CAREM 25 Fuel Cycle Optimization. ATF use & design impact evaluation.

International Conference on SMRs and their applications

H. A. Lestani, J. Bergallo, E. M. Lopasso

Vienna, Austria 21-25th October 2024

Table of contents I

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience
- Most SMRs include passive safety features to improve reliability

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience
- Most SMRs include passive safety features to improve reliability
- But there is still room for improvement in severe accident conditions

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience
- Most SMRs include passive safety features to improve reliability
- But there is still room for improvement in severe accident conditions

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience
- Most SMRs include passive safety features to improve reliability
- But there is still room for improvement in severe accident conditions

MARCH 15, 2011 | 5 MIN READ

Partial Meltdowns Led to Hydrogen Explosions at Fukushima Nuclear Power Plant

Hydrogen and steam explosions pose ongoing risks at the stricken Fukushima nuclear power plant, where three such events have already occurred in the past five days

BY DAVID BELLO

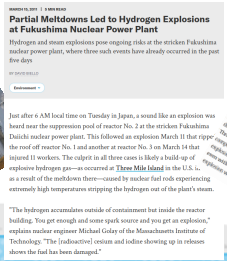
Environment

Just after 6 AM local time on Tuesday in Japan, a sound like an explosion was heard near the suppression pool of reactor No. 2 at the stricken Fukushima Daiichi nuclear power plant. This followed an explosion March 11 that ripped the roof off reactor No. 1 and another at reactor No. 3 on March 14 that injured 11 workers. The culprit in all three cases is likely a build-up of explosive hydrogen gas—as occurred at Three Mile Island in the U.S. in 1979 as a result of the meltdown there—caused by nuclear fuel rods experiencing extremely high temperatures stripping the hydrogen out of the plant's steam.

"The hydrogen accumulates outside of containment but inside the reactor building. You get enough and some spark source and you get an explosion," explains nuclear engineer Michael Golay of the Massachusetts Institute of Technology. "The [radioactive] cesium and iodine showing up in releases shows the fuel has been damaged."

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience
- Most SMRs include passive safety features to improve reliability
- But there is still room for improvement in severe accident conditions



MARCH 15, 2011 | 5 MIN READ

Partial Meltdowns Led to Hydrogen Explosions at Fukushima Nuclear Power Plant

Hydrogen and steam explosions pose ongoing risks at the stricken Fukushima nuclear power plant, where three such events have already occurred in the past five days

BY DAVID BELLO

Environment

Just after 6 AM local time on Tuesday in Japan, a sound like an explosion was heard near the suppression pool of reactor No. 2 at the stricken Fukushima Daiichi nuclear power plant. This followed an explosion March 11 that ripped the roof off reactor No. 1 and another at reactor No. 3 on March 14 that injured 11 workers. The culprit in all three cases is likely a build-up of explosive hydrogen gas—as occurred at Three Mile Island in the U.S., as a result of the meltdown there—caused by nuclear fuel rods experiencing extremely high temperatures stripping the hydrogen out of the plant's steam.

"The hydrogen accumulates outside of containment but inside the reactor building. You get enough and some spark source and you get an explosion," explains nuclear engineer Michael Golay of the Massachusetts Institute of Technology. "The [radioactive] cesium and iodine showing up in releases shows the fuel has been damaged."

International Journal of Hydrogen Energy

An analysis of the hydrogen explosion in the Fukushima-Daiichi accident

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience
- Most SMRs include passive safety features to improve reliability
- But there is still room for improvement in severe accident conditions

MARCH 15, 2011 | 5 MIN READ

Partial Meltdowns Led to Hydrogen Explosions at Fukushima Nuclear Power Plant

Hydrogen and steam explosions pose ongoing risks at the stricken Fukushima nuclear power plant, where three such events have already occurred in the past five days

BY DAVID BIELLO

Environment

Just after 6 AM local time on Tuesday in Japan, a sound like an explosion was heard near the suppression pool of reactor No. 2 at the stricken Fukushima Daiichi nuclear power plant. This followed an explosion March 11 that ripped the roof off reactor No. 1 and another at reactor No. 3 on March 14 that injured 11 workers. The culprit in all three cases is likely a build-up of explosive hydrogen gas—as occurred at Three Mile Island in the U.S., as a result of the meltdown there—caused by nuclear fuel rods experiencing extremely high temperatures stripping the hydrogen out of the plant's steam.

"The hydrogen accumulates outside of containment but inside the reactor building. You get enough and some spark source and you get an explosion," explains nuclear engineer Michael Golay of the Massachusetts Institute of Technology. "The [radioactive] cesium and iodine showing up in releases shows the fuel has been damaged."

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience
- Most SMRs include passive safety features to improve reliability
- But there is still room for improvement in severe accident conditions
- ATF are fuels whose materials and technolgies improve these responses

Motivation for this study to be done

- SMRs come to solve big NPPs problems: smaller capital investment, shorter construction times, modularity and standardization
- Most SMRs have internalized the lessons learned from decades of experience
- Most SMRs include passive safety features to improve reliability
- But there is still room for improvement in severe accident conditions
- ATF are fuels whose materials and technolgies improve these responses
- So we decided to evaluate feasibility of avoiding Zr in the cladding

Motivation for this study to be done

- Amongst ATFs we focused on avoiding Zr because of its oxidation potential and the H_2 production when overheated

Motivation for this study to be done

- Amongst ATFs we focused on avoiding Zr because of its oxidation potential and the H_2 production when overheated
- An Iron based alloy was preferred for the vast industrial experience with Iron alloys

Motivation for this study to be done

- Amongst ATFs we focused on avoiding Zr because of its oxidation potential and the H_2 production when overheated
- An Iron based alloy was preferred for the vast industrial experience with Iron alloys
- But the use of such alloy to replace Zr implies a big increase in neutronic absorptions

Motivation for this study to be done

- Amongst ATFs we focused on avoiding Zr because of its oxidation potential and the H_2 production when overheated
- An Iron based alloy was preferred for the vast industrial experience with Iron alloys
- But the use of such alloy to replace Zr implies a big increase in neutronic absorptions
- This work focuses on the neutronic implicancies of increasing the cladding absorptions

Motivation for this study to be done

- Amongst ATFs we focused on avoiding Zr because of its oxidation potential and the H_2 production when overheated
- An Iron based alloy was preferred for the vast industrial experience with Iron alloys
- But the use of such alloy to replace Zr implies a big increase in neutronic absorptions
- This work focuses on the neutronic implicancies of increasing the cladding absorptions
- How can we compensate this increase in absorptions?

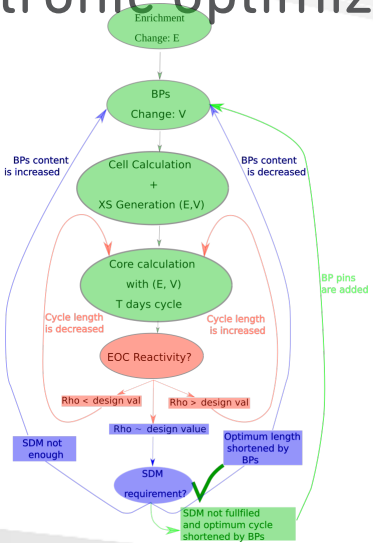
Motivation for this study to be done

An enrichment increase is necessary, but how much?
When introducing ATF, do we increase enrichment as to compensate absorptions or what?
How is enrichment affected by design and operational parameters?
How are safety requirements complied with while optimizing enrichment?

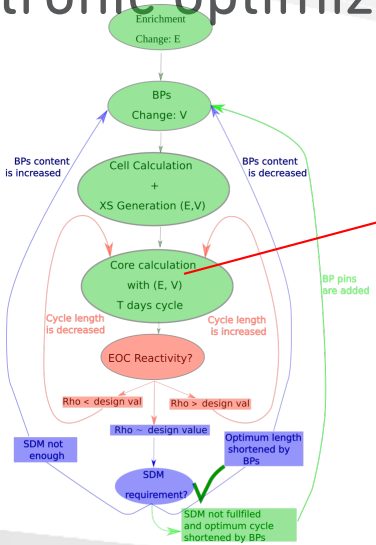
Fuel Cycle neutronic optimization

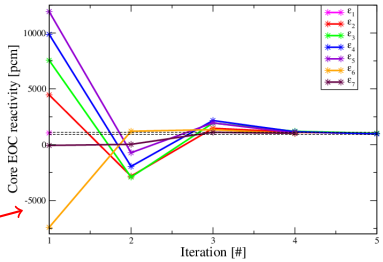
A neutronic optimization scheme is proposed.

Fuel Cycle neutronic optimization

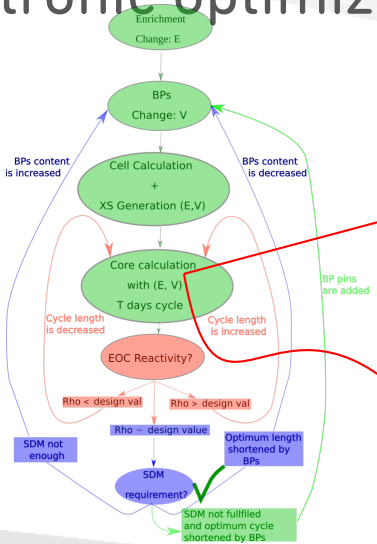


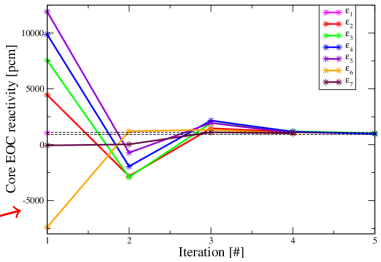
Fuel Cycle neutronic optimiza

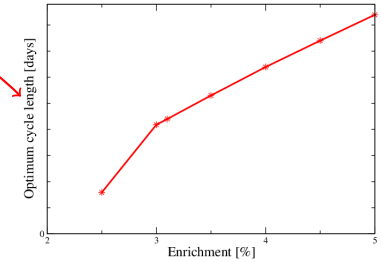




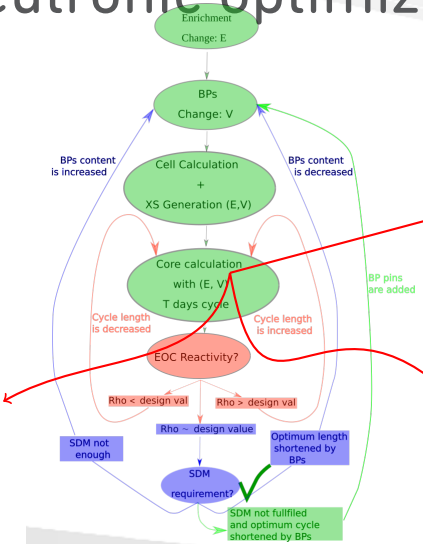
Fuel Cycle neutronic optimiza

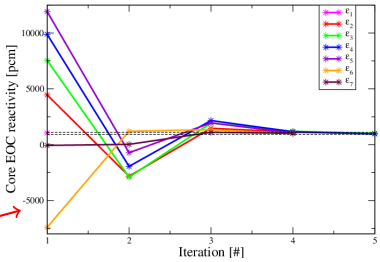


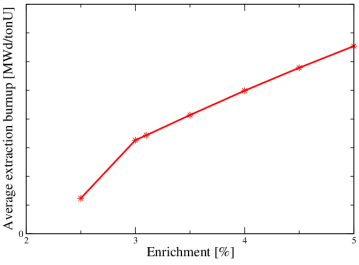


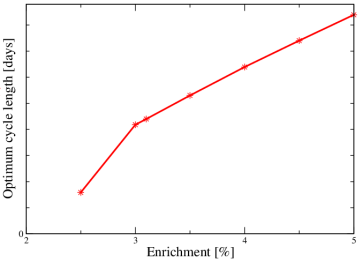


Fuel Cycle neutronic optimiza

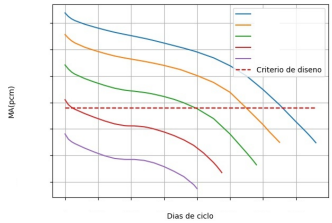


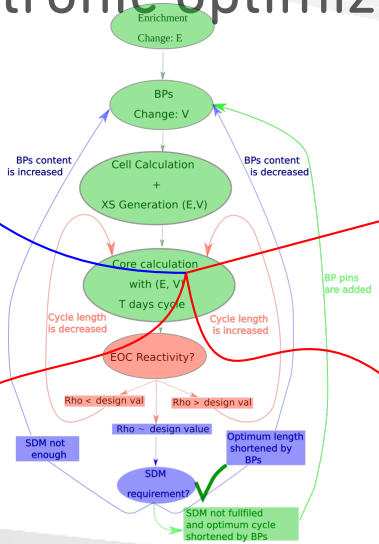


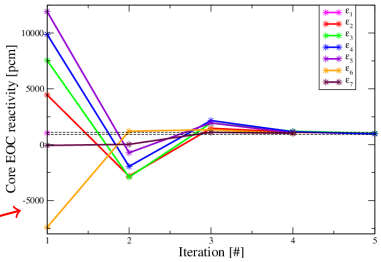


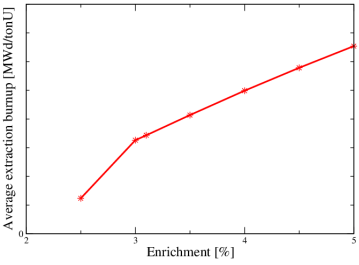


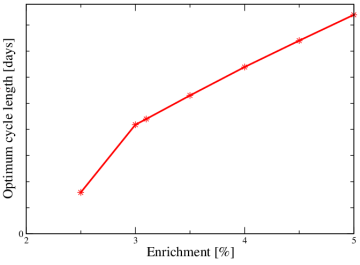
Fuel Cycle neutronic optimiza



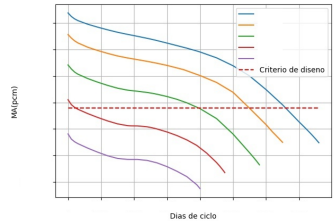


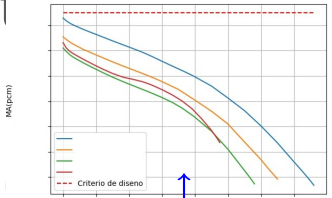


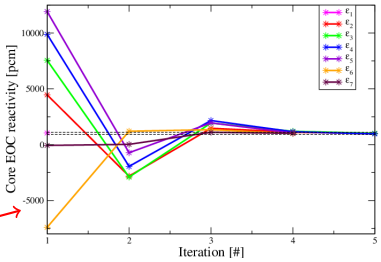


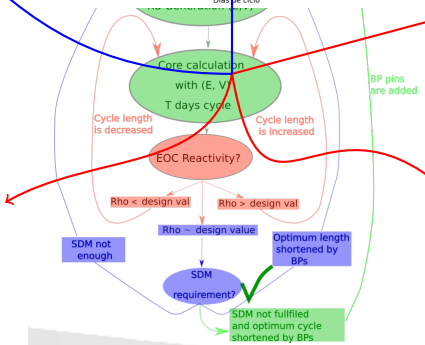


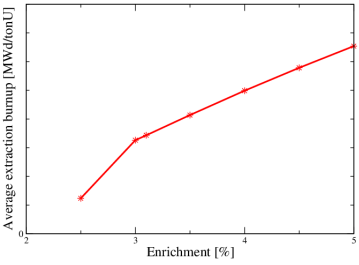
Fuel Cycle neut

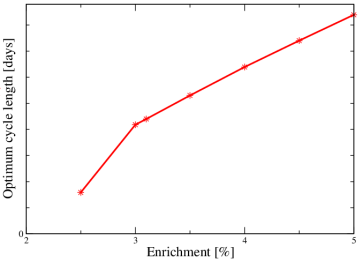




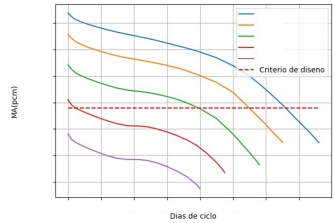


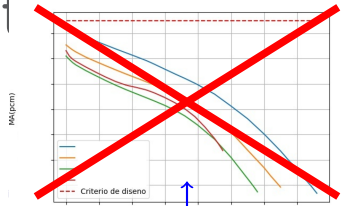


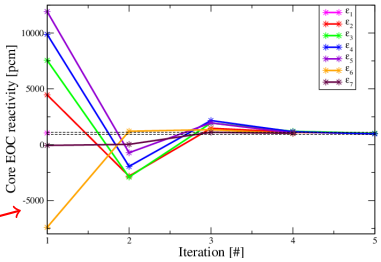


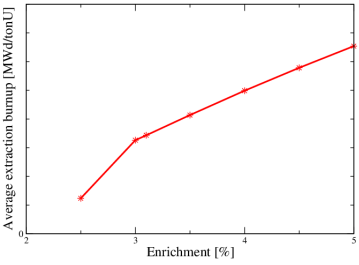


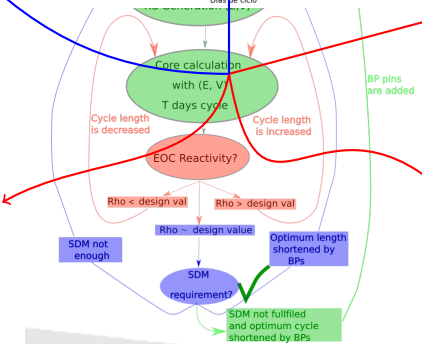
Fuel Cycle neut za

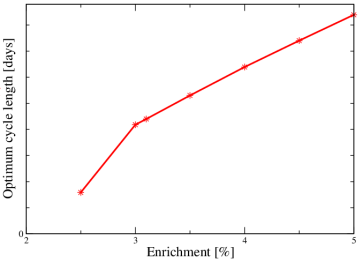




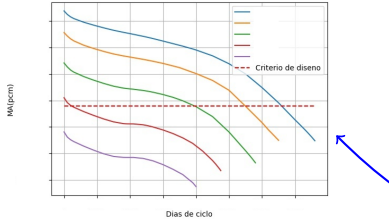


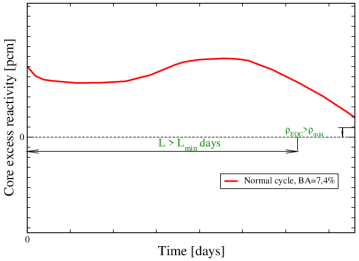


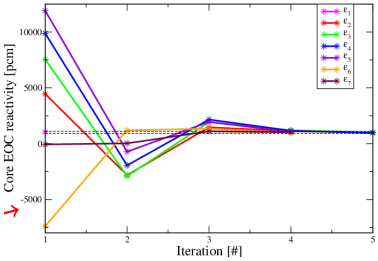


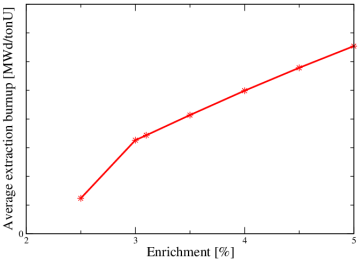


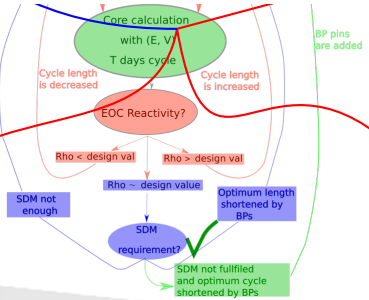
Fuel Cycle req

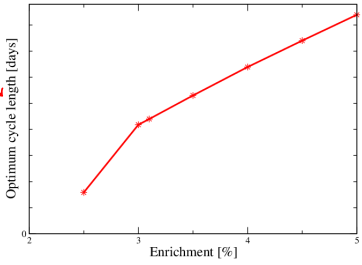




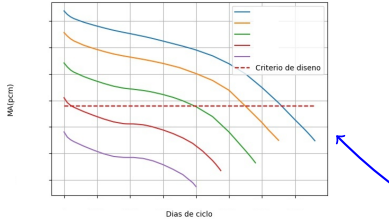


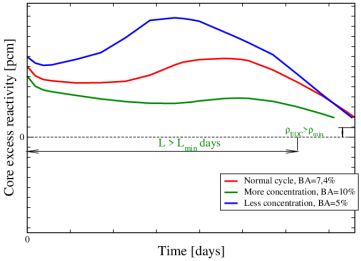


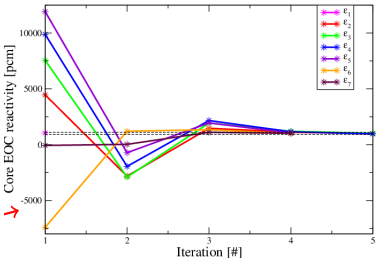


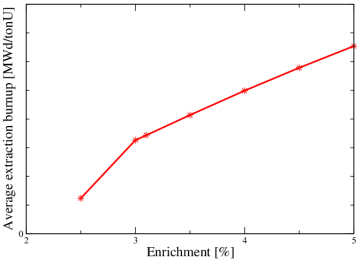


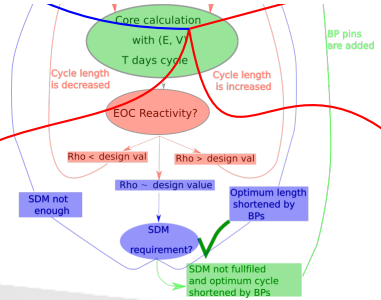
Fuel Cycle req

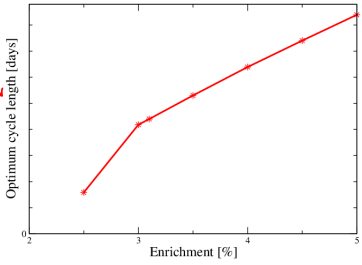




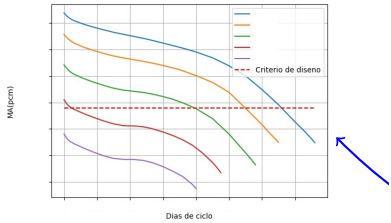


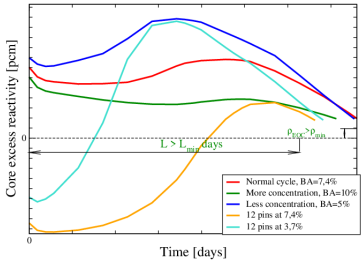


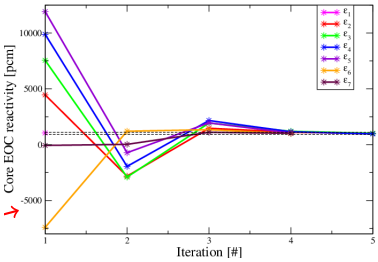


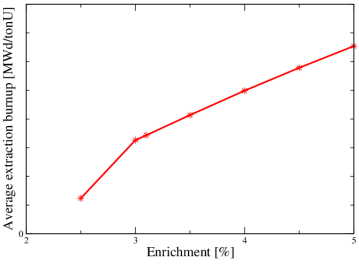


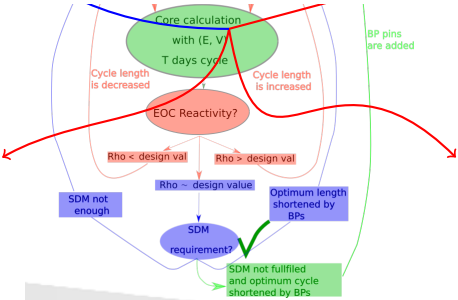
Fuel Cycle req

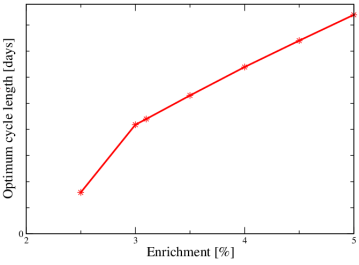








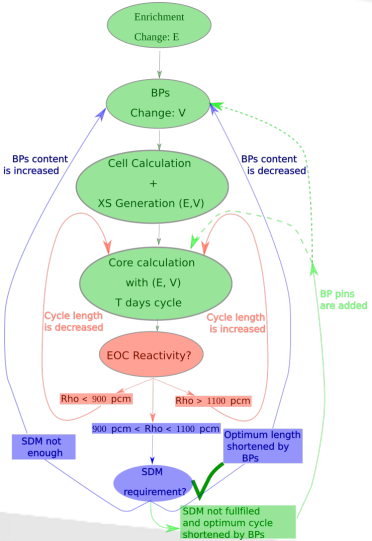


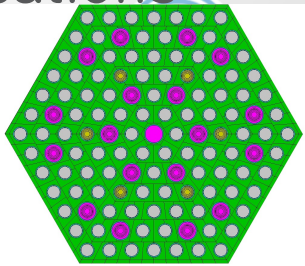


Neutronic optimization: modifications

Venenos quemables

- The amount of burnable pins is adjusted to avoid reactivity peaks at BOL

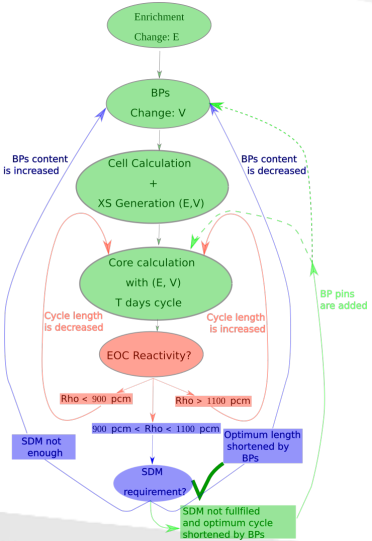


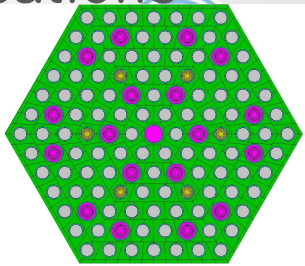


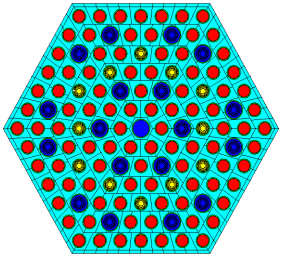
Neutronic optimization: modifications

Venenos quemables

- The amount of burnable pins is adjusted to avoid reactivity peaks at BOL
- The BAs concentration is adjusted to avoid reactivity peaks near EOL



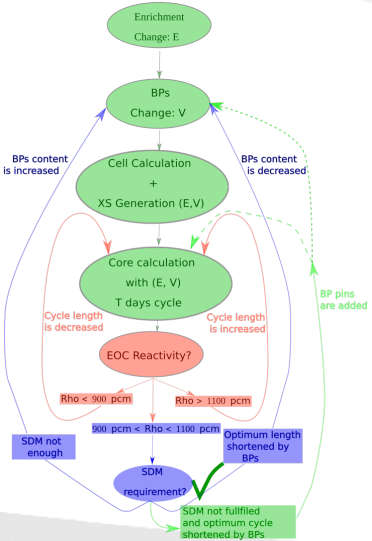


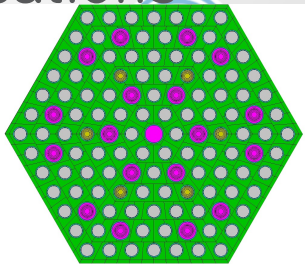


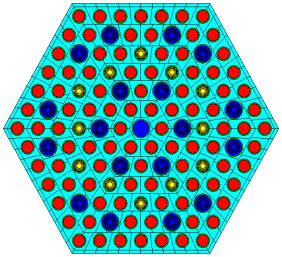
Neutronic optimization: modifications

Venenos quemables

- The amount of burnable pins is adjusted to avoid reactivity peaks at BOL
- The BAs concentration is adjusted to avoid reactivity peaks near EOL
- BA pins location is defined fine tuning the reactivity and power peaking factor



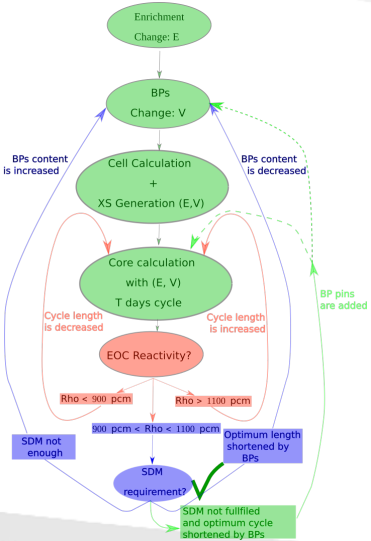


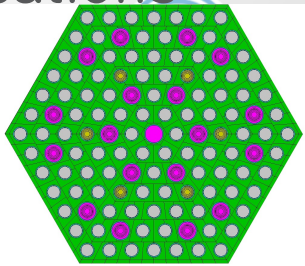


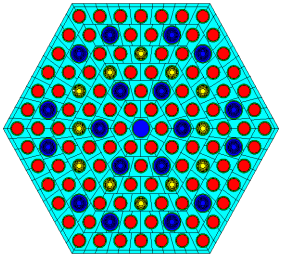
Neutronic optimization: modifications

Venenos quemables

- The amount of burnable pins is adjusted to avoid reactivity peaks at BOL
- The BAs concentration is adjusted to avoid reactivity peaks near EOL
- BA pins location is defined fine tuning the reactivity and power peaking factor
- Enrichment in BA pins is rised to ease power distribution







Neutronic optimization: modifications

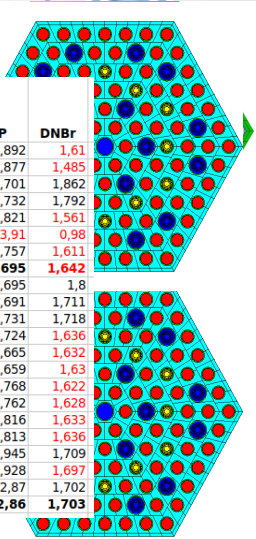
Venenos quemables

- The amount of burnable pins is adjusted to avoid reactivity peaks at BOL
- The BAs concentration is adjusted to avoid reactivity peaks near EOL
- BA pins location is defined fine tuning the reactivity and power peaking factor
- Enrichment in BA pins is rised to ease power distribution

Enrichment Change: E

Quemado [MWd/tonU]	MA [pcm]	MA-FU [pcm]	MA-SER-op [pcm]	MA-SAC [pcm]	FP	DNBr
291,9	−2368,7	−179,1	−5030,7	−1695	2,892	1,61
140	−2687,5	−438,4	−4941,3	−1789,2	2,877	1,485
515,27	−2531,9	−512,6	−5103,6	−2164,4	2,701	1,862
469,31	−2591,5	−576,4	−5162,2	−2340,9	2,732	1,792
078	−3231,7	−1222,8	−4988,3	−3303,5	2,821	1,561
	−2323,5	−365,7	−6540,7	−4936	3,91	0,98
060	−2928,9	−905,5	−5106	−2455,4	2,757	1,611
i806	**−3006,7**	**−1001,1**	**−5116,9**	**−3019,1**	**2,695**	**1,642**
898,3	−2821,5	−803,8	−5083,2	−2642,8	2,695	1,8
844,6	−2872,3	−854,6	−5097,8	−2622	2,691	1,711
914,3	−2885,7	−880,3	−5100,2	−3061	2,731	1,718
860,4	−2930	−924,7	−5137,9	−3043,8	2,724	1,636
509	−2934,3	−931,5	−5069,1	−2875,8	2,665	1,632
456	−2983,7	−980,7	−5095,1	−2858,7	2,659	1,63
834,5	−2955,4	−991,3	−4872,7	−2917,3	2,768	1,622
835,1	−2996	−1031,3	−4870,7	−2906,6	2,762	1,628
185,5	−3028,7	−1063,2	−4846,7	−3046,5	2,816	1,633
132,1	−3065,4	−1100	−4824,6	−3034,4	2,813	1,636
778,2	−2902,3	−957,8	−4554,7	−3179,7	2,945	1,709
724,9	−2940,3	−997,1	−4632	−3159,4	2,928	1,697
320	−2910,1	−974,5	−4543,7	−2970,4	2,87	1,702
'266,8	**−2936,1**	**−1001,2**	**−4643,7**	**−2949,2**	**2,86**	**1,703**

and optimum cycle shortened by BPs



Neutronic optimization: modifications

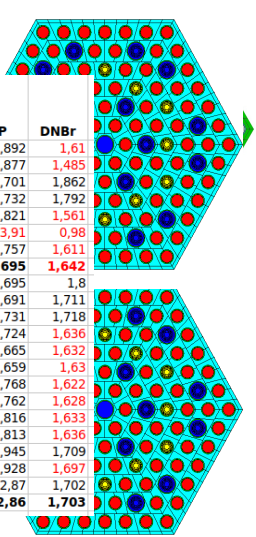
Venenos quemables

- The amount of burnable pins is adjusted to avoid reactivity peaks at BOL
- The BAs concentration is adjusted to avoid reactivity peaks near EOL
- BA pins location is defined fine tuning the reactivity and power peaking factor
- Enrichment in BA pins is rised to ease power distribution
- But the increase in ϵ_{235_U} lowers CRs weight, which narrows the possibilities for higher enrichements

Enrichment Change: E

Quemado [MWd/tonU]	MA [pcm]	MA-FU [pcm]	MA-SER-op [pcm]	MA-SAC [pcm]	FP	DNBr
291,9	−2368,7	−179,1	−5030,7	−1695	2,892	1,61
140	−2687,5	−438,4	−4941,3	−1789,2	2,877	1,485
515,27	−2531,9	−512,6	−5103,6	−2164,4	2,701	1,862
469,31	−2591,5	−576,4	−5162,2	−2340,9	2,732	1,792
078	−3231,7	−1222,8	−4988,3	−3303,5	2,821	1,561
	−2323,5	−365,7	−6540,7	−4936	3,91	0,98
060	−2928,9	−905,5	−5106	−2455,4	2,757	1,611
i806	**−3006,7**	**−1001,1**	**−5116,9**	**−3019,1**	**2,695**	**1,642**
898,3	−2821,5	−803,8	−5083,2	−2642,8	2,695	1,8
844,6	−2872,3	−854,6	−5097,8	−2622	2,691	1,711
914,3	−2885,7	−880,3	−5100,2	−3061	2,731	1,718
860,4	−2930	−924,7	−5137,9	−3043,8	2,724	1,636
509	−2934,3	−931,5	−5069,1	−2875,8	2,665	1,632
456	−2983,7	−980,7	−5095,1	−2858,7	2,659	1,63
834,5	−2955,4	−991,3	−4872,7	−2917,3	2,768	1,622
835,1	−2996	−1031,3	−4870,7	−2906,6	2,762	1,628
185,5	−3028,7	−1063,2	−4846,7	−3046,5	2,816	1,633
132,1	−3065,4	−1100	−4824,6	−3034,4	2,813	1,636
778,2	−2902,3	−957,8	−4554,7	−3179,7	2,945	1,709
724,9	−2940,3	−997,1	−4632	−3159,4	2,928	1,697
320	−2910,1	−974,5	−4543,7	−2970,4	2,87	1,702
'266,8	**−2936,1**	**−1001,2**	**−4643,7**	**−2949,2**	**2,86**	**1,703**

and optimum cycle shortened by BPs



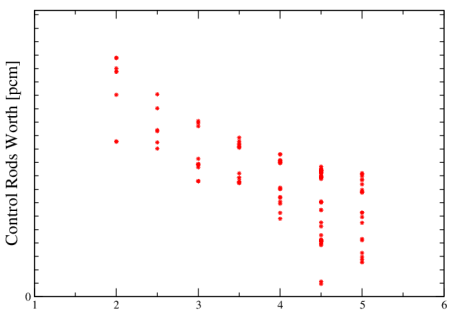
Neutronic optimization: modifications

Venenos quemables

- The amount of burnable pins is adjusted to avoid reactivity peaks at BOL
- The BAs concentration is adjusted to avoid reactivity peaks near EOL
- BA pins location is defined fine tuning the reactivity and power peaking factor
- Enrichment in BA pins is rised to ease power distribution
- But the increase in ϵ_{235_U} lowers CRs weight, which narrows the possibilities for higher enrichements

Enrichment Change: E

Quemado [MW
291,9
140
515,27
469,31
078
060
806
898,3
844,6
914,3
860,4
509
456
834,5
835,1
185,5
132,1
778,2
724,9
320
266,8



−2936,1 −1001,2 −4643,7 −2949,2 2,86 1,703

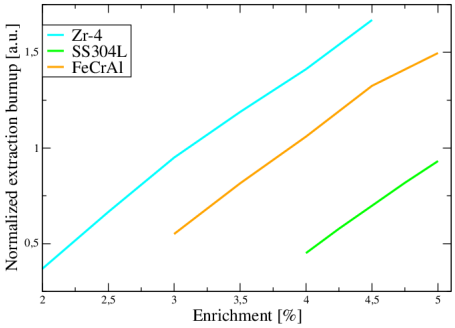
and optimum cycle shortened by BPs

Optimization results

¿What are the core configuration results?

Optimization results

Clad	ϵ [%]	# BP pins	Max. BP conc. [%]	ϵ in BP pins [%]
Zircaloy-4	2.0	0	0.0	0.711
	2.5	6	1.0	0.711
	3.0	6	7.4	0.711
	3.5	9	7.5	0.711
	4.0	12	10.0	0.711
	4.5	15	11.0	2.5
SS304-L	4.0	6	0.5	0.711
	4.5	6	2.1	0.711
	5.0	6	4.2	0.711
FeCrAl	3.0	6	0.5	0.711
	3.5	6	1.4	0.711
	4.0	6	7	0.711
	4.5	10	7	2.5
	5.0	11	9	2.5



Conclusions

¿What could be concluded so far?

Conclusions

- Any enrichment change has to be accompanied by a BA optimization strategy.
- The assessment of new and safer nuclear fuels must include cost analysis. Something safer but unaffordable, is hardly going to be used, will be replaced by other sources of energy (wind, solar or coal, for example).
- We were able to find configurations using FeCrAl cladding, with neutronically compensated enrichment and BAs content so as to comply with core design requirements.
- The economical evaluation of these configurations has already been made and is in the process of peer review for publication.
- **We found it is economically feasible to avoid H_2 production as a result of Zr oxidation with the use of FeCrAl cladding.**

Thanks

for your attention

Vielen Dank

Muchas Gracias