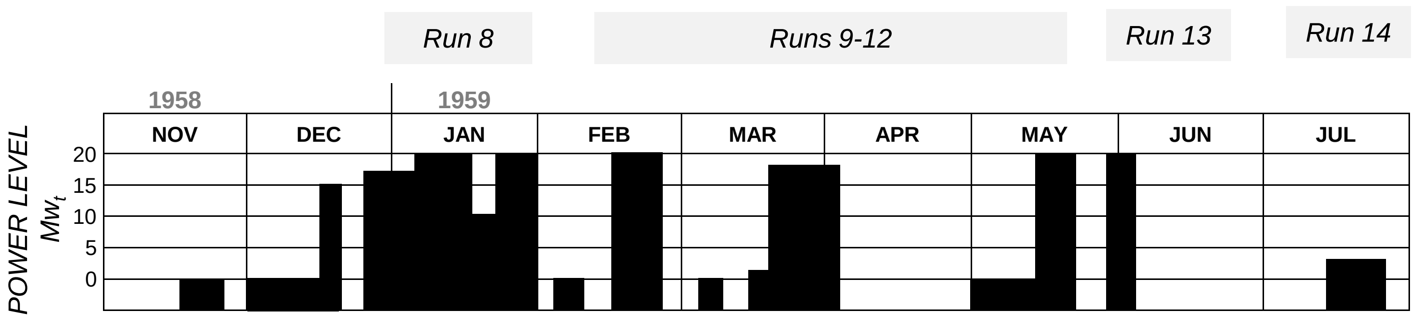
SRE Accident Description

Status of SRE Operations Prior to Run 14 Fuel Damage Event



- **Run 8** Oxygen contamination observed in sodium; higher than expected temperatures observed in some channels

    Fuel bundles and black residue removed, resulting in improved reliability of temperature measurements

- **Run 9** High power run – fuel channel exit temperatures higher than expected
- **Run 11** 20 MW_t power; fuel channel exit temperatures still higher than expected; fluctuations in primary sodium flow observed; several reactor scrams (shutdowns) experienced
- **Run 13** Various temperatures measured across the core were observed to increase steadily with time

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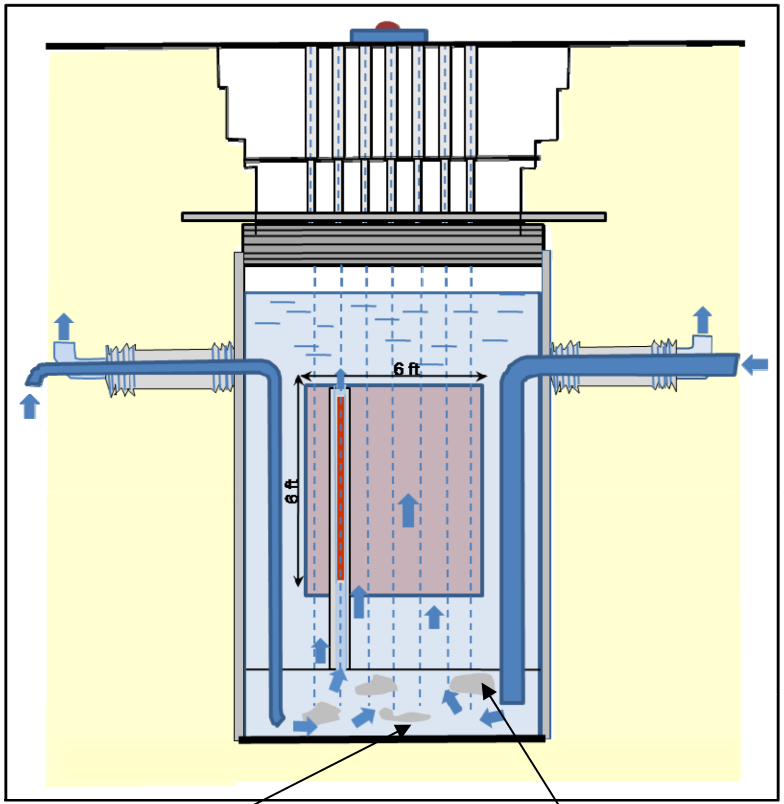
Observed Temperature and Power Variations Caused by Coolant Flow Blockages

- Leak in primary pump seal allowed organic pump coolant (*Tetralin,* $C_{10}H_{12}$) to leak into primary cooling system
- Tetralin decomposed at high temperature leaving an insoluble "carbon" material, which coated reactor internal components and formed partial blockages
- Blockages restricted coolant flow to fuel bundles, resulting in significantly higher fuel temperatures
- Erratic power response observed due to sodium voiding and re-flooding
- Leakage of Tetralin and associated temperature anomalies were recognized during these earlier runs
- Potential consequences of coolant blockages were not recognized



Tetralin ($C_{10}H_{12}$) coolant formed carbon blockages in inlet channels

Higher fuel temperatures in partially blocked channels

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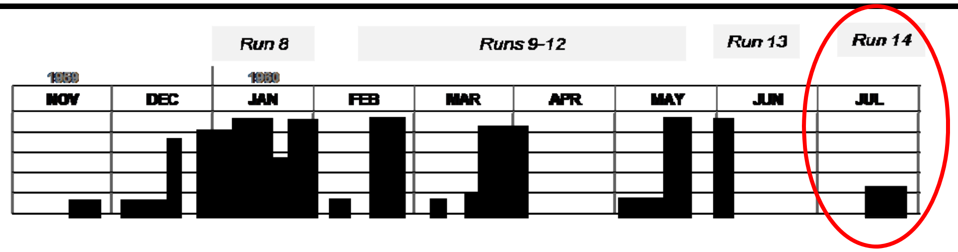
SRE Accident Run 14 Summary



July 12, 1959 Start up
July 26, 1959 Shutdown

- **July 12** – Initial operation – higher than expected fuel temperatures in some channels; high radiation levels (~0.5R/hr) recorded in reactor building due to shield plug leakage
- **July 13** – Startup after shield plug replaced; observed power changes were not consistent with control rod movements; reactor was shut down after a rapid power rise (excursion); power anomalies were caused by sodium boiling and re-flooding
- **July 14-26** – continued operations at various power levels were conducted to investigate reasons for temperature and flow readings; highest fuel temperatures were recorded in the July 22-24 period
    - Operations resulted in damage to 13 of 43 of the reactor's fuel bundles – cladding failures and partial melting
    - Fission products were released from the fuel into the reactor's primary sodium coolant
    - Primary reactor vessel did not fail, but some gaseous radionuclides escaped into reactor building from the cover gas
    - During Run 14 and the subsequent fuel recovery processes, fission products in the cover gas were periodically vented to the environment

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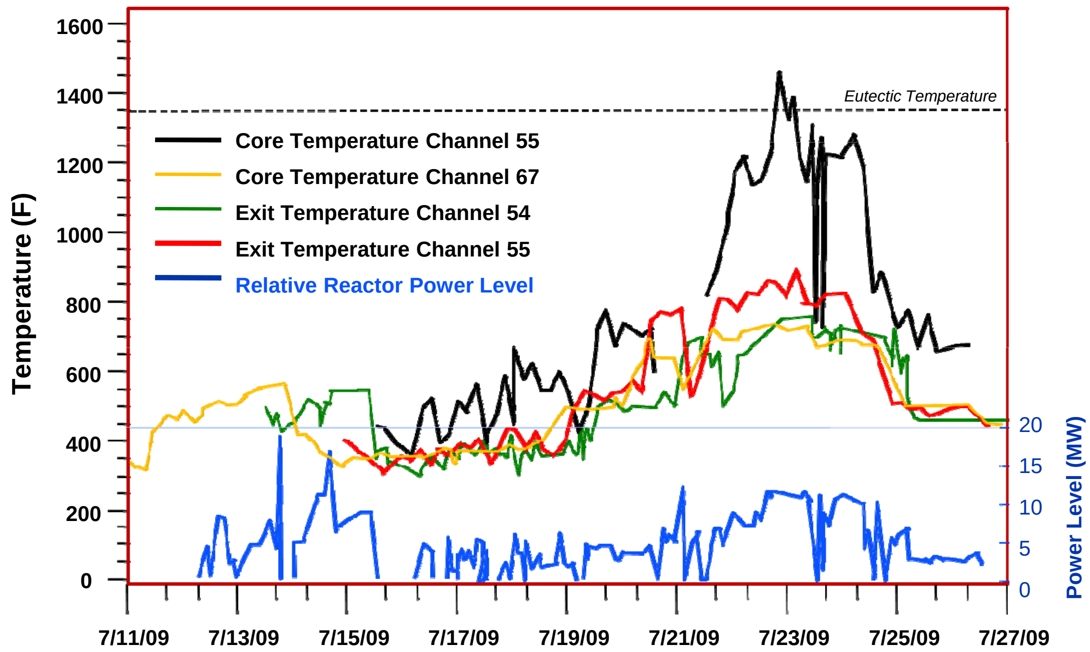
Continued Operations During Run 14

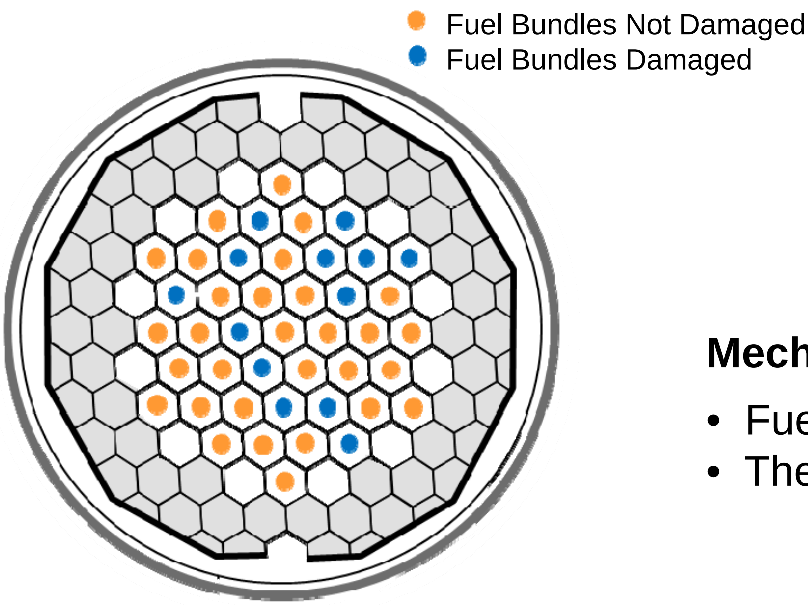
Temperature History for the 2-Week Period

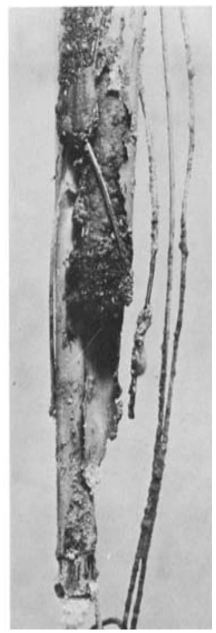
1. Core and sodium exit temperatures continued to increase
2. Highest fuel temperatures occurred July 22-24; most fuel damage probably occurred during this time
3. High fuel temperatures in blocked coolant channels allowed a low melting point alloy to form between cladding and fuel, causing local melting and cladding failure
4. Cladding was also breached as a result of fuel expansion and formation of the fuel/cladding alloy
5. Breached cladding allowed gaseous and some volatile fission products to be released to sodium coolant
6. Reactor shutdown on July 26th



SRE Damaged Fuel Description

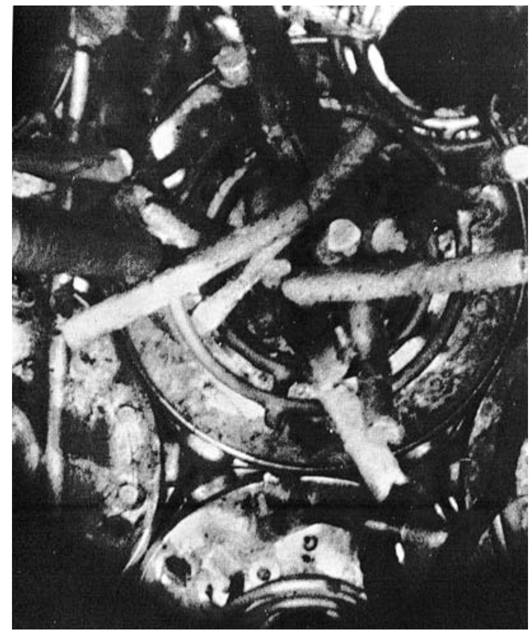
- 13 out of 43 total fuel bundles damaged
- Damaged fuel bundles showed evidence of local melting and cladding failure
- Additional fuel bundles may have been damaged during removal
- Most fuel slugs were still intact (i.e., had not melted**)**





Bottom section of damaged fuel bundle

Mid-section of damaged fuel bundle



Intact fuel slugs on top of core during damaged fuel bundle removal

Mechanisms

- Fuel/cladding melting
- Thermal cycling, cladding failure

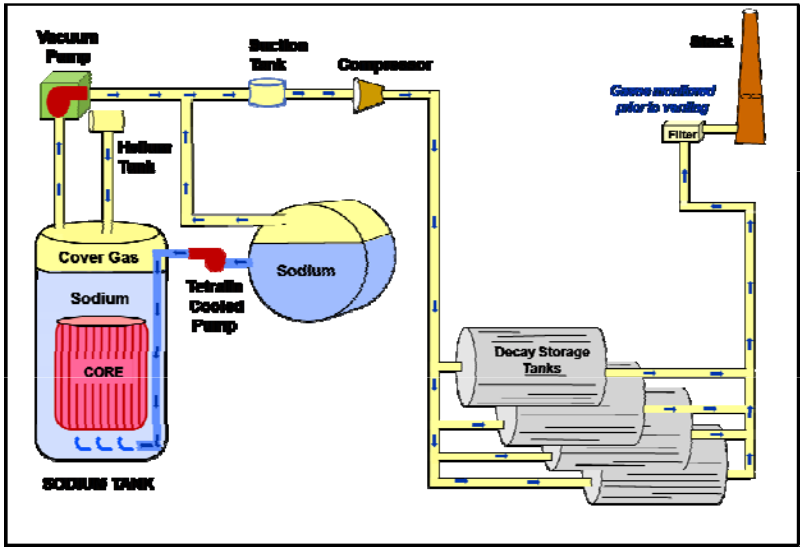
Observations Relevant to Releases from Damaged Fuel*

Cover Gas: Primarily noble gases observed in cover gas. Estimated to be less than ~1% of inventory. Radiation levels in cover gas much higher during and after Run 14. Iodine was not detected.

Sodium Coolant: Levels observed for different fission products varied but were generally less than 1% of inventory.

Iodine: Levels in sodium were less than expected. Iodine adsorbtion on internal structures was small.

Carbonaceous Material: Was an effective fission products collector (concentrations were ~1000 times higher than sodium).



Review of accident included:

- Sandia calculation of inventory at end of Run 14
- Review of retention and release mechanisms for the key fission products

** NAA-SR-6890, "Distribution of Fission Product Contamination in the SRE", R.S. Hart, March 1, 1962*

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Comparison of Core Radionuclide Inventory with Original SRE Analysis

- Sandia recalculated the SRE inventory after Run 14 using current methods (ORIGEN)
  - Based on best estimate of power history from early reports
- Sandia total inventory results were about 10% lower than original analysis
  - Noble gases (Xe, Kr) – essentially the same as original (1959) analysis
  - Non-volatiles (Zr, Ba, Ru, Ce) – specific radionuclides differ, but totals slightly lower
  - Volatiles (I, Cs...) – Cs-137, Sr-90 lower, but I-131 about 20% higher
- Original estimates were generally consistent with current Sandia inventory analysis

Total SRE Reactor Inventory, Curies			
Isotope	**Half Life**	**Hart Inventory**	**Sandia Inventory**
Cs-134	2.062 y	200	80
Cs-137	30.0 y	8,700	7,754
Sr-89	50.5 d	160,000	148,100
Sr-90	29.12 y	8,150	7,512
I-131	8.04 d	16,800	21,390
Ce-141	32.50 d	127,000	136,200
Ce-144	284.3 d	169,000	159,800
Ru-103	39.28 d	75,200	83,620
Ba(La)-140	12.74 d	56,100	62,640
Zr(Nb)- 95	63.98 d	553,000	295,800
Kr-85	10.72 y	1,100	934
Xe-133	5.245 d	50,800	48,930
Xe-131M	11.9 d	--	408
I-133	20.8 h	--	62,420
I-135	6.61 h	--	58,350
Totals:		***1,226,050***	***1,093,937***

Hart, R.S., Distribution of Fission Product Contamination in the SRE NAA-SR-6890 Atomics International, March 1, 1962.

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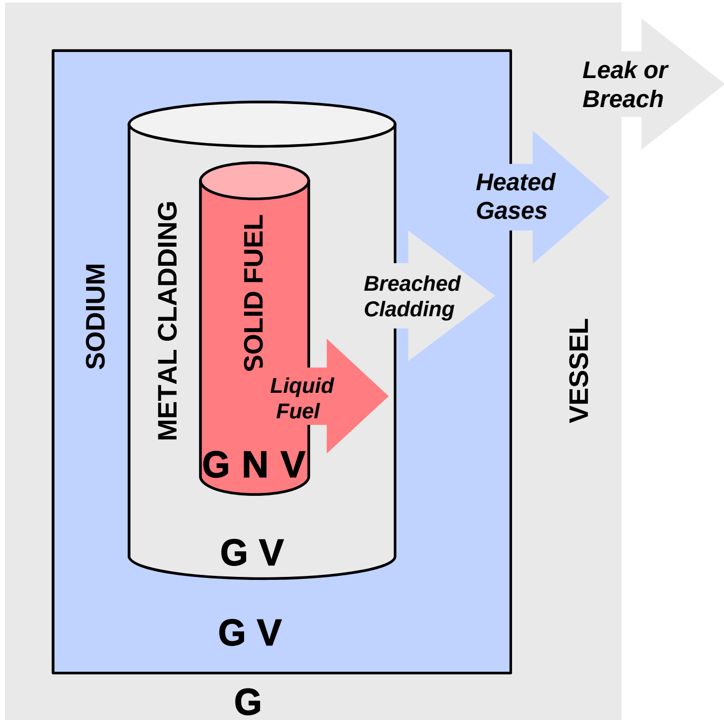
Fission Products Release Mechanisms

- **Noble gas radionuclides** (Xe, Kr…) are inert, can be released from liquefied fuel, are not retained in sodium, and reside in the cover gas
    - Less than 1/3 of fuel bundles were damaged (13/43)
    - Cladding breached in all 13 damaged bundles
    - High levels of noble gases were observed in cover gas during accident, which were subsequently vented through the stack
    - Liquefied fuel (uranium-iron alloy formation) occurred only at highest temperature locations

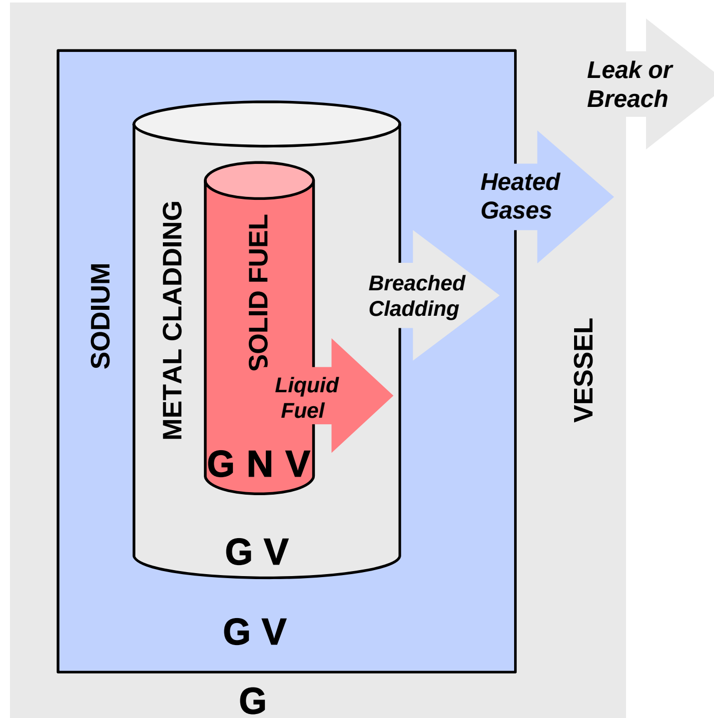
- **Non-volatile radionuclides** (Zr, Ba, Ru, Ce...) are low vapor pressure elements that tend to remain in fuel and will remain in the sodium



Radionuclides
G – Nobel gas
N – Non-volatile
V - Volatile

Fission Products Release Mechanisms (cont'd)

- **Volatile radionuclides** (I, Cs…) can be released from fuel, but will react with sodium
- Iodine reacts with sodium to form a soluble iodide (*NaI melting point 651º C, 1204º F*); most remains in the sodium
- Some release of volatiles can occur with high temperatures or sodium boiling at local fuel damage locations; these volatile fission products would then likely react with cooler bulk sodium
- Uranium metal fuel chemistry may explain low iodine readings in sodium
  - Iodine reacts with metal fuel to form non-volatile uranium triiodide (*UI_3, melting point 766º C, 1411º F*)
  - Unlike uranium oxide fuel (UO_2), a significant fraction of iodine is trapped in solid metal fuel as UI_3
  - Results from cladding breach experiments in EBR II (Idaho), and other tests indicated no elemental iodine released to sodium coolant – almost all retained in fuel as an iodide



Radionuclides
G – Nobel gas
N – Non-volatile
V - Volatile

SRE Conclusions

Observations and Comments

- Existing documentation from 1959 provides a reasonable description of the SRE accident and causes
- Fuel and cladding damage causes and mechanisms are consistent with current understanding
- The inventory was re-calculated using current tools and data, which confirmed original inventory estimates for important fission products
- Conclusions:
  - Absence of iodine radionuclides in the cover gas is consistent with known chemical mechanisms
    - Metal fuel and sodium form nonvolatile iodides
    - Similar observations from EBR-II and other experiments
  - From this review, primary release should have been noble gases
  - The July accident itself should not have resulted in major releases of volatile fission products

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