Nuclear Reactor Safety

Talk at the

Kennedy School of Government
Managing the Atom program

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I will discuss the safety issues appropriate for a Pressurized Water Reactor. The reactor at Seabrook is about 1100 MWe, 3000 MWthermal, of a Westinghouse design.

The reactor is used to heat water at high pressure, through a heat exchanger (steam generator) to produce steam which is sent to steam turbine which turns an electricity generator. Excess heat is removed by another heat exchanger which is cooled by seawater.

As shown in the picture here, the reactor is a very small part of the whole system. But I start by describing it

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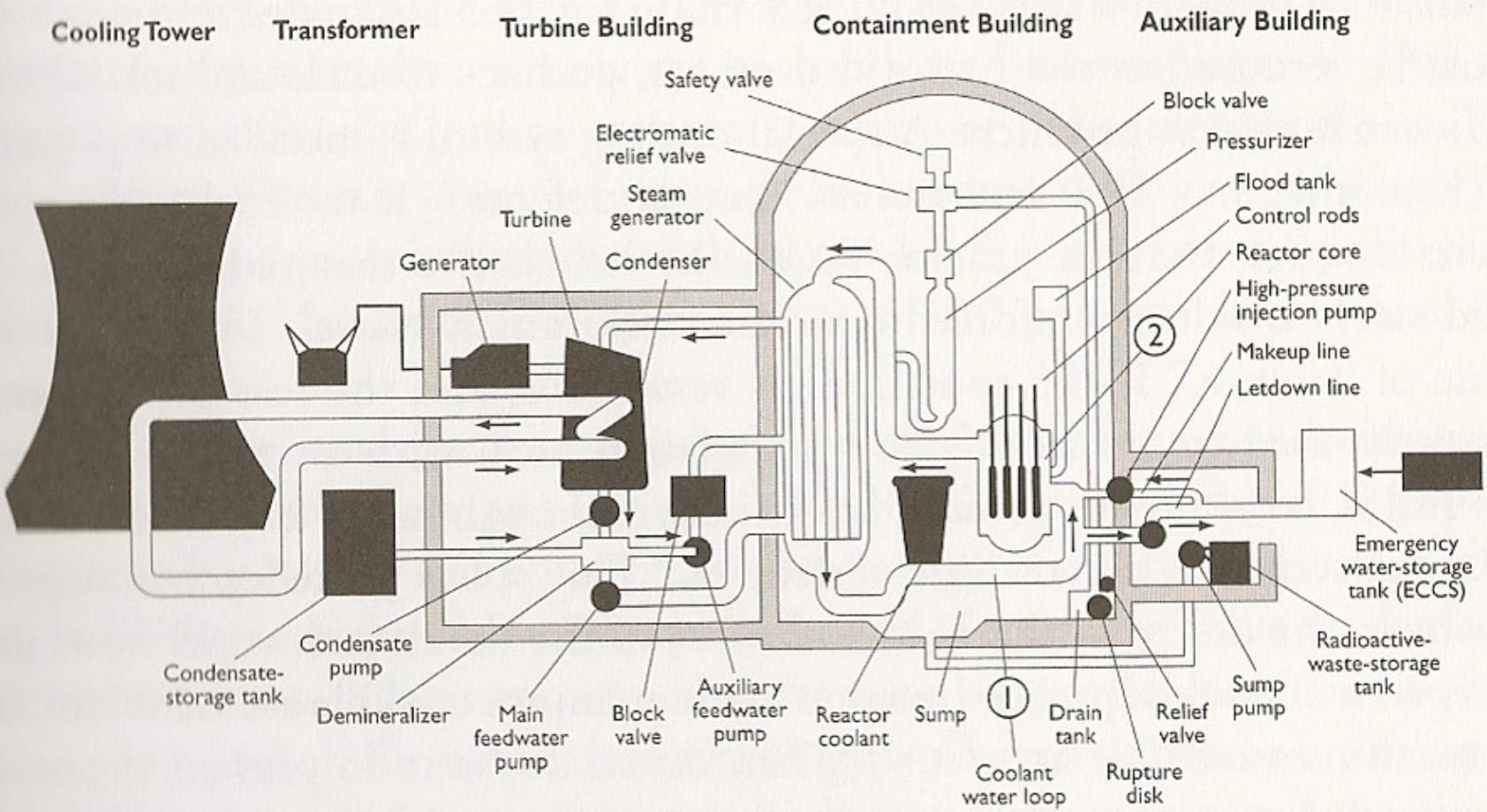
Schematic of Nuclear Power Plant with Emergency Core Cooling System (ECCS)

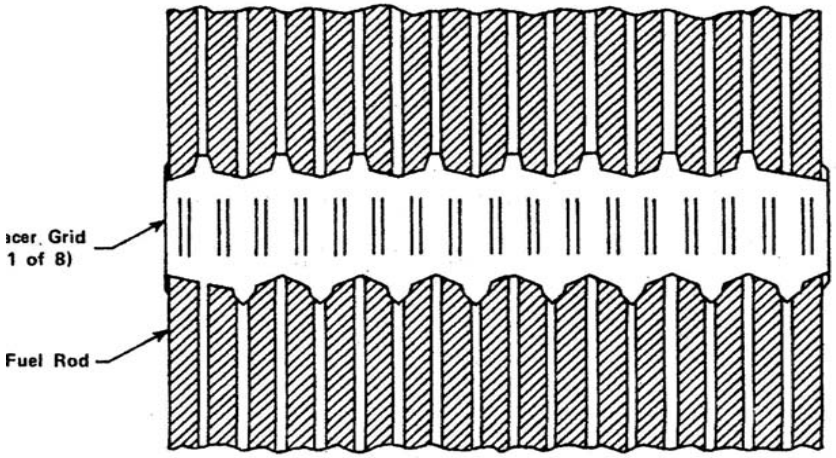


Light Water Reactor
(pressurized water type)

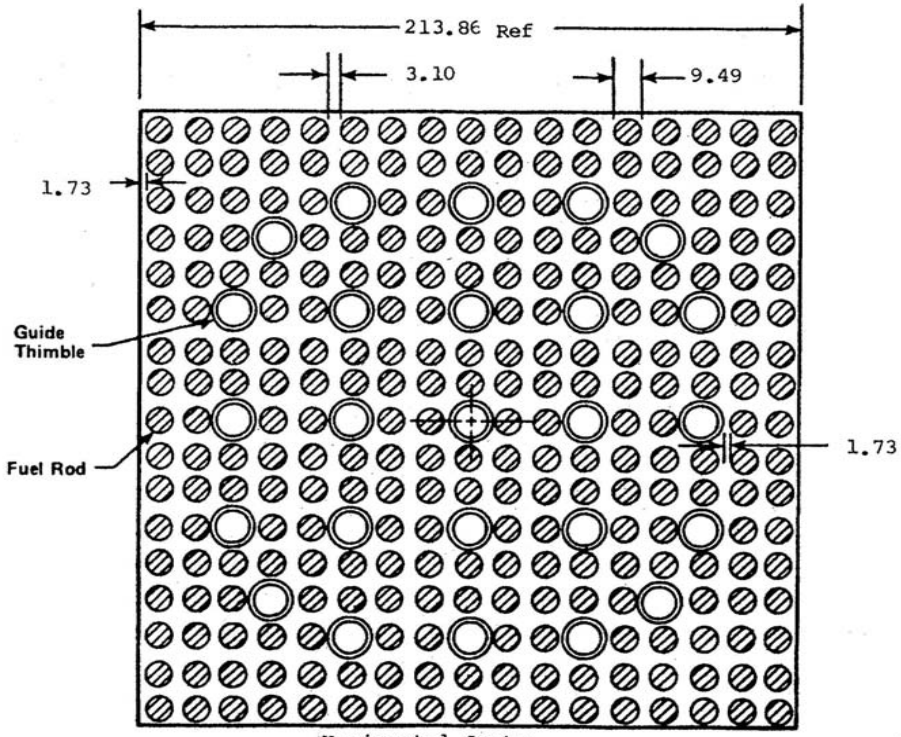
The nuclear Chain Reaction

U 235+ N -> U 236 which splits into two big bits
One element near Sr 90
one near Xe 138
+ 2.5 neutrons

92% of the energy is in kinetic energy of the fission fragments, about 3% in neutrinos and about 10% in energy of radioactive decay. Of which most is in charged particles and the rest in neutrinos.



Vertical Section



Horizontal Section

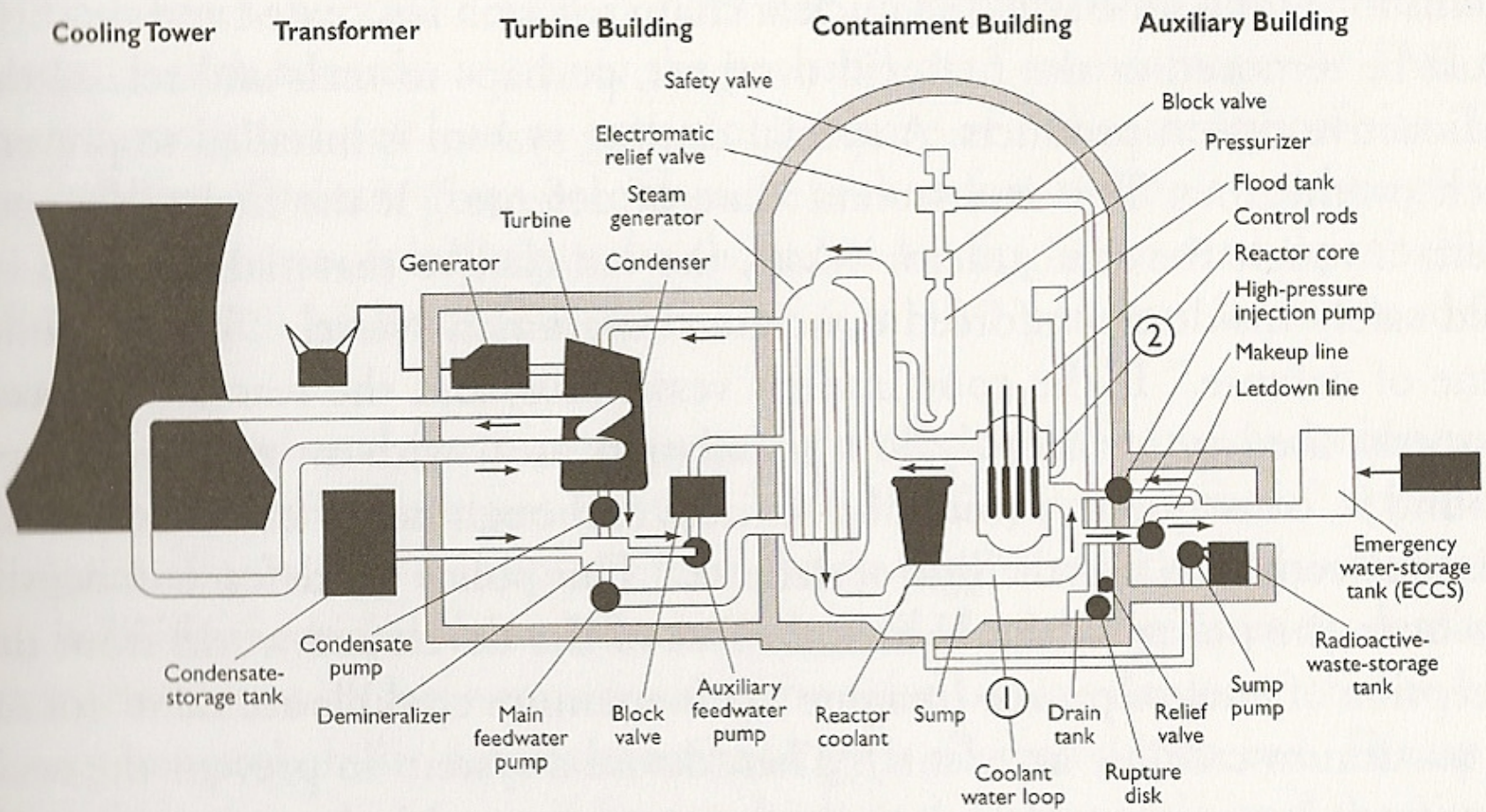
(dimension in mm)

The neutrons are slowed down in the “moderator” of water. Most are captured by various elements or escape the reactor reacts with another uranium atom to continue the chain. The capture happens with the slow neutrons only after about 100 microseconds. The reaction is controlled by boron control rods entering from the top of the reactor. Boron soaks up neutrons readily To start, the rods are moved till exactly one neutron is left to continue the chain reaction. Then the reactor is said to be “critical”

Of the neutrons, 0.8% are delayed by 0.1 to 20 seconds. If the reactivity changes are less than 0.8% then the time constant for changes is a second or so. But if changes are more than 0.8% the reactor can "prompt critical" and the time constant is 100 microseconds or so, too fast for effective control (Chernobyl)

The reactor is carefully designed with stability coefficients to shut down if things go wrong.
e.g if the water expand the water is less effective at slowing down, and the reaction stops.
This is DESIGN and is considered very reliable (except for RBMK)

Schematic of Nuclear Power Plant with Emergency Core Cooling System (ECCS)



Light Water Reactor
(pressurized water type)

Nuclear Reaction is used to heat water

Water is converted to steam

For 250 years we have used steam to run an engine

Second Law of Thermodynamics -
The higher temperature the higher efficiency
Therefore high temperature steam means high pressure
Problem is possible failure of the pressure vessel or piping

Even if the reactor is switched off there is enough decay heat (7%) is still high enough to melt the fuel This falls slowly as T^-1.2 (Wigner-Way law) in a well determined amount

If the fuel melts
radioactivity will be released
Dangerous ones:
Iodine: half life 14 days
Cesium (half life 30 years)
Solutions:
(a) don't let it melt
(b) contain the products as much and as long as possible

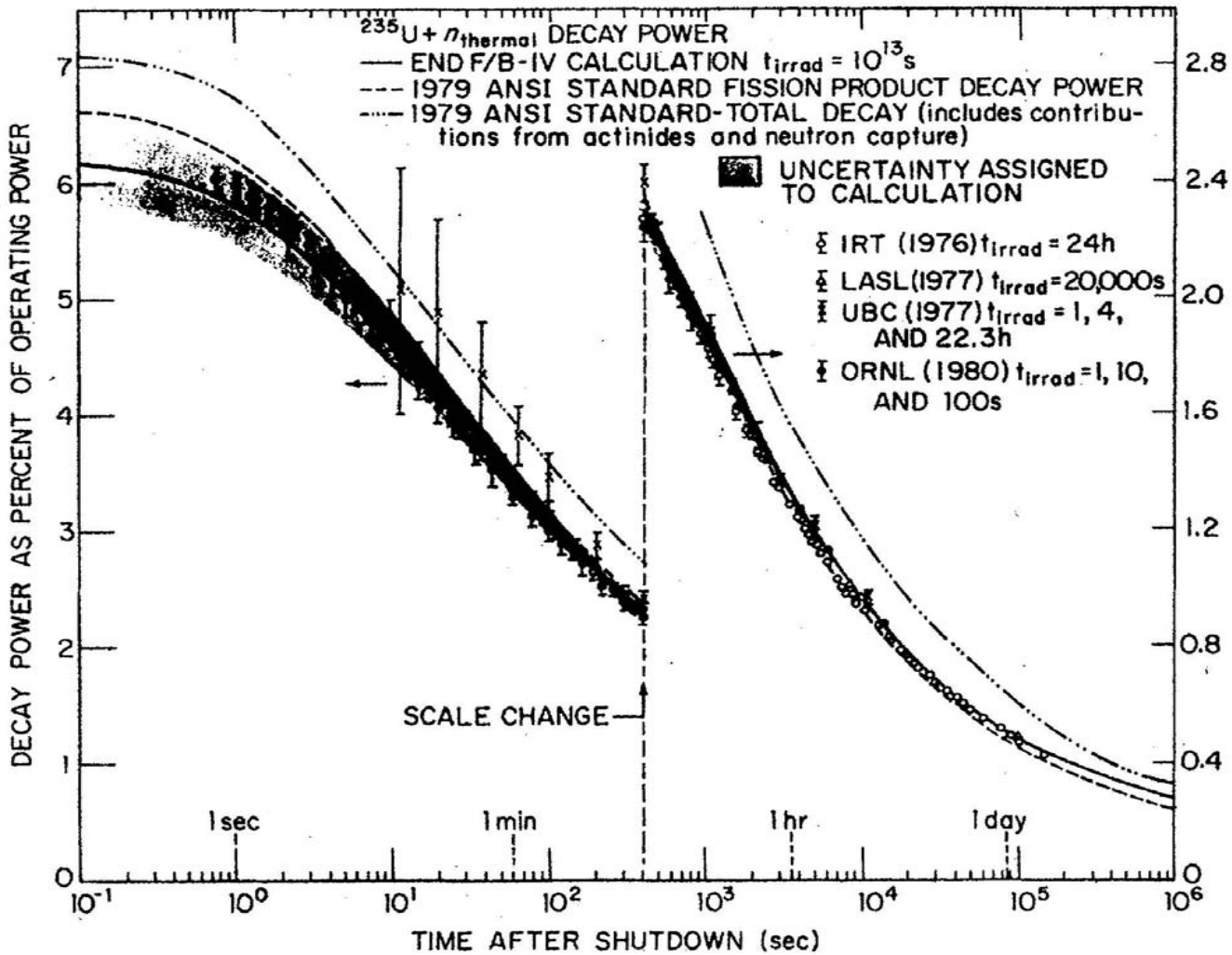


FIG. III.A.1. Decay power of fission products and actinides as calculated from the 1979 ANSI standard compared to various experimental results.

Radionuclides	Half-life $t_{1/2}$ (days)	inventory (10^6 Ci)	D_c/χ_0 (rem m^3/Ci s)	(rem/Ci inhaled) (0—50 yr)	D_g/S (rem m^2/Ci)
Noble gases					
Kr-85	3950.0	0.56	0.475E −03	0.310E +00	
Kr-85m	0.183	24.0	0.364E −01	0.260E +00	
Kr-87	0.0528	47.0	0.181E +00	0.100E +01	
Kr-88	0.117	68.0	0.467E +00	0.230E +01	
Xe-133	5.28	170.0	0.906E −02	0.700E +00	
Xe-135	0.384	34.0	0.567E −01	0.120E +01	
Iodines					
I-131	8.05	85.0	0.872E −01	0.600E +03	0.708E +03
I-132	0.0958	120.0	0.511E +00	0.700E +02	0.107E +03
I-133	0.875	170.0	0.154E +00	0.200E +03	0.311E +03
I-134	0.0366	190.0	0.533E +00	0.300E +02	0.414E +02
I-135	0.280	150.0	0.419E +00	0.150E +03	0.285E +03
Cesiums and rubidiums					
Cs-134	750.0	7.5	0.350E +00	0.470E +05	0.369E +04
Cs-136	13.0	3.0	0.478E +00	0.590E +04	0.410E +04
Cs-137	11 000.0	4.7	0.122E +00	0.360E +05	0.131E +04
Rb-86	18.7	0.026	0.207E −01	0.660E +04	0.185E +03
Telluriums and antimony					
Te-127	0.391	5.9	0.936E −03	0.340E +02	0.813E +00
Te-127m	109.0	1.1	0.110E −02	0.240E +04	0.584E +02
Te-129	0.048	31.0	0.147E −01	0.980E +01	0.198E +01
Te-129m	0.340	5.3	0.783E −02	0.300E +04	0.246E +03
Te-131m	1.25	13.0	0.314E +00	0.550E +03	0.960E +03
Te-132	3.25	120.0	0.475E −01	0.150E +04	0.308E +04
Sb-127	3.88	6.1	0.151E +00	0.790E +03	0.920E +03
Sb-129	0.179	33.0	0.268E +00	0.110E +03	0.104E +03

Radionuclides	Half-life $t_{1/2}$ (days)	Shutdown inventory (10^6 Ci)	Cloud D_c/χ_0 (rem m^3/Ci s)	Inhalation, κ_i (rem/Ci inhaled) (0—50 yr)	Ground D_g/S (rem m^2/Ci)
Alkaline earths					
Sr-89	52.1	94.0		0.410E+04	
Sr-90	11 030.0	3.70		0.240E+06	
Sr-91	0.403	110.0	0.169E+00	0.310E+03	0.205E+03
Ba-140	12.8	160.0	0.444E−01	0.190E+04	0.365E+04
Volatile oxides (Ru)					
Co-58	71.0	0.78	0.216E+00	0.420E+04	0.244E+04
Co-60	1920.0	0.29	0.600E+00	0.820E+05	0.588E+04
Mo-99	2.8	160.0	0.364E−01	0.420E+03	0.325E+03
Tc-99m	0.25	140.0	0.306E−01	0.980E+01	0.162E+02
Ru-103	39.5	110.0	0.111E+00	0.190E+04	0.116E+04
Ru-105	0.185	72.0	0.179E+00	0.660E+02	0.794E+02
Ru-106	366.0	25.0	0.431E−01	0.620E+05	0.456E+03
Rh-105	1.50	49.0	0.182E−01	0.960E+02	0.567E+02
Nonvolatile oxides (La)					
Y-90	2.67	3.9		0.780E+03	
Y-91	59.0	120.0	0.625E−03	0.560E+04	0.591E+01
Zr-95	65.2	150.0	0.162E+00	0.560E+04	0.177E+04
Zr-97	0.71	150.0	0.422E−01	0.520E+03	0.538E+03
Nb-95	35.0	150.0	0.166E+00	0.190E+04	0.164E+04
La-140	1.67	160.0	0.567E+00	0.920E+03	0.180E+04
Ce-141	32.3	150.0	0.183E−01	0.110E+04	0.182E+03
Ce-143	1.38	130.0	0.681E−01	0.340E+03	0.224E+03
Ce-144	284.0	85.0	0.431E−02	0.320E+05	0.120E+03
Pr-143	13.7	130.0		0.820E+03	
Nd-147	11.1	60.0	0.314E−01	0.790E+03	0.305E+03
Np-239	2.35	1640.0	0.308E−01	0.250E+03	0.202E+03
Pu-238	32 500.0	0.057	0.525E−04	0.730E+08	0.620E+01
Pu-239	8.9E+06	0.021	0.230E−04	0.820E+08	0.263E+01
Pu-240	2.4E+06	0.021	0.464E−04	0.830E+08	0.547E+01
Pu-241	5350.0	3.4	0.417E−09	0.150E+07	0.221E−02
Am-241	1.5E+05	0.0017	0.465E−02	0.860E+08	0.143E+03
Cm-242	163.0	0.50	0.500E−04	0.190E+07	0.546E+01
Cm-244	6630.0	0.023	0.142E−02	0.430E+08	0.346E+02

1950:

AEC Advisory Committee on Reactor Safeguards
Edward Teller, Richard Feynman, others

Defense in Depth
Imagine what might go wrong
Devise a system to prevent any consequences.
Core must not be allowed to melt
(Emergency Core Coolant System or ECCS)

Define:
Maximum Credible accident

Typically:
Imagine a pipe break that leads to immediate flashing of water to steam as the pressure falls

Put water back in ASAP to avoid melt (Emergency Core Cooling System)

1975

Rasmussen's Reactor Safety Study

Look quantitatively at events that might exceed the “Maximum Credible Accident”.

Set up an EVENT TREE

time goes left to right

Crucial Assumption:
Assume that the steps in the system are independent of each other and consider separately dependences.

Set up the tree so that this is so.
(Judgment needed here)

Simplified Event Trees for a Large LOCA

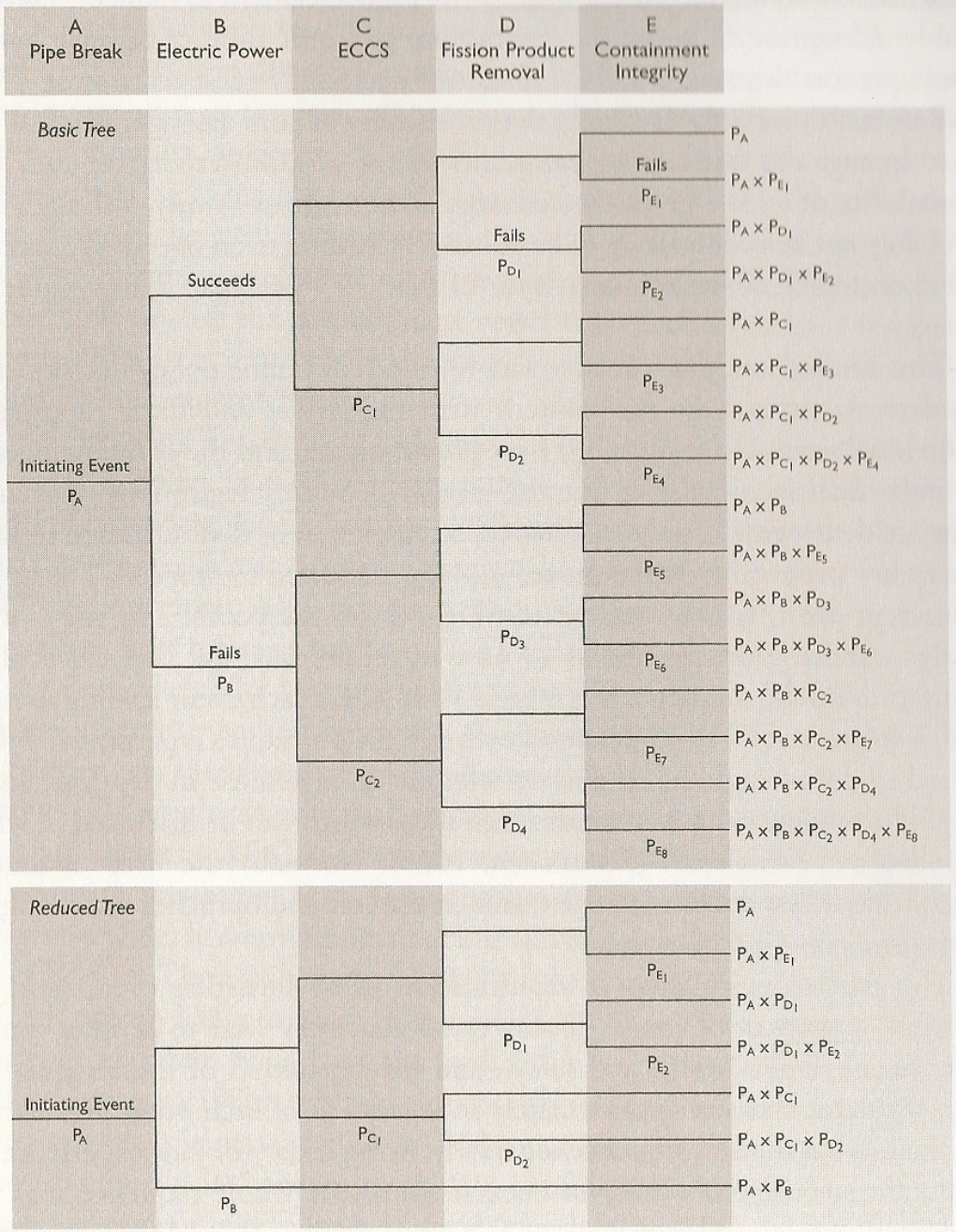
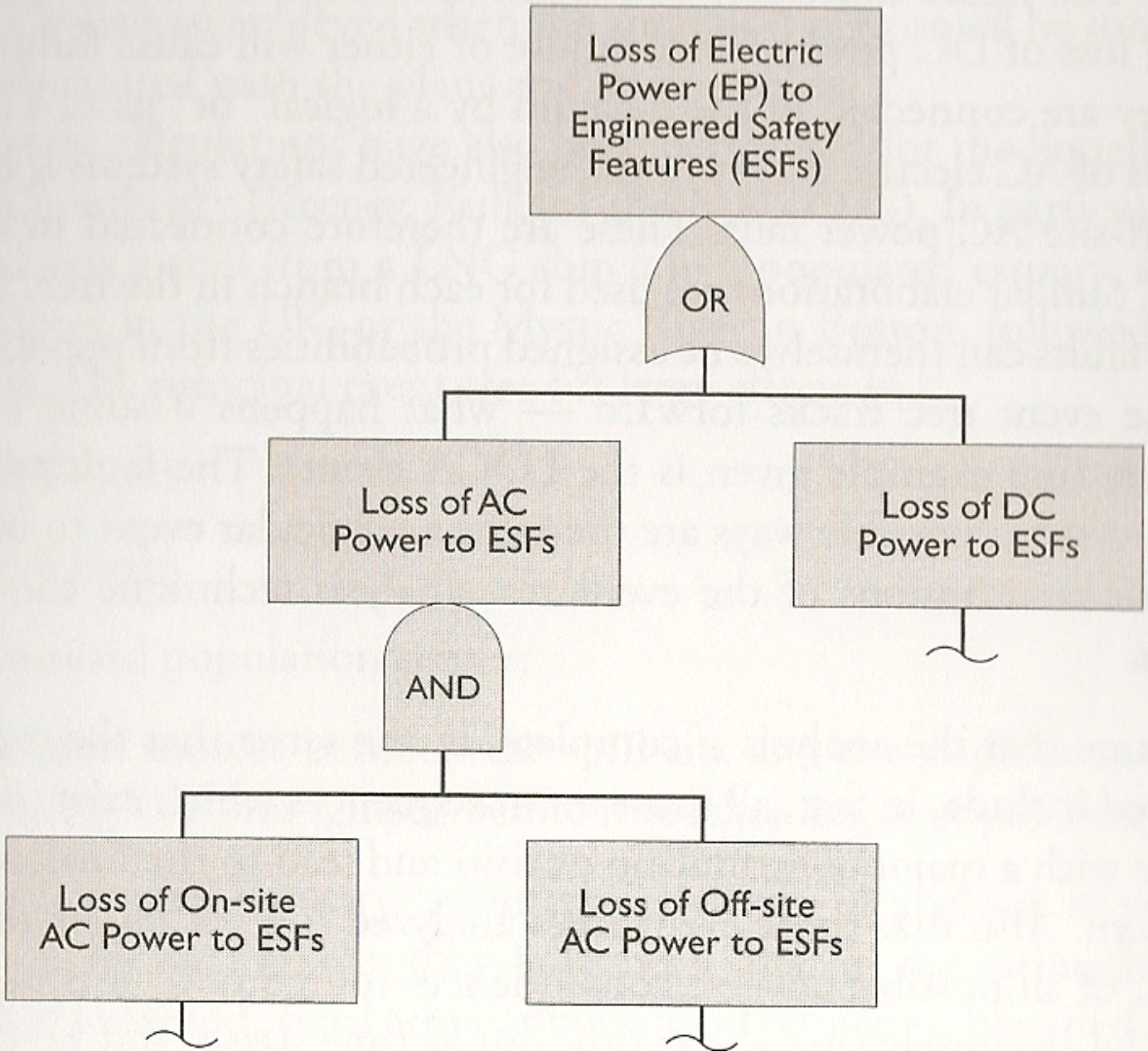


FIGURE 2-6

Illustration of Fault Tree Development



P_1 = the probability of a pipe break, which may be estimated from historical experience with pipes firstly in other industries, secondly in the limited experience of the nuclear industry and finally with the theory of metal failure

P_2 = is the probability of failure of electric off-site power

P_{C2} = probability of failure of the emergency core cooling system (ECCS)

P_{D4} = is the probability of failure of fission product removal (by containment sprays for example)

P_{E8} = is the probability of containment violation

Further simplification:
Pipe Break:
Probability (P1) from history – originally laundries, fossil fuel plants etc. Now we can use reactor experience with better pipes

Does ECCS work? Failure (P2) ? That can be tested but it also depends on availability of electricity .

Does Containment Hold? Probability of Failure Failure (P3)

Is wind blowing reactivity to city? (P4)

If these are independent:
P (overall)= P1 x P2 x P3 X P4
Typically
Reactor history P1 < 1/10000
from test P2< 0.03
Sandia failure tests P < 0.3
Geometry + effect of radiation P <0.01

P< 1/10,000,000

Various events can correlate these in spite of our best efforts

Fire (Brown's Ferry)
Earthquake(no example so far)
Human activity (TMI)
Miscevous human activity
Sabotage, terrorism

The procedure enable us to focus on these

A “sleeper” terrorist or group might:

(a) Learn about reactor safety in MIT's nuclear safety course

(b) Join a specific utility and learn details of the plant.

THEN

(1) Set off a bomb to create a pipe break

(2) Switch off the ECCS system

(3) Simultaneously set off a bomb to make a hole in the containment

(4) Do this when the wind is blowing to the city

"[The RSS] was a substantial advance over previous attempts to estimate the risks of the nuclear option. The methodology has set a framework that can be used more broadly to assess choices involving both technical consequences and impacts on humans.

"[The RSS] was largely successful in at least three ways: in making the study of reactor safety more rational, in establishing the topology of many accident sequences, and in delineating procedures through which quantitative estimates of the risk can be derived for those sequences for which a data base exists. . . .

"Despite its shortcomings, [the RSS] provides at this time the most complete single picture of accident probabilities associated with nuclear reactors. The fault-

If the report of this 1977 Congressionally mandated committee had been heeded by any one of:

Babcock and Wilcox
The Utility Company
Nuclear Regulatory Commission
Nuclear Critics

The TMI accident would have been avoided

Terrorism and Sabotage already considered for nuclear power.

Do not store a lot of fuel in one place near a lot of people in one place.

(Remote siting)

“A saboteur could not do worse than those clowns did on their own”

(NF Rasmussen after TMI)

BUT:

a saboteur can increase the frequency

GENERAL RULE for TERRORISM

concentrate on Low Probability High Consequence events

The containment vessel solves many problems

(even air plane hits)

but:

study carefully whether such action outside the containment can set off an accident

Simulation suggests that the event tree procedure reduces overall risk a factor of 30 compared to the “old” engineering approach of setting standards and following them

The event tree procedure is now being applied to LNG tanks

Chemical refineries,

NASA launches

but not yet to

Building failures