SAND2009-5433P

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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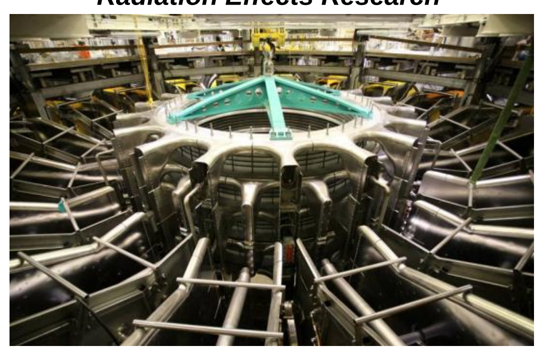
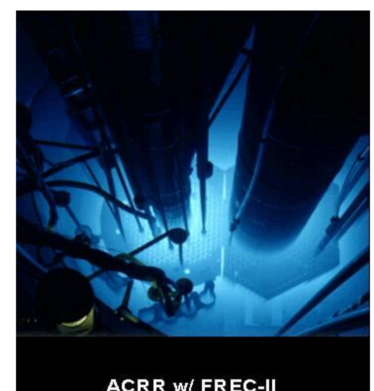


Inertial Confinement Fusion



Nuclear Energy Safety Research

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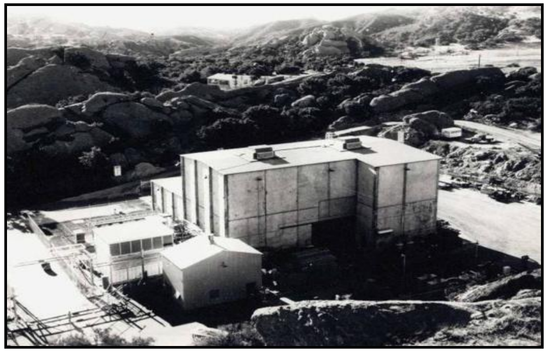
Presentation Purpose and Approach

- **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***

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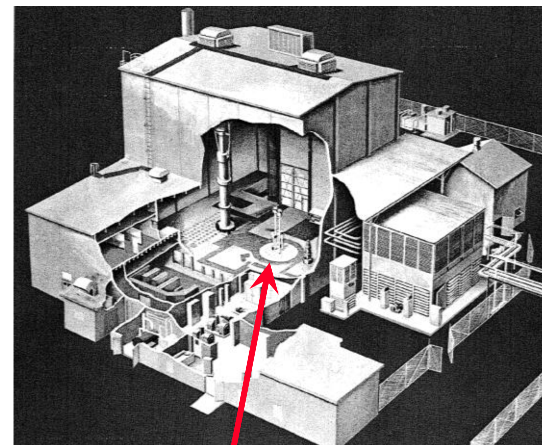
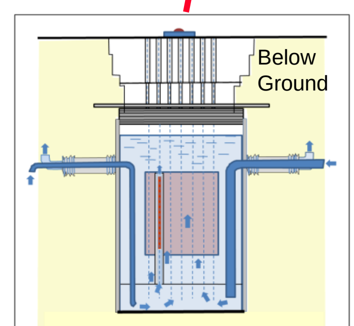
Sodium Reactor Experiment Description

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

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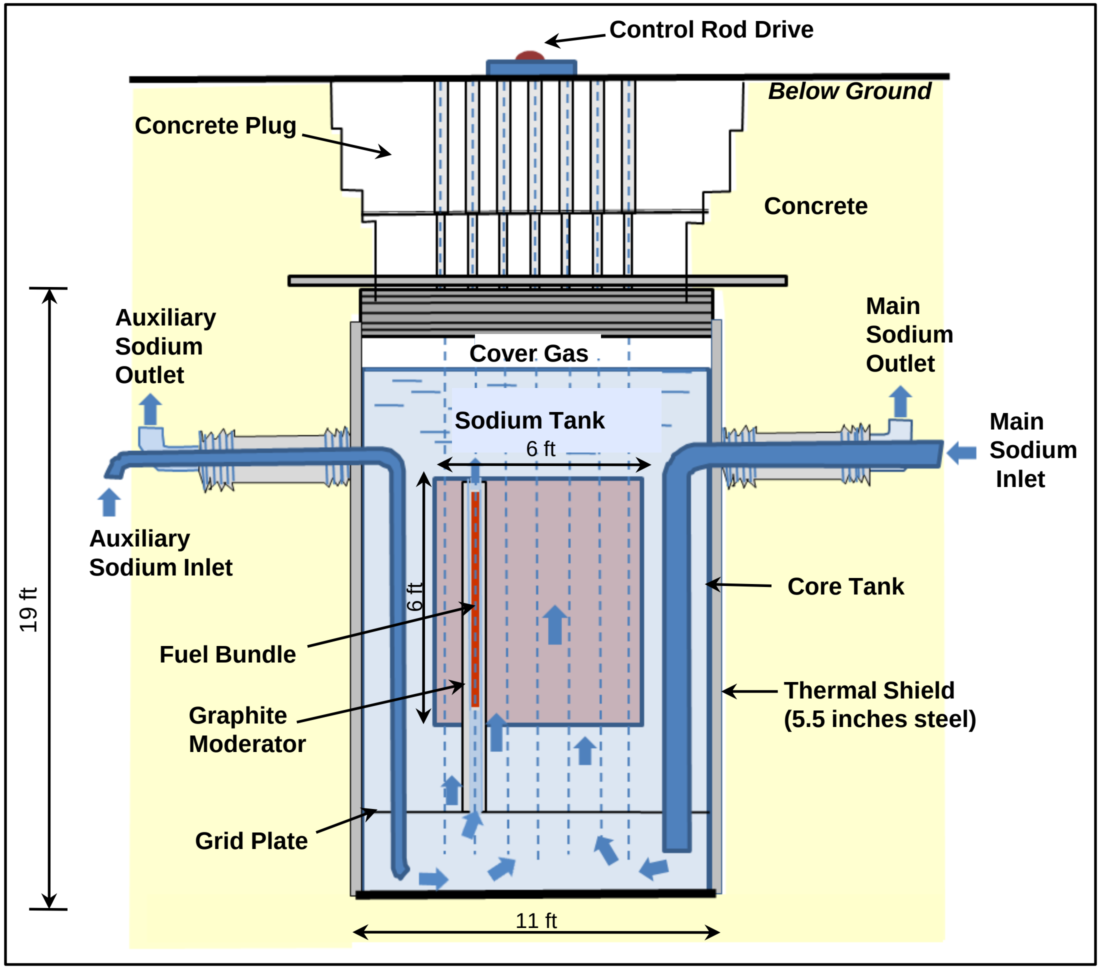
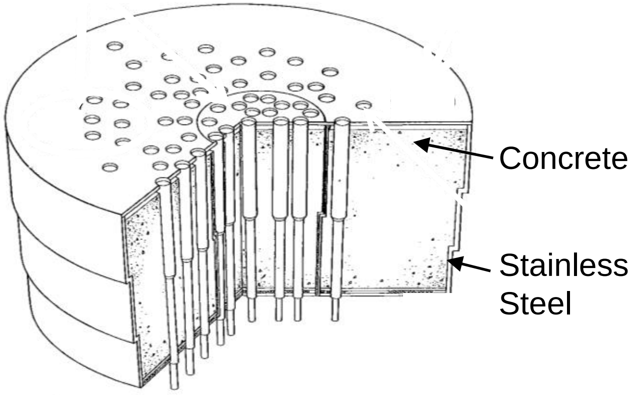
SRE Core and Vessels



Vertical Section of SRE Reactor

Handling of Upper Concrete Plug



SRE Upper Concrete Plug

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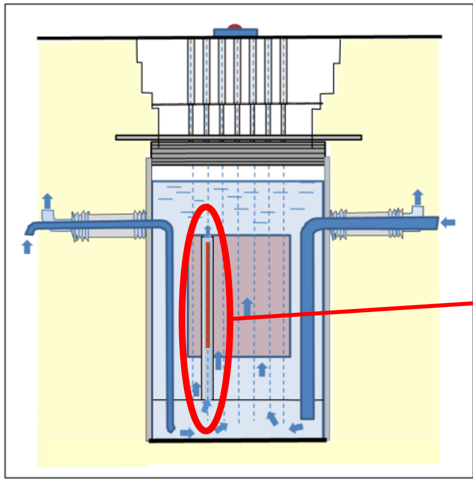
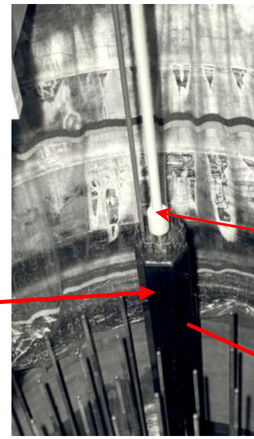
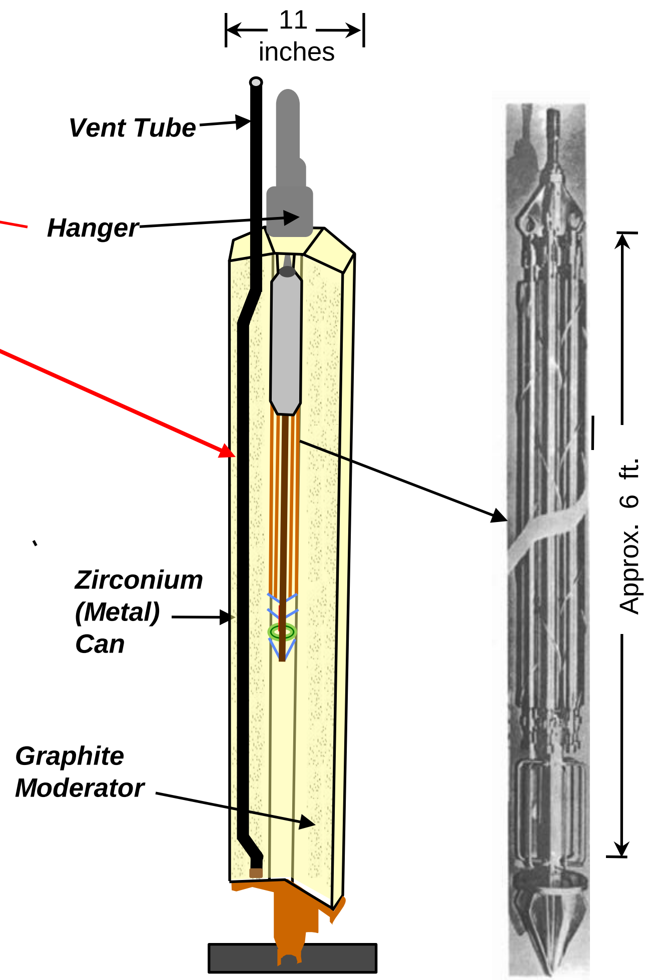
SRE Fuel Bundle and Moderator Can

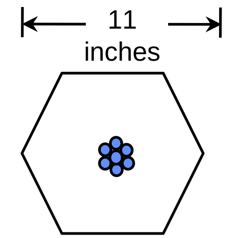




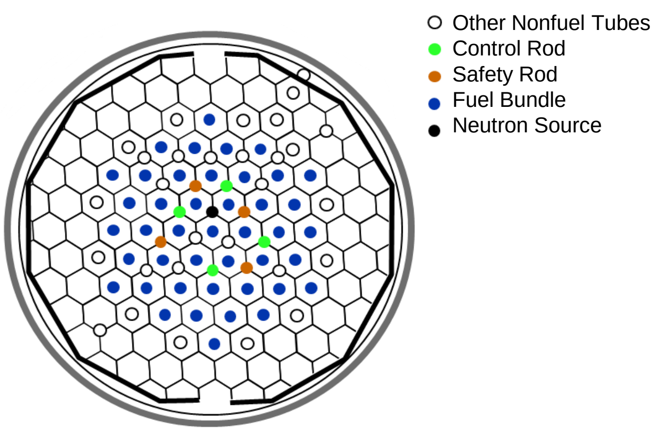


Moderator Can Assembly

Fuel Bundle



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

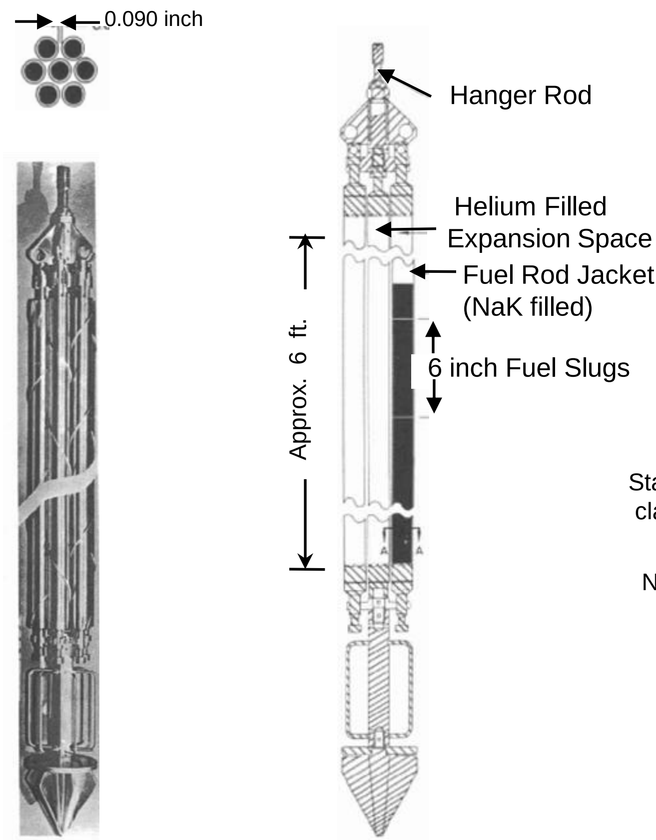


Hexagonal Moderator Cans Containing Fuel Bundles (Top View)

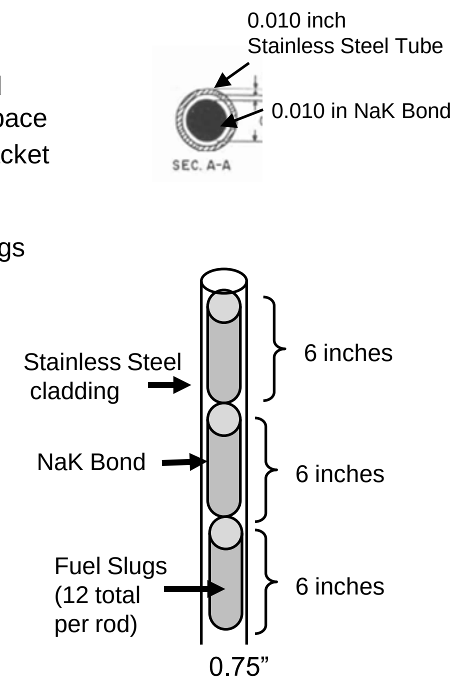
SRE Fuel Bundle

- **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

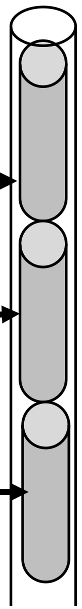


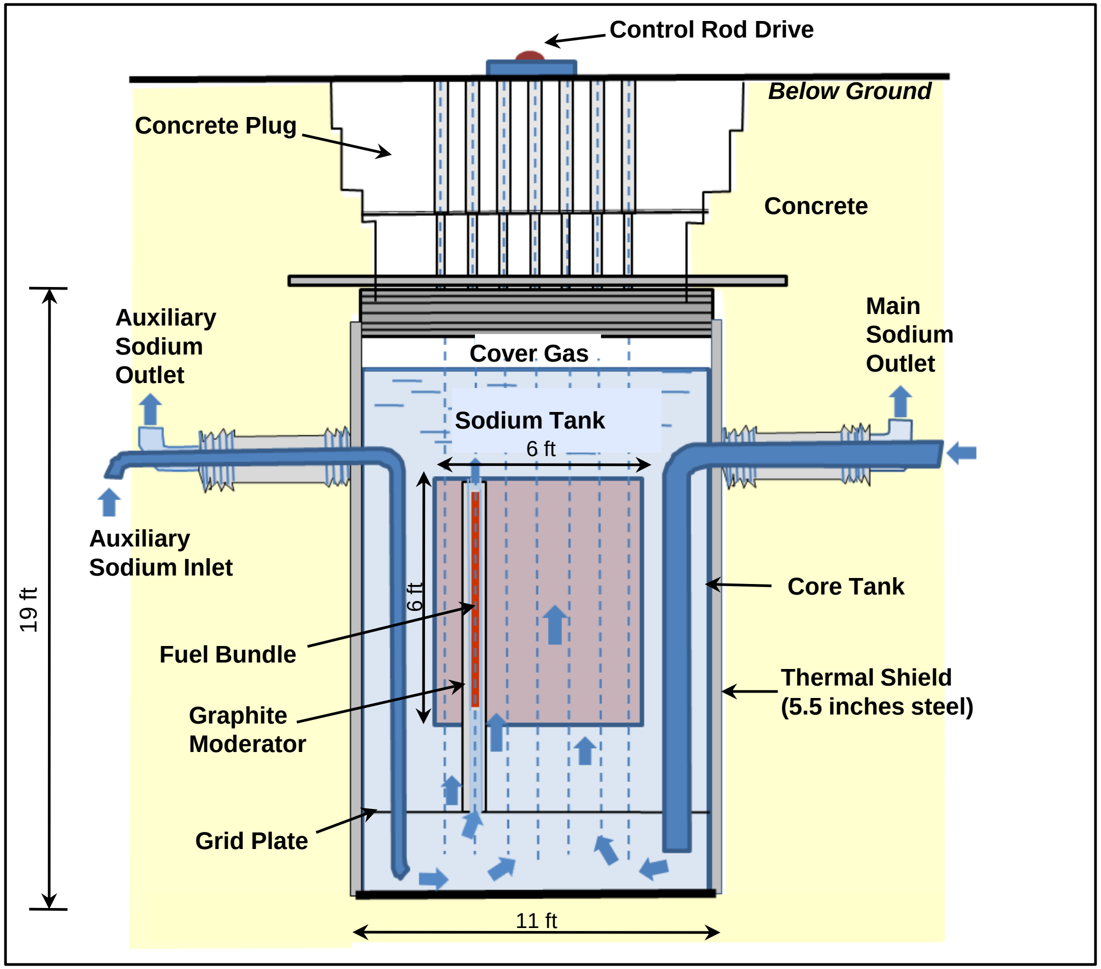
7-Rod Fuel Bundle



Fuel Rod

SRE Fuel Bundle Cooling





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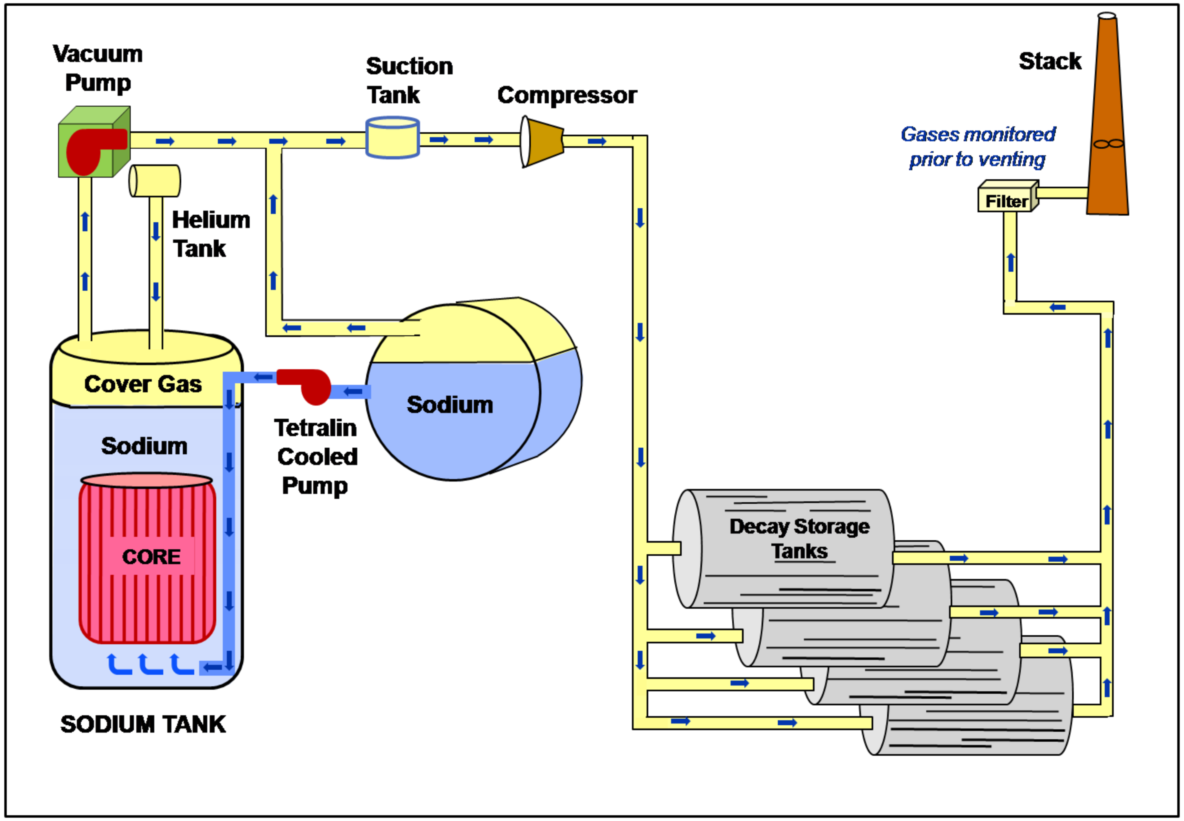
SRE Cover Gas and Venting System Under Normal Operations



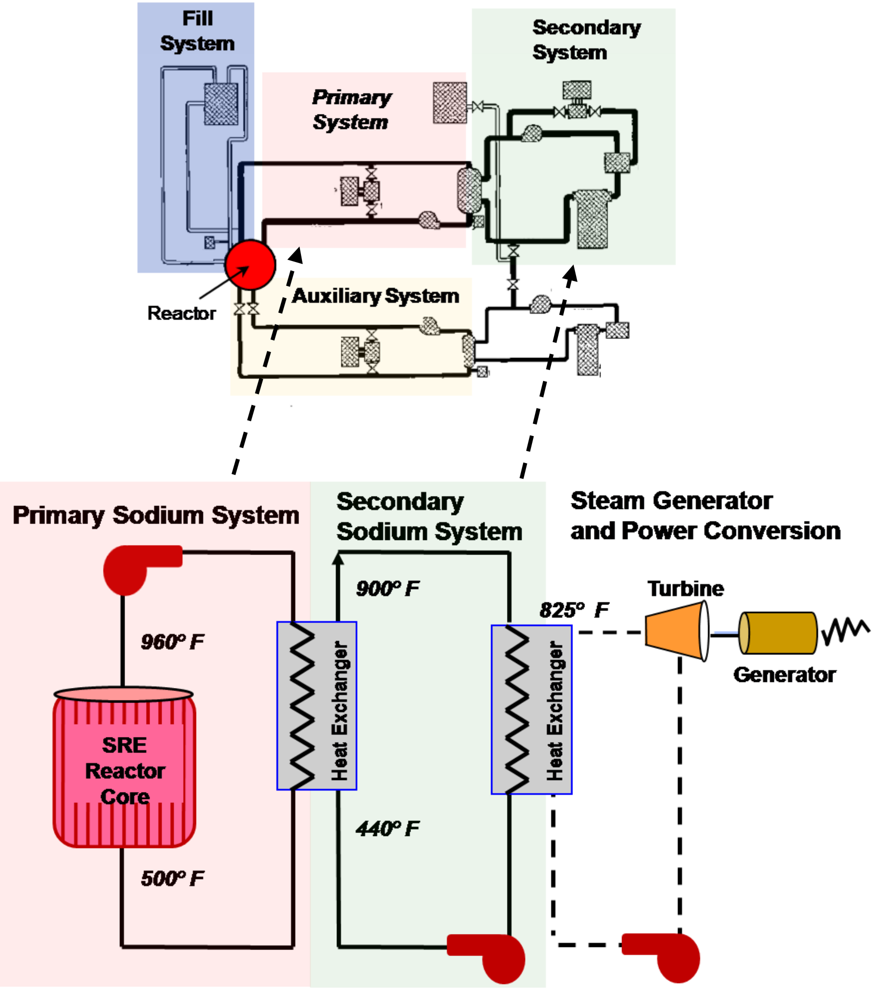
- **Gaseous activation products* produced during normal operations would collect in the cover gas**
- **Cover gas was pumped to storage tanks to allow activation products to decay**
- **After decay to acceptable release levels, storage tanks were vented to atmosphere through a HEPA filter and stack**
- **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*

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



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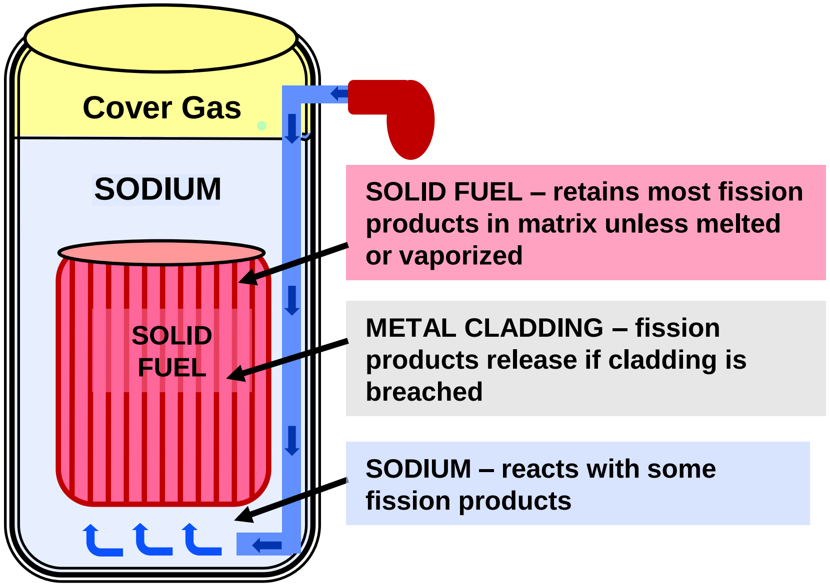
Barriers to Release of Fission Products under Accident Conditions

- 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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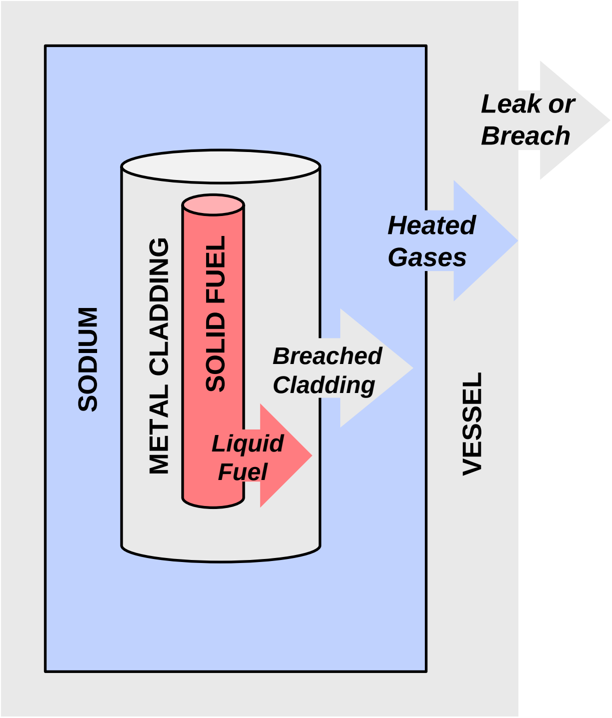
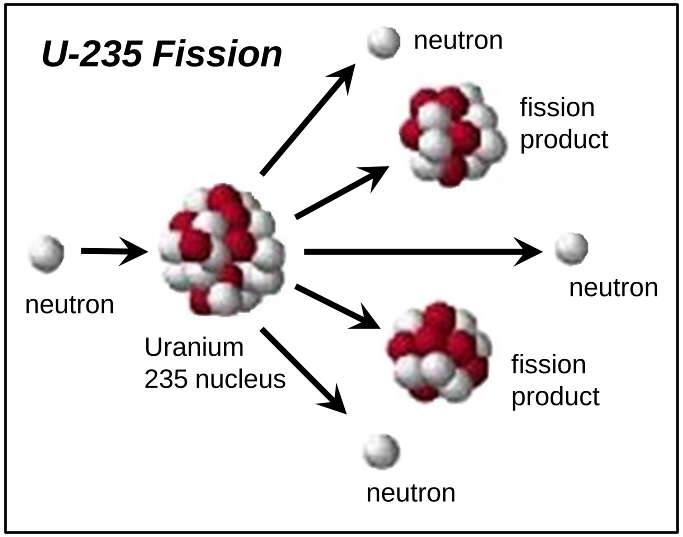
General Types of Fission Products

- **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



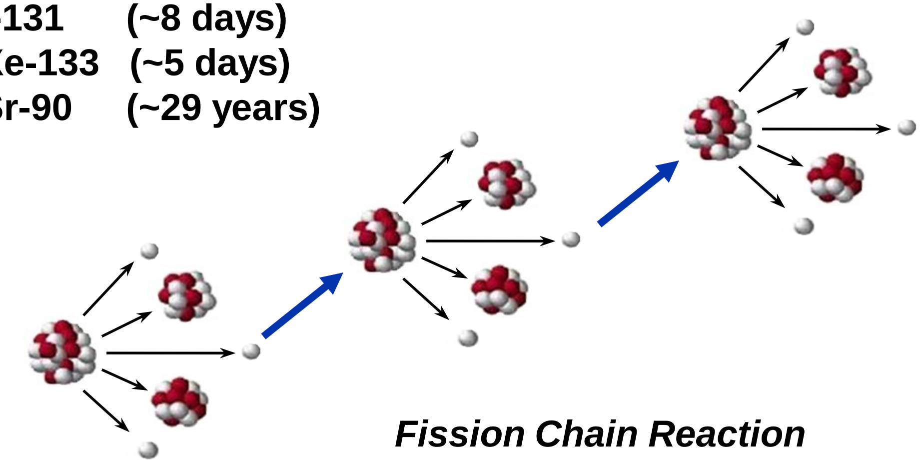
Barriers to Fission Products Release

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)

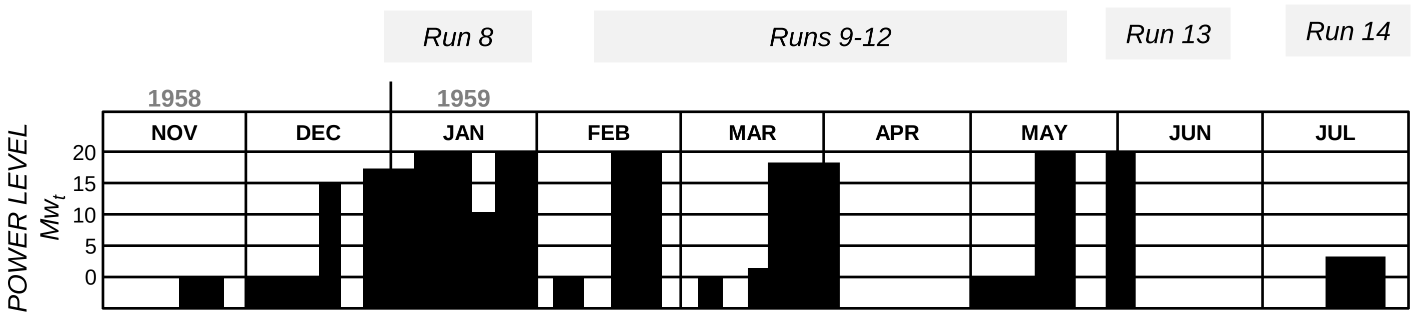


Fission Chain Reaction

- 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)

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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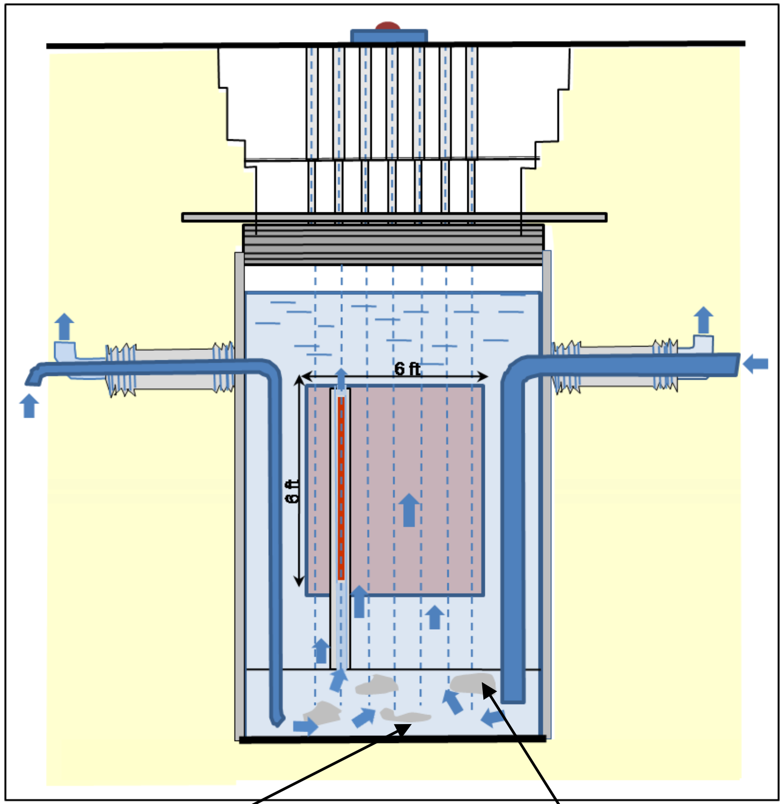
Observed Temperature and Power Variations Caused by Coolant Flow Blockages

- 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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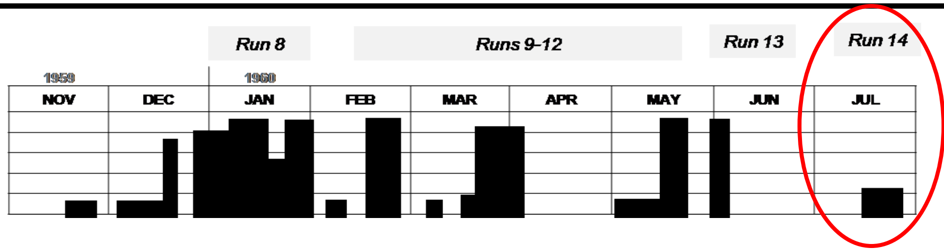
SRE Accident Run 14 Summary



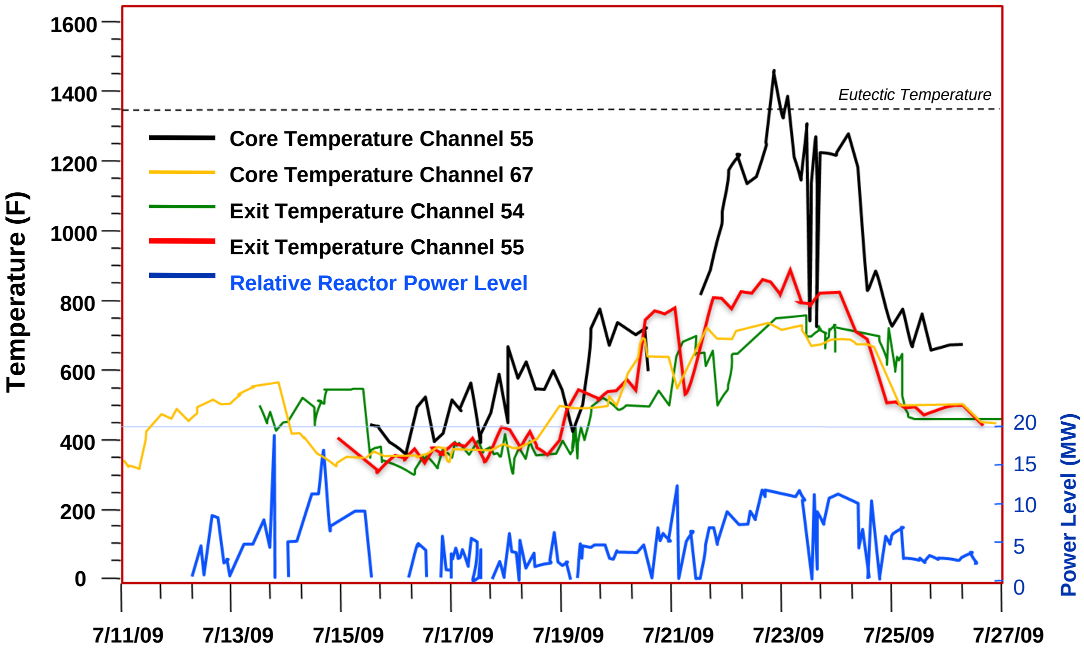
July 12, 1959 Start up
July 26, 1959 Shutdown

- **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

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



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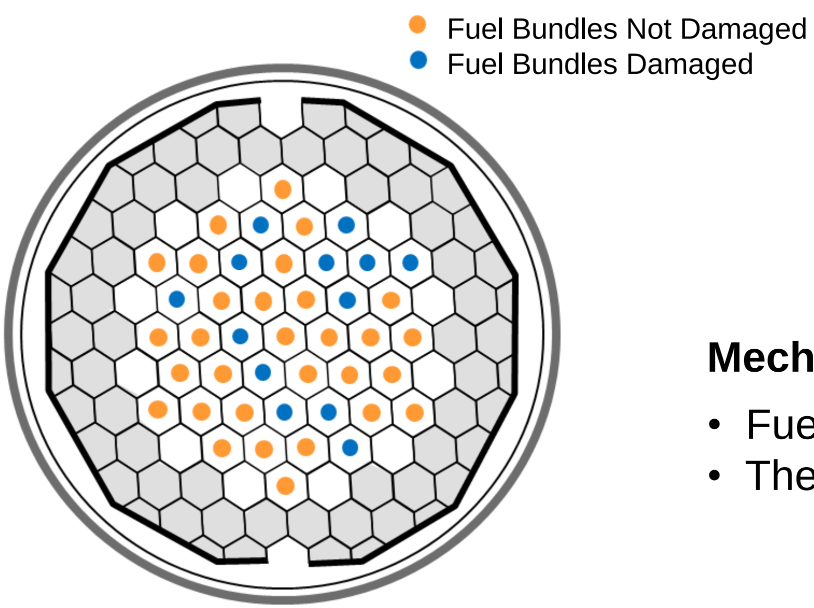
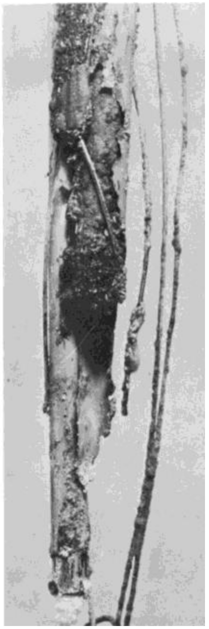
SRE Damaged Fuel Description

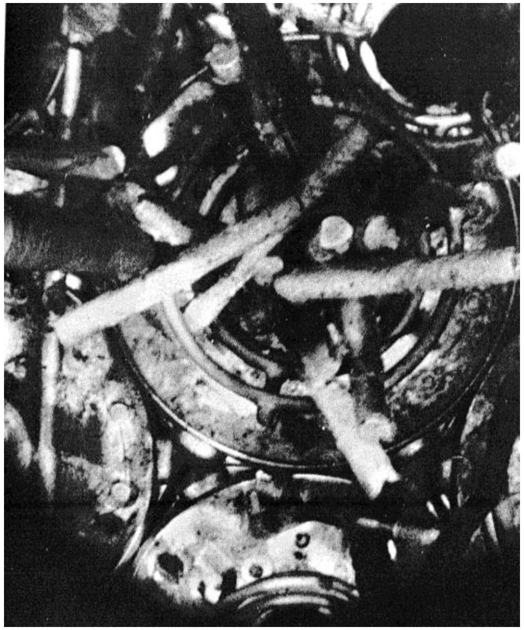
- 13 out of 43 total fuel bundles damaged
- Damaged fuel bundles showed evidence of local melting and cladding failure
- Additional fuel bundles may have been damaged during removal
- Most fuel slugs were still intact (i.e., had not melted**)**





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

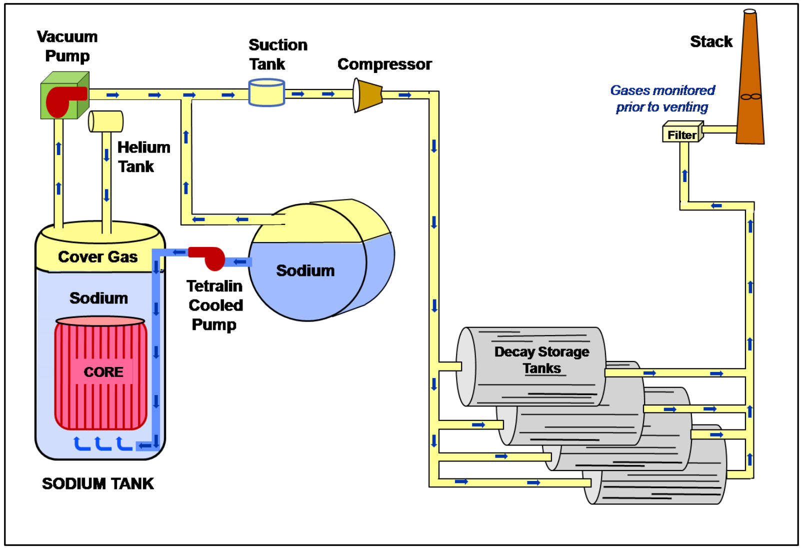
Observations Relevant to Releases from Damaged Fuel*

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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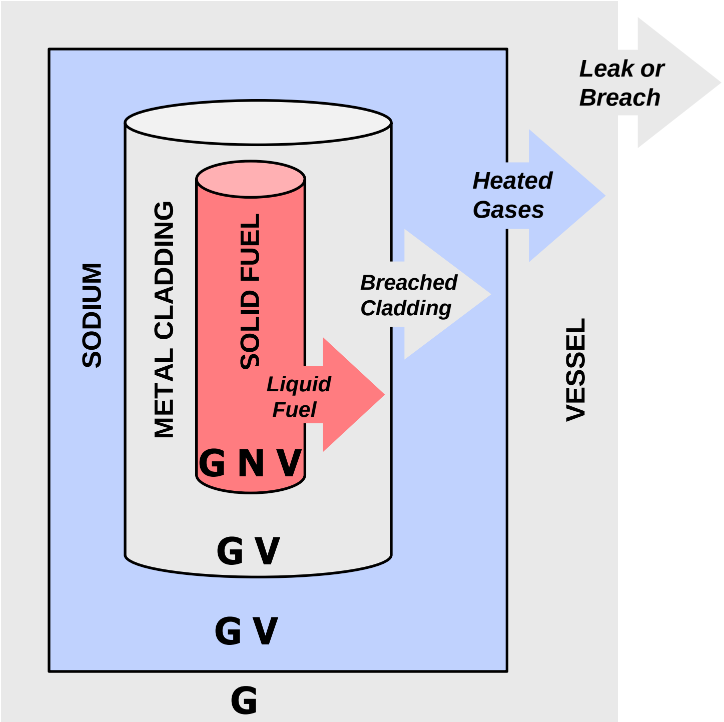
Fission Products Release Mechanisms

- **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

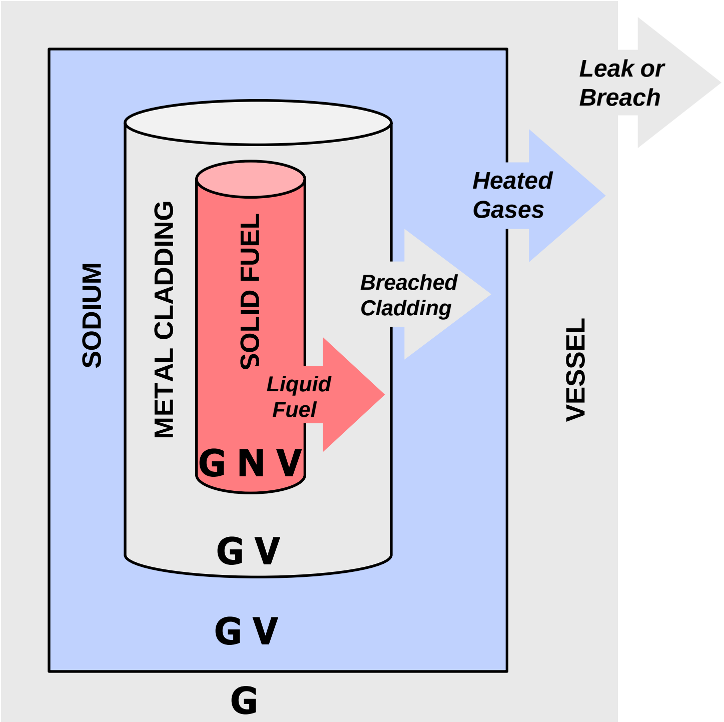
- **Non-volatile radionuclides** (Zr, Ba, Ru, Ce...) are low vapor pressure elements that tend to remain in fuel and will remain in the sodium



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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Dr. Paul S. Pickard, Sandia National Laboratories

- Senior Scientist/Engineer in the Advanced Nuclear Energy Programs at Sandia, BS in Physics - Wheaton College, MS/PhD in Nuclear Engineering--University of Arizona, Former faculty member in Nuclear Engineering at the U of Arizona and U of Illinois
- Research programs on advanced nuclear power conversion systems for next generation reactors, thermochemical cycle research for hydrogen production using high temperature nuclear reactors, and design and development of advanced reactors
- Technical Director for the US DOE Nuclear Hydrogen Initiative and the Generation IV Advanced Reactor Power Conversion Programs
- Responsible for Sandia Reactor Safety Experiment Program sponsored by Nuclear Regulatory Commission on Liquid Metal Fast Breeder Reactor & Light Water Reactor in core accident progression to evaluate the safety of light water & sodium cooled reactors

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Representative References on Volatile Fission Product Behavior in Sodium and Uranium Metal Fuels

US, Great Britain, German, French papers on behavior in sodium

- A.W. Castleman, Jr. and I.N. Tang, “Fission Product Vaporization from Sodium Systems”, BNL-13099, Brookhaven National Laboratory Upton, New York, 1968
- R.S. Hart and C.T. Nelson, “Fission Product Retention Characteristics of Sodium at High Temperatures”, NAA-SR-MEMO-8712 Special, Atomics International Canoga Park, CA
- W.S. Clough, “The Partition of Iodine between Liquid Sodium and the Gas Phase at 500 ◦C”, Journal of Nuclear Energy, 23 (1969) 495-503.
- H. Sauter and W. Schütz, Aerosol and Activity Releases from a Contaminated Sodium Pool into an Inert Gas Atmosphere, KfK 3504, Kernforschungszentrum Karlsruhe, Germany, 1983.
- M. Berlin, E. De Montaignac, J. Bugresne, and G. Geisse, “Evaluation of the Sodium Retention Factors for Fission Products and Fuel”, Rapport DSN #599e, Conferénce Internationale sur La Súreté des Reactures á Métal Liquide et ses aspects conception et Fonctionnement, Lyon, France, July 19-23, 1982.

US, Canada papers on behavior in uranium metal fuel

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