Sodium Reactor Experiment
Fuel Meltdown—July 1959

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Introduction

I have been asked to review selected documents related to the partial fuel meltdown accident that occurred at the Sodium Reactor Experiment (SRE) in July 1959, and present my views regarding the accident. I begin with several general observations.

First, I am a nuclear physicist with a background also in health physics. I am not a chemist.

Second, I have not read all the documentation related to this accident. In fact, I do not believe anyone has done so. Not all the documentation has been provided to those of us speaking here today.

Third, it should be noted that the SRE accident in July 1959 is not the only reactor accident that occurred at the Santa Susana site, and it is not the only source of hazardous materials, including non-radioactive releases, from the site.

Fourth, this analysis does not address the disposition of the sodium or other contaminated materials associated with the cleanup of the site following the accident. There is evidence, for example, that sodium was intentionally burned in open-air pits.

Fifth, this accident occurred during a period when the U.S. Atomic Energy Commission (AEC) and its contractors frequently kept radioactive releases secret from the public and mislead the public about radiation risks. Atomics International (AI) and the AEC kept this accident secret from the public for more than a month. AI issued a press release on a Saturday morning, August 29, 1959. The timing of the press release was surely designed to minimize its impact. Moreover, the press release presented false information to the public, namely, "The fuel element damage is not an indication of unsafe reactor conditions. No releases of radioactive materials to the plant or its environs occurred and operating personnel were not exposed to harmful conditions." The last sentence of this quote is similar to one of the findings of the AI interim report release six weeks later, "In spite of the cladding failure to at least 11 of the fuel elements, no radiological hazard was present to the reactor environs." [1]

One has to question the extent to which AI staff members who participated in the analysis of the SRE accident were complicit in writing or reviewing the press statement; surely

[1] A.A. Jarrett (General Editor), "SRE Fuel Element Damage, Atomics International, NAA-SR-4488, November 15, 1959, p. I-2.

being aware that radioactivity was intentionally discharged to the environment during and after the accident, including the venting on July 15. Consequently, the press statement, if not the interim report, raises concerns regarding the validity of some of the subsequent analyses and reports of the accident published by AI.

The most important factor affecting the safety of a reactor of this size or larger is not the design, but the safety culture at the plant. The safety culture at the SRE reactor was appalling by today's standards, and unwarranted even by the standards of the day. As concluded by Theos J. Thompson, an MIT reactor expert, five years after the accident,

> During that time so many difficulties were encountered that, at least, in retrospect, it is quite clear that the reactor should have been shut down and the problems solved properly. Continuing to run in the face of a known Tetralin leak, repeated scrams, equipment failures, rising radioactivity release, and unexplained transient effects is difficult to justify.[2]

There have been several estimates of the air-pathway release of radioactivity to the environment by different experts and expert groups. These include a 1959 interim report by AI,[3] a 1962 AI analysis by R.S. Hart;[4] a study by Arjun Makhijani that is under court seal as a condition of settlement of the case, O'Connor v. Boeing, 2005 analyses by John A. Daniel[5] and Jerry D. Christian,[6] that are rebuttals to Makhijani's report, reports by a panel of experts released in 2006 by the Santa Susana Field Laboratory Advisory Panel[7] including reports by David Lochbaum,[8] and Jan Beyea;[9] a rebuttal to the Lochbaum and Beyea reports prepared by John R. Frazier for Boeing;[10] and reports prepared for today's

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[2] T. J. Thompson and J.G. Beckerley, Editors, *The Technology of Nuclear Reactor Safety*, *Volume 1, Reactor Physics and Control*, prepared under the auspice of the Office of Technical Information, U.S. Atomic Energy Commission, The MIT Press, Cambridge, 1964, Chapter 11, "Accidents and Destructive Tests," by T.J. Thompson, p. 644. Theos J. Thompson was the chairman of the AEC's Advisory Committee on Reactor Safeguards, recipient of the AEC's Ernest Orlando Lawrence Award, and later became a commissioner of the AEC.

[3] A.A. Jarrett (General Editor), "SRE Fuel Element Damage, Atomics International, NAA-SR-4488, November 15, 1959.

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

[5] John A. Daniel, "Investigation of Releases from the Santa Susana Sodium Reactor Experiment in July 1959," Daniel & Associates, Inc., TDR-DA/0502, May 27, 2005. I do not know whether this report is meant to be under seal by the court.

[6] Jerry D. Christian, "Chemical Behavior of Iodine- 13 1 during SRE Fuel Element Damage in July 1959," May 26, 2005. I do not know whether this report is meant to be under seal by the court.

[7] "Report of the Santa Susana Field Laboratory Advisory Panel," October 2006. See http://www.ssflpanel.org/

[8] David A. Lochbaum, "An Assessment of Potential Pathways for Release of Gaseous Radioactivity Following Fuel Damage During Run 14 at the Sodium Reactor Experiment," 5 October 2006.

[9] Jan Beyea, "Feasibility of Developing Exposure Markers for use in Epidemiologic Studies of Radioactive Emissions From the Santa Susana Field Laboratory," October 5, 2006.

[10] John R. Frazier, "Report of John R. Frazier, Ph.D.," November 4, 2006.

presentations, including analyses by Sandia Laboratories,[11] Richard S. Denning,[12] and by me herein.

Extensive analyses by other experts were developed as part of a class action lawsuit, O'Connor v. Boeing, related to this accident. It is my understanding that this lawsuit was settled for $30 million under an agreement whereby the expert testimony was sealed by the court. Written testimony by at least one expert for the plaintiffs, Arjun Makhijani, is sealed and unavailable to me. Discovery records also are not been made available. Rebuttal testimony by experts Daniel and Christian for the defendant, Boeing, has been made available to us. This makes our analysis somewhat one-sided and unfair, but it is what it is.

Lacking contemporaneous off-site environmental measurements, estimating the atmospheric releases involves a step-by-step process of estimating the amount of radioactivity available for release and tracing it through potential leak paths. First, for each radioisotope of potential concern, an estimate is made of the inventory of the isotope in the reactor core at the time of the accident. Next, one estimates the fraction of each of these isotopes that could have been released from the breached fuel assemblies into the reactor coolant; then the fraction that reached the cover gas. Finally, one estimates the fraction of the activity reaching the cover gas that may have been released to the environment through the two most probable leak or release paths. At each step in this process the uncertainties get progressively larger.

When all is said and done the controversy over potential off site exposures boils down to differences in expert opinions regarding two potential scenarios. All parties agree that there was not sufficient noble gas radioactivity alone to cause significant public harm. Therefore the analysis turns on what experts believe happened to selected volatile fission products, primarily, iodine-131. One set of experts believes, on the basis of phenomenological chemistry considerations, that relatively little iodine would have escaped from the uranium fuel. You will hear these arguments from Dr. Pickard and Professor Denning. Another set of experts believes it is possible that significant amounts of noble gases and iodine could have been released from the fuel, bubbled up through the sodium to the helium cover gas and subsequently released. During the course of the accident these experts believe the cover gas containing the noble gases and volatile fission products was pumped into the radioactive decay holding tanks and then these tanks were purged through the stack. There is not hard reliable data associated with the SRE reactor accident itself to favor one scenario over the other.

Reactor Characteristics

The SRE was a 20 megawatt-thermal (MW_t) research reactor, designed to produce 6.5 MW of electrical power.[13] It was a thermal reactor with a zirconium canned graphite

[11] Paul S. Pickard, "Sodium Reactor Experiment Reactor, July 1959," Sandia National Laboratories, SRE Workshop, Semi Valley, California, August 29, 2009.

[12] Richard S. Denning, "An Assessment of Radioactive Material Release during the Accident at the Sodium Reactor Experiment," SRE Workshop, Semi Valley, California, August 29, 2009.

moderator. The primary and secondary loop coolant was liquid sodium. There were approximately 22 tonnes (t) of sodium in the reactor core and primary sodium coolant loop. The initial fuel loading was low-enriched uranium (2.778 weight % U-235) metal. Sandia's best estimate is that the initial reactor core contained 2.965 t of fuel. Daniel reports the fuel loading was 2,190 kg (U-238) and 83.4 kg (U-235), which totals 2.2734 t of fuel.[14] Daniel's reported U-238 number is in error, and is inconsistent with his reporting that the fuel enrichment was 2.778% U-235. Daniel appears to have transposed two numbers in reporting the U-238 inventory, in which case he probably meant to write 2,910 kg (U-238). In which case the initial core loading would be 2.993.4 t with a fuel enrichment of 2.78% U-235, and consistent with the Sandia estimate. Assuming this is the case, it would not affect Daniel's estimates of radioactive inventories.

Comparative risks

In assessing the risks and harm from the July 1959 accident, it is worth noting that this reactor is small relative to the power of today's operational nuclear power reactors. The Three Mile Island Unit 2 (TMI-2), which experienced a partial core meltdown accident beginning March 28, 1979, was rated as 2,568 MW_t. It power was 128 times larger than that of the SRE. The TMI-2 reactor was within a sealed secondary containment structure. The SRE reactor had no such sealed secondary containment.

Radioactivity in the Core

Radioisotopes, neutrons and heat are co-produced in the reactor during the nuclear chain reaction, during which the fuel is fissioned or "burned." The amount of fuel that is fissioned can be reported as a percent of the initial fuel loading, but since the heat produced is proportional to the number of fissions, often the amount of fuel fissioned is reported in terms of the total heat energy generated. AI estimated the burnup through June 1959, which would be up to but not including Run # 14, was 2,409 MW_t -days (MWd),[15] and after Run # 14 it was 2,425.8 MWd.[16] Working from the same power history data, Sandia's best estimate of the fuel "burnup" at the end of July 26 is 2,426.4 MWd, duplicating the calculation made by Daniel.[17] Thompson reported that Run # 14 logged 14 MWd.[18] Sandia and Beyea, quoting Hart, give 16.1 MWd for Run # 14.[19]

By taking into account the radioactive decay and nuclear reaction of radioisotopes after they are produced, one can calculate the changing inventory of the various isotopes as a function of the fuel burnup or energy produced over time. These calculations are straight forward but quite complicated. Today they are performed by sophisticated computer codes; one of the best of which is called ORIGEN2. Daniel and Sandia both used

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[13] The power of the reactor (measured in megawatts of thermal energy, abbreviated "MW_t") and production of heat energy (measured in "MW_t -days," abbreviated "MWd") are estimated from measurements of the coolant temperature and flow rates.
[14] Daniel, Table 2-1, p. 2-4.
[15] A.A. Jarrett, p. II-B-1.
[16] A.A. Jarrett, p. IV-C-10.
[17] Daniel, Table 5-2, p. 5-3.
[18] T.J. Thomson and J.G. Beckerley, p. 643.
[19] See, Beyea, October 5, 2006, Revision 0b, p. 16.

ORIGEN2. Their calculations should be more accurate than similar calculations by Hart made more than 40 years earlier.

Using the ORIGEN2 computer code, the inventory of selected gaseous, volatile and non-volatile radioisotopes at the time of the accident was calculated by Sandia. Sandia estimates that the total inventory of radioactive materials—consisting of fission products, actinides and activation products—in the reactor core when it was shut down on July 26, 1959—that is, when the fuel burnup was estimated to be 2,426.4 MWd—was 6.81 million curies. Approximately 16 percent of this amount consists of gaseous and volatile radioisotopes, that represent the highest potential to leak from the ruptured fuel into the coolant and a fraction of which are more likely to leak from the reactor vessel.

Table 1 (below) compares the core inventory estimates of these gaseous and volatile radioisotopes as estimated by Hart, Daniel and Sandia.

SRE Core Inventory, Curies				
Isotope	**Half-Life**	**Inventory (Hart)**	**Inventory (Daniel)**	**Inventory (Sandia)**
Cs-134	2.062 y	200	Not computed	80
Cs-137	30.0 y	8,700	7,890	7,754
Sr-89	50.5 d	160,000	129,000	148,100
Sr-90	29.12 y	8,150	7,800	7,512
I-131	8.04 d	16,800	19,200	21,390
Ce-141	32.50 d	127,000	122,000	136,200
Ce-144	284.3 d	169,000	154,000	159,800
Ru-103	39.28 d	75,200	71,800	83,620
Ba(La)-140	12.74 d	56,100	55,400	62,640
Zr(Nb)- 95	63.98 d	553,000	197,000	295,800
Kr-85	10.72 y	1,100	982	934
Xe-133	5.245 d	50,800	92,200	48,930
Xe-131M	11.9 d	Not computed	715	408
I-133	20.8 h	Not computed	92,200	62,420
I-135	6.61 h	Not computed	2,350	58,350
Totals:		***1,226,050***	***952,537***	***1,093,937***

Table 1. Estimates of the inventory of selected radioisotopes in the SRE core after 2,426.4 MWd, i.e., on July 26, 1959.

The inventory of the radioisotopes whose half-lives are in the range from several hours to a few days would have varied considerably during the two-week period of Run # 14. They would have been higher during periods when the power level was higher than it was at the end of the run, and they would have been lower during periods when the reactor was shut down and when the power level was lower than it was at the end of the run.

The sums of the estimated radioactivity for these gaseous isotopes—krypton (Kr) and xenon (Xe)—and the volatile isotopes—iodine (I), cesium (Cs) and strontium (Sr)—are

of particular interest because these isotopes are more likely to have escaped from the damaged fuel than the non-volatile isotopes.

The total inventories in Table 1 agree within 30 percent, and the estimates for the inventory of individual isotopes, with one exception, agree within a factor of two. The large discrepancies between Daniel and Sandia estimates have not been explained, but some of the larger differences relate to non-volatile isotopes, e.g., Zr(Nb)- 95, which are of less concern. Also, as should become apparent as we continue with our analysis these differences do not affect my overall conclusions since the relative uncertainty in the core inventory estimates is significantly smaller than the uncertainty in other factors that contribute to estimates of how much radioactivity escaped from the reactor.

The start of the accident

The SRE achieved initial criticality on April 25, 1957. Run # 14, operating using the initial fuel core loading, began at 6:30 am on July 12, 1959 and concluded at 11:20 am on July 26, 1959. During Run # 14, between July 12th and 26th, a partial fuel melting of the core occurred. Part of the debate over how much radioactivity was released turns on when the accident started. This is because radioactivity in four decay tanks was purged to the stack on July 15.

The AI technical staff, at the time of their 1959 interim report, believed the accident started at the beginning of Run # 14:

> It seems quite likely that the first cladding failure occurred during the afternoon of the first day (July 12) of run 14. This conclusion is drawn from the observation that the radioactivity in the high-bay area (over the reactor loading face) increased markedly at this time and were almost certainly due to leakage of reactor cover gas into the area. It was believed at the time that a seal had failed on the sodium level probe. It now seems more likely that the leak had existed for some time and was suddenly noticeable because of the large increase in the radioactivity of the cover gas. The activity in the radioactive gas decay tanks also showed a sharp increase with the first samples taken after the start of run 14 on July 15 (see Figure IV-C-1) [reproduced on the next page]. The activity in these tanks decayed continuously after July 15, indicating that most of the cladding failures had occurred by this time.[20]

Lochbaum also believes the accident started on or about July 13, 1959.[21]

[20] A.A. Jarrett, p. IV-A-34.
[21] Lochbaum, p. 6.

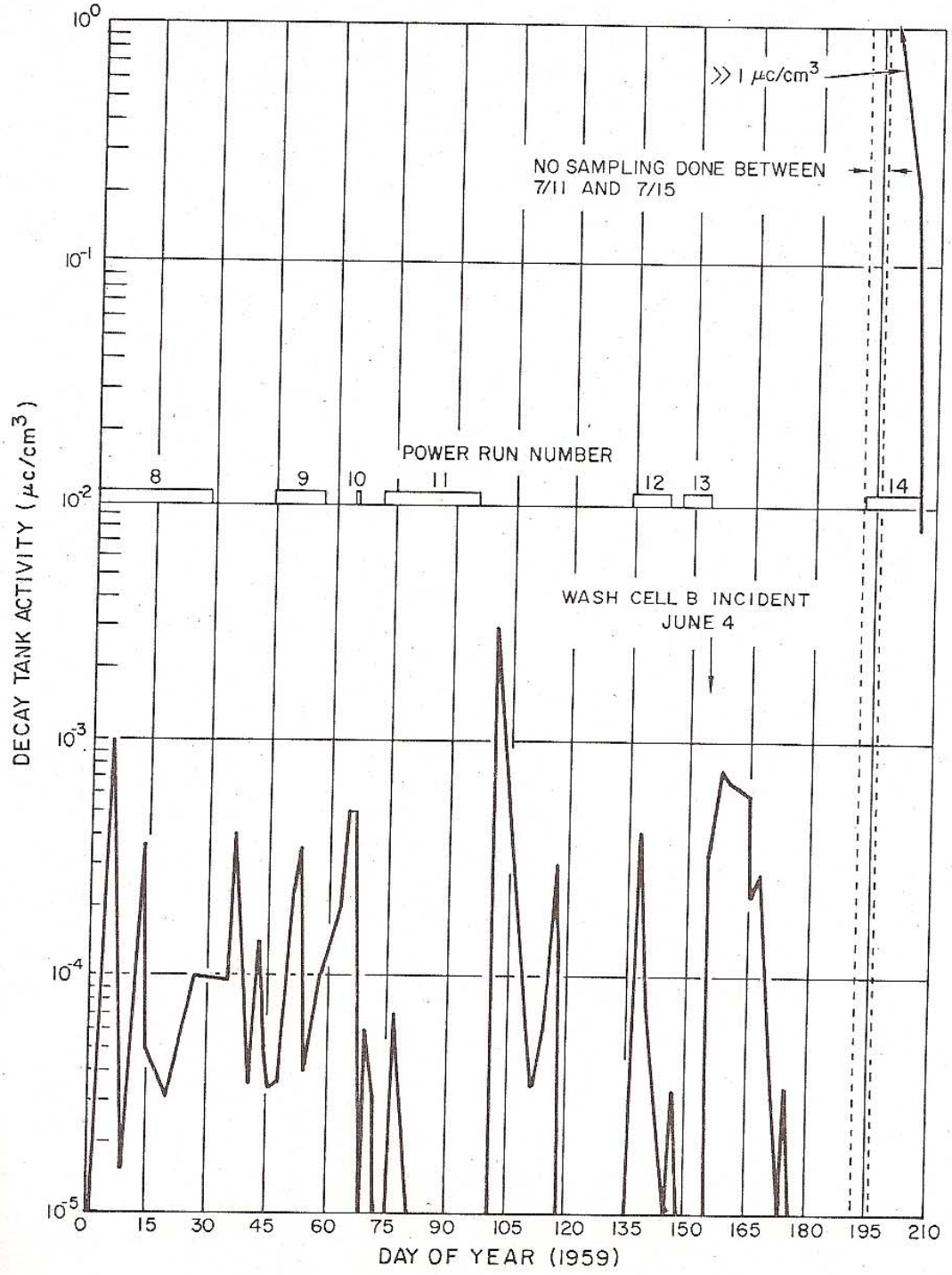
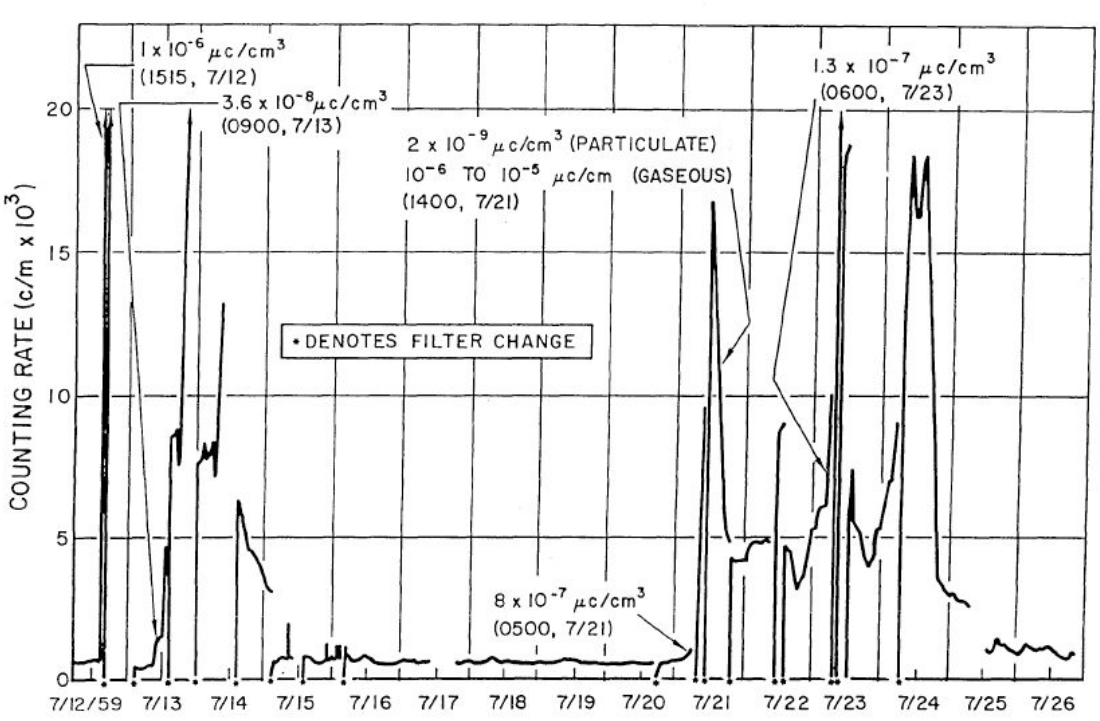


Figure IV-C-1. Radioactive Gas Decay Tank Activities
(Lines between points do not represent decay.)

From thermocouple readings, Daniel, Christian and presumably Sandia National Laboratories[22] estimate the fuel melting most likely occurred late on July 23rd or early July 24th. Daniel does not exclude the possibility that "some damage occurred to the fuel cladding or to the fuel itself during the power excursion of July 13, . . ."[23] It was helpful to the plaintiff for its witnesses, Daniel and Christian, to arguing that most of the damage occurred later in Run # 14, because it would mean that there would have been less radioactivity n the decay tanks when they were purged on July 15. This argument must be reconciled with evidence of off-scale readings of radioactivity in the holding tanks when readings were first taken on July 15. The holding tanks surely contained noble gases. The extent to which they also contained iodine and other volatile fission products is unknown. No spectroscopic measurements appear to have been made which would have permitted identifying the contribution of individual isotopes to the total activity readings.

I believe the accident started during the first day or two of Run # 14. The reactor operators thought the high readings in the high bay area were due to leakage of radioactivity from the cover gas. See figure below.[24]



High Bay Area Airborne Activity
(Concentrations shown made with spot sampler.)

The reactor operators tried it reduce the amount of escaping radioactivity by pumping the contaminated cover gas into the four radioactive decay holding tanks.[25] On July 15, (day

[22] J.D. Smith, Sandia National Laboratories, private communication.
[23] Daniel, p. 4-6.
[24] Figure IV-C-2, from Jarrett, p. IV-C-20.

196), when the first readings of radioactivity were made in the holding tanks, the readings were off scale. See Figure IV-C-1 reproduced on the previous page.

> The first storage tank sample taken on July 15, 1959, after the start of run 14, indicated an extremely high activity; so high in fact that the counter had not been calibrated in that range. The sample chamber itself read several mr/hr at the surface, which can be compared with the value of 30 mr/hr from the reactor cover-gas sample taken on July 18, 1959. From the fact that the activity in the storage tanks decayed continually following July 15, it can be concluded that most of the fuel damage must have occurred just after the start of run 14 (within the first 3 days).[26]

Radioactivity that escaped from the fuel assemblies

Following the accident it was discovered that 13 of 43 fuel assemblies had been breached. Thus, 13/43 = 0.3 (or 30%), of the assemblies were breached. Therefore, at this point in our analysis, about 300,000 to 400,000 curies of gaseous and volatile radioisotopes are still in play in terms of our interest in tracking whether they escaped from the reactor.

Also at this point in the analysis the analytical approaches taken by various experts differ. Daniel is aware that the fuel burnup is not uniform throughout the reactor core. He corrects for differences in the average burnup of the various fuel assemblies.[27] According to the fuel burnup data for the individual assemblies presented by Daniel, 810 MWd of fuel burnup (one-third of the total) was attributable to the 13 damaged fuel assemblies. As it turns out the difference between (13/43 = 0.3 (30%), and (810/2426 = 0.33 (33%) is not a significant correction. Daniel fails to correct for the fact that the fuel burnup within the core is not uniform axially, i.e., along the length of the fuel assemblies. The neutron flux axial distribution is Gaussian-shaped.[28] Consequently, the burnup of the failed slugs could be 20% to 30% greater than the 810 MWd estimate made by correcting only for radial variations.

Unfortunately, AI did not perform any mass balance measurements to determine the fraction of fuel that was damaged. Based on examining photographs of damaged fuel Sandia has made a very rough estimate that some 20% of fuel slugs in the 13 breached fuel assemblies were damaged, and the remaining 80% remained largely intact. If this is correct it suggests that 20% of 30% = 6% of the fuel slugs in the reactor could have released significant gaseous and volatile radioactive isotopes to the primary (sodium)

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[25] "At 1530 [July 12], both reactor room (high bay area) air monitors showed a sharp increase in activity. In an attempt to reduce the activity level, the reactor pressure was lowered to less than 1 prig from its former pressure of 2 psig.", A.A. Jarrett, p. III-10; and "It was decided to pressurize and vent the reactor atmosphere once in order to reduce the radioactivity level caused by the xenon in the cover gas. At 0550, July 15, the reactor pressure was reduced from 1.8 psig to 0.6 psig, repressurized to 3.0 psig, and then reduced to 1 psig. Upon venting core pressure, . . ," A.A. Jarrett, p. III-13.

[26] A.A. Jarrett, p. IV-C-16.

[27] Daniel, Table 5-2, p. 5-3.

[28] Proceedings of the International Conference on Atomic Energy, Geneva, 8-20 August 1955, W.E. Perkins, "The Sodium Reactor Experiment," Figure 8, p. 301.

coolant and the cover gas region of the reactor vessel. This estimate does not correct for difference in the distribution of the fuel burnup across the reactor. Also, the fuel was subjected to thermal oscillations in fuel that arguably could have forced gaseous and volatile fission products out of some of the more intact fuel. The Sandia estimate does not speak to whether the iodine chemically bonded with the uranium and was not released into the coolant or cover gas.

I believe it is reasonable to postulate that some 6% to 10% of the gaseous (Kr and Xe) were released from damaged fuel, and 1.5% to 10% of the volatile (I, Cs and Sr) fission products may have been released out of the fuel, although in theory larger fractions are credible. The low end of the range, i.e., 1.5%, reflects the potential that the key volatile fission products (I, Cs and Sr) may have chemically combined with the uranium and the release fraction was therefore less. This lower limit, in my view, does not apply to the noble gases.

If we use Sandia's estimate of the reactor core inventory, then the range in the release of radioactivity released from the fuel is given in Table 2 (on the next page) with 6% release assumed for the "Mid" values for the volatile fission products. No attempt has been made here to account for differences in the release fraction as a function of the relative volatility of the radioisotopes and other effects.

CRE Radioactivity Potentially Released from the Fuel, Curies				
Isotope	**Half-Life**	**Low Estimate**	**Mid Estimate**	**High Estimate**
Cs-134	2.062 y	1	5	8
Cs-137	30.0 y	116	465	775
Sr-89	50.5 d	2,222	8,886	14,810
Sr-90	29.12 y	113	451	751
I-131	8.04 d	321	1,283	2,139
Kr-85	10.72 y		56	93
Xe-133	5.245 d		2,936	4,893
Xe-131M	11.9 d		24	41
I-133	20.8 h	936	3,745	6,242
I-135	6.61 h	875	3,501	5,835
Totals:		***4,584***	***21,353***	***35,588***

Table 2. Estimates of the inventory of selected radioisotopes potentially released from the fuel.

In 1962 Hart estimated that 5,000-10,000 curies of radioactivity were released.[29] It is unclear how this estimate was made or even what he was referring to by "released," but in any case Hart's estimate is at the low end of the range in Table 2.

Beginning August 2, 1959 (seven days after the reactor was shut down), measurement were made of the radioactivity in the primary sodium and the cover gas. From these measurements Hart estimated the inventory of several key radioisotopes in the coolant and cover gas as of July 26, 1959.[30] Hart's measurement-based estimates are reproduced in Table 3.

CRE Radioactivity, Curies		
Isotope	**Half-Life**	**Hart Estimate**
Estimated in the Coolant		
Cs-134	2.062 y	0.4
Cs-137	30.0 y	27.7
Sr-89	50.5 d	444
Sr-90	29.12 y	21.4
I-131	8.04 d	16.3
Estimated in the Cover Gas		
Kr-85	10.72 y	0.2
Xe-133	5.245 d	47
Totals:		***538***

Table 3. Estimates cited by Hart of the inventory of selected radioisotopes in the coolant and cover gas as of July 26, 1959, based on measurements taken later.[31]

These values are substantially lower than the respective ranges in Table 2.

If some 50 to 90 curies of krypton-85 were potentially released from the fuel and only 0.2 curies was left in the cover gas, where did the krypton go? It was not appreciably absorbed by the coolant or other materials because it does not react chemically. There are three logical alternatives: 1) it never got out of the fuel; 2) Hart's noble gas measurements in the cover gas are in error; or 3) most of the noble gases were released from the cover gas to the environment prior to the measurements, e.g., when the holdup tanks were vented on July 15.

With regard to alternative 1) Denning claims,

[29] R.S. Hart, "Distribution of Fission Product Contamination in the SRE," Atomics International, NAA-SR-6890, March 1, 1962, p. 10.
[30] R.S. Hart, Table IV, p. 11.
[31] The sodium also contained other, less volatile, radioisotopes. "The significance of radiometric analyses performed on the sodium samples is only good to within a factor of 10." A.A. Jarrett, p. IV-C-8.

> The data collected at the time of the accident indicated that although there were small amounts of iodine and cesium found in the sodium pool, the amount of these radionuclides released to the gas space (cover gas) was so small that it could not be detected.[32]

This claim is unsupportable. First it should be noted,

> The helium cover gas over the sodium pool is in direct communication with the primary sodium fill-tank atmosphere which vents directly to the gaseous storage tanks. Reactor cover gas reaches the storage tanks principally on three occasions:
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> > a) When the reactor is brought up to temperature, the sodium level in the pool rises, thus forcing the helium cover gas to the storage tanks.
> > b) Whenever the operating pressure is reduced.
> > c) Whenever the reactor cover gas is purged.
>
> Also, during normal reactor power operation, it is important to note that there is a small amount of leakage past the pressure relief valve which separates the filltank atmosphere from the storage tanks. As a result of this leakage, radiation measurements of the cover gas activity have only limited meaning, even when information is available concerning the operating history of the reactor, including power level, length of operating, and amount of cover gas bled off to the storage tanks. General trends of the activity level in the cover gas, however, can be of some use. [33]

Cover gas would have moved to the decay tanks due to sodium temperature increases at the time of restarts following numerous scram during Run # 14. The cover gas was purged to decay tanks as a consequence of reducing operating pressure at 0550 on July 15[34] and "bleed down to negative" on July 29.[35] Also, as noted by Christian, venting operations occurred on July 19 and 20.[36]

Hart noted, "It is difficult to interpret cover gas samples subsequent to the July 26 shutdown since bleeding and flushing operations to the gas decay tanks and out the stack were almost immediately commenced."[37] Thus, any iodine and cesium released to the cover gas prior to July 15, 1959, would have been pumped to the holding tanks and the cover gas replenished with fresh uncontaminated helium.

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[32] Richard S. Denning, "An Assessment of Radioactive Material Release during the Accident at the Sodium Reactor Experiment," SRE Workshop, Semi Valley, California, August 29, 2009.
[33] A.A. Jarrett, pp. IV-C-12 and IC-C-14.
[34] A.A. Jarrett, p. III-13.
[35] A.A. Jarrett, p. IV-C-14.
[36] Christian, p. 40.
[37] R.S. Hart, "Distribution of Fission Product Contamination in the SRE," Atomics International, NAA-SR-6890, March 1, 1962, p. 13.

In sum, we can discount alternative 1) because of i) purging of the cover gas on July 15, ii) there was only one cover gas activity measurement recorded during Run # 14, and it was on July 18,[38] and iii) the off-scale readings of radioactivity in the holding tanks when measurements were first made on July 15.

With respect to alternative 2), we know AI believed, "The significance of radiometric analyses performed on the sodium samples is only good to within a factor of 10."[39] The cover gas measurements may have had similar large uncertainties.

Regarding alternative 3), Hart acknowledges that there was radioactivity in the holding tanks when they were vented to the stack July 15 and we know the readings of radioactivity in the holding tanks were off-scale when measurements were first made on July 15.

Thus, the noble gas measurements in the cover gas and the lack of other fission products cannot be used to back calculate the fraction of fuel that was severely damaged or draw conclusions regarding the fraction of radioactivity that did not escape from the fuel. Similarly, the iodine, cesium and strontium estimated to be in the coolant as of July 26, 1959, cannot be used to estimate what was released from the fuel to the extent that these radionuclides passed through the sodium to the cover gas and were subsequently purged to the holding tanks.

Since noble gases do not react chemically with other materials, any noble gases released from the fuel, and not subsequently lost as a consequence of radioactive decay, would have been eventually released from the reactor to the environment. The radioactive half-life of krypton-85 is 10.72 years, so very little of it would have been lost through radioactive decay. The same cannot be said of xenon-133, with its much shorter half-life of 5.2 days.

We note in passing that the releases of all the noble gases from the damaged fuel are not likely to have caused significant harm to the public. The radiation doses were most likely too low. By way of comparison, seven months after the TMI-2 accident, over a two week period from June 28 to July 11, 1980, an estimated 43,000 curies of krypton-85 and less than 20 curies of iodine-131 were vented from the reactor building into the environment. The estimated whole body dose equivalent before the venting was 0.045 milli-rems (mrem) and a skin dose of 4.5 mrem. Consequently, if there was a serious risk to the public, it would have come from other radioisotopes, and more likely from the volatile fission products (I, Cs and Sr).

We return to the release of iodine, which is more volatile than cesium or strontium. Here the challenge is to reconcile the release of 300 to 2000 curies of iodine-131 from the fuel (Table 2) with only 16 Ci measured in the coolant (Table 3). If there was little iodine measured in the coolant and none measured in the cover gas, where did the iodine go if it did not stay in the fuel? Similarly, where did the cesium and strontium go?

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[38] A.A. Jarrett, p, IV-C-14.
[39] A.A. Jarrett, p. IV-C-8.

Thompson concluded, presumably based on the earlier analysis of AI, that "From the available evidence of the accident it would appear that the fission products other than the noble gases are retained well in sodium."[40] This does not appear to be the case based on Hart's estimates. Sandia concludes,

> 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 766ºC, 1411ºF*)
> - 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[41]

Sandia would have to reach the same conclusion regarding the cesium and strontium, or alternatively conclude that because of their lower volatility, a substantially smaller fraction of cesium and strontium are released from the damaged fuel relative to the fraction of the noble gases released. Sandia and Denning do not indicate, at least not in their PowerPoint slides, whether their respective conclusions are consistent with analyses of the partial fuel melt down accidents at EBR-I or Fermi-I, both of which were uranium metal-fueled sodium-cooled reactors.

In estimating the fraction of the volatile isotopes released from the fuel but not retained in the sodium coolant, we confront several additional problems. In the blocked and partially blocked fuel channels one would anticipate sodium boiling and sodium voids during the period of fuel melting. It is unknown how extensive these voids were and to what extent they represented a significant pathway to the top of the reactor core. However, there was about one meter of sodium above the reactor core through which gas vapor bubbles would have to travel without being appreciably absorbed by the sodium. If a significant fraction of the vapor bubbles collapsed before reaching the surface of the sodium one would expect a significant fraction of the iodine released to be captured by the sodium. There is no data that I am aware of that resolves this issue.

There are two potential pathways by which radioactivity released to the cover gas could have been released to the environment. First, it could leak through penetrations in the reactor head, i.e., the upper shield plug, into the high bay area directly over the reactor and from there it would have been exhausted to the environment through the high bay area ventilation system. The second pathway is from the reactor cover gas region to the four decay storage tanks and from there through or around a filter system and then out the stack.

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[40] Thompson and Beckerley, p. 644.

[41] Paul S. Pickard, "Sodium Reactor Experiment Reactor, July 1959," Sandia National Laboratories, August 29, 2009, Slide 27.

With respect to the first pathway, the reactor was plagued by leaks from the cover gas to the high bay area (see figure reproduced on p. 8 above). Air monitor measurements in the high bay area of the reactor building confirm that the reactor vessel head often leaked radioactivity from the cover gas to the high bay area. Air monitor chart data indicates that these leaks were frequent and on at least two occasions the monitor readings went off the chart. The CWS filter was removed from the high bay area ventilation system at the time of Run # 14.

Nevertheless, leaks through the shield plug would have been constrained by the size of the gaps along the leak paths, and there would have been additional plated on the colder surfaces in the high bay area and ventilation system. The high bay area over the reactor was approximately 100 feet long by 50 feet wide by 45 feet high, thus having an approximate volume of 255,000 ft^3 (7.22 x 10^9 cm^3); with two exhaust fans moving 12,000 cfm each, or 1.44 x 10^6 ft^3/hour (4.08 x 10^{10} cm^3/hr).[42] Hypothetically, to exhaust 200 curies over 5 hours, the building concentration would have to be 0.001 $\mu c/cm^3$, which is one million times greater than the then maximum permissible concentration of 10^{-9} $\mu c/cm^3$. Activity concentrations this high, i.e., on the order of 0.001 $\mu c/cm^3$, do not appear to have occurred in the high bay area (see figure on page 8, with the caveat that on several occasions the air concentrations were off-scale). Consequently, I do not believe the leakage from the reactor into the reactor building (into the high bay area), and subsequently discharged by the building ventilation system, lead to significant off-site exposures.

The releases to the high bay area are important in assessing whether volatile fission products made it to the cover gas. "The activity levels [measured in the high bay area] during run 14 are shown on Figure IV-C-2 [reproduced on p. 8]. This data was recorded by a model AM-2 continuous air monitor. This unit is a fixed filter, integrating-type recording air monitor, and primarily measures the beta activity of the particulates building up on the filter through which the air passes."[43] Since noble gases would not be trapped on the filter paper, the reading may have been due primarily to volatile fission products, rather than noble gases. This is consistent with the recollection of John Pace, who was employed as an intern at the reactor at the time of the accident. He recalled that after the accident, employees were engaged in an extensive effort to decontaminate the high bay area walls and floor, and that contaminated equipment and records were taken outside of the reactor building. If the contamination resulted from the leaks into the high bay area this would be inconsistent with an assumption that only noble gases reached the cover gas area. But the contamination may have been a result of "attempts to free a fuel slug which had jammed the fuel handling cask after it had removed a damaged fuel element from the core"[44] after Run # 14.

The second pathway, discussed earlier, is the pathway that I believe would have resulted in more significant releases. The holdup tanks in this pathway were designed to permit

[42] Christian, p. 8.
[43] A.A. Jarrett, p. IV-C-19.
[44] A.A. Jarrett, p. IV-C-23.

radioactive decay of short half-life radioisotopes prior to venting the gas out through the stack. There was no sampling of the radioactivity in these tanks during at least during the early part of Run # 14. There was an "absolute filter" system between the storage tanks and the stack that could be bypassed. The Sandia PowerPoint slide, "SRE Cover Gas and Venting System Under Normal Operations", does not show the filter bypass valve and piping.[45] These tanks were intentionally purged to the stacks during and after Run # 14.[46] It is through this pathway that the remaining noble gases were intentionally released to the environment after the accident.

Some fraction of iodine, cesium or strontium that made it to the cover gas could have been purged from the decay holdup tanks through the stack. It is not known whether the purges during Run # 14 were through the filter system, which would be consistent with "normal operations," or whether the filter system was bypassed, intentionally or inadvertently.

> Radioactivity routed to the stack from the gaseous storage tanks passes through absolute filters and is then diluted with 25,000 cfm of outside air. Exhaust from the high bay area is not vented to the stack but rather to a separate outlet located on top of the high bay area. The high bay exhaust is passed through CWS filters only when potentially hazardous operations are in progress within the reactor building, e. g., during reactor operation or fuel handling. The original design of the gaseous waste handling system incorporated radiation-level-actuated by-pass valves in the line leading from each source of gaseous activity to the storage tanks. In this way, automatically and depending on the activity level, the gas would be vented either to the stack or to the storage tanks. This system was later modified, because of malfunction, and a manually operated bypass was placed in the reactor control room.[47]
>
> Two instances in which the stack monitor readings indicated activity concentrations in excess of allowable values were noted during run 14. The first of these occurred on July 12 at 1700, at which time the stack activity rose sharply to a value of 1.5×10^{-4} μc/cm^3. This instance of apparent high activity levels occurred simultaneously with the high radiation levels which were detected above core channel number 7 and, as a result, the stack monitor was responding to this direct radiation. The activity level returned to normal by 2200 on the same day. The second instance occurred on July 15 at 0600; this time the stack activity rose sharply to 7×10^{-5} μc/cm^3. The activity level continued intermittently high until about 1100 on July 15. No explanation can be offered for this second occurrence unless it is assumed that the storage tank bypass switch had inadvertently been-placed in the bypass position. If this were in fact the case, the activity concentrations in the cover gas were

[45] Paul S. Pickard, "Sodium Reactor Experiment Reactor, July 1959," Sandia National Laboratories, August 29, 2009, Slide 13.
[46] "At 1700 [on July 12], a sharp increase in the stack activity to 1.5 x 10-4 μc/cm3 was noted. This returned to normal by 2200." A. A. Jarrett, General Editor, Atomics International, "SRE Fuel Element Damage: An Interim Report," NAA-SR-4488, November 30, 1959. p. III-10.
[47] A.A. Jarrett, p. IV-C-24.

> certainly sufficient magnitude to cause the high stack effluent activities noted.[48]

For large amounts of iodine to have been released through the stack, the filters would have to have been inefficient, or intentionally or inadvertently bypassed.

Conclusion

Based on my limited review of the documents made available to me, my best estimate is that the amount of noble gas radioactivity released as a consequence of the SRE accident in July 1959 was too small to have posed by itself a significant risk to the health of the public. Significant harm to the public, if it occurred, would have been from the release of volatile fission products, i.e., iodine, cesium and strontium, or a combination of noble gas and volatile fission products. I do not believe available information is adequate to resolve what fraction of these noble gas and volatile fission products remained in the fuel and what fraction were released to the environment.

With respect to assessing harm there are two issues of interest. First is the carcinogenic risk to the highest exposed individuals. Second is the cumulative risk to the larger population where the individual risks may have been small. I have not made any attempt to quantify the individual risk or the effects of the collective population exposure. It is likely that the risk to the maximally exposed individual was smaller than the risk of cancer from other causes, yet at the same time the collective exposure could have resulted in some cancers in the population.

[48] A.A. Jarrett, pp. IV-C-24 and IV-C-25.