Conceptual Design for Advanced Burner Breeder Reactor

Victor Cabral, Dwight Chambers,
Bo Feng, MinWah Leung,
Jeffrey Perez, Drew Reese,
Emily Slutsky, Bradley Sutton,
Katherine Thornton, Christopher Waits,
Jamie Warburton, Joshua Whitman

Abstract

- Conceptual fast reactor design capable of burning minor actinides from spent LWR fuel, breeding fuel in blankets surrounding core, and producing low-cost electricity
- Based on Clinch River Breeder Reactor (CRBR) 975 MWt, ceramic fuel

Overview

- GNEP Goals and Fuel Processing
- Core Design
- Thermal Hydraulics
- Economics

GNEP & Fuel Processing

Jamie Warburton, Bradley Sutton

GNEP

- Goals
  - Effectively meet increasing energy demands through nuclear power
- Concerns
  - Safety
  - Waste Disposal
  - Proliferation

GNEP continued

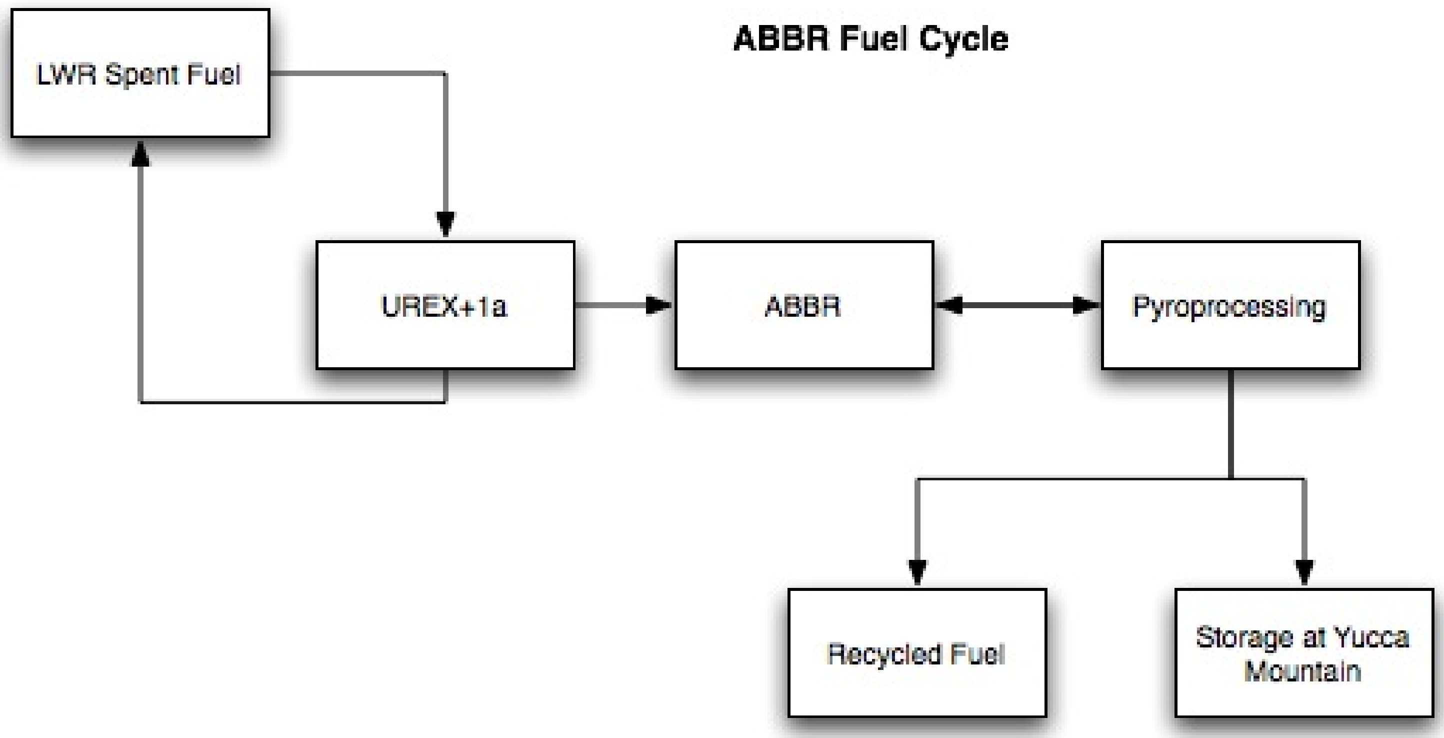
- Benefits
  - Reduce dependence on fossil fuels
  - Reduce carbon emissions & greenhouse gases
  - Recycle used nuclear fuel in order to maximize energy recovery and supplement uranium supply
  - Recycle fuel to minimize waste and keep number of repositories to a minimum
  - Allow developing nations to utilize nuclear energy

ABBR & GNEP

- ABBR will be flexible to breed or burn depending on needs
- Benefits
  - Breed
    - New fuel generated
    - sustain energy demands in limited uranium resources
  - Burn
    - Minimize waste
    - Limit required number of repositories
    - Maximize energy recovery from spent LWR fuel
    - Inhibit proliferation

Methods

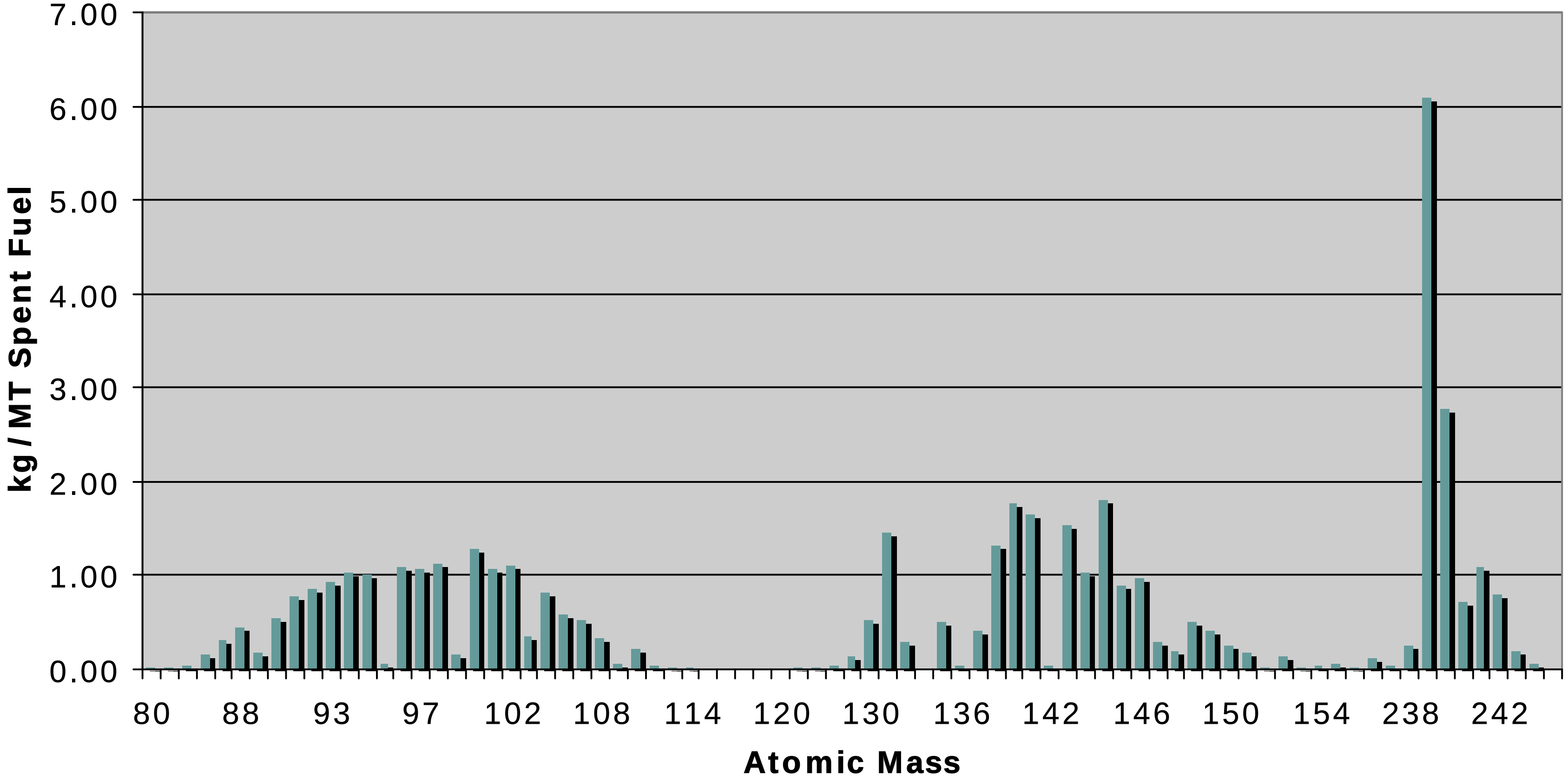
- In order to reduce spent fuel inventories & extract maximum energy from nuclear fuel
  - LWR spent fuel reprocessed
    - UREX+1a
  - Streams are used for input fuel in ABBR
  - Spent fuel from ABBR reprocessed
    - Pyroprocessing

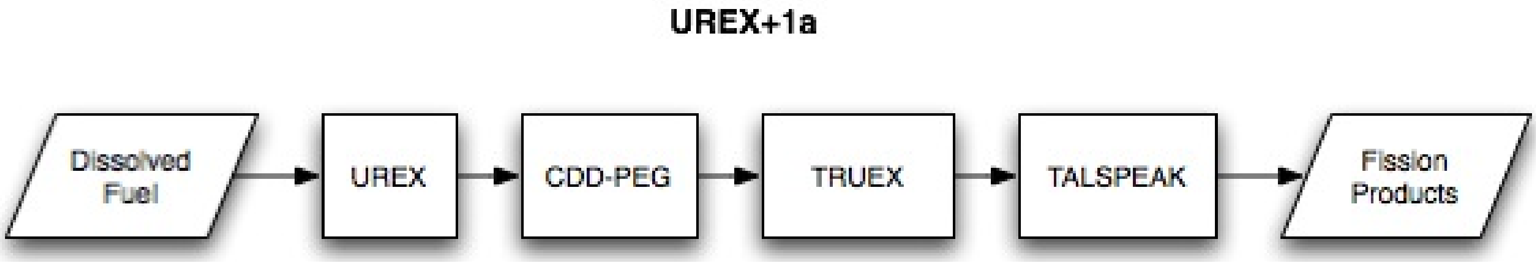

ABBR Fuel Cycle
LWR Spent Fuel
UREX+1a
ABBR
Pyroprocessing
Recycled Fuel
Storage at Yucca Mountain

LWR Spent Fuel

- Composition
  - Compiled for all reactors in US & DOE inventories
- Volume
  - Commercial Storage: 44,000 MTHM
  - DOE Storage: 12,000 MTHM
  - 2,000 MTHM generated annually
- Capacity of repository
  - 70,000 MTHM
  - Full by 2012 (estimations vary)

Mass Distribution of Atoms in Spent Fuel





- Has been demonstrated on a large-scale
- UREX: removes uranium & technetium
  - 99.9 & 98.3% efficiencies
- CDD-PEG: Extracts cesium & strontium
  - 99.2 & 99.9% efficiencies
- TRUEX: Separates transuranics
  - 99.9% efficiency
- TALSPEAK: Actinide & lanthanide separation
  - 99.9% efficiency

Pyroprocessing

- Used to treat spent ABBR fuel
- Very high temperatures are used
- Has not been demonstrated on a large-scale yet
- Separates
  - Uranium: 99.9% efficiency
  - Plutonium: 99.9% efficiency
  - Minor actinides (Np, Am): 99.9% efficiency
  - Fission products (Cm, Tc, I): 95% efficiency

Summary

- ABBR to meet GNEP goals
  - Sustain increasing energy demands
  - Reduce waste inventory
  - Extract maximum energy from spent fuel
  - Keep US repository requirements to a minimum
  - Increase safety of fuel cycle & proliferation resistance

Core Design

Dwight Chambers, Jeffrey Perez, Drew Reese,
Bo Feng, Victor Cabral

Overview

- ABBR Design Goals
- Design Strategy (CRBR template)
- Calculation Methods/Benchmarking
- Fuel Manipulation/Minor Actinide Additions
- Performance Results/Safety
- Future Work

ABBR Design Goals

- Minor Actinide Destruction-hard spectrum of fast reactors is optimal for fissioning MA from spent LWR fuel (Np237, Am241, Am243, Cm244)
- Fuel Breeding-utilization of fertile blankets for fissile production
- Improved Safety-achieve reactivity controllability similar to current LWR's
- Optimum Power Level-achieve modular design while minimizing overall cost

Design Strategy

- Modify current fast breeder reactor concept to include actinide burning (addition of 1-5% wt. MA’s in fuel region)
- Core Requirements:
  - Optimal power level for modular design (~1000 MWt)
  - Sufficient NRC licensing preparation
  - High breeding ratio (~1.2)
  - Sodium cooled core due to high thermal conductivity, non-corrosive, large liquid temp. range, lots of experience
- Core template of choice:
  - Clinch River Breeder Reactor (CRBR)

CRBR Overview

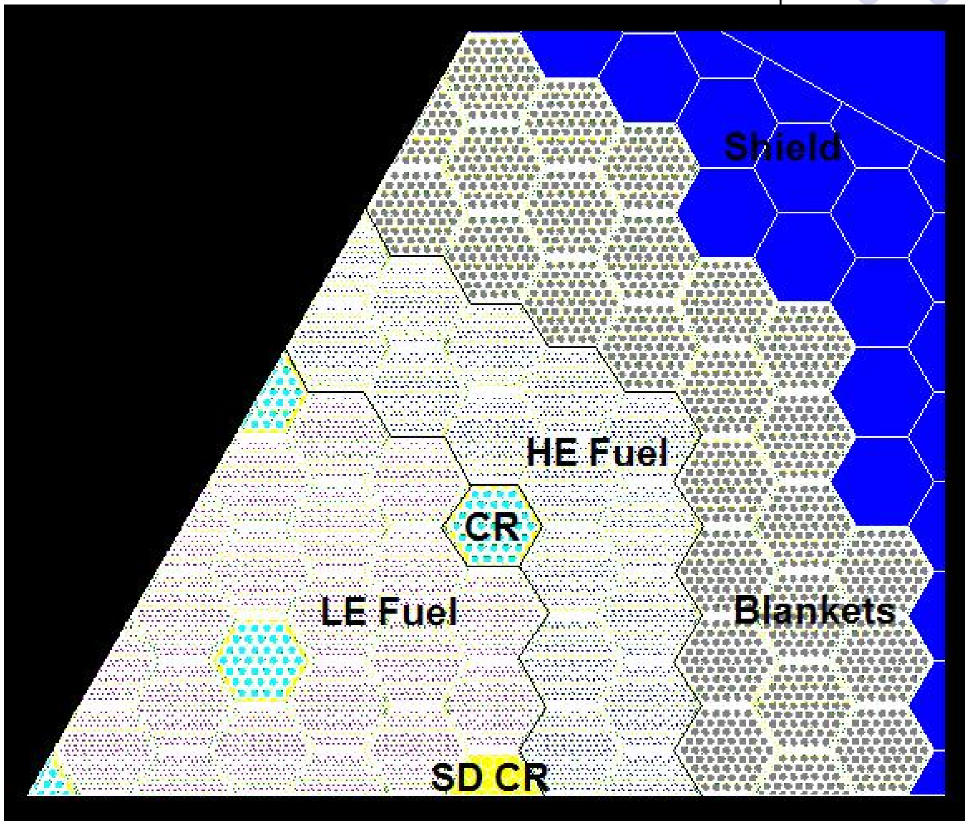
Reactor	CRBR
Fuel Type	Ceramic
Power Rating (MWt/MWe)	975/350
Pu wt% (inner/outer core)	**18.7/27.1**
Peak Linear Power (W/cm)	475.7
Mean Linear Power (W/cm)	229.7
Average Power Density of Fuel (kW/L)	1023
Specific Power (kW/kgHM)	148.38
Radial Peaking Factor	**1.2**
Initial Breeding Ratio	**1.23**
Initial Peak BU (MWD/T)	80,000
Refueling Time (years)	12
Doppler, Temperature, and Power Coefficients	**negative**

maintained

Bench marked

Core Geometry

Fuel Pin Outer Diameter (cm)	0.5842
Pitch/Diameter (hexagonal)	1.25
Core Height (cm)	91.44
Fuel Region Radius (cm)	101
Blanket Height (cm)	162.56
Pins per Fuel Assembly	217
Low Enrichment (inner) Assemblies	108
High Enrichment (outer) Assemblies	90
Axial Blanket Assemblies	198
Pins per Blanket Assembly	61
Radial Blanket Assemblies	150
Pins per CR Assembly	37
Control Rod Assemblies	19
(Primary)	16
(Secondary-Shutdown)	3



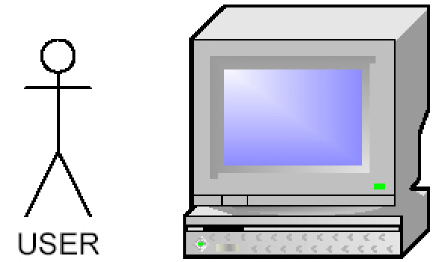
- Entire core geometry of CRBR maintained for ABBR

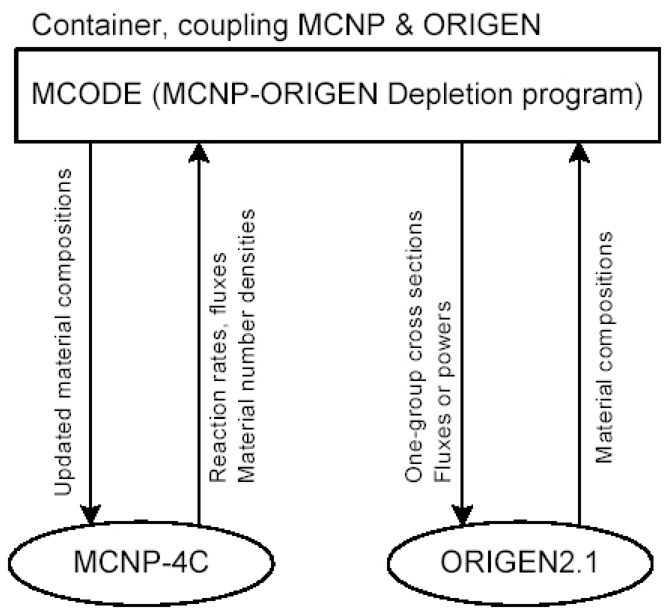
Calculation Methods – CRBR Benchmarking

- MCNP
  - 1/6th core slice model (average run 200 active cycles)
  - Calculated steady-state properties (k-eff, flux)
  - Doppler coefficient, coolant density coefficient, radial PPF's, breeding ratio all successfully benchmarked
- Reactivity Balance Equation (IFR passive safety criteria)
  - Used feedback coefficients to determine overall reactivity controllability

Calculation Methods – Burnup

- MCODE (MCNP + ORIGEN) Coupled steady-state MCNP with depletion code ORIGEN
- Calculated material compositions over 5 stages of first cycle (128 EFPD) and MA destruction rate





Stage	1	2	3	4	5
Days	14.5	43.5	72.5	101.5	127.9
Control Rod Insertion	82%	70%	60%	40%	20%
Insertion Length [cm]	75.0	64.0	54.9	36.6	18.3

Fuel Modifications

Inner Fuel Zone

Isotope	CRBR Fuel atom density (atoms/cm-b)	Spent LWR Fuel atom density (atoms/cm-b)	CRBR 2.3% MA Fuel atom density (atoms/cm-b)
U235	1.30E-04		1.25E-04
U238	1.82E-02		1.75E-02
Np237		2.53E-04	2.53E-04
Pu238		9.77E-05	9.77E-05
Pu239	2.82E-03		2.82E-03
Pu240	8.04E-04		8.04E-04
Pu241	4.24E-04		4.24E-04
Pu242	1.01E-04		1.01E-04
Am241		2.60E-04	2.60E-04
Am243		5.16E-05	5.16E-05
Cm244		1.71E-05	1.71E-05
O16	4.50E-02		4.50E-02
total atom density	6.74E-02		6.74E-02

Outer Fuel Zone

Isotope	CRBR Fuel atom density (atoms/cm-b)	Spent LWR Fuel atom density (atoms/cm-b)	CRBR 2.3% MA Fuel atom density (atoms/cm-b)
U235	1.16E-04		1.12E-04
U238	1.63E-02		1.56E-02
Np237		2.53E-04	2.53E-04
Pu238		9.77E-05	9.77E-05
Pu239	4.09E-03		4.09E-03
Pu240	1.17E-03		1.17E-03
Pu241	6.14E-04		6.14E-04
Pu242	1.46E-04		1.46E-04
Am241		2.60E-04	2.60E-04
Am243		5.16E-05	5.16E-05
Cm244		1.71E-05	1.71E-05
Oxygen	4.49E-02		4.49E-02
total atom density	6.74E-02		6.74E-02

- Maintain Pu inventories for both zones
- Replace 2.3% wt of depleted U with MA to maintain overall fuel atom density

MA Fuel Flexibility

2.3% MA Fuel → **5.0% MA Fuel**

	Inner Core	Outer Core
Isotope	**Weight %**	**Weight %**
U235	0.48	0.43
U238	68.62	61.30
Np237	**0.99**	**0.99**
Pu238	0.38	0.38
Pu239	11.11	16.11
Pu240	3.18	4.62
Pu241	1.68	2.44
Pu242	0.40	0.58
Am241	**1.03**	**1.03**
Am243	**0.21**	**0.21**
Cm244	**0.07**	**0.07**
O16	11.85	11.84

	Inner Core	Outer Core
Isotope	**Weight %**	**Weight %**
U235	0.46	0.41
U238	65.94	58.62
Np237	**2.15**	**2.15**
Pu238	0.38	0.38
Pu239	11.11	16.10
Pu240	3.18	4.62
Pu241	1.68	2.44
Pu242	0.40	0.58
Am241	**2.25**	**2.25**
Am243	**0.45**	**0.45**
Cm244	**0.15**	**0.15**
O16	11.85	11.83

- MA Burning flexibility tested by enriching MA content to 5% wt.
- MA ratios maintained, 5% wt. depleted Uranium removed

Performance Results

CRBR Fuel Design	MA-free	2.3% MA	5% MA
K-effective	1.00441	1.00782	1.00489
Average Flux [neutrons/cm^2 s]	1.68 x 10^{15}	1.64 x 10^{15}	1.61 x 10^{15}
Na Density Coefficient [cents/K]	0.042	0.058	0.131
Na Density Coefficient [cents/F x 10^3]	23.1	32.1	72.7
Doppler Coefficient [cents/K]	-0.28	-0.2	-0.17
Doppler Coefficient [TdT/dK x 10^4]	-69.9	-49.7	-41.4
Max Radial PPF	1.35	1.33	1.33
Breeding Ratio (Day 14)	1.31	1.28	1.24
Breeding Ratio (Day 128)	1.35	1.30	1.26

- Increased sodium density coefficient with additional MA's and subsequent decrease in depleted U (but still less than IFR's 0.18 c/K)
- Less negative Doppler coefficient

Minor Actinide Destruction

2.3% MA Fuel

MA	Percent Change (%/yr)	Rate of Change (kg/yr)	Destruction Rate (kg/MWt-yr)
Np-237	**-20.36**	-15.13	0.016
Am-241	**-14.63**	-11.38	0.012
Am-243	**-8.42**	-1.31	0.001
Cm-244	**+34.05**	1.77	-0.002
Total	**-15.07**	-26.05	**0.027**

5.0% MA Fuel

MA	Percent Change (%/yr)	Rate of Change (kg/yr)	Destruction Rate (kg/MWt-yr)
Np-237	**-20.1**	-32.54	0.033
Am-241	**-17.98**	-30.47	0.031
Am-243	**-13.84**	-4.69	0.005
Cm-244	**+31.01**	3.5	-0.004
Total	**-17.05**	-64.2	**0.066**

- Compared to MIT's MABR's (lead cooled fertile free MA burner) rate of **0.34 kg/MWt-y** *[Hejzlar]*

Burnup Results

- Total mass (kg) of heavy metals in core and blanket from 0 to 128 Effective Full Power Days

	MA-free Fuel (kg)		2.3% MA Fuel (kg)		5.0% MA Fuel (kg)	
Isotope	**Day 0**	**Day 128**	**Day 0**	**Day 128**	**Day 0**	**Day 128**
U-235	82.01	76.77	79.40	74.57	77.93	73.33
U-238	26334.34	26181.82	25491.78	25350.29	25282.28	25143.73
Np-237	0.00	0.35	74.31	68.67	161.92	149.56
Pu-238	0.00	0.04	28.85	31.01	29.01	36.25
Pu-239	**999.27**	**1027.30**	**1007.37**	**1031.75**	**1013.10**	**1034.94**
Pu-240	286.36	295.23	288.69	296.53	290.33	297.43
Pu-241	151.30	136.18	152.52	137.81	153.39	138.70
Pu-242	36.15	37.69	36.44	38.58	36.65	39.49
Am-241			77.77	73.55	169.45	157.97
Am-243			15.55	15.08	33.89	32.15
Cm-244			5.18	5.74	11.30	12.42

- 2.3% and 5.0% MA fuel produced **24.4 kg** and **21.8 kg** of **Pu-239**, respectively compared to CRBR production of **28 kg**

Safety

- $0 = \Delta\rho_{\text{power}} + \Delta\rho_{\text{flow}} + \Delta\rho_{\text{temperature}} + \Delta\rho_{\text{external}}$

- $0 = (P-1)*A+(P/F-1)*B + \Delta T_{\text{inlet}}*C + \Delta\rho_{\text{external}}$
  - **A** $= (\alpha_{\text{Doppler}} + \alpha_{\text{Fuel Expansion}})*T_f$
    - T_f is the temperature difference between the average fuel temperature and the bulk sodium temperature
  - **B** $= (\alpha_{\text{Doppler}} + \alpha_{\text{Fuel Expansion}} + \alpha_{\text{Sodium Density}} + 2*(\alpha_{\text{CRD}} + (2/3)*\ \alpha_{\text{Core Radial Expansion}}))*T_c/2$
    - T_c is the temperature rise across the core
  - **C** $= (\alpha_{\text{Doppler}} + \alpha_{\text{Sodium Density}} + \alpha_{\text{Core Radial Expansion}} + \alpha_{\text{Fuel Expansion}})$

Passive Safety Criteria

- **S1 Criterion**: A/B<1.4 Power/Flow Events
- **S2 Criterion**: 1<C*Tc/B<2 Temperature Events
- **S3 Criterion**: $\Delta\rho$TOP/|B|<1 Worth Stored

	2.3% MA Fuel	5.0% MA Fuel	
A	-196.2	-169.3	
B	-56.2	-41.3	
C	-0.51	-56.4	
S1	**3.5**	**4.1**	**Unsatisfactory**
S2	**1.27**	**1.37**	
S3	**0.26**	**0.42**	

- Passive safety not achieved, controlled SCRAM required
- Not an improvement from CRBR safety design

Oxide v. Metallic Fuels

Oxides

- Chemically inert
- Reduced swelling concerns
- Higher melting point
- Higher burnup efficiency
- Experienced reprocessing methods

Metallic

- Higher thermal conductivity
- Higher fissionable atom density
- Higher thermal expansion
- Cheaper to fabricate

Oxide fuel chosen given industry experience and Clinch River design optimization for ceramic fuels

Metallic Fuel

Inner Core

Isotope	CRBR Fuel atom density (atoms/cm-b)	Spent LWR Fuel atom density (atoms/cm-b)	CRBR Metallic Fuel atom density (atoms/cm-b)
U235	1.30E-04	2.26E-04	2.21E-04
U238	1.82E-02	3.07E-02	3.13E-02
Np237		2.53E-04	2.53E-04
Pu238		9.77E-05	9.77E-05
Pu239	2.82E-03		2.82E-03
Pu240	8.04E-04		8.04E-04
Pu241	4.24E-04		4.24E-04
Pu242	1.01E-04		1.01E-04
Am241		2.60E-04	2.60E-04
Am243		5.16E-05	5.16E-05
Cm244		1.71E-05	1.71E-05
Zr			1.06E-02
total atom density			4.69E-02

- Pu inventory maintained in inner and outer fuel zones
- Added same amount of MA's as 2.3% MA weight ceramic fuel
- U density increased to increase overall fuel density from 10 g/cc to 15.85 g/cc
- Oxygen replaced by Zirconium

Metallic Fuel Results

Composition (wt %)

	Inner Core	Outer Core
Isotope	Weight %	Weight %
U235	0.54	0.51
U238	77.44	72.83
Np237	0.62	0.62
Pu238	0.24	0.24
Pu239	7.01	10.16
Pu240	2.00	2.92
Pu241	1.06	1.54
Pu242	0.25	0.37
Am241	0.65	0.65
Am243	0.13	0.13
Cm244	0.04	0.04
Zr	10.00	10.00

MA %	1.45	1.45

Coefficient Comparisons

CRBR Fuel Design	MA-free	2.3% MA	5% MA	Metallic MA Fuel
K-effective	1.00441	1.00782	1.00489	**0.98415**
Na Density Coefficient [cents/K]	0.042	0.058	0.131	**0.245**
Doppler Coefficient [cents/K]	-0.28	-0.2	-0.17	**-0.06**
Na Density Coefficient [cents/F x 10^3]	23.1	32.1	72.7	**136.1**
Doppler Coefficient [TdT/dK x 10^4]	-69.9	-49.7	-41.4	**-14.4**

- Larger sodium density coefficient mainly due to larger amount of U-238 (larger reactivity swing)
- Smaller Doppler coefficient
- Fuel expansion coefficients expected to be much better than ceramic fuel
- Passive Safety?

Thermal Hydraulics

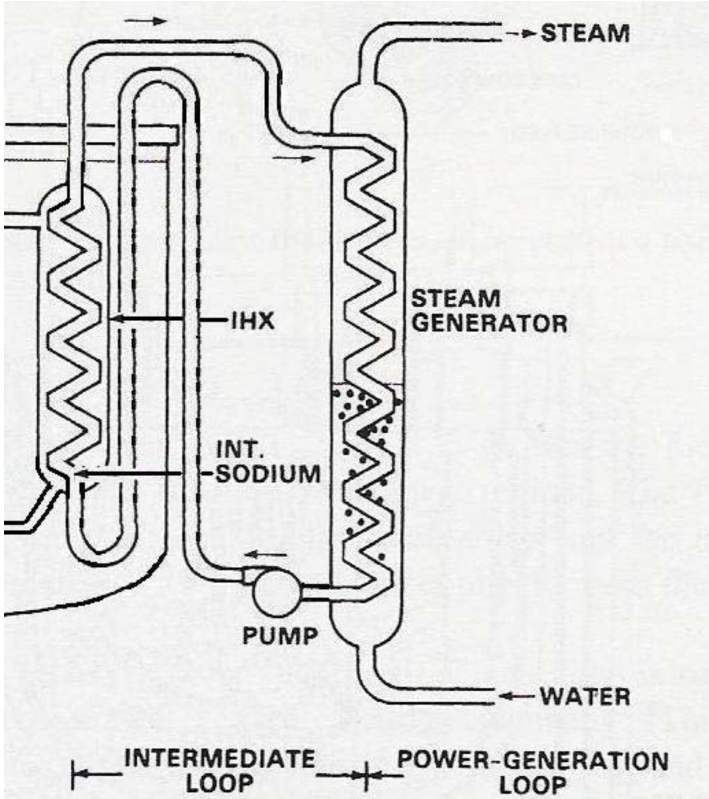
Josh Whitman, Katherine Thornton, MinWah Leung, Christopher Waits

Thermal Hydraulics

- Power Conversion Unit
  - Efficiencies and flow rates
- Intermediate Heat Exchanger
- Primary Loop
  - Pressure drop, mass flow rates, maximum temperatures within the core
- DBA
  - Seismic Accident
  - DHR

Power Conversion Unit

- Three loops: 39.5% plant efficiency
- Secondary sodium loop to separate radioactive sodium and water



Power Conversion Unit

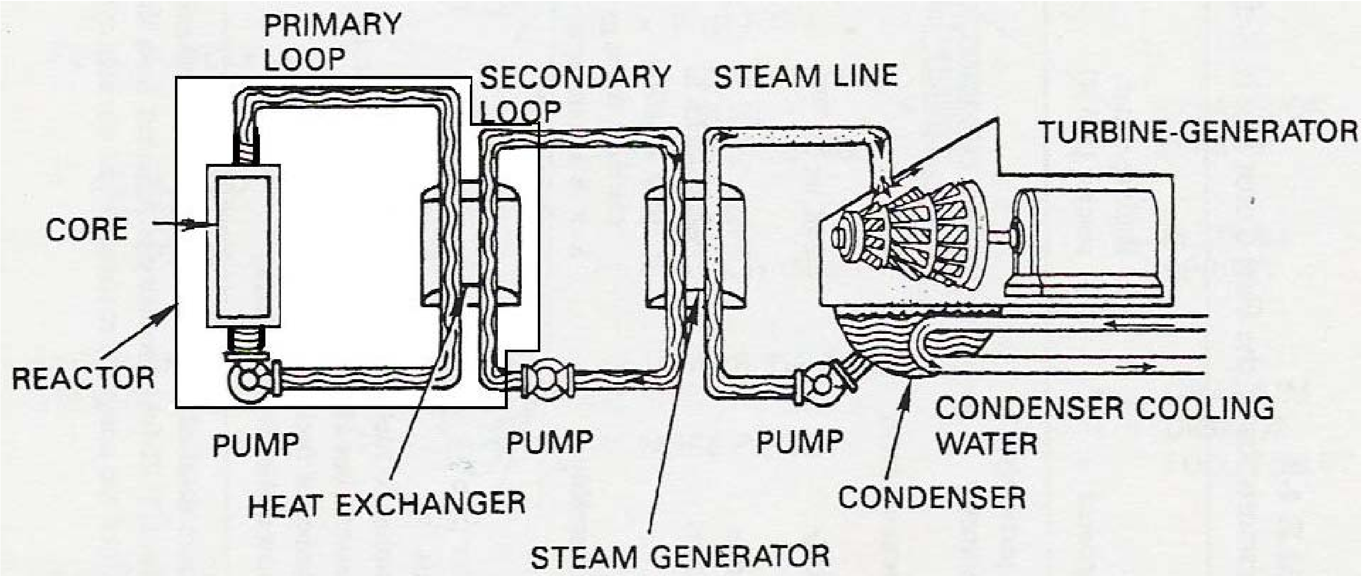
- Primary Loop:
  - Mass flow rate: 5240 kg/s
  - Reactor inlet temperature: 388°C
  - Reactor outlet temperature: 535°C
  - IHX efficiency: 99%
- Secondary Loop:
  - Mass flow rate: 4831 kg/s
  - Hot leg: 502°C
  - Cold leg: 344°C
  - Steam generator efficiency: 95%

Power Conversion Unit

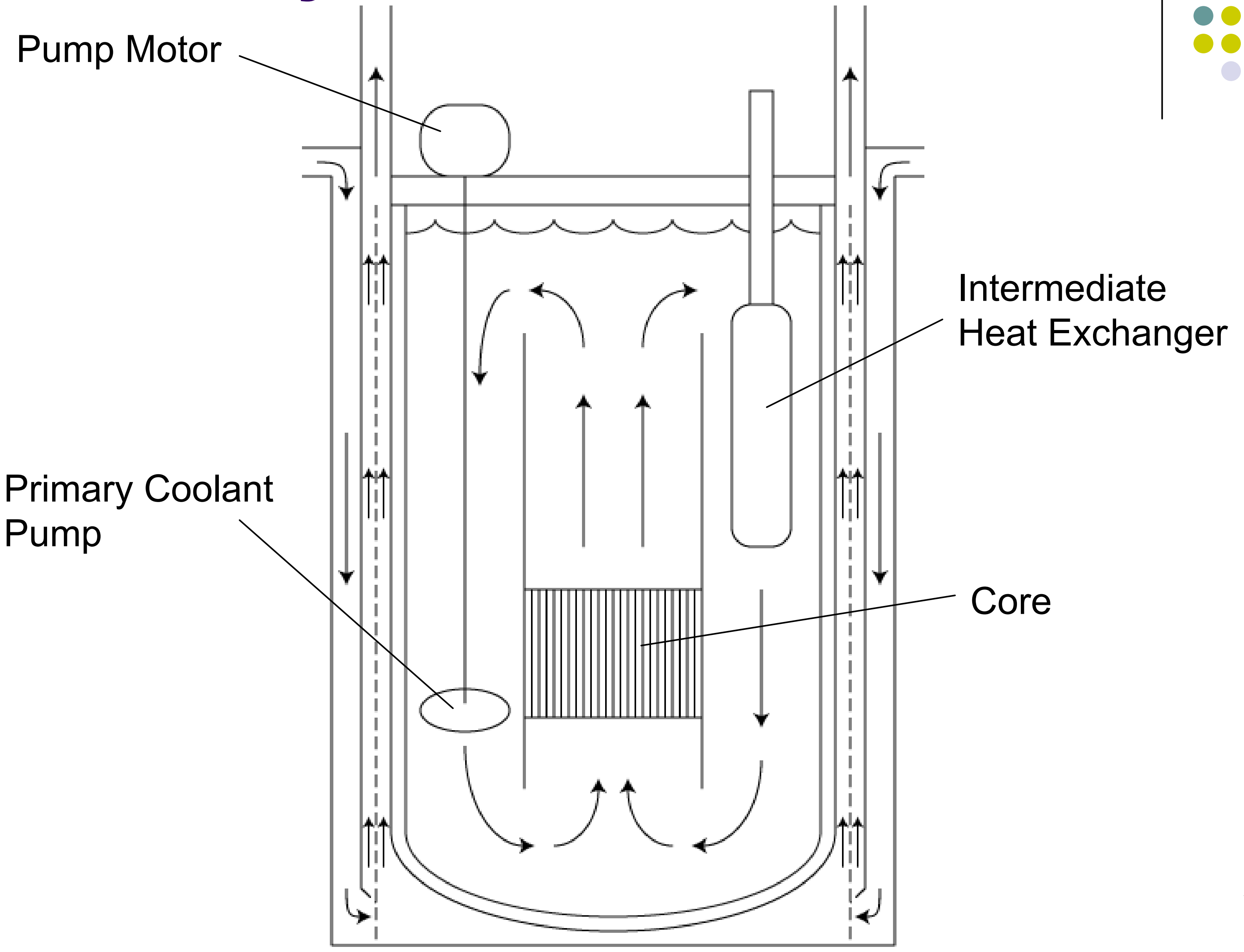
- Brayton vs. Rankine
  - Temperatures low for Brayton cycle
  - More information and operational experience for Rankine cycles; less of a risk

Power Conversion Unit

- Tertiary Loop:
  - Mass flow rate: 420 kg/s
  - Temperature entering SG: 285℃
  - Temperature exiting SG: 482℃
  - Temperature exiting turbine: 326℃
  - Turbine efficiency: 41.8%



Plant Layout



Advantages of Pool over Pipe

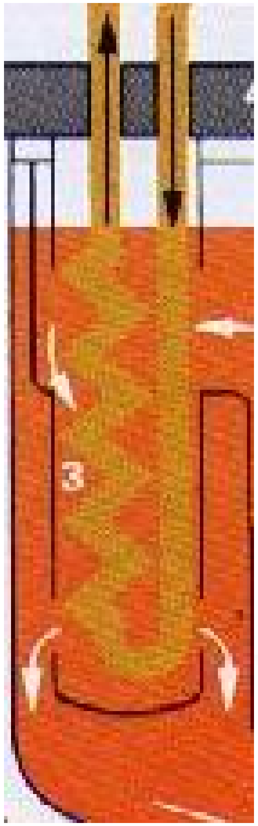
- Eliminate LOCA as a possible DBA
  - Especially important with flammable coolant
- Easier to achieve passive core cooling in accident scenario
- Overall simpler design

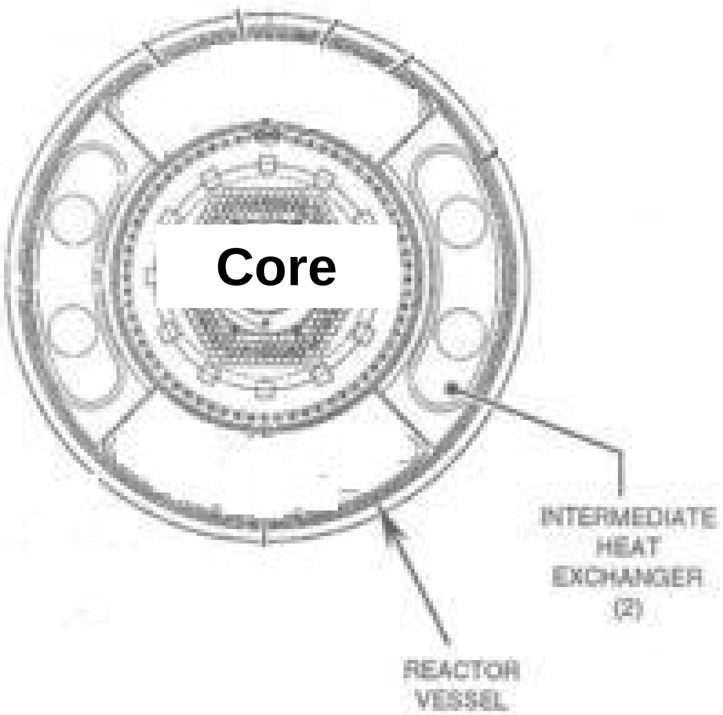
Reactor Dimensions

- Guard Vessel
  - Height: 19.5 m
  - Outer Diameter: 9.6 m
  - Thickness: 2.5 cm
- Reactor Vessel
  - Outer Diameter: 9.15 m
  - Thickness: 5 cm
- Core Barrel Diameter
  - 3.7 m

Intermediate Heat Exchanger

- Kidney-shaped cross section
- Counterflow shell and tube
  - Provide maximum heat transfer
- Efficiency: 99%
- 2 IHXs





Intermediate Heat Exchanger

- Modeled after ALMR IHX
- Utilized ALMR dimensions (shell and tube)
- Mass flow rate and temperatures determined by core calculations
- Only difference is number of tubes in ALMR IHX and ABBR IHX
  - 4200 tubes in ABBR

Primary Loop Thermal Hydraulics

Constraints:

- Core inlet and outlet temperatures equal to CRBR (661 K inlet, 808 K outlet)
- Fuel clad temperature not to exceed 980 K during normal operation
- Fuel centerline temperature not to exceed 3000 K

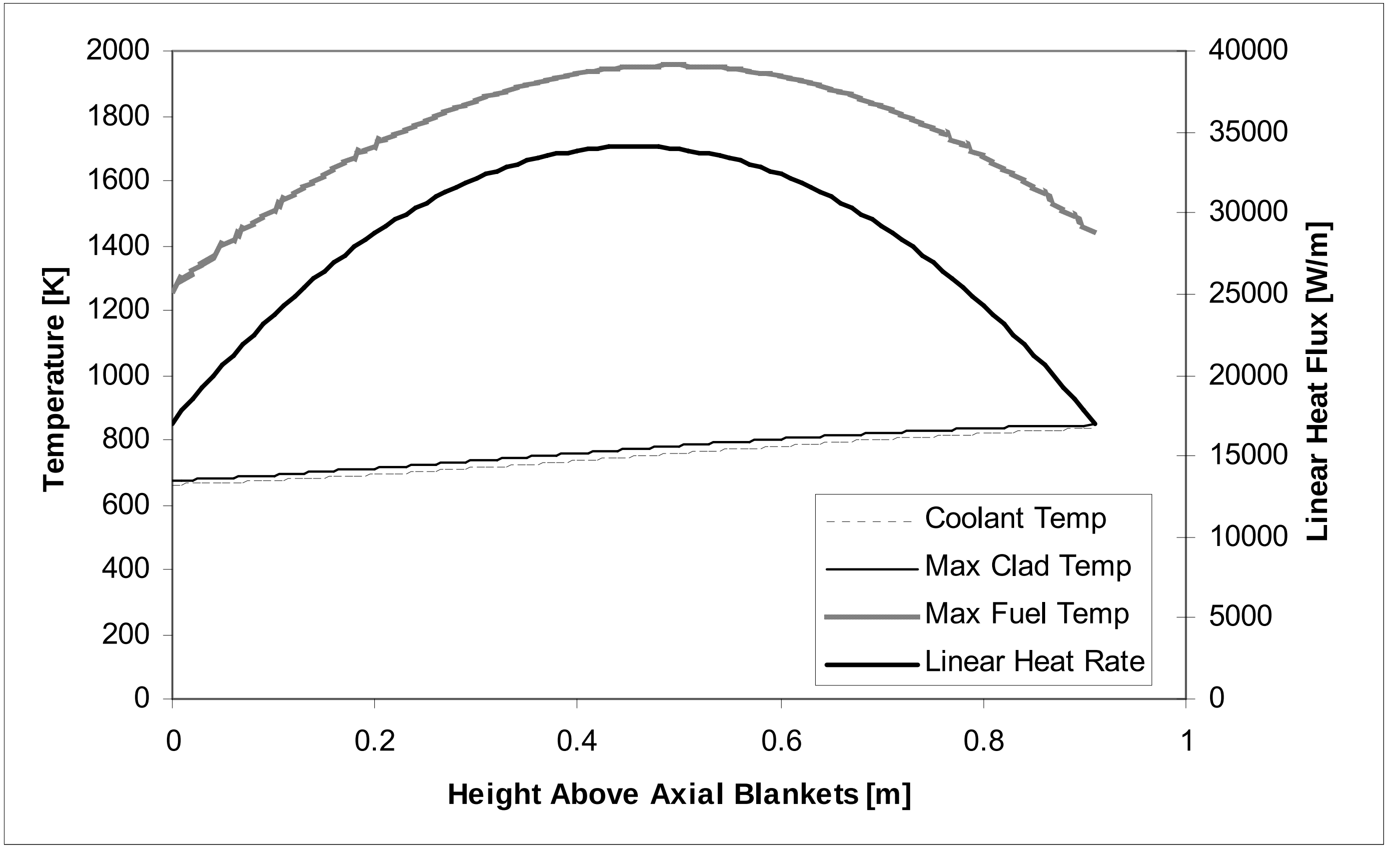
Thermal Hydraulics Analysis Techniques

- Examine hot and average fuel assemblies
- Generate parabolic axial flux distribution
- Use wire-wrap spacers within fuel bundles
  - H/D of 10 chosen
- Examine temperatures nodally through the core

Results

- Inlet Temperature: 661 K / 388°C
- Outlet Temperature: 808 K / 535°C
- Maximum Cladding Temperature:846 K / 573°C
- Maximum Fuel Temperature: 1955 K / 1682°C
- Pressure drop across core: 500,000 Pa
- Average Velocity of Coolant through fuel assembly: 5.82 m/s
- Mass Flow Rate: 5240 kg/s

Axial Flux and Temperature Distributions in Fuel Region of Core (Hot Assembly)



Design Basis Accidents

- Major DBA summarized by European fast reactors:
  - Control Rod Withdrawal
  - Seismic Activity
  - Primary pipe rupture downstream of pump
- Reactor will SCRAM in all cases
- Following SCRAM, DHR may proceed passively if necessary

Seismic Activity

- Reactor vessel to withstand 0.5 g
- Maximum stress for Stainless Steel is 263.1 MPa
- Modified Buongiorno and Hawkes' model for vessel resonance behavior during earthquake
- Determined seismic isolation necessary for ABBR vessel dimensions
- Utilize S-PRISM isolation design: large diameter seismic bearings
  - reduce the horizontal natural frequency to 0.7 Hz

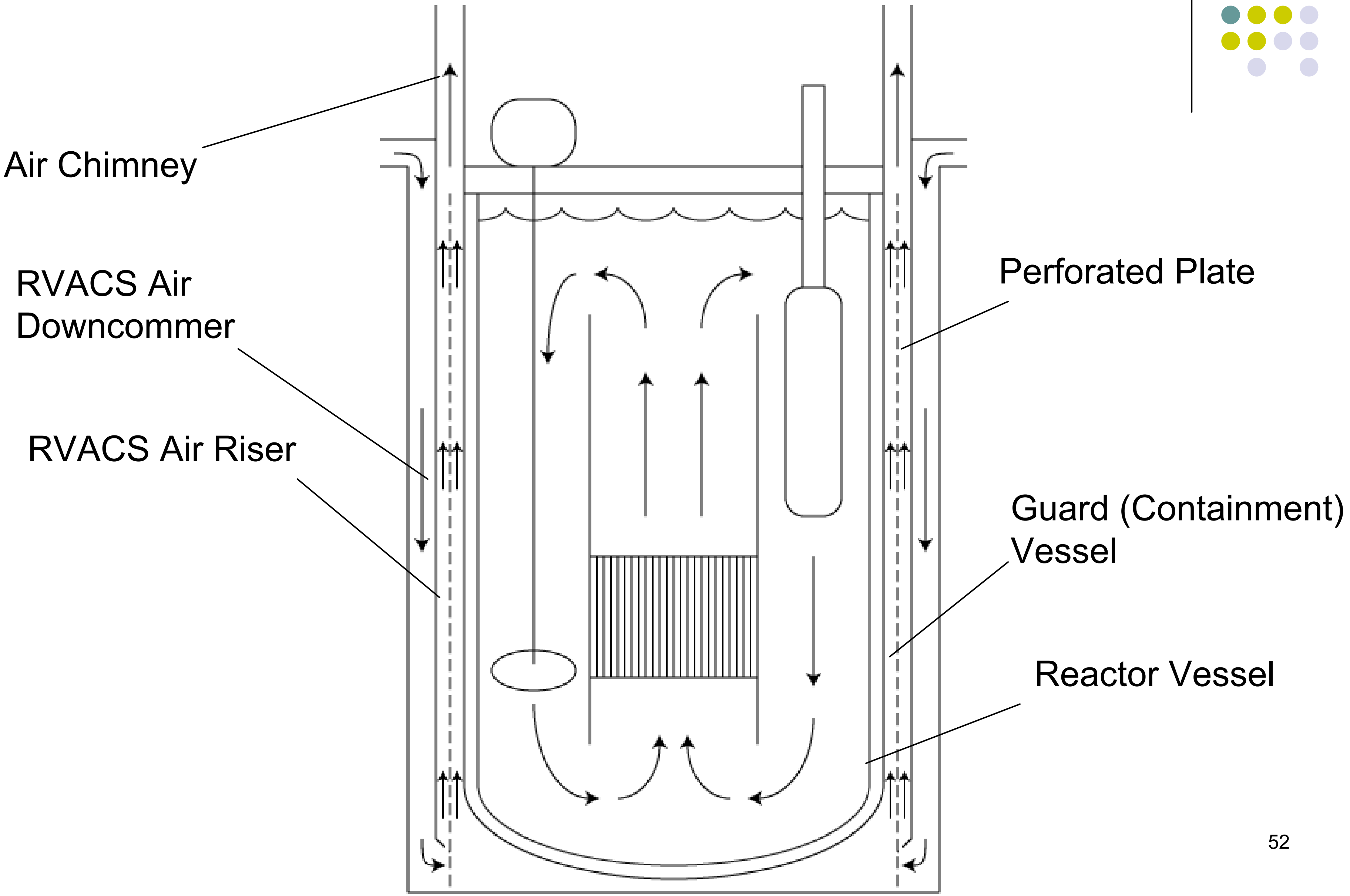
Passive Decay Heat Removal:

- During normal operation and shut-down, intermediate loop is used for DHR
  - Minimizes thermal stresses on reactor
  - Decreases cool-down time
- In the event of primary loop pump failure or loss of power, decay heat can be passively removed without breaching vessel temperature limits by using RVACS system

RVACS

- Reactor Vessel Auxiliary Cooling System, modeled after GE's S-PRISM design
- Uses air chimneys to enhance natural circulation along the guard vessel outer wall
- Natural circulation also provides cooling and heat transfer within the reactor vessel
- Use of two vessels eliminates need for LOCA assessment, provides additional barrier between fuel and environment/public

RVACS


Air Chimney
RVACS Air Downcommer
RVACS Air Riser
Perforated Plate
Guard (Containment) Vessel
Reactor Vessel

Economics

Emily Slutsky

Structure of Nuclear Generation Costs

- 3 Main Components:
  - Non-Fuel Operation and Maintenance
  - Capital Investment
  - Fuel
- Minor Components
  - R & D
  - Post-operational expenditures
  - Decommissioning

O&M Costs

Assuming Typical LWR Staffing

O & M Breakdown	Cost
Onsite Staff (520)	$22M
Offsite Technical Support Staff (100)	$10M
Maintenance Materials	$10M
Supplies + Expenses	$12M
Administrative + General	$23M
Total	$75M

Lifespan = 30 years

Clinch River Breeder Reactor Capital Analysis

- Estimated in 1972 to be $699M (350 MWe) = $1997/kWe
- 1974 = $1.7B, assuming operation in 1982
- Re-estimated to over $4B in 1983 = Over $11,000/kWe [Ref. 1]

Capital Costs – Generation IV Estimates for Sodium Breeder Reactor

	Gen-IV (4 years)	**Best Case (4 years)**	**Worst Case (8 years)**
Overnight: Direct/Indirect	$1.25B	$1.25B	$2B
Interest During Construction	$0.25B	$0.25B	$0.8B
Total Plant Cost	$1.5B	$1.5B	$2.8B

Worst Case Scenario = $4667/kWe

ABBR Capital Estimate

- Fast reactor should be scaled on the order of 5 to even 6 times that of a PWR [Ref 2]
- Design should realistically fall within the range of $6000/KWe - $8000/KWe, with a cost of $3B-$4B
- Predicts a production yield of 2.995x10^9 KWh/year, assuming 90% Capacity Factor

Remaining Costs

- Fuel Cost = ABR would be about 11 Mills/KWh, significantly higher than LWR nuclear power plants at about 6 Mills/KWh [Ref 3]

- Based upon 2025 projections of dismantling of Super Phenix Fast Breeder Reactor = $800 Million - $900 Million [Ref 4]

ABBR Design Summary

Capital Cost Estimate	$4B
O & M Cost Estimate	$75M
Fuel Cost Estimate	$330M
Decommissioning Cost	~ $800M
Cents/kwhr	~ 20 c/kwhr

Summary

- Goals Achieved:
  - Recycling and Waste Disposal (GNEP)
    - Utilizes processed spent LWR fuel
    - MA destruction rate 24-64 kg/yr (15-17%/yr)
  - Sustainability
    - Breeding ratio comparable to CRBR (1.24 to 1.31)
  - Flexibility
    - Adjustable burner/breeder from 0% to 5% MA enrichment
- Future Goals:
  - Safety
    - Achieve passive shutdown without SCRAM
  - Cost
    - Make economically competitive with current LWR's

Questions?