NE585
NUCLEAR FUEL CYCLES
Incore fuel management
6a

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Learning objectives

Explaining how fuel is managed in the core for maximum burnup

Analyzing fuel performance in the core

Learning nodes

Reprocessing policy

Reloading

Batches

Burnup

Outages

Fuel management

Fuel management is a broad term

The main component of fuel management is access to nuclear materials

Power history of the reactor

Core loading

Refueling

Storage and disposal

There are also several regulatory constraints

Peak to average power ratio

Maximum core temperature

Deviation from nucleate boiling

Core reactivity

Temperature coefficient

Fuel cost needs to be minimized

Though it's not a huge expense

Back in the 1950s, federal government was to buy reactor produced Pu to use in breeders

Plants also thought that the government was going to take back used fuel after 5 years

So there was only limited onsite storage

Also assumed reprocessing

Reprocessing policy

The federal government issued a **GESMO** in the 70s which is a stupid acronym

Generic Environmental Impact Statement for Mixed Oxide Fuel (GESMO)

The idea was that there were going to be a lot of reprocessing facilities

The Atomic Energy Commission concluded based on study from 1957 to 1972 that 'widescale use of mixed oxide fuel should be approved'

Published in August 1974

Became NRC in 1975

Carter canceled reprocessing in 1977

The idea was the risk of Pu diversion

Even though USA is a nuclear weapons state

But he wanted other nations to follow suit

Reagan lifted the ban in 1981, but there wasn't any other investment

Carter cited it not being cost effective

But the report indicated starting soon that it would be

There's also been zero cases of civilian diversion to start a weapons program

We even have Carter's speech

The benefits of nuclear power are thus very real and practical. But a serious risk accompanies worldwide use of nuclear power–the risk that components of the nuclear power process will be turned to providing atomic weapons.

First, we will defer indefinitely the commercial reprocessing and recycling of the plutonium produced in the U.S. nuclear power programs. From our own experience, we have concluded that a viable and economic nuclear power program can be sustained without such reprocessing and recycling.

Third, we will redirect funding of U.S. nuclear research and development programs to accelerate our research into alternative nuclear fuel cycles which do not involve direct access to materials usable in nuclear weapons.

Without reprocessing, plants were running out of storage space

Redesign pools to rack more fuel

Extend the burn cycle to 24 months

Higher burnup fuels to 50 GWD/MTU

Requires higher enrichment so increased costs because SWU is intensive

Roses are red; Violets are blue; No one likes nuclear because we use SWU.

NWPA addressed storage issue

Among the other issues about siting a repository

DOE obligated to take used fuel from plants for final disposal

If plant needs storage space before government can take the fuel, interim storage must be provided

Utilities paid $0.001/kWh to the Nuclear Waste Fund

Since 1983, more than $30 billion collected – suspended in May 2014

NEI urges DOE, OMB to Address Nuclear Waste Fund Inequities

Reloading

Core has assemblies with different initial enrichments

Batch = group of assemblies of same fuel type and enrichment

So core is reloaded by batch

$$B \equiv \frac{P_0 \cdot \epsilon \cdot T}{M(t)}$$

$$\epsilon \equiv \frac{\int_0^T P(t)dt}{P_0 T}$$

So burnup is proportional to initial of enrichment of fuel

Initial reactivity is also proportional to enrichment

$$\rho \equiv \frac{k-1}{k}$$

Once the reactor starts operating, negative reactivity increases due to poisons

$$\rho_{net} = \rho_{fuel} - \rho_{FP} - \rho_{T}$$

Positive reactivity decreases linearly with time

$$\rho = \rho_0 - aB$$

What is net reactivity at critical?

That's where the control rods come in

Reactivity control from boric acid, control rods

Boron is removed from coolant over the cycle

$$\rho_{net} = \rho_{fuel} - \rho_{FP} - \rho_{T}$$

Reactivity swing is the positive reactivity in the core available during operation

Should be minimal because you don't want to have to use the control rods to suck up all the neutrons

Cores operate on multiple batches

This changes reactivity calculations

Operator needs to know real-time reactivity though

For the one batch core – $\rho_1(t) = \rho_0[1 - \frac{B_1^1(t)}{B(T)}]$

ρ_0 – fresh fuel reactivity for unburned core

$\rho_1(t)$ – the time dependent reactivity at t

$B_N^n(t)$ – burnup of a batch at cycle n in the N-batch core at t

$B(T)$ – final burnup in the core at end of life

Use of multiple batches reduces the reactivity swing

Assume the total core reactivity is the average of the batch reactivities

$$\rho_2(t) = \frac{\rho_0}{2}[(1 - \frac{B_2^1(t)}{B(T)}) + (1 - \frac{B_2^2(t)}{B(T)})]$$

$$\rho_3(t) = \frac{\rho_0}{3}[(1 - \frac{B_3^1(t)}{B(T)}) + (1 - \frac{B_3^2(t)}{B(T)}) + (1 - \frac{B_3^3(t)}{B(T)})]$$

Assume equal fractional contribution of burnup in each batch

$$\rho_2(T) = \frac{\rho_0}{2}[(1 - \frac{1}{2} \cdot \frac{B_2(T)}{B(T)}) + (1 - \frac{2}{2} \cdot \frac{B_2(T)}{B(T)})]$$

$$\rho_3(T) = \frac{\rho_0}{3}[(1 - \frac{1}{3} \cdot \frac{B_3(T)}{B(T)}) + (1 - \frac{2}{3} \cdot \frac{B_3(T)}{B(T)}) + (1 - \frac{3}{3} \cdot \frac{B_3(T)}{B(T)})]$$

And increases burnup

With $\rho_N(T) = 0$

$$B_2(T) = \frac{4}{3}B(T)$$

$$B_3(T) = \frac{3}{2}B(T)$$

PWRs go on 3 batches

BWRs, 4

The core has to be loaded to fall within safety constraints

But there are operational goals

Fuel needs to achieve a certain burnup

Flat power profile across the core – low peak:average power

It's an optimization problem

Core loading strategies typically assume equilibrium

0 = fresh fuel

cycle 1 – b1,0,b2,0,b3,0

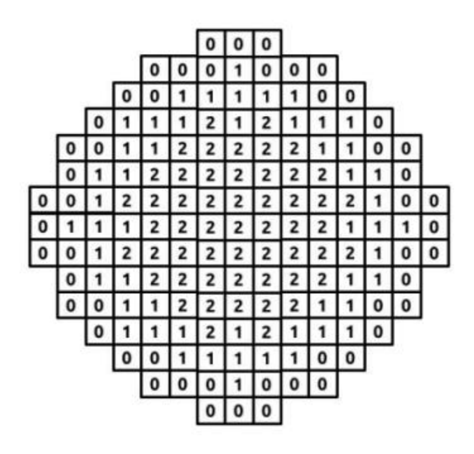
cycle 2 – b2,1,b3,1,b4,0

cycle 3 – b3,2,b4,1,b5,0

cycle 4 – b4,2,b5,1,b6,0

cycle 5 – b5,2,b6,1,b7,0

Older, out-In core loading applies concentric region



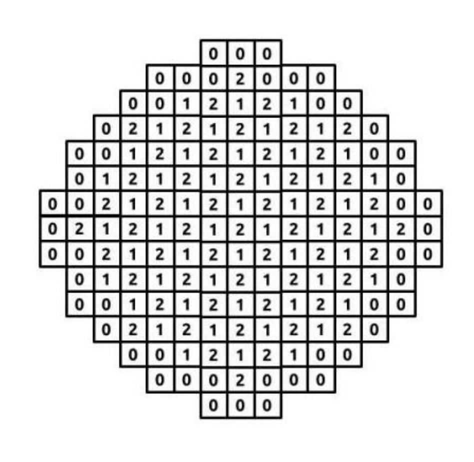
Innermost fuel discharged

Other batches moved to center

Fresh fuel always on the end

Not used anymore

In the scatter loading, the core is divided into small regions



Assemblies with highest burnup replaced with fresh fuel

What advantages does this configuration offer?

The pressure vessel suffers damage from neutron leakage

Function of power generated and flux shape

What shape is angular flux?

Reduce flux without reducing power

Placed burned assemblies on the periphery

Relocate assemblies from structural critical points

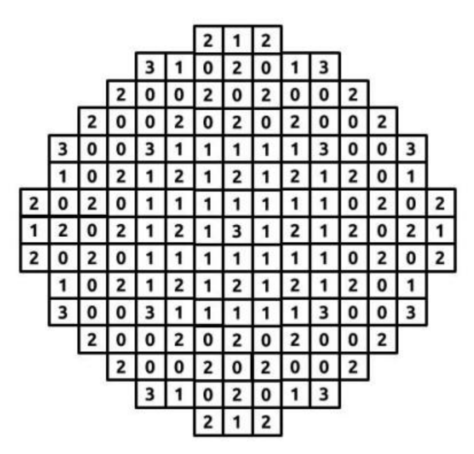
Replace some peripheral assemblies with empty ones

Add attenuating materials between core and vessel

Or add more poisons to peripheral positions

Not sure how some of those not reducing power

The low leakage configuration moves fresh fuel from vessel



Reducing leakage increases burnup

Moves peak power closer to center

Use of poisons dependent on plant to maintain peak:average

Each with different enrichments, on different cycles

Burnup management

Better fuel utilization will achieve higher burnup

Switch to the 18, 24 month cycle

Requires higher enrichment

Reduction in rod worth due to more Pu mass with higher enrichment

Pu increases fast:thermal flux

Control rods absorb mainly thermal neutrons

Increased burnup affects structural materials

Increased fission gas production

More radiation damage from fast neutrons

‘Increased risk of fuel failure’

Though I would question by how much since this isn’t happening

It’s not clear what the effect of higher burnup on fuel pools is

Neutron multiplication would be higher per assembly

There would be more Pu generated

But there would be more fission product poisons too

And the fuel would be more fissioned out

Obviously, there needs to be an accurate measurement to ensure criticality safety

Burnup is measured in a variety of ways

Direct measurement – sensors, fission chambers, flux wires – during operation

Indirect measurement – after discharge

^{137}Cs activity – $B = a + bA_{Cs}$

Directly measures 662 keV gamma

Relative measurement –

$B = c(e, r) + d(e, r) \cdot \frac{^{134}Cs}{^{137}Cs}$

e = enrichment; r = power rating

$B = ae^{b \ln R_0}$, $R_0 = \frac{^{106}Ru \cdot {}^{137}Cs}{^{134}Cs^2}$

Good for fresh fuel because of short Ru half-life

NUREG/CR-6998 Table 3.1 burnup confirmation

Cs-137 direct measurement

Insensitive to variations in reactor power rating

Requires well defined geometry between detector and assembly

Cs-134:Cs-137

Insensitive to geometry

Short half life, less then 20 y cooling time

Dependent on inital enrichment, power rating

Ru

Insensitive to geometry

Less than 9 years cooling time

Passive neutron measurement can also be used

Cm-244 spontaneous neutron emission dominant source

95% after 10 years

92% after 20 years

Uniform signal from all pins

Good for safeguards

Strong function initial enrichment

Geometry sensitive

Affected by poisons

Outage management

Refueling needs to get done as quickly as possible

Lots of activities going on during shutdown

Emma Redfoot – Diablo internship

Maintenance and refueling

Schedule shutdown during time of low demand

Where does the power come from during shutdown?

When would be peak demand in Idaho?

Outages cost a lot of money

Up to $2 million per day

Minimize shutdown period

How will SMRs do it?

Then the utility may have to buy replacement power

Establish outage organization

Inventory of tasks to perform (12,000)

Schedule all of the tasks

Requires expertise in risk management and decision making

1,200 workers hired for a big job at Northwest's only nuclear power plant

Outage best practices

Remove vessel head, prepare fuel handling equipment prior to reloading

Assembly, pressure vessel, fuel inspections after unloading

In-vessel and ex-vessel equipment repair

Reload fuel and close vessel

Major equipment inspection and repair (pumps, turbine, etc.)

Startup testing

In addition to refueling, there's lots of inspections and testing

Reactor vessel; Steam generator; Pumps

Turbine and generator; Control rods; Pressurizer

Moisture separator; Coolant system; Containment testing

Fuel handling system; Instrumentation

Diesel generators; Piping; Valves

Residual heat removal; Cooling towers