# Czech University of Life Sciences Prague
# Faculty of Environmental Sciences

## Diploma Thesis

2014 KRISTÍNA ZAKUCIOVÁ

**Czech University of Life Sciences Prague**
**Faculty of Environmental Sciences**
**Department of Applied Ecology**

# Comparison of the Radioactive Waste Quantity Resulting from the Operation of GEN III+ Nuclear Reactors for NPP Temelin completion

DIPLOMA THESIS

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# CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Department of Applied Ecology

Faculty of Environmental Sciences

# DIPLOMA THESIS ASSIGNMENT

Zakuciová Kristína

Thesis title

**Comparison of the Radioactive Waste Quantity Resulting from the Operation of GEN III + Nuclear Reactors for NPP Temelin completion**

## Objectives of thesis

The objective of the thesis is to analyse the different types GEN III reactor systems and expected types of radioactive waste (RAW) that will be produced by them.

There are two main aims of the thesis:

1. It is necessary to compare and select suitable treatment technologies for the waste resulting from the GEN III+ reactors .
2. Comparison of the amount of the waste among currently operating CZ reactors and GEN III+ reactors before and after the proposed treatment.

## Methodology

Expected methodology should be fulfilled by the computations of the amount of the waste before and after the selected treatment. According to the computation results further comparisons have to be made.

1. Calculation and finding the waste amount before selected treatment;
2. Comparison of the technology and select the most suitable one;
3. Calculation of the waste amount after selected treatment.

## Schedule for processing

2013

Introduction, The aim of the thesis, Literature research, Methodology, Data collection, Data analysis

2014

Current state of the problem, Results, Discussion, Conclusion

### The proposed extent of the thesis

approximately 60 pages text and 20 pages annexes

### Keywords

Waste Treatment Technology, Radioactive Waste Management, Nuclear Waste, Nuclear Reactors,

### Recommended information sources

HÁLA J., NAVRATIL J. : Radioactivity, Ionizing Radiation and Nuclear Energy, Brno 2003, ISBN 80-7302-053-X, 467s
Horak W., 1997: Cogeneration in former Soviet union, New York, 6p.
ÚJV Řež a.s, 2008: Analýza požadavků na nově budované blokz JE Generace III v oblasti řízení a monitorování chemických a nakládání s RAO, včetně vyřazování JE z provozu, Systémy nakládání s radioaktivními odpady. Praha, 42p.
ÚJV Řež a.s, 2008: Vývoj projektových modifikací zaměřených na oblast chemických režimů a nakládání s RAO. Praha, 132p.
Tamas Janos Katona (2011). Long-Term Operation of VVER Power Plants, Nuclear Power - Deployment,Operation and Sustainability, Dr. Pavel Tsvetkov (Ed.), ISBN: 978-953-307-474-0

International Atomic Energy Agency, 2003: WWER-1000 reactor simulator,Overview of WWER-1000 systems and operation.
ÚJV Řež a.s, 2008: Analýza požadavků na nově budované bloky JE Generace III v oblasti řízení a monitorování chemických a nakládání s RAO, včetně vyřazování JE z provozu, Systémy nakládání s radioaktivními odpady. Praha, 42p.
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Správa úložišť rádioaktívních odpadů, 2012:Limity a podmínky bezpečného provozu ÚRAO Dukovany, Příloha 1. Podmínky přijatelnosti. Praha, 16p.

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Electronic approval: April 14. 2014

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Dean

# Author's declaration

I hereby declare that I wrote this diploma thesis independently, under the direction of Ing. Zdenek Keken . UJV Rez a.s. provided me with other information. I have listed all literature and publications from which I have acquired information.

In Prague, 20th April 2014 ..............................

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In Prague, 20th April 2014 ..............................

# Abstract

The Radioactive Waste management and the development of a new technology for waste minimization are the important issues which affect not only energy industry economy but also socio-economic area. It is the reason why the understandable explanations, predictions and comparisons in the field of waste issue are crucial to be spread among the academic and public sectors. This thesis as an environmental expertise shows how the Czech Republic fulfills the increasing energy consumption by the decision of Nuclear Power Plant Temelin completion with three selected Generation 3+ reactors. The aim of the diploma thesis is to compare and select proper technology for the treatment of the waste resulting from the operation of these three Generation 3 + reactors. The main scopes are the comparisons of the amount of the waste among currently operating CZ reactors and considered Generation 3 + reactors before and after the proposed treatment.

# Key words

Waste Treatment Technology, Radioactive Waste Management, Nuclear Waste, Nuclear Reactors.

# Table of contents

# List of figures

# List of tables

# List of abbreviation

| | |
|---|---|
| Bq | Becquerel |
| EPR | Evolutionary Power Reactor |
| FA | Fuel assemblies |
| FBR | Fast breeder reactor |
| FNR | Fast neutron reactor |
| GEN III+ reactors | Generation III+ reactors |
| GW | Gigawatt |
| Gy / h | Gray per hour |
| HIC | High integrity container |
| ILW | Intermediate-level active waste |
| $K_R$ | Volume Reduction Factor |
| LLW | Low-level active waste |
| MIR | Modernised International Reactor |
| MOX fuel | Mixed oxide fuel |
| MWe | Electrical megawatt |
| MWt | Thermal megawatt |
| mSv/hour | Millisieverts per hour |
| NPP | Nuclear power plant |
| PE | Polyethylene |
| PVC | Polyvinyl chloride |
| PWR | Pressurized water reactor |
| RAW | Radioactive waste |
| RCS | The reactor coolant system |
| SG | Steam generators |
| WWER | Water-Water Power Reactor |

# 1 Introduction

The main role of the energy industry is to obtain and distribute all forms of energy, especially electric energy. It deals also with mining and with utilization of the raw materials such as coal, oil, natural gas, nuclear fuel and wood. Other important role is the utilization of the renewable energy sources such as solar energy, wind energy, hydropower, biomass etc. On the Czech labor the dominant company for the production of the electricity is CEZ which operates 10 coal-fired, 2 nuclear, 12 hydro, 1 wind and 1 solar power plant and produces almost three-quarters of the total electricity production in the country. Thermal power plants produce 66% of electricity in the country, nuclear 30% and water 3,7%. Peaceful use of nuclear energy has become a natural part of the energy mix in a number of developed countries in the world. The Czech Republic is no exception. No matter what type of reactor is elected, it can be assumed that nuclear power will have a major impact on economic development in the future. In a global context, yet there is no better source of energy that would simultaneously cover the growing energy demand and also would not contribute to environmental degradation (CEZ, 2013b).

Despite of no contribution to the environment pollution there remains a nuclear waste issue mainly because of its long lasting radio activity and because of the difficulties with the selection of a location for the long-term storage. That is why new innovations and treatments are crucial for the nuclear industry and research. One of the examples of the Czech's innovations is the Temelin Nuclear Power Plant (NPP) completion with two new reactor units of Generation III+ (GEN III+). These new reactors should provide advance technology not only for the production of the electric output but also for the reduction and minimization of the waste volume. Reactors for the completion are in the tender where lots of various factors are assessed. One of them is also the amount of the waste from the reactors production.

The issue of GEN III+ reactors waste production has a lot of security restrictions. That is the reason why the public accessible sources provide only predictions or final results but no concrete information or comparisons. This thesis can be the guidance how such an evaluation of the waste volume can be done and which of the reactors technologies are the most suitable for NPP Temelin completion in the terms of the waste minimization.

# 2 Aims

There are two main aims of the thesis:

1. It is necessary to compare and select suitable treatment technologies for the waste resulting from the GEN III+ reactors .
2. Comparison of the amount of the waste among currently operating CZ reactors and GEN III+ reactors before and after the proposed treatment .

Expected methodology should be covered by the computations of the amount of the waste before and after the selected treatment. According to the computation results, further comparisons have to be done. The methodology design is showed in the following figure.

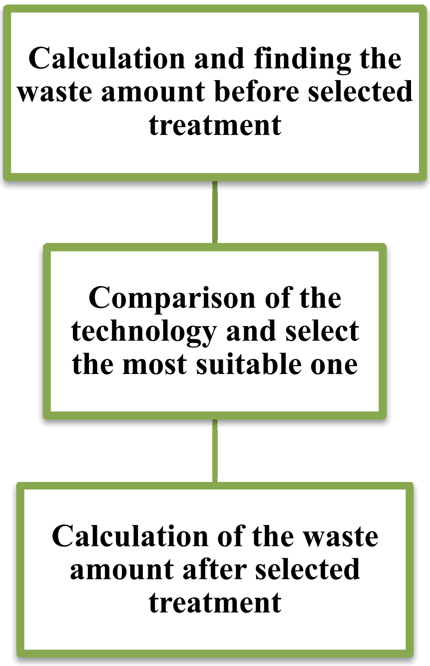


**Fig. 1** The methodology design

# 3 Literature review

## 3.1 Nuclear Reactors and their classification

A nuclear reactor can be described as a facility in which the chain fission reaction proceeds in a self-sustaining and controlled manner. The heat is generated and continuously removed (GIF, 2010). According to the purpose of a reactor, various types are built:

- Research reactors;
- Reactors for production of radioisotopes, plutonium and heavier transuranium elements;
- Demonstration reactors;
- Power reactors used in the submarines as energy source for engines;
- Power reactors which generate heat that is used in the secondary circuit for electricity production (GIF, 2010).

Another classification of the reactors is according to their historical evolution (Figure 2). Nuclear power plant technology has developed in a four design generations:

- *"First Generation: prototypes, and first realizations (~1950-1970)"* (GIF, 2010).
- *"Second Generation: currently operating plants (~1970-2030)"* (GIF, 2010).
- *"Third generation: improvements to current reactors (~2000 and on)"* (GIF, 2010).
- *"Fourth generation: advanced and new reactor systems (2030 and beyond)"* (GIF,2010).

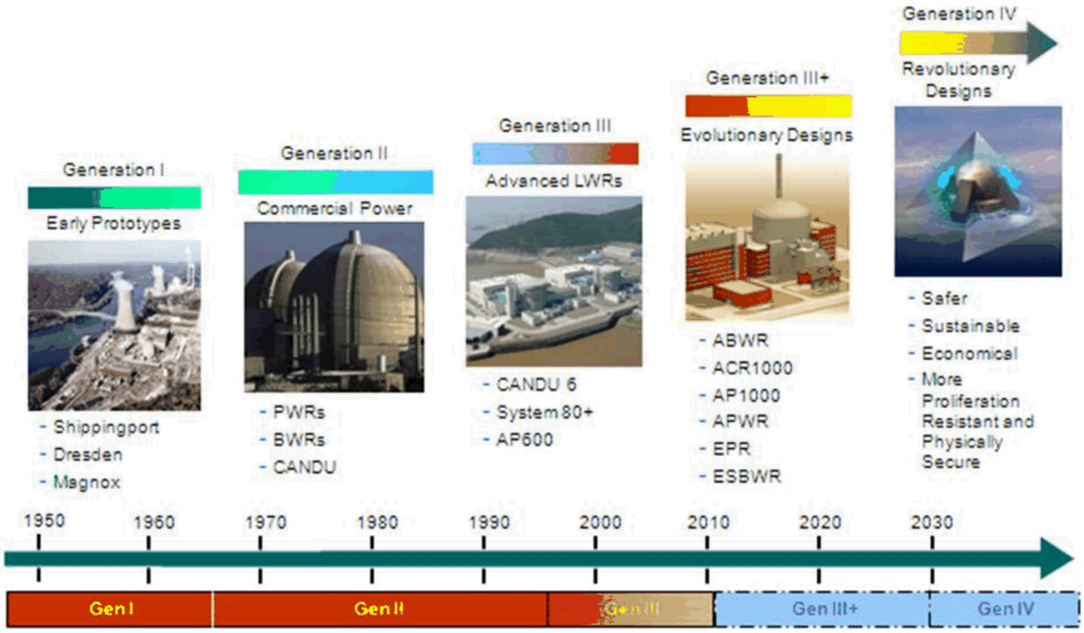


**Fig. 2** Evolution of Nuclear Power and generations of various reactors types (NEA, 2012; OECD, 2012)

The power reactors are classified as slow and fast reactors, according to the energy of neutrons inducing fission. *"The advantage of FNR is that uranium is burned more efficiently. If FNRs are designed to produce more plutonium than they consume, they are called Fast Breeder Reactors (FBR). Although FNRs can utilize uranium about 60 times more efficiently than a normal reactor, they are expensive to build and operate"* (WNA 2013).

*"A thermal (slow) reactor is a nuclear reactor that uses thermal neutrons. Most nuclear power plant reactors are thermal reactors and use a neutron moderator to slow neutrons until they approach the average kinetic energy of the surrounding particles"* (ENS, 2013).

It means that speed of the neutrons is decreasing and then neutrons are called thermal neutrons. The thermal reactors can be classified by the used moderator to:

***1) Light-water reactors:***

- Pressurized water reactor (PWR) : light – water reactor concept used most widely in current nuclear power plants;
- The boiling water reactor (BWR): light – water moderated and cooled reactor at atmospheric pressure.

2) ***Heavy-water reactors:***

- The heavy – water reactor of Canadian design CANDU (Canada-Deuterium-Uranium): reactor with pressure channels cooled and moderated by heavy water.

3) ***Graphite reactors:***

- Reactor Bolshoy Moschnosti Kanalniy (High Power Channel Reactor) (RBMK): is water cooled with a graphite moderator;
- Gas cooled reactors (GCR): uses graphite as a neutron moderator and carbon dioxide (helium can also be used) as coolant;
- The advanced graphite moderated reactor (AGR): uses enriched uranium (2,7%) and carbon dioxide ;
- The light – water cooled graphite – moderated reactor (LWGR): the graphite moderator is cooled by nitrogen gas (Hala, Navratil, 2003; ENS, 2013; WNA 2013).

As seen in the Figure 3, percentage of different types of nuclear reactors in the world shows that the most common type of nuclear reactors (around 60 %) is Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR).

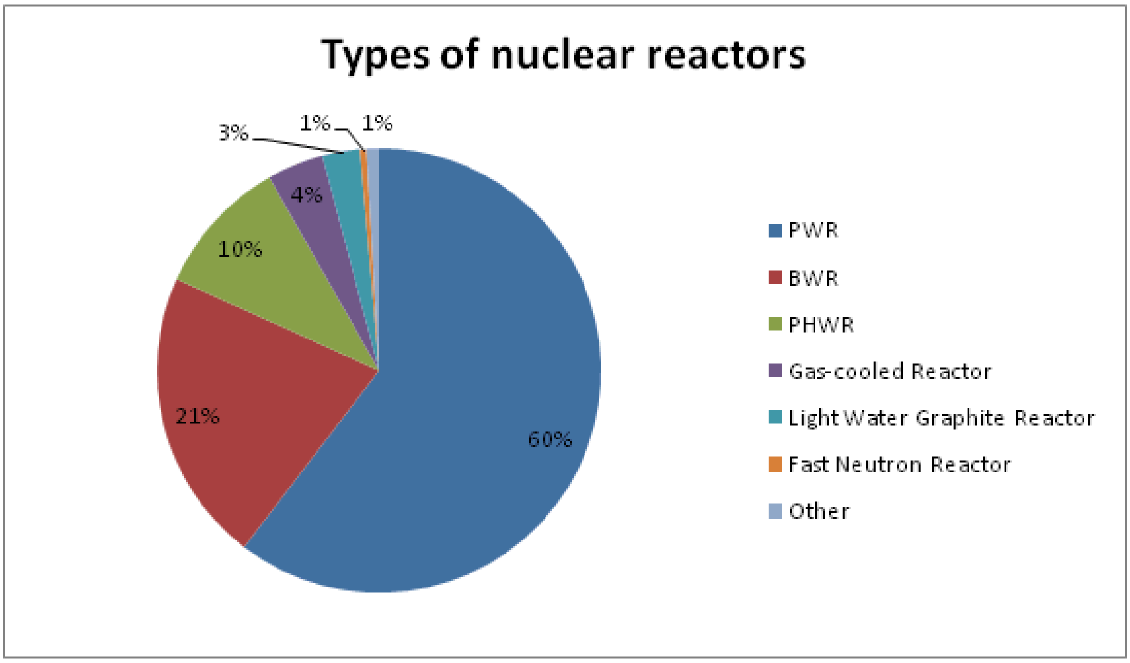


**Fig.3** Percentage of different types of nuclear reactors in the world (WNA, 2013)

### 3.1.1 Reactors design (WWER-1000, WWER-440)

Nuclear power plant (NPP) has many different systems which perform their functions for generating electricity. This chapter discusses the purposes of some of the major systems and components of currently operating reactor types in the Czech Republic.

The WWER is the Russian version of the Pressurized Water Reactor (PWR). *"The WWER reactors are light-water-moderated and water-cooled i.e. Pressurized Water Reactors (PWRs). The name comes from Russian Vodo-Vodyanoi Energetichesky Reaktor (Water-Water Energetic Reactor WWER)"* (Katona, 2011). The WWERs were developed in the 1960s and there are 52 Russian designed WWER-type PWRs operating in the world today under of 437 nuclear reactors (Katona, 2011).

There are 3 standard designs:

1. two 6 loop- 440 Megawatt;
2. 4 loop-1000 Megawatt output designs (The Virtual Nuclear Tourist, 2006).

There are 51 NPP Units with WWER in the operation (20% of population of the pressurized light water reactors). 39 Units have been already commissioned since 1999 and 8 of them are Units with WWER reactors (Mokhov, Trunov 2009).

WWER power stations are used by Armenia, Bulgaria, China, Czech Republic, Finland, Hungary, India, Iran, Slovakia, Ukraine, and the Russian Federation. In the Czech Republic there are two NPP using WWER reactors, thus Temelin and Dukovany (CEZ, 2013a).

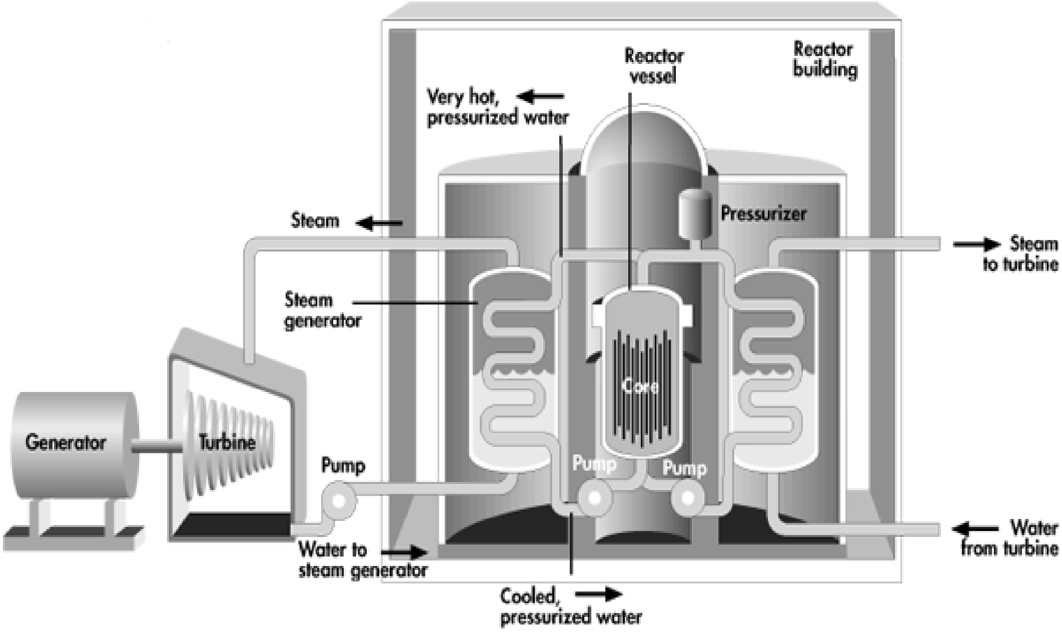


**Fig.4 WWER** Reactor design (The Virtual Nuclear Tourist, 2006)

The main features of the WWER are described in Fig. 4 and compared to other PWRs are:

- Horizontal steam generators;
- Hexahedral fuel assemblies;
- No bottom penetrations in the pressure vessel;
- High-capacity pressurizes providing a large reactor coolant inventory (OKB 2013).

### 3.1.2 WWER-1000 and WWER-440 in the Czech Republic

The Czech Republic operates two nuclear power plants Temelin and Dukovany. NPP Temelin produces electricity in two production units with PWR reactors WWER 1000 type **V 320**. NPP Dukovany has 4 PWR reactors WWER 440 model **V 213** in two production units (CEZ, 2013).

| **Nuclear Power Plants** | **Installed electric power output(MWe)** | **Year of commission** |
|---|---|---|
| **Dukovany** | 2 x 440; 2x 456 | 1985 - 1988 |
| **Temelin** | 2 x 1000 | Unit 1 - 2002<br>Unit 2 - 2003 |

**Tab.1** Nuclear Power Plants in the Czech Republic and their power output (CEZ 2013)

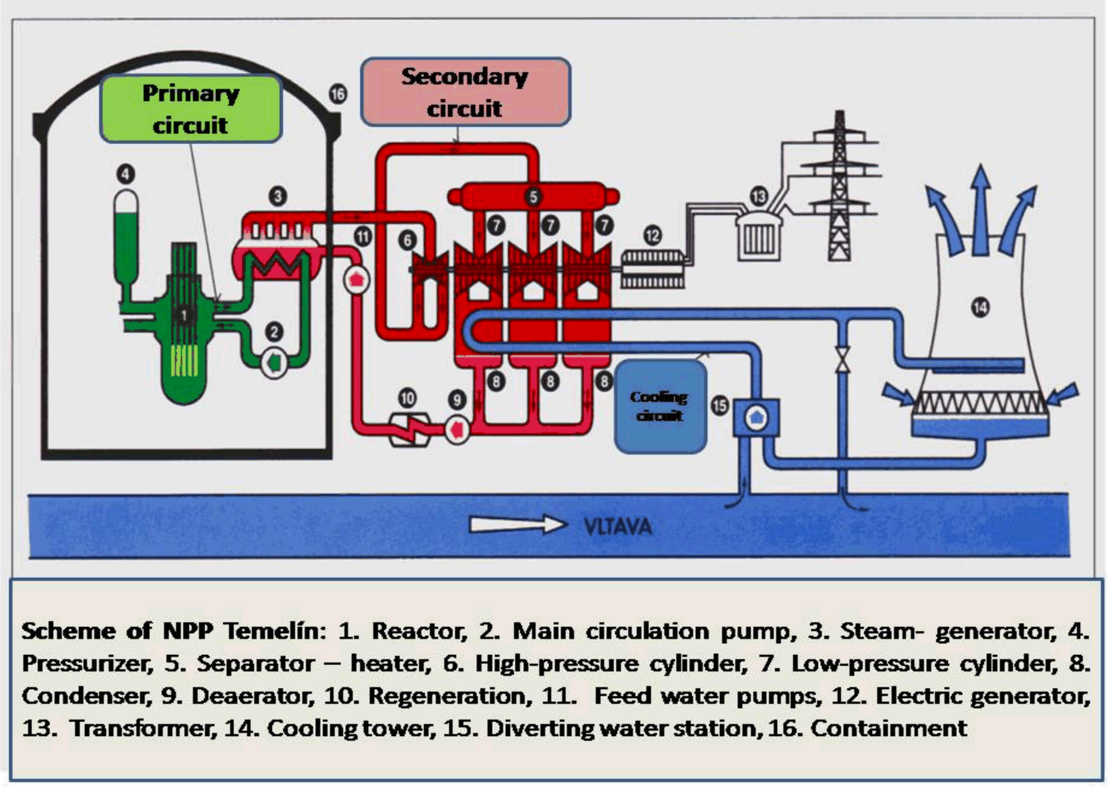
WWER-1000 and WWER-440 models are technically the same in the terms of types of the low and intermediate radioactive waste (RAW) produced but the volumes might differ. The main differences between these two models are mainly in their power output which illustrates table 1 and in their different construction. Both nuclear power plant's PWR reactors are fuelled by $UO_2$, uranium dioxide enriched by an average of 3,5% of the fission isotope $^{235}U$ (CEZ, 2013).

*"**In Dukovany**, the reactors fuel is placed in the reactor in 312 fuel assemblies. Each assembly consists of 126 fuel rods with a hermetically sealed fuel. In addition, the reactor contains 37 control rod assemblies with the fuel part. Each reactor forms a set with two three-casing turbines, each with one high-pressure and two low-pressure sections running at 3000 revolutions per minute. Reactors include six primary coolant loops, each with horizontal steam generator. In each loop there are main isolating valves on the cold and hot legs, one main circulation pump. The pressurizer with safety valves is connected to the primary loop. The technological schema of the power plant in **Temelin** corresponds to the latest world parameters. The entire primary circuit including the nuclear reactor, four steam-generators, circulation pumps, etc., is located in a fully pressurised reinforced concrete containment facility hermetically enclosed in a protection envelope. A turbo-generator developing 1000 MW output is situated in the secondary circuit. The reactor core contains 163 fuel assemblies, each with 312 fuel rods, and 61 regulating rods. These types of reactors use four coolant loops and horizontal steam generators. Detail functions and construction components of WWER reactors are described for WWER -1000 types below"* (CEZ 2013, Katona 2011).

### 3.1.3 Construction and functions of NPP with WWER-1000 reactor

The main systems of the NPP with WWER-1000 reactor are the following (Fig. 5):

- Reactor;
- Primary circuit: main circulation pipelines, main circulation pumps (MCP), steam generators (SG);
- Secondary circuit steam lines and feed water pipelines
- Safety systems;
- Primary circuit feed and bleed system, including boron regulation;
- Pressurizer and primary circuit pressure compensating system;
- Control and protection system (IAEA, 2003).



**Scheme of NPP Temelín: 1. Reactor, 2. Main circulation pump, 3. Steam- generator, 4. Pressurizer, 5. Separator – heater, 6. High-pressure cylinder, 7. Low-pressure cylinder, 8. Condenser, 9. Deaerator, 10. Regeneration, 11. Feed water pumps, 12. Electric generator, 13. Transformer, 14. Cooling tower, 15. Diverting water station, 16. Containment**

**Fig. 5** Main components of the NPP Temelín with WWER-1000 reactor (Fi.Muni, 2014)

- **Reactor**

International Agency for Atomic Energy (IAEA, 2003) defines the WWER-1000 reactor as, “a *Light Water Reactor where chemically purified water with boric acid is used as coolant and also as moderator. Regulation of reactors power includes control rods system and boron regulating system. Reactivity regulation is based* *on changing the position of the control rods and on changing the boron concentration of coolant in the primary circuit*" (IAEA, 2003). The reactor includes the following components illustrated in the Figure 6:

- Core;
- Reactor vessel;
- In-vessel installations;
- Step-type electro-magnetic gears of the control rods;
- Neutron flux measuring instrumentation (IAEA 2003).

*"The coolant enters the reactor through input nozzles, passes a ring gap between the reactor vessel and the core-well and, through a perforated bottom plate and enters fuel assemblies installed in the reactor core. The coolant then passes through the perforated plate, then goes to the ring gap between the core well and the vessel and through outlet nozzles exits the reactor vessel to the hot leg"* (IAEA 2003).

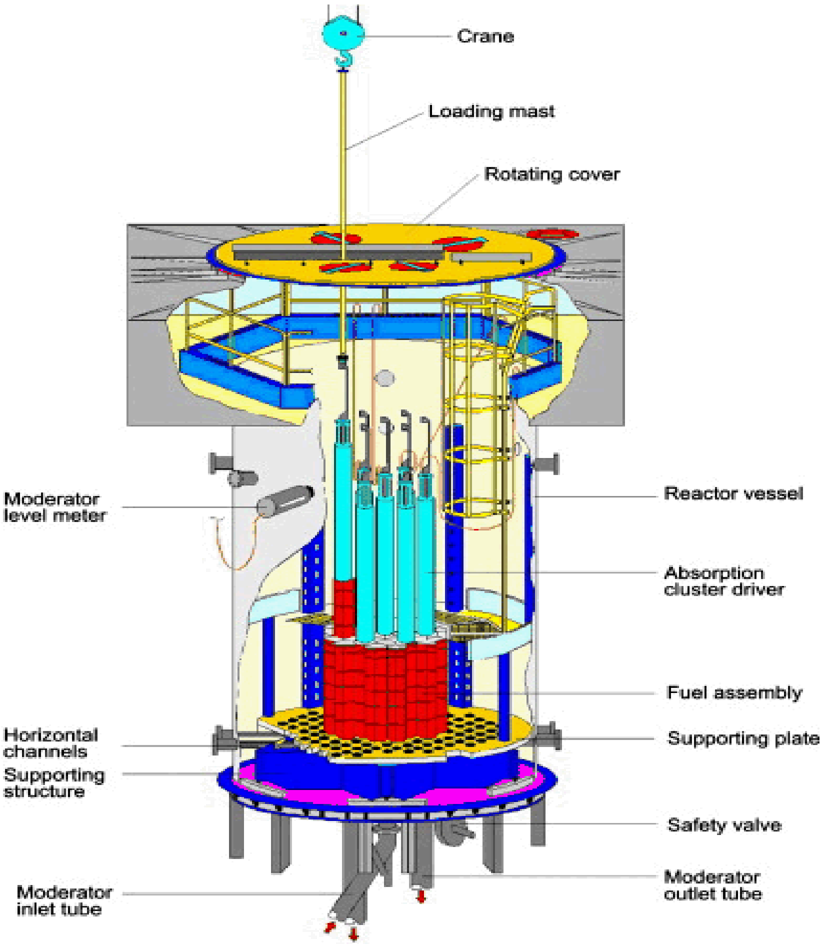


**Fig. 6** Inner view of research reactor LR-0 (Centrum Vyzkumu Rez, 2013)

- **Reactor core**

The WWER-1000 core is composed of fuel assemblies in a hexagonal form and located on a hexagonal grid (see Fig. 6). The fuel assembly for the WWER-1000 consists of a regular grid of fuel rods. In certain positions fuel rods are replaced with non-fuel elements such as absorbing elements of control rods or rods with burnable absorbers (IAEA, 2003).

- **Main circulation pumps**

*"Four main circulation pumps (MCP) are vertical centrifugal pumps with mechanical shaft seals. Each pump is driven by a vertical air-water cooled electric motor. The MCP rotating part has significant rotation inertia and if the MCP stops completely, natural circulation maintains core cooling"* (IAEA 2003).

- **Steam generators**

Steam generator removes heat from primary circuit coolant and forms saturated steam in the secondary circuit. SG at NPP with WWER-1000 reactors are of the horizontal type (IAEA 2003).

- **Primary circuit, feed and bleed system**

International Atomic Energy Agency states that, "*in the primary circuit heat generated in the reactor core from the fission of nuclei in the fuel is removed by the coolant. After leasing the reactor core, the coolant is transported along the part of the primary circulation circuit called "hot leg" to the steam generator. The steam generator is a heat exchanger in which the heat from the primary circuit coolant transfers in the form of steam in the secondary circuit. After the steam generator, the coolant is transported along the part of primary circulation circuit called "cold leg" back to the reactor vessel. There are four circulation loops in the primary circuit of the NPP with WWER-1000 reactor. The coolant is pumped by four main circulation pumps."* (IAEA, 2003).

The primary circuit feed and bleeds system is designed for:

- Controlling the inventory of the primary circuit coolant;
- Changing boron concentration in the primary circuit coolant;
- Bleeding leakages from primary circuit equipment;
- Primary circuit coolant purification and return;

- Feeding water to MCP sealing;
- Feeding boron concentrate to the primary circuit in case of electric power loss (IAEA, 2003).

Primary circuit inventory control systems are performed via feed and bleed valves. If the pressurizer level is below the setpoint it shows that there is insufficient coolant mass in the primary circuit and an additional amount of coolant is then fed into the primary circuit from the primary coolant storage tank until the level in the pressurizer reaches the setpoint. On the other hand, a pressurizer level above the setpoint sets that there is excess coolant mass in the primary circuit, and the bleed flow increases while the feed flow decreases thus reducing coolant mass in the primary circuit. "*Bleed coolant from the primary circuit passes to the regenerative heat exchanger where it is cooled by feed water return flow to the primary circuit. After cooling, the bleed coolant is purified in the low-pressure water purification system. After purification, the coolant flows to the feed water deaerator for degassing from which it is returned to the primary circuit"* (IAEA, 2003).

- **Secondary circuit**

The secondary circuit of the WWER-1000 includes:

- 4 steam generators;
- steam isolation valves and steam discharge valves;
- main steam header;
- turbine;
- 4 condensers;
- feed water rating systems;
- feed water supply system.

*"In the secondary circuit, steam formed in the steam generators is transported to the "balance of plant systems". Most of the steam formed in the steam generators is sent to the turbine. After the turbine, steam is dumped to the condenser and condensed. From the condenser the water is transported through the low-pressure heaters to the deaerator for removal of noncondensable gases. From the deaerator, feed water is transported through high-pressure heaters to the steam generator"* (IAEA, 2003). The steam formed in all steam generators is collected in the main steam header. Under the normal operation conditions most of steam flow goes to the high-pressure

cylinder of the turbine. Steam exiting the high-pressure cylinder enters the separator to remove extra moisture. After the separator, steam passes to the reheater where it is heated and enters the low-pressure cylinders. From the condenser, the condensate is pumped through low-pressure and high-pressure reheating heat exchangers. Then the condensate goes to the deaerator in which all non-condensable gases are removed. Then the resulting feed water is pumped to the steam generator. (IAEA, 2003).

- **Cooling circuit**

"*The cooling circuit is an open circuit taking water from an outside reservoir such as a lake or river. Evaporative cooling towers, cooling basins or ponds exhaust waste heat from the generation circuit and release it into the environment*" (Horak 1997).

- **Reactor control and protection system**

Regulation of reactor power and control of the fission chain reaction is carried out by 2 systems which regulate reactivity that are based on two different principles:

1. Insertion of solid absorbers - control rods system;
2. Injection of liquid absorber - boron regulation system.

Control rods are used for changing reactivity and for reactor shutdown in normal and emergency operation conditions. Boron regulation is used for the slow changes in reactivity (IAEA 2003).

## 3.2 Radioactive Waste Management - Description of radioactive waste management systems in the CZ NPP

In general, almost all human activities produce various type and amount of the waste. The same is with the sector of nuclear energy which produces RAW. Radioactive wastes produced by nuclear power plants are formed by release of fissile products from the fuel or because of neutron activation of the materials and media in an active zone of the reactor. The fissile and activation products of coolant from primary circuit contaminate various gaseous, liquid medias and solid materials (IAEA, 2009). Radioactive waste is generally divided by activity on:

- Very low level waste: Waste that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Typical waste in this class includes soil and rubble with low levels of activity concentration;
- Low-level active waste: Waste that is above clearance levels, but with limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities;
- Intermediate-level active waste: Waste which contains long lived radionuclides and because of that, waste needs a greater degree of containment and isolation in greater depths of tens of metres to a few hundreds meters;
- High-level active waste: Waste with large amount of long lived radionuclides like spent nuclear fuel. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of this type of waste (IAEA, 2009).

According to Decree SUJB No 307/2002 radioactive wastes are divided into gas, liquid and solid. Solid radioactive wastes are classified into three basic categories: temporary, low and intermediate and high-level active waste. Temporary are such a waste which after long term storage (max. 5 years) exhibit lower level of the radioactivity than release levels. Also, Decree is showing that low and intermediate level radioactive waste is divided into two subgroups long-lived and short-lived. The short-lived have a half life of the contained radionuclides less than 30 years (including Cs-137) and limited mass activity of long-lived alpha emitters (in a single package up to 4000 kBq/kg and the mean value of 400 kBq / kg in the total volume of waste generated per year). Long-lived wastes are those that do not belong to a subgroup of short-lived radioactive waste (SUJB, 2002).

Another classification of RAW is according to their places of formation into:

- RAW formed in nuclear power plants;
- Institutional RAW – waste formed in medicine, geology, agriculture, etc (SUJB, 2008).

The objective of radioactive wastes management is to :

1. minimize waste volume for safety disposal into RAW repository;
2. minimize activity in effluents (waste realeased to the enviroment in accordance to legislative requirements);
3. decrease contamination of liquid, gaseous medias and solid materials (UJV Rez,2008a).

Minimization of the radioactive waste activity is mostly achieved through the high quality coverage of the fuel elements, appropriate (from the anti-corrosion point of view) chemical mode of the primary circuit and construction materials selection of the active zone of reactor and the whole primary circuit. The contamination decreasing needs cleaning processes of the gaseous and liquid media, decontamination of the facilities and structural surfaces. These processes concentrated the activity into radioactive wastes, which, after being processed, are carried away from the power plant to the repository where they are isolated from the environment. Because of the wastes minimization, waste must be classified from place of their formation by activity and by the anticipated method of processing and conditioning. Radioactive waste management systems provide collection, classification, treatment and processing of all types of waste generated in the controlled area. In addition, ensure activities leading to the release of media and materials into the environment. Waste products that comply with the clearance levels (currently limits are determined in accordance with the requirements of Act 18/97 Sb. (The Atomic Act), as amended, and decree. 307/2002 coll. about radiation protection, as amended by decree. No. 499/2005) can be released into the environment in the form of liquid and gaseous effluents or solid contaminated materials (UJV Rez, 2008a). The total amount of the waste from the production of the both CZ NPP is listed in the tab. 2 and tab.3. , Appendix 1.

### 3.2.1 Technology systems of liquid radioactive waste management

The primary source of the liquid media activity is water of the primary circuit where radionuclides are present in both soluble and partly in an insoluble form (especially corrosion products). The dominant component of the coolant in primary circuit in the PWR reactors is boric acid in average concentration about 3g/l. In order to waste minimization, waste is sorted from the point of the formation according to the activity to the active and potentially inactive waste. Liquid radioactive wastes from the controlled area are collected separately with regard to the origin of the formation and subsequent treatment process into:

- Potentially inactive water includes water from special laundry: washing and rinsing, hygienic loops and laboratories;
- Conditionally active water: water, in which the occurrence of activities is minimal - a space with an indefinite stay, drainage and ventilation equipment and water distribution for own consumption, distribution of cooling water, water heating and steam heating, etc;
- Potentially active water with chemical additives: water, for which there is minimal occurrence of activities and are just chemically contaminated;
- Solutions for steam generator blowdown filters : potentially active water with chemical additives with the assumption of direct release out of NPP;
- Water containing boric acid: waste containing waters only with boric acid. These waters are processed together with other water sources in the regeneration of boric acid and returned to the NPP technological systems. Only in the case that cannot achieve the purity required for the use of the NPP, they are pumped to the processing of waste radioactive water;
- Other special waters drainage are collected in a drainage system (UJV Rez 2008a).

Active waste water is processed in technological systems that deal with liquid radioactive waste. These are unorganized effluents from the primary circuit, which are the main source of activity of sewage water and effluents from other technological equipment. This sewage also receives water from the laboratory and water decontamination and from cleaning of rooms and equipments from controlled area. In the NPP 2 x WWER 1000/320 the wastewater is processed, stored and treated in the following technological systems:

a) In the sewage treatment plant , which includes technology nodes of centrifugation, distillation plants for wastewater, filtration station of condensate polishing, processing of laundry water, supply NPP with purified condensate, water effluents;
b) In storage system of liquid radioactive waste;
c) In final treatment of liquid RAW (UJV Rez 2008a).

**The sewage treatment plant**: The radioactive waste water cleaning is based on gradual process – 1. Collection, 2. Centrifugation, 3. Evaporation and filtration.

1. Collection:

To collect radioactive waste water from the NPP technological systems before it`s further treatment serves the sedimentation tank (150 m$^3$). The sedimentation tank collects waste water (washing water, transport water of spent sorbents, waste decontamination solutions and condensate from the liquid radioactive waste solidification.) and sludge from special sewage pits and purification stations. The settled sludge is then transported into the tanks of sorbents into interim storage of liquid radioactive waste and water after sedimentation leaves the overflow tank and then through the waste water filter (mechanical filtration) into the wastewater tank prior to evaporators (UJV Rez 2008a).

2. Centrifugation:

Second technological process consists of several interconnected equipments with individual functions. Waste water from the sedimentation tank is led to the pulverizer which grinds larger particles. Then it goes through the single-stage process (centrifuge) or a two-stage process (decanter +centrifuge). Sludge from single stage process is collected in the sludges collection tank and is pumped into the intermediate storage of liquid RAW into the concentrate tank or back into the sedimentation tank. Sludge from the two-stage process is collected from the decanter to 60 or 200 L drums, and can be processed by fixation into aluminosilicate matrix SIAL. The two-stage process can be used for processing low-active laundry water and for water from sanitary closures (UJV Rez 2008a).

3. Evaporation and filtration:

The next level of the waste water treatment is the processing in the evaporators. Waste water from which were removed larger particles (centrifugation or sedimentation and purification on mechanical filters), is collected in the tanks of waste water. Emerging concentrate of the salt content about 200 g/L is discharged to concentrate tanks in a liquid radioactive waste intermediate storage. Vapor steam is condensed in the condenser - degasser. Condensate is cleaned in four series connected line filters. Lines are three and work in connection with the operation of the evaporation station. According to the needs of the individual filters, filters are loosening, recovered, washed, flushed and sluicing. Purified condensate is fed to the control tanks. The control tanks with purified condensate after radiochemical control are transported either into the water tank self-consumption for reuse in the NPP or into the pure condensate tank from which further adds to the primary circuit is made or the water effluents are pumped outside NPP (UJV Rez 2008a).

**Control of liquid effluents** is ensured by system of radiation monitoring and sampling systems in which samples are analyzed in the radiochemical laboratories. The purpose of the monitoring and sampling of effluents is to monitors the compliance of the authorized limits to prevent unauthorized discharges and releases of radioactive substances into the environment. In the case of excess of permitted levels of activity of discharged water, the situation is signaled to the control room of radiation monitoring and discharge from control tanks is interrupted. Monitoring and sampling is provided for all types of liquid effluents from which we can obtain detectable amounts of radioactivity discharged from the NPP, both during normal operation, abnormal operation and accident and post-accident conditions (UJV Rez 2008a).

**Interim storage of liquid radioactive waste** in the tanks is used for collecting the concentrated radioactive waste, generated in a process of radioactive water processing before final fixation into bitumen. Sorbent tanks are used for storage the medias from filters of radioactive water treatment plants which are transported into storage tanks as a suspension. Solid particles of suspension are settled in tanks, transport water after sedimentation is routed through the overflow tank system into the cycle of radioactive waste water. Technological node of tanks for radioactive concentrate is used for storage of concentrated residue from evaporation of active wastewater. The final treatment of liquid radioactive waste is installed bituminisation line which is used for the treatment of the concentrate which is formed after concentration of wastewater by evaporation. Radioactive sludge from the collection tanks is specified as a special type of waste. It is assumed that sludge will be processed simultaneously with the concentrate or will be fixed in the SIAL matrix after centrifugation. As a fixation medium is used bitumen of the domestic production, which is stored outdoor in the tanks, heated by steam. Individual concentrate and sorbents are processed separately. In the evaporator, both media are mixed. The mixture flows to the bottom of the evaporator where it flows into prepared 200 L drums which are placed on a rotary carousel. Barrels with product are located on rotating carousel where they are gradually cooled, capped, weighted and measured the dose rate on the surface of the barrel. Then the barrels are stored on rail platform and exported. Condensate water from bituminisation evaporator is led through a drop eliminator in the head of evaporator to the condenser. The condensate is pumped to the waste water system (UJV Rez 2008a).

### 3.2.2 Technological systems of management of solid radioactive waste

Solid radioactive waste is produced especially during scheduled shutdowns for maintaining and cleaning work, decontamination equipment and rooms. The source of contamination of various objects is the contact with active media- especially with water from primary circuit of NPP, often mediated by deposit of contamination on equipments. Besides this randomly or irregular formation of RAW there is assumption of regular formation of solid radioactive waste. The highest production of solid radioactive waste is assumed in the phase of decomissioning of NPP operation (UJV Rez 2008a).

- **Collection and partial classification (according to origin and methods of treatment) in a place of formation**

For collecting small waste in a controlled area of NPP there is a system of stable and temporary collection points where the waste is sorted according to the character of further processing. High-volume waste is measured, if necessary, decontaminated in the place of formation (or with the use of the decontamination bath) and according to the needs in the site is fragmented into transport dimensions up to 1,1 x 1,8 x 2 m and into maximum transport weight 3 t. Subsequently it is transported to further fragmentation (processing) in the central workplace to the warehouse or directly for the processing (UJV Rez 2008a).

- **Transport to the central workplace**

Operational waste is collected into containers located in the controlled area and regularly shipped to the central workplace for further processing. If a regular radiation monitoring of collection points indicates higher surface dose rate on the container than a limit dose of 100 μGy/h, the waste must be immediately transported in a shielded container or a barrel to the central workplace (in order to avoid unnecessary exposure of the personnel) (UJV Rez 2008a).

- **Sorting by activity and type (method of treatment and storage)**

Operational waste with a dose rate below 100 μGy/h is sorted in special two-sorting equipment. In the first stage in the so-called carousel there is measuring and sorting of whole collecting containers. According to the surface dose rate the solid RAW can be divided into four groups:

1. to 1 μGy / h potentially releasable to the environment;
2. 3 μGy / h allow to 2-3 months decay and then measured again;
3. 3-20 μGy / h progressing to the 2nd degree of sorting;
4. above 20 μGy / h is considered as active waste (UJV Rez, 2008a).

In the second stage of sorting the content of the collection containers is sorted by hand into the active fragments and to the potentially releasable to the environment. The separated fractions are again concentrated in collection containers. For the small waste sorting there is a assumption of inactive part in a proportion of about 50%. Only about third of the active part exceeds the surface dose rate 100 μ Gy / h. Waste with a surface dose rate of more than 1 mGy / h occures only rarely. High-volume waste after decontamination usually has the character of inactive material (UJV Rez 2008a).

- **Processing RAW into a form suitable for storage**

Active waste is further treated by a low pressure molding, if necessary, it is fragmented and fixed by bituminization in order to be inserted into the storage container (200 L drum) (UJV Rez 2008a).

- **Transport to storage, storage and export to the environment**

Before transportation to the repository Dukovany treated waste is stored in the special rooms. Waste, sorted as potentially releasable to the environment, is stored separately. Transport of treated radioactive waste to a repository has to be in a compliance with the requirements for the transport of hazardous waste according to European Agreements on international highway/ railway transport of dangerous materials, valid in the Czech Republic. Waste sorted out as potentially releasable to the environment (with dose rate of less than 1 $\mu$ Gy / h ) demonstrated the possibility of the disposal into landfill or used as secondary raw materials (UJV Rez 2008a).

- **Management of high-level RAW**

Excore and incore measuring sensors of the reactor and cartridges of surveillance samples are considered as a high-level RAW. This type of waste is not possible due to increased activity, dispose in the repository. They can be stored only in sealed envelopes in the storage of high- level active radioactive waste. Liquidation of this storage is expected to perform in the decommissioning process of the power plant after ending of its operation (UJV Rez 2008a).

### 3.2.3 Technology systems of management of gaseous radioactive waste

The basic source of the activity of gaseous media comes from the water of the primary circuit (assuming a 1% coverage violation fuel cell fission gases). Gaseous radioactive waste are air mass of active technological systems after processing and air mass from a rooms of controlled zone of NPP which is contaminated with radioactive gases and aerosols. Their activity does not allow uncontrolled discharge into the environment. Contaminants are mainly $^3H$ and radionuclides Xe, Kr, Ar, C, N, halogen, Ru, and Te. The biggest sources of the gaseous radioactive waste activities (primarily gaseous fission products) are auxiliary systems of the primary circuit. Air from these systems is fed to the purification technological system of venting. Other sources of gaseous radioactive waste are purified in the ventilation systems with filtration. Treatment of gaseous radioactive waste involves separation of radioactive substances from contaminated air mass by filtration or retention on a suitable adsorbent material for a significant decline of their activities. Gaseous radioactive wastes are therefore consists mainly of radionuclide noble gases, tritium radioactive aerosol, radionuclides of iodine and other halogens. Design activity value of gaseous effluents from the NPP is expected to be 1,59 x $10^{15}$ Bq / year. The measured discharge values of most radionuclides are below the calculated design values (UJV Rez 2008a).

## 3.3 Radioactive waste repository

Management of RAW includes also disposal of RAW. Disposal of radioactive waste is the final step in a long sequence of carefully controlled activities, which include the collection and sorting of waste, storage, processing, and transportation. The main purpose of these activities is to protect humans and the environment. That is the reason why radioactive waste is need to be isolated from the environment and biosphere for such a long time until radioactive substances fall apart by spontaneous processes to other stable substances. For this purpose - the isolation of radioactive waste at the required time – the radioactive waste repository is used.

The RAW groups mentioned in the chapter 3.2 could be contaminated with artificial radionuclides (there are created by the action of neutrons , charged particles and gamma radiation on the atom of stable elements or by fission of nuclei of heavy elements) or could contain natural radionuclides ($^{226}$Ra, $^{232}$Th). These classifications also lead to build a repository with different constructions and type of isolation. That's why currently in the Czech Republic there are three repositories in operation: the largest repository Dukovany, the Richard by Litomerice is smaller and smallest is Bratrstvi by Jachymov. Dukovany repository has design comparable to similar constructions in Western countries. Low-and intermediate-level active waste generated by NPPs Dukovany and Temelin are stored here. Institutional waste contaminated with artificial radionuclides is stored in the repository of radioactive wastes Richard. Institutional waste containing natural radionuclides is disposed in Bratrstvi repository. I will be focused on the repository Dukovany, how it facilitates the low-and intermediate-level active waste from current both CZ NPP (SURAO,2013a; SUJB 2008).

### 3.3.1 Dukovany

The Dukovany repository was built for the disposal of the low-level and intermediate-level radioactive waste generated by the nuclear power sector. This state-owned repository, covering 1,3 hectares, is situated at the Dukovany nuclear power plant site near Trebic. At present, drums in repository are containing operational radioactive waste principally from the Dukovany and Temelin NPPs. The 55 000 m$^3$ storage space (which can accommodate approximately 180 000 drums) provides enough capacity for all the operational waste generated at both CZ NPP, even if their design life were to be extended to 40 years. The Dukovany repository consists of 112 shallow reinforced concrete vaults arranged in four rows of 28 vaults each. Each vault can accommodate approximately 1600 individual 200-litre drums. When the vault is full, the space between the drums is filled with concrete backfill and the vault covered with a thick sheet of polyethylene. Each vault is covered with a thick concrete panel. When the repository finally reaches full capacity, the vaults will be covered by a number of insulating and drainage layers. The repository is then closed and guarded. The impact on the surrounding environment is constantly monitored (SURAO, 2009).

"*The undesirable release of radioactive materials from the repository site into the surrounding environment might occur as a result of water flow through the site. In order to prevent such an occurrence, a system of engineered barriers has been installed. This system consists of insulating layers isolating the inner space of the vaults from the surrounding environment, i.e. the vault's concrete walls, the concrete backfill that surrounds the waste drums within the emplacement vault, as well as the drums themselves and the bitumen with which certain waste is mixed. In addition to these engineered barriers, natural barriers, i.e. the geological properties of the repository site, also protect the surrounding environment. The Dukovany repository is sited on impermeable Quaternary clay sediments. Since the repository is of the above-ground type, there is no threat of groundwater penetration. Two drainage systems have been built at the repository with the purpose to monitor the isolating capacity of the repository. These systems are designed to collect water from the immediate vicinity of the repository in a retention tank where its radioactivity level can then be checked. Should the water be found to be contaminated, it will be handled as waste water from a nuclear power plant"* (SURAO, 2009).

Character of the RAW which is disposed in the repository Dukovany are:

- packing set with bitumen product;
- packing set with non-fixed waste;
- packing set with used ion exchange resin fixed into SIAL matrix;
- packing set with institutional waste (SURAO, 2009).

- **The safety of the repository**

Safety is ensured by the compliance of limits and conditions of safe operation and disposal. Compliance of these requirements is ensured by long-term isolation of radionuclides in repository, secured with multibarrier system. With the compliance of the limits and conditions of safe operation , both operational and long term safety of the repository are ensured in terms of the requirements of the legislation, i.e the protection of workers, the population and the environment. Safety in the operating period is documented by monitoring of workers, workplaces and surroundings. Power values of effective dose and volume activity values in boreholes are measured in the vicinity of the repository area. Every of requirements of the acceptability RAW into repository Dukovany are specified with following information: aim, limit requirement or limit requirements for certain RAWs parameter, validity, activity, requirements for control and operational directive (SURAO, 2012).

- **Total activity of radionuclides in the repository**

The aim is except the disposal of waste with activity and amount which could cause default limits of people exposure, requirements of disposal of RAW and requirements of safe operation of repository. The limit condition shows that total inventory of chosen radionuclides disposed in one sump or in two double-rows has not to exceed values which are define in table 1, Appendix 1. Institutional RAW values have not to exceed values which are noted in table 4, Appendix 1 (SURAO, 2012).

- **Activity of radionuclides in RAW**

The aim is the same as in total activity of radionuclides in repository. Limit requirement described that the volume of RAWs accepted for disposal into repository cannot be higher than values illustrated in table 5, Appendix 1 (SURAO, 2012).

- **Power values of effective dose on the surface of packaging set with RAW**

The aim is to limit power values of effective dose on the surface of packaging set with RAW in correspondence with requirements on protection of radiation workers when they are working with equipments. Limit requirement is that values of effective dose rate have not to be more than 12mSv/hour (SURAO, 2012).

- **Leachibility**

Process of leaching is based on a movement of radionuclides from radioactive waste fixed with bitumen into leaching medium. The quality of product is characterized by small migration of radionuclides from product to surroundings. Migration depends on the shape of sample and on its content, temperature and quality of leaching medium and on a time of leaching. Limit conditions:

a) Leachibility of bitumened and vitrified waste: The leaching test for vitrified or bituminized RAW cannot give higher values of the ratio of radionuclides released into the solution than given in table 6, Appendix 1;

b) Leachibility of RAW fixed with cement or aluminosilicate matrix: For waste fixed with cement or aluminosilicate the leaching test cannot give higher values of the ratio of radionuclides released into the solution than given in the table 7, Appendix 1 (SURAO, 2012).

### 3.3.2 Deep geological repository

Most low-level radioactive waste is usually sent to land-based disposal immediately following its packaging for long-term disposal. Focusing on intermediate-level waste and high-level waste, many long-term waste management options have been investigated worldwide which seek to provide publicly acceptable, safe and environmentally friendly solutions to the management of radioactive waste. Some countries such as Czech Republic are at the beginning of their investigations. Experts agree that repositories located in deep geological formations are the most suitable place for the disposal of spent nuclear fuel and high-level waste. "*It is expected that such geological formations, in combination with an engineered barrier system, will ensure sufficient isolation of the waste from the environment for tens of thousands to hundreds of thousands of years over which time the risk such waste poses to the environment will decrease to the natural level"*( SURAO, 2013a).

Both Czech NPPs Dukovany and Temelin will produce approximately 4000 tons of spent nuclear fuel during their 40-year design lifetime. Spent nuclear fuel is currently stored in so-called interim storage facilities. Even if spent fuel is re-used, it does not mean that deep repositories will not be required. The volume of waste to be disposed of will naturally be lower as will be the risk to the environment. Thus, the planned repository will be used more efficiently. In any case, a certain amount of spent nuclear fuel and other high-level waste will still need to be disposed of (SURAO, 2013a; WNA, 2013b).

### 3.3.3 Deep Geological Repository Concept in the Czech Republic

In the Czech Republic, spent nuclear fuel after its removal from the reactor is currently stored to the wet storage facility and then it is transferred to a dry storage facility. Both facilities are located at the Dukovany NPP. In the open nuclear fuel cycle (without reprocessing) spent nuclear fuel is the main waste material. Spent fuel requires long-term storage. The deep geological repository project counts with the disposal chambers which will be constructed in a stable geological formation at a depth of approximately 500 and waste will be placed in special long-lifetime containers. The underground disposal chambers and the waste disposed of in them will not have any impact on above-ground activities and environment. The disposal chambers will be connected with the above-ground area. The necessary technical facilities will be constructed within the repository’s above-ground premises. The disposal containers will be very crucial in the long-term safety of the repository and must comply with a number of exacting requirements, e.g. long-term impermeability, chemical and stress resistance etc. The geological repository will most likely be constructed in a granite rock mass or a similar rock environment made up of gneiss which are suitable for geologic conditions in the Czech republic. Most importantly, it will be constructed in a seismically stable area (SURAO, 2013a).

The underground and surface layouts are shown in Fig. 7 and Fig. 8.

“*In addition to the structures shown in the figures, an operations building, buildings to house workers, an administration building, an information centre, roads etc. will be necessary to service the repository most of which will be located in the so-called non-active zone; the active zone is provided with special sophisticated safety protection”*( SURAO, 2013b).

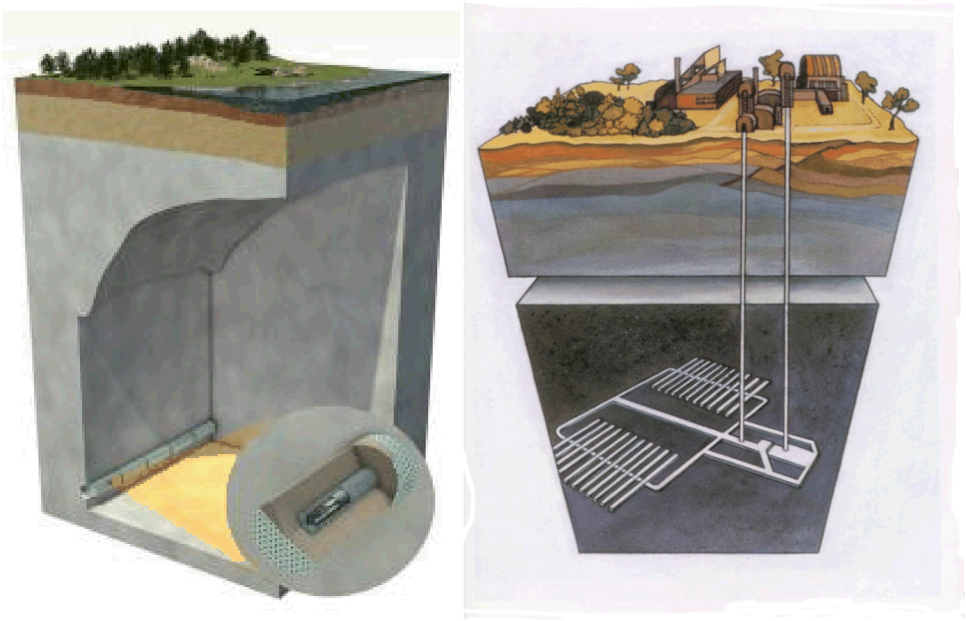


**Fig. 7** Model of the planned Czech deep repository (SURAO, 2013b)

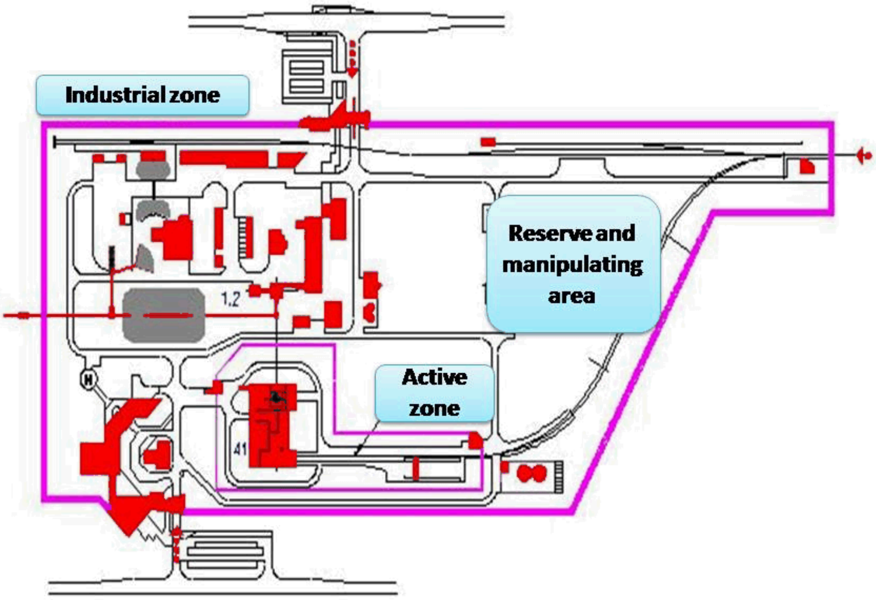


**Fig. 8** Repository above-ground area (SURAO, 2013b)

*“The underground area comprises access and ventilation shafts, tunnels and disposal chambers. A major part of the underground area is made up of a complex network of galleries in which spent nuclear fuel containers will be placed. The containers will be arranged both vertically beneath the disposal gallery*

*and horizontally in the gallery walls. The access galleries will gradually be sealed to prevent any contact between the underground chambers. A system of multiple barriers will be constructed; repository safety must be at such a level that the system will function even in the event that one of the barriers loses its isolation capability. Spent nuclear fuel and high-level waste containers will be surrounded by sealing materials (bentonite) and placed in chambers excavated in the host rock at a depth of approximately 500 metres"* (SURAO, 2013a; SURAO, 2013b).

## 3.4 Reactors of the Generation III and III+

Several generations of reactors have been distinguished. Generation I reactors were developed in 1950-60s, and outside the United Kingdom none of them are still running today. Generation II reactors are common nowadays almost everywhere in the world. So-called Generation III (and III+) are the Advanced Reactors. The first are in operation in Japan and others are under construction or ready to be ordered such as in the Czech Republic. Generation IV designs are still on the drawing board and will not be operational before 2020 at the earliest (CEZ, 2013a).

So-called third-generation reactors have:

- a standardized design, reduce capital cost and reduce construction time;
- a simpler design;
- higher availability and longer operating life - typically 60 years;
- further reduced possibility of core accidents;
- resistance to serious damage that would allow radiological release from an aircraft impact;
- as nuclear power plants do not emit $CO_2$, other greenhouse gases, dust and other pollutants, which means that they do not contribute to global warming or pollute the air;
- higher burn-up to use fuel more fully and efficiently and reduce the amount of waste;
- greater use of burnable absorbers ("poisons") to extend fuel life (CEZ,2013a).

The original project of the Temelin NPP has already been designed for four units. The investment project to build a plant in Temelín with the installed capacity of 4 x 1000 MW was approved in February 1979. The first project was designed by Energoprojekt Prague in 1985 and the construction of operating buildings commenced in 1987. After November 1989, under new political and economic conditions, a decision to reduce the number of units to two was made (CEZ, 2013a). The nuclear power units currently operating have been found to be safe and reliable, but they are being superseded by better designs. The addition of two units (Unit 3 and Unit 4) to the Temelin NPP serves as an example for the further design development of the NPP. Furthermore, it represents a fulfillment of the electricity consumption capacities in the Czech Republic (CEZ, 2013b).

Several options of the most modern PWR reactors have been considered for completion of the Temelin NPP. They are designs of III and III+ generation. According to CEZ there are following reasons for selection of PWR:

- *"Worldwide expansion of nuclear power plants with PWR reactors"* (CEZ, 2013c).
- *"Designs of so-called III and III+ generation tested with 50-year operation and improved in relation to current safety standards"* (CEZ, 2013c).
- *In process construction of such designs in Europe and elsewhere in the world"* (CEZ, 2013c).
- *"Experience of the CEZ Company with operation of this type of power plant - Dukovany and Temelin are PWR of generation II"* (CEZ, 2013c).
- *"Power corresponding with optimal utilisation of the current Temelin location and needs of the Czech Republic for future years, including extending possibilities of power regulation"* (CEZ, 2013c).

### 3.4.1 MIR 1200-Atomstroj

Reference AES-2006 (at present MIR 1200) contains a design which is derived from the WWER 1000 type reactors. It is a PWR reactor design developed by the Atomstroyexport and Gidropress companies (under Russian licence). The design of AES-2006 of Generation III+ with V-491 reactor is an evolutionary development of the designs with the WWER-1000 water cooled and water moderated reactor proved by a long-time operation. The AES-2006 design is based on the principle of safety assurance for the personnel, population and environment. The principle meets the requirements for the standards of radioactive substance releases into the environment and their content at normal operation (Gidropress, 2011).

The design concept is shown in tab.2. The integrity of MIR 1200 design is based on the following technologies:

- optimized safety system configuration;
- digital Instrumentation & Control system;
- increased turbine plant efficiency;
- higher fuel utilization (Gidropress, 2011).

The performance of MIR-1200 has following advantages:

- finalized design in full compliance with European rules and standards ;
- life cycle up to 60 years;
- minimum quantity of production waste, especially radioactive waste;
- life time of non-interchangeable equipment not less than 60 years;
- self-protection from accidents;
- using non-changeable part of the design to ensure constructability of entities within a wide range of environmental conditions and unification of the main and auxiliary equipment (Gidropress, 2011; JSC, 2011).

MIR 1200 the highest priority is to contribute to the global greening, to minimize nuclear power externalities, and to establish base for environmentally friendly energy-mix development (Gidropress, 2013; JSC, 2011).

| Parameter | AES 2006 |
|---|---|
| Nominal electric power, MWe | 1198, 8 |
| Number of loops in the primary circuit | 4 |
| Effective hours of nominal power use, hours/year | 8065 |
| Number of fuel assemblies in the core | 163 |

**Tab. 2** Design concept of MIR 1200 (JSC, 2011)

Each Power Unit of MIR 1200 consists of a V-491 reactor unit with a PWR reactor with electric power more than 1195 MW. It has a double-loop thermal circuit. The reactor plant includes following main equipment and systems:

1. pressurized water vessel reactor with thermal power 3200 MW with heat exchanger pressure, the water with boric acid is the heat exchanger and the moderator in the reactor;
2. 4 horizontal steam generators;
3. four reactor coolant pump sets;
4. main circulation pipeline;
5. pressure compensation system;
6. equipment of reactor concrete vault;
7. safety systems ( JSC, 2011).

The secondary circuit is not radioactive and includes steam generators, main steam pipelines, one turboset, their auxiliary equipment and service systems, equipment for deaeration, heating and supply of feed water to the steam generators (JSC, 2011).

**Reactor coolant system** - system removes the heat from the reactor core by coolant circulation in a closed circuit and provides heat transfer to the secondary side.

*"The reactor coolant system comprises a reactor, a pressurizer and four circulation loops, each one comprising a steam generator, reactor coolant pump set and main coolant pipelines that provide the loop equipment-to-reactor connection. A steam generator links the primary and the secondary sides. The steam generator headers and heat-exchange tubes are a barrier between the primary coolant and the working medium of the secondary side"* (Gidropress, 2011).

**Reactor core -** The reactor cores contain 163 fuel assemblies (FA). The FAs are constructed for heat generation and its transfer from the fuel rod surface to coolant. Each FA contains 312 fuel rods. Then $UO_2$ pellets with a 5% maximum enrichment are inside the cladding (JSC, 2011).

**The reactor -** is a vertical high-pressure vessel with a cover (head). It contains reactor internals, the core, control rods and in-core instrumentation sensors. The reactor is intended for converting the nuclear fuel energy into thermal energy and to transfer the thermal energy to primary coolant of double-circuit reactor plant of an NPP power unit (JSC, 2011).

The reactor is located in the concrete cavity with a shielding and a cooling system. The reactor design is given in the following  Figure 9.

1 - In-core instrumentation detectors
2 - Upper unit
3 - Protective tube unit
4 - Core barrel
5 - Core baffle
6 - Surveillance specimens
7 - Core
8 - Nuclear reactor vessel

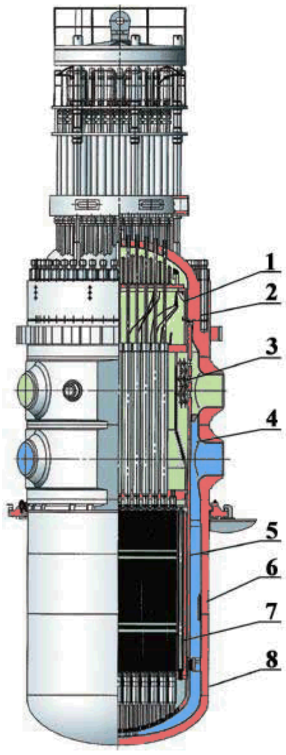


**Fig. 9** MIR 1200 reactor design (JSC, 2011)

**Steam generator-** removes heat from the primary circuit coolant and generates the saturated steam. The steam generator is a horizontal heat exchange apparatus with heat exchange surface consisting of horizontally positioned pipes, distribution system of main and emergency feed water, submerged plate and steam collector (JSC, 2011).

**Pressurizer -** includes steam pressurizer with a set of electric heaters, 3 safety devices, bubbler and pipelines with valves. "*The main function of the system is pressurizing the primary circuit, maintaining pressure under steady-state conditions, limiting pressure variation under transient and emergency conditions and reducing pressure in the primary circuit during cool-down"* (JSC, 2011).

The following safety systems are provided to restrict the damage of the reactors:

- protective systems;
- localizing systems;
- supporting system;
- control systems (JSC, 2011).

**High and low pressure emergency injection system,** "*is used for boric acid solution supply to the reactor coolant system in the case of loss-of coolant accident exceeding the compensating capacity of the normal make-up system at pressure in the coolant below system working pressure*" (JSC, 2011).

**Residual heat removal system -** is system which provide residual heat removal and reactor plant cool down during the power plant regular shutdown. It also provides conservation of integrity of the primary circuit (JSC, 2011).

### 3.4.2 Areva EPR reactor

Another type of the reactor which is considering as the most suitable for completion of the Temelin NPP is Areva EPR reactor. It is a PWR reactor design developed by the AREVA Company as an improvement on the N4 and Konvoi reactors which are currently operated in Germany and France. It is licensed in the country of origin i.e. in France, Finland and also China (CEZ, 2013c).

The EPR reactor has an electrical production capacity of 1650 MWe, which shows that the reactor takes place among the most powerful reactors in the world (Areva, EDF, 2012).

The EPR reactor has following innovations:

- an enhanced defence-in-depth approach which increased protection for surrounding environment;
- a reactor vessel made for resisting aging by the optimised steel;
- a reduction in effluent release (including radioactive and chemical) and radioactive waste;
- a significant reduction of radioactive releases in accident situations;
- operator friendly human-machine interface (Areva, EDF, 2012).

These innovations contribute to the high level of performance, efficiency, operability and economic competitiveness of the EPR reactor. The EPR reactor uses less uranium resources and produces less long-lived radioactive wastes when compared with the water reactors which are in the operation today (Areva, EDF, 2012).

Safety and operational performance of EPR reactor are ensured by drastic reduction of the probability of accidents and their consequences on the environment. An EPR power plant can operate with uranium enriched up to 5%, reprocessed uranium or MOX fuel. Economical competitiveness of electricity production is stated by the costs reduced by 10%, compared with current plants. The less production of the waste also contributes to the economical effectiveness. It is under construction in Finland (Olkiluoto), in France (Flamanville) and in China (2 units in Taishan), and is currently undergoing certification in the United States and the United Kingdom (Areva, 2013).

The EPR nuclear systems (see Fig. 10) include as other PWRs Reactor Coolant Systems, Secondary and Safety Systems. Thus:

- Reactor Coolant System;
- Fuel handling and storage system;
- Shut-down and reactivity control systems;
- Emergency Core Cooling systems, Containment cooling system, Chemical and Volume Control System, In-Containment Refuelling Water Storage Tank (Craig, Petit, 2012).

**The Reactor Coolant System** fulfils the following functions:

**a)** Control of radioactive release;

**b)** Heat transfer from the reactor - core cooling (Craig, Petit, 2012).

The main function of the Reactor Coolant System is to transfer heat from the reactor core to the secondary system, where steam is produced for use in operation of the turbine. Heat from the reactor core is transferred to the steam generators by the reactor coolant. Heat is exchanged with the feedwater in the steam generators, generating steam which is then routed to the turbine (Craig, Petit, 2012).

**c)** Neutron moderator

Neutron moderator is limiting the velocity of neutrons to the velocity of thermal range (Craig, Petit, 2012).

**d)** Reactor coolant pressure control

The pressure of the reactor coolant system must be greater than the saturation pressure corresponding to the temperature of the hot leg. This pressure difference is necessary to prevent a departure from nucleate boiling producing adverse impacts on heat transfer and reactivity control. Control of the reactor coolant pressure is achieved by the pressuriser (Craig, Petit, 2012).

The Reactor Pressure Vessel (RPV) contains the core with fuel assemblies. It contains the reactor core, the control rods, the neutron shield, and the supporting and flow directing internals (Ardron, Lonjaret, 2012).

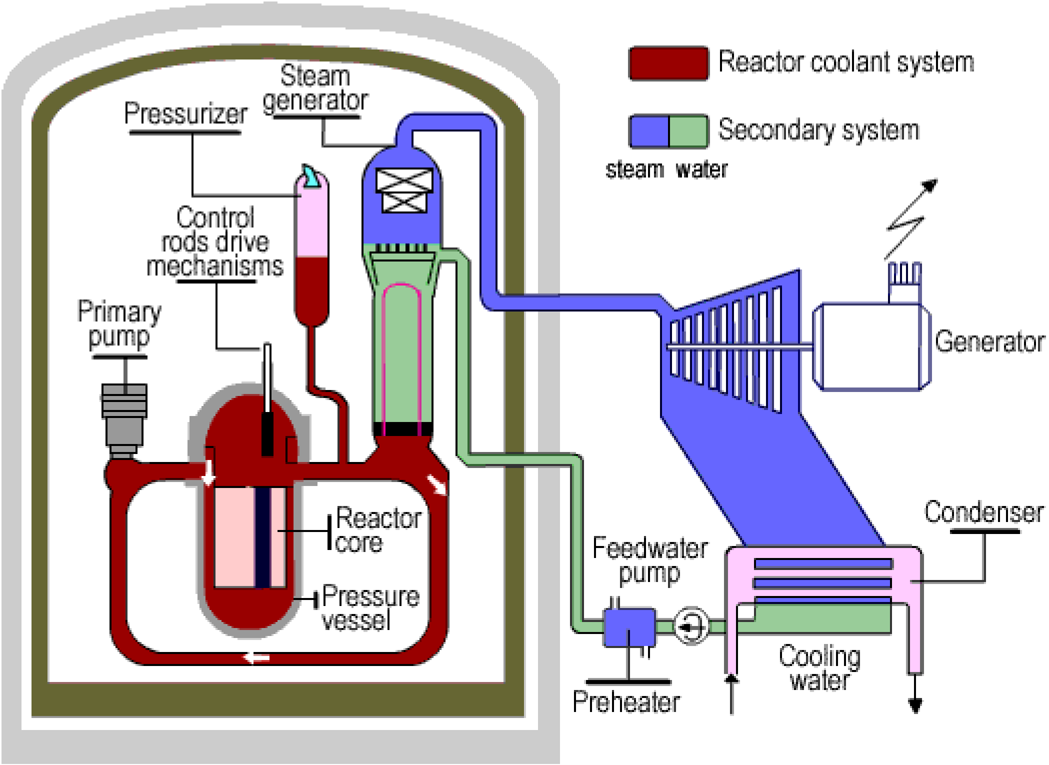


**Fig. 10** Areva EPR reactors coolant system and secondary system (Kable, 2014)

**Pressuriser-** provides pressure control and also serves as the coolant expansion vessel of the RCS (Craig, Petit, 2012).

**Steam Generators -** The SGs are vertical shell, natural circulation, U-tube heat exchangers with integral moisture separating devices. The heat conveyed by the reactor coolant is transferred to the secondary fluid through the tube walls of the tube bundle (Craig, Petit, 2012).

**Reactor core -** contains the nuclear fuel where the fission reaction, as in many other reactors, produces the energy. The reactor core consists of a specified number of fuel rods which consist of uranium or MOX (uranium plus plutonium) pellets. Each fuel assembly is made up of 265 fuel rods. The core is cooled and moderated by light water (Blair Page D., 2012).

**Safety systems** and functions have been designed according to the following principles:

- Simplification by separation of operational and safety functions;
- Strict physical isolation between buildings where the different safety systems are located (Ardron, Lonjaret, 2012).

### 3.4.3 AP 1000 (Westinghouse)

The AP 1000 design is a single, PWR which generates nominally 1117 MW of electricity (see tab.3). AP stands for 'advanced passive' which is showed in Fig. 11. It describes that the AP 1000 uses passive safety systems such as natural circulation and gravity. Westinghouse claims that, "the *AP 1000 safety systems are designed to mitigate the consequences of plant failures, ensuring the reactor shuts down, decay heat is removed, and releases of radioactivity are prevented."*(ONR, 2010; Westinghouse, 2012).

The AP 1000 design leads to several advantages:

- New design saves money and time with an accelerated construction time period of approximately 36 months;
- The AP 1000 simple design concept relies on the natural forces of gravity, natural circulation and compressed gases to keep the core and containment from overheating;
- Multiple levels of defense for accident mitigation are provided;
- Reduced radiation exposure and less production of waste;
- 60-year design life (Saiu G., Frogheri M.L., 2010).

Environmental consideration is also important for AP 1000 design. The safeties of the public, the power plant workers, and the impact to the environment have been ensured by following features:

- Operational releases have been minimized by design features;
- Aggressive goals for worker radiation exposure have been set and satisfied;
- Total radioactive waste volumes have been minimized;
- Other hazardous waste (non-radioactive) has been minimized. (Saiu G.; Frogheri M.L., 2010**)**.

The AP1000 design is derived directly from the AP 600, a 2-loop, 600 MWe PWR. The Westinghouse AP 1000 Program implements the AP 1000 plant to provide a further improvement in plant economics and also try to maintain the passive safety advantages established by the AP 600 (Saiu G.; Frogheri M.L., 2010).

**The reactor coolant system** (RCS) : "*The system consists of 2 heat transfer circuits each with a single hot leg and two cold legs, a pressurizer, a steam generator, and two reactor coolant pumps installed directly onto the steam generator*" (Saiu G., Frogheri M.L., 2010).

| Parameter | AP 1000 |
|---|---|
| Net Electrical Power, (MWe) | 1117 |
| Reactor Power, (MWt) | 3400 |
| Hot Leg Temperature, (°C) | 321 |
| Number of Fuel Assemblies | 157 |
| Type of Fuel Assembly | 17x17 |

**Tab. 3** Selected AP1000 Parameters (Saiu G., Frogheri M.L., 2010)

**Reactor core and fuel design -** In the reactor core, the uranium oxide fuel (enriched up to 5% of $^{235}U$*)* is cooled by water in a the primary circuit. This water also acts as the neutron moderator (ONR, 2010).

Fuel performance improvements include grids, removable top nozzles, and longer burnup features (Saiu G., Frogheri M.L., 2010).

**Reactor pressure vessel** – The reactor vessel is the high-pressure containment boundary used to support and enclose the reactor core (Saiu G., Frogheri M.L., 2010).

**Steam generators -** 2 steam generators are used in the AP 1000 plant. " *Steam generator design enhancements include hydraulic expansion of the tubes in the tubesheets, tube support plates, improved anti-vibration bars, upgraded primary and secondary moisture separators, enhanced maintenance features, and a primary-side channel head design that allows for easy access and maintenance by robotic tooling*" (Saiu G., Frogheri M.L., 2010).

**Pressurizer** - The AP 1000 pressurizer is of conventional design, based on proven technology. The large pressurizer leads to the more reliable plant. (Saiu G., Frogheri M.L., 2010).

**Reactor coolant pumps** – *"The reactor coolant pumps are highly-reliable, low maintenance, hermetically sealed canned-motor pumps that circulate the reactor coolant through the reactor core, loop piping, and steam generators"* (Saiu G., Frogheri M.L., 2010).

**Main coolant lines -** Reactor coolant system piping is ensured by two identical main coolant loops, each employing a hot leg pipe to transport reactor coolant to a steam generator. Two cold leg pipes in each loop (one per pump) transport reactor coolant back to the reactor vessel to complete the circuit (Saiu G., Frogheri M.L., 2010).

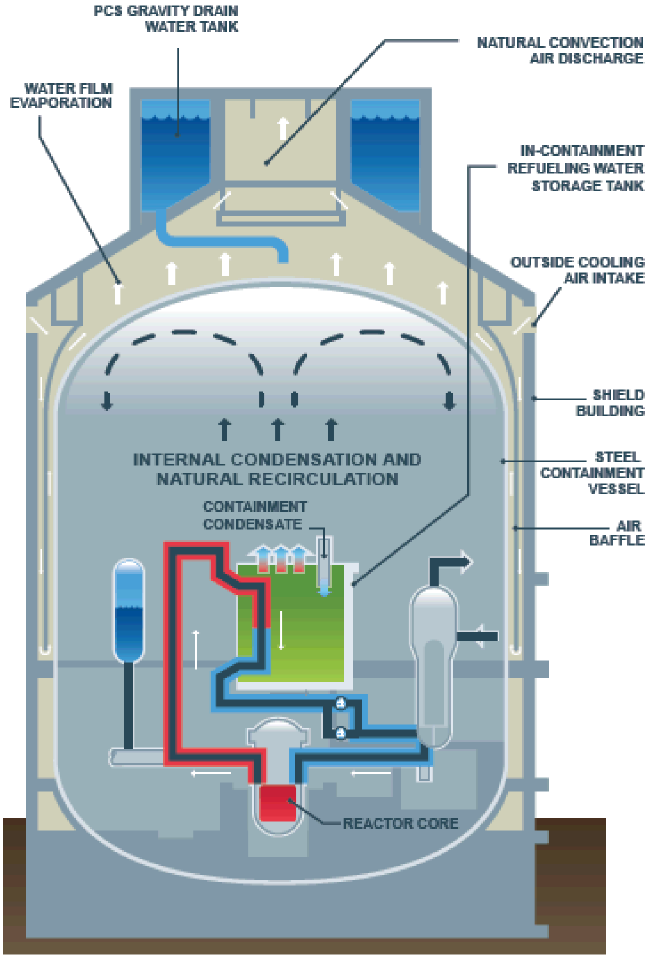


**Fig. 21** AP 1000 Passive Containment Cooling System (Westinghouse, 2011)

## 3.5 Waste from MIR 1200, AP 1000 and EPR reactors production

### 3.5.1 Waste from MIR reactors production

***Liquid RAW management*:** The NPP design count with the systems for collection, reprocessing and temporary storage of liquid radioactive media in all the station operating conditions. Thus:

- dedicated sewage system;
- sump water recycling system;
- liquid radioactive media intermediate storage system (Gidropress, 2011).

The requirements which are noted below were taken into account in designing the liquid radioactive media recycling systems:

- reduction the total volume of the liquid radioactive media;
- reduction in the volume of liquid radioactive waste for temporary storage to be sent to the solidification plant for subsequent burial in the storages;
- reduction in the volume of disbalanced water in the controlled area (Gidropress, 2011).

The liquid radioactive media that are collected in the system of intermediate storage comprise:

- salt concentrate from the evaporation plants;
- spent ion-exchange resins(filtering materials);
- crud (Gidropress, 2011).

***Solid RAW management:*** Solid RAW comprise of the followings:

- Overalls, footwear, means of individual protection not to be subjected to decontamination; construction and thermal insulation materials;
- gas purification and venting system filter components;
- solidified liquid radioactive media (Gidropress, 2011).

*"At all the stages of the NPP service life management of all kinds of RAW has been arranged to ensure safety at their transportation and storage. To reduce their volume before they go to the storage the solid RAW are subjected to treatment: chopping, burning, pressing"* (Gidropress, 2011).

***Gaseous RAW management system**:* The system of gaseous radioactive waste management comprises the special venting systems and gaseous radioactive blowdown decontamination system. The system of the process blowdown decontamination is designed to reduce the releases of radioactive inert gases, gaseous compounds of iodine and aerosols from the gas blowdowns of the process equipment in reactor compartment to permissible levels (Gidropress, 2011).

### 3.5.2 Waste from AP 1000 production

***Liquid RAW system***: includes tanks, pumps, ion exchangers, and filters. According to Westinghouse, the liquid system is designed to process, or store radioactively contaminated wastes in four major categories:

- Borated, reactor-grade, waste water – *"this input is collected from the reactor coolant system effluents, primary sampling system sink drains and equipment leak offs and drains"* (Westinghouse, 2007). *;*
- Floor drains and other wastes –*" with a potentially high suspended solids content - this input is collected from various building floor drains and sumps"* (Westinghouse, 2007). *;*
- Detergent wastes – *"this input comes from the plant hot sinks and showers, and some cleanup and decontamination processes. It generally has low concentrations of radioactivity"* (Westinghouse, 2007).*;*
- Chemical waste –*" this input comes from the laboratory and other relatively small volume sources. It may be mixed hazardous and radioactive wastes or other radioactive wastes with high dissolved-solids content"* (Westinghouse, 2007).

***Gaseous RAW system***: During reactor operation, radioactive isotopes of xenon, krypton, and iodine are created as fission products. A part of these radionuclides is released to the reactor coolant because of a small number of fuel cladding defects. Leakage of reactor coolant can result in a release to the containment atmosphere of the noble gases. Chemical and volume control system removed iodine by ion exchange (Westinghouse, 2007).

***The solid RAW system*** "*is designed to collect and accumulate spent ion exchange resins and deep filtration media, spent filter cartridges, dry active wastes, and mixed wastes generated as a result of normal plant operation, including anticipated operational occurrences"* (Westinghouse, 2007).

### 3.5.3 Waste from EPR reactor production

Areva has indicated that six operational intermediate-level waste streams could potentially arise from normal operation of an EPR:

• Ion exchange resins – *"organic resins that arise from the clean-up of primary circuit water and water from the Liquid Waste and spent fuel Treatment Systems"* (NDA, 2014)*;*

• *Spent cartridge filters (ILW+ LLW) – "filters from the clean-up of primary circuit water and water from the Liquid Waste and spent fuel Treatment Systems"* (NDA, 2014)*;*

• *Operational wastes >2mSv/hr – "a range of materials, including contaminated metal, plastics, cloth, glassware and rubble, arising from operations during planned shutdown periods (hence 'operational wastes'); – filters, similar to, but typically smaller in size than spent cartridge filters (ILW)"* (NDA, 2014)*;*

• *Wet sludges – sludges - "arising from cleaning the bottoms of liquid waste treatment tanks and various sumps"* (NDA, 2014)*;*

• *Evaporator concentrates –"residues from the evaporation of waste water"* (NDA, 2014).

Specialists from UJV Rez simplified the division of the liquid and solid RAW. Liquid RAW is divided into concentrate, sludges, sorbents and others. Solid RAW consist of many materials which is classified into pressable, combustible, non - pressable and others. Contaminated oils belong to the others liquid RAW and spent filters belongs to others solid RAW (UJV Rez, 2014).

## 3.6 Technology of the RAW treatment in the Czech Republic and abroad

Quantity, type and characteristics of the waste produced from existing sources and a realistic estimation of the waste production from envisaged resources are important for determination and selection of the strategy for RAW treatment. The selection of the most suitable technology is based on the total evaluation of the technology which include:

- Technological aspects - includes power, volume reduction factor and frequency of use of technology;
- Economical aspects - investment costs, operational costs;
- Safety and impact on the environment- demand of the technology from the radiation protection point of view, classical safety and impact on the humans health and the environment (UJV Rez, 2008b).

Total evaluation of all these aspects on the target technology for different kind of waste is listed in the tables 8- tab. 13. The lower number of the evaluation has the target technology, the better and effective the technology is. The range of the total evaluation is between 0-9. From tab 8 - tab. 13 the best technology reach the total evaluation number 6, 75. The lowest evaluation number is 3,45 (UJV Rez, 2008b).

### 3.6.1 Technology used in the Czech Republic

In the Czech republic 7 basic technologies and their combination are using for the RAW treatment:

1. Fixation into inorganic binder material (cementation, geopolymerization)
2. Bituminization
3. Low-pressure molding
4. High-pressure molding
5. Combustion
6. Fragmentation
7. Metal melting (UJV Rez, 2008b).

Combustion, high-pressure molding and metal melting are the technologies which are provided by the foreign companies' .These technologies result in the final product which is suitable for the Czech repositories (UJV Rez, 2008b).

**1. Fixation into inorganic binder materials:**

The method of fixation into inorganic binder materials includes two processes:

- cementation
- geopolymerization (UJV Rez, 2008b).

Cementation is the fixation of radioactive waste into cement (concrete) matrix. There is a difference in the cementation of solid and liquid radioactive waste. While the aqueous liquid radioactive waste are mixed directly with cement to form a cement slurry, solid radioactive waste are shed by previously prepared cement (concrete) slurry which can be active or inactive. Geopolymerization is using for the immobilization of RAW by the reaction of activated aluminosilicate in an alkaline aqueous solution. It is a polycondensation reaction of aluminosilicate and it forms a siloxane-sialate network which is composed of tetrahedron of silicon and aluminum. Alkali-activated materials (geopolymers) can be prepared from different precursors. The most frequently used are the solutions of Na(K)OH, $Na(K)_2CO_3$, $Na_2SiO_3$ (UJV Rez, 2008b). Application:

- Concentrate treatment
- Liquid RAW treatment
- Solid RAW treatment
- Sludges and ion exchange resins treatment

Technology of the cementation is very famous and suitable for the treatment of concentrates from the operation of NPP of WWER type (Jaslovske Bohunice, Slovakia). Cementation is used for the treatment of all operational RAW except organic liquids (e.g. contaminate oils). A certain disadvantage also seems a low reduction factor in comparison with bituminization. It slightly increases the volume of the final product. The advantage of the geopolymerization is greater capacity for immobilization of soluble salts in comparison with cementation. Financially it is more expensive than the "classic" cements. In the Czech Republic is this technology used in NPP Temelin. NPP Temelin is using aluminosilicate matrix SIAL for the fixation of sludges and ion exchange resins from the active technological waste waters (UJV Rez, 2008b).

### 2. Bituminization

Bitumination is the heat hardening process during which the liquid RAW is added into molten bitumen or into the preheated bitumen emulsion. Evaporation of the water contained in RAW is occurred at temperatures of 160-200 °C. The resulting salts together with radionuclides are remaining fixed in the bituminous matrix. Bituminization is used for the fixation of concentrates, sludges and ion exchange resins. In comparison with cementation the reduction factor is 2-3 times higher. On the other hand this technology is characteristic by high cost per matrix . Although this technology is used in the Czech Republic, use of this technology abroad is not very common. The filling the drum with the bitumen product is illustrated in the following figure (UJV Rez, 2008b).

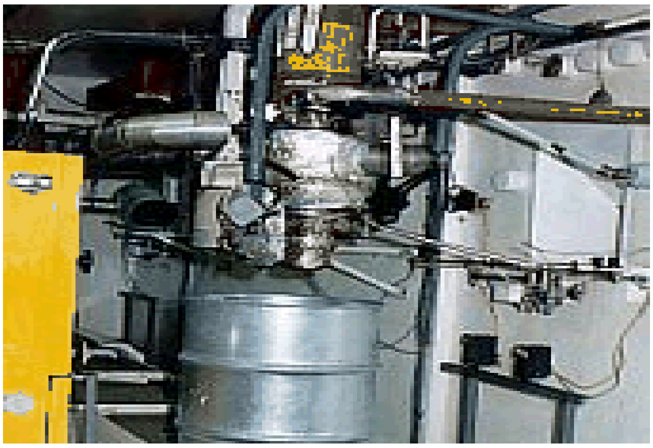


**Fig. 12** Filling 200l drums with bitumen product (CEZ, 2008)

### 3. Low pressure molding

Low pressure molding technology is based on compressing the waste in a barrel by using hydraulic, pneumatic or screw piston. Low-pressure molding machines (Fig. 13) are working with a pressing force up to 2000 kN . Application:

- Used protective equipment (contaminated gloves, sleeves, etc.)
- Pulp, paper, PE bags, thin-walled glass containers, insulating and sealing material
- Air insoles

Low pressure molding is an advanced technology for the WWER NPP including both Czech NPP. It is a technology with easy operation that is currently very well managed. The lower reduction factor is compensated with relatively low cost (UJV Rez, 2008b).

**Fig.13** Low-pressure molding machine from NUKEM Technologies (UJV Rez, 2008b).

### 4. Combustion

Combustion means a rapid exothermic reaction between the combustible material and oxygen. The final products of combustion are oxides of elements that are present in the combusted material. Application:

- Dry solid waste;
- Wet waste: ion exchange resins and filter cartridges;
- Liquid waste: organic liquids.

Combustion technology is now virtually the only method that can be recommended for processing the combustible radioactive waste including contaminated oils and resin. However, it is characterized by high investment and operating costs. The big advantage is the high volume reduction. The incinerator plant Studsvik (Fig.14) in Sweden provides combustion process of RAW for the Czechs NPP (UJV Rez, 2008b).

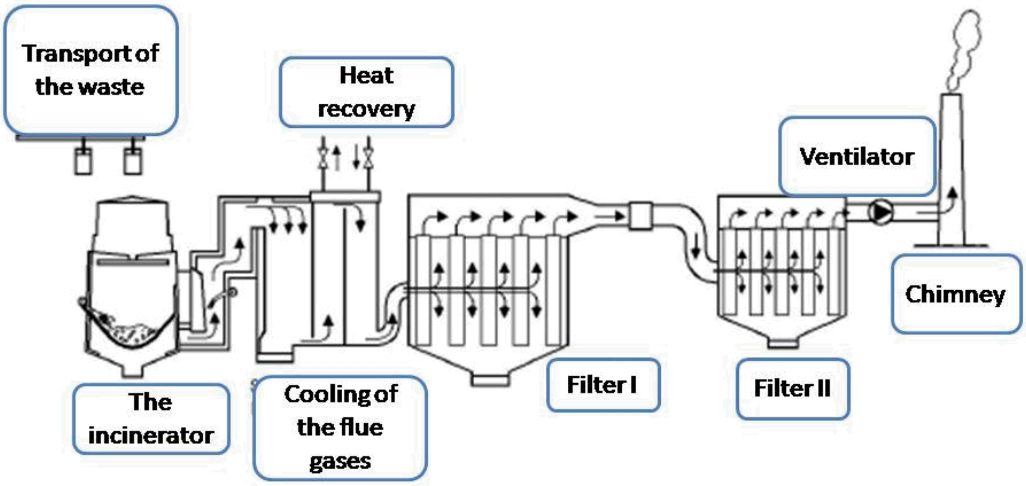


**Fig. 14** Incineration plant in Swedish Studsvik (UJV Rez, 2008b).

### 5. Fragmentation

Fragmentation means partitioning large size solid radioactive waste (tank, piping, greater technological units, pieces of concrete, etc.) into smaller pieces so that it can be further processed (compression, combustion, decontamination, etc.), or treated. Fragmentation is used for solid RAW (metal, plastic, etc.). It is only additional technology where is need for cutting large piece RAW that would otherwise could not be further processed or disposed to the repository. Fragmentation is widely used in all processing centers around the world (UJV Rez, 2008b).

### 6. High pressure molding

High pressure molding machine (pressing force up to 20 000 kN) compresses the entire standard metal barrel with embedded waste (Fig. 15). The resulting pellets are organized stacked in the bag for storage and in the package are fixed with cement. In the figure we can see a drum filled with the waste, and the drum after high - pressure molding**.** Application:

Dry solid waste:

- Ash and slag from incineration plants;
- All technological waste (scrap metal, construction materials, paper, wood, plastics, glass, filter materials, insulation, concrete, building materials, soil).

Wet waste:

- Non-combustible;

- Non-metallic filter media (UJV Rez, 2008b).

Thanks to the versatility, safety, high volume reduction processed waste, this method is very attractive. The use of this method in CZ would be highly advantageous, if there would be an appropriate legislative changes concerning payments from producers of waste from the nuclear energy for waste disposal in the repository. Nowadays, the high-pressure molding machine for the CZ is provided by the German company NUKEM (UJV Rez, 2008b).

**Fig. 15** Drum filled with the waste, and the drum after high-pressure molding (UJV Rez, 2008b).

#### 7. Metal melting

Melting of the metal is performed in the melting furnace. Metal RAW must be sorted according to each metal (melting point, the final product can be used as a secondary raw material) and fragmented in suitable proportions, so that they can be inserted into the furnace. The final product is homogeneous monolith (ingot). Some of the ingot can be directly released to the environment. This technology is suitable for the treatment of a big amount of metals. For the CZ NPP metal melting is provided by the Swedish company Studsvik Nuclear AB (UJV Rez, 2008b).

### 3.6.2 Promising technology using abroad

#### 1. Vitrification:

The principle of vitrification is the incorporation of radionuclides into glass matrix at temperatures of 1000 - 1200 ° C to form a homogeneous mixture. The mixture is then put into the package (cartridge), wherein the melt after cooling in the vitreous form is disposed in the repository. Another similar method is vitrification by the method of the “Cool Cup”. Both of these methods are used for the treatment of high-level RAW from the reprocessing of spent fuel. In the Czech Republic there is no potential NPP for reprocessing of the spent fuel. That is why these methods are not perspective in the Czech Republic (UJV Rez, 2008b).

**2. Reducing the volume of the concentrate**

The volume of saline (liquid) concentrate can be reduced in two ways: thickening or by separation of the radiocontaminants from boric acid. These principles essentially lead to the same result, to a reduction the amount of waste that is disposed in the repository. It is a good method for treatment of the concentrates from the evaporators and for boric concentrates. The final product for disposal (saline block, granules) requires quality package (HIC- high integrity container) which in the conditions of Czech NPP is not available yet (UJV Rez, 2008b).

**3. Drying in the drum**

Typically, 200 L of storage drum is filled with liquid waste, and the content is heated in a closed space where is progressively deprived of water. The liquid waste is added till the drums are filled by desiccated salts. Drum is then covered. Vapors are discharged into condenser and the condensate is treated as secondary waste. The metal drum do not meet the conditions for CZ storage (UJV Rez, 2008b).

**4. Pelletizing**

Pelletizing technology serves to strengthen the liquid radioactive waste. It is a drying of the liquid waste into a powder, converted into powder compact mold and cut into small pieces, shape reminiscent of pellets. Technological device is not yet commercially offered. Currently, this method cannot be considered as promising for the Czech Republic (UJV Rez, 2008b).

**5. Melting the mixed RAW in the melted metal**

Dry (metal, concrete, etc.), but also wet (e.g. ion exchange resins) radioactive waste are fed into a container in which the molten metal is located. Induction heating is ensured. The melting temperature ranges between 1500 - 1575 ° C. A major amount of radioactivity was found in the foam, which is collected from the surface of the molten metal. After cooling there is a formation of a solid slag. Small part of the radioactivity remains in the molten metal. The slag is stored as a low-level radioactive waste (UJV Rez, 2008b).

### 6. Plasma Arc Melting

This technological method ensures the temperatures around 20 000°C. It is possible by melting with electrical arc where electrical current is passing through two-atomic gas. In the Czech Republic there are no experiences with this technology (UJV Rez, 2008b).

### 7. Hot isostatic pressing

In this process, ion exchange resins are dried in the dryer into the resulting moisture content of 12% to 50%. Subsequently, the waste is filled into special metal cartridges and promptly transported to high-pressure press with heating device. Wastes with additives form pressure compact mass at the high temperatures. It is a difficult technological process and it is not economically suitable for the Czech Republic (UJV Rez, 2008b).

### 8. Compaction of plastic waste by melting

Polyethylene which contains from 15% of PVC and rubber is loaded in the bags in the standard 200 L drum. The drum is placed in isolated oven for 3-4 hours at 170-180 ° C until the waste is fully melted and compacted (UJV Rez, 2008b).

### 9. Molten Salt Oxidation

It is flameless oxidation process, which is an alternative to conventional combustion. Can also be used as a secondary system for cleaning the flue gas generated during combustion or pyrolysis . This technology is as the other high-temperature oxidizing technology financially very challenging (UJV Rez, 2008b).

### 10. Absorption

Use of superabsorbent polymer is based on the use of substances based on the sodium polyacrylate and compounds which are structurally similar molecules. Molecules are able to incorporate into their molecular structure large quantities of liquids. According to the type of waste and product features, this method is not suitable for liquid waste from the Czech NPP (UJV Rez, 2008b).

### 11. Selective absorption

Among one of the advantages of inorganic sorbents is their property to sorb the radionuclides selectively. Another advantage is also that inorganic sorbents are characterized by much higher selectivity than organic sorbents. The technology in the Czech Republic seems to be promising for the treatment of radioactive contaminated media but there would have to be solved the problem of dispose the product into the repository (UJV Rez, 2008b).

### 12. High integrity container (HIC)

HIC are storage units for low and intermediate active waste. These containers are made from high-dense polyethylene. The biggest advantage is the long durability of the material in comparison with metal storage units (drums) even in radiation field. The waste in HIC is not necessary fixed into matrix**.** In combination with some of the above described technology the HIC would be beneficial for storage with the processed RAW into repository, but there would have to be the licensing of this technology in the Czech Republic (UJV Rez, 2008b).

# 4 Methodology

As is mentioned above, almost every operation in the NPP leads to the production of different kind and amount of waste. Liquid radioactive media as well as solid and gaseous wastes are generated in the course of a NPP operation. The chosen reactors for the NPP Temelin completion (Atomstroj MIR 1200, EPR and AP 1000) produce different amount of the waste but with almost the same composition. It is important to choose right technology of the treatment to reduce the amount of waste but also the technology has to be in compliance with the waste composition and also the final waste product should meet the limits and requirements for the final disposal.

## 4.1 Chosen technologies for the waste treatment from MIR 1200, AP 1000 and EPR reactors

Technology for RAW treatment is different in performance, sensitivity to the type and to the composition of the treated waste .The chosen technology has to be in compliance with the characteristics of the treated waste (chemical composition, the quality and quantity of radionuclides, mechanical properties solid radioactive, etc.). Product must comply with the relevant conditions of acceptability for the final disposal into the storage. As was mentioned in the chapter 3.6, there are several RAW treatment technologies used in the Czech Republic and abroad. In the case of GEN III+ reactors the decision of the chosen technology was made according to following factors:

- Popularity of the technology used in the Czech Republic (the most experience from the operational point of view);
- Form of the final product after treatment which should be able to be disposed in the CZ repositories ;
- Total evaluation of the technologies according to technical, economical and safety aspects (UJV Rez, 2008b).

All these three factors are described in the chapter 3.6.

### 4.1.1 Chosen technology for MIR 1200

Liquid RAW:

Liquid RAW include concentrate from evaporators, sludges and spent sorbents. I chose treatment by the Inorganic binders for them.

Solid RAW:

MIR reactors produce pressable solid RAW and in the category others belong the large-size waste (usually metal pipes). For the pressable waste I chose low-pressure molding and also combustion.

### 4.1.2 Chosen technology for AP 1000

Liquid RAW:

In the case of the reactor AP 1000 the liquid RAW includes sorbents and other liquid RAW (waters with chemical solutions). For the spent sorbents and other liquid RAW I chose again the fixation in the inorganic binders.

Solid RAW:

Solid RAW from AP 1000 includes: pressable, non-pressable and other RAW. For the pressable the treatment is the same as for the MIR reactor, low-pressure molding and combustion with fixation. For the non-pressable I chose the same principle as for the reactor MIR - fragmentation. For the all other solid waste, I chose fixation into inorganic binders.

### 4.1.3 Chosen technology for EPR

Liquid RAW:

Liquid RAW is composed by all types of waste: evaporator concentrates, spent sorbents, sludges and other liquid RAW – contaminated oils. For the sorbents, concentrates and sludge the chosen treatment is the same – fixation into inorganic binders. For the contaminated oils the methods of combustion with further fixation are available.

Solid RAW:

Solid RAW include: Pressable, non-pressable, combustile and the other RAW. For the pressable it can be used low-pressure molding. For the combustile RAW the combustion and further fixation can be chosen. For the non- pressable RAW and other liquid RAW-filter cartridge the method of the fragmentation was chosen.

## 4.2 Calculation of the final amount of the waste from the reactor EPR, AP 1000 and MIR 1200 after the chosen technology treatment

Each technology for the waste treatment is characterized by the Volume Reduction Factor ($K_R$). High volume reduction factor means that the target technology can reduce the volume of the initial amount of waste effectively and the final amount of the waste after the treatment is much lower. If the number of the factor is low, reduction of the initial volume of the waste is lower than the final amount of the waste after treatment. This relation is obvious from the following equations:

$K_R = \frac{V_0}{V_t}$ ;(1) (UJV Rez, 2008b) where

$K_R$ - Volume Reduction factor

$V_0$ – volume of waste before treatment ($m^3$)

Vt – volume of waste after treatment ($m^3$)

There are three different scenarios for $K_R$:

1. $K_R > 5$ ; high volume reduction factor
2. $2 < K_R < 5$ ; middle volume reduction factor
3. $K_R < 2$; low volume reduction factor (UJV Rez, 2008b).

Different technologies have different $K_R$ and also numbers can be various in different range (see tab.4 below). I am mentioning only the $K_R$ of the technologies which I chose. If there is range of numbers (e.g. Combustion 80-110) it is considering the average number as the target $K_R$ (e.g. combustion ( 80+110)/2 = 95 ). When there is known the initial volume of the waste $V_0$ and the volume reduction factor for each technology, it can be calculated the final volume of the waste after treatment $V_t$ from the equation (1): $V_t = \frac{V_0}{K_R}$ ; (2) (UJV Rez, 2008b).

| **Technology** | **$K_R$** |
|---|---|
| Geopolymers for the wet ion exchange resin | 0,4 |
| Geopolymers for the dry ion exchange resin | 0,2 |
| Cementation | 0,5 |
| Combustion | 80-110 |
| Low-pressure molding | 2-4 |
| High-pressure molding | 2-5 |
| Fragmentation | 1-2 |
| Superabsorbent polymers | 1-100 |
| Selective absorption | 1-100 |

**Tab.4** Reduction volume factor for the certain technology (UJV Rez, 2008b)

## 4.3 Final amount of the waste and comparisons

Calculation of the waste from GEN III+ before the treatment and amount of the waste after the selected treatment is crucial for the evaluation of the total waste production. For the evaluation of the GEN III+ reactors waste production, it is important to compare the amount of the waste of both CZ NPP and GEN III+ before and after the treatment.

### 4.3.1 Comparison of the amount of the waste before treatment

The production of the waste from Dukovany and Temelin is shown in tab. 2 and tab. 3 in Appendix 1. The amount of the liquid RAW is obvious but the solid RAW is described by the percentage amount. There is need for calculation the amount of pressable, combustible and metal solid RAW from 80t for Dukovany NPP and from 30t for Temelin NPP. For the comparison of the amount of the solid waste from CZ NPP with the solid RAW of GEN III+ reactors, it is necessary to find volume ($m^3$) of the solid waste from the Dukovany and Temelin reactors. This is derived from the easy equation for the computation of the materials density:

$$\rho = \frac{m}{V}\ [\mathrm{kg/m^3}] \Longrightarrow V = \frac{m}{\rho}\ ;$$ (Bures, 2002)

Density of the pressable, combustible and metal solid RAW is approximately estimated from the average number of the materials densities. For pressable RAW, densities were found for PVC, paper, glass, rubber. For combustible RAW it is wood, paper, oils, PVC. For metal RAW it is Fe, Cu, Ni, Co. Densities are showed in the following table .

| Material | Density [kg/m$^3$] |
|---|---|
| Wood | 100-300 |
| Paper | 700-1 100 |
| Glass | 2 400-2 800 |
| PVC | 1 200-1 500 |
| Rubber | 960-1 300 |
| Nickel | 8908 |
| Iron | 7860 |
| Cobalt | 8900 |
| Copper | 8960 |
| Transformator oil | 866 |

**Tab. 5** Density for the materials of the solid RAW (Bures, 2002)

The amount of the waste from the production of GEN III+ reactors were estimated by the specialists from UJV Rez (see chapter Results below).

### 4.3.2 Comparison of the amount of the waste after treatment

In average yearly 320 m$^3$ (1600 of 200 L drums) of the fixed waste is disposed in the repository Dukovany. For the further evaluation of the capacity of the repository Dukovany in the case of the Temelin NPP completion , it is important to predict 60 years(operation on every NPP is prolongate to 60 years) production of the waste from the GEN III+ reactors and amount of the vaults which could repository Dukovany accommodate in the 60 years. Other important view is the comparison the number of disposed drums per the electric power output of each reactor. It means there is need to figure out how many drums for final disposal are produced from the each reactor per 1 GW of the power output production (SURAO, 2009).

# 5 Current state of problem

As was stated in the chapter 3.4, addition of two new units for Temelin NPP completion is considered. Main benefits according to CEZ of the completion of units 3 and 4 in the Temelin NPP are:

- “*The completion results in lower dependence of the Czech Republic on imports of gas and oil*” (CEZ, 2013b).
- “*The completion of the Temelin Nuclear Power Plant ensures reliable covering of the growing electricity consumption in the Czech Republic*” (CEZ, 2013b).
- “*Electricity generation in a nuclear power plant offers, unlike other resources, the lowest costs*” (CEZ, 2013b).
- “*Realisation of the construction at Temelin is most advantageous in terms of economical, logistic, technical reasons and even in terms of environmental impacts*” (CEZ, 2013b).
- “*The completion of will bring work opportunities to Czech employees, trade opportunities to domestic suppliers and investments to the development of the region*” (CEZ, 2013b).
- “*The world has sufficient reserves of uranium and there are sufficient production capacities for nuclear fuel from a number of suppliers, and as a result, there is no threat of dependence on potentially risky countries*” (CEZ, 2013b).

The reviewed reactors of GEN III+ (MIR 1200, EPR, AP 1000) are already in the tender which was conducted by CEZ company. CEZ authorities must decide on selecting the winner or the termination of the tender. Selection is based on the different analysis (technical, safety, economical, environmental, etc.) which need to be carefully assessed. Different design parameters of the three reactors results also to the production of different amount of the waste. The production of the waste is one of the crucial parameter which is considered in the whole analysis assessment cycle (Lidovky, 2014).

In the range of the CZ NPP the technology for the RAW treatment are known. It can be assumed that this technology would be also used for the new two reactor Units because the type of the waste is the same as in currently operating CZ reactors. The amount of the waste before and after the proposed treatment can give the idea which of the three reactors has the most advanced technology in the sense of the waste production. In other words, which of the reactors produce the least amount and which the highest amount of the waste and what reasons could possibly influence these results.

# 6 Results

## 6.1 Calculation of the amount of the amount of the waste for both CZ NPP and for EPR, AP 1000 and MIR 1200 before treatment:

### 1. Calculation of the solid RAW for Dukovany NPP :

Pressable solid RAW:

80t….100%  Average density: 1475 kg/m$^3$

x t…….30%

x = 24t

$V=\frac{m}{\rho}$  $V=\frac{24000\text{kg}}{1475\ \text{kg/m}^3}=$ 16,27 m$^3$

Combustible solid RAW :

80t….100%  Average density: 765kg/m$^3$

x t…….50%

x = 40t

$V=\frac{m}{\rho}$  $V=\frac{40000kg}{765\ kg/m^3}=$ 52,3 m$^3$

Metal solid RAW:

80t….100%  Average density: 8657kg/m$^3$

x t…….10%

x = 8 t

$V=\frac{m}{\rho}$  $V=\frac{8000kg}{8657kg/m^3}=$ 0,92 m$^3$

### 2. Calculation of the solid RAW for Temelin NPP :

The computations are similar only the total amount of the waste is different-> 30t.

Pressable solid RAW:

30t….100%

x t…….30%

x =9 t

$$V = \frac{9000 kg}{1475\ kg/m^3} = 6{,}1\ m^3$$

<u>Combustible solid RAW:</u>

$$V = \frac{15\ 000\ kg}{765\ kg/m^3} = 19{,}6\ m^3$$

<u>Metal solid RAW:</u>

$$V = \frac{3000\ kg}{8657 kg/m^3} = 0{,}34\ m^3$$

These volumes are from the all four reactors of Dukovany NPP and from two reactors of Temelin NPP. If we want to be precise, it is important to divide these volumes by 4 for Dukovany and with 2 for Temelin to find the volume of the waste per one reactor. The results are in the following table:

| | **Solid RAW ($m^3$)** | | | |
|---|---|---|---|---|
| | **Pressable** | **Combustible** | **Metal** | **Others** |
| **Dukovany** | 4,06 | 13,075 | 0,2 | 0,25 |
| **Temelin** | 3 | 9,8 | 0,1 | 0,1 |

**Tab. 6** The amount of the solid waste before the treatment from the Dukovany and Temelin per one reactor

The amount of the waste resulting from the operation of the GEN III+ reactors is provided by the UJV Rez specialists. They noted that combustible waste from MIR 1200 and AP 1000 is included in the pressable waste (UJV Rez, 2014). The summary of the solid and liquid RAW resulting from the operation of Dukovany, Temelin and each GEN III+ reactors are in the following tables.

|  | Production of one block of reactor ($m^3$) per one year |  |  |  |  |
|---|---|---|---|---|---|
| Type of the solid waste before treatment | Dukovany | Temelin | EPR | MIR1200 | AP 1000 |
| Presable | 4,06 | 3 | 40 | 81 | 135 |
| Combustible | 13,075 | 9,8 | 150 | - | - |
| Metal | 0,2 | 0,1 | 2 | 2,5 | 1 |
| Others | 0,25 | 0,1 | 10 | 2,5 | 1 |

**Tab. 7** Amount of the solid waste before the treatment from Dukovany , Temelin reactors and GENIII+ reactors (Jan Krmela, 2014, personal communication).

|  | Production of one block of reactor ($m^3$) per one year |  |  |  |  |
|---|---|---|---|---|---|
| Type of the liquid waste before treatment | Dukovany | Temelin | EPR | MIR1200 | AP 1000 |
| Concentrate | 87,5 | 125 | 18 | 22 | - |
| Sludges | - | - | 2 | 3 | - |
| Sorbents | 2,5 | 3 | 2 | 10 | 12 |
| Other liq.RAW | 0,25 | 1 | 1 | - | 1 |

**Tab. 8** Amount of the liquid waste before the treatment from Dukovany , Temelin reactors and GENIII+ reactors (Jan Krmela, 2014, personal communication).

## 6.2 Calculation of the final amount of the waste from the reactor EPR, AP1000 and MIR1200 after the chosen treatment technology

For the reactor EPR, the volume of the concentrate before the treatment was $18m^3$ (see tab.8 ). I chose the treatment by the inorganic binders, which reduction volume factor wet ion exchange resins is 0,4. The volume of the waste after using the fixation to the inorganic binders is calculated according to the equation (2). In the result it means:

$V_0 = 18m^3$

$K_R = 0,4$

$V_t = \frac{V_0}{K_R} = \frac{18}{0,4} = 45\ m^3$ of the concentrate after the fixation into inorganic binders

According to the equation (2) all other volumes of the waste after different treatments are computed. When the final volume in cubic meters is known, I can calculate how many 200 liters drums are needed for the disposal or storage the target volume of the waste after treatment. This shows following computation:

1 drum …. 200 L (0,2 $m^3$)

x drums …. $45m^3$ of the concentrate

$x = \frac{45}{0,2} = 225$ drums

In the results the numbers of drums for GEN III+ reactors which should be disposed yearly are showed in the tab. 14-16, Appendix 1. In summary the final amount of the waste after all treatments is:

- **For EPR:** $80m^3$/398 drums
- **For MIR:** $105m^3$/526 drums
- **For AP 1000:** $64m^3$/320drums

The technology of the bituminization is used in the CZ NPP Temelin, so it is good to consider also this possibility of the treatment of the concentrates and sludges. The amount of the sludge and the concentrate after bituminization is seen in the following table.

| | AP 1000 | | EPR | | MIR 1200 | |
|---|---|---|---|---|---|---|
| **Bituminization** | Before | After | Before | After | Before | After |
| **Sludge $K_r$=0,6** | 0 | 0 | $18m^3$ | $30m^3$ | $3m^3$ | $5m^3$ |
| **Concentrate $K_r$= 2,5** | 0 | 0 | $2m^3$ | $0,8m^3$ | $22m^3$ | $8m^3$ |

**Tab. 9** The amount of the waste before and after the bituminization of the sludge, concentrate for GEN III+ reactors

## 6.3 60 years production of the waste from CZ NPP and GEN III + reactors:

1. **Dukovany repository (waste from the both CZ NPP)**

$320m^3$ x 60years = 19 200$m^3$ $\Longrightarrow \frac{19\,200m^3}{0{,}2m^3} =$ 96 000 drums

1 vault…..1600 drums

x vaults…… 96 000 drums

$X = \frac{96\,000}{1600} =$ **60 vaults**

2. **EPR**

For the Temelin completion there should be counted into the predictions amount of the waste from two of the new GEN III+ reactors. That is why all the amount of the waste from the GEN III+ reactors is multiplied by 2.

2x $80m^3$x 60years = $9600m^3$ $\Longrightarrow \frac{9600m^3}{0{,}2m^3} =$ 48 000 drums

1 vault…..1600 drums

x vaults…… 48 000 drums

$X = \frac{48\,000}{1600} =$ **30 vaults**

3. **MIR**

2x $105m^3$x 60 =12 600$m^3$ $\Longrightarrow \frac{12600m^3}{0{,}2m^3} =$ 63 000 drums

1 vault…..1600 drums

x vaults…… 63 000 drums

$X = \frac{63\,000}{1600} =$ **40 vaults**

4. **AP 1000**

2x $64m^3$x 60 = $7680m^3$ $\Longrightarrow \frac{7680m^3}{0{,}2} =$ 38 400 drums

1 vault…..1600 drums

x vaults…… 38 400 drums

---

$x = \frac{38\,400}{1600}$ = **24 vaults**

## 6.4 Production of the waste per 1GW of the electric output for the EPR, MIR 1200, AP 1000 and both CZ NPP

- **For EPR reactor: yearly 80m$^3$/398 drums**

  Electric power output/GW :

  1650MW $\Longrightarrow \frac{398\ \text{drums}}{1{,}7GW} =$ 234 drums/GW (47,06 m$^3$/GW)

- **For MIR 1200 reactor : yearly 105m$^3$/526 drums,**

  Electric power output/GW:

  1198MW $\Longrightarrow \frac{526\ \text{drums}}{1{,}2GW} =$ 438 drums/GW (87,5 m$^3$/GW)

- **For AP 1000 reactor : yearly 64m$^3$/320drums**

  Electric power output/GW:

  1110MW $\Longrightarrow \frac{320\text{drums}}{1{,}1GW} =$ 290 drums/GW (58,2m$^3$/GW)

- **For both CZ NPP:** yearly 320 m$^3$/1600 drums

**Electric power of CZ NPP:**

Dukovany 2x 440 MW; 2x 456 MW –> 1792 MW

Temelin 2x 1000MW – > 2000MW

**Electric output of the both CZ NPP:**

2000 + 1792 = 3792 MW $\Longrightarrow \frac{1600\ \text{drums}}{3{,}8\ GW} =$ 421 drums/GW (84,2m$^3$/GW)

# 7 Discussion

## 7.1 Chosen technologies for the waste treatment for MIR 1200, AP 1000 and EPR reactors

### 1. Chosen technology for MIR 1200

Liquid RAW:

For the fixation of the liquid RAW (concentrate from evaporators, sludges and spent sorbents) the chosen technology is fixation into Inorganic binders. One of the reason is that this technology belongs to the the most common technology used for the fixation of the liquid RAW (see chap.3.5). Total evaluation of all the technical and economical, safety aspects shows the range between 4,0 and 4,35 which explains that:

- Technically it proves famous and simple technology ;
- Economically , the main aspect is the low prize of the cement ;
- Safety is ensured by high stability of the final product, low leachibility of the radionuclides (UJV Rez, 2008b).

Solid RAW:

Pressable solid RAW can be treated by the chosen technology of the low pressure molding and combustion , thus combustible waste is included into pressable solid RAW. Low-pressure molding is using in the both Czechs NPP. Total evaluation for solid waste is relatively low 3,55 which shows that this technology is well managed and available technology. It has an easy installation of the equipment and it is easy to operate and to provide service. On the other hand it has a low reduction volume factor 3 in comparison with combustion. It is good to realize that pressable solid RAW can be also combustible. That is why I chose also combustion. Total evaluation for combustion is quite higher (6, 55). This method has economically higher costs but as a compensation it has high reduction volume factor 95. Because of the high volume factor I decided that the majority of the waste will be treated by this method of combustion. The production of the contaminated ash is associated with the combustion. This ash should be fixed with inorganic binders into the drum. If we assumed that in other solid RAW the 1m$^3$ of the 5m$^3$ waste contain large-size waste treatment, it is good to consider low-pressure molding method where huge pieces can be molded to the compact smaller matrix and then it can be further processed by the fixation into the drums. The remaining waste (4 m$^3$) can be processed by fragmentation method where huge pieces can be chopped to smaller (UJV Rez, 2008b).

### 2. Chosen technology for AP 1000

Liquid RAW:

Sorbents and other waters with chemical solutions can be treated by the fixation into inorganic binders. The reasons are the same as for the fixation of the liquid RAW in the case of reactor MIR 1200. It means simple technology, economical effectivty, ensured safety (UJV Rez, 2008b).

Solid RAW:

Pressable, non-pressable and other RAW belongs to the solid RAW of the reactor AP 1000. Low-pressure molding and combustion with fixation was chosen for the pressable RAW. Combustion and fixation was chosen because combustible RAW is included into pressable RAW. Non-pressable RAW is treated by the fragmentation of the large size waste into smaller sizes. No specific compositon of the other solid RAW leads to the treatment by the simple and available fixation into inorganic binders (UJV Rez, 2008b).

### 3. Chosen technology for EPR

Liquid RAW:

Sorbents, concentrates and sludge has the same chosen treatment– fixation into inorganic binders. Other liquid RAW-contaminated oils are treated by the combustion with further fixation which is specific treatment for the contaminated oils (UJV Rez, 2008b).

Solid RAW:

Pressable, non-pressable, combustile and the other RAW-filter cartridge are included into solid RAW for the reactor EPR. For the pressable logically the treatment of the low-pressure molding can be used. For the combustile RAW the most effective method in the range of the Czech Republic is the combustion and further fixation. Non-pessable waste and filter cartridge can be treated by the simple and relatively cost effective method of the fragmentation (UJV Rez, 2008b).

## 7.2 Final amount of the waste resulting from the reactor EPR, AP 1000 and MIR 1200 before and after the chosen treatment technology

According to the example calculations of the final amount of the waste after the treatment from the EPR reactor, it can be concluded that in the reactor EPR after the fixation of the 18m$^3$ of the concentrate in the inorganic binders, the volume of the waste (45m$^3$) increased, because of the additional volume of the cement or geopolymers. So there is need for the fixation of the concentrate into 225 drums, each with volume of 200 L. Similar computations were done for each waste and technology. The results are shown in the tables 14-16, Appendix 1.

As is seen in the table 9, the amount of the concentrates and sludges are less after bituminization than after fixation into inorganic binders. The main disadvantage of bituminization method is that there are high requirements on fire fighting safety and it means high investments. That is why in the case of concentrate and sludge treatment I chose the fixation into inorganic binders (UJV Rez, 2008b).

### 7.2.1 Comparison of the amount of the waste before treatment

Dukovany and Temelin produce much more evaporator concentrate than reactors GEN III+. In the case of AP 1000 it could be caused by the fact that concentrate and sludges are filtrated by the sorbents. It means that there is no direct production of the concentrate and sludges in case of the AP 1000 reactor. It is also the reason why volume of the sorbents in AP 1000 is the highest. For all other reactors of GEN III+ it is caused by the better effectivity of the work with the cooling liquids and other liquids. Temelin and Dukovany NPPs do not produce measurable amount of the sludges. That is why in table 8 there is no note about the amount of the sludges. On the other hand, 2 m$^3$ and 3m$^3$ of sludges production demonstrates that GEN III + reactors are counting with the specific treatment of sludges. That is why there is a prediction of the sludges production which will be separated from other liquid RAW (Jan Krmela, 2014, personal communication).

In the case of the production of the solid RAW it can be concluded that the amount of the waste from the reactors of GEN III+ is almost 10 times higher. The possible reason could be that the reactors of GEN III+ operate in higher power output than reactors of Temelin and Dukovany. The higher power output could cause higher production of the solid waste. High power output requires higher requirements on materials and also higher amount of the structural components of different systems (mainly safety systems). Another reason according to specialists from UJV Rez is that the GEN III+ reactors are not counting with the solid waste which could be released into the environment. That is why the amount of the solid waste could be generated. It is important to emphasize that these results are the predictions and the real operation could give different results (Jan Krmela, 2014, personal communication).

### 7.2.2 Comparison of the amount of the waste after treatment

Whole capacity of the repository Dukovany is 50 000 $m^3$/250 000 of 200 L drums. It is known that one vault of the repository yearly accommodates approximately 1600 individual 200 L drums from the both CZ NPP. So whole Dukovany capacity represents 156 vaults. For 60 years of the waste disposal from the both CZ NPP there would be 19 200$m^3$ / 96 000 of 200 L drums of the disposed waste which takes approximately 38% of the total repository's capacity which represents 60 vaults. It means that beyond the production of the current reactors, there would be still 62% (96 vaults) of the repository Dukovany available for the waste disposal. From the reactor of GEN III+ in the 60 years prediction it can be expected the number of the vaults around 40 which is 24% of the total capacity of the repository Dukovany. Therefore, 40 more vaults are the minimum which are need to be taken into account in the repository's capacity. In the result in 60 years prediction there would be enough space (156 repository vaults-60 CZ NPP vaults-40 GEN III+ vaults= 56 remaining vaults) to accommodate waste from the both CZ NPP and from one of the GEN III + reactors. Additional vaults could be filled by the waste from the decommissioning (SURAO 2009).

If we keep looking on the production of the waste from current both CZ NPP and compare it with the MIR reactor production, the amount of the waste per 1 GW is similar. The one of the reason could be that MIR reactor is the modification of the current WWER reactors. The design of the MIR reactor is based on the technology of pressurized water reactors having firm fundamentals in the characteristics of WWER-440, WWER-640 and WWER-1000 type reactors (Skoda JS, 2009).

This could be also the reason why the MIR reactor produces the highest amount of the waste among the remaining GEN III+ reactors. From the amount of the waste in the sense of the electric output there is obvious that the reactor EPR with the highest electric output 1,7GW yearly could produce the lowest number of the waste fixed into drums (234 drums/ GW). The possible reason could be that higher electric output requires also higher energy efficiency of the all operational systems. This implies that efficient operational systems (e.g. efficient combustion, work with cooling liquids etc.) produce lower amount of the waste. AP 1000 performs in the lowest electric output and produce higher amount of the fixed waste then EPR reactor. The possible reason was mentioned above that low electric output (AP 1000-1110MW) could lead to the production of the higher amount of the waste in the sense of the level of systems operational efficiency (Jana Dymackova, 2014, personal communication).

In general there is an assumption that the amount of the waste depends on the number of the frequency of the reactors operational shutdowns. Operational shutdowns are made because of corrections, reparations of some systems of the reactor and also for the changing of the fuel in the reactor. This leads to the production of waste. More shut downs are made; more waste is produced and generated (CEZ, 2014).

# 8 Conclusion

The radioactive waste issue belongs to the global questions and concerns. It is necessary to stay focused and take into account every new intervention for waste amount minimization which occurred in the labor. In the Czech Republic energy capacity consumption can be covered by the building of 2 new reactors units in Temelin NPP. But more development leads to more production and therefore, more amount of the waste. That is why selection of the suitable technology which has to comply with the clearance and acceptance requirements is crucial. Subsequently the selection of the treatment can fundamentally impact the amount of the waste which was produced before the chosen treatment.

It is expected that GEN III+ reactors will produce lower amount of the waste than currently operating reactors. The results confirm the expectations in the sense of liquid RAW production. Solid RAW according to results is higher than in the case of currently operating reactors. Reason could be that new technology requires new materials and possibly more systems which can ensure mainly the safety of the new development.

In the range of the Czech Republic utilization of Inorganic Binders for liquid RAW seems to be the most effective from economical, safety and popularity point of view. Inorganic Binders are also suitable for fixation of remaining ash from the combustion or for some other solid RAW. Solid RAW includes pressable waste for which simple low-pressure molding can be used. Combustion is the logical treatment for combustible and some of the non-pressable RAW. Fragmentation takes place more-less as a secondary treatment beyond main treatments thus bigger parts of the waste can be chopped to the smaller.

According to the comparison of the waste amount after the chosen technology the EPR reactor could be the best choice for the completion of the Temelin NPP in the sense of the waste production per 1 GW after the chosen treatment. It also concurred with the findings mentioned in chapter 3.4.2 that Areva EPR reactor is considered as the most suitable for completion of the Temelin NPP (CEZ, 2013c).

This is the important fact for the investors and energy producers because nowadays the trend is to increase the electric output, increase the efficiency and at the same time decrease the amount of the waste in the sense of the economic efficiency. Also, according to the Atomic Energy Act, the waste producers pay for the all expenditures related to the management and disposal of the RAW (UJV Rez, 2008b ).

That is why less production of the waste is beneficial. Another reason for EPR choice is that the 60 years prediction of the waste production results in the reasonable number of vaults (30) which can be accommodated in the repository Dukovany. It shows that EPR reactor is the “golden middle choice” among other two reactors for the Temelin NPP completion.

Transparency of the waste issue during the Temelin completion tender is not clear. Information management is the subject of the strict security measures to which CEZ has earmarked tens of millions of crowns. That is why the precise comparison of reference with the results stated in this thesis could not be done. The input information was mainly provided by the specialists from UJV, Rez who have a lot of experience with the area of the production, management and treatment of the RAW in the Czech Republic and in the world. This fact of information security shows the importance of the predictions and calculations of the amount of waste made in the thesis. It is a way how to approach the public and academic society with this complex topic in an understandable manner (EurActiv, 2007).

According to the latest news the tender for NPP Temelin completion has been canceled. CEZ stated that there are several legal and bussiness reasons of a economical nature - no investments return. But the tender is not absolutely excluded in the further future. Czech president Milos Zeman believes that NPP Temelin will be completed and he will fully support the completion. The three candidates for the completion (AREVA, Westinghouse and MIR) will be still in a course. Therefore, the studies of the RAW production are still crucial for the whole tender assessment. (iDNES, 2014).

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# Appendix 1: Tables

| **Radionuclide** | **Sump(Bq)** | **Two double-row sumps (Bq)** |
|---|---|---|
| $^{14}$C | 2,2. $10^{11}$ | 1,0.$10^{13}$ |
| $^{14}$Ca | 3,0. $10^{10}$ | 3,0.$10^{11}$ |
| $^{59}$Ni | 3,0.$10^{11}$ | 3,0.$10^{12}$ |
| $^{63}$Ni | 3,0.$10^{12}$ | 3,5.$10^{13}$ |
| $^{90}$Sr | 1,0.$10^{12}$ | 1,0.$10^{13}$ |
| $^{94}$Nb | 3,0.$10^{9}$ | 3,0.$10^{10}$ |
| $^{99}$Tc | 1,0.$10^{11}$ | 1,0.$10^{12}$ |
| $^{129}$I | 1,0.$10^{10}$ | 1,0.$10^{11}$ |
| $^{137}$Cs | 3,0.$10^{13}$ | 3,0.$10^{14}$ |
| $^{239}$Pu | 5,0.$10^{8}$ | 6,0.$10^{9}$ |
| $^{241}$Am | 1,0.$10^{9}$ | 1,0.$10^{10}$ |

**Tab. 1** Total activity of radionuclides in repository Dukovany (SURAO 2012)

|  | **Production** |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  | **Spent sorbents** | **Concentrate** | **Sludges** | **Organic liquids** | **Solid RAW** | **Other Solid RAW** |
| **Dukovany** | 5- 10 $m^3$ | 350$m^3$ | - | 1$m^3$ | 80t | 1$m^3$ |
| **Temelin** | 3$m^3$ | 250$m^3$ | - | 10kg org.liq.and 1$m^3$ contaminated oils | 30t | 0,3$m^3$ |

**Tab. 2** Total amount of RAW in the NPP Dukovany and Temelin
(UJV REZ, 2008b)

| **Type of solid RAW** | **Typical representation of RAW in VVER - 1000 (volume %)** |
|---|---|
| Pressable | 30 |
| Combustible | 50 |
| Metal | 10 |
| Others | 10 |

**Tab. 3** Solid RAW from the VVER block in Temelin (UJV REZ, 2008b)

| **Radionuclide** | **Sump (Bq)** | **Two double-row sumps (Bq)** |
|---|---|---|
| $^{14}$C | $1.10^{9}$ | $1.10^{10}$ |
| $^{14}$Ca | $1,5.10^{9}$ | $1,5.10^{10}$ |
| $^{59}$Ni | $1,5.10^{10}$ | $1,5.10^{11}$ |
| $^{63}$Ni | $1,5.10^{11}$ | $1,5.10^{12}$ |
| $^{90}$Sr | $5.10^{10}$ | $5.10^{11}$ |
| $^{94}$Nb | $1,5.10^{8}$ | $1.5.10^{9}$ |
| $^{99}$Tc | $5.10^{9}$ | $5.10^{10}$ |
| $^{129}$I | $5.10^{8}$ | $5.10^{9}$ |
| $^{137}$Cs | $1,5.10^{12}$ | $1,5.10^{13}$ |
| $^{239}$Pu | $2.5.10^{7}$ | $3.10^{8}$ |
| $^{241}$Am | $1,5.10^{7}$ | $1,5.10^{8}$ |

**Tab. 4** Total activity of radionuclides in disposed RAW of institutional origin (SURAO,2012)

| **Radionuclide** | **Volume activity (Bq/m$^{3}$)** |
|---|---|
| $^{14}$C | $3.10^{9}$ |
| $^{14}$Ca | $1.10^{9}$ |
| $^{59}$Ni | $1.10^{10}$ |
| $^{63}$Ni | $1.10^{11}$ |
| $^{90}$Sr | $3.10^{10}$ |
| $^{94}$Nb | $1.10^{8}$ |
| $^{99}$Tc | $3.10^{9}$ |
| $^{129}$I | $3.10^{8}$ |
| $^{137}$Cs | $1.10^{12}$ |
| $^{239}$Pu | $2.10^{7}$ |

**Tab. 5** Limit values of volume activity of disposed radionuclides (SURAO 2012)

| **Range of volume activity** | **Maximal leachiable rate** |
|---|---|
| Volume activity of product over $3.10^9$Bq/m$^3$ | 0,4% |
| Volume activity of product from $2.10^7$Bq/m$^3$ to $3.10^9$Bq/m$^3$ | 4% |
| Volume activity od product under $2.10^7$ Bq/m$^3$ | Not determined |

**Tab. 6** Limit values of leachibility of RAW (SURAO 2012)

| **Range of volume activity** | **Maximal leachiable rate** |
|---|---|
| Volume activity of product over $2.10^7$ Bq/m$^3$ | 4% |
| Volume activity under $2.10^7$ Bq/m$^3$ | Not determined |

**Tab.7** Limit values of leachibility of RAW (fixed in cement or aluminosilicate matrix) (SURAO,2012)

| **Technology** | **Total evaluation** |
|---|---|
| Drying in the drum + HIC | 4,20 |
| Thickening and crystallization liq.concetrate + HIC | 4,20 |
| Inorganic binders | 4,35 |
| Bituminization | 5,75 |
| MSO+ HIC | 6,20 |
| Vitrification | 6,55 |
| Vitrification Cold Cup | 6,75 |

**Tab. 8** Evaluation of the technologies for treatment and processing of the concentrate from VVER production (UJV Rez, 2008b)

| Technology | Total evaluation |
|---|---|
| Inorganic binders | 4,10 |
| Drying in the drum + HIC | 4,20 |
| Pelletizing | 4,25 |
| Hot isostatic pressing | 4,70 |
| MSO+HIC | 5,00 |
| Bituminization | 6,30 |
| Combustion | 6,55 |
| Combustion+ Inorganic binders | 6,55 |
| Plasma Arc Melting | 6,75 |

**Tab. 9** Evaluation of the technologies for treatment and processing of the ion exchange resins and the wet sludges from VVER production (UJV Rez, 2008b)

| Technology | Total evaluation |
|---|---|
| High pressure pressing | 3,45 |
| Low pressure pressing | 3,55 |
| Combustion | 6,55 |
| Combustion+ Bituminization | 6,55 |
| Combustion + Inorganic binders | 6,55 |
| Plasma Arc Melting | 6,75 |

**Tab. 10** Evaluation of the technologies for the treatment and processing of solid combustible RAW from the production of VVER 1000 (UJV Rez, 2008b)

| Technology | Total evaluation |
|---|---|
| High pressure pressing | 3,45 |
| Low pressure pressing | 3,55 |

**Tab. 11** Evaluation of the technologies for the treatment and processing of pressable, non combustible RAW from the production of VVER 1000 (UJV Rez, 2008b)

| Technology | Total evaluation |
|---|---|
| High pressure pressing + Drum | 4,00 |
| HIC | 4,10 |
| Metal Melting | 6,55 |
| Plasma Arc Melting | 6,75 |

**Tab. 12** Evaluation of the technologies for the treatment and processing of metal RAW from the production of VVER 1000 (UJV Rez, 2008b)

| Technology | Total evaluation |
|---|---|
| High pressure pressing + Drum | 4,00 |
| Inorganic binders | 4,10 |
| HIC | 4,10 |
| Plastic compaction by melting + Drum | 4,45 |
| Bituminization | 6,30 |
| Plasma Arc Melting | 6,75 |

**Tab. 13** Evaluation of the technologies for the treatment and processing of other solid RAW from the production of VVER 1000 (UJV Rez, 2008b)

| **Reactor EPR** | **Type of RAW** | **Technology** | **Reduction Volume factor ($K_R$)** | **Volume of RAW after treatment (Vt)** |
|---|---|---|---|---|
| **Liquid RAW** | **Concentrate** | Inorganic binders | 0,4 | **45 $m^3$**<br>**225 drums** |
| | **Sludges** | Inorganic binders | 0,4 | **5 $m^3$**<br>**25 drums** |
| | **Sorbents** | Inorganic binders | 0,4 | **5 $m^3$**<br>**25 drums** |
| | **Others liq. RAW** | Combustion | 95 | 0,01 $m^3$ |
| | | Inorganic binders | 0,4 | **0,025 $m^3$** |
| **Solid RAW** | **Pressable** | Low pressure molding | 3 | **13,3 $m^3$**<br>**67 drums** |
| | **Combustible** | Combustion | 95 | 1,6 $m^3$ |
| | | Inorganic binders | 0,4 | **4$m^3$**<br>**20drums** |
| | **Non-pressable** | Fragmentation | 1,5 | **1,3 $m^3$**<br>**6 drums** |
| | **Others - filters** | Fragmentation | 1,5 | **6$m^3$**<br>**30 drums** |
| **Total volume of the waste after treatment** | | | | **80$m^3$/398 drums** |

**Tab. 14** The volume of the RAW in EPR reactor after the selected treatment

| **Reactor AP 1000** | **Type of RAW** | **Technology** | **Reduction Volume factor ($K_R$)** | **Volume of RAW after treatment (Vt)** |
|---|---|---|---|---|
| **Liquid RAW** | **Concentrate** | - | - | - |
| | **Sludges** | - | - | - |
| | **Sorbents** | Inorganic binders | 0,4 | **LLW 10m$^3$/50 drums**<br>**ILW 20 m$^3$ /100drums** |
| | **Others liq. RAW** | Inorganic binders | 0,4 | **2,5m$^3$**<br>**13 drums** |
| **Solid RAW** | **Pressable** | Low pressure molding | 3 | **22,5 m$^3$**<br>**113 drums** |
| | **Pressable** | Combustion | 95 | 0,71m$^3$ |
| | | Inorganic binders | 0,4 | **1,8 m$^3$**<br>**9 drums** |
| | **Combustible** | - | - | - |
| | **Non-pressable** | Fragmentation | 1,5 | **4,6 m$^3$**<br>**23 drums** |
| | **Others** | Inorganic binders | 0,4 | **2,5 m$^3$**<br>**12 drums** |
| **Total volume of the waste after treatment** | | | | **64m$^3$/320drums** |

**Tab. 15** The volume of the RAW in AP 1000 reactor after the selected treatment

| **Reactor MIR** | **Type of RAW** | **Technology** | **Reduction Volume factor ($K_R$)** | **Volume of RAW after treatment (Vt)** |
|---|---|---|---|---|
| **Liquid RAW** | **Concentrate** | Inorganic binders | 0,4 | **55 $m^3$**<br>**275 drums** |
| | **Sludges** | Inorganic binders | 0,4 | **7,5$m^3$**<br>**38 drums** |
| | **Sorbents** | Inorganic binders | 0,4 | **25 $m^3$**<br>**125 drums** |
| | **Others liq. RAW** | - | - | - |
| **Solid RAW** | **Pressable** | Low pressure molding | 3 | **LLW 13,5 $m^3$ /68 drums** |
| | **Pressable** | Combustion | 95 | LLW 0,43 $m^3$ |
| | | Inorganic binders | 0,4 | **1,07$m^3$/5 drums** |
| | **Combustible** | - | - | - |
| | **Non-pressable** | - | - | - |
| | **Others** | Fragmentation | 1,5 | **2,6 $m^3$**<br>**13 drums** |
| | **Others** | Low pressure molding | 2,5 | **0,4 $m^3$**<br>**2 drums** |
| **Total volume of the waste after treatment** | | | | **105$m^3$/526 drums** |

**Tab. 16** The volume of the RAW in MIR reactor after the selected treatment