

Question Regarding ESF Leakage

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Question:

What is the potential impact of fuel fragmentation and dispersal on evaporating ESF leakage to dryness and thus greatly increasing iodine partitioning from that leakage?

Assumptions:

1. Core power = 3238 MWt
2. UO₂ mass = 216600 lbm
3. Initial coolant mass = 543560 lbm
4. Percentage of core dispersed into coolant as fuel fragments from failed pins = 2%
5. Fragment and minimum ESF leak path diameter = 1 mm
6. Single ESF leak path
7. Leakage temperature = 212 F
8. Leakage density = 59.8 lbm/ft³
9. Hydraulic head driving leakage = 100 feet (41.5 psi)
10. ESF leakage pathway hydraulic loss coefficient = 3
11. Leakage latent heat of vaporization = 970.32 BTU/lbm
12. Maximum total ESF leakage = 2 gpm (0.266 lbm/sec) (Note that this maximum leakage would permit 690740 lbm of coolant to leak in 30 days, 27% more than the initial RCS coolant mass of 543560 lbm.)
13. Fractional decay power = $0.27 \cdot (t+108.5)^{-0.34}$ for t in seconds (curve fit of APCSB 9-2)
14. Fuel fragments are uniformly distributed in the initial coolant mass 543560 lbm. A decay power (i.e., fragment concentration) multiplier is incorporated to evaluate skewed distribution (i.e., fuel fragment concentrations greater than uniform). The maximum value for the multiplier is 10 (max concentration = 10 x uniform). The minimum value is assumed to be unity (corresponding to the uniform distribution in the initial coolant mass of 543560 lbm). No values less than unity are included, although they are certainly possible and even likely as fragments deposit within the RCS and are unavailable to be leaked.
15. Decay power of the RG 1.183-activity release in the leaked water is neglected. (Justification: By t = 2 hours, the maximum decay power of the RG 1.183 releases - as derived from licensing basis HNO₃ production for G = 0.007 molecule/100 eV - is less than 2% of the full decay power. By t = 8 hours, it is only 0.7% of the full decay power. Moreover, it takes time for the activity to be released and to be deposited in the coolant water whereas the release of the fragmented fuel contribution is assumed to be instantaneous.)

Approach:

1. Establish a lower threshold leakage by calculating leakage from a 1 mm diameter leak path. Smaller leak paths would not pass the 1 mm fuel fragment.
2. The decay power in the leaked coolant is calculated from the expression given in Assumption 13. The Assumption 13 value is multiplied by 0.02 times the fraction of 543560 lbm leaked up to any point in time to represent the decay power of the fragments leaked with the coolant. Per Assumption 14, a concentration multiplier between unity and 10 is used to evaluate non-uniform concentration of fuel fragments in the total leakage.
3. The differential equation that must be solved to determine the time-dependent leaked mass is as follows (for the ESF leak rate, \dot{m} , in lbm/sec, m in lbm, and t in seconds):

$$\frac{dm}{dt} = \dot{m} - \frac{0.02 * 0.27 * M * \dot{m} * t * 3238 \text{ MWt} * 948 \frac{\text{BTU}}{\text{sec} - \text{MWt}}}{543560 \text{ lbm} * 970.32 \frac{\text{BTU}}{\text{lbm}}} * (t + 108.5)^{-0.34}$$

where M is the multiplier used to evaluate the effect of non-uniform distribution of the fuel fragments in the coolant mass. When $M \cdot \dot{m} \cdot t$ exceeds 543560 lbm, the fraction $M \cdot \dot{m} \cdot t / 543560$ is set to unity so that the decay power in the accumulated leakage does not exceed the maximum value of 2% of the instantaneous value of the Assumption 13 curve fit.

4. Solving the DE for the appropriate range of total ESF leakage rates and decay power multipliers will allow one to determine if the accumulated leakage mass, m, ever becomes zero indicating "evaporation-to-dryness".

Calculation and Results:

1. The minimum leak rate to be considered is that corresponding to a 1 mm diameter leak path. The flow area of a 1 mm diameter leak path is equal to 0.785 mm² or 7.85E-7 m². In English units, this would be 8.45E-6 ft². Using Assumptions 8, 9, and 10, the mass leak rate of water through such a path would be 0.0234 lbm/sec, corresponding to a volumetric leak rate of 3.9E-4 cfs or 0.176 gpm. With this value as the minimum, one can determine that once the decay power of the fragments (2% of the core) goes below the value of 0.0234 lbm/sec * 970.32 BTU/lbm = 22.7 BTU/sec, evaporation to dryness cannot occur due to the decay power alone. This is especially true considering that a potentially significant fraction of the gamma radiation would likely escape the pooled leakage without being fully attenuated. The corresponding full-core decay power would be 1136 BTU/sec (i.e., 0.037% of full-core operating power).
2. Differential equation solution:

First the expression is simplified by creating a single constant corresponding to the various factors:

$$\frac{dm}{dt} = \dot{m} * (1 - M * t * 3.143E - 5 * (t + 108.5)^{-0.34})$$

Then, recognizing that the solution is variable separable and integrating:

$$m = \dot{m} * \left[\frac{3.143E - 5 * 108.5 * M * (t + 108.5)^{(1-0.34)}}{(1 - 0.34)} - \frac{3.143E - 5 * M * (t + 108.5)^{(2-0.34)}}{(2 - 0.34)} + t \right] + K$$

To evaluate K, recognize that when t = 0, m = 0. The expression then becomes:

$$K = \dot{m} * M * \left[\frac{3.143E - 5 * 108.5^{(2-0.34)}}{(2 - 0.34)} - \frac{3.143E - 5 * (108.5)^{(2-0.34)}}{(1 - 0.34)} \right]$$

And simplifying:

$$K = -0.06863 * \dot{m} * M$$

Then:

$$m = \dot{m} * M * \left[\frac{3.41E - 3 * (t + 108.5)^{(1-0.34)}}{(1 - 0.34)} - \frac{3.143E - 5 * (t + 108.5)^{(2-0.34)}}{(2 - 0.34)} - 0.06863 \right] + \dot{m} * t$$

Or:

$$m = \dot{m} * M * \left[5.167E - 3 * (t + 108.5)^{(1-0.34)} - 1.893E - 05 * (t + 108.5)^{(2-0.34)} - 0.06863 + \frac{t}{M} \right]$$

This is the equation that's solved up to the point in time where $M \cdot \dot{m} \cdot t$ exceeds 543560 lbm. At this time, the difference between m and $\dot{m} \cdot t$ is the coolant mass evaporated by the decay heat of the core fragments inter-mixed with the accumulated leakage.

An alternative version of the differential equation is applicable when $M \cdot \dot{m} \cdot t$ exceeds 543560 lbm (i.e., when all of the core fragments have been released with the leaked coolant):

$$\frac{dm}{dt} = \dot{m} - 17.08 * (t + 108.5)^{-0.34}$$

The solution to this alternative is:

$$m = \dot{m} * t - 25.88 * (t + 108.5)^{(1-0.34)} + K$$

To evaluate K one may note that m is the accumulated mass when $t = 543560/(M*\dot{m})$. Let that value of m be known as m'. Then K may be solved for as follows:

$$K = m' + 25.88 * \left[\frac{543560}{M * \dot{m}} + 108.5 \right]^{0.66} - \frac{543560}{M}$$

The complete expression to be evaluated for each combination of M and \dot{m} for $t > 543560/M/\dot{m}$ is as follows:

$$m = m' + \dot{m} * t + 25.88 * \left\{ \left[\frac{543560}{M * \dot{m}} + 108.5 \right]^{0.66} - (t + 108.5)^{0.66} \right\} - \frac{543560}{M}$$

3. Application of the differential equation solution:

The minimum leak rate to be considered is that corresponding to a leak path of 1 mm. That value is 0.0234 lbm/sec. Additional leak rates to be considered include 0.0468 lbm/sec (2 x the minimum), 0.0936 lbm/sec (4 x the minimum), 0.1404 lbm/sec (6 x the minimum), 0.2106 lbm/sec (9 x the minimum), and 0.266 lbm/sec (the maximum corresponding to 2 gpm).

For each of the leak rates, a concentration multiplier of unity is the base case (Multiplier 1). A concentration multiplier of three is also used (Multiplier 2). Finally, a maximum concentration multiplier equal to or less than 10 is considered. The maximum multiplier (Multiplier 3) is one that just results in evaporation-to-dryness within 30 days. Note that for large leak rates, no evaporation-to-dryness occurs even for the maximum concentration multiplier of 10.

The following table provides the time (in days) by which all of the core UO₂ fragments (corresponding to 2% of the core) have been released. Beyond the stated times, any further coolant leakage would be assumed to be fragment-free. Where percentages appear, the release is incomplete at t = 30 days; and the fractional fragment release at that time (t = 30 days) is characterized by the given percentage.

Table 1

Leak Rate	Mult 1 =	Mult 2 =	Mult 3 =
lbm/sec	1	3	3.1/10
0.0234	11.2%	33.5%	34.5%
0.0468	22.3%	67.0%	68.9%
0.0936	44.6%	22.4	19.4
0.1404	67.0%	14.9	6.6
0.2106	29.9	10.0	3.0
0.266	23.7	7.9	2.4

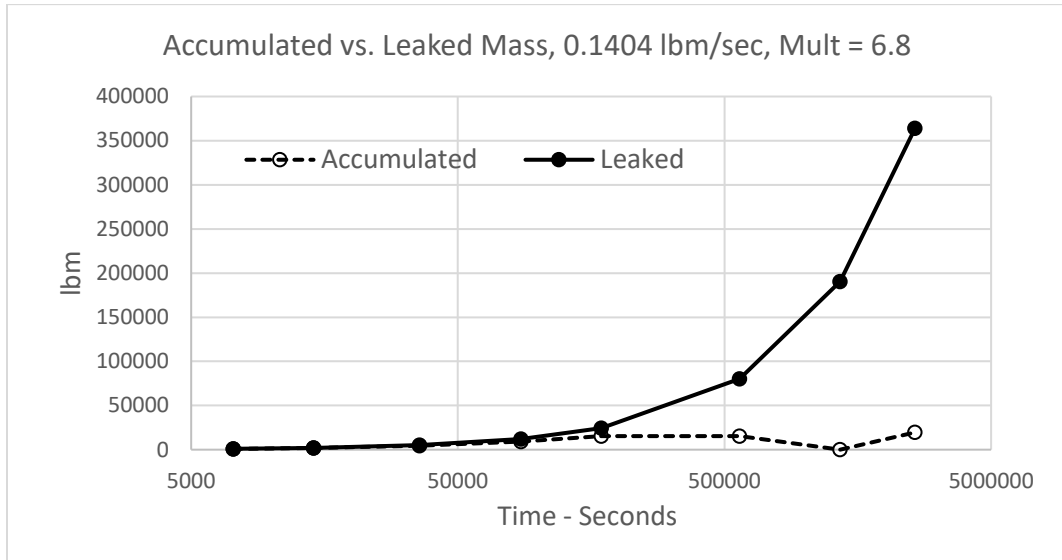
A similar table can be used to show whether or not evaporation-to-dryness occurs within 30 days:

Table 2

Leak Rate	Mult 1 =	Mult 2 =	Mult 3 =
lbm/sec	1	3	3.1/10
0.0234	No	No	Yes
0.0468	No	No	Yes
0.0936	No	No	Yes
0.1404	No	No	Yes
0.2106	No	No	No
0.266	No	No	No

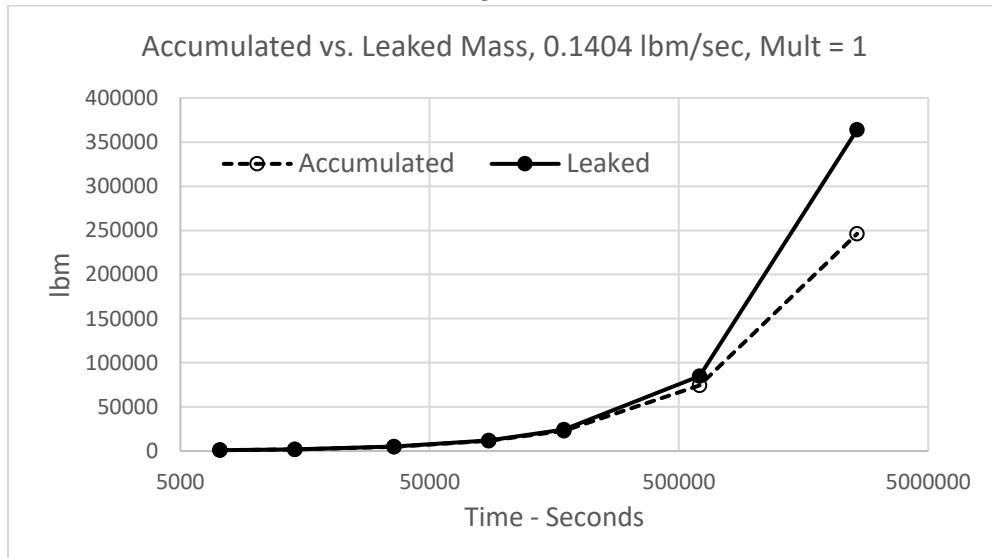
In all cases, a concentration multiplier >3 was needed to bring about evaporation-to-dryness within 30 days. Interestingly, for the 0.1404 lbm/sec, Multiplier 3 case (with a concentration multiplier of 6.8 for which all fuel fragments were released by $t = 6.6$ hours), evaporation-to-dryness occurs at $t = 15.7$ days. Beyond 15.7 days, the decay power of the core debris fragments falls below that needed to evaporate the leak rate (136.2 BTU/sec), and the coolant leakage once again begins to accumulate as illustrated in the following Figure 1:

Figure 1



For comparison, Figure 2 presents the same case with a concentration multiplier of unity:

Figure 2

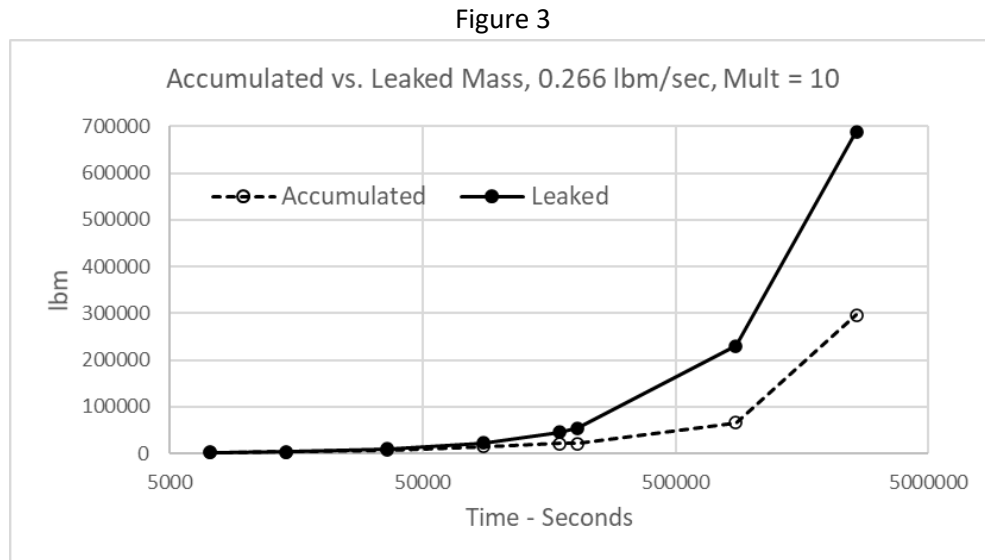


These figures are somewhat crude with respect to the number of time points defining their shape; but they illustrate the overall behavior. The difference between the Leaked and Accumulated plots corresponds to the amount of coolant evaporated by the decay heat of the fuel fragments up to any point in time.

4. Interpretation of results:

As a frame of reference to better appreciate the results, one may note that integrating the APCS 9-2 decay power curve fit over 30 days leads to just under two full-power hours. Multiplying this integral by two percent gives the total energy generated by the fuel fragments available to evaporate leaked coolant. The maximum mass that can be evaporated is 442075 lbm.

The following Figure 3 is for the maximum 2 gpm leak rate analyzed with a concentration multiplier of 10. For this case, as seen in Table 1, all of the fuel fragments are expelled with the leaked coolant by $t = 2.4$ hours. By 30 days, the difference between the leaked coolant mass and the accumulated leakage is 392666 lbm, 89% of the maximum value of 442075 lbm.



The assumption in this assessment that there exists only a single ESF leakage pathway is important. We can observe, for example, from Table 2 that for a total leak rate of 0.2106 lbm/sec through a single pathway, there is no potential for evaporation-to-dryness even with a 1 mm fragment concentration in the leakage ten times greater than uniform. However, one must keep in mind that if the same leakage area were distributed evenly among ten pathways, the situation would be even more favorable; i.e., the leak paths would be too small to pass even a single 1 mm fragment.

For the 0.2106 lbm/sec case and a concentration multiplier of unity (uniform concentration), all of the fragments would be expelled by 29.9 days; i.e., just within the 30-day dose calculation “window”. Even for this case, the leak path would have to pass 132 fragments per second to release the $3.41E8$ 1 mm diameter fragments (2% of the core UO_2 mass) within the 30-day time interval. Overall, it seems unlikely that so many fragments could be delivered continuously through a 3 mm diameter leak path to the accumulated ESF leakage outside containment. Even if that were possible, a concentration multiplier three times greater (with that many more fragments per second) still would not produce evaporation-to-dryness for any of the leak rates studied.

5. Conclusion:

It seems to me unlikely that a sufficient number of particles could be deposited in ESF leakage to bring about evaporation-to-dryness. Leak paths would have to be few and relatively large and particle concentrations in the leakage would have to be well above uniform to bring that phenomenon about.