

Experiences and Techniques in the Decommissioning of Old Nuclear Power Plants

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1. Introduction

Decommissioning of a nuclear power plant or other nuclear installations can be defined as the cessation of operations and the withdrawal of the facility from service, followed by its transformation into an out-of-service state and eventually, its complete removal, the so-called "green field" status, which, in principle, restores the site to the conditions existing before the construction of the plant. Alternative end conditions may include a situation in which the buildings, free of any radioactive contamination, are left for future conventional demolition, or situations in which these buildings, or the site itself, are used for other industrial purposes.

We will discuss the decommissioning activities starting from a situation in which spent fuel is not present any more on-site, or at least, in a completely independent storage facility. This removes from the plant more than 99,99% of the radioactivity present in the plant at the time of operation.

The main goal for the decommissioning activities is to place the facility in a condition that eliminate any risk for the health and safety of the general public and the environment, removing, in particular, from systems and structures any radioactivity that may have been accumulated during plant operations. Of course, all the decommissioning activities shall be carried out with great attention to assure the minimization of the risks to both the public and the workers involved in the process.

Decommissioning is a complex, long lasting and highly technological activity that presents smaller challenges, but similar to the plant construction activities. In some countries, in fact, it is called de-construction. Activities include use of technological tools, control of industrial safety, environmental impact minimization, licensing, safety analysis, structural analysis, etc. Other aspects very relevant are the activity planning, the calculation of related cash flow and anticipation of the funds needed to perform the activities. Aspects related to waste disposal and spent fuel strategy shall be covered as well.

2. Current decommissioning activities in the world

All power plants, coal, gas and nuclear, have a finite life beyond which it is no longer economical to operate them. Generally speaking, Nuclear Power Plants (NPP's) were designed for a life of about 30 years, though some have proved capable of continuing well beyond this term. Newer plants are designed for a 40 to 60 years operating life. To date, 70 commercial power reactors, over 250 research reactors and a number of fuel cycle facilities, have been retired from operation. Some of these have been fully dismantled. Assuming an average of about 25-years lifespan, almost 300 nuclear power plants would have to be decommissioned by the year 2010. By appropriate refurbishment, replacement or upgrading of some equipment, operations at many of these plants can probably be extended well beyond this conservative estimate.

However, ultimately it becomes either technically or economically advantageous to retire a facility from operation and, if necessary, replace it with a new plant.



Figure 1 – Location of Italian NPP's in decommissioning

In Italy 4 Nuclear Power Plants have been prematurely definitely shutdown and are now in different stages of decommissioning. They were operated by the National Electrical Utility ENEL, now partially privatized. In figure 1, the names and location of these plants are reported. The responsibility of carrying out the decommissioning projects and to manage the spent fuel has passed in the 1999 to SOGIN Company (which includes all nuclear competences of ENEL), which is now completely owned by the Italian Government (Ministry of Treasury). In Table 1 the main characteristics of these plants are summarized.

Table 1 - Italian NPP's main data

<i>Plant</i>	<i>Type</i>	<i>Designer</i>	<i>Mwe</i>	<i>Commercial operations</i>	<i>Plant shutdown</i>
Latina	Magnox	TNPG	200	1963	1986
Garigliano	BWR Dual cycle	General Electric	150	1964	1978
Trino	PWR	Westinghouse	260	1964	1987
Caorso	BWR	AMN - GETSCO	860	1978	1986

3. Possible decommissioning strategies

Possible approaches to decommissioning a Nuclear Power Plant may be widely varied and the optimal choice is made on the bases of a number of parameters which, in most cases, are site specific or, at least, country specific. Therefore there is no single optimal approach for all facilities. Decommissioning process could be subdivided, in somewhat schematic way, into stages. There is no official definition of the different stages, each country using its own definitions which vary slightly to suit each case. We could mention, as an example, the IAEA Technical Reports Series N° 375, "Safe Enclosure of Shut Down Nuclear Installations", 1995, which provides the following definitions:

"According to the definition of IAEA stages of decommissioning, the nuclear fuel or radioactive materials in the process systems as well as radioactive waters produced in normal operation is first removed by routine operation. Each of the three decommissioning stages of a nuclear plant can be defined by:

- *the physical state of the plant and its equipment ;*
- *the surveillance, inspections and tests necessitated by that state.*

Stage 1

- a) *The first contamination barrier is kept as it was during operation but the mechanical opening systems are permanently blocked and sealed (valves, plugs etc.). The containment building is kept in a state appropriate to the remaining hazard. The atmosphere inside the containment building is subject to appropriate control. Access to the inside of the containment building is subject to monitoring and surveillance procedures.*
- b) *The unit is under surveillance and the equipment necessary for monitoring radioactivity both inside the plant and in the area around it is kept in good condition and used when necessary and in accordance with national legal requirements. Inspections are carried out to check that the plant remains in good condition. If necessary, checks are carried out to see that there are no leaks in the first contamination barrier and the containment building.*

Stage 2

- a) *The first contamination barrier is reduced to a minimum size (all parts easily dismantled are removed). The sealing of that barrier is reinforced by physical means and the biological shield is extended if necessary so that it completely surrounds the barrier. After decontamination to acceptable levels, the containment building and the nuclear ventilation systems may be modified or removed if they no longer play a role in radiological safety and, depending on the extent to which other equipment is removed decontaminated, access to the former containment building, if it is left standing, can be permitted. The non-radioactive parts of the plant (buildings or equipment) may be converted for new purposes.*
- b) *Surveillance around the barrier can be relaxed but is desirable for periodic spot checks to be continued, as well as surveillance of the environment. External inspections of the sealed parts should be performed. Checks for leaks are no longer necessary on any remaining containment buildings.*

Stage 3

All materials, equipment and part of the plant, the activity of which remains significant despite decontamination procedures are removed. In all remaining parts contamination has been reduced to acceptable levels. The plant is decommissioned

(released) without restrictions. From the viewpoint of radiological protection, no further surveillance, inspection or tests are necessary.’’

Other terms that are widely used to describe the strategy adopted for the decommissioning are those that have been introduced in USA by the Nuclear Regulatory Commission (US NRC):

DECON (or one step dismantling):

In this strategy, all components and structures that are radioactive are cleaned or dismantled, packaged and transported to a low-level waste disposal site (if available) or stored temporarily on site. Once this task is completed, the facility can be used for another power plant or other purposes, without restrictions.

SAFSTOR (or Safe Storage):

In SAFSTOR, the nuclear plant is kept intact and placed in protective storage for a very long time (up to 60 years²), and afterwards it is dismantled. This method, which involves locking that part of the plant containing radioactive materials and monitoring it with an on-site security force, uses time as a decontaminating agent—that is, the radioactive atoms "decay" by emitting their extra energy to become non-radioactive or stable atoms.³ Once radioactivity has decayed to low levels, the activity is the same as the one described above as DECON. All building structures and systems which are necessary for workers and public safety shall be maintained in service during the safe storage period. A pre-condition to reach the safe storage condition is that the fuel has been removed from the plant and that radioactive liquids have been drained from systems and components and then processed.

ENTOMBMENT:

The radioactive inventory is enclosed in a monolithic structure, e.g. concrete, to secure the public safety. The monolithic structure should ensure integrity for about 100 years to derive benefit from the decay of the nuclides. After the entombment period, all enclosed components are very low radioactive and the assumption should be that dismantling at that time can be performed in a "conventional" way. During entombment the plant remains under a nuclear license.

The 3 categories presented above are a crude schematization of various situations. The DECON strategy for example may imply a really "quick" decommissioning and dismantling, or a longer process, that might optimize the use of plant personnel and reduce costs associated with engulfing activities on site.

² 60 years is a limitation existing in the USA. In other countries this condition may last longer up to 100 years and more

³ If a plant is allowed to sit idle for 30 years, for example, only about 1/50th of its original radioactivity from cobalt-60 will remain; after 50 years, some 1/1,000th will remain.

On the other side, the SAFSTOR option may really imply a simple “close and seal the door”, or a combination of immediate dismantling and safe store. In the latter case it may be considered the immediate dismantling of systems and buildings which are not, or only slightly, contaminated and a SAFSTOR strategy for the most radioactive portion of the plant. Also the safe storage period may range from 30 to more than 100 years, depending on a number of parameters and conditions that will be discussed later.

The third strategy (ENTOMBMENT) has never been applied yet to a NPP. There are several reasons for that. The first one is that the size of a NPP is too large to be simply entombed. A second reason is related to the fact that most power reactors will have radionuclides in concentrations exceeding the limits for unrestricted use even after 100 years and more and therefore this strategy cannot be successful. ENTOMBMENT is, however, a possible strategy for smaller reactors and for other small nuclear facilities.

4. Main decommissioning activities

The complete decommissioning process involves a number of stages (or activities) that shall be performed, even if the logical sequence may be changed according to the specific strategy.

Decommissioning Planning – The decommissioning planning is usually started while the plant is still operating. Some decision making process and some planning, associated with some cost evaluation shall be started well on time, since it is needed also for fund accumulation, that usually is performed during plant operation.

Post-Operation – It is the sum of the activities that are needed to maintain the safety of the plant even after the plant has been definitely shutdown. These activities are more relevant while the spent fuel is still present in the plant.

Characterization – The knowledge of the radioactive inventory in the systems, components and structures before start of decommissioning is a fundamental information to define strategy, costs, technologies and so on. Characterization is also an important process during plant dismantling in order to know exactly the content of the produced wastes. Finally, characterization is also an important, and complex activity to demonstrate that structures and systems, that have not been dismantled because no radioactive, are actually in this condition. In Table 2 a typical list of radioactive isotopes relevant to the decommissioning of NPP's is reported.

Decontamination – It is an activity that is oriented to remove radioactivity from systems and structures, in order to release components, to reduce doses to workers and to reduce the volume of wastes. It is applied to floors, walls, piping, etc. and may be performed essentially with mechanical or chemical means.

Dismantling – It is the real demolition activity. It may be a rather simple and quick activity, using conventional tools, but it may also be a very complex activity in the case of highly radioactive parts, using remote cutting and other sophisticated tools.

Safe Storage – It is the period in which the plant is left in dormancy, waiting for the radioactive decay. The plant is not left without controls, but a number of activities are still needed and, in some cases, some maintenance and even construction activities are necessary to maintain the safety for the workers and the public.

Table 2 – Major radionuclides identified in facility characterization

Isotope	Half-life (years)	Principal decay mode	Associated γ energy (MeV)	Materials where isotopes can be found
NEUTRON ACTIVATION PRODUCTS FOUND IN NUCLEAR REACTORS⁴				
H ³ ⁵	12,3	β^-	-	C, O, S ²
C ¹⁴	5730	β^-	-	G, M, S
Na ²² ²	2,6	EC, β^+	0,51 - 1,28	O
Cl ³⁶	3,1 10 ⁸	β^- , EC	-	C
Ar ³⁹ ²	269	β^-	-	C
Ca ⁴¹	1 10 ⁵	EC	-	C
Ca ⁴⁵	0,4	β^-	-	C
V ⁴⁹ ²	0,9	EC	-	S ²
Mn ⁵⁴	0,9	EC, γ	0,83	A, M, S
Fe ⁵⁵ ²	2,7	EC	-	C, M, O, S ²
Co ⁵⁷ ²	0,7	EC, γ	0,12 - 0,14	S ²
Co ⁶⁰ ²	5,3	β^- , γ	1,2 - 1,3	C, M, O, S, Z
Ni ⁵⁹	7,5 10 ⁴	EC	-	C, M, O, S, Z
Ni ⁶³ ²	100	β^-	-	C, M, O, S ²
Zn ⁶⁵	0,7	β^+ , γ , EC	0,51 - 1,12	A
Zr ⁹³	1,5 10 ⁶	β^-	-	O, Z
Nb ⁹⁴	2 10 ⁴	β^- , γ	0,70 - 0,87	M, O, S, Z
Mo ⁹³	3,5 10 ³	EC, γ^-	0,3	M
Ag ^{108,m}	130	EC, γ	0,4 - 0,6 - 0,7	M, O, S
Ag ^{110,m}	0,7	β^- , γ	0,6 - 0,9	M, O, S
Ba ¹³³ ²	10,7	EC, γ	0,08 - 0,36	C
Sm ¹⁵¹	93	β^- , γ	0,02	C
Eu ¹⁵²	13,4	β^- , γ , EC	0,1	C, G
Eu ¹⁵⁴	8,2	β^- , γ	0,1 - 1,3	C, G

⁴ Fission products are also often found in nuclear reactors as a result of defects in the fuel cladding

⁵ Important in fusion devices also

5. Major factors relevant to the decommissioning strategy and planning

Optimization of a decommissioning strategy is a rather complex process. The parameters to be considered can be grouped in 3 categories: technical, economical, socio-political.

In the first group it is possible to list the following aspects:

- **Radioactive inventory** – Depending on the amount and characteristics of the radioactive inventory the strategy can change. For example, plants which experienced accidents with radioactive release or incidental spilling on the floors, or contamination of insulation, may require special attention. On the other side plants which have been prematurely shutdown may have a lower total inventory and a long Safe Storage period may not be justified.
- **Presence of other operating units on the same site or in the country** – This situation may imply the maintenance of a high level of nuclear technology that will be available for a longer time. To have them on the same site means also that the site cannot be released anyway and that work force can be easily re-employed. Therefore, generally, it is convenient to wait some time before dismantling.
- **Availability of a national waste repository** – Decommissioning and dismantling means essentially to cut in pieces a NPP and to concentrate and package the radioactivity. This is of little advantage if all the radioactive material shall remain on-site. In addition, if a repository does not exist, uncertainties are present on the specification of packaging that will be finally required by the repository, once it will be made available.
- **Clearance levels and waste disposal costs**– Clearance levels are of fundamental importance to decide which strategy and which technologies shall be used. Since clearance levels can vary even by one order of magnitude and more, correspondingly the amount of radioactive wastes to be generated, classified as such, can vary by even more than one order of magnitude. This, in connection with the cost of waste final disposal, can force the decision in favor or against the preliminary decontamination of systems and structures.
- **Plant layout** – Difficulties in the dismantling process due to very compact layouts may lead to decisions about preliminary decontamination and different cutting strategies
- **Safety conditions of structures and systems** – Costs of maintaining the safe storage condition for decades shall be low to make the SAFSTOR strategy convenient. This means that structural conditions and corrosion conditions of all components shall be good and capable to withstand the expected conditions for several decades, without any need for major refurbishment.

- **Expectations about development of licensing rules and of technologies for decommissioning** – Licensing rules and available technologies change usually more quickly than expected. This is the experience of the last years. Extrapolations of the situation in 50 or 100 years are extremely difficult to be made and, more important, extremely uncertain. This means that in the case of the safe storage strategy it is wise to use contingencies in cost calculations and to leave open the introduction to new technologies.
- **Connections between conventional and nuclear safety** – In a NPP there are also some conventional safety issues and a production of conventional waste (such as asbestos). Complications may arise when the same waste is at the same time radioactive and toxic, such as in the case of contaminated asbestos. The extent of such situation may lead to the use of special techniques of dismantling and waste packaging.
- **Status of plant configuration documentation** - In the lack of a good documentation about plant design bases, plant modifications and plant conditions, the knowledge of the plant staff might lead to the decision to perform as many as possible activities, while the people are still available.

Worker doses are not included in the previous list, since it is assumed that with proper preparation and the use of proper tools, including remote operations and decontamination activities, the worker dose can always be reduced to acceptable levels. Also environment and public health impact levels have not been included in this list, since they are generally so low that do not present any serious concern. Of course also these elements have to be taken into account in a complete strategy evaluation.

In the second group, the following elements have to be considered:

- **Availability of funding** - Generally the fund accumulation during plant operation is based on a cost evaluation, which, in turn, is based on a specific strategy. Any change of the strategy would imply the identification of different fund sources.
- **Expectations about cost evolutions** - Calculated costs are affected by a certain level of uncertainties. Uncertainties grow with the extension of calculation extrapolation, because of the uncertainties in the evolution of technologies and the evolution in the safety rules and in the costs of waste disposal. The need to reduce uncertainties implies a reduction of decommissioning duration
- **Expectations in terms of inflation rate** - Funds tend to grow, because, with proper investments, they will produce a net interest. Assumptions about this net interest (that usually range from 2% to 5 %) are very sensitive for the definition of the convenience of different strategies
- **Assumptions in terms of contingencies** - Excessive contingencies intended as provisional funds to cover unexpected situations may tend to increase the needed

funds. In general, the amount of contingencies may be reduced, obviously, when the decommissioning time is shortened.

In the third group, the following aspects can be listed:

- **Work force policy** - In general at the time of final plant shutdown of one unit the work force is between 200 and 500 people. If the unit is isolated on the site and if the utility has no other nuclear operating plant, the social situation may become acute, also in areas industrially developed. Therefore the worker decrease curve shall be carefully studied and their useful employment in the decommissioning process shall be planned, even considering their requalification.
- **Pressures by central or local authorities** - Pressures may exist from local and central authorities to clean up the site as soon as possible to solve the occupational issue mentioned above, to improve the "image" of a certain area with touristic or agricultural objectives, and so on.

Detailed planning of the decommissioning activity is also a difficult task. Very few activities are routine activities and some last for years.

Dismantling can be approached in several ways, depending on the specific circumstances. For example the process can be followed "room by room", dismantling everything present in a specific room of the plant, possibly starting from the most contaminated components to reduce the overall doses, or from the easiest components, in order to facilitate the remaining operations. Or it may proceed, system by system, keeping operating some support systems that may be still useful in the operations. In the general case the solution is a combination of the two strategies, to be decided on a case by case basis.

It is also necessary to mention that planning is also difficult because the plant configuration is different day by day. To keep under control the status of the plant and its configuration is an heavy task, addressed generally with complex and specific planning tools.

6. Waste management

Wastes related to plant decommissioning come only from the structures of the plant which have been either irradiated or contaminated with radioactive isotopes.

Criteria for waste classification are not standardized worldwide and therefore a consensus classification is not possible. Criteria may be related to the type of isotopes, to their concentration and/or to the total amount of radioactivity in a package. However, in general, 3 categories of wastes are identified:

1. Low level radwaste – these are waste that would not be radioactive (i.e. their radioactivity will be below the clearance level⁶) in a period that can last from few days to some decades. This type of waste is not the waste that concern most in the decommissioning. In the cases in which also concentration is important, then it becomes a very important issue for decommissioning. In fact, one of the isotopes that may influence the entire decommissioning process is Cobalt-60, which has an half-life of 5,3 years. Since it is present in significant quantities in all plants and since it is dangerous to workers, because it decays with a strong gamma, it may lead to very large quantities of waste. Therefore the need for concentration of radioactivity, the appropriate treatment and the waste form is strictly related to the country regulations, definitions and disposal costs for such a type of waste.
2. Intermediate level radwaste – this is the waste which needs up to some centuries to decay below the clearance threshold level
3. High level radwaste – All other radioactive waste, that do not fit in the 2 previous categories are classified as high level waste. This category may include activated materials, components contaminated with transuranic isotopes, Carbon-14 isotopes, such as graphite blocks of Magnox reactors, etc. Vitrified residues of reprocessing certainly fall into this category.

The need for proper processing indeed exists. However, in many cases the required technologies and the goals are the same as those for operational wastes. In particular, the goals to be achieved and optimized should be minimization of the quantities and volumes at the origin, stabilization, concentration, conditioning, sorting and packaging. Among the technologies used for waste conditioning we may recall: nitrification, bitumization, polymerization, cementation, super-compaction, incineration, vitrification, etc.

In fig.2 below a flow diagram is depicted to show the process of producing, treating, characterizing and packaging of decommissioning wastes.

⁶ The clearance “is the removal of material from a system of regulatory control provided that the radiological impact of these sources after removal from the system is sufficiently low as not to warrant any further control”

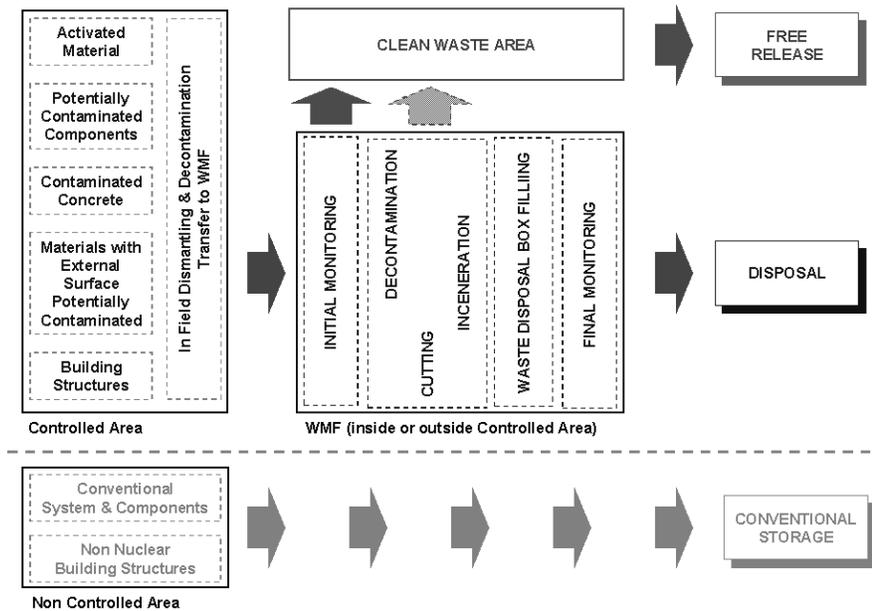


Figure 2 - Decommissioning waste processing

7. Decontamination technologies

The decontamination process is defined as the removal of contamination from the surfaces of installation structures and from internal and external surfaces of piping and equipment.

The major categories of techniques are washing, heating, chemical action, electrochemical action and mechanical action

The objectives of a decontamination process are:

- Reduce worker doses
- Reuse of materials and equipment
- Reduce the amount and volume of radioactive wastes to be disposed
- Remove radiological restraints in all or part of the plant
- Eliminate removable contamination and fix the other one
- Reduce the time after which a material can be freely released

Decontamination objectives can vary according to the specific strategy chosen and according to the specific phase of the decommissioning process. For example in the SAFSTOR strategy the decontamination can be reduced to eliminate the easy removable contamination and to minimize the doses to workers at the end of the safe store period.

In the definition of the most appropriate decontamination strategy considerations of cost-benefit must be applied. Decontamination itself causes doses to the operators and produces secondary wastes to be evaluated in terms of quantity and typology. This "cost" shall be compared with the corresponding savings expected as a consequence of the activity.

In the choice of a specific technology attention must be given to the specific geometry, surface characteristics and materials of the parts to be decontaminated.

Chemical techniques use diluted or concentrated solvents which come in contact with the radioactive substances to be dissolved. The dissolution may imply also the dissolution of part of the base material or simply of the radioactive deposit film on the surface. This last way is adopted when there is an interest in maintaining the integrity of the base metal such as in the case of operating plants, where the decontamination is applied only to reduce worker doses during maintenance activities. Chemical decontamination is applied by a continuous flushing in intact piping, creating a closed loop, and it is preferred for areas where access is difficult and for decontaminating the internal surfaces of piping. Chemical decontamination can be also successfully used for large areas such as floors and walls.

Mechanical decontamination (automatic or manual, locally or remotely controlled) is based on purely physical processes. It includes washing, flushing in closed loops, pipe swabbing, foaming agents and latex-peelable coatings. Most aggressive mechanical processes include wet or dry abrasive blasting, surface grinding, concrete spalling.

8. Dismantling technologies

The dismantling of a nuclear installation requires the cutting and segmenting of equipment and structures with varying sizes, dimensions, and materials. To assume a final decision it is necessary to take into account the acceptance specification of the national disposal site, where these wastes will be sent. In the USA, for example, some plants have disposed the entire reactor vessel, without any fine cutting. In other countries the vessel shall be segmented, generally with remote control techniques under water.

The conditions under which the cutting operations are carried out depend on the location and space of the working area, on the qualification and experiences of the

personnel, on the available tools and technologies as well as on the environmental conditions under which the operations will be performed: under water, in the air, under radioactive radiation, under contaminated atmosphere, etc.

There is a great diversity in existing cutting tools, which are useful and available under industrial conditions or in the R&D phase, each tool having its own performances, conditions and field of application.

The following techniques are presently available:

- thermal cutting
- hydraulic cutting
- laser cutting
- mechanical dismantling
- microwave spalling
- explosive cutting

When choosing cutting techniques the following factors should be taken into account:

- the technique (tool) should be used in practice, so that experience exists and a safety in furnish, spare parts and handling is available
- the technique (tool) should only generate a minimum of secondary waste, e.g. dust, particles, smokes, aerosols with controlled dispersion, liquid effluents
- low risk of contamination for personnel on site
- the technique (tool) has to be compatible to the working-environment.

In thermal cutting techniques, the solid material is melted and then blown away. Since molten states of material are present, the net amount of force needed is much smaller than for the techniques which use strain energy. Hence the contribution of mechanical force is only a minor part of thermal cutting processes.

It is possible to subdivide the thermal cutting techniques, according to the type of heat source, in:

- gas processes
- arc processes
- plasma arc processes
- a composition of the above processes

The energy density of the heat source increases from the gas flame over the arc and the plasma arc to the laser beam.

The abrasive water jet cutting technique is based on the application of plain water jets. Abrasive particles are accelerated by a high speed water jet and cause the removal of the material. Instead of an erosion process as in case of plain water jets, abrasive water jets cut by micro-chipping the material by the sharp-edged particles. When using the correct abrasive material, which has to be harder than the work piece material, any material can be cut - metals as well as ceramics, glass and concrete. With abrasive water jets, severance cutting as well as gouging, is possible. To generate abrasive water jets two different methods are currently available. The abrasive can be added to a plain water jet in a special mixing head (injection jet), or a premixed and pressurised abrasive water suspension can be released to the nozzle to form the abrasive jet (suspension jet). Sharp-edged mineral particles such as silicon sand, corundum or garnet sand are used as abrasives. The increasing number of cutting applications has helped the abrasive water suspension jet (AWSJ) to become more important despite the high consumption of water and abrasives.

The last groups of techniques are the mechanical cutting techniques. A limited list of such techniques is reported below as an example of the available alternatives to be optimized on a case by case basis:

- Grinder
- Hacksaw and Guillotine Saw
- Shears
- Milling Cutters and Orbital Cutters
- Knurl Tube Cutter (rotary disk knife or cutting wheel or plumber's pipe cutter)
- Diamond Saws and Cables

9. Health and safety aspects

The issue of health and safety aspects and the broader one of the environmental impact of the decommissioning process is far reaching and it may only be summarized.

It is convenient to distinguish at least three aspects:

1. Occupational safety, or safety of the workers directly involved in the decommissioning activities
2. Public safety, or the safety of the population surrounding the plant in decommissioning, excluding therefore those who may be affected by the waste disposal process
3. Environmental protection, including those aspects that are not directly related to human health

The first aspect is probably the most significant. Decommissioning is a very labour intensive activity and workers will be in contact with radioactive and other toxic wastes. However, all the means of the plant are still available to reduce the worker doses to the minimum and, while individual doses will always be below acceptable levels, an ALARA (As Low As Reasonably Achievable) analysis of single activities and process could reduce the cumulative occupational doses to values below a few years of plant operation for the entire decommissioning process (few hundreds of man-Sv).

Risks to the public are extremely low in comparison with those associated with plant operation. Radioactive inventory available for release to atmosphere or water bodies is a very small fraction of the previous ones. In general the most dangerous situations are associated with large fires in contaminated areas, breaks in tanks with large inventories of liquid radwaste, drop of contaminated loads. All these situations, however, in general would not even require the activation of an emergency plan.

The environmental issues, finally, are treated in a Environmental Impact Assessment (EIA), which is now required in Europe by a Directive of the European Union. Currently a lot of work is undergoing for a better harmonization of such assessments among the member countries. It is also needed to discuss the interaction between the EIA, presented generally to the Ministry of Environment, and the safety assessments that are presented to the Nuclear Regulatory Bodies. As in other EIA, the assessment would present an overall broad view on all interactions of the decommissioning with various environmental matrixes, and would include aspects not included in the Safety Report such as, for example, those related to site restoration, impact of material (radioactive and non radioactive) transports, disturbance to the local flora and fauna, etc.

10. Economic and financial aspects

Decommissioning is a costly activity. Therefore it is needed to calculate its cost well in advance and accumulate the funds during plant operation as an assurance for being able to close the existence cycle of the plant. Therefore both aspects of cost calculations and funding will be briefly addressed.

The total cost of decommissioning is dependent on the sequence and timing of the various stages of the program. Deferment of a stage tends to reduce its cost, due to decreasing radioactivity, but this may be offset by increased storage and surveillance costs.

Even allowing for uncertainties in cost estimates and applicable discount rates, decommissioning contributes less than 5% to total electricity generation costs. In USA many utilities have revised their cost projections downwards in the light of experience, and estimates now average 325 million dollars per reactor all-up.

The cost of decommissioning nuclear power plants is based on the following factors:

- The sequence of decommissioning stages chosen;
- The timing of each decommissioning stage;
- The decommissioning activities accomplished in each stage.

In addition, costs depend on such country- and site-specific factors as the type of reactor, waste management and disposal practices and labor rates. The importance of the last item is due to the fact that decommissioning is a labour intensive activity and, therefore, its cost is strongly connected with labour practices, working hours and, of course, labor rates.

Total decommissioning costs include all costs from the start of decommissioning until the site is released for unrestricted use.

The cost estimates are based on previous decommissioning and decontamination experience, on the cost of maintenance, surveillance and component replacements, and on the cost of similar non-nuclear work. Estimates for large NPPs. have been made by several European countries as well as Japan, Canada and the United States.

The results, which include a 25 per cent contingency factor, showed a range of costs for an immediate Stage 3 decommissioning of between 97 and 173 million U.S. dollars (1984). Costs for combining Stages 1 and 3 ranged from 117 to 181 million dollars. Only the United States estimated the costs of combining Stages 2 and 3, from 158 to 186 million dollars. While these figures cannot be absolutely precise, due to differences in the original contingency factors and definitions of decommissioning stages among countries, they nevertheless show what order of magnitude actual decommissioning costs are likely to be for large power plants.

Various methodologies are available for the calculation of decommissioning costs, which present different levels of reliability and precision and are used according to the different objectives of the evaluations. The major reasons that usually lead to the need of a cost evaluation are the following:

- To provide an input for the decommissioning funding during plant operational life
- To compare costs associated with different strategies for the decision making process
- To prepare long term budgeting and cash flow
- To provide a tool for project control

According to the above objectives, the methods include:

- Scaling up or down from similar plant evaluations or experiences according to plant power, or to the total plant activity or to the waste masses, or to other criteria
- Simple calculations based on unit costs for a number of overall parameters like mass of activated metals, mass of contaminated concrete, mass of contaminated metals. This method can be used also for a generic power plant (not site specific)
- Detailed site specific calculations based on a very detailed bottom-up approach, separating each elementary work package

In the last case a detailed database and a computer code treating a large number of information are needed.

For example, one of these computer codes (STILLKO) has been developed in Germany by NIS Company and has been extensively used not only in Germany, but also in many European countries, including Italy. The STILLKO Cost Breakdown Structure (CBS) includes all decommissioning activities that are necessary for the successful completion of the decommissioning project, beginning with the licensing procedure up to the green field status at the end. The CBS is organized into different levels in a hierarchical structure as described in fig. 3.

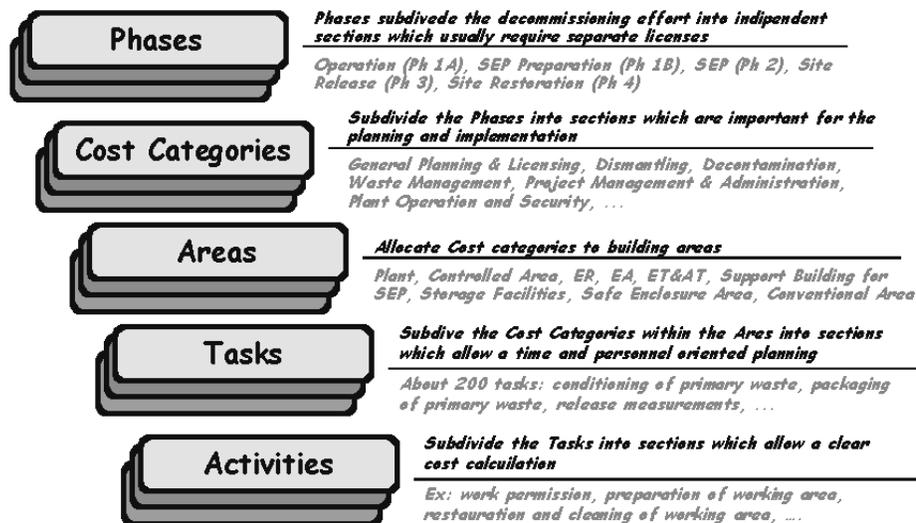


Figure 3 - Decommissioning Cost Breakdown Structure (CBS) Organization

On the first level the division of a decommissioning project is effected according to decommissioning phases which are separated according to time and obtained or necessary permits.

On the second level, the decommissioning phases are divided into the following cost categories:

- Project management and project administration
- Planning and licensing
- Plant operation and security
- Plant technical activities for Safe Enclosure
- Preparations for Dismantling
- Dismantling activated and contaminated components
- Decontamination
- Conventional dismantling
- Waste management
- Radiological and conventional worker protection

These cost categories have been created according to functional points of view and represent the volume of the decommissioning activities. The cost categories may occur in every decommissioning phase, with suitable contents of the cost categories regarding the respective phase.

The third level is used to allocate the decommissioning activities to the buildings and areas on site. Using this level in the cost structure it is possible to assign the work directly to the place where it arises but also to determine the sequence of the activities and their schedule in relation to the specific building.

On the fourth level, individual tasks are defined which allow a room by room or system by system planning, regarding to the situation on site. The execution of the tasks may be done parallel in different buildings, building levels or rooms.

On the fifth, the lowest level, the decommissioning tasks are divided into activities. These activities are formed in a way that each of them can be individually calculated.

It is useful to mention that a standardization of cost items has been developed in the framework of OECD and European Union and that it can be a useful reference for the future.

About financing methods, several alternatives can be used depending on the circumstances of each utility and the country in which it operates. In several countries, a fund of some type has been established, or proposed, to assure the availability of financing. This is usually done by an early estimation of the cost of decommissioning at the end of the normal plant lifetime and requiring payments, either annually or on a charge per kilowatt-hour basis, to ensure that this sum is in place. This estimate is updated regularly and the charge adjusted accordingly.

The drawback to this system is that the amount estimated would not be in place if the plant were to be shut down before the end of its normal lifetime. To avoid this, a fund could be established at the start of the plant's operation which would cover the cost of decommissioning whenever it became necessary. However, this represents a heavy burden for the utility at the moment when construction and start-up costs are already high, and thus, although it may be imposed by law, this solution is clearly not favoured by utilities.

Financing methods vary from country to country. Among the most common are:

- External sinking fund (Nuclear Power Levy): This is built up over the years from a percentage of the electricity rates charged to consumers. Proceeds are placed in a trust fund outside the utility's control. This is the main US system, where sufficient funds are set aside during the reactor's operating lifetime to cover the cost of decommissioning.
- Prepayment, where money is deposited in a separate account to cover decommissioning costs even before the plant begins operation. This may be done in a number of ways, but the funds cannot be withdrawn other than for decommissioning purposes.
- Surety fund, letter of credit, or insurance purchased by the utility to guarantee that decommissioning costs will be covered even if the utility defaults.

However, the uncertainties in cost calculations are among the issues in decommissioning that shall be further developed.

In Italy a fund has been established to enable the decommissioning of Italian NPPs and the closure of the nuclear fuel cycle. These special provisions are included in the Financial Statement of the SOGIN Company.

11. The need for R&D

From what has been seen, NPP's decommissioning appears to be a mature technology. However, while it is certainly true that we have today available all or most technologies needed to dismantle a NPP and return the site to essentially the initial, undisturbed condition, large margins exist for the process optimization in terms of efficiency, waste generation, occupational doses and especially costs. Specific areas that can be mentioned are:

- decontamination technologies : chemical, electrical, mechanical, ultrasonic ...
- dismantling technologies;
- improvement of waste volume minimisation ;
- non-metallic material recycling ;
- control and measurement techniques ;
- remote operations.

In this field the role of the universities may be limited, since the matter is more related to an industrial development in many cases at competitive levels among suppliers, but it is anyway important, in the advanced and high technology fields (advanced chemical decontamination, waste treatment such as vitrification, robotization, waste stream characterization), as well as in computer codes for dose or environmental impact calculations.

12. The Italian experiences in decommissioning

First ENEL and then SOGIN have carried out a number of activities in the framework of the general decommissioning programs. They are both in-field activities and planning and designing activities. The current situation at the four NPP's is the following:

Garigliano

- Reactor defuelling and off-site shipment of spent fuel: 1985 - 1987
- Radiological characterisation of plant systems, components and structures: 1990
- Safe Enclosure of Reactor building: 1990 - 1998
- Safe Enclosure of Turbine building: 1994 - 1995
- Treatment of low-level waste and retrieval/conditioning of intermediate-level and high-level waste: 1988 - 1999
- Dismantling and safe enclosure of existing Radwaste system, demolition of Off-gas stack and Safe Enclosure condition to be reached within the year 2003

Latina

- Reactor defuelling and off-site shipment of spent fuel: 1988 - 1991
- Radiological characterisation of plant systems, components and structures: 1992
- Decontamination and dismantling of systems and components: 1992 - 1996
- Decontamination of the spent fuel pool: 1996 - 1999
- Treatment of radioactive waste, dismantling of primary circuit ducts and components and Safe Enclosure condition to be reached within the year 2006

Trino

- Radiological characterisation of plant systems, components and structures: 1992 - 1994
- Reactor defuelling: 1991
- Temporary dry storage of spent fuel at plant site within the year 2003
- Safe Enclosure condition to be reached in the year 2007

Caorso

- Radiological characterisation of plant systems, components and structures: 1992 - 1995

- Reactor defuelling: 1998
- Temporary dry storage of spent fuel at plant site within the year 2004
- Safe Enclosure condition to be reached in the year 2009

Most of the above mentioned decommissioning activities (in particular at Garigliano and Latina sites) were carried out using experience and skill gained by Company personnel during plant operation, in particular:

- headquarters personnel were involved in the design and licensing activities,
- plant personnel, who operated the plant, were involved in the activities for plant operation termination and decontamination/dismantling activities.

Engineering and R&D Departments of ENEL were also involved in the development and design of special equipments and tools, used for waste retrieval and decontamination of structures.

After plants shutdown the plant staff were significantly reduced; part of the personnel were transferred to fossil power plants, and retired personnel were not replaced.

13. Conclusions

Some broad conclusions can be drawn from the issues that have been briefly discussed.

The first point is that decommissioning is mainly a management challenge. It is a complex and multi-faceted problem, whose optimum solution requires a multidisciplinary approach. Nuclear experts, therefore, should be highly interested in being involved in it without living this experience as a kind of tedious and dirty job that somebody else has to do.

From a technical standpoint it is a substantially mature technology, which may have, however, important margins of improvement. Application of new advanced technologies may lead to reduced doses to workers and reduced amount of wastes to be disposed, with consequential important economic advantages. It is also clear that the sooner the decommissioning is prepared (even during plant operation) the better it is. We might also say that decommissioning is something that should be addressed as early as in the plant design process, as currently imposed by utility requirements as EUR (European Utility Requirements) for advanced NPP's. And it should be understood that the proof that decommissioning can be completed in reasonable time and economically **may be a prerequisite for building new NPP's**.

From the financial standpoint, decommissioning is also a challenge, because it is a cost intensive activity without any important direct investment return, if we exclude site reuse and returns in terms of image for the utility or the region. Therefore, a

correct funding scheme is very important to provide for all necessary funds at the end of the plant operating life.

International consensus and harmonization are needed in several areas. This need has been recognized only recently, in the last years, when a greater number of NPP's have terminated their service life.

A decision making process transparent both to the politicians and to the public, who deserve the information they want in an activity that is finally for their assurance, is undoubtedly useful.

Finally, let me introduce an example of design of a modular inherently safe reactor, called MARS, developed since 1983 at the University "La Sapienza" of Rome, in which the decommissioning aspects have been taken into account since the beginning.

This design has been aimed at strongly simplifying the plant layout, the components construction and assembling on the site in order to reduce construction times and costs.

This effort has produced, as a parallel significant result, a huge simplification of all decommissioning activities. In particular, the basic design choices of the MARS plant affecting decommissioning are shown in Table 3. These choices produce the results shown in Table 4.

A quick sequence of pictures (figs. 4 to 6) is self-explaining of the decommissioning phases for this reactor.

Table 3 - MARS main design choices affecting decommissioning

The selected plant characteristics (specific power, temperature, pressure, thermal inertia, etc.) have allowed to simplify all non safety-related auxiliary systems thanks to reduced performances.
The extensive use of passive systems to assure plant safety has allowed to eliminate some traditional safety-related auxiliary systems (e.g. injection systems) or to strongly simplify other ones, reducing the number of redundant components (e.g. boron emergency shutdown).
The selected plant power has allowed to reduce the size of main components, making them easily transportable.
The selected process parameters, even if reducing the plant global efficiency, guarantee a great retention of fission products inside the fuel matrix, that, together with low stressed fuel cladding, strongly reduce the amount of fission products dispersed within the primary coolant.
The selected structural materials (extensive use of stainless steel, elimination of cobalt alloys, etc.) have allowed to reduce the materials activation.
The adoption of metal structures to support components, to build the working floors and the biological screen, have allowed to limit the amount of concrete in the plant, simplifying and speeding the construction phase.
The adoption of flanged connections between components and piping (also for the primary loop) has allowed the easy mounting and dismounting of all components.
The adoption of an innovative design for all big components has allowed the possibility of their easy and fast construction, assembling and disassembling.

Table 4 - MARS decommissioning characteristics

The disassembling of flanged connections allows the easy and fast removal of all primary loop components (the biggest components may be also disassembled in transportable sub-components) with no needs for special equipment or complex activities to disassembly activated components inside the reactor building.
The general plant simplification allows a huge reduction, up to 50% in comparison with a same size traditional plant, of the number of contaminated or activated components (pumps, valves, tanks, etc.), with the correspondent reduction of the amount of radioactive materials.
The limited size, as well as the possibility of disassembling of components allows their easy transportability.
The use of a "clean" primary coolant and the reduced number of components allows the reduction of total and specific contamination of all materials facing the primary coolant.
The exclusive use of metallic structures allows the strong reduction, up to 50% in comparison with a same size traditional plant, of the volume of concrete buildings potentially contaminated.
The reduced number of components to be removed, their limited size and the presence of flanged connections make the decommissioning operations faster and faster than in traditional plants (usually characterized by a lot of big components welded to piping).
The short and easy decommissioning phase allows a strong reduction of doses to personnel.
The short and easy decommissioning phase allows a strong reduction of decommissioning cost.

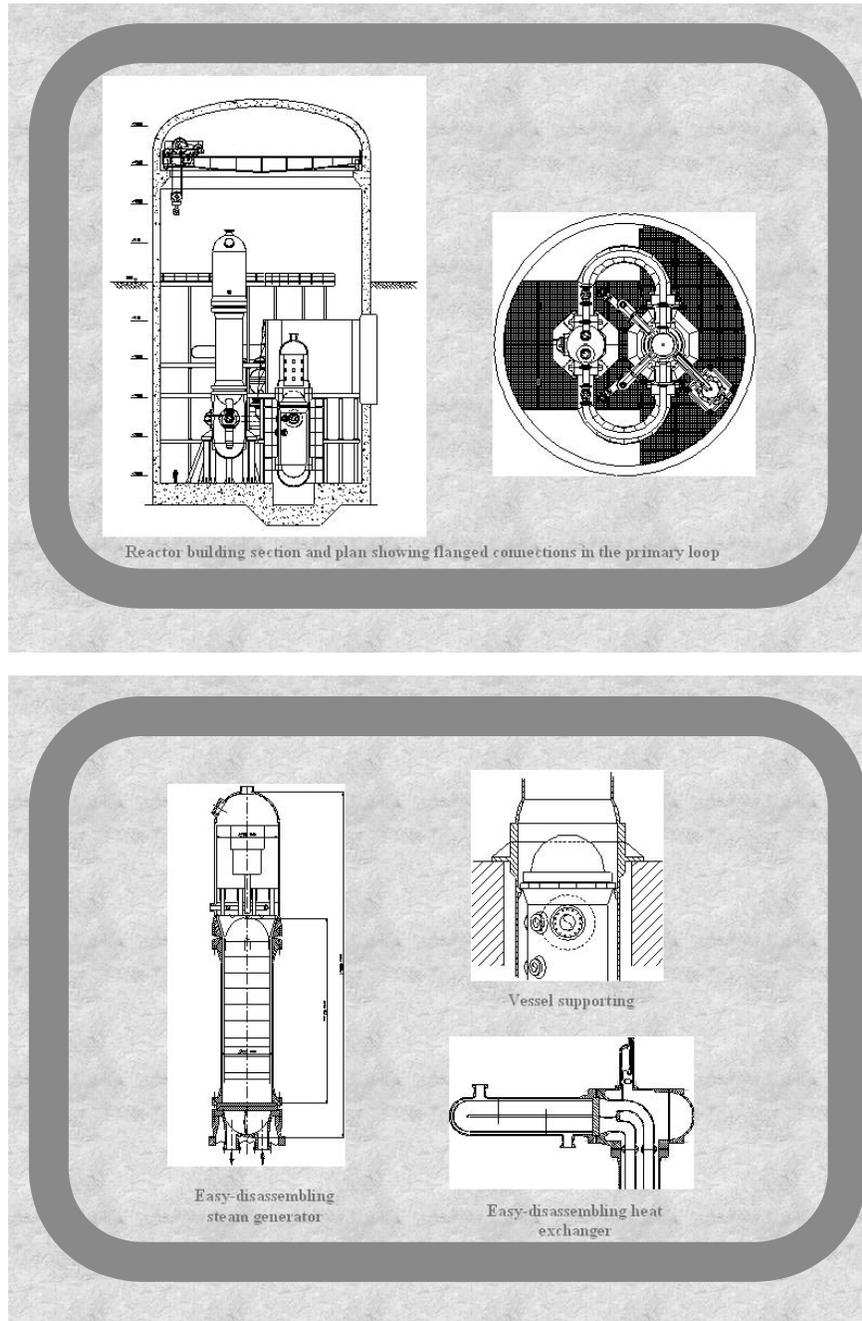


Figure 4 - MARS reactor design (Multipurpose Advanced Reactor inherently Safe)

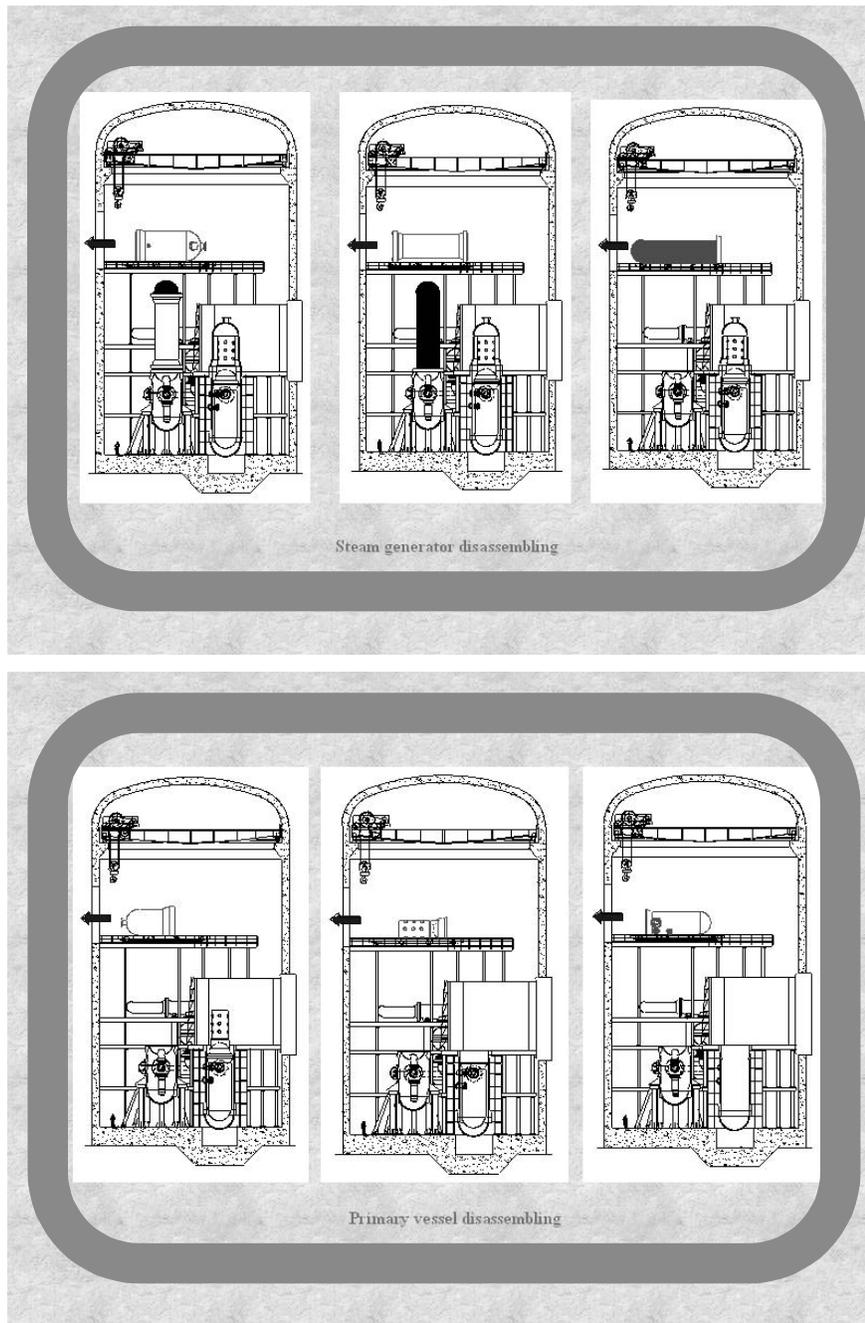


Figure 5 - Phases of decommissioning of MARS reactor

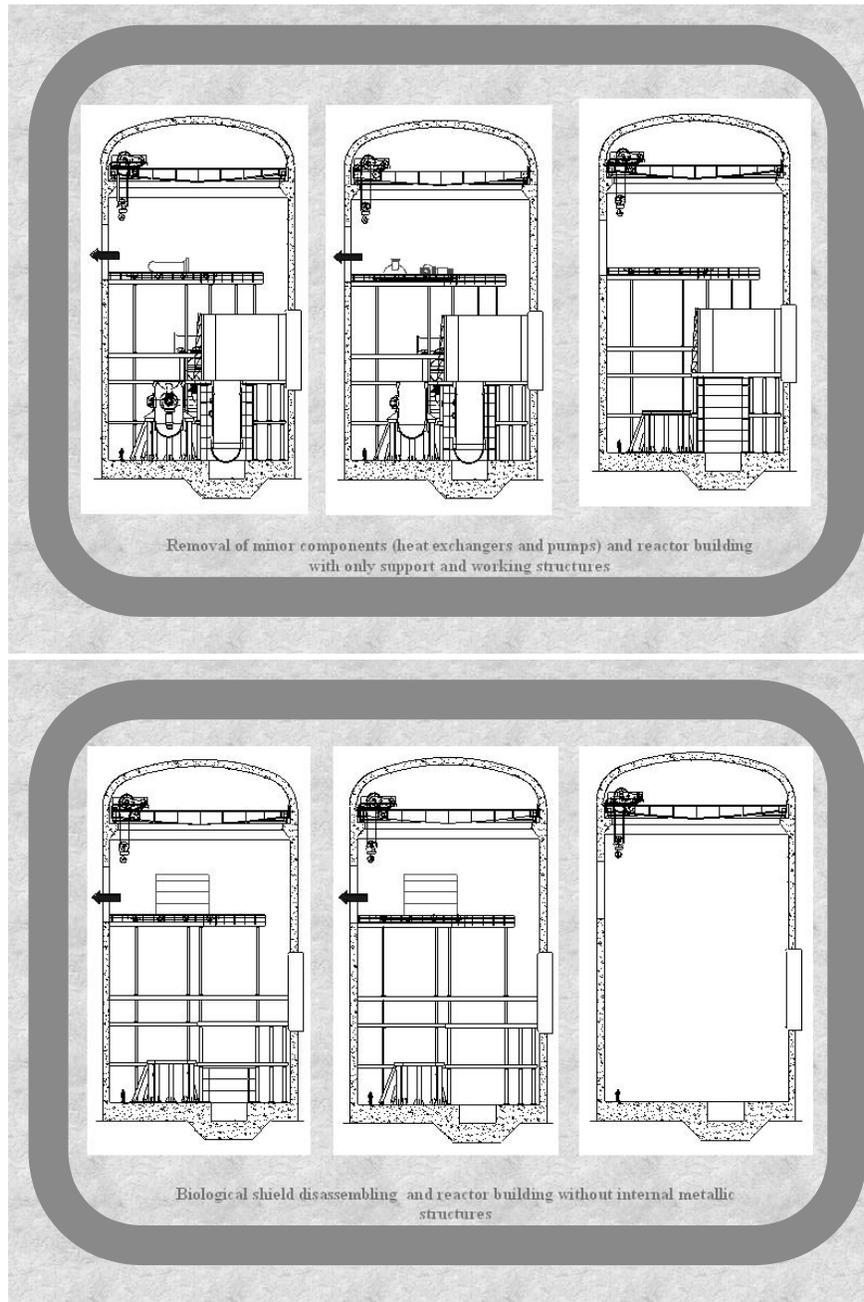


Figure 6 - Phases of decommissioning of MARS reactor