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MP98, AN INNNOVATIVE REACTIVITY CONTROL SYSTEM FOR LWR AND VHTR, TESTS RESULTS ON PROTOTYPES

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ABSTRACT

MP98' Reactivity Control System is now a technology tested on a real scale prototypes. Demonstrator is working at PWR real conditions (155 bars, 320° C), and many accidents configurations could be simulated. This paper presents the technology, describes the demonstrator design and presents some results. Mock up and demonstrator have permitted to optimize the design of MP98' devices to prepare industrialization.

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Keywords: Reactivity control system, power modulation, flux map optimization, spectral shift.

1. INTRODUCTION

The MP98 system is a reactivity control system designed for LWR, powered by pressurized helium.
MP98' system is a boron free system, fully passive, suitable as well for BWR, PWR, compact PWR and VHTR.
"MP98 reactivity control system" is the skeleton of each assembly. It is a passive system powered by pressurized helium. The neutron absorber is in tanks located upper the fuel assembly, and could be flushed at anytime for shut down or to shape the flux.
The MP98 system is ready for industrialization, all device and sensor needed are developped, some are already used in reactors for many years and are reliable.
Safety analysis and possible failure cases could be tested on demonstrator.

MP98 system is able to perform a shut down from hot to cold conditions without boron.
Injection time (shut down) is 0.7s on a 1000 MW PWR (to be compared to 2.4s for shut mechanical rods).

2. SITUATION OF THE PROJECT DEVELOPMENT

MP98 system design is clearly defined.

The neutron calculation, the mechanical calculation and the thermodynamic calculation are done for PWR.

BWR adaptation is under adaptation.

New studies begin for VHTR and GFR.

MP98 new studies show some opportunities to perform the fuel design, but these optimizations will not affect the MP98 design deeply.

In 2004 first tests have been performed on a simple mock-up under real PWR conditions. Therorical results have been comfirmed by trials on this mock-up,

A demonstrator of the MP'98 design has been build to show the all technology including level sensor and flux sensors.

MP98'system is now suitable for any kind of PWR reactors including existing plants.

3. MP98'SYSTEM DESCRIPTION

MP98' system is a passive system, helium powered. The helium is stocked inside the upper internals of the reactor vessel. Shut down is realized when a valve located outside the vessel is opened, or if a leak appears at any place on the helium circuit.

The MP98' principle is shown in scheme N°1.

MP98 is a simple net work of tubes fixed in the fuel instead moving control rods. the tubes or channels are filled by a metallic compound made of liquid metallic mixture (Indium cadmium alloy). The metallic mixture is solid when the temperature is low (under 170°C) and liquid when the primary circuit is at the working temperature.

The channels are inserted in and provided with the fuel. Each fuel assembly comes complete with the conduits inserted in place of the presently used rods.

All penetration are suppress in the reactor vessel and in vessel head.

The injection channels are separated in three groups for shut down, axial off set and reactivity variation.

They can be filled or be emptied at will to modulate the power or for shut down.

As the channels for shut down and reactivity variation are completely filled.

To correct axial deformations some axial offset channels could be filled partially.

In any type of rods, the metallic compound is pushed in or flushed out by a pressurized gas (helium) from a tank into a channel rod made with capillaries fixed inside an external concentric tube.

Injection may be progressive (long term control) or very fast (emergency shutdown).

Electric device commands gas distribution during shut down or to shape flux.

In a MP98 controlled reactor, the primary coolant could be demineralized water, without added neutron absorbers. This has one important feature : Like in Boiling Water Reactors, the effect of temperature on the moderation follows a constant law.

All MP98 equipment inside the reactor vessel is fully passive. Active device, mainly pilot valves for gas pressure control, are located outside of the reactor vessel, close to the reactor pool and may be easily tested and maintained.

4. SYSTEM FUNCTIONS

The automatic reactor control system uses the pressure of helium in the tanks to introduce or remove neutron absorbers inside the fuel assemblies.

Each assembly is capped with a standard MP98 design made with two tanks containing neutron absorbers(As shown in picture N°2). By introducing different combinations of channel absorbers located all over the core, the reactor control system will maintain the criticality of the core, keep the temperature within the acceptable limits, and optimize the flux distribution while facing the following variables:
The power demand of the grid.
The development of poisons in the fuel.
The burn-up of the fuel.

Some tanks are assigned specific functions. We shall now review these functions and show how they cope with various problems linked with the operation of a reactor (PWR or BWR).
To limit the number of tanks inside vessel, we decided to put one shut down emergency rod on two assemblies. It is enough to shut down core from hot conditions to cold conditions.
So in the place where shut down is needed, the biggest tank in our standard MP98 device is dedicated for emergency shut down, which we refer to as "S-tank" (for Shut down tanks). when it is located on a place beside shut down place, it is used for burn up variation. In that case we refer to as “B- tank” (for burn up tank), even if design and neutron absorber are the same for both uses. Each “S- tank” or “B-tank” is connected to 16 injection channels

The other tank upper is a smaller one used for axial off set , temperature variation .
we refer to it as “A tank” for axial offset and temperature variation and “P- tank” (for power variation tank) when it is located in 16 homogeneously chosen places in the core.

5 - CONTROLLING THE REACTOR USING MP98

- *“S-Tanks”*

Regulation (and common sense) command that the operator should at all times have a sufficient reserve of anti-criticality to be able to shut down the reactor even if only part of the means to do so are available. The S-tanks contain a very strong neutron absorber. They correspond to the traditional Emergency Shut-Down Clusters. They are not used in normal operation to preserve the poison.

High speed emergency shut down rods system

When reactor temperature is upper than 170°C, the neutron absorber alloy is liquid. At this time the emergency shut down system is ready, we are in safety conditions.

The shut down rods are empty, neutron absorber is in the “S tanks”(N°4 figure N°1).

Helium tank (N°5 figure N°1) is at the pressure of 162 absolute bars
(For concerns about the consequence of rupture or leakage of a capillary tube of MP98, please refer to our document N°MP98/1998/03/001/EN and MP98/2002/07/001/FR where this question is discussed in details).

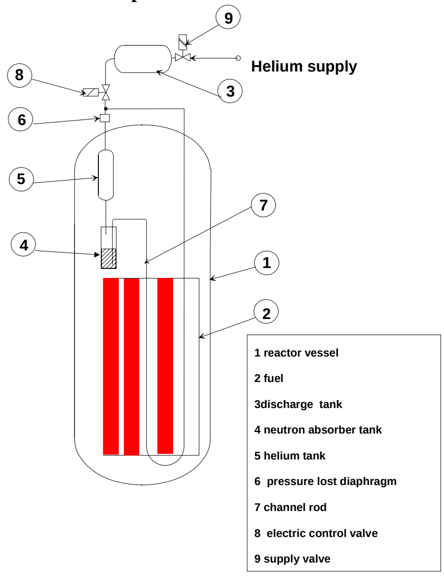


Figure N°1

This helium tank is inside vessel and so is at vessel temperature at any time. It is located inside MP98 upper internal.

Discharge tank (N°3 figure N°1) is at 2 absolute bars, and so discharge tank integrity is controlled at any time. When leaks pressure decrease to 1 absolute bar.

Control valve (N°8 figure N°1) is closed. This valve is an open valve when power loss.

When shut down is needed, or if voltage loss, valve N°8 opens, pressure inside helium tank N°5 expands, because drop pressure is done by diaphragm (N°6 figure N°1).

Helium pressure flushes neutron absorber inside the capillaries of the emergency shut down rods.

The emergency shut down rods are made with an external tubes and five capillaries joint in parallel to be filled quicker. This artfulness gives our emergency shut down rods the facility to be efficient enough to stop nuclear reaction in 0.7S.

After injection the two part of the emergency shut down rods are at the same pressure and this situation is fixed, with no possibility to flush back to tank, until the chief reactor operator allows the emergency shut down rods to emptied. To do so he pressurizes the all conduits at 57 absolute bars. Because diaphragm creates a differential pressure neutron absorber compound goes back to S tanks. Inside each tank a level measurement device detect when tank is full.

Operator decides to go to 162 absolute bars, emergency shut down rods system is ready again.

This deign is a entirely passive emergency shut down system.

The S- emergency shut down rods with 5 capillaries have a better cross-section as the traditional control rods, (For concerns about MP98'shut down efficiency, please refer to CEA calculation).
The S- emergency shut down rods alone contain enough neutron absorbers to make the reactor sub-critical. This provides the required redundancy, because the other kinds of tanks, especially the B-types dedicated to burn up, can also used in redundancy to shut-down the reactor.

Note that there is no equivalent risk to the cluster ejection existing in the traditional rods system.

6 - OTHERS FONCTIONS NEEDED FOR REACTOR CONTROLLING

- *Fuel burn up Compensation (B-tanks)*

In present reactors, some fuel manufacturers incorporate some burnable poisons inside the fuel rods, to allow some "overfilling" of the fuel elements. This extends the lifetime of the fuel load. However, it is difficult to match exactly the decay of the poisons and the burning up of the fuel, and this technique is limited by the impossibility to add or remove the poisons from the fuel during the operation of the reactor. MP98 allows you to do just that.

This tank is strictly the same that "S-tank" with 16 injection channels connected to it, but this tank is connected to "B- system" witch controlled the burn up.
At the reactor cycle starting all "B-rods" are filled all over the core.
Step by step, under flux control system the operator decides to empty the "B-rods" of one assembly or of one assembly in each quarter of the core to be symmetric.
And so follows, under flux map will the fuel burn-up.
In some special fuel core, or for long cycle, more anti reactivity could be needed.
MP98 gives the opportunity to filled B tanks with a compound made with metallic alloy added with gadolinium particles. MP98 allows to add or remove burnable poisons during the operation of the reactor. The metallic alloy , in that case is chosen at same density than gadolinium to avoid stratification. Particles aggregation is not feared if size is under 300microns.
With such neutron absorber compound very long cycle are allowed. At opening the gadolinium decays at fuel speed, and as before when gadolinium is decay, operator emptied "B-tanks" when needed. In that case gadolinium is are strictly separated from fuel and fuel manufacturing is cheaper.

- *Axial off set and temperature compensation (A-tank)*

“A-tanks “come in stacks of eight rods , and are located upper “S-tanks”(or “B tanks). They are used to compensate undesirable physics effects like the Xenon-Samarium effect, the Axial Offset, and the temperature difference between a cold start and a hot start.
For xenon samarium effect, some “A-tanks “are flushed to compensate for the Xenon poisoning, and filled up again by steps as the Xenon decays

Compensation of the Axial Offset

The absence of boric acid results in a strong temperature effect which favors the nuclear reaction at the (colder) bottom of the core. This results in an uneven consumption of the fuel elements. The consequences are a wastage of fuel, a limitation of the reactor power, and a risk of concentration of fission by-products in the lower part of the core, which creates a thermal risk in case of LOCA.

A radial distortion of this effect may favor the development of the "Xenon oscillations".

The solution is to introduce some neutron absorbers at the bottom of the reactor to even out the axial distribution of the flux. This is simply done in BWR's , because the control rods are introduced from the bottom.

In MP98, “A rods” could be partially filled. When connected to helium regulation system, the pressure difference on each part of the injection channel controls the neutron absorber level inside “ A rods”. to is dedicated to the compensation of the axial offset. , “ A rods” are built with a very thin inner channel, so that only the cross-section of the outer channel need be taken into consideration for neutron absorption. The neutron absorber is brought down at the lower part of the conduit through the inner channel, and rises in the wide outer channel up to a level specified by the control system. The later uses the flux measurement data supplied by the in-core or ex-core neutron detectors, to adjust the level in the “ A rods”
The analysis of the data obtained along the height of the core for each sector allows the control system to optimize the distribution of the levels in the “ A rods” depending of their location in the core (central of peripheral). Xenon oscillations can be detected at an early stage and damped out since PA-tanks can be controlled individually.

- ***Power adjustment (P-tanks)***

The P-tanks are dedicated to the global reactor power control.

MP98 makes use of the strong influence of the temperature on the core reactivity. Around 300°C, a variation of 1°C in the average reactor temperature affect the core reactivity by about 40 pcm. A change of 2°C in the average temperature, which is technically acceptable for the operation of the plant, provides a variation of 80 pcm. When the power is requested by the grid to change beyond the range allowed by this temperature variation, some neutron absorber must be introduced in or removed from the core. In a reactor using only pure water as a moderator, a variation of 1500 pcm is required to cover 100% of the power range. The one step variation in reactivity of the core must be limited to diverge with delayed neutrons. The acceptable limit for a single step variation in reactivity is 40 pcm. This criterion comes from the multiplication of neutrons in the core which cannot be immediately compensated by the temperature effect of the moderator.

The criterion is met by flushing the P-rods by sub-groups. We can roughly estimate the minimum number of P-tanks required to control the reactor power from 0 to 100% of its capacity. One step in power control must add no more than 40 pcm. We therefore need at least 1500/40 = 37 steps.
40 "A-tanks" will be dedicated to power variation.

7 - MP98 DESIGN

MP98 design could be used in PWR,BWR compact PWR.
To avoid penetrations in reactor vessel and in head reactor vessel
Conduits are disposed inside upper internals in the purpose to provide helium pressure to the neutron absorber tanks. In such internals some wirings are also disposed to connect internal electric or optic sensors to outside vessel control system.

<u>The upper internals:</u>

They are build in two parts, the internal to maintain fuel, is under. the internal where conduits are disposed to link outside reactor vessel control and command equipments with inside reactor vessel MP98' devices .
Helium tanks (refers device N°5 figure 1) are located Inside internals. These tanks are only bigger pipes .to stock the helium inside the vessel at working temperature. With such design emergency shut down is fully passive.

Picture N°1 - Upper Internals

MP98’ devices

MP98 device is the skeleton of the assembly. All functions needed to shut down and control nuclear reactors are in the assembly and provide with. Transport and storage are safer.
This Mp98’device is a shut down device, as you can see the red cap. We shall discuss, now, about MP98’ device specificities.
In this picture, you can see, from the top, the connection cap, the repartition nod, the “P-tank” in charge of power variation, the emergency shut down tank above the repartition plates, and at the bottom, the two type of neutron absorber channel (at the place where mechanicals rods are in an PWR assembly).
All design integrates the water flux and some artfulness are used to minimize pressure drop.

Picture N°2 - MP98’ controlled assembly

MP98’ controlled assembly ready for refueling

On this top view you can see a standard MP98assembly with connection cap on.
This cap is not screwed on the assembly for refueling, but it helps to understand the normal operation.
This connection cap has got eight connectors.
Four pressure connectors (two for each tank)are used for tank pressure supply.
We have Four electric(or optic) connectors.
The first is used for neutron flux measurement sensors. We have one neutron flux measurement sensor on four assembly, on four different levels to get a 3D flux map.
The second is used by the neutron absorber level sensors inside each tank.
The third is used temperature sensors
The last one is a redundancy of level measurement.

Picture N°3 - MP98’ controlled assembly, top view

MP98' controlled core

On this cropped view, you can see the two assembly types. The red cap assemblies equipped with emergency shut down channels, the blue cap assemblies with burn up tanks.

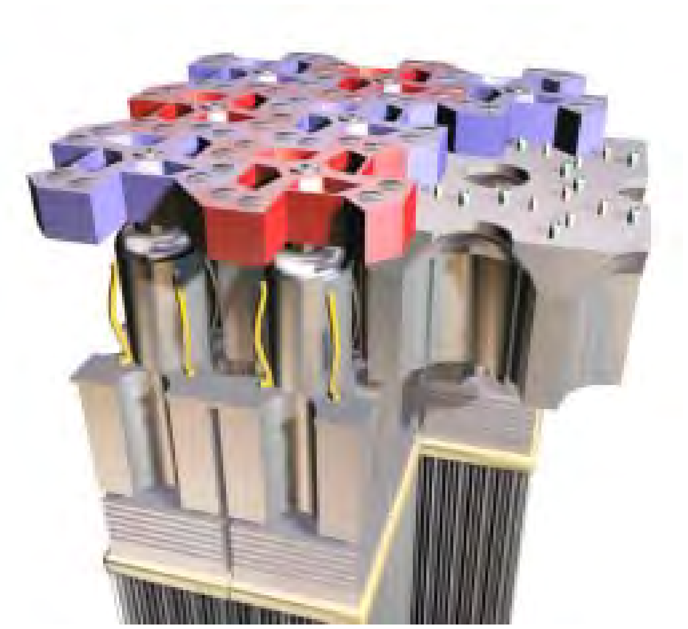
As you can see the caps are self blocked up.

With MP98 Refueling operation are done as follow:

- fuel is disposed in reactor vessel,
- first upper internal is staid on,
- then second internal are fixed on previous one,
- caps are locked on head assemblies,
- connections are lock in save conditions.

At any time helium connections are controlled, leaks are detected before closure and could be repaired without taking off upper internals. Even during cycle, connection leaks are detected and could be, most of the time stopped from outside containment.

In safety enhancement paragraph we shall discuss briefly about MP98 self protections.



Picture N°4 - MP98' controlled core

Replacing control rods by MP98 offers the following merits from the point of view of Nuclear Safety:

The control rod ejection doesn't exist any more.

The anti reactivity doesn't change with temperature of the neutron absorber.

Dilution accident is suppress.

The control rods are operable under seism.

The risk of failure of one channel is divided by the number of channel. And in our application have no consequences.

The neutron absorber injection time is shorter .

The neutron absorbers chosen are more efficient and give us a safety coefficient, even with MOX fuel.

The space between the fuel grid and the rod is no more block by precipitated boric acid.

Without boric acid, the nuclear criticality is always negative.

The MP98 system is fixed on the fuel and provided with it.

The channels are filled with neutron absorber witch is solid at low temperature, during transport, manipulation, storage, and when the primary circuit is under the working temperature.

The MP98 injection is a passive system.

The operability of the rod is controlled permanently by the pressure of the gas tank.

The deformation of the fuel assemblies or the necking of the rod guide tube under radiation have no effect.).

The over flow rate has no effect on the neutron absorber injection time.

An important necking of one channel will affect only the injection time.

Every element (eutectics, materials) or industrial process exist and are used in the nuclear field. It means the calculation programs, the justification reports have already been done.

8- MP98 ADVANTAGES AND BENEFITS

A simple network of fixed tubes could operate under seism and is not affected by over flow and vibration worn.
No external control rod mechanisms means, for PWR no vessel head penetration and for BWR, no button control rods penetration. Size of vessel could be, reduce.
No boron minimizes corrosion, radioactive wastes and contamination. Steam generator are protected, chemical circuits (BAST, BTR, CVCS,LWP, RWPS) are simplified or suppressed. Dilution accident is suppress.
Each fuel element is individually controlled during operation, neutron flux quality factor is improved, extended burn up is allowed.

1) MP98 Advantages in PWR

Design is minimized and simplified for internals and vessel.
Number of circuits minimized.
All penetrations in vessel head are suppressed (PWR).
Containment size minimized
Suppression of many potential accidents.
Better margins in normal working.
boric acid is suppress
low pH corrosion at 300°C is easier.
RCS corrosion is minimized (less lithium used, and no pH fluctuation.
Liquid wastes and solid (resins) are minimized (dilution, boric add are minimized).
less oxides (pH stable, less lithium).
less metallic particles activated.
tritium is 80% less (tritium is due to Bore 10 decay under flux).
less circuits, means less maintenance
liquid control rods could operate under seism.

MP98 system is static and fully passive.

Rod vibration worms are suppress.

MP98 could be used on standard PWR, compact PWR design, BWR, and propulsion reactors.

MP98 could used special fuels like over moderation fuel, spectral shift fuels, Pu9 fuels, high reactivity fuels.

2) MP98 specific Advantages on BWR

All assemblies could be done on the same square design, with the same MP98 device inside each BWR fuel.

The flux is equilibrated and could be modify as will with the rods.

The penetrations in the vessel bottom could be done elsewhere. So the earthquake protection is easier to achieve (no need to save space for the rods under the vessel).

The rods are more simple, safer, and could be use to modulate power.

The burn up is better, energy and money are saved.

The water chemical filtration circuit is minimized.

The vaporization point could be upper the core and fixed at the most convenient place.

3) Exploitation :

The waste quantity is smaller, the dosimetry is lower. It has a cost, and for nuclear business, waste and human dosimetry are major problems to solve to be accepted by people.

The fuel burn up is better.

The neutron flux distribution is control in the two axes and could be modify as will, and give the advantage of an homogenous fuel burnout(energy saved, suppression of hot spots on fuel rods).

The operability of the rods is controlled by the pressure of tank before starting up.

The fuel reshuffling may be no more needed all long the cycle

The temperature variation of the primary water is use to modulate the power .

It is possible to modulate power quickly on a large range under load follow.

With a criticality always negative it is possible to operate the control rods.

The fuel assemblies are standards (except for the external assemblies, some of them could be filled with neutron reflector).

4) MP98 specific advantages on a new power plant design :

The containment could be smaller, the only limit is the steam expansion under accident in rate of the maximal stress of the concrete (the new concrete can support more than (80 MPa) and the cost of the concrete is a major budget in the financial balance.

The number of circuits is reduce.

The reactor vessel could be smaller

The vessel pool is smaller

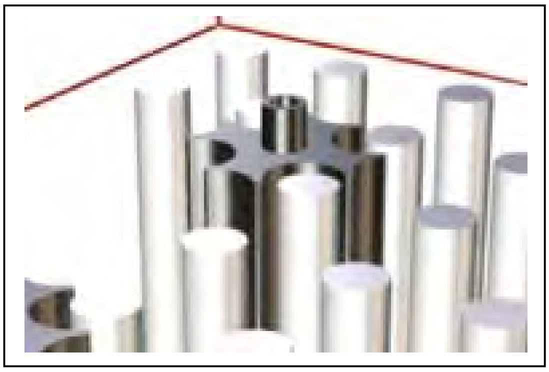
the storage fuel pool is filled with free bore water.

The upper internals are more simple and shorter.

9 - SPECTRAL SHIFT FUEL OPTION:

MP98 design could also be used with MP98 special spectral shift fuel.

In this fuel a pressure bell is around emergency shut down channels. This bell is connected to helium supply and so could be filled or emptied, as will, with the water of the reactor vessel.



When the bell is empty we get spectral shift, when filled over moderation.

In such fuel design energy could be used in a better way.

10 - NEUTRONICS ON SPECTRAL SCHIFT STRATEGY

Hypotheses

Core equivalent to a standard 1500 MW

This diagram compares different burn up strategies with MP98 spectral shift fuel

QUALIFICATION of CALCULATION

Done with APPOLLO standard code

Comparison with a real exact calculation MC (TRIPOLI 4).

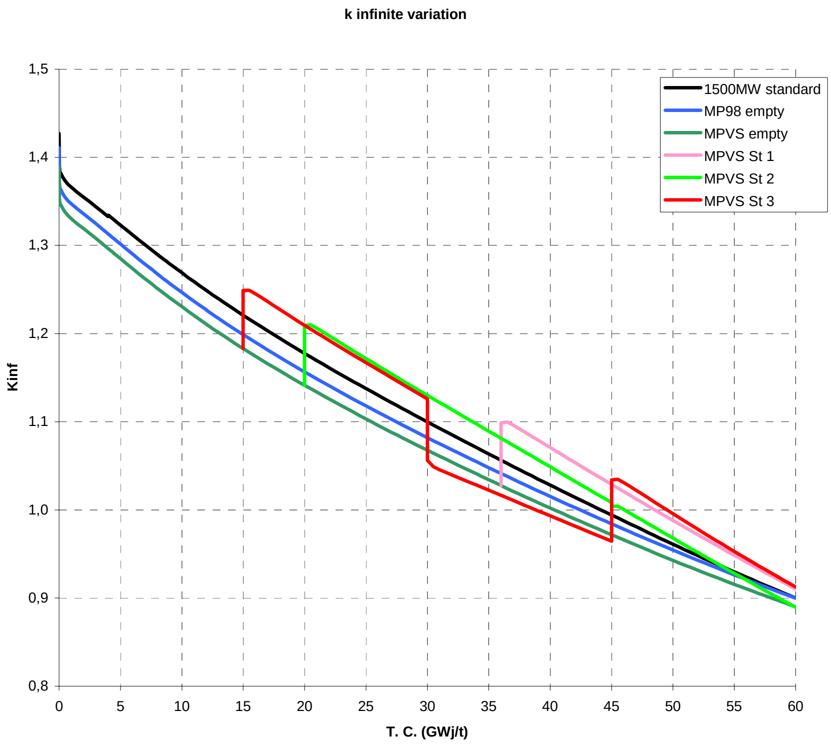
T 20 °C

Concentration at hot condition

Configuration 1

Qualification - Model

Regrouping cellules (self protection).



This diagram shoes interests of this type of fuel in PWR

11 - REACTORS EXAMPLES :

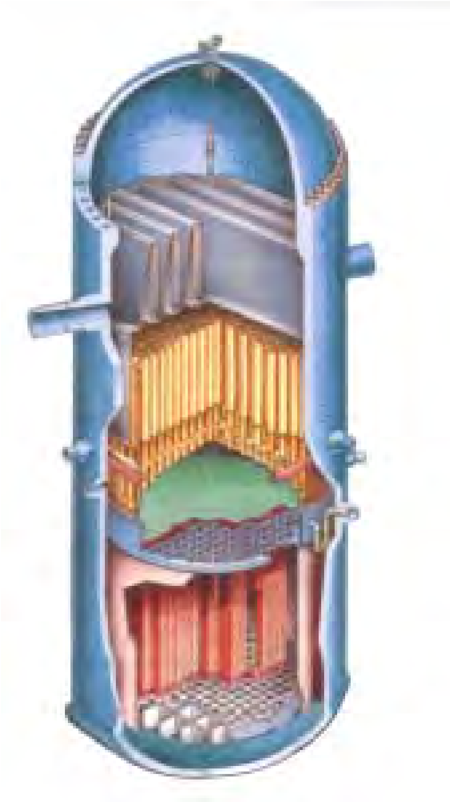


Figure N° 2 - MP98 controlled bwr

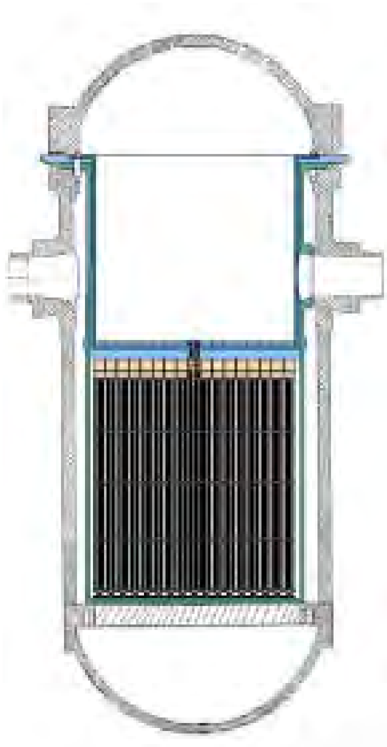


Figure N°3 - MP98 controlled standard pwr

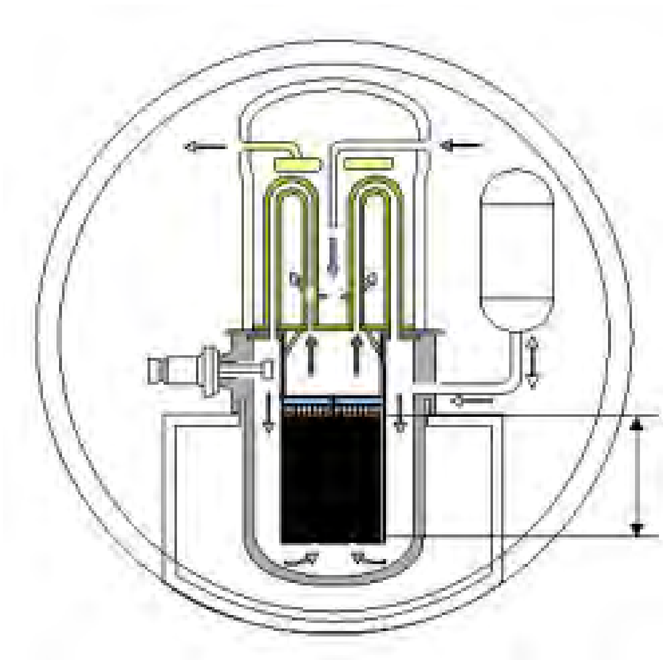


Figure N° 4 - mp98 controlled compact PWR

12 - SAFETY ENHANCEMENT

Conduits failure analysis:

Conduits are located in the upper internal, the probability of a leakage in these conduits is very low. Only one conduit is going out the upper internal to the command valves.

Quick tubes failure analysis:

If the tube connecting the conduits inside the upper internal to the discharge tank breaks, the injection will be done as far as the helium tank inside the upper internal is pressurized.

The helium pressure is surveyed at any time. That disposition increases the security of the system.

Slow tubes leakage analysis:

This small leakage will be compensated by helium supply.

Wrong pressure in the helium tank:

A pressure of **7 bars** inside the helium tank is enough to proceed to the neutron absorber **injection (in 2,1s instead of 0,7s)** inside the emergency shut down channel.

That means the system could be operated by a standard air supply network.

Leakage of one or several injection channels in a fuel assembly:

In our 17X17 fuel assembly design, we have 16 emergency shut down channels. If the pressure inside the helium tank is upper than the pressure inside the reactor vessel, a leakage of one tube will not avoid the other shut down channel to be filled with the neutron absorber. In MP98 the leakage of one channels does not affect all the channels of one fuel assembly and had no effect on the others.

The demonstrator is design to test this kind of failure.

Leakage of the pneumatic connection in the connecting cap:

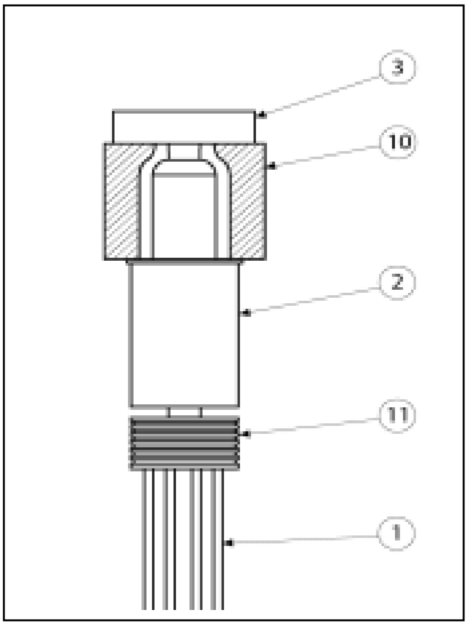
The tightness of connecting cap is verified before closing. The verification procedure is as follows:

When a connecting cap is fixed on the upper internal, the pressure of the helium circuit is increased to 162 bars. At this time, the reactor vessel is open, the pressure in the primary water is the highness of water upper the connecting cap(nearly 0.8bar). In working condition the difference of pressure between the helium tank and the water will be 7 bars. The verification of the tightness, with a 162 bars inside the circuit is a very strong proof of the good tightness. But anyway let us take the hypothesis that the tightness of the connecting cap is not enough.

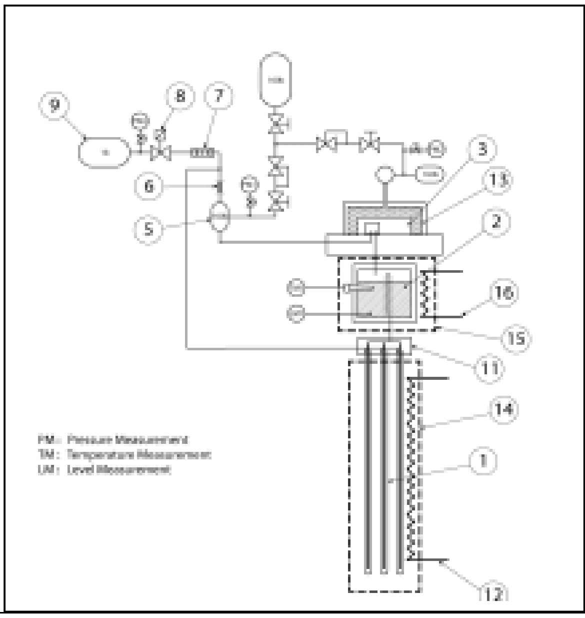
If the connecting cap (rep 3, on scheme N°3) has leakage in working conditions, the helium will leak inside the reactor. The operator will know it immediately by the pressure sensor on the circuit, but let us go forward.

The pneumatic connections on each side of the shutdown channel are physically separated.

Scheme N°3



13 – MOCK-UP DESIGN

The mock up is designed to simulate the real working conditions in a PWR: working conditions : 155bars, 321°C. Possible extended test conditions : Up to 200bars for the connecting cap test Temperature range for shut down channel: From 150°C to 350°C.	

Description of the mock up:

The mock up is divided in two functions:

the first function is a containment build to simulate the real pressure condition for the connecting cape.

The second function is to verify the shut down system at working conditions (155 bars, 320°C). This second function will also be used to performed the axial offset system and variation system.

In the axial offset correction system a variation of the level is needed. The neutron absorber level inside the tubes must be well known and stabilized even if the temperature of the coolant varies.

Axial offset channels are design to minimize the level variation when temperature increased.

Test results:

The theorical results are confirmed by trials on the mock-up, injection time is close to 0.7s.

Other safety analysis tests have been done on this mock-up , please refer to our document MP98

14 – CONCLUSION

A real scale demonstrator has been build in 2004 to show the whole MP98'technology, including prouved sensors for level and flux measurment.

The goal of the demonstrator is to give opportunity to utilities to discover an advanced technology suitable for any kind of reactors including existing reactors.

MP98 is ready for all kind of reactors, PWR, BWR, compact PWR.
MP98 is design for assembly from 15X15 to 21X21 for Uo2, Pu, and spectral shift fuel without any change inside reactor vessel.
MP98 could help utilities , with MP98'spectral shift , for electriciy tradding.
MP98 system saves 3US $ a MWh (on new reactor), and could also increase ratio betwwen fuel and energy by 9%.

MP98 system had been successfully assessed in 2002:
in France by experts from EDF (Electricité de France), CEA (French Atomic Energy Commissariat) and Framatome- ANP.
In usa by westinghouse, science and energy department.

- 2004 CEA new calculation confirme the first results and open new perspectives for impovments.

MP98 system is, now, ready to give significant advantages to LWR design and their exploitation.
MP98 system could also be suitable for VHTR at 1000°C, design must be adapted, connecting devices are under test.

References:

MP98 documentation including CD ROM
2002 CEA report on MP98'system neutronic and thermohydrolic analysis
2004 CEA report on MP98'system neutronic possible improvment

