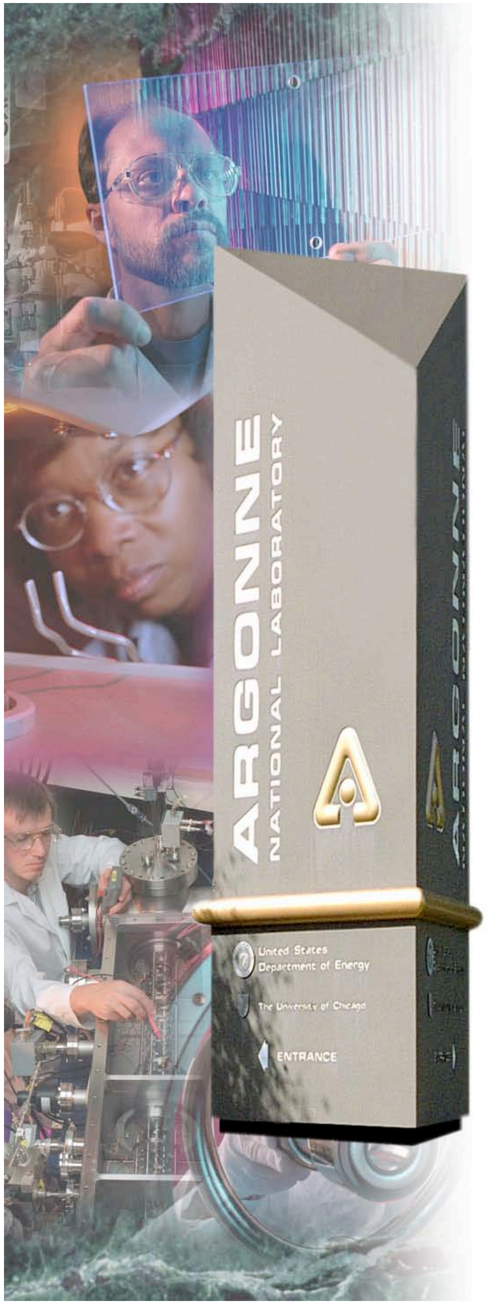
DISCLAIMER



Operational Safety of Spent Nuclear Fuel

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Lecture 6.1b

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Argonne National Laboratory

Office of Science
U.S. Department of Energy

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Office of Science Laboratory
Operated by The University of Chicago

Expected Outcomes from this Lecture

As a result of this lecture,
the student will be able to:

- **Identify the Decay Heat Standard ANSI/ANS-5.1 1979**
- **Be able to compute the decay heat as a function of time after shutdown for one or more fuel assemblies**
- **Recognize the various conditions where fuel assemblies may be at risk from overheating**

Decay Heat Standard Reference:

Decay Heat Power in
Light Water Reactors

ANSI/ ANS – 5.1-1979

Published by the American Nuclear Society
555 N. Kensington Avenue
Lagrange Park, Illinois, 60525 USA

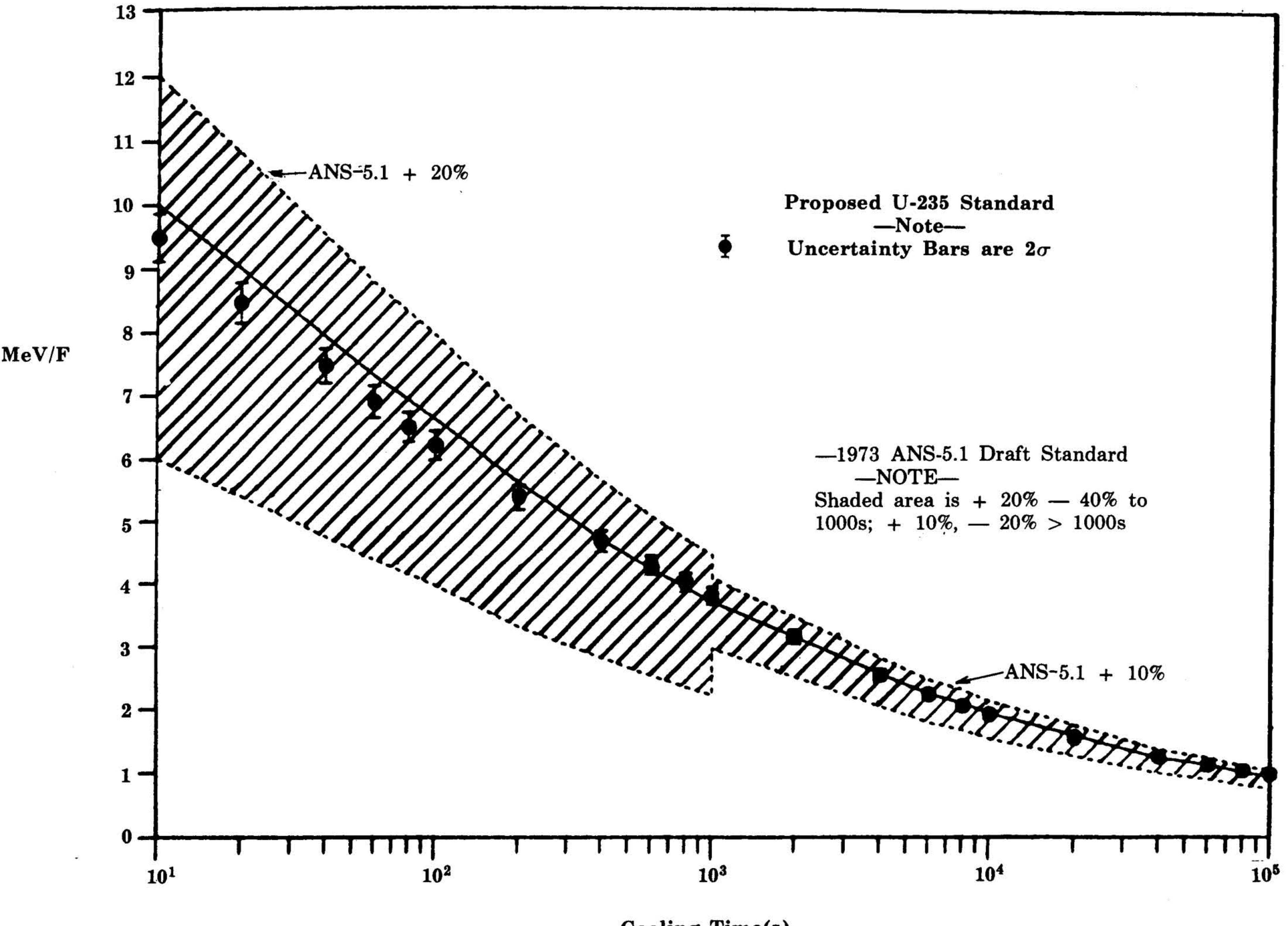


Figure F-1. Comparison of Revised Standard F(t,∞)

Decay Heat in Light Water Reactor Fuel

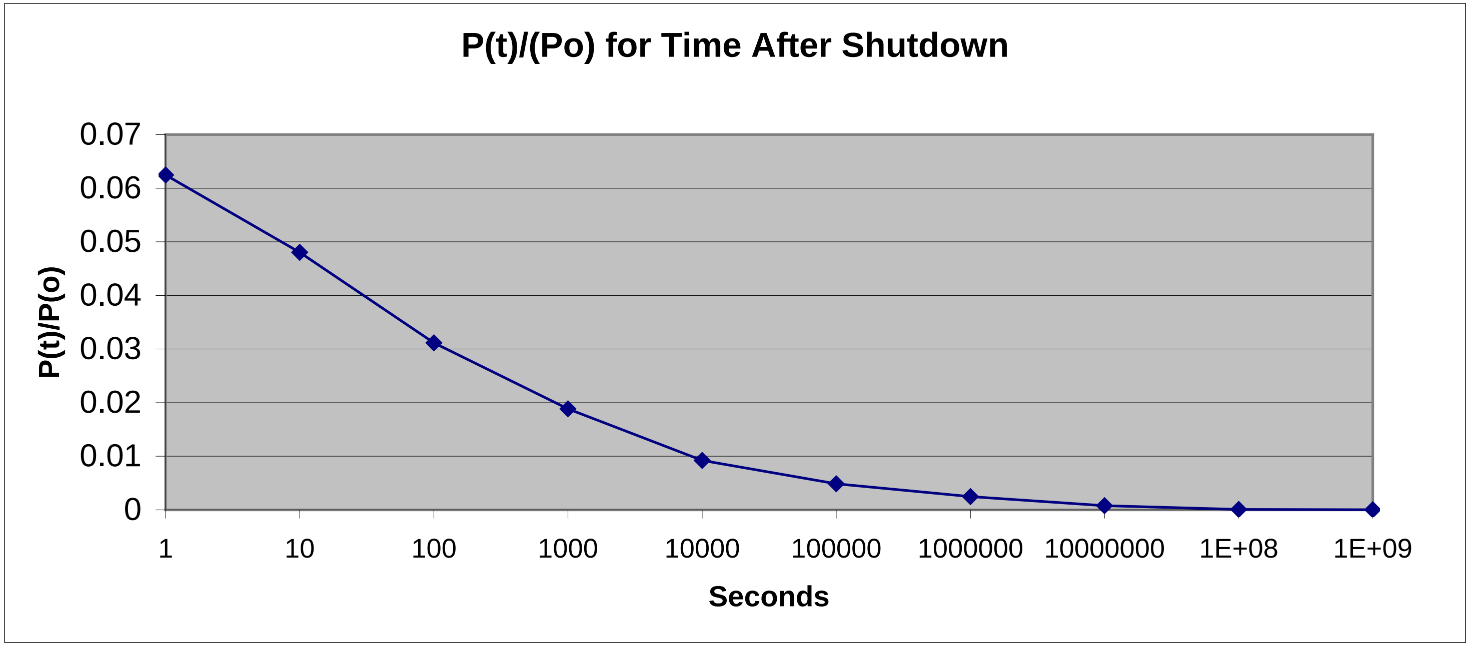
Measured From Time After Shutdown
(Irradiation time: 1020 days ~ three years)

Seconds after shutdown	P (t) /P(0)	Multiplier	Note(s)
1.00E+00	6.247	6.25E-02	
1.00E+01	4.804	4.80E-02	
1.00E+02	3.115	3.12E-02	
1.00E+03	1.886	1.89E-02	
1.00E+04	0.9237	9.24E-03	
1.00E+05	0.487	4.87E-03	1
1.00E+06	0.247	2.47E-03	2
1.00E+07	0.0775	7.75E-04	3,4
1.00E+08	0.00994	9.94E-05	5
1.00E+09	0.00174	1.74E-05	6

Notes:

- **(1) 1.0E+5 seconds ~ 1 day (8.64E+4 sec)**
- **(2) 1.0E+6 seconds ~ 12 days (1.0368 E +6 sec)**
- **(3) 1.0E+7 seconds ~ 120 days (1.0368 E +7 sec)**
- **(4) 1 year = 365 days = 3.153 E +7 sec**
- **(5) 1.0E +8 seconds = 3.17 years**
- **(6) 1.0E +9 seconds = 31.7 years**

1	0.06247
10	0.04804
100	0.03115
1000	0.01886
10000	0.009237
100000	0.00487
1000000	0.00247
10000000	0.000775
100000000	0.0000994
1000000000	0.00001736



Fuel Assembly Decay Heat Calculation:

Imagine a Hypothetical 1000 Mw(e) Power Reactor that has 300 fuel assemblies:

- **If the thermal efficiency is 33% then the Thermal power is 3000 Mw(th)**
- **3000 Mw(th) divided by 300 assemblies equals 10 MW(th) per assembly**
- **10 Mw(th) per assembly is 10,000 kw per assembly.**

Let 10,000 kw per assembly be identified as the assembly power at time zero.

- **Hence P(0) = 10,000 kw.**
- **Using the decay heat table, we can obtain the thermal output as a function of time after shutdown.**

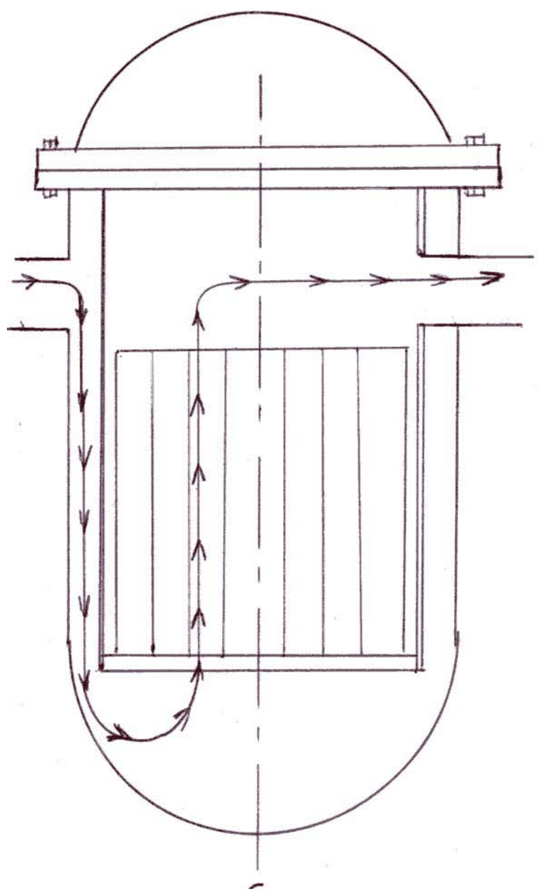
Fuel Assembly Decay Heat Calculation:

Thermal Power of a 10 Mw Fuel Assembly (in Seconds After Shutdown)

Seconds after Shutdown	Multiplier	Thermal Power P (t) (kw)
1.00E+00	6.25E-02	624.7
1.00E+01	4.80E-02	480.4
1.00E+02	3.12E-02	311.5
1.00E+03	1.89E-02	188.6
1.00E+04	9.24E-03	92.4
1.00E+05	4.87E-03	48.7
1.00E+06	2.47E-03	24.7
1.00E+07	7.75E-04	7.8
1.00E+08	9.94E-05	1.0
1.00E+09	1.74E-05	0.2

Six Cases Involving Shutdown Plants and Spent Fuel

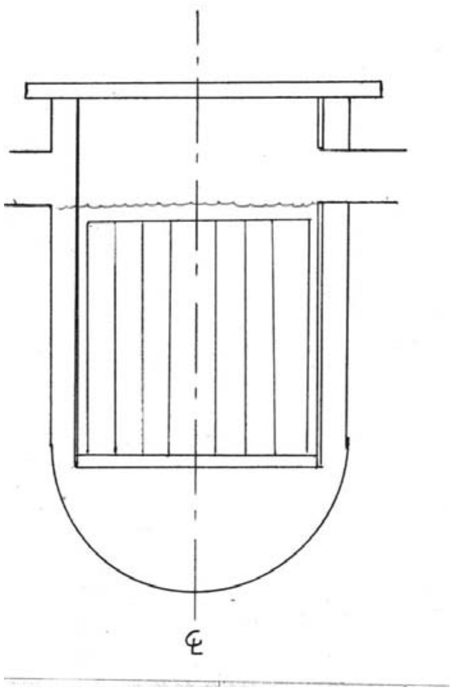
- Case #1: Fuel in Closed Reactor Vessel
- Case #2: Fuel in Open and Drained Reactor Vessel
- Case #3: Fuel in Spent Fuel Pool –Natural Circulation
- Case #4: Fuel in Completely Drained Spent Fuel Pool
- Case #5: Fuel in Partially Drained Spent Fuel Pool
- Case #6: Dry Fuel Movement and Storage



Case #1: Fuel in Closed Reactor Vessel

Decay Heat Regime: 1 to 30 days

- **Important to keep fuel covered with water at all times.**
- **Important to have heat removal from reactor coolant system.**
- **Assure that control rods fully inserted, and/or soluble boron levels are adequate, and there are no reactivity issues.**
- **If water in reactor system is removed for any reason, this could lead to heat removal problems.**
- **If boiling occurs, this could lead to voiding and possible fuel damage.**
- **Need to be particularly careful when system is partially drained**



Case #2: Fuel in Open and Drained Reactor Vessel

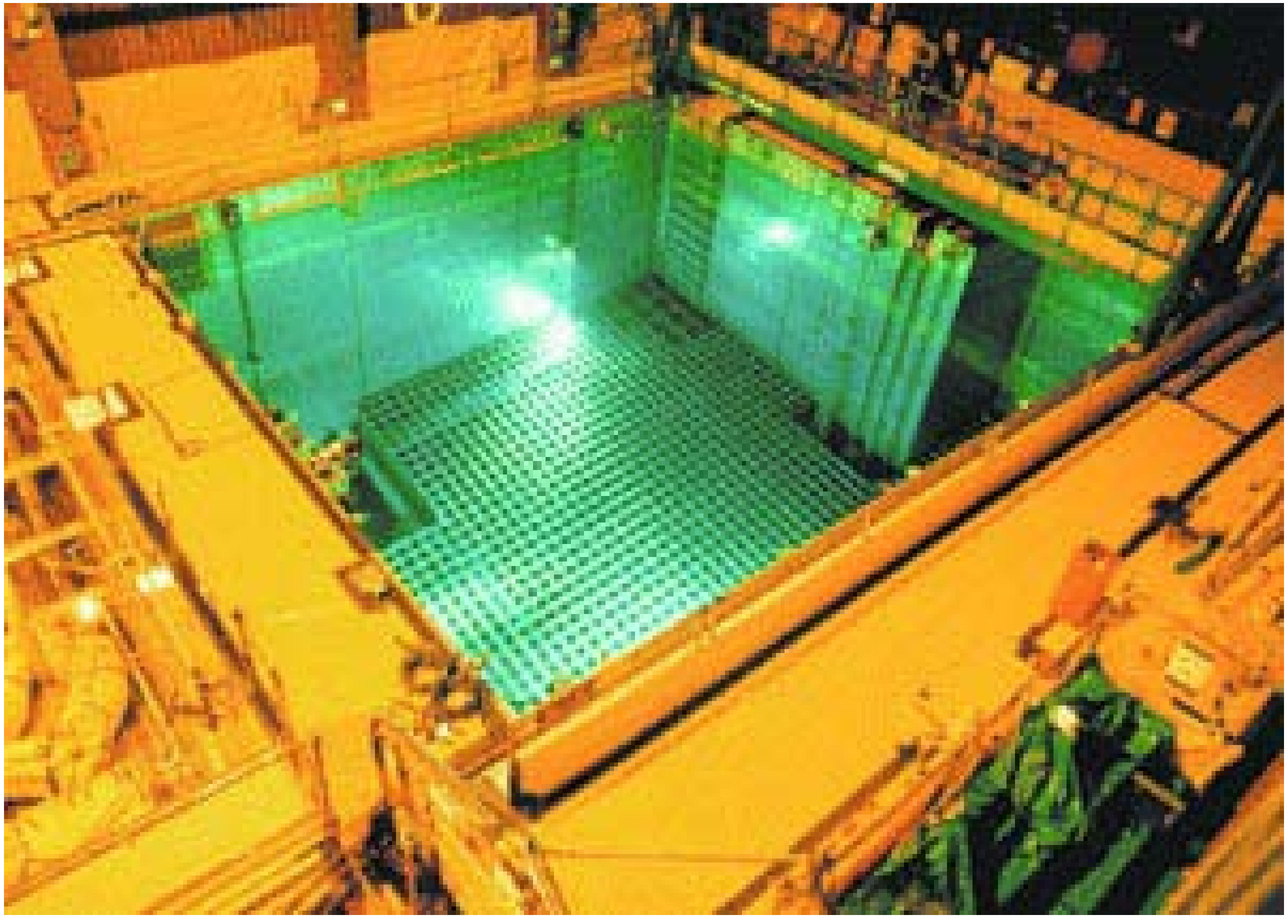
Decay Heat Regime: 3 to 50 days.

•An early industry practice was to drain loops for Steam Generator Maintenance. Mistakes in this practice have lead to dangerously low water levels in the reactor vessel.

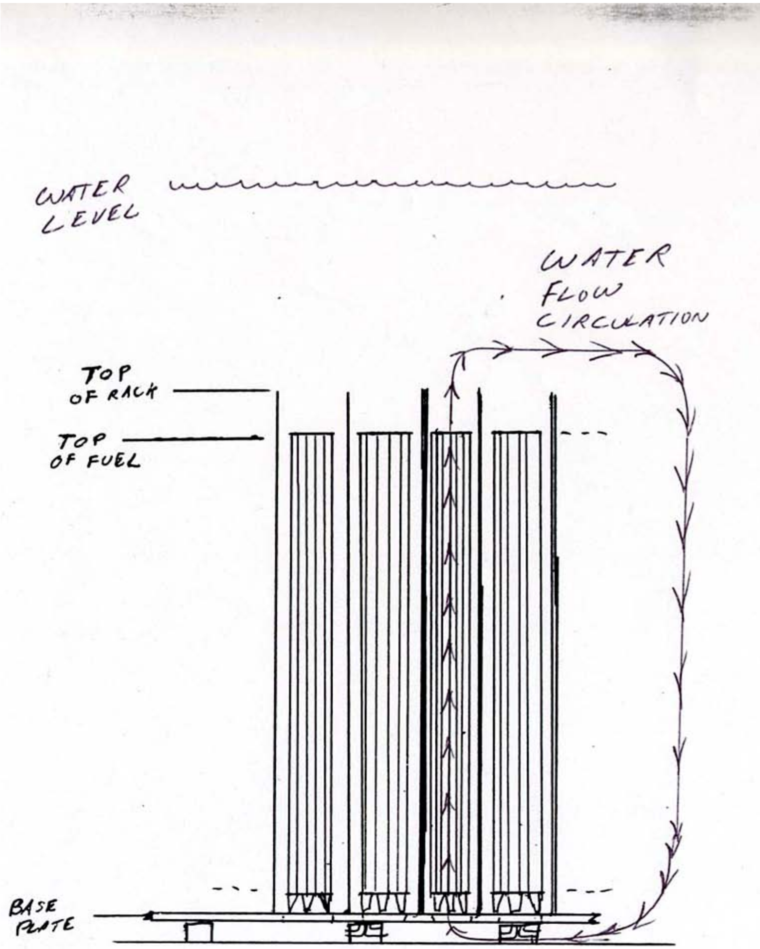
•Classic case for "time to boil" calculations:
- **-Estimated volume of water**
- **-Known heat rate –from decay heat curves.**
- **- Calculate time to boil, boil-off rate, time to uncover fuel, possibly fuel clad and centerline temperatures.**

•This configuration is seldom used today in the U. S.

Spent Fuel Pool

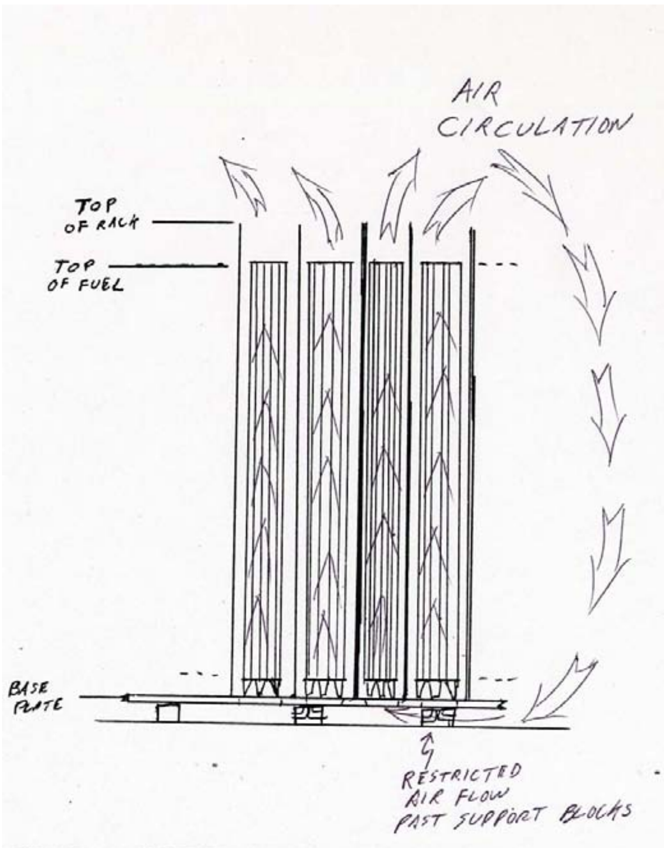


Case #3: Fuel in Spent Fuel Pool –Natural Circulation



Decay Heat Regime: 5 days to 40 years.

- **Water circulates through fuel assemblies in spent fuel pool. Cooler water sinks to bottom of pool and is heated by fuel assemblies. Water rises and a natural circulation process occurs.**
- **Fuel pools have cooling systems to cool the water from the pool.**
- **Failure of cooling system is not critical due to the large mass of water above the fuel. Rise in pool water temperature is easily detected.**
- **Ample time available to repair or compensate for failed cooling systems.**
- **Loss of pool water from leaks is an area of growing concern in aging plants and fuel storage facilities where corrosion may have advanced considerably.**
- **This concern is augmented by concerns about sabotage or terrorist attack.**

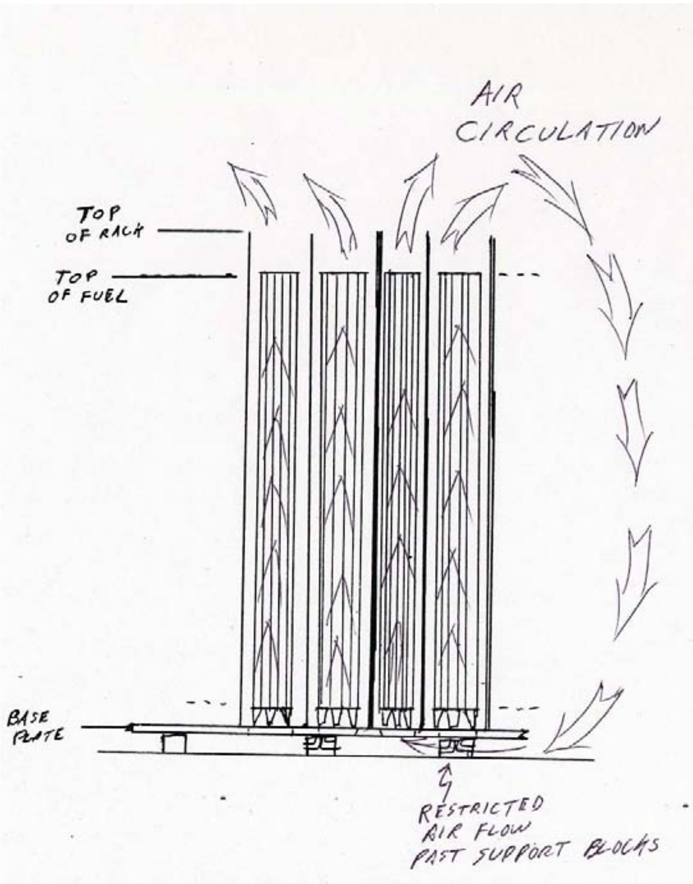


Case #4: Fuel in Completely Drained Spent Fuel Pool

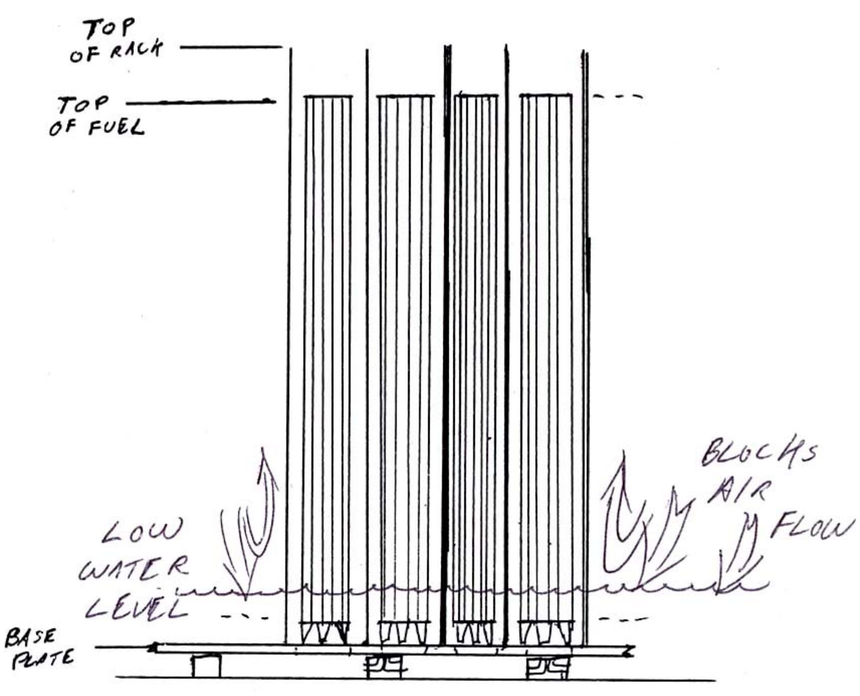
Decay Heat Regime: 5 days to 50 years.

- **This case is of intellectual interest as an "end point" of the water loss problem in a spent fuel pool. Which fuel assemblies are safe, and which fuel assemblies are at risk?**

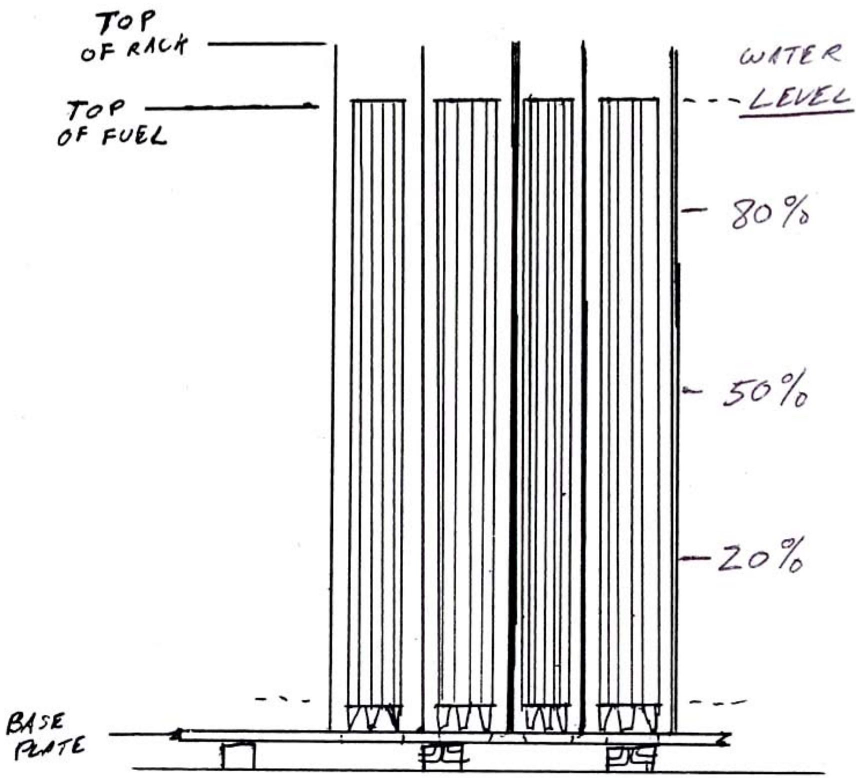
- **The decay heat curves are used, with added heat rates to cover uncertainties, to calculate conductive, convective and radiative heat losses (i.e. thermal radiation) to structural components and fuel assemblies.**



- The general view among the industry is that fuel assemblies that have aged for more than about 120 days will rise to an elevated temperature and achieve equilibrium with a circulating air environment. This stable temperature will have the cladding below the 1100-1200 C temperatures at which combustion of zirconium begins. This temperature is also below the melting temperature of commonly used steel alloys of around 1400 C.
- Substantial oxidation of zirconium may occur at these elevated temperatures.
- The elevated temperatures and loads may cause structural damage to the fuel pool or fuel racks. Detailed calculations are needed to model these effects.
- Heat rate at 120 days is about 7 kw per assembly.
- Assemblies with higher heat rates may reach “ignition” temperatures and eventually melt.



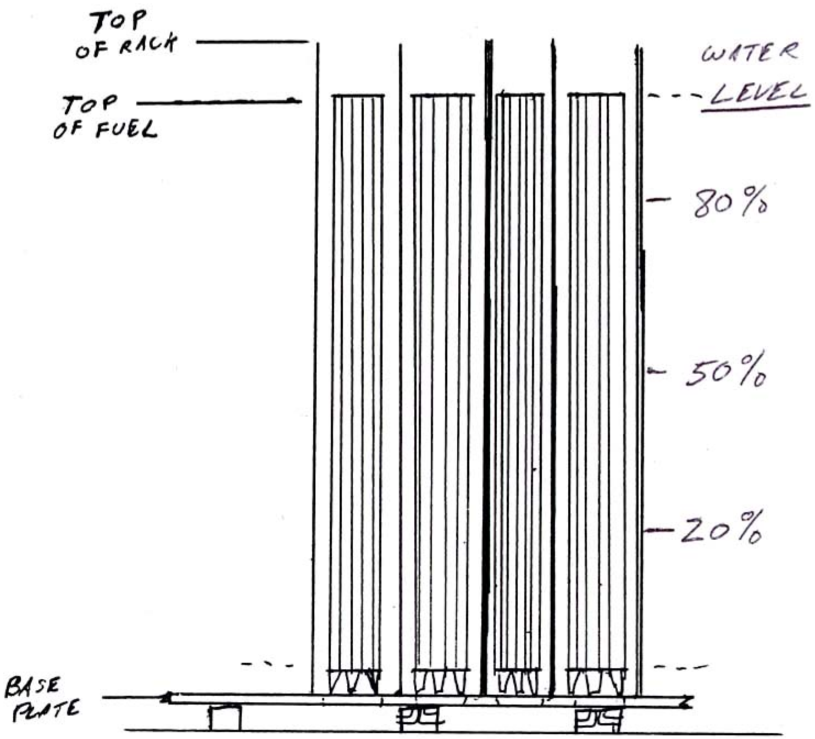
<u>Water addition:</u> adding water to the bottom of an empty spent fuel pool can damage an assembly with a heat rate of 7kw or less that has reached equilibrium in air! -- ***The water can block the circulation of air and cause the fuel assembly to overheat. The heat removed by the low level of water is insufficient to cool the assembly.***



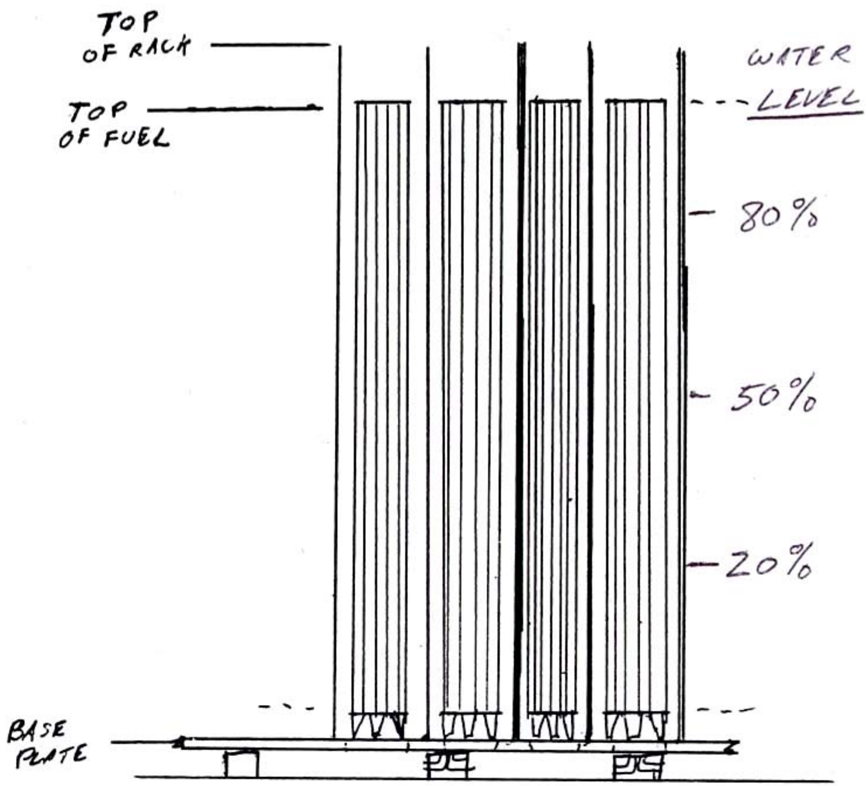
Case #5: Fuel in Partially Drained Spent Fuel Pool

Decay Heat Domain: 5 days to 50 years.

- **What is the effect of water level on spent fuel in a rack in a pool?**
- **A water level above the top of the rack allows natural circulation of water to occur.**
- **When the water level falls to the top of the fuel racks, natural circulation stops and water heat-up begins.**

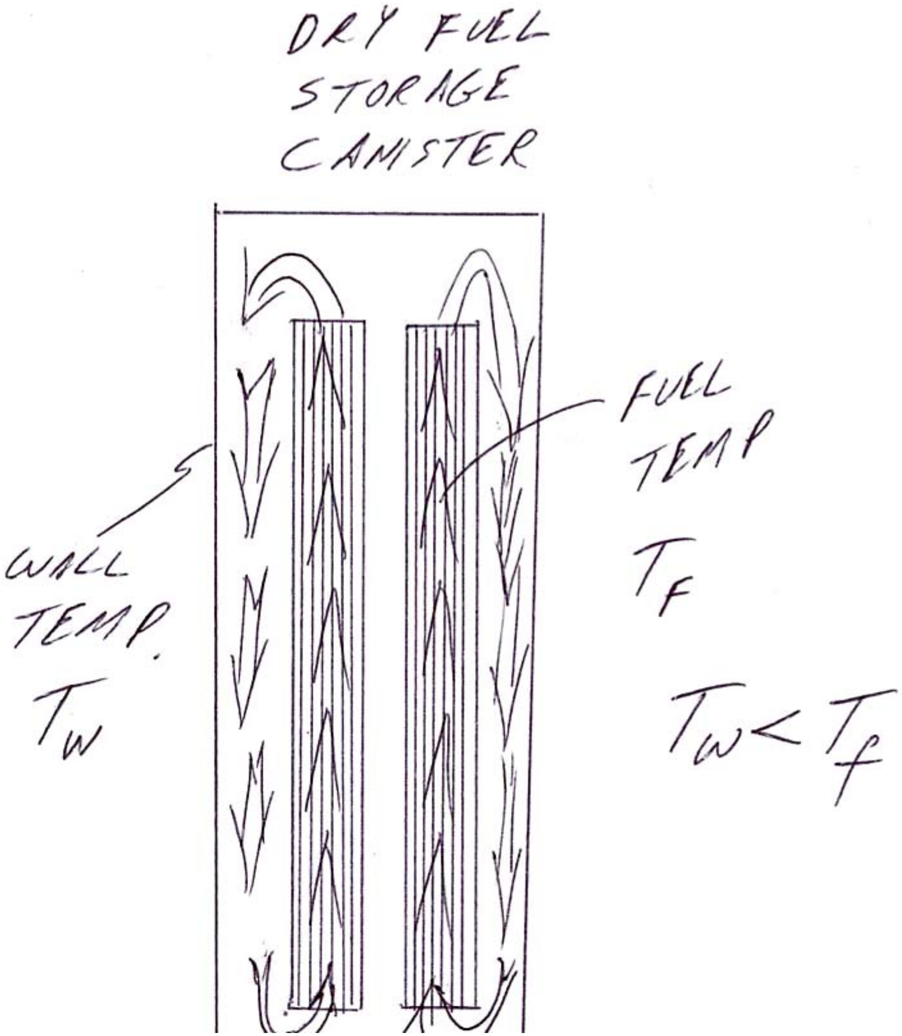


- Water temperatures will rise and boiling will eventually occur in the hotter assemblies.
- Water will flow along the bottom the pool from cooler assemblies to hotter assemblies.
- Boil-off will occur and water levels will drop—probably over the time scale of hours.
- As the levels drop, steam from the boil-off will cool the uncovered parts of the fuel.
- At some point, the rising steam will be insufficient to cool the uncovered fuel and clad temperatures will rise until they reach the "ignition" point.
- Where is this level? Detailed calculations are needed. Experts suggest that it is somewhere between 20 and 80% of assembly height, possibly around the mid-point.



- When the water is at the bottom of the fuel, say about the 20% level, the steaming rate is probably insufficient to cool the rest of the assembly, and air circulation is not possible. So fuel assemblies that may be safe in air are likely to melt with a low water level.

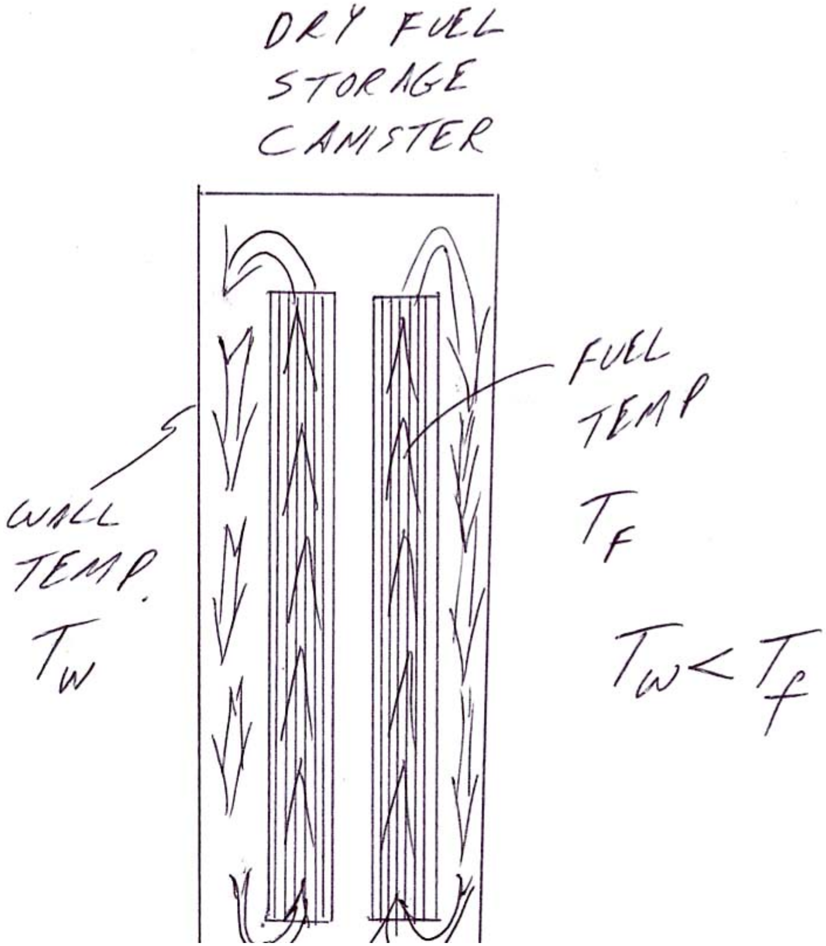
- Detailed calculations are needed to address specific issues of geometry and heat transfer.



Case #6: Dry Fuel Movement and Storage

Decay Heat Regime: 5+ years to 50 years

- **We have seen that after about 120 days it is possible that an assembly can be cooled in air without melting. Heat rates are about 7 kw per assembly at that time. After about three years, the heat rate drops to about 1 kw per assembly, and although the risk of melting in air is clearly lower, corrosion is still an issue as fuel centerline and clad temperatures are still elevated.**



- Remember that assemblies that may not melt in a good air flow, may melt if that air flow is blocked.
- The design of spent fuel storage canisters and casks considers these issues and a spectrum of possible accidents that can occur in dry storage and transport.
- Extensive testing is done on spent fuel shipping containers to account for crashes, drops, drops onto a penetrating object, fire, and flooding after a fire—remember that a small amount of water in the wrong place in a dry canister can block air flow and lead to possible fuel melting.

Summary and Conclusions

- Decay heat effects in spent nuclear fuel are well understood—the classic standard has existed since 1979.
- Spent nuclear fuel must be adequately cooled at all times.
- It is necessary to understand the physical circumstances for cooling spent nuclear fuel and to guard against conditions that could undermine this cooling.
- Computer analyses of spent nuclear fuel pools can provide detailed information that can help to provide strategies to manage and reduce risks of spent nuclear fuel handling, treatment and storage.

The End

Any Questions?