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Issues for Nuclear Power Plants Steam Generators

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1. Introduction

Steam Generators (SGs) are one of the big metal components in nuclear power plants. The function of Steam Generators is the removal of the thermal power generated into reactor core and its transfer to the secondary side of the tubes where secondary coolant flows. The preservation of the complete separation between the primary and secondary fluid is of capital importance in order to avoid radioactive contamination of secondary fluid and small loss of coolant also.

Mainly two designs have been developed for nuclear thermal power plants: vertical U-tubes with upstream and downstream flow for primary water, and horizontal steam generators. Also once through design can be found, but vertical U-tubes steam generators prevail.

A brief focus on operating life, of inspections and mainteinance, and of water conditions is presented. Water conditions both at the primary and secondary side of the steam generator are of primary importance. During operating life, cooling radioactive contamination occurs, but water conditions must be mantained inside specific ranges. A typical PWR isotopic composition of contamination inside primary circuit components is presented. To avoid unwanted degradation of water conditions and of thermal exchange, specific ispections and interventions are applied.

Problems associated with Steam Generators in nuclear power plants are tube denting, wastage, thinning, corrosion, flow-induced vibrations, cracking and deformation of U-tube bend, or of support plates, tube leakage, fractures. We consider the case of a leakage, a rupture which would compromise the integrity of separation between radioactive and not-radioactive fluid, and the main symptoms and interventions.

The periodical inspections of SG have shown localized corrosion and mechanical wear problems on some SG tubes and degradation of SG lifetime (Bezdkian 2009). A replacement management program is necessary to achieve 40 years lifetime.

According to Wade (1995) in the United States 35 steam generators had been replaced in 12 plants and a list of 23 units are identified as potential candidates for steam generators replacement or shutdown.

When approaching end of life, decontamination and decommissioning of Steam Generators must be planned. Decommissioning is the end of life of a facility. It implies many issues: strategic, technological and scientific, measurement, environmental, legislation, and economic issues.

Finally, we focus just on Steam Generators degradation problem and decommissioning issues. We consider the step of radiological characterization and the characteristics of the available techniques for decontamination and cutting.
Steam Generators material should be managed with an eye toward reuse, recycling and clearance of all material and scrap. Steam Generators are typically the primary circuit components which the greater contaminated surface belongs. Decontamination can be performed by washing, heating, chemical or electrochemical action, mechanical cleaning, or other techniques.

2. Design of steam generators

The current status of the nuclear industry (2010) shows 441 nuclear power reactors in operation with a total net installed capacity of 374.692 GW(e), 5 nuclear power reactors in long term shutdown, 60 nuclear power reactors under construction (Power Reactors Information System, http://www.iaea.org/programmes/a2/index.htm).
The 2010 new connection to the grid are: Rostov 2 (950 MW(e), PWR-VVER (Pressurized Water Reactor Russian Design), Russia, (Rostov is a new official name of Volgodonsk reactor units); Rajasthan 6 (202 MW(e), PHWR (Pressurized Heavy Water Reactor), India; Lingao 3 (1000 MW(e), PWR, China; Qinshan 2-3 (610 MW(e), PWR, China; Shin Kori 1 (960 MW(e), PWR, S. Korea. Figure 1 shows their locations.

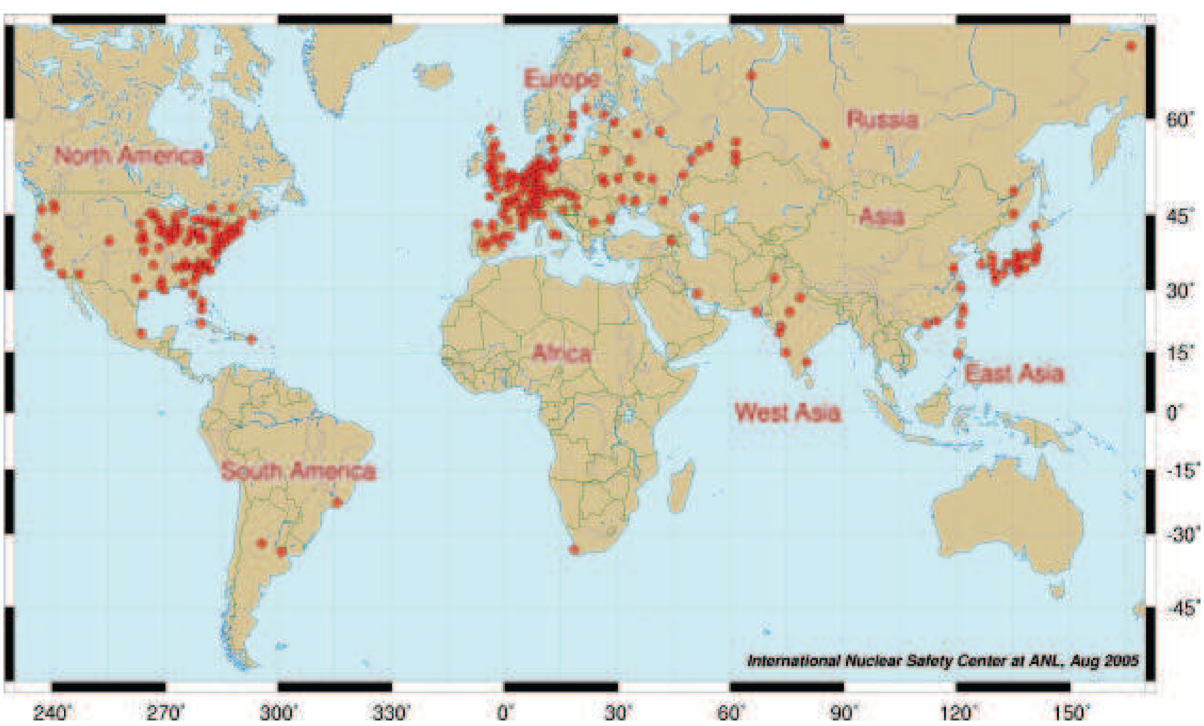

Fig. 1. Locations of Power reactors in the world (International Nuclear Safety Center, operated by DOE)

In the world there are 46 PHWR units for 22840 MWe power and 269 PWR units for 248295 MWe power.
In these plants Steam Generators raise very important issues about the design, the operation, the periodi inspections, the ageing management and the decommissioning.
In this chapter we will consider water reactors.

The function of Steam Generators (SG) in water reactors nuclear power plants is the heat transfer from the reactor cooling system, also called prymary system, to the secondary side of the tubes which contain feedwater.
Primary coolant water receives heat passing through the core, then flows through the steam generator, where it transfers heat to the secondary coolant water to make steam (Green & Hetsroni, 1995). The steam then drives a turbine connected to an electric generator to produce energy.
The steam is then condensed and returns the steam generator as feedwater. PWR power plants have two, three or four SG and are called two-loop, three loop or four loop units. A general schematic view of a PWRs with 4 primar circuits is shown in figure 2. In contrast to a boiling water reactor (BWR), pressure in the primary coolant loop prevents the water from boiling within the reactor. In BWRs (Boiling Water Reactors), primary water produces steam directly, thus these concerns do not subsist anymore, and steam generators are not used.

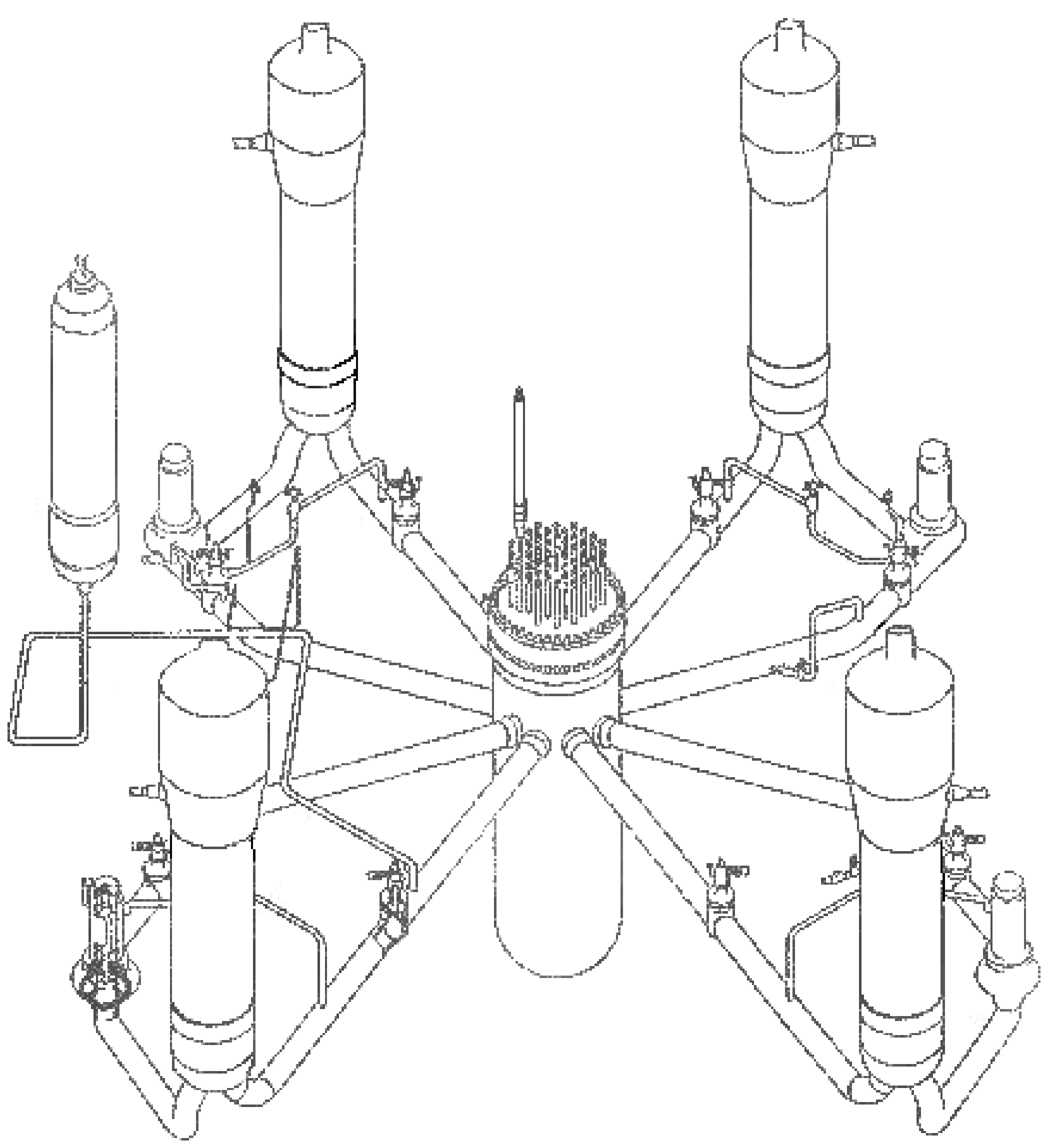

Fig. 2. General scheme of PWR primary circuit

Notice that the steam that flows from the steam generator must be pure and not contain any radioactive material, as it flows out of the containment structure. Conversely, the primary fluid does contain many radioactive material: the preservation of the complete separation between the two fluids is of capital importance. The integrity of tubes must be mantained. These tubes have an important safety role because they constitute one of the barriers between the radioactive and non-radioactive sides of the plant. For this reason, the integrity of the tubing is essential in minimizing the leakage of water between the two sides.
The integrity of the primary system must be assured in any case.
The steam generators may also contain a steam separation region.

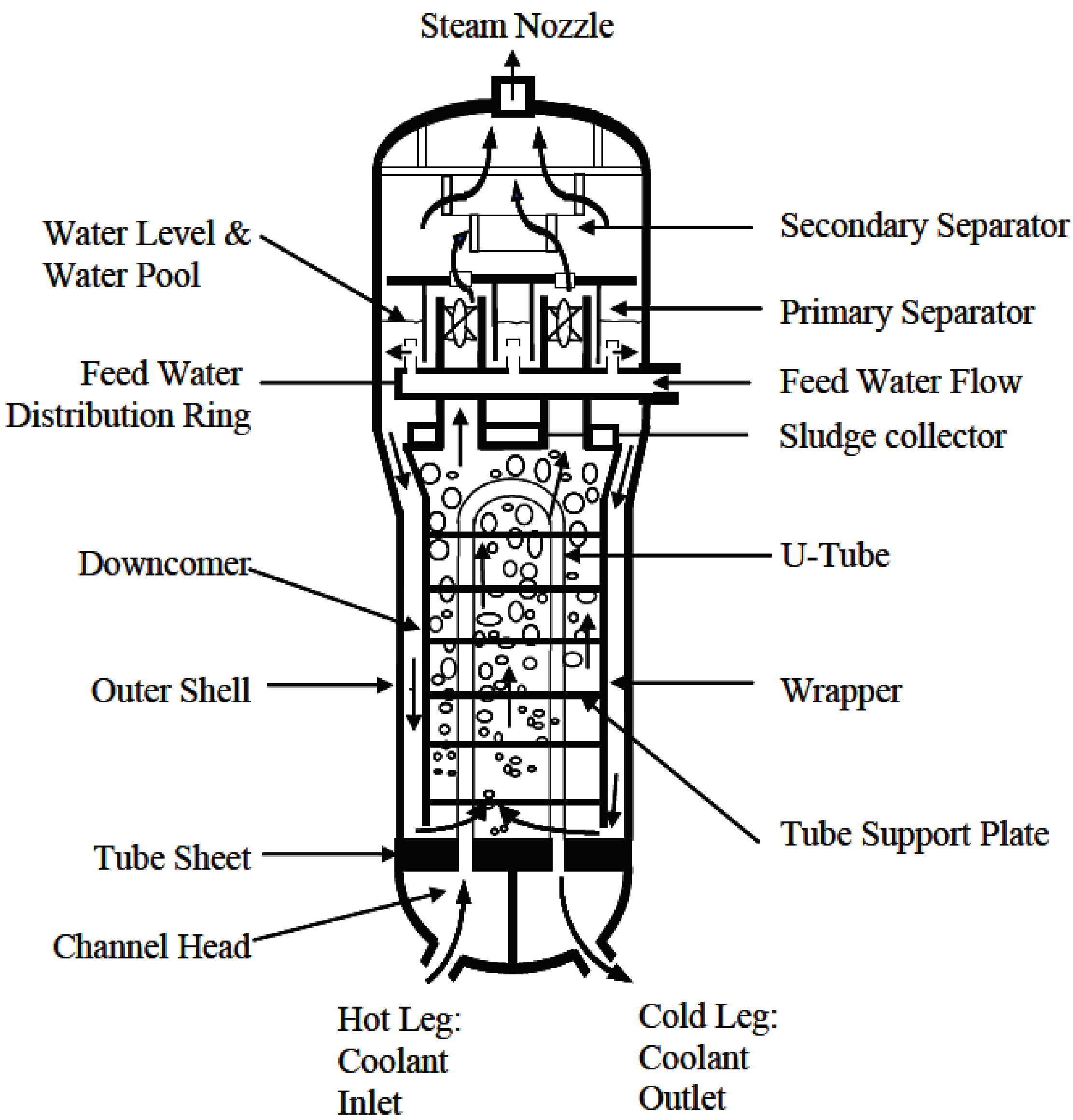

Fig. 3a. Schematic of a vertical PWR steam generator

Mainly two designs have been developed: vertical U-tubes with upstream and downstream flow for primary water (fig. 3a), and horizontal steam generators (fig. 3b). Also once through design can be found (fig. 3c).

In a horizontal design (fig. 3b) the steam generator have a horizontal cylindrical housing and horizontal coils. The steam is dried at the top of the housing by gravitational separation.

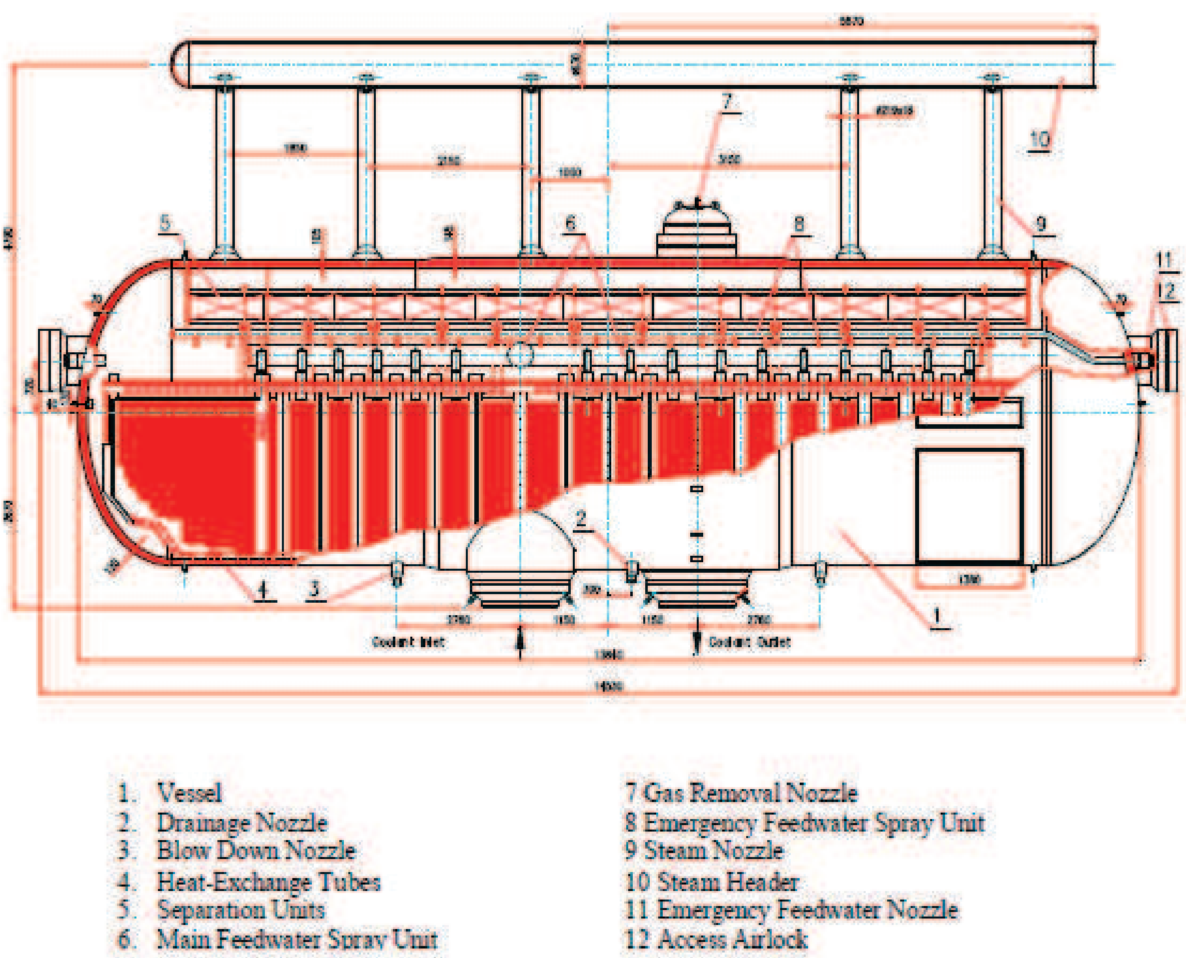

Fig. 3b. Typical Horizontal Steam Generator of the VVER-1000 Plant (Sánchez-Espinoza 2009)

In a once through design, the primary-side water enters at the steam generator at the top, flow through the generator in unbent tubes end exits at the bottom (fig. 3c).
According to the Power Reactor Information System (PRIS) of International Atomic Energy Agency (IAEA 2005) the steam generators of a power plant are described by the following data: type of SG (vertical, horizontal), steam output (saturated or superheated steam), number of steam generators (from two to six), number of drum separator (if present), tub shape (U tube or straight), ,tube material , SG shell material, drum separator shell material, design thermal capacity for single SG, design heat transfer surface.
Other important data, not present in PRIS database, are the nominal thermal power, the steam production rate, the steam pressure and temperature at the exit, the exit moisture content of the generated steam, the water store, the outer diameter of housing, and the hosing length. Important data of heat exchange of tubes are materials, number of tubes, average length, diameter, wall thickness, heat-exchange surface, metal mass without and with supports.
SG performance, degradation, lifetime and management program are strongly dependent of design data and operating experience.

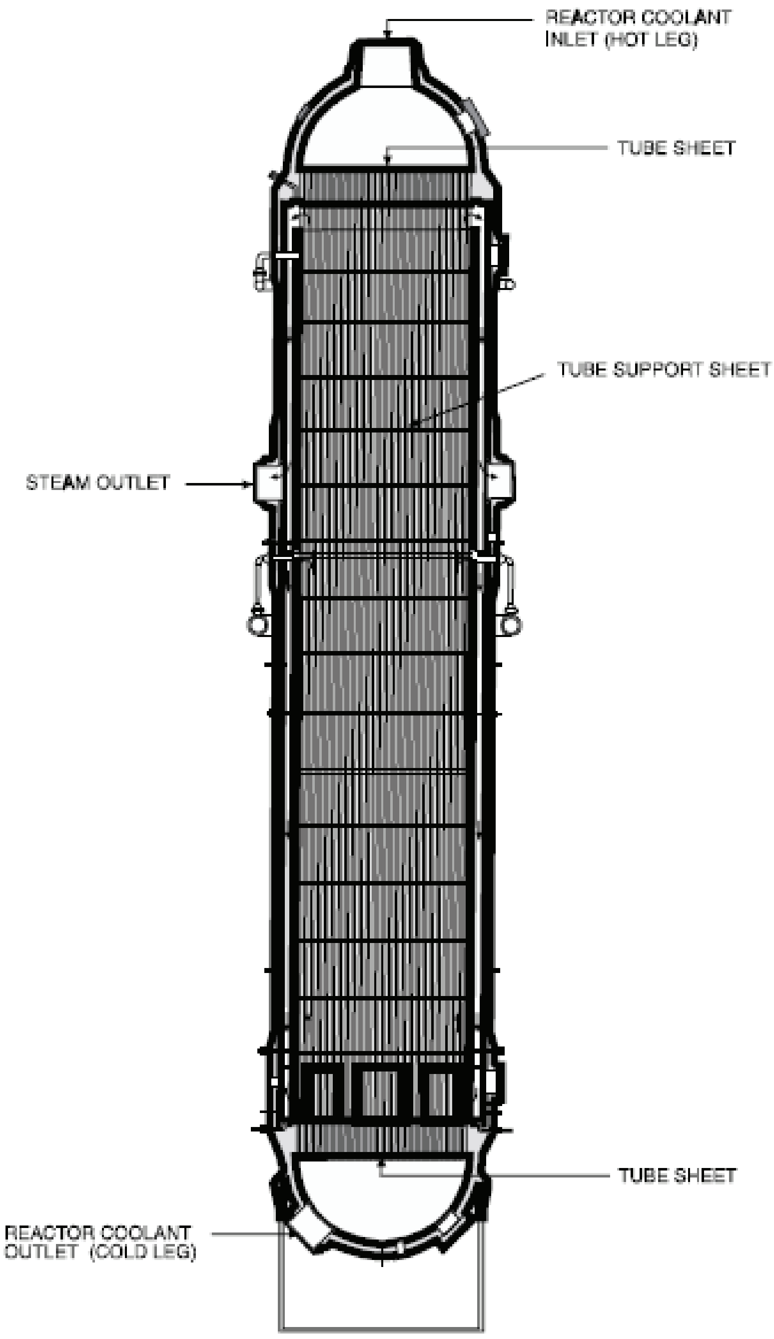

Fig. 3c. Typical Babcock & Wilcox Once through steam generator

The horizontal design is considered to be less susceptible to degradation than the vertical U-tube one. More specifically, the orientation of a tube has effects on boiling and on occurrence of boiling crisis causing differences on their behaviour to stress conditions (Merilo, 1977).
On the basis of operating experience gained over many years, horizontal steam generators have advantages over vertical steam generators, the main ones being (Trunov et al, 2008):
moderate steam load (steam outflow rate from the evaporation surface 0.2–0.3 m/sec); simple gravity-based separation scheme;

- moderate velocity of the medium in the second loop (up to 0.5 m/sec), preventing any danger of vibrations of the heat-exchange tubes and damage from foreign objects;

- validated serviceability of the 08Kh18N10T austenitic steel tubes (the maximum operational age is 38 years for
- PGV-440 and 23 years for PGV-1000);
- vertical arrangement of the first-loop collectors, preventing accumulation of sludge deposits on their surfaces,
- thereby decreasing the danger of corrosion damage to the heat-exchange tubes in the region where the tubes are
- built into the tube sheet;
- larger store of water in the second loop, enabling cool-down of the reactor via the steam generator in the case where normal and emergency water feeding has stopped;
- the principle of stepped evaporation, making it possible to maintain an admissible concentration of dissolved impurities in the critical zones and increasing the reliability from the standpoint of corrosion effects;
- horizontal arrangement of the heat-exchange surface, enabling reliable natural circulation of the first-loop coolant even with a massive water level below the top rows of the heat-exchange tubes;
- convenient access to the tube sheet for servicing and checking from the first- and second-loop sides; there are no heat-exchange tubes at the bottom of the housing, so that sludge is more easily removed through the purge system;
- presence of equipment for disconnecting the collectors from the main circulation pipelines, making it possible to decrease the time required to perform scheduled–preventative maintenance work and to increase the installed capacity utilization factor by performing work simultaneously on several steam generators and refueling the reactor.

Mainly, vertical U-tubes steam generators are used. The steam generator consists of a heat exchange section and a steam drum section. The heat exchange section consists of a vertical, inverted U-tube bundle with the tube plate and the channel head. The steam drum portion consists of the internal moisture separating equipment and the enclosing pressure shell, In operation, primary coolant from the nuclear reactor vessel is circulated through the U-tubes. During this passage, the coolant gives off heat to the secondary water on the shell side of the steam generator, causing it to boil to steam. This steam, in turn, is passed through the moisture separating equipment in order to reduce the entrained moisture content and produce essentially dry steam.

2.1 Detailed description

Coolant enters the inlet nozzle from the reactor and circulates through the U-tubes and out of the outlet nozzle into the coolant pumps suction line. Heat is transferred through the walls of the tubes from the coolant, thus boiling the water on the shell side and generating steam.

Feedwater to the steam generator enters just below the normal water level and joins the water being recirculates as it flows downward to the bottom of the shell through the annular downcomer between the shell and the tube bundle wrapper. At the bottom of the active tube surface, this mixture of recirculated water and feedwater is introduced uniformly into the tube bundle. It then flows upward by natural convection through the bundle absorbing heat and leaves the top of the active tube surface as a steam water mixture. Moisture is separated from the mixture, essentially dry steam is discharged through the steam outlet nozzle.

Separation of liquid water from the steam-water mixture is done in the upper part of steam generators,and usually consists of three phases:

- Primary separation, normally done by means of centrifugal separators.
- Gravity separation, which occurs in the space between the primary separators ad the driers.
- Secondary separation, normally done by means of corrugated shape separators, or driers.

The efficiency of steam separation and the pressure drop are the two most important features of steam separators.

The vessel shell consists of a barrel fabricated of carbon steel plate, welded to an hemispherical head of the same material. The shell or secondary side nozzles consist of the feedwater inlet nozzle., liquid level indicator and liquid level control connections, surface and bottom blowdown connections, shell drain connection, pressure test connection, steam sample connection, and steam offtake connection.

The tube plate consists of a carbon steel clad on the primary side with stainless steel, and contains holes whose number is the double of the number of tubes. In our case study the number of tubes is 1662. The tube plate separates the primary and secondary fluids and contains the U-tubes which extend into the secondary or shell side of the steam generator.

Many support plate designs are available (drilled, without flow holes, broached-trefoil, quatrefoil, egg-create…) (Green and Hetsroni, 1995).

The vertical steam generator is supported by means of a lower set of trunnions. The upper trunnions are provided for emergency support and may also be used foe lifting purposes.

A general scheme of a U-tube vertical SG is shown in figure 3.

2.2 Operating phase

During a nuclear plant operation, cooling radioactive contamination is caused by the presence of:

- Fission products,
- Uranium and Transuranium elements,

(caused by fuel rod cladding insulation defects), as well as:

- fuel fission products,
- Uranium and Transuranium elements,

(originating from free Uranium particles which undergo fission outside fuel cladding), or finally from

- relevant fuel rod cladding insulation defects.

These may cause direct contact between primary coolant and fuel. The last two mechanisms are also called 'recoil phenomenon'.

Corrosion products may be:

- Corrosion products which have been activated while flowing through the reactor core.
- Activated corrosion products, which belong to corrosion of activated reactor materials.

All these materials create particular conditions for steam generators management, inspection, cleaning, maintenance, and decommissioning.

During operating phase, some precautions must be considered. For example, in the case of excessive carryover, correction should be made immediately or permanent damage to the turbine may result. This condition may be caused by either a high water level or a high solids concentration in the boiling water: correction may be either lowering the water level or blowing down.

The water level must be observed periodically, as well as temperature limitation to the steam side and the maximum heating or cooling rate to the primary coolant, all in concordance with the specific plant operating instructions.
Some of the observed material degradations for primary side SG are (Riznic 2009):

- Fatigue;
- Pitting;
- Stress corrosion cracking and intergranular attack (a form of corrosion occurring when the boundaries of crystallites of the material are more susceptible to corrosion than their insides);
- Fretting;
- Degradation of primary header divider plates;
- Tube plugs;
- SG tube magnetite build-up (degradation of thermal efficiency, and possible safety related impact on inspection capabilities);
- Presence of foreign materials.

The degradation of primary header divider plates doesn't lead to major safety impacts, but can lead to loss of thermal efficiency. Degradation permits hot reactor outlet header fluid to by-pass the tube bundle. An increase in reactor inlet header temperature has been observed.
When the primary header divider design is the 'segmented', or 'lap joint' designed (plate segments bolted to each other), leakage may occur:

- Around periphery between plate segments and seat bars;
- Between plate segments;
- Through bolt holes;
- Around corner filler blocks

When the primary header divider design is the welded floating plate designed (welded construction, no bolted lap joints), there are no leakage at bolted lap joints, but leakage still possible around periphery of the plate.
Geometry issues and magnetite in primary water may lead to flow assisted corrosion in carbon steel elements at periphery of plates. In any case, no significant degradation of this nature has been experienced to date.
A possible mitigation intervention is the application of Inconel overlays to segmented / lap joint divider plates on hot leg side, but this could lead to notable drop in reactor inlet header temperature (RIHT).
Concerning tube plugs, a general practice is to visually inspect Hot Legs and Cold Legs tube plug during outages. Leaking tube plug welds are normally identified during inspections. Tubes with poor plug welds could become pressurized and fail due to tube degradation if it progressed. This problem contributes to primary to secondary leakage if tube contained a leaking defect.
Tube fouling may lead to decrease in solubility of magnetite from in heavy water with decreased temperature, causing:

- Magnetite deposits in SG tubes;
- From a thermal performance perspective, increases in RIHT may occur;
- From a safety perspective, deposits can impact tube inspection capabilities (tubes may become obstructed preventing tool passage, and magnetite deposits may affect flaw detectibility and sizing)

Foreign materials left in primary side of SGs could introduce scratches on tubes, and constitute a possible initiation sites for in-service degradation, so leading to possible damage to other primary side SG internals. Moreover, materials could be transported through the circuit and into reactor.

Some of the observed material degradations for secondary side SG are (Riznic 2009):

- Tube support degradation;
- Secondary side deposits and sludge piles;
- Foreign materials;
- Tube degradation mechanisms.

Tube supports made of carbon steel have been subject to a variety of degradation mechanisms, as:

- Under deposit corrosion and cracking or degradation of U-bend bar supports;
- Corrosion of tube support plates leading to tube denting and loss of tube support;
- Tube fretting at supports.

Secondary side depositsare associated to:

- Generally pitting at supports or along straight legs;
- Deposits contain higher concentrations of impurities than secondary side water and form crevices;
- Pitting observed at tube supports.

In this case, mitigation strategies include secondary side chemistry control, secondary side chemical cleaning and finally waterlancing. Waterlancing is a common SG cleaning technique; it is done routinely at many plants. It entails directing a high-pressure water jet between the tubes from the (central) tube-free lane. The jet oscillates in a vertical plane. It requires access through the shell and the downcomer shroud.

Foreign materials is associated to debris fretting. Sources of debris identified include:

- Welding electrodes;
- Wire;
- Screws;
- Gasket material

Some materials may have been left behind during construction.

It is known that degradation of the heat-exchange tubes in the steam generators in nuclear power plants with VVER reactors (Trunov et al. 2008) occurs during operation for the following reasons:

- the presence of copper-containing materials in the second loop, which, in the first place, makes it impossible to
- increase the pH of the feed water above 9.2 in order to reduce the amount of the products of corrosion of iron entering from the second loop to a minimum and, in the second place, results in deposits on the heat-exchange surfaces of the steam generators of, together with iron compounds, a substantial quantity of copper and its compounds and engenders local forms of corrosion;
- breakdown of the water-chemistry regime;
- ill-timed chemical laving;
- corrosion of the heat-exchange tubes in downtime regimes.

The defects which result in degradation of heat-exchange tubes include pitting, corrosion pits, and cracks of different depth and length, right up to through cracks.

2.3 Inspections and cleaning

Commercial PWR steam generators have experienced reliability problems within the first decade of operation associated with material degradation, one of the causes of which is particle deposition and tube fouling. As a result steam generators often require costly outages for inspection and cleaning of fouling deposits (Srikantiah & Chappidi, 2000).
In-service inspections are critical in maintaining steam generator tube integrity. The scope and frequency of these inspections vary from plant to plant based on each facility's operating experience. The purpose of inspection is to determine the condition of the apparatus and to locate any defects which may require repairs.
The components comprising separator, purifier, piping and drains may require servicing. Check all internal surfaces for corrosion or erosion and note unusual conditions is essential. Damage is often indicated by the presence of scale, grit, or other foreign matter.
Access to the inside of the primary channel may be accomplished by means of two manways. Prior to performing any work, the area around the steam generator should be carefully monitored to determine the radiation level. Workers and radiation field must be measured and controlled as stated by the Health Physics Department of the plant.
Other than inspection purpose, another repair work could be the plug leaking tubes.
During plant operation, the thickness of the tubes can be measured, in order to insulate those tubes which are affected by deterioration. Insulation consists in welding plugs on both sides of the U-tube.
Cleaning shall consist of the removal of slag, grease, paint or any other foreign matter when present. It is important to remove all organic materials since they would decompose and contaminate, and remove all particles of dust from heated surfaces. Cleaning must be extended at least to all heated surfaces. Various chemical and mechanical methods may be used (chemical methods, vapour cleaning, brushing…).

3. Water conditions

Water conditions both at the primary and secondary side of the steam generator are of primary importance.
Water conditions are intended to define the conditions under which the steam generator will operate properly. The condition of the boiling water should be tested by sampling at least once a day or as required by the operating instructions. The values of alcalinity and solids in excess of those specified may cause scaling of the steam generator tubes.
Feedwater must be maintained as free from impurities as possible. This requirement involves careful attention to the entire system through which the water flows, either in the form of steam or water, for even though water is used as feedwater be pure at the same time of its entry into the system, it may absorb impurities from the various parts of the installation. Specific attention should be directed to possible points of water leakage from the service water system, as in the main and auxiliary condensers. Feedwater must be treated to maintain the required water conditions.
The parameters to observe are, for the primary side:

- Impurity content, not considering the presence of inhibitors and chemical additives, which are necessary to the operation of the plant.
- Total dissolved solid, which is one of the causes of performance degeneration.
- pH.
- Hydrogen.
- Dissolved oxygen.

- Chlorides.
- Boric acid (with chemical shim[1] or without chemical shim).

The parameters to observe for the secondary side, are:

- Total dissolved solid.
- pH.
- Dissolved oxygen.
- Chlorides.

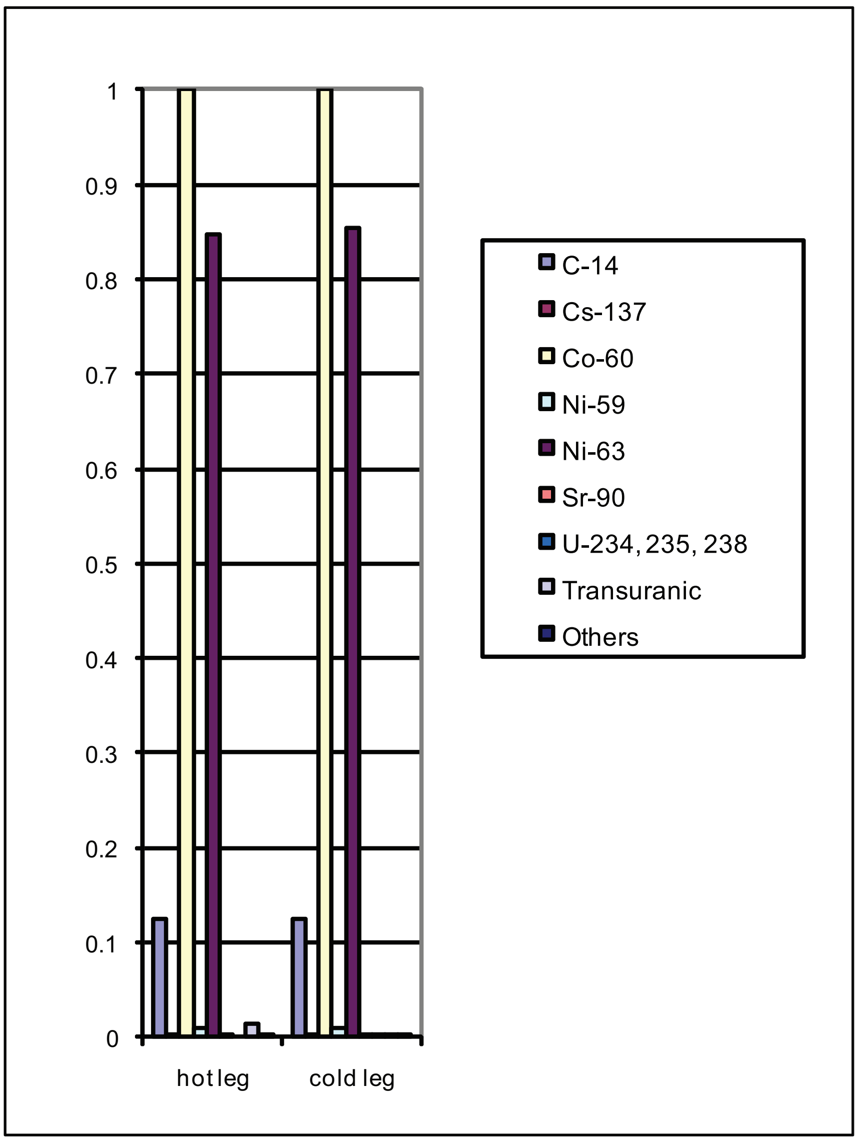

Fig. 5. Example of isotopic composition of contamination inside one of the steam generators of a decommissioned NPP

[1] The power level is controlled by control rods, temperature, and chemical shim. By chemical shim, we mean that boric acid is dissolved in the coolant/moderator. Boron-10 has a high neutron aborption cross-section and can be used to poison the chain reaction. If it is desired to increase power, then the boric acid concentration can be diluted, removing B-10 from the reactor core and decreasing its poisoning effect. Chemical shim is used in PWRs (Pressurized Water Reactors) and, to a small extent, in CANDUs. (Canada Deuterium-Uranium). Boric acid is not used in BWRs (Boiling Water Reactors).

Steam entering the main header from the steam offtake nozzle will have a moisture content not exceeding a determinated value (usually a percentage of the steam flow under certain conditions, like constant power steam generation, or power increasing or decreasing up to a percent of full power).

In pressurised water reactor nuclear power plants it is necessary to filter corrosion products transported by the main flow, as well as radioactive particulate.

Activity must be controlled: fission products must be detected, as well as noble gases and iodines or activation products. Gamma spectra are acquired at many locations along the circuit. Gasborne activity is measured by means of coolant samples (e.g. fission gases isotopes of krypton and xenon). In the composition of primary coolant activity monitoring system, there are devices to detect Iodine volume activity. Isotopic composition of contamination inside primary circuit components comprises: C-14, Cs-137, Co-60, Ni-59, Ni-63, Sr-90, U-234, 235, 238, Transuranics, and, to a small degree, Nb-94, Cl-36, Tc-99, I-129 (figure 5).

For purifying primary coolant, ion exchange resins are utilised, as well as demineralizers.

Spent ion exchange resins constitute the most significant fraction of the wet solid waste produced at power reactors. They are wet solid waste arising during operation of a nuclear power plant.

The main wastes arising during the operation of a nuclear power plant are components which are removed during refuelling or maintenance (mainly activated solids, e.g. stainless steel containing cobalt-60 and nickel-63) or operational wastes such as radioactive liquids, filters, and ion-exchange resins which are contaminated with fission products from circuits containing liquid coolant. Powdered resins are used in PWRs, but are commonly used in BWRs with pre-coated filter demineralizers.

The make-up water for the steam generation system is similar to fossil fuel power plants: pre-treatment is followed by reverse osmosis system.

4. Ruptures and maintenance

Problems associated with Steam Generators in nuclear power plants are tube denting (denting results from the corrosion of the carbon steel support plates and the corrosion product in the crevices between tubes and the tube support plates), wastage, thinning, corrosion, flow-induced vibrations, cracking and deformation of U-tube bend, or of support plates, tube leakage, fractures.

Considering a leakage, which would compromise the integrity of separation between radioactive and not-radioactive fluid, the main symptoms are:

- Low level alarm for primary circuit pressurizer.
- Low pressure alarm for primary coolant.
- Low level alarm for low pressure expansion tank.
- High level alarm for activity in steam generator purge line.
- High level alarm for activity in turbine condenser void pumps discharge line.
- High level alarm in the steam generator.
- Imbalance between steam flow and feedwater.

The Steam Generator should be then insulated, and the part of system discharged, when needed, and maintenance operations must be carried out.

When a certain percent of the tubes have been plugged as described above, heat transfer deteriorates too much and a final intervention is needed. Typically it requires up to 60 days to replace a Steam Generator.

Replacement of Steam Generators is a practice followed by nuclear power stations across the world to ensure longer life to the plant. During the 40 year initial license period of a power plant, normally steam generation replacement is not considered. To achieve license extension, and extend operating life, this practice has become of wide application all over the world. Some examples are the reactors of: Three Miles Island Unit 1 (U.S.A.), Angra 1 (Brasil).

Referring to French power plants, localized corrosion and mechanical problems are observed on some SG tubes (Bezdikian 2009). During the 80's, the thermal aging phenomenon was confirmed, so French Utility and the Manufacturer decided to take measurements to predict the metallurgical aging mechanism to assess for:

- 1st step 40 years evaluation,
- 2nd step 60 years prediction.

The objectives was to assess the ability of the cast elbows in existing plants to withstand continued and to maintain components in operating respect safety requirements. The strategy applied was to combined Elbows replacement with Steam Generators replacement.

After studies based on economic and technical criteria, EDF set up a Steam Generator replacement program in compliance with the safety rules. These operations are classified into exceptional maintenance operations (all maintenance operations programmed nationally, on large number of NPPs usually carried out once during the lifetimeof units), and have therefore significant cost and impact on availability. They are integrated in new routine manteinance program.

All units in study were classified into groups:

- Group 1. Units with SG affected by important degradations and Steam Generator replacement will be carry out in future;
- Group 2. Units with SG lifetime evaluation is with incertainties, evolution of degradations is unknown;
- Group 3. Units with SG Lifetime equal to Plant lifetime.

Before removal from the reactor building, all decommissioned SG openings are closed up by welding metal plates to make up sealed sources, and thereby preventing the release of contamination.

After removal, EDF adopted a standard building project suitable for all French sites, equipped with a concrete roof, walls from 50 to 80 cm thick, for environmentally-safe site storage. This building can accommodate the 3 decommissioned SG of a unit without causing any pollution of the air, water or soil, without generating any waste.

5. Decontamination and decommissioning of steam generators

When approaching end of life, decontamination and decommissioning of Steam Generators must be planned. Decommissioning is the end of life of a facility. It implies many issues: strategic, technological and scientific, measurement, environmental, legislation, and economic issues. In this chapter we focus just on Steam Generators decommissioning issues.

Steam Generators are one of the big metal components in decommissioning nuclear power plants. Their material should be managed with an eye toward reuse, recycling and clearance of all material and scrap (Anigstein et al., 2001; IAEA, 2004; IAEA 2000; NEA, 2008; Nieves et al, 1998).

Surface contamination and volume activity must be controlled.

When activity decreases below clearance levels, then legal constraints on material can be eliminated (IAEA, 2004; IAEA, 2000). Clearance levels are a set of requirements on radionuclides concentrations below which radioactive waste is no longer considered a radioactive hazard.
Levels for unrestricted release of material are not internationally harmonized, but in any case have to comply with radiation protection principles.
Clearance levels are recommended by EC (European Commission) and other international organizations. Although some cost-effective options to clearance exist, in the long term clearance is the best waste management choice intenrationally accepted (NEA, 2008).
When decontamination is possible and justified, metal material will undergo decontamination process in order to fit clearance levels or to reduce occupational exposure of workers, limiting potential releases and exposures, or to allow material reuse and make its management easier. The remaining metal will undergo the process of characterization as radioactive waste.
During the decommissioning of nuclear power plants large metallic components like steam generators (or reactor pressure vessels) play a relevant role. Depending on their radiological properties a disposal or a recycling is possible.
Different strategies are used. These strategies are planned considering economic costs, radiological protection or the site situation. A relevant aspect is the possible clearance of the waste material which can be achieved after decay storage if necessary or afteer a decontaminatio process.
Based on these conditions different strategies are resulting. Large components can be dismantled on site with the objective of a final storage. Another strategy is achieving the clearance of at least a part of the large components material.
This can typically be achieved by treatment of the fragmented or entire large components, eventually including decay storage before or after fragmenting.
Three main strategies for big metal components are usually considered:

- transport to an external treatment facility (option number 1)
- transport to an interim storage on site and treatment after decay (option number 2)
- in situ treatment (option number 3)

As an example of in situ treatment (option number 3) we can cite Gundremmingen nuclear power plant. The Steam Generators were filled with water, frozen and cut in situ by a band saw. The main advantage is that the pieces could be treated directly on site, avoiding the transport of heavy parts. On the other hand, it took a time of several years.
As an example of transport to an external treatment facility (option number 1) we can cite the Steam generator of the nuclear power plant Stade (Germany). They have been transported to Studvik Radwaste (Sweden) for: dismantling, melting and clearance of material. The large components are leaving the plant at an early stage, allowing the use of the empty place for the dismantling of other parts. Moreover, the decommissioning will be accelerated. In any case, the the transport has to be planned very carefully, considering national law prescriptions, and it is cost intensive.
An example of transport to an interim storage on site and treatment after decay is the Decay storage of several reactor pressure vessels and steam generators in the interim storage Nord (Lubmin / Germany) (option number 2). The aim is to achieve the clearance of these components after cutting but without melting. In fact, the decay storage reduces the activity and allows an easier clearance of material without decontamination or other treatment. It

avoids component trasnport. This strategy is very sensitive for changes in clearance regulations during the decay time (Bauerfeind & Feinhals 2010).

5.1 Decontamination techniques

Decontamination is the removal of contamination from surfaces of facilities or equipment. It can be performed by washing, heating, chemical or electrochemical action, mechanical cleaning, or other techniques.

Decontamination is one of the main decommissioning activities. The objectives of decontamination are:

- reduce radiation exposure;
- reduce the volume of equipment and materials requiring radioactive waste management;
- remove loose radioactive contaminants and fix the remaining contamination in place in preparation for further activities;
- reduce the magnitude of the residual radioactive source.

Decontamination process will produce much secondary waste, thus a facility for secondary waste treatment is needed (processing chemical solutions, debrids, etc…). Liquid waste and, in general, concentrated waste, must be solified for disposal, or treated for waste reduction or recycling.

When a treatment is undertaken, there may be an increase in: occupational exposure rates, potential for a release or uptake of radioactive material. These may be higher then to those due to removing, packaging and disposal of the radioactive material without decontamination treatment. All interventions must be defined after an economic / technical / environmental assessment of treatment.

Prior to performing actions, the appropriate knowledge on the presence, kind and distribution of radioactivity inside the item should be known. This stage is the radiological characterization step.

Radiological characterization and radioactivity inventory for decommissioning purpose is an evaluation of systems internal contamination and activation in order to plan the best procedure of intervention.

Radiological characterization of a facility starts from the historical analysis of plant operating life and of conditions that could lead to accidental contaminations. Representative components for each system can be identified and the materials belonging to these systems can be grouped into: contaminated/ activated/not contaminated or activated.

This first classification is followed by dose rate measurement campaign and radiochemical analysis campaign on representative components in order to detect the level of specific contamination, its isotopic composition, and correlation factors between easily-measured radionuclides and other critical nuclides.

Dose rate measurements should be performed on each component, with radiometric survey to detect superficial removable contamination lying on outer surfaces. To evaluate the deposition of contamination on components inner surface, calculation codes are applied. SGs are typically the primary circuit components which the greater contaminated surface belongs.

A complete description of decontamination techniques may be found in literature (IAEA 2006, NEA 1999).

For our pourpose, just a brief introduction to the available techniques will be presented. After that, a practical example will be provided.

Washing, swabbing, foaming, abrasive blasting, grinding, scarifying, are some examples of physical (mechanical) decontamination techniques. These last techniques are most applicable to the decontamination of structural surfaces. Usually give very high decontamination factors.

Decontamination factor is used to express the capability of a process to remove decontaimnation. It is defined as the ratio of radiation level of the material or component prior to the treatment, and the level of the same measured immediately after decontamination.

These techniques are not applicable for complicated surfaces.

Chemical decontamination is based on the use of chemical reagents in contact with the contamination layer to remove, in this case, to dissolve. Generally, the process may be continued or repeated untill the required decontamination factor is achieved, taking care of the material involved. Chemical decontamination is often carried out by circulating the selected reagents in the system, while segmented parts may be decontaminated by immerging them into the reagent. Application of specific chemical decontamination depends on many factors, e.g., complexity of shape and dimensions of the item to be treated, kind and vharacteristics of the chemical reagents, type of material and contamination, availability of proper process equipment, and so on. It may be mild or aggressive, which involves the dissolution of the base metal.

Chemical flushing is recommended for remote decontamination of intact piping systems. It is also suitable for use on complex geometries as well as for a uniform treatment of piping surfaces. These techniques, however, require efficient recycling of reactive chemicals.

Compliance with basic health and safety practices regarding chemical agents is required, in addition to the radiological safety aspects. As a minimum, workers – suitably trained - will be equipped with the proper DPI (individual protection devices) such as glasses, full-body protective coveralls, impermeable gloves and foot covers.

Additional safety equipment depends on the toxicity of contaminants.

When a chemical decontamination is assisted by an electrical field, we speak about an electrochemical decontamination. It usually involves the immersion of the item in electrolyte bath or using a pad. The electric current causes an anodic dissolution and removal of metal and oxyde layer from the sirface in tretment. It may be only applied to conductive surfaces.

Melting may also be considered as a decontamination method, although generally limited by specific national law constraints. It homogens a number of radionuclides in the ingots and concentrating others in the slag. It is used often for complex geometries, avoiding the problem for inaccessible surfaces.

Also many hybrid technologies between those cited above are in use (Kinnunen 2008).

5.2 Dismantling techniques

A wide range of dismantling techniques, both mechanical and thermal, are developed and tested during decommissioning of plants (IAEA 1999; Cumo et al., 2002; Eickelpasch et al., 1997; Klein et al., 2001; Steiner et al., 1997), often supported by European Community research programmes. There is a large variety of dismantling techniques that are state of the art and in use.

They can be grouped into mechanical (sawing, shearing, milling, diamond wire sawing, pipecutting…), usually used for activated component cutting, thermal (oxy-fuel cutting, lance cutting, plasma-arc cutting, laser beam cutting…) and hydraulic (water jet cutting, abrasive water jet cutting).

Table 1. Characteristics of some main cutting techniques

Technique	Applicability	Secondary emissions	Underwater Cutting	Specific hazard
Oxy-fuel cutting	Steel, mild steel, low alloys. It cuts a max. thickness greater then 2000 mm	Hot oxides, fumes, aerosols	Yes, with reduced cutting speed	Preheating flame ar oxide ejected from cutting zone
Lance cutting	All kind of material (reinforced concrete and thermal resistant materials included). It cuts a max. thickness of 2000 mm of concrete	Gaseous and solid products, dust	Yes, but the lance must have been lighted before	High gaseous emiss fumes and soli products ejected f the cutting zon
Plasma cutting	All conductive materials (ferrous and not ferrous). It cuts a max. thickness of 170 mm of stainless steel.	Gaseous products and dust	Yes	Fire hazard, elect discharge, brightn gas and fumes emi
Laser	All kind of material. It cuts a max. thickness of 110 mm of stainless steel	Gaseous products and dust	Yes	Laser beam, fumes aerosols
Water jet	Many kinds of material, also sandwiches of different compositions. It cuts a max. thickness of 1 mm of steel	Fluid products and dust	Yes, but performances are reduced	Effluents should collected and trea
Mechanical	All kind of material. It cuts a max. thickness greater then 2000 mm	Scraps, burrs, dust	Yes	Noise and vibrati

Table number 1 proposes a classification of cutting techniques for metal for decommissioning purposes. A complete description of these techniques may be found in literature (EPRI, 2008; EPRI, 2007; EPRI, 2005; EPRI, 2001; EPRI, 2000).
Also many hybrid technologies between those cited above are in use. An interesting example is the case of the dismantling of the SG in unit A at Gundremmingen nuclear power plant (Germany) (Steiner et al. 1997). To perform this segmentation, the use of thermal cutting would cause a large amount of radioactive and metal aerosol, moreover it is performed in direct contact with the item, thus exposing the operator to a high radiation field. The presence of non-fixed single tubes excludes the application of a sawing machine. The tube bundle would vibrate excessively. The solution choosen for this cutting is called the 'ice sawing technique'. The heat exchanger has been filled up with water on the secondary side and the whole component has been freezed downl to about -20°C by blowing cold air through the primary side. After freezing it has been possible to cut through the whole component by a suitable band saw. The advantages of this technique are: reduction of the local dose rate, fixing of the heat exchangers tubes, minimizing the aerosol generation during cutting phase, cooling of the saw blade.
Waste will contain radionuclides with different radio-toxicity levels (radio-toxicity classes are set by Italian law in the *Decreto Ministeriale del 27 luglio 1966*). Radio-toxicity is the potential capacity to cause harmful effects on living tissues because of radionuclide inhalation, ingestion or intake by skin and wounds. Radio-toxicity level is influenced by the kind of radiation, its energy, physical and biological half time, radio-sensibility of tissue or organ. The greater part of radionuclides present in decommissioning waste belongs to high radio-toxicity classes of nuclides.
Contamination spread as consequence of metal cut can normally be overcome by the use of individual radioprotection devices and devices for protection of respiratory track, as emissions retaining rooms, filtering systems, masks, gloves and suits (Bonavigo et el. 2009).

6. Conclusion

Steam Generators are one of the main components in nuclear systems. Their management poses many issues.
The steam that flows from the Steam Generator must be pure and not contain any radioactive material, as it flows out of the containment structure. The primary fluid contains many radioactive material: the preservation of the complete separation between the two fluids is of capital importance. In this chapter we considered the issue of contamination of secondary system and we analysed how to preserve the separation between the two fluids, considering the main kind of inspections and mainteinance, and the kind of nterventions which are applied.
An interesting observation is that life of nuclear power plants all over the world is approaching its end. The goal of license extension is cost effective and postpines all decommissioning operations, and new plant construction. Typically, extension is 20 years. In the U.S.A., more of the half of the plants have applied for , or are in the process of applying for, license extensions for another 20 years under the NRC's License Renewal Rule. License extensions for existing power plants are considered as crucial to the nation's ability to maintain a continuous supply of cost-effective energy as the nuclear energy industry transitions to the next generation of nuclear power plants. Often, the substitution of some

components may be applied in order to achieve this task, inside the refurbishment process. Steam Generators are the main component to which this concept refers.
When approaching end of life, decontamination and decommissioning of Steam Generators must be planned. During the decommissioning of nuclear power plants large metallic components like steam generators (or reactor pressure vessels) play a relevant role. Depending on their radiological properties a disposal or a recycling is possible.
We considered some different approaches to theis issue, showing european examples.
The step of radiological characterization should be broaden to ensure the best operation planning and material management.
We considered the main issues concerning decontamination and cutting of this metal component.
We focused on some possible techniques.
In any case, reuse, recycle and clearance of material are key-concepts and should always be applied. They are stressed by all international institutions concerning nuclear installations safety and radioprotection.
High decontamination factors may be achieved. On the other hand, contamination spread as consequence of metal cut can be overcome by the use of individual radioprotection devices and devices for protection of respiratory track, as emissions retaining rooms, filtering systems, masks, gloves and suits.

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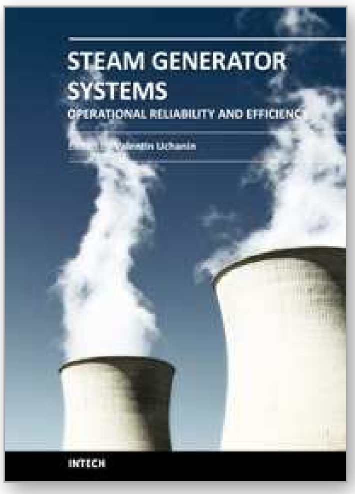

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