In: Floodplains ISBN 978-1-61728-277-5
Editor: Marc A. Alvarez, pp.

PLEASE QUOTE THIS DOCUMENT AS

Locatelli, G., Mancini, M. "Emergency planning zone: Constraints and opportunities for the development of nuclear energy and exploitation of its process heat"
(2011) Energy Resources: Development, Distribution and Exploitation, pp. 79-138.
PUBLISHER: Nova Science Publishers, Inc.

Chapter x

EMERGENCY PLANNING ZONE: CONSTRAINTS AND OPPORUNITIES FOR THE DEVELOPMENT OF NUCLEAR ENERGY AND EXPLOTATION OF ITS PROCESS HEAT

Giorgio Locatelli [*]
Mauro Mancini

Politecnico di milano department of Management, Economics & Industrial Engineering Via Lambruschini, 4B (Building 26/B) - 20156 Milano, Italy

[*] Corresponding author: POLITECNICO DI MILANO; Department of Management, Economics & Industrial Engineering; Via Lambruschini, 4B (Building 26/B) - 20156 Milano, Italy Tel: +39 02 2399 4096 Fax: +39 02 2399 4083
E-mail: giorgio.locatelli@polimi.it

ABSTRACT

Light Water Reactors (LWR), which represent the most common reactor in operation and under construction, have an average thermal efficiency of about 33%-35%, therefore two third of the thermal energy produced by the nuclear reaction is typically wasted. The literature presents many possible applications of this thermal energy, however most of them are not feasible because of economic and legislative constraints: among the others the Emergency Planning Zone (EPZ) is one of the most critic. The EPZ is the area surrounding the Nuclear Power Plants (NPP) subject to specific rules constraining the development of the area. These constraints avoid the complete exploitation of the energy produced by the power plants.

Small Medium Nuclear Reactors (SMR) can offset some of the constraints since they are intrinsically safer and therefore can theoretically require a smaller EPZ. This chapter deals with the relationships among the Emergency Planning Zone (EPZ), the reactor size and the possibilities of cogeneration. After a review of the constraints for the EPZ in the different countries it show the relationship among EPZ and NPP size and presents the various options of nuclear cogenerations. These options are evaluated according to the commercial feasibility of the different technologies clustering the solutions in short and long term options.

INTRODUCTION

A nuclear power plant (NPP) considered as a whole presents some by-products that can be exploited to create interesting synergies between the plant itself and potential nearby facilities. These by-products can be ascribed directly or indirectly to the nuclear plant:

- *Directly* if they derive from the nuclear reactor itself;
- *Indirectly* if they are due to the presence of the nuclear power station and, consequently, to the features of the location, the need of ancillary installations or the safety measures required by the NPP.

The main issue is whether - and how - these by-products can be harnessed in order to increase both the economic attractiveness and the social acceptability of the nuclear power plant.
The average electric efficiency of a Light Whater Reactor (LWR), the most common technology for existing reactor and proposed plant (as

EPR, AP1000, ABWR, IRIS etc…) is about 33%. These two thirds of the thermal power produced by the reactor are wasted in the environment while converting heat into electricity. The “wasted” heat can be used in a co-generation mode for several purposes, depending mainly on the outlet temperature of the reactor (and, consequently, on the reactor type). Co-generation allows achieving overall efficiencies (thermal and electrical) up to 85%. This means that the primary energy used to produce at the same time heat and electricity is much lower than the primary energy that would be required to produce separately the same amounts of heat and electricity. Moreover, the cost of heat production is lower if compared to the separate mode, because of the availability of an almost free heat source. Finally, the consumption of fossil fuels for heat production is strongly reduced: this leads to reduced greenhouse gas emissions.

Depending on the reactor type, it is possible to combine applications operating at low or high temperature. Low temperature applications basically belong to three categories: district heating (for residential, commercial or agricultural use), desalination and process heat delivery to factories with low-temperature requirements. High temperature applications are more innovative and can be subdivided into: hydrogen production (in order to store and distribute energy), process heat for industries that operate at high temperatures, oil shale extraction and biomass gasification or other fuel syntheses. Potential nuclear heat applications are described in section 2.

Nuclear legislation prescribes mandatory safety measures, such as Emergency Planning Zones (EPZs) and site selection criteria. As a consequence, NPPs are usually placed in scarcely populated areas, surrounded by kilometres of unused land. In particular, the EPZ around a nuclear plant causes major impediments to human activities and industrial uses of the site, as it imposes measures such as the possibility of a total evacuation in case of an accident. The current challenge is to reduce the width of emergency zones, making them proportional to the safety and size of the reactor. Therefore, EPZs for new reactors belonging to Generations III+ and IV are likely to have a smaller extension than traditional reactors, however, this is not sure. Moreover, nuclear legislation differs from country to country, and some governments could decide to maintain standard EPZ sizes even for innovative reactors. If such reductions won’t be possible, the mentioned areas should then be exploited in the most profitable way. These areas can be employed with applications that require wide extensions of ground but that do not require a high human density, such as industrial parks, or farming installations for the cultivation of energy crops, or renewable energy generation plants, such as photovoltaic or wind turbines, depending on the meteorological conditions of the site. Particular attention has been posed on the EPZ topic, which is developed in the next sections

In order to identify possible applications to harness the by-products of a NPP, it is necessary to understand what implications the construction of a NPP would bring, both on the human and the industrial development of the surrounding areas. For example, it is important to know the minimum distance at which people can be settled, the allowed density, and whether there are legislations that *a priori* exclude the development of certain applications, as the related facilities interacting with the NPP are considered too hazardous.

The analysis starts from the risk zoning around a NPP and the site selection criteria for its construction. Risk zoning is the identification of diverse EPZs (Emergency Planning Zones) around the NPP, where particular safety measures have to be taken: this chapter gives the official definition of EPZs and describes the risk zones around a NPP, according standards set by the IAEA (International Atomic Energy Agency) and the NUREG (NUclear REGulation of the USA), in order to supply a regulatory frame. Then, it describes the current status of EPZs in many countries. Thus, it notice that, despite suggestions provided by international legislations, each country can decide its own EPZ features, and the risk zoning methods vary significantly from country to country: international regulations are rather guidelines that can be taken as reference. It goes trough the site selection criteria in order to identify constraints and rules for the siting of a NPP and for population and industrial development in the adjacent areas. The main idea that emerged is that the presence of a particular facility cannot be excluded *a priori*: international standards state that although a facility may be regarded as potentially hazardous, its feasibility has to be investigated and justified through economic, environmental, safety and technical factors. It is also necessary to analyze its interaction with the NPP in order to definitively prove its safety.

1 SECTION ONE: THE EPZ

1.1 IAEA's definition of EPZ

The IAEA (IAEA, 2003) defines three threat categories of nuclear reactors reported in Table 1.

For most accident types, emergency response takes place over two distinct areas:

1. *On-site area:* it is the area surrounding the facility and within the security perimeter, fence or other designated property marker. This area is under the immediate control of the facility or operator;
2. *Off-site area:* it is the area beyond the on-site area. For facilities with the potential for emergencies resulting in major off-site releases or exposures (threat categories I and II), the level of planning will vary depending on the distance from the facility, as explained later.

The threat category of nuclear reactors depends on their power, as shown in Table 2

THREAT CATEGORY	***DESCRIPTION***
I	Facilities, such as NPPs, for which on-site events (including very low probability events) are postulated that could give rise to <u>severe deterministic health effects off the site</u>, or for which such events have occurred in similar facilities.
II	Facilities, such as some types of research reactors, for which on-site events are postulated that could give rise to <u>radiation doses to people off the site that warrant urgent protective actions</u> in accordance with international standards, or for which such events have occurred in similar facilities.
III	Facilities, such as industrial irradiation facilities, for which on-site events are postulated that could give rise to radiation doses that warrant or contamination that warrants urgent protective actions on the site, or for which such events have occurred in similar facilities.

Table 1 – Emergency Planning Categories (IAEA, 2003)

REACTOR POWER	*THREAT SUMMARY*	*TYPICAL THREAT CATH.*
> 100 MWth	*Off site:* Emergencies involving <u>severe core damage</u> have the potential for causing <u>severe deterministic health effects, including deaths</u>. Radiation doses in excess of the urgent GILs (Generic Intervention Levels) are possible more than 5 km from the facility. Deposition resulting in radiation doses in excess of the relocation GILs and ingestion GALs (Generic Action Levels) is possible at great distances from the facility. An emergency not involving core damage has only a small potential for exceeding urgent GILs. *On site:* For core damage emergencies, doses sufficient to result in severe deterministic health effects, including deaths, are possible.	I or II
2 – 100 MWth	*Off site:* Radiation doses due to inhalation of short lived iodine in excess of urgent GILs are possible if cooling of the core is lost (core melt). *On site:* Potential for radiation doses in excess of urgent GILs if fuel cooling is lost. If shielding is lost, direct shine dose could exceed urgent GILs or result in severe deterministic health effects.	II or III
< 2 MWth	*Off site:* No potential for radiation doses in excess of urgent GILs. *On site:* Potential for radiation doses in excess of urgent GILs from inhalation (depending on design) if fuel cooling is lost. If shielding is lost, direct shine dose could exceed urgent GILs or result in severe deterministic health effects.	III

Table 2 – Threat categories for nuclear power reactors (IAEA, 2003)

Reactors with a power greater than 100 MWt (i.e. 33 MWe) will account for almost the totality of the market. Such designs include large reactors (LR) such as EPR Areva or AP 1000 by Westinghouse (about 4.500 MWth), or even small-medium reactors (SMR) like IRIS (335MWe - 1.000 MWth LWR). Moreover, all the reactors currently used in electro-nuclear power plants belong to category I. Thus, the chapter will only take into account EPZs for category I facilities.

Emergency planning (EP) for category I plants is the most demanding. According to the IAEA, planning and implementing the capabilities to handle emergencies in category I facilities will ensure that the capability exists to handle events belonging to the other categories. However, for on-site and local organizations, planning and implementation should be based on local practices and activities (IAEA, 1997). As concerns off-site facilities, emergency planning can be discussed for two EPZs, as illustrated in Figure 3 and described as follows (IAEA, 2003).

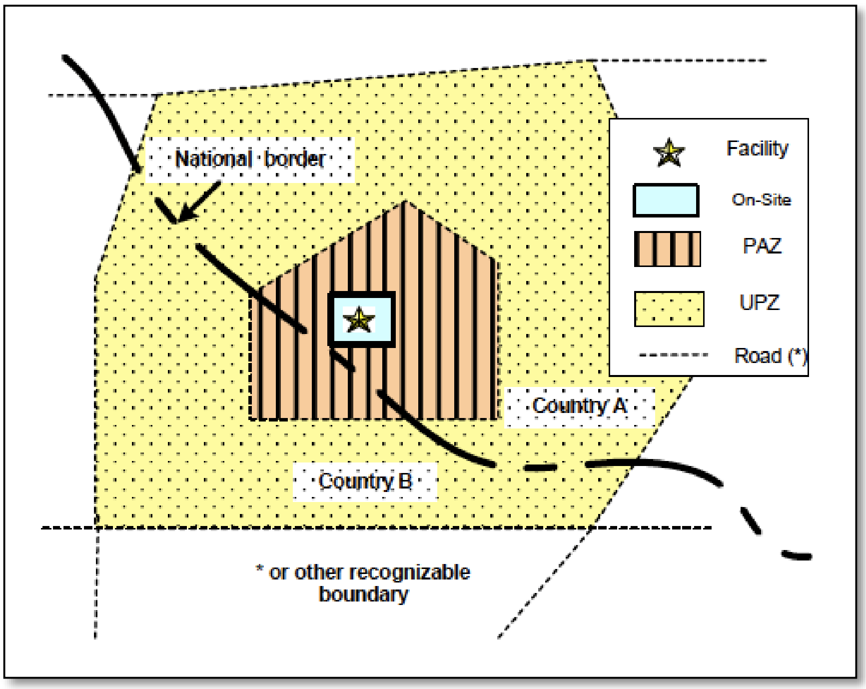

Figure 3 – Concept of Emergency Zone (IAEA, 2003)

Precautionary action zone (PAZ)

This is a pre-designated area around a facility in threat category I, where urgent protective actions has been pre-planned and will be implemented immediately upon declaration of a general emergency. The goal is to substantially reduce the risk of severe deterministic health effects by taking protective action within this zone before or shortly after a release.

Urgent protective action Planning Zone (UPZ)

This is a pre-designated area around a facility in threat category I or II. Inside the UPZ, preparations are made to promptly implement urgent protective actions based on environmental monitoring data and assessment of facility conditions, the goal being to avert radiation doses specified in international standards.

Long term protective action Planning Zone (LPZ)

It is the furthest pre-designated area around a facility and includes the UPZ. It is the area where preparations for the effective implementation of protective actions to reduce the long-term radiation dose from deposition and ingestion should be developed in advance (IAEA, 1997). When the IAEA-TECDOC 953 was updated in 2003, LPZ was replaced with "*Food Restriction Zone*", as shown by comparing Figures 4 and 5.

As pointed out later, only the PAZ and the UPZ as belonging to the EPZ, excluding the LPZ (or FRZ), because it does not impose evacuation planning.

EPZs should be roughly circular areas around the facility, their boundaries defined by local landmarks (e.g. roads or rivers) to allow easy identification during a response. It is important to note that the zones do not stop at national borders.

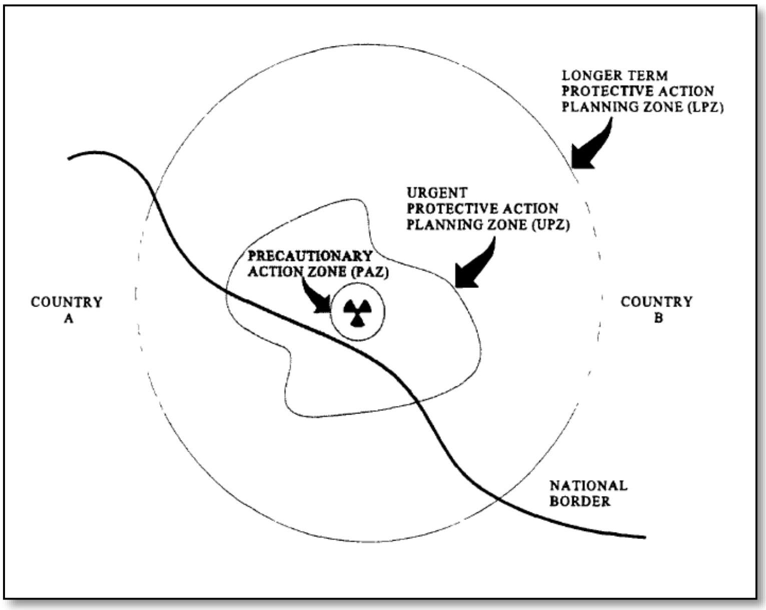

Figure 4 – Emergency planning zones and radii (IAEA, 1997)

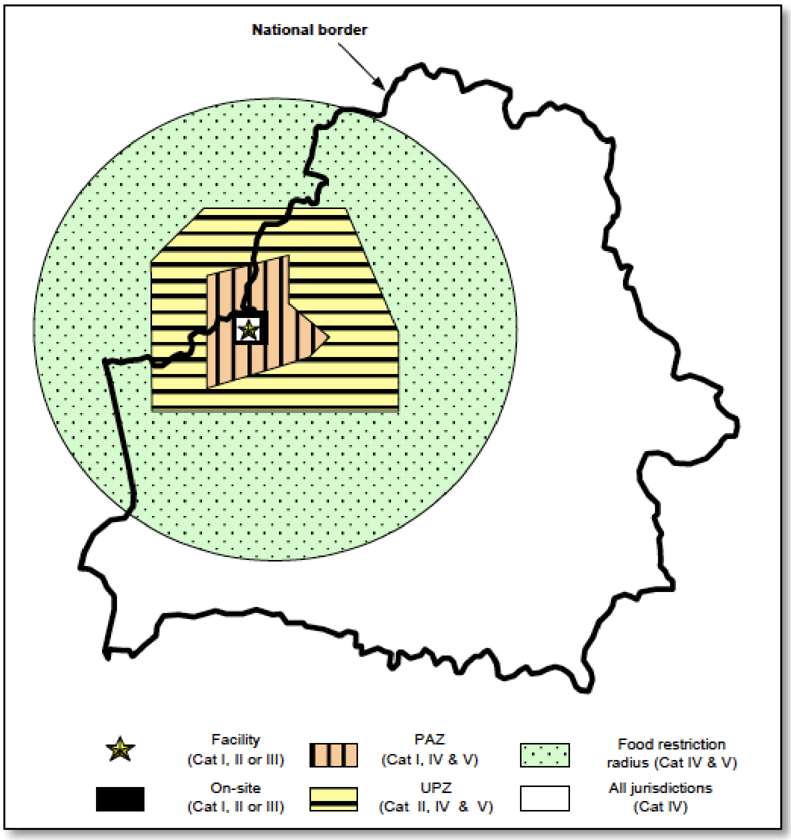

Figure 5 – Emergency zones and radii updated (IAEA, 2003)

The size of the zones has to be determined by an analysis of the potential consequences following an accident. However, previous studies ((NRC, 1990) and (NRC, 1988)) of a full range of radiological and nuclear accidents provide a basis for generic zone sizes, as summarized in Table 3. It must be noticed that these <u>suggestions are provided with recognition of the great uncertainties involved and variation by a factor of two or more during application is reasonable</u>. The choice of the suggested radii represents a judgment of the distance to which it is reasonable to make advanced arrangements in order to ensure effective response. In a particular emergency zone, protective actions may be warranted only in a small part of the zones. For the worst possible emergencies, protective actions might need to be taken beyond the suggested radii (IAEA, 2003).

Facility category	***Reactors power***	***PAZ Radius***	***UPZ Radius***	***LPZ Radius (*)***	***FRZ Radius***
I	> 1000 MWth	3-5 km	25 km	50-100 km	300 km
I	100-1000 MWth	0.5-3 km	5-25 km	50-100 km	50-300 km

(*) LPZ has been substituted with FRZ (Food Restriction Zone)

Table 3 – Suggested emergency zones and radii for threat category I and II (adapted from (IAEA, 2003) and (IAEA, 1997))

The suggested sizes for the PAZ were based on expert judgment considering the following (IAEA, 2003):

- ❖ urgent protective actions taken before or shortly after a release within this radius will prevent radiation doses above the early death thresholds for the vast majority of severe emergencies postulated for these facilities;
- ❖ urgent protective actions taken before or shortly after a release within this radius will avert radiation doses;
- ❖ radiation dose rates that could have been fatal within a few hours were observed at these distances during the Chernobyl accident;
- ❖ <u>the maximum reasonable radius for the PAZ is assumed to be 5 km because</u>:
    - ▪ except for the most severe emergencies, it is the limit to which early deaths are postulated;
    - ▪ it provides about a factor of ten reduction in the radiation dose compared to the dose on the site;
    - ▪ it is very unlikely that urgent protective actions will be warranted at a significant distance beyond this radial distance;
    - ▪ <u>it is considered the practical limit of the distance to which substantial sheltering or evacuation can be promptly implemented before or shortly after a release</u>;
    - ▪ implementing precautionary urgent protective actions to a larger radius may reduce the effectiveness of the action for people near the site, who are at the greatest risk.

The suggested sizes for the UPZ are based on expert judgment considering the following (IAEA, 2003):

- ❖ these are the radial distances at which monitoring to locate and evacuate hot spots (deposition) within hours/days may be warranted in order to significantly reduce the risk of early deaths for the worst emergencies postulated for power reactors;

- at these radial distances there is a reduction in concentration (and thus risk) by a factor of 10 of a radiation release, compared to the concentration at the PAZ boundary;
- this distance provides a substantial base for expansion of response efforts;
- 25 km is assumed to be the practical limit for the radial distance within which to conduct monitoring and implement appropriate urgent protective actions within a few hours or days. Attempting to conduct initial monitoring to a larger radius may reduce the effectiveness of the protective actions for the people near the site, who are at the greatest risk;
- under average meteorological (dilution) conditions, for most postulated severe emergencies, the total effective radiation dose for an individual beyond this radius would not exceed the urgent protective actions for evacuation.

This chapter reports only the information about the suggested sizes of PAZ and UPZ distances, and not those about LPZ and FRZ, because only the PAZ and the UPZ impose safety measures such as evacuation, that limit the presence of people thus posing impediments on the development of applications that require a high density of personnel/users at a short distance from the plant. Even though this chapter considers the PAZ and the UPZ, the radius of the zone that imposes evacuation can reach 25 km. Anyway, these distances are just a suggestions, and they are probably the results of very conservative criteria. It will be proved in section 1.3.1. that such a long distance for evacuation is taken into consideration by very few countries.

1.2 Definition of EPZ by NRC

NRC (Nuclear Regulatory Commission, USA) developed the most important reference documents for risk zoning around a NPP and emergency planning zones (NRC, 1998; NRC, 2003; NRC, 1998). According to these documents, the zones around a NPP are the following (Figure 6).

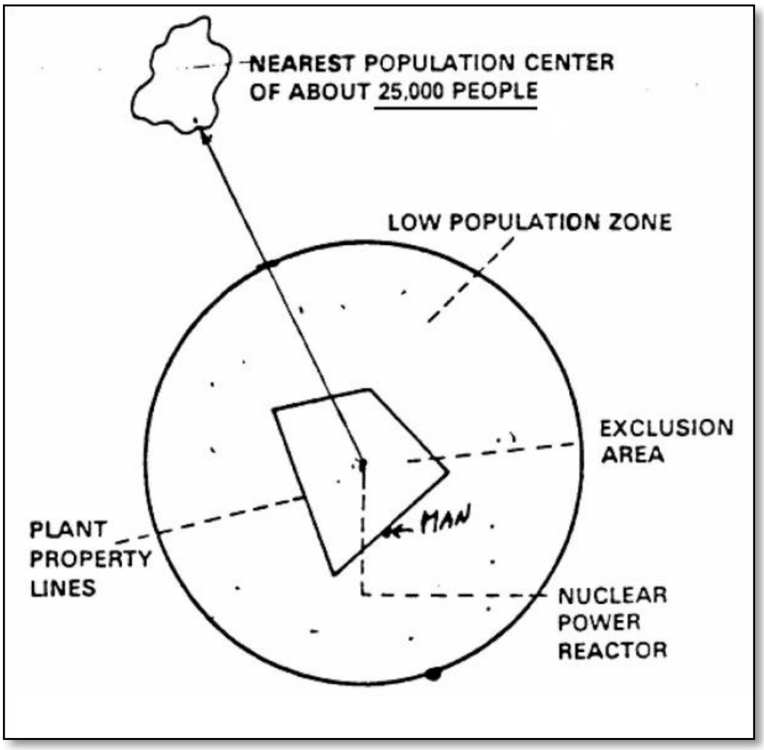

Figure 6 – 10CFR100 requirements (NRC, 1962)

Exclusion Area (EA or EAB)

It is the area surrounding the reactor, where the reactor licensee retains the authority to determine all activities, including exclusion or removal of personnel and property from the area. This area could be traversed by a highway, railroad, or waterway, if they do not interfere with normal operations of the facility and it is possible to control traffic on the highway, railroad, or waterway, in case of emergency, to protect the public health and safety. <u>Residence within the exclusion area shall normally be prohibited.</u> In any event, residents shall be subject to ready removal in case of necessity. Activities unrelated to operation of the reactor may be permitted in an exclusion area under appropriate limitations, provided that no significant hazards to the public health and safety will result (NRC, 2003).

<u>The EA size is not fixed:</u> it must be of such size that an individual located at any point on its boundary for two hours immediately following onset of the postulated fission product release would not receive a total radiation dose to the whole body in excess of 25 rem or a total radiation dose in excess of 300 rem to the thyroid from iodine exposure. Thus, the required

EA size involves consideration of the atmospheric characteristics of the site as well as plant design (NRC, 2003).

The concept of Exclusion Area originated in the USA in the early 1950s, when an acute awareness existed about the potential effects of nuclear accidents on the nearby population. This idea was mooted primarily to insulate the public from the harmful effects of low-probability, high-consequence accidents. The earliest attempt to size the EA (the so called "rule of thumb") was made by NRC (NRC, 1950): the exclusion distance was numerically specified as a circle of radius $R = 0.01 \times P^{0.5}$ [miles], where P is the reactor thermal power (kW). This formula would not yield practical sizes for medium-sized or large power reactors: for a typical 3000 MWth reactor, this formulation gives an exclusion radius of 17.3 miles (27.9 km). Thus, the US siting practice as embodied in 10 CFR Part 100 for the determination of the exclusion boundary and the low population zone around a reactor, updated in 2003 (NRC, 2003), lately defined these radial distances in a more correct way, based on the radiation dose after an accident. The methodology for implementing this in the US Context is coded in the NRC document TID-14844 (NRC, 1962).

<u>When implemented, the exclusion distances for most US reactors fall in the range of 0.5–1.6 km.</u>

The factors determining the exclusion boundary are: reactor type and power, engineered safety features, containment design and characteristics of the site. The US code of practice assumes a severe beyond design basis accident and does not give credit to design features save the containment (BARC, 1975).

Some examples of Exclusion Area Boundaries (EAB) recently assessed for different reactors are the following:

1. ABWR (Lungmen nuclear project, Taiwan, expected to be commissioned in July 2010): in the Preliminary Safety Analysis Report it is stated "the distance from the centre of reactor building to the EAB is 300 m. There are no waterways, railroad, or public highways that traverse the boundary of the exclusion area"(AEC, 2005);
2. CANDU: "because of the lower design leak rate from containment, the EAB radius for the siting of CANDU 9 can be as small as 500 m, significantly reducing site area requirements for CANDU 9 plants. This is an important advantage in the context of meeting siting requirements and land availability" (Hedges, 2005);

3. EPR: "Site boundary considerations for new nuclear Darlington (Canada)" considers ACR-1000, EPR and AP-1000 reactors. EPR meet the dose acceptance criteria from RD-337 with an EAB of 500 m (OPG, 2009).

Low Population Zone (LPZ)

It is the area immediately surrounding the exclusion area which contains residents, the total number and density of which are such that there is a reasonable probability that appropriate protective measures could be taken in their behalf in the event of a serious accident. These guides do not specify a permissible population density or total population within this zone because the situation may vary from case to case. Whether a specific number of people can, for example, be evacuated from a specific area, or instructed to take shelter, on a timely basis will depend on many factors such as location, number and size of highways, scope and extent of advance planning, and actual distribution of residents within the area.

The LPZ size is not fixed. It must be of such size that:

1. an individual located at any point on its outer boundary who is exposed to the radioactive cloud resulting from the postulated fission product release (during the entire period of its passage) would not receive a total radiation dose to the whole body in excess of 25 rem or a total radiation dose in excess of 300 rem to the thyroid from iodine exposure;
2. the population centre distance (distance from the reactor to the nearest boundary of a densely populated centre containing more than about 25,000 residents) is at least one and one-third times the distance from the reactor to the outer boundary of the LPZ.

The boundary of the population centre should be determined considering population distribution, not political boundaries. Where very large cities are involved, a greater distance may be necessary because of total integrated population dose consideration. The size of the LPZ depends upon atmospheric dispersion characteristics and population characteristics of the site, as well as aspects of plant design. (NRC, 2003)

For plants licensed in USA in the 1960s and early 1970s a LPZ radius of about 5 km was found acceptable. (BARC, 1975)

The TID-14844 (NRC, 1962) provides the distances needed for the exclusion area, the LPZ and the population centre as a function of the thermal power of the LWR to be sited at a particular location. These distances are recapped in Figures 7 and 8.

Plume Exposure Pathway and Ingestion Exposure Pathway Zones

To facilitate a pre-planned strategy for protective actions during a radiological emergency, there are two emergency planning zones around each NPP (NRC, 1998). The exact size and shape of each zone is a result of detailed planning which includes consideration of the specific conditions at each site, unique geographical features of the area, and demographic information. This pre-planned strategy for an emergency planning zone provides a substantial basis to support activity beyond the planning zone in the extremely unlikely event it would be needed. The two zones are described as follows and in Table 4:

1. *Plume Exposure Pathway zone (PEP):* the PEP zone has a radius of about 16 km (10 miles) from the reactor site. Predetermined protective action plans are in place for this zone and are designed to avoid or reduce radiation dose from potential exposure of radioactive materials. These actions include sheltering, evacuation, and the use of potassium iodide where appropriate. The principal exposure sources from these pathways are:
    a. whole body external exposure to gamma radiation from the plume and from deposited materials;
    b. inhalation exposure from the passing radioactive plume.

    The duration of principal potential exposures could range in length from hours to days. Figure 9 depicts a typical 10-mile PEP zone map. The centre of the map is the location of the commercial NPP reactor building. Concentric circles of 2, 5, and 10 miles have been drawn and divided into triangular sectors identified by letters from A to R. Municipalities identified to be within the 10-mile PEP have been assigned numbers from 1 to 24. The triangular sectors provide a method of identifying which municipalities are affected by the radioactive plume as it travels
2. *Ingestion Exposure Pathway zone (IEP):* the IEP has a radius of about 50 miles (80 km) from the reactor site. Predetermined protective action plans are in place for this zone and are designed to avoid or reduce radiation doses from potential ingestion of radioactive materials. These actions include a ban of contaminated food and water. The principal exposure from this pathway would be from ingestion of contaminated water or foods such as milk or fresh vegetables. The duration of principal exposures could range in length from hours to months.

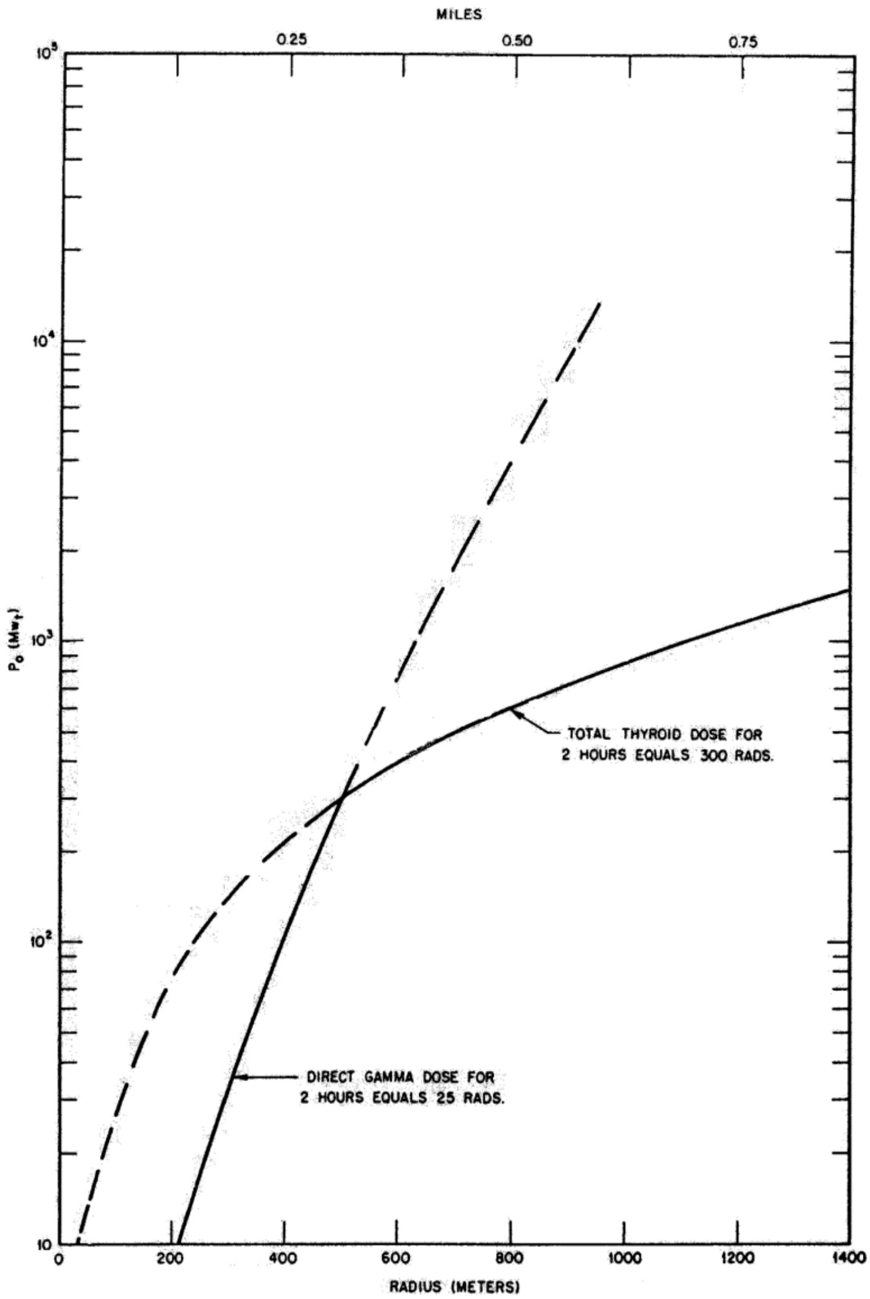

Figure 7 – EA determination (NRC, 1962)

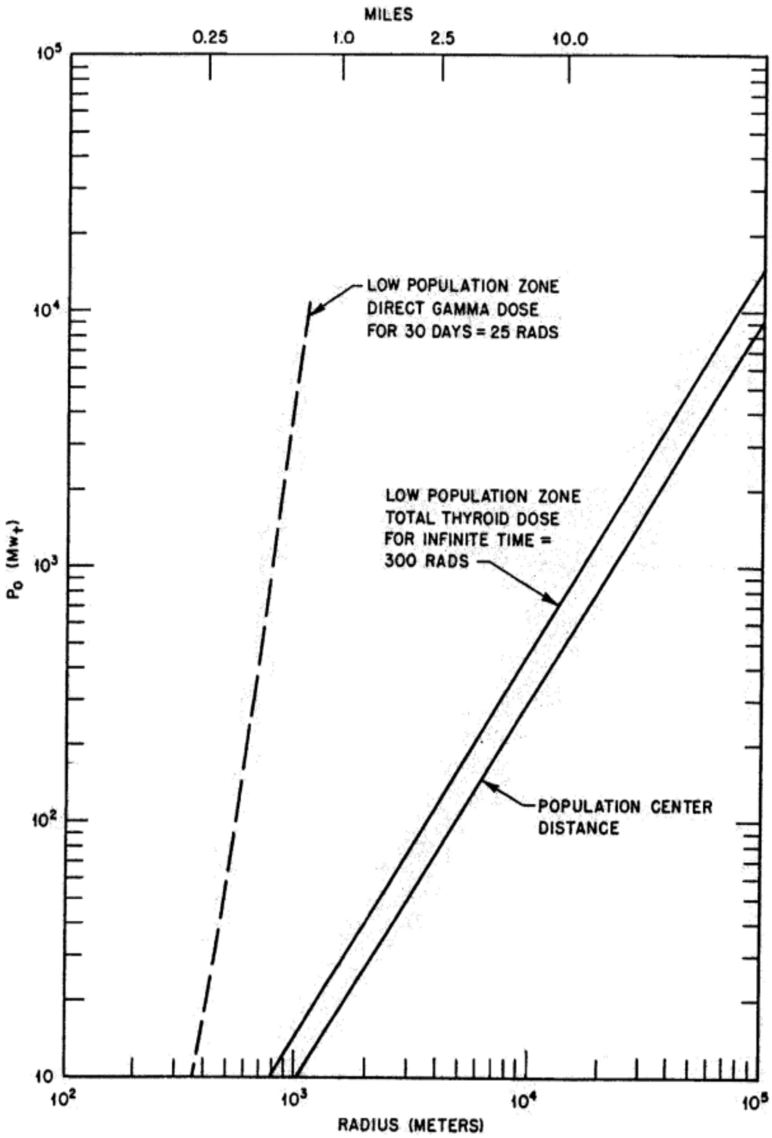

Figure 8 – LPZ and population centre distance (NRC, 1962)

ACCIDENT PHASE	*CRITICAL ORGAN AND EXPOSURE PATHWAY*	*EPZ RADIUS*
PEP	Whole body (external radiation) Thyroid (inhalation) Other organs (inhalation)	About 16 km
IEP	Thyroid, whole body, bone marrow (ingestion)	About 80 km

Table 4 – Guidance on size of PEP and IEP zones (NRC, 1998)

Figure 9 – Typical 10-mile PEP zone map (NRC, 1998)

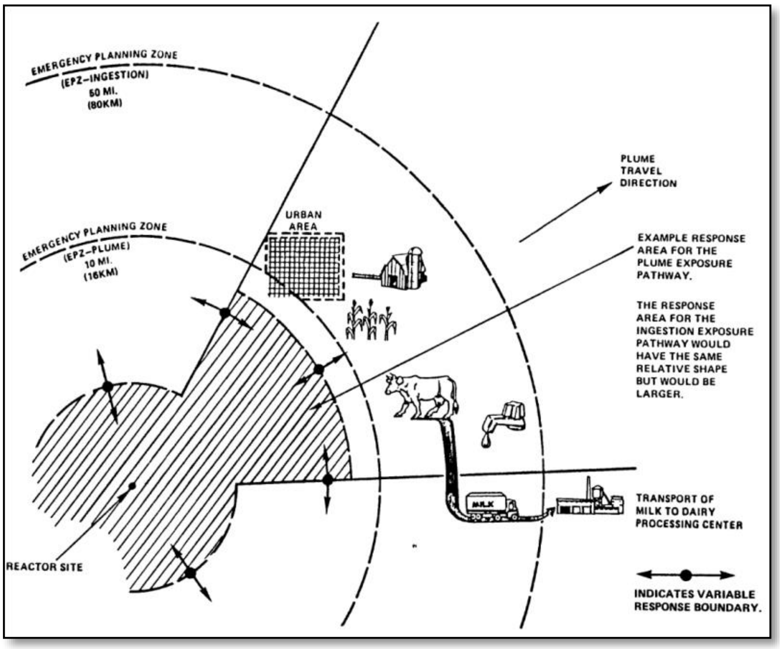

Figure 10 – Concept of PEP and IEP zones (NRC, 1998)

1.3 EPZs worldwide

1.3.1 Differences in EPZ regulations around the world

Current regulations vary among IAEA Member States. They either prescribe the EPZ size through a deterministic, or a risk-based approach, or appear as some combination thereof. The technical basis is not always clearly spelled out (IAEA, 2005).

Around nuclear installations, planning zones for the implementation of countermeasures are pre-established, but their sizes vary among different countries:

- the planning zone for evacuation is, in general, in the order of 10 km around the nuclear installation;
- the planning zones for sheltering and stable iodine are generally of the same size, and range from 10-20 km, larger than the evacuation zones. Choosing identical planning zones indicates that sheltering and stable iodine are often implemented together.

In all cases, zone sizes are based on detailed analyses of possible accidents, their severity and consequences (OECD/NEA, 2003).

In Table 5, an overview of the current practices for risk zoning around NPPs is presented.

<table>
<tr><th>Country</th><th colspan="3">Zones</th></tr>
<tr><td>Australia</td><td colspan="3">Zone 1: 500 m pre-planned evacuation zone
Zone 2: 2.2 km (dependant upon conditions)
ANSTO exclusion zone – 1.6 km</td></tr>
<tr><td>Belgium</td><td colspan="3">Evacuation: 10 km</td></tr>
<tr><td>Canada</td><td colspan="3">Evacuation zone: 7 km
Sheltering zone: 10 km
Iodine zone: 10 km</td></tr>
<tr><td>Czech Republic</td><td colspan="3">NPP Dukovany: 10 km evacuation zone, 20 km sheltering and stable iodine zone
NPP Temelin: 5 km evacuation zone, 13 km sheltering and stable iodine zone</td></tr>
<tr><td>Finland</td><td colspan="3">Protective zone: 5 km distance from the facility
EPZ: extending to about 20 km from the facility</td></tr>
<tr><td>France</td><td colspan="3">Evacuation: 5 km
EPZ (sheltering and iodine): 10 km</td></tr>
<tr><td>Germany</td><td colspan="3">Central Zone: Surrounds the nuclear facility in a 2 km radius.
Intermediate Zone: A circle with a radius of up to about 10 km around the NPP
Outer Zone: A circle with a radius of up to about 25 km around the NPP</td></tr>
<tr><td>Hungary</td><td colspan="3">Internal zone: 3 km
Sheltering zone, where evacuation can be considered: 31 km
Zone where sheltering can be considered: 71 km</td></tr>
<tr><td>Japan</td><td colspan="3">Sheltering zone, including evacuation zone (for NPPs): 8 to 10 km</td></tr>
<tr><td>Luxembourg</td><td colspan="3">Iodine: up to 25 km
Evacuation and sheltering: case by case decision</td></tr>
<tr><td rowspan="10">Netherlands</td><td colspan="3">Radius Implementation zone around the NPP:</td></tr>
<tr><td><100 MWe: 5 km</td><td>100-500 MWe: 10 km</td><td>>500 MWe: 15 km</td></tr>
<tr><td colspan="3">Radius Countermeasure zones for the respective MWe, distance from the NPP:</td></tr>
<tr><td colspan="3">Evacuation</td></tr>
<tr><td>0</td><td>5</td><td>5</td></tr>
<tr><td colspan="3">Iodine prophylaxis</td></tr>
<tr><td>4</td><td>10</td><td>15</td></tr>
<tr><td colspan="3">Sheltering</td></tr>
<tr><td>7</td><td>20</td><td>30</td></tr>
<tr><td colspan="3">In a segment depending on the wind direction. For evacuation > 100 MWe always also in a circle with 2 km radius</td></tr>
<tr><td>Norway</td><td colspan="3">For two research reactors, zones are being established according to the draft IAEA Safety Series on emergency planning and response</td></tr>
</table>

Country	***Zones***
Slovakia	Internal zone: 3 km for Bohunice Inner emergency zone: up to 12-15 km in radius around the NPP Indication zone: up to approximately 50 km in radius around the NPP EPZ: 30 km Bohunice, 20 km Mochovche (divided into zones of 5 and 10 km)
South Africa	Internal zone: 5 km UPZ: 5 to 16 km LPZ: 80 km
Sweden	Inner emergency zone: up to 12-15 km in radius around the NPP Indication zone: up to approximately 50 km in radius around the NPP
Switzerland	Internal zone: 3 to 5 km Zone 1: Approximately 4 km in radius around the NPP (= sheltering zone) Zone 2: Approximately 20 km in radius (= sheltering zone)
United Kingdom	1 to 3 km
USA	PEP Zone: 16 km IEP Zone: 80 km

(*) Internal zone is generally defined as the zone in which no further development is allowed

Table 5 – Overview of emergency planning practices in different countries (Kirchsteiger, 2006) and (OECD/NEA, 2003)

In a recent paper the current status of the emergency and risk zones around a NPP has been analyzed for several countries. It pointed out that (Kirchsteiger, 2006):

- many countries use the relevant IAEA documents (e.g. the 2003 updated version of IAEA TECDOC 953);
- <u>there are significant differences in the EPZ radii in different countries, ranging from a few up to 80 km,</u> as shown in Table 5;
- there is a striking contrast in the extent of using probabilistic information to define EPZs between the nuclear and other high risk industry sectors, such as the chemical process industry, and the reasons for these differences are not entirely clear, since the risk in the chemical industry is similar to that of the nuclear sector;

- the approach to emergency planning is, in general, strongly deterministic. The usual approach is that a reference accident is defined and used as a basis for drawing up the emergency plans;
- the difference seems to be more related to risk perception than to actual risk potential;
- there is a strong need to communicate risk information to the public both before and following an accident, and to educate the public so they can understand risk information in a comparative sense;the issue needs to be addressed on whether there are any advantages or disadvantages in imposing larger EZs.

1.4 EPZ reduction and the role of small reactors

The EPZ itself does not pose particular issues to the co-location of NPPs and other facilities, it imposes some limitations on the presence of people; reducing the EPZ would reduce this problem. According to INPRO (*International project on innovative nuclear reactors and fuel*) and GIF (*Generation IV International Forum*), innovative, small reactors could allow the reduction or even elimination of the EPZ. This section deals with the main issues linked to the presence of the EPZ, the motivations and goals for its reduction and the main advantages this would bring.

Emergency planning requirements may represent a significant burden for the plant owner (utility), both in the construction and in the operating phases. During the construction, it may be necessary to build infrastructures (highways) to comply with the requirements. During operating phases, it is necessary to maintain an evacuation capability in a relatively wide area. Moreover, one of the consequences of emergency planning requirements is the "freezing" of any human development in a large area around the plant. Finally, the fact that the off-site zone around a NPP is subject to particular constraints may spread distrust towards nuclear power safety (Augutis, 2005).

1.4.1 Attempts to reduce the EPZ

Even though the concept of EPZ has been joined with nuclear power since the very beginning, many attempt to reduce it have been experimented (IAEA, 2006):

1. in 1985, the licensee of the plant of Calvert Cliffs (Maryland) requested an EPZ reduction from ten to two miles, and in 1986 the plant of Seabrook (Texas) requested its reduction to one mile. Both petitions were rejected by the NRC: the former because severe

accident issues were still under study by the NRC and the latter because the supporting documentation did not contain sufficient justification. After these two early failures, there were no more licensee petitions, but rather studies and investigations continued, performed by various organizations, fuelled by the excellent safety record of operating plants and the enhanced safety characteristics of advanced reactors;

2. in 1993, the NRC staff raised the following issue: "*should advanced reactors with passive advanced design safety features be able to reduce EPZ and requirements?*". No changes were actually proposed, but it indicated that a revision of the EPZ was not impossible;
3. in 1997, an evaluation of emergency planning for advanced reactors was conducted by the NRC in SECY-97-020, reaching the conclusion that the existing NUREG-0396 approach was also appropriate for the new plants, that were on the drawing boards. At the same time, however, it was recognized that "changes to emergency planning requirements might be warranted to account for the lower probability of severe accidents and the longer time period between accident initiation and release of radioactive material for most severe accidents associated with evolutionary and passive advanced LWRs". In order to justify these types of changes, three main issues had to be addressed:
    1) Probability level below which accidents will not be considered for emergency planning (the so-called "cut-off probability");
    2) Use of increased safety in one level of defence in depth to justify reducing requirements in another level;
    3) Acceptance by federal, state and local authorities.
4. the task of Group 1 within the CRP i25001 (*Coordinated Research Project on small reactors without on-site refuelling*) is to develop a methodology and to identify regulatory approaches to revise (reduce or eliminate) off-site emergency measures such as evacuation and relocation for NPPs with innovative reactors. The general objective of Group 1 activities assumes there may be several equivalent, similar, or related practical implementations, such as to:
    - eliminate the need for off-site response;
    - revise the need for off-site relocation and evacuation measures;
    - reduce the size of the EPZ;
    - reduce the EPZ to fit within site limits (eliminating the off-site response).

It is recognized that while the complete elimination of off-site EPZ may be difficult, eliminating or even reducing most costly measures may provide similar economic effects/benefits (IAEA, 2005).

1.4.2 EPZ reduction/elimination goals

The trend is to improve the level of safety for future NPPs (Generation IV reactors and small/medium reactors - SMR). This would significantly reduce the probability of severe accidents and releases of radioactive material from the plant. In principle, this could be considered to reduce, or perhaps eliminate, the need for emergency planning. Further considerations need to be given about how EP and EPZs may be defined for future NPPs where the risk in term of large off-site releases of radioactivity was much lower than in current plants. Consideration needs to be given on whether the moral obligation to provide an EP would outweigh the technical conclusion that EP would not be required any more. (Kirchsteiger, 2006)

The idea of EPZ reduction for advanced nuclear reactors is based on two factors (Maioli, 2006):

1. the safety level of new reactors: for example, in the case of IRIS, a LERF (Large Early Release Frequency) of 10^{-9} has been estimated;
2. the fact that EP is based on risk perception rather than on a risk assessment.

Elimination of EPZ is one of the goals of INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) and GIF (Generation IV International Forum):

- ❖ IAEA TECDOC 1434 states that "<u>innovative nuclear energy systems (INS) shall not need relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility</u>", which means that INS could be sited in very similar locations to those of other energy producing systems. The corresponding criterion is specified as "probability of large release of radioactive materials to the environment", and the acceptance limit considered is $<10^{-6}$ per plant-year, or excluded by design,
- ❖ it also suggests that the end point should be to make the risk of INS comparable to that of industrial facilities used for similar purposes, so that <u>for INS there will be no need for relocation or evacuation measures outside the plant site</u>;

- one of the goals of the GIF is to reach a condition with "no need for offsite response". A reasonable measure of this goal could be expressed as "no credible accident scenarios that could result in offsite release of radiation exceeding US protection action guidelines. These guidelines may change as improved radiation dose-response models are developed" (IAEA, 2005).

Achieving licensing without EPZs would offer significant societal and economic benefits to member countries, general public and plant owners/operators, including ((Augutis, 2005) and (IAEA, 2006)):

- no *a priori* impediment to further development and settlements in areas around the plant;
- increased public acceptance of nuclear power, since NPPs would be treated as any other industrial facility;
- reduced need for infrastructure to facilitate rapid evacuation, thus reducing connected costs;
- reduced operational costs, since there would be no need for special training of personnel and for periodic evacuation drills;
- <u>enabling of co-generative applications, including district heating, desalination, industrial process heat supply, where the plant cannot be located remotely from the intended user (cost of extended transmission lines avoided);</u>
- enabling the choice of sites that would reduce transmission costs;
- enabling a wider choice of sites in countries with relatively high population density.

1.4.3 Correlation between size and EPZ dimension

<u>There is a correlation between the reactor size and the EPZ size</u>. First of all, it must be underlined that the reactor size varies from country to country: some countries rely predominantly on large reactors, other countries on small ones, and finally some countries have a balanced mix. The situation for the countries analyzed is summarized in the following table.

Reactor size	***Countries***
Predominantly large (more than 700 MW)	Belgium, France, Germany, South Africa, USA
Predominantly small (less than 700 MW)	Hungary, Netherlands, Slovakia, UK
Mixed (small and large in the same proportion)	Czech Republic, Finland, Japan, Switzerland, Canada

Table 7 – Countries and reactor size adopted

It is possible to divide EPZ sizes in three categories, as shown in table 8. The connection between the reactor size and the EPZ size for various countries is provided in table 8 and figure 12. The tendency is to establish large EPZs if LRs are employed and small EPZs for small reactors. There are no countries using small reactors that have large EPZ, but there are some (France and Germany) that have small EPZ even though all reactors are large.

EPZ size	***Radius range***	***Countries***
Small	Less than 5 km	Slovakia, Hungary, UK, Switzerland, France, Germany
Large	Between 5 and 10 km	Netherlands, Finland, Canada, Czech Republic, South Africa
Very Large	More than 10 km	USA, Japan, Belgium

Table 8 – EPZ size and relative countries

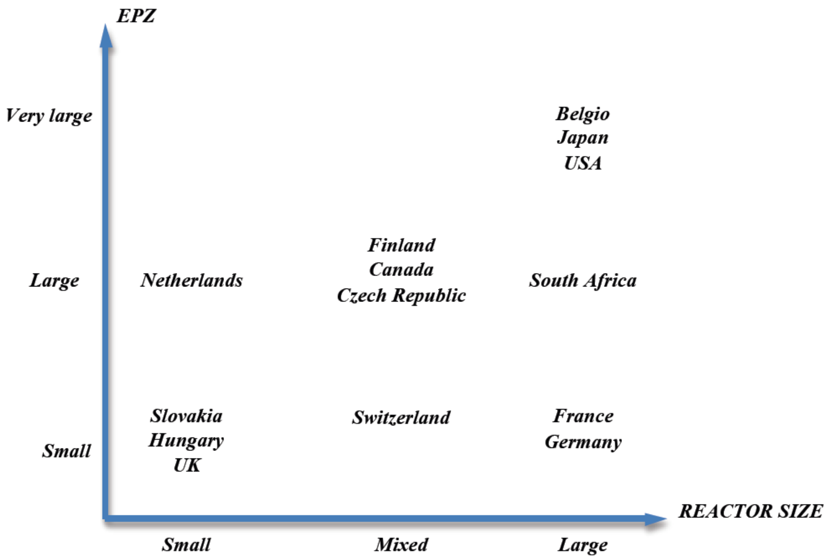

Figure 12 – Correlation between reactor size and EPZ size

1.5 Conclusions

The collected data demonstrate that:

- EPZs size around a NPP are neither set by an international regulation, nor imposed by the reactor vendor or by other authorities;
- the exact size and configuration of the EPZs should be determined with respect to local emergency response needs and capabilities, as they are affected by conditions as: atmospheric characteristics of the site, plant design, demography, topography, land characteristics, access routes, jurisdictional boundaries;
- agencies like the IAEA and the NUREG tried to suggest typical sizes for EPZs, but all the suggestions are provided with recognition of the great uncertainties involved (a variation by a factor of two or more during application is reasonable) and in any case exact sizes must be confirmed by case-specific studies;
- current EPZs are extremely different from country to country;
- the determination the radius of an EPZ is related to the size (in terms of power) and to the level of safety of the reactor, but it has to be the result of a precise and complete case-by-case risk assessment analysis;
- the guides do not specify a precise permissible population density or total population within the closest zone to the NPP because the

situation may vary from case to case: whether a specific number of people can be evacuated from a specific area on a timely basis will depend on many factors such as location, number and size of highways, as well as actual distribution of residents within the area;

- the importance of EPZ reduction (in terms of off-site emergency planning elimination) for innovative small reactors with enhanced safety has been recognized, and it is based on the fact that:
  - it would lower the transmission cost for co-generative applications (district heating);
  - it would enable a wider choice of sites to locate NPP;
  - it would eliminate *a priori* impediments for the economic and human development in the area surrounding the plant;
  - EPZ is based on risk perception rather than on risk assessment.

2 SECTION TWO: POTENTIAL APPLICATIONS IN THE EPZ

2.1 Introduction

The EPZ represents an inhibition to the urban and economic growth of the area within its borders; however, despite hindering the development of the territory as a whole, can also represents an attractive opportunity to single appliances: all the by-products of a NPP are available inside the EPZ perimeter, and the EPZ itself can be regarded as a valuable by-product, because its wide, uninhabited, low cost areas are the ideal location for many industrial/energetic facilities.

This fact raises two major questions:

1. What synergies do the nuclear by-products offer inside an EPZ?
2. What industrial/energy applications could be implemented to exploit these synergies?

This section tries to answer these two questions, identifying attractive synergies between nuclear power and different kinds of applications. In general co-generation is the simultaneous generation of heat and electricity; when a heat source is used to produce only electricity (e.g., through a steam turbine), about one third of the heat is converted, while the remaining two thirds are wasted. Part of this heat can be recovered extracting a certain amount of steam from the turbine. When the heat source is a nuclear reactor the issue is called nuclear cogeneration. Depending on the temperature reached in the reactor, nuclear co-generation applications can be at low temperature or at high temperature. It is wise to divide the applications in two main group: low temperature and high temperature.

2.2 Low temperature applications

Low temperature applications presented in the following paragraphs are actual or viable in the short-term (5 years or less), thanks to the maturity of the employed technologies and to the commercial availability of nuclear reactors capable of providing heat at the needed temperature. Considerable experience has been accumulated worldwide both for nuclear-powered district heating and for industrial uses of nuclear heat, that will be now briefly described.

2.2.1 Nuclear district heating

In district heating the extracted steam from high and/or low-pressure turbines is fed to heat exchangers to produce hot water/steam, which is delivered to the consumers. Depending on the transportation distance and the number of end users, a certain number of pumping stations are located between the heating source and end users. Heat transportation pipelines are installed either above- or under-ground. They are well insulated, in order to minimize heat losses. Steam from low-pressure turbines is usually used for the base heat load, while steam from high-pressure turbines is used, when needed, to meet the peak heat demand. The portion of steam retrieved for heat production represents a part of the total steam produced by the reactor, the remaining portion of the steam being used to produce electricity (IAEA, 2002). In principle, any portion of the heat can be extracted from co-generation reactors as district heat, subject to design limitations. Co-generation plants, when forming part of large industrial complexes, can be readily integrated into an electrical grid system to supply any surplus generated. In turn, they would serve as a back-up for the assurance of the energy supply. This guarantees a high degree of flexibility (IAEA, 2007). Correct function of interface equipment is an important basis for good operating performance. Operating experiences of interface equipment for nuclear district heating are not different from those in commercial thermal plants (except for the radioactivity monitoring devices) (IAEA, 1998).

Figure 14 depicts a simplified scheme of nuclear district heating. Its principal components are the nuclear reactor (1), the supply of steam to the turbine (2), the turbine unit (3), the supply of feed-water to the reactor (4) and the heat consumer (5).

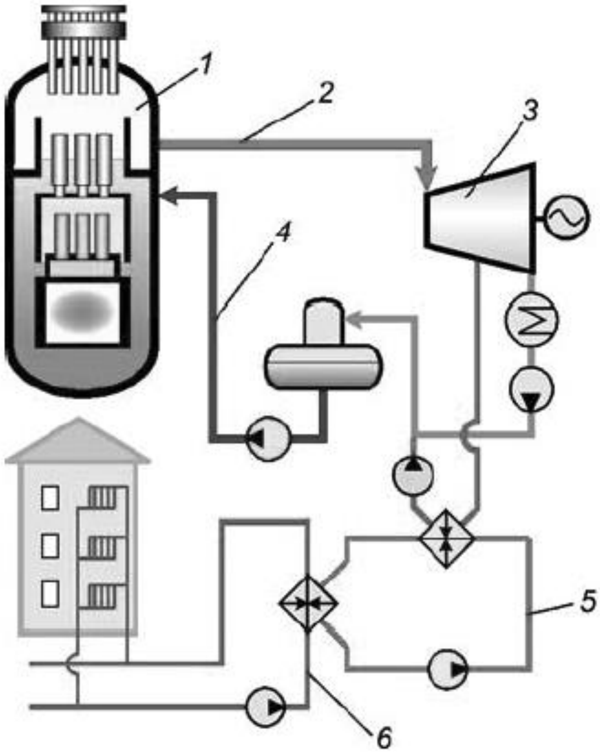

Figure 14 – Nuclear district heating concept (Kutznetsov, 2008)

Technical requirements for nuclear district heating

Required temperatures

District heating systems are supplied with steam or hot water in a typical temperature range of 80-150 °C (IAEA, 2007).

Suitable reactors

From the technical point of view, nuclear reactors are basically heat-generating devices. There is plenty of experience of using nuclear heat in district heating, so the technical aspects can be considered well proven. There are no technical impediments to the application of nuclear reactors as the heat source for district heating. In principle, any type and size of nuclear reactor can be used for these purposes. Thus, all existing reactor types (light water, heavy water, fast breeder, gas cooled and high temperature) are potentially applicable to cogeneration for district heating (IAEA, 2007).

Distance from the user

Due to high losses over longer transmission distances, the heat source must be relatively close to the customer, typically within 10-15 km (IAEA, 2007). In commercial scale heating networks, the transportation distances are usually less than 10 km, in most cases between 3 and 6 km (IAEA, 1998). Anyway, in some cases the heat source can be located further from the customer (up to 100 km) depending on the economics based on the size of the plant and the level of insulation technology (OECD/NEA, 2004). Heat losses along the network can be extremely reduced if pre-insulated pipes are utilized: a typical results is a 3% loss on the transported power (0.1°C/km, if the temperature difference between feed and return is 15°C along a 5 km network). The maximum loss is about 1°C/km. (RENAEL, 2004).

The impact of the distance on heat transportation cost is given in table 10, where the cost of a 5-km-transfer is taken as a base. The distance between the nuclear power plant and the user is not a problem in terms of heat losses, but the cost of heat transportation grows linearly with the distance: thus, it should be minimized in order to reduce transmission costs.

Distance [km]	***Cost of heat transportation***
5	1
10	2.5-3.5
15	4.5-5.5
20	6.5-8.0

Table 10 – Impact of distance on the heat transportation costs (IAEA, 2002)

Capacity

The district heat generation capacities are determined by the collective demands of the customers. In large cities an installed capacity of 600-1200 MWth is normal, while the demand is much lower in towns and small communities (10 to 50 MWth). Large capacities of 3000-4000 MWth are exceptional (IAEA, 2007).

Load factor

The annual load factor is normally not higher than 50%, since heat is supplied only in the colder part of the year. This is still way below what is needed for base load operation of plants. (IAEA, 2007). The annual load factor can increase if the distribution of sanitary hot water is provided.

Expected availability of a heat distribution network

District heat involves the supply of space heating and hot water through a district heating system, which consists of heat plants (producing electricity simultaneously) and a network of distribution and return pipes. Thus, the availability of a heat distribution network plays an important role in the prospect of nuclear district heating development. (IAEA, 2007)

Availability factor

The experience shows that availability factors of 70%, 80% or even 90% can be achieved (similar to the availabilities achieved by fossil fuelled power plants). The frequency and duration of unplanned outages can be kept very low with good preventive and predictive maintenance, but not eliminated: consequently, redundancy is needed. Multiple-unit co-generation power plants, modular design, or backup heat sources are necessary to achieve the required availabilities. (IAEA, 2007)

Backup capacity

To ensure a reliable supply of heat to the residences served by the district heat network, adequate backup heat generating capacity is required. This implies the need for redundancy and generating unit sizes: at least two nuclear power units, or a combination of nuclear and fossil fired units, corresponding to only a fraction of the overall peak load (Csik, 1997).

Heat storage

Heat storage allows a matching of the heat supply to the heat demand. Today there are many examples of short-term storage, for instance, on the daily scale that relies on hot water accumulator tanks. In the future, more innovative concepts for long-term storage facilities may be realized, such as storage in underground water layers (IAEA, 2007).

Safety

Potential radioactive contamination of the district heating networks is avoided by appropriate measures. No incident involving radioactive contamination has ever been reported for any of the reactors used for these purposes (Csik, 1997). Because of the need to site the source close to the customer, nuclear safety is very important. It is not only required that the level of safety is technically sufficient, it is also necessary that the adequacy of safety be sufficiently proved to the public and confirmed by the licensing process. (IAEA, 2002).

Concluding remarks

- All existing reactor types are potentially applicable to cogeneration with district heating purposes, and several European countries already have experience in nuclear district heating for residential, agricultural and commercial sector: thus, nuclear district heating is technically feasible;
- Nuclear district heating can compete economically in densely populated areas with individual heating arrangements. Economic studies generally indicate that district heating costs from nuclear power are in the same range as costs associated with fossil-fuelled plants, but a site-specific comparison of the cost of nuclear heat production with those of competing technologies is necessary;
- Nuclear district heating offers the possibility of strongly reducing air pollution in urban areas: the full integration of external costs in the nuclear case would render nuclear district heating the most attractive option in economic terms, even compared with renewable;
- There is a major trade-off in siting reactors intended for district heating: the site must satisfy both the requirements of the nuclear plant (the EPZs require the location of district heating users far from the reactor) and of the heat application (low transmission costs are achieved if users are located near the reactor);
- The heat output of a large reactor is far larger than the demands likely for district heating;
- The development of nuclear district heating will be favoured by the diffusion of small, modular reactors: low cost, better match of the heat demand, enhanced safety, potential to reduce EPZ and increase social acceptance.

2.3 Nuclear process heat

Process heat implies the supply of heat required for industrial processes from several centralized heat generation sites through a steam transportation network. Wasted heat from the nuclear reactor can be used for this purpose: from a technical point of view, the functioning is similar to that of district heating. Thus, most considerations done for district heating are valid here. Differences come from the required temperatures and the annual load factor, which are both higher.

Technical requirements for nuclear process heat

Required temperatures

Within the industrial sector, process heat is used for a very large variety of applications with different heat requirements and with temperature ranges covering a wide spectrum. The application of nuclear industrial process heat is tightly connected to the temperature (Csik, 1997):

- ❖ The lower range, up to about 200 to 300 °C includes industries such as seawater desalination, pulp and paper, or textiles;
- ❖ Chemical industries, oil refining, oil shale and sand reprocessing, and coal gasification are examples of industries with temperature requirements of up to the 500 to 600 °C level;
- ❖ Refinement of coal and lignite, and hydrogen production by water splitting are among applications that are renewing the interest and they require temperatures between 600 and 1000 °C;
- ❖ The upper range above 1000 °C is dominated by the iron/steel industry.

This section considers only the applications that are feasible with commercially developed reactors: that means up to 600 °C (low and medium temperature).

High temperature applications are discussed in section 2.4. A series of industrial process at low and medium temperature and their temperature ranges are represented in figure 16.

Suitable reactors

The required heat parameters determine the applicability of different reactor types. There are no technical impediments to the application of nuclear reactors as heat sources for process heating, thus, all existing reactor types and sizes are potentially applicable to producing process heat depending on the required temperature of the processes (IAEA, 2002). The applications of temperature range between 20° C and 600 °C and the reactors meeting these requirements are represented in Figure 16. However, an important market for nuclear process heat at low temperature exists. As illustrated in figure 17, about 30% of the total industrial heat demand is required at temperatures below 100°C and 57% at temperatures below 400°C. Moreover, in several industrial sectors, such as food, wine and beverage, transport equipment, machinery, textile, pulp and paper, the share of heat demand at low and medium temperature (below 250°C) is about, or even above, 60% of the total figure (ECOHEATCOOL, 2006).

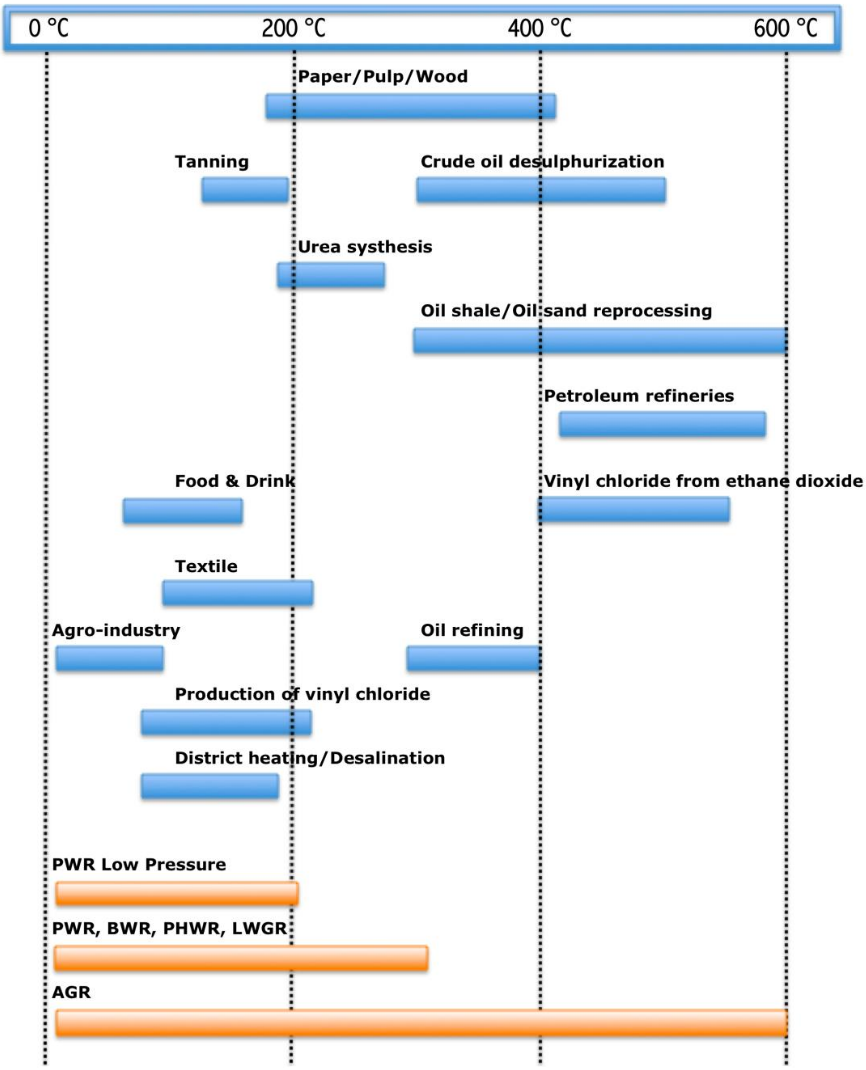

Figure 16 – Required temperature for industrial processes and reactor types (adapted from (IAEA, 2007), (IAEA, 1998) *and* (IAEA, 2002)*)*

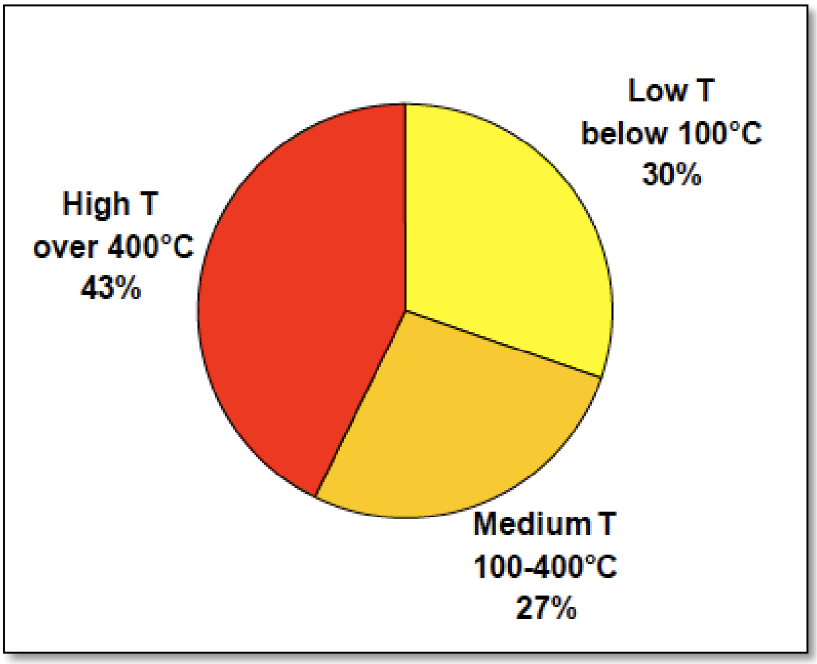

Figure 17 – Share of industrial heat demand by temperature in EU (EUROHEATCOOL, 2006)

Distance from the customer

Due to thermal losses over transportation, the heat source has to be relatively close to the customer (IAEA, 2007). Although, this is not as critical as it is in district heating systems: since industrial complex are not densely populated (on the contrary of residential areas), they can be sited more easily near the NPP in order to optimize the trade off safety/transmission costs. This would also lead to a better exploitation of the EPZ.

Annual load factor

Since process heat demand does not depend on climatic conditions, the supply of industrial heat is more uniform throughout the year than that of district heat. The demands of large industrial users usually have base load characteristics, with annual load factor of 70-90%. Nuclear reactors, which are typically run in base load operation, will be quite useful in this context (IAEA, 2007).

Needed availability factor

Almost all industrial users need the assurance of energy supply with a very high degree of reliability and availability, approaching 100% in particular for large industrial installations and energy intensive processes. The average adequate steam supply availabilities for chemical processing and oil refineries are respectively 98% and 92% (IAEA, 2007).

Backup capacity

Most industrial processes require highly reliable heat supply, even though some processes (e.g. drying) can also work with interruptible heat supply. Industrial heat consumers can be supplied with steam from a multi-unit or from a single unit nuclear station. In both cases, one or several backup capacity is required. The frequency and duration of unplanned outages can be kept very low with good preventive and predictive maintenance. Availability and reliability of a reactor, however, can never reach the nearly 100% levels required by most large heat users: multiple unit co-generation power plants, modular designs, or backup heat sources are suitable solutions for redundancy (IAEA, 2007).

Safety

Potential radioactive contamination of the networks is avoided by appropriate precautions, such as intermediate heat transport circuits with pressure gradients, which act as effective barriers. No incident involving radioactive contamination has ever been reported for any of the reactors used for these purposes (Csik, 1997). The siting of an industrial heat user close to the NPP will require specific safety features appropriate to the location and the application (IAEA, 2000).

Market for nuclear process heat

Market fragmentation

The industrial heat market is highly fragmented, and it is characterized by a steady decrease in the number of users as the power requirements become higher (IAEA, 2000):

- ❖ about half of the users require less than 10 MWth;
- ❖ another 40% of the users require between 10 and 50 MWth;

- ❖ about 99% of the users are included in the range of less than 300 MWth, which account for about 80% of the total energy consumed;
- ❖ individual large users with energy intensive industrial processes cover the remaining portion of the industrial heat market with requirements up to 1000 MWth, and exceptionally even more.

Thus, the large-scale introduction of heat distribution system supplied from a centralized nuclear heat source need the presence or the development a sort of industrial park, where several users are concentrated.

Process heat users: main industries

Generally, the industries that are main consumers of heat are:

- ❖ Petroleum and coal processing;
- ❖ Chemical and fertilizers;
- ❖ Primary metal;
- ❖ Paper and products;
- ❖ Food and products;

The apportionment varies from country to country, but the chemical and petroleum industries are the largest consumers worldwide. These would be key target clients for possible applications of nuclear energy (IAEA, 2002).

Market size does not matter for nuclear penetration. The main question is whether nuclear technologies can prove to be competitive. The market for industrial heat is highly competitive. Heat is produced predominantly from fossil fuels, with which nuclear energy will have to compete (IAEA, 2002).

Worldwide experiences in nuclear process heat

There is experience in providing process heat for industrial purposes with nuclear energy in Canada, Germany, Norway, Switzerland and India. New plants are being designed in Russia, the Republic of Korea and Canada (IAEA, 2007). The most significant examples of nuclear process heat are listed in Table 13.

Country (Location)	*Reactor type*	*Start of reactors operation*	*Power [MWe]*	*Heat delivery [MWht]*	*T at interface [°C]*	*Remarks*
Canada (Bruce)	CANDU	1981	848 (8)	5.350		D_2O production and six industrial heat customers
Germany (Stade)	PWR	1983	640 (1)	30	190/100	Salt refinery
Switzerland (Goesgen)	PWR	1979	970 (1)	45	220/100	Cardboard factory
India (Kota)	CANDU	1980	160 (1)	85	250	D_2O

Table 13 – Experiences in industrial process heat applications (adapted from (IAEA, 2007))

Both for the number of different users served and for the huge quantity of thermal power supplied, the most synergic plant is the Bruce Energy Centre in Canada, where steam is used for heavy water production plants and for an adjacent industrial park. It is the world's largest nuclear steam/electricity generating complex. It includes eight CANDU nuclear reactors with a total output of over 7.200 MWe, the world's largest heavy water plant. The initial development focused primarily on agriculture-based industry. Then, a sustainable development model was presented, with the aim of demonstrate commercial application of "closed loop" and integrated systems, the introduction of nuclear hydrogen and absorption of CO_2. The sustainable development model is based on the following points (IAEA, 2000):

- Cogeneration of electricity and process steam using a nuclear reactor;
- A menu of feedstocks ranging from farm produced carbo-hydrates and solid wastes to low grade carbon sources and carbon dioxide;
- A series of state of the art processing, synthesizing and refining processes;
- End products that have markets and in their own right have environmental value-added.

The six private industries currently established in the park are (IAEA, 2007): a plastic film manufacturer, a 30.000 mq greenhouse, a 12 million liter/year ethanol plant, a 200.000 ton/year alfalfa dehydration, cubing and pelletising plant, an apple juice concentration plant and an agricultural research facility.

Siting and construction

Similar to nuclear district heating, the close siting of a nuclear plant to the customer is preferable, as the heat transportation costs grow significantly with distance. On the contrary of residential complexes, industrial process heat users do not have to be located within highly populated areas. Many of the process heat users, in particular the large ones, can be, and usually are, located outside urban areas, often at considerable distances. This makes joint siting of nuclear reactors and industrial users of process heat not only viable, but also desirable in order to drastically reduce the heat transport costs, provided that the co-siting does not adversely affect the safety case for the nuclear installation (IAEA, 2000). In Germany and Switzerland there have been experiences with nuclear process heat and the distances from the industries were respectively 1.5 km (the PWR of Stade for a salt refinery) and 2 km (the Goesgen PWR for a cardboard factory) (OECD/NEA, 2004). Installing a new nuclear co-generation plant close to existing and interested industrial users has better prospects. Even better would be a joint project whereby both the nuclear co-generation plant and the industrial installation requiring process heat are planned, designed, built and operated together as an integrated complex (IAEA, 2007).

The role of SMRs in nuclear process heat

Coupling a large reactor with a small industrial facility does not allow a significant exploitation of heat from the reactor. The only chance to use a relevant fraction of the available heat from a large reactor is a large industrial complex requiring a high quantity of steam for different businesses (e.g. Bruce Eco Industrial Park in Canada, see section *Worldwide experiences in nuclear process heat*). Moreover, the EPZ around a NPP could be so large that the location of a lot of industries is not only viable, but also preferable in order to exploit this unused area. Such a kind of multi-business industrial park is quite difficult to implement, as it requires an extremely accurate choice of businesses and the presence of interested investors.

The reasoning could be inverted as well: if a high demand of heat is difficult to find, it is possible to reduce the offer. In this sense, the diffusion of small, innovative reactors with lower power and less EPZ requirements, could increase the attractiveness of coupling the nuclear power plant with a small industrial user.

According to this, the development of nuclear process heat applications could depend on the development of SMRs. For large size reactors used in co-generation mode, electricity would always constitute the main product. Such plants, therefore, have to be integrated into the electrical grid system and optimized for electricity production. For reactors in the SMR size range, and in particular for small and very small reactors, the share of process heat generation would be larger, and heat could even be the predominant product. This would affect the plant optimization criteria, and could present much more attractive conditions to the potential process heat user. Consequently, the prospects of SMRs as co-generation plants supplying electricity and process heat are considerably better than those of large reactors (IAEA, 2007).

Conclusions about nuclear process heat

- All existing reactor types and sizes are potentially applicable to producing process heat, depending on the required temperature of the processes;
- Process heat has base load characteristics, as well as nuclear reactors: the matching between demand and supply is better than in the district heating case;
- The siting issue is not as critical as it is for district heating, because industrial complexes do not require high population density and they can be located near the NPP (i.e. inside the EPZ). This would lead to a better exploitation of the EPZ;
- The industrial process heat market is highly fragmented (few large users, lot of small users) and it is difficult to find such demanding users that can harness a significant amount of the heat supplied by a large reactor. Thus, there are two options to favour the utilization of nuclear heat for industrial processes:
    1. The concentration of small industrial users in so-called industrial parks to match the demand and the supply: if the interaction between NPP and other plants is proven to be safe, they can be located inside the EPZ;
    2. The large-scale commercialization of small reactors;

  In the first case, a joint project, whereby both the nuclear co-generation plant and the industrial installations requiring process heat are planned, designed, built and operated together is preferable.

2.4 High temperature applications

The feasibility of high-temperature applications exploiting nuclear heat is dependent upon the commercialization of nuclear reactors operating at adequate temperature, which is envisaged in about 10-30 years, depending on the technology (WNA, 2009). The technology of some high-temperature processes discussed in this section is not yet mature as well (e.g. thermo-chemical H_2 production), despite their advanced stage of development and the confidence of international literature. For these reasons high-temperature applications are characterized by a higher level of uncertainty than low-temperature ones. High temperature applications are divided into traditional ones (process heat at high temperature) and innovative ones. Traditional applications will not be discussed in depth, as information given in the previous section about low temperature process heat apply to them as well. The only difference lies in the temperature, therefore in the reactor and, as a consequence, in the technology availability, which is supposed to be due in about 2030. Our choice is to give relevance to innovative applications. All high temperature reactors are small, innovative reactors of Generation IV, thus it makes sense to hypothesize a small EPZ for the applications.

Considerations referred to low temperature process heat are similar to high temperature traditional applications. Here, the development of the applications is bound to the development of HTGR. In order to show the potential use of high temperature reactors for industrial steam supply, the following figure presents the different temperatures required by some typical industrial processes.

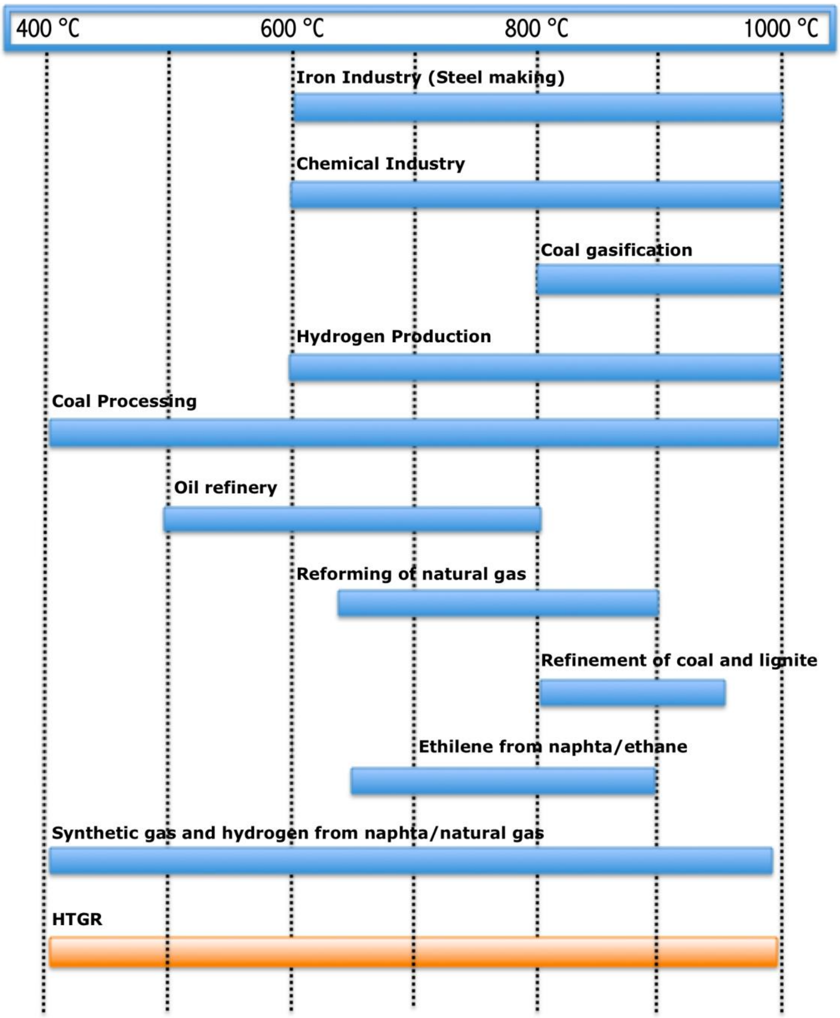

Figure 19Temperature required by some industrial processes at high temperature (adapted from (IAEA, 2007), (IAEA, 1998) *and* (IAEA, 2002)*)*

2.4.1 Gasification via nuclear heat

Gasification is a means to convert fossil fuels, biomass and wastes into either a combustible gas or a synthesis gas for subsequent utilization (Minchener, 2005), consisting primarily of hydrogen (H_2) and carbon monoxide (CO). The oxidant used can be air, pure oxygen, steam or a mixture of these gases (Ciferno & Marano, 2002). Under an economic point of view, the gasification process converts solid or liquid feedstock of lesser market value than premium gas or liquid fuels, into a synthesis gas that is suitable for use in electricity production or for the manufacture of chemicals, hydrogen, or transportation fuels (Stiegel & Maxwell, 2001).

Technological options

There are three gasifier configurations, described below: they differ in flow geometry and in process parameters such as temperature and pressure.

1. *Moving bed gasifiers* (also called fixed bed g.) have been the traditional choice for gasification. Gases flow relatively slowly upward through the bed of feedstock material (Minchener, 2005); depending on the direction of the airflow, moving bed gasifiers are further classified as updraft, downdraft or cross-flow, and each class is characterized by different operating temperatures (McKendry, 2002) (see table 14);
2. *Fluidized bed gasifiers*, in which feedstock particles are suspended in the gas flow, and the material entering the gasifier is mixed with that already undergoing gasification. Two main kinds of fluidized bed gasifiers are in use: circulating fluidized bed g. and bubbling bed g. (McKendry, 2002) (see table 14).
3. *Entrained flow gasifiers*, in which pulverized coal particles and gases flow concurrently at high speed. They are the most commonly used gasifiers for coal gasification (Minchener, 2005), but the need for a finely divided feed material (<0.1–0.4 mm) creates problems for fibrous materials such as wood, thus making the process unsuitable for most biomass materials (McKendry, 2002).

Gasifier configuration	*Operating temperature [°C]*
Moving bed gasifier	1000
Fluidized bed gasifier	900
Entrained flow gasifier	1200-1600

Table 14 – Gasifier operating temperatures (Minchener, 2005)

All gasifier configurations require air, oxygen or steam at high temperatures (McKendry, 2002) (see Table 14): this prevents their combining with state-of-the-art/LWR NPPs, that cannot reach, the needed temperatures.

Feedstock

Gasification can be operated either with biomass or coal as a feedstock, each having different characteristics, availability and costs:

1. *Gasification of biomass:* biomass is the organic material from recently living things, including plant matter from trees, grasses, and agricultural crops (Ciferno & Marano, 2002). The chemical composition of biomass varies among species, but basically consists of high moisture content, a fibrous structure consisting of lignin, carbohydrates or sugars, and ash- Biomass possesses a heating value lower than that of coal (see Table 15), and it is very non-homogeneous in its natural state: this non-homogeneous character poses difficulties in maintaining constant feed rates to gasification units, often resulting in a low heating value for the product syngas, typically <2.5 MJ/m3 (Ciferno & Marano, 2002); to be considered interchangeable with conventional fossil fuels and to ensure maximum flexibility for industrial or utility applications, the syngas heating value needs to be above 11 MJ/m3 (the heating value for natural gas being approximately 37 MJ/m3) (Turn, 1999).

Biomass	*Heating value [MJ/Kg]*
Agricultural residues	
Sawdust	19,3
Bagasse	17
Corn cob	17
Short rotation woody crops	
Beech wood	18,4
Herbaceous energy crops	
Switchgrass	15,4
Straw	17,0
Miscanthus	12,0
Municipal solid waste	
Dry sewage	8,0
Coals	
Subbituminous	24,6
Bituminous	27,0

Table 15 – Potential biomass gasifier feedstock and heating value (Ciferno & Marano, 2002)

2. *Gasification of coal:* coal gasification involves converting solid coal into a gaseous fuel that can be used similarly to natural gas; the objective of the conversion is to mitigate some of the drawbacks associated with the combustion of solid coal (WNA,

2010). In particular, gasification allows a significant reduction of air emissions from the direct combustion of coal (e.g. particulates, sulphur oxides and heavy metals). An important advantage of coal gasification is that of the resource base. In general, the use of gasified coal has the same advantages as the use of natural gas, but the world current reserves of coal are much larger than those of natural gas;
3. *Co-gasification of coal and biomass:* biomass, whether as a dedicated crop or a waste-derived material, is renewable. However, the availability of a continuous biomass supply can be problematic (for example, crop supply may be decreased by poor weather or by alternative uses, and the availability of a waste material can fluctuate depending on variations in people’s behavior) (Komabe, Hanaoka, & Fujimoto, 2007). The principle of co-gasification is to adjust the amount of coal fed to the gasifier so as to alleviate biomass feedstock fluctuations. Co-gasification is a new area of study, and only pilot studies are being carried on.

Products and applications

Different outputs of the gasification process are listed and described below:

1. *Gasification can create Substitute Natural Gas (SNG)* from coal or other feedstock: using a “methanation" reaction, the SNG - chiefly carbon monoxide (CO) and hydrogen (H_2) - can be then profitably converted to methane (CH_4) (Mozaffarian, Zwart, Boerrigter, & Deurwaarder, 2004);
2. *Gasification can generate power directly:* gasification can produce electric power via a direct combustion boiler/steam turbine: this system has a low efficiency (between 20 and 25%) (Ciferno & Marano, 2002). Power generation can also be accomplished via gasification of biomass, followed by a combustion engine, combustion turbine, steam turbine or fuel cell. These systems can produce both heat and power and can achieve greater system efficiencies, in the range of 30 to 40%. If the feedstock is coal, the *Integrated Gasification Combined Cycle* (IGCC) is the baseline choice: this particular coal-to-power technology allows the continued use of coal without the

high level of air emissions associated with conventional coal-burning technologies. In contrast, conventional coal combustion technologies capture the pollutants after combustion, which requires cleaning a much larger volume of the exhaust gas, leading to increased costs, reduced reliability, and generating large volumes of sulfur-laden wastes that have to be disposed (Minchener, 2005);

3. *Gasification can synthesize chemicals and fertilizers:* it produces valuable byproducts such as ammonia and phosphates, that have potential on the fertilizer market (Ro, Cantrell, Elliott, & Hunt, 2007);
4. *Gasification can produce H_2* for the hydrogen economy: production of H_2 from renewable sources derived from agricultural or other waste streams offers the possibility to lower greenhouse gas emissions (without carbon sequestration technologies) (Levin & Chahine, 2009). The key problem with gasification is how to separate and purify the H_2 from other gases in the syngas; the technology is not yet mature for a satisfying implementation.

2.4.2 Hydrogen production via nuclear heat

As an alternative path to the current fossil fuel economy, a hydrogen economy is envisaged in which hydrogen would play a major role in energy systems and serve all sectors of the economy, substituting for fossil fuels (IAEA, 2007). Hydrogen possesses a number of attractive features that could allow it to become a key secondary energy carrier in the future:

- Hydrogen combustion (either hot or cold) is generally clean, since it does not produce the characteristic emissions of fossil fuel combustion. The problem of NO_x production from high temperature combustion is practically eliminated in modern engine designs (Conte, Iacobazzi, Ronchetti, & Vellone, 2001).
- Technologies similar to those used for the combustion of fossil fuels can be used for hydrogen combustion to generate heat, electricity and propulsion energy; for example, hydrogen can be used as fuel in catalytic combustions (in diffusion burners, fuel cells), in internal combustion engines and in gas turbines (WNA, 2010).

- Hydrogen is storable, which is convenient for an energy carrier and gives the possibility of making the energy system much more flexible than at present, in particular by using the conversion of electricity to hydrogen (through water electrolysis) and vice versa (through fuel cells), as necessary (WNA, 2010).
- Hydrogen could be a third product from power plants, in addition to electricity and heat (Forsberg, 2003).

Making the fullest possible use of the above advantages, hydrogen can be considered a key element of an environmentally benign and sustainable energy system, including transportation.

Market perspectives

The annual world consumption of H_2 is about 50 million tons, which is used primarily for ammonia production and conversion of heavier crude oils to clean liquid fuels (Forsberg, 2003). The hydrogen market has been growing steadily in the last decade, and this growth is expected to continue with a 10% yearly rate (Blanchette, 2007), doubling the demand by 2020. Moreover, in the long term, should the hydrogen economy occur, the use of hydrogen for all our transportation needs would require a factor of 18 more hydrogen than currently used. Use of hydrogen for all our non-electric energy needs would imply a factor of 40 increase (Schultz, Brown, Besenbruch, & Hamilton, 2003).

Hydrogen production methods

Nuclear energy provides a source of heat to produce H_2. Multiple processes are being investigated to produce H_2 from water and heat. If nuclear energy is to be used for H_2 production, the nuclear reactor must deliver heat at conditions that match the requirements imposed by the H_2 production process. The viability of H_2 production from nuclear power ultimately depends upon the economics, which, in turn, depend upon both the proposed methods of H_2 production and the available reactors. Four methods have been proposed to produce H_2 from nuclear power:

- *Electrolysis:* electrolysis of water to produce H_2 is an old technology that is used today to produce ultrapure H_2 and to produce H_2 in small quantities at dispersed sites. Electrolysis is not currently competitive for the large-scale production of H_2 (Forsberg, 2003).

- *Steam reforming:* today, H_2 is produced primarily from the steam reforming of natural gas. Steam reforming is an energy-intensive endothermic low-pressure process requiring high-temperature heat as an input. Natural gas is used as the reduced chemical source of H_2 and burned to produce heat to drive the process at temperatures of up to 900°C. The amount of natural gas required for steam reforming can be significantly reduced when heat is provided by a nuclear reactor. The Japan Atomic Energy Research Institute is currently preparing to demonstrate the production of H_2 by steam reforming of natural gas with the heat input provided by its High-Temperature Engineering Test Reactor (HTTR). The nuclear power plant provides heat that replaces that from a gas flame. Because this system uses standard H_2 production technology, it represents the near-term nuclear H_2 technology, once HTTRs are commercially viable (Forsberg, 2003).
- *Hot electrolysis:* electrolysis can be operated at high temperatures (700–900°C) and low pressures to replace some of the electrical input with thermal energy. Because heat is cheaper than electricity, the H_2 costs via this production method could ultimately be lower than those for traditional electrolysis. Equally important, the high temperature results in better chemical kinetics within the electrolyser that reduces equipment size and inefficiencies. However, the technology is at an early stage of development although it derives much of its technology from solid-oxide fuel cells. Hot electrolysis requires collocation of H_2 production close to the nuclear reactor to provide the heat (Forsberg, 2003).
- *Thermo-chemical hydrogen production:* hydrogen can be produced by direct thermo-chemical processes, in which the net reaction is: heat plus water yields H_2 and oxygen. These are the leading long-term options for production of H_2 using nuclear energy. For low production costs, however, high temperatures (more than 750°C) are required to ensure rapid chemical kinetics (i.e., small plant size with low capital costs) and high conversion efficiencies. Of the advanced methods for hydrogen generation using nuclear power, thermo-chemical cycles have received the most attention because current estimates indicate that thermo-chemical H_2 production costs could be as low as 60% of those from room-temperature electrolysis (Forsberg, 2003).

- *Biomass gasification:* hydrogen can be produced with lower or no greenhouse emissions via the gasification of agricultural or other waste (Levin & Chahine, 2009).

Thermo-chemical processes are currently regarded as the most promising technology for massive production of hydrogen in the next decades (Forsberg, 2003).

Process requirements

Process requirements for H_2 production via nuclear steam reforming of methane, hot electrolysis, and thermo-chemical cycles are similar. All three technologies impose similar requirements on the nuclear reactor (Forsberg, 2003):

- *Reactor power:* H_2 production facilities match best with reactor powers below 1000 MWe (Forsberg, 2003), but larger reactor scales (such as the 1650 MWe AREVA reactors that are planned to be constructed in Italy (WNA, 2009)) do not prevent H_2 production applications.
- *Peak temperature:* all the methods previously described (see *Hydrogen production methods*) but electrolysis requires high temperature heat (750–900◦C).
- *Temperature range of delivered heat:* all of the endothermic high-temperature chemical reactions operate at a nearly constant temperature. Heat should therefore be delivered over a small temperature range.
- *Pressure:* the chemical reactions go to completion at low pressures. High pressures reverse the desired chemical reactions. The H_2-nuclear interface should be at low pressure to minimize the risk of pressurization of the chemical plant and minimize high-temperature materials strength requirements.
- *Isolation:* the nuclear and chemical facilities should be isolated from each other so that upsets in one facility do not impact the other. The system must also minimize tritium (radioactive hydrogen) production and transport from the reactor to the H_2 production facility.

Nuclear reactor selection

The high peak temperatures reached by all the processes (750-900°C, see *Process requirements*) except standard electrolysis are not endurable by currently commercialized reactors (WNA, 2009); therefore, although several methods to produce H_2 using high temperature heat are available, significant development work is required before any of these processes can be actually put in practice.

Sandia National Laboratories evaluated various nuclear reactors for their ability to provide the high temperature heat needed, and to be interfaced safely and economically to the hydrogen production process (Schultz, Brown, Besenbruch, & Hamilton, 2003). The recommended reactor technologies were supposed to require minimal development to meet the high temperature requirement and also to be free from any significant design, safety, operational or economic issues.

The following conclusions were drawn:

- PWR, BWR and organic-cooled reactors: not recommended, because they cannot achieve sufficiently high temperatures.
- Liquid-core and alkali metal-cooled reactors: they imply serious development risk, due to material concerns at the needed temperatures.
- Heavy metal and molten salt-cooled reactors: promising, but they require a significant development effort.
- Gas-core reactors: not recommended, too speculative at present.
- High-temperature gas-cooled reactors: baseline choice. In particular, only modest development is needed for helium gas-cooled reactor, which has historically been considered the one reactor that would be used for the purpose. Alternatively, a reactor can be designed specifically for H_2 production: the Advanced High-Temperature Reactor (AHTR) has been proposed; this concept is similar under many features (core design, fuel cycle) to the General Atomics modular helium reactor (Forsberg, 2003).

Economics of H_2 production

Nuclear power plants are characterized by high capital costs and low operating costs; therefore, the economics are strongly dependent upon maintaining base-load operations with continuous output. Two characteristics of hydrogen help doing so:

- Constant base-load demand for H_2 favors technologies with low fuel costs, such as nuclear energy (Forsberg & Peddicord, 2001).
- Hydrogen packing (increasing the pressure) creates significant storage capacity, which can mitigate potential variations in

demand; using the techniques developed by the natural gas industry, H_2 storage in large volumes is expected to be relatively low cost (Forsberg, 2003).

In addition, the need for security, the difficulty in finding social acceptance for nuclear plants and the economic advantages of using common facilities encourage siting multiple reactors at each site.

Economics of H_2 distribution

Hydrogen transport is the major concern for the accomplishment of the hydrogen economy: if the hydrogen economy occurs as is prefigured, the scale of H_2 production is expected to evolve from distributed to midsize and only eventually (after 2030) to centralized.
Central station plants are assumed to have a production capacity of 1.200.000 kilograms per day (kg/d) and to operate with a 90 percent or higher capacity factor, therefore producing on average 1.080.000 kg/d H_2 and supporting nearly 2 million cars; midsize plants are assumed to have a production capacity of 24,000 kg/d (operating with a 90 percent capacity factor, they produce on average 21,600 kg/d H_2 which is enough to support about 40.000 cars); distributed plants have different production capacities corresponding to the differing capacity factors: those that operate with a 90 percent capacity factor are assumed to have a production capacity of 480 kg/d H_2, producing on average 432 kg/d (Committee on Alternatives and Strategies for Future Hydrogen Production and Use, 2004).
The nuclear energy source is only compatible, for the number and size of plants, with centralized production (Committee on Alternatives and Strategies for Future Hydrogen Production and Use, 2004). If no breakthrough technologies are conceived, dedicated pipelines will be the most convenient solution for the transport of hydrogen from central station plants to users; line transmission of hydrogen, although, is expected to be highly capital-intensive, because costly steel and valve metal seal connections will be required in order to avoid long-term embrittlement and possibilities of leakage. According to the analysis conducted by the Committee on Alternatives and Strategies for Future Hydrogen Production and Use, pipeline shipment and dispensing will cost \$0.96/kg H_2, which is essentially equal to the cost of H_2 production from natural gas, and higher than the cost of its production via thermal splitting with nuclear energy.
If and when extensive new hydrogen transmission pipelines are needed in the decades ahead, research in such areas as lower-cost pipeline materials, technology for dual-use of natural gas-and-hydrogen pipelines, layout

optimization, and even pipeline emplacement technologies will be of critical importance.

2.4.3 Shale oil extraction

If carbon dioxide releases from liquid-fuels production are to be minimized, liquid fuels should be produced only from high-quality light crude oils; unfortunately, the resources of light crude oil are limited (Forsberg, 2009). What is required is a technology to create large quantities of light crude oil without the release of large quantities of greenhouse gases: one option is a nuclear light-oil production system (Forsberg, 2008). This system may allow massive underground resources of fossil fuels, which are economically unrecoverable with existing technologies, to be converted into liquid fuels (Forsberg, 2009). Examples include the following:

- Old oil fields: over half the oil remains in a depleted oil field trapped by capillary forces between grains of sand or within cracks in the rock (Forsberg, 2009).
- Tar sands: tar sands are a mixture of sand, clay, water, and bitumen (viscous heavy oil). Unlike conventional oil, bitumen is too viscous to be pumped to the surface. The feasibility of oil recovery from tar sands is limited to surface deposits and underground deposits where steam heating can reduce the viscosity of the oil until it flows (Finan, Miu, & Kadak, 2005).
- Oil shale: oil shales are fine-grained sedimentary rocks containing relatively large amounts of organic matter (known as ‘kerogen’) from which significant amounts of shale oil and combustible gas can be extracted (World Energy Council, 2007); shale oil, when adequately processed, can be utilized as a crude oil substitute in most applications (Ots, 2007).
- Soft coal: soft coal, if heated, is converted to chat and a liquid fuel.

The extraction of oil from these categories of fossil deposits poses a challenge to the oil industry (Forsberg, 2009).

Shale oil reserves in the world

World shale oil resources[1] derivable from oil shale beds are estimated by the *European Academies Science Advisory Council* (EASAC) at approximately 3.2 trillion US barrels (EASAC, 2007). Two-thirds of the listed deposits are located in North America, while Europe accounts for approximately 12%. The Russian territory holds more than 60% of European oil shale, and the Italian peninsula contains most of the remaining quantity (about 20% of the total, see Figure 20) (EASAC, 2007).

Shale oil extraction technologies

The two classes of shale oil recovery are surface mining, which is the traditional means to extract shale oil from oil shale, and in-situ refining.

Surface mining

Surface mining is operated through an open-pit recovery of oil shale with heavy-ton trucks and electric or hydraulic shovels; the ore is then sent to an extraction plant where the rock is separated from the kerogen, which undergoes a refining process (see Figure 21, left side: traditional refining) (Finan, Miu, & Kadak, 2005).

In-situ refining

Starting in the 1970s, researchers began to examine methods for underground oil recovery from the previously described fossil deposits; because of technological developments, concerns about greenhouse gas and CO_2 emissions, and higher oil prices, these technologies have now progressed to field testing, with initial leasing of properties for commercial production in pioneer countries with large oil shale reserves (Forsberg, 2008).

---

[1] Resources also comprehend those quantities of a commodity that are estimated to be potentially recoverable but which are not currently considered commercially recoverable (EASAC, 2007).

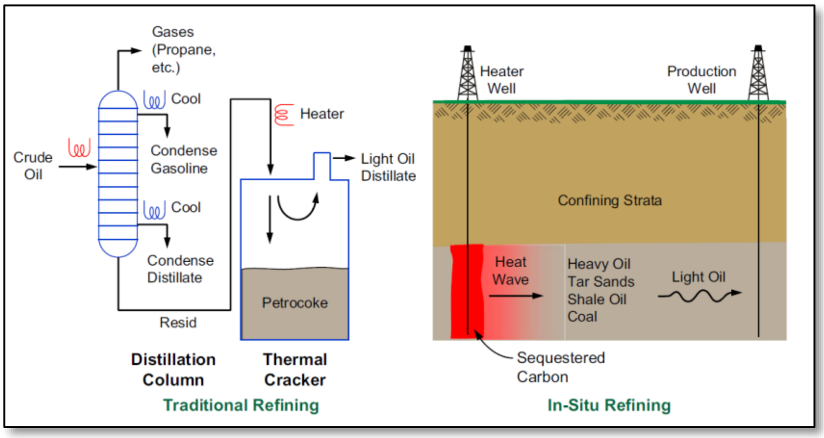

Figure 21 – Distillation and thermal cracking of high-molecular-weight hydrocarbons in a refinery and in an underground reservoir (Forsberg, 2009).

The technology is conceptually simple (see Figure 21, right side: In-situ refining): a fossil deposit is heated to temperatures around 370°C through the injection of high-temperature heat at 700°C from the heater well); as the temperature increases, any volatile hydrocarbons will vaporize (be distilled), move as gases toward a recovery well, condenses in the surrounding cooler zones, and be pumped out of the ground as a liquid or vapor (Forsberg, 2009). This distillation process leaves most impurities behind; as the temperature further increases, heavier hydrocarbons that have not been vaporized will be thermally cracked and turn into lighter volatile hydrocarbons, that can be recovered.

This process has two major technical advantages:

- ❖ Ability to extract deep-situated resources: approximately 80% of the oil shale deposits worldwide are too deep for surface mining and can only be recovered with in-situ methods (Finan, Miu, & Kadak, 2005);
- ❖ Control of carbon dioxide emissions: unlike in traditional refining, the solids from an underground thermal-cracking process remain sequestered underground as carbon (Forsberg, 2009); if the heat was provided by an energy source that did not emit carbon dioxide as well, such as nuclear heat the result would be low emissions of carbon dioxide from the entire process, since a high-quality crude oil is distilled that requires little added refining to produce transport fuels (Forsberg, 2008).

Nuclear energy as a source of heat for in-situ shale oil recovery

The shale oil heating process requires large quantities of high-temperature heat - about one-sixth the heating value of the product (IAEA, 1997). The heating of oil shale yields both liquids and gases (Forsberg, 2009); it is currently proposed to burn the gases, representing one-third of the recovered energy, to produce electricity, that is in turn converted into heat for further underground heating (Forsberg, 2009). This solution implies the release of greenhouse gases produced during the gas combustion. Although, a heating option exists that can maintain the process a greenhouse-free one: the use of high-temperature nuclear reactors to produce the required heat (see figure 22) (IAEA, 1997).

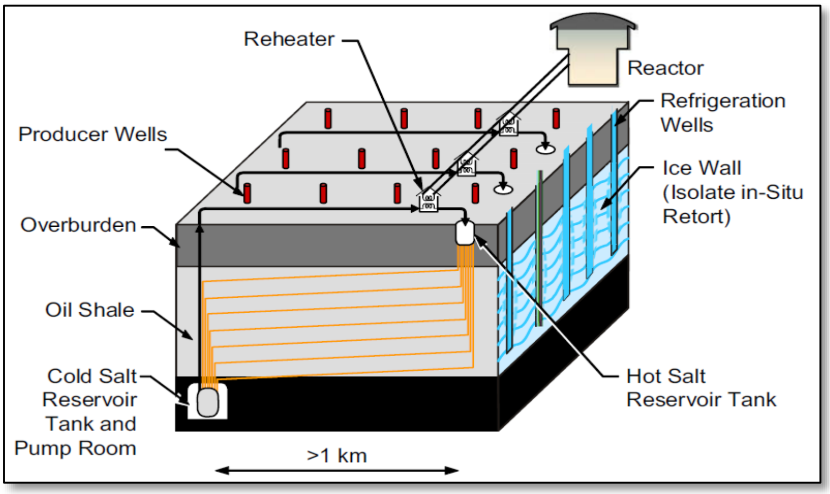

Figure 22 – Configuration for underground heating of oil shale via nuclear heat (Forsberg, 2009).

Heat from nuclear plants guarantees two main advantages when compared to heat from the combustion of oil shale gases:

- It erases the necessity to burn part of the products to generate heat, substituting it with bleeded heat; the thermal energy cost in thus substantially decreased.
- It avoids emissions of carbon dioxide throughout the production process.

(Forsberg, 2006) identifies nuclear heat as a potentially viable thermal source because of a particular characteristic of many U.S. oil shale deposits: they are more than 200m thick and can yield up to 625 million barrels of oil per km^2. This means the concentrated layout of American shale-oil deposits make it practical and economically viable to transfer heat over limited distances from a reactor to the deposit.

Economics

There is uncertainty about the commercial viability of shale oil as a crude oil substitute: the 2005 study *Oil Shale Development in the United States: Prospects and Policy Issues*, (RAND, 2005), indicates that oil production based on in-situ refining can be profitable if crude oil prices consistently stay above at least $50 per barrel; the current price of crude oil is about 80 dollars per barrel, but the time horizon for the commercial development of in-situ technologies is more than 20 years (RAND, 2005); the oil price forecast is not reliable on such a long term, due to uncertainties in the development of crude oil consumption, extraction technologies, oil substitutes, and to the political instability of supplier countries.
Nuclear heat can make in-situ refining more economically competitive: the state-of-the-art Shell in-situ retorting process uses electric power as the source for down-hole heating; about 250 to 300 kilowatt-hours are required for down-hole heating per barrel of extracted product (RAND, 2005). Assuming electricity at $0.05 per kilowatt-hour, power costs for heating using electrically-generated heat amount to between $12 and $15 per barrel (crude oil equivalent). Assuming nuclear power as a cost-zero source of heat, in-situ refining via nuclear heat could become competitive with crude oil prices above 35 to 38 dollars per barrel, which is less than half the current market price. Of course, the commercial development of in-situ technology will require high investments: Shell reports that it has spent tens of million dollars in developing its in-situ conversion technology, and that a pre-commercial demonstration plant that would produce about 1,000 barrels per day will cost additional 200 million dollars (RAND, 2005). Further investments would be needed to reach a mature, commercially viable technology.

Environmental *considerations*

If the economic feasibility of shale oil production is verified, there are issues that need to be reckoned on the environmental front, including (EASAC, 2007):

- *Land use:* large tracts of public land would need to handed over to the production and processing of oil shale. There would be the concomitant requirement of infrastructures: roads, power supply and distribution systems, pipelines, water storage and supply facilities; In-situ retorting would be less disruptive to the landscape than open-pit mining, nonetheless it would involve the drilling of a large number of wells. Due to the poor flow conditions within the shale, the wells would have to be drilled close to each other; the wells would need to be connected to an shale oil and gas treatment plant by a network of pipelines (RAND, 2005);

- *Water quality:* potential sources of water pollution include mine drainage, point-source discharges from surface operations associated with solids handling, retorting, upgrading, and plant utilities; there is little understanding of the long-term impact of the underground liquefaction and gasification on groundwater quality, but it is envisaged to be a very disruptive one;
- *Water consumption:* estimated water requirements for mining and retorting range from 2.1 to 5.2 barrels of water per barrel of shale oil product; in-situ processing eliminates or reduces a number of these water requirements, but it would still require a considerable use of water for oil and gas extraction, post-extraction cooling, and products upgrading and refining.

2.5 Conclusions

Three main dimensions affect the development of the applications described in par 2:

1. Temperature required: low, medium or high;
2. Reactor size: traditional, large ones or small innovative ones;
3. EPZ size: small or large.

The main conclusions about possible applications, in relationship with these aspects, are discussed in Table 18.

The hypothesized influence of the EPZ on the different applications can be schematized as follows:

- If the application considered is at low temperature and the reactor is a large, traditional one, the EPZ is hypothesized to be large and must be exploited in some way.
- If the application temperature is low, but the reactor is a small, innovative one (e.g. IRIS), the EPZ will be probably reduced or even collapsed in the NPP on-site area. Thus, the influence of EPZ in this case is not a major constraint;
- The same consideration is valid for high temperature applications: they all envisage Generation IV reactors, for which the reduction of EPZ is a goal announced by GIF and INPRO.

These observations are schematized in Figure 29.

However it is not possible to assume the EPZ reduction for small reactors as a certainty. Even though the EPZ for these reactors is likely to be small, the very last decision is under responsibility of each country's legislation.

<table>
<thead>
<tr><th>Dimension</th><th>Conclusion</th></tr>
</thead>
<tbody>
<tr><td rowspan="3">Temperature required</td><td>Near term applications requiring low temperatures can be realized by commercial nuclear reactors, such as LWR and PHWR.</td></tr>
<tr><td>Applications at medium temperature could be realized with gas reactors like AGR. However, the chapter will not focus on them for the following reasons:
❖ They are generation II reactors and it is unlikely to invest on them;
❖ There is no experience (and literature) in heat applications from them.</td></tr>
<tr><td>Long term applications at high and very high temperature are highly innovative and constitute a major field of study: the commercialization of HTGR is envisaged for 2030.</td></tr>
<tr><td rowspan="2">Reactor size</td><td>Near term applications at low temperature can be realized using both large and small reactors. In particular, large reactors of generation III and III+ are available, while the commercialization of small, innovative reactors is envisaged for 2016. There is a lot of experience and literature about nuclear heat applications at low temperature using traditional reactors.</td></tr>
<tr><td>Long term applications, requiring high and very high temperature, are mainly addressed to small reactors such as Generation IV VHTR (2030).</td></tr>
<tr><td rowspan="3">EPZ size</td><td>Only district heating is strongly influenced by the EPZ size, as it requires a high density of people relatively near the reactor. If a large reactor is used, the NPP will be probably located far from the population centre which harnesses the heat, due to EPZ constraints: in this case, a way to exploit the unused area around the plant must be found. If a small, innovative reactor with enhanced safety is used, the EPZ could be reduced or even eliminated: however, this is not a certainty.</td></tr>
<tr><td>All other applications are not highly influenced by EPZ as they do not require a large amount of people near the plant: on the contrary, it makes sense to assume that they can be located inside the EPZ, avoiding long and expensive heat transmission lines, and allowing the exploitation of the unused area around the plant.</td></tr>
<tr><td>In order to reduce/eliminate EPZ, the option to locate the NPP offshore is very interesting.</td></tr>
</tbody>
</table>

Table 18 – Main conclusions about possible applications

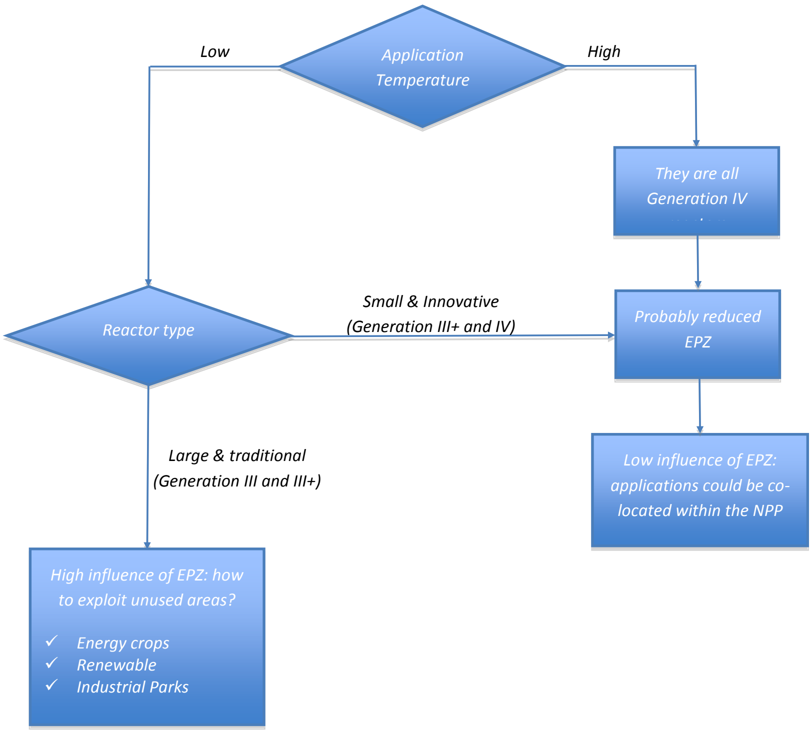

Figure 29 – Influence of EPZ on the applications

REFERENCES

AEC. (2005). Retrieved 2010 from Atomic Energy Council: http://www.aec.gov.tw/www/english/nuclear/psar/lm_document_psar_02_01.pdf

Augutis. (2005). Economic benefits of revising the need for relocation and evacuation measures unique to NPPs for innovative SMRs for regions with electricity co-generation. *LEI.*

BARC. (1975). BARC Highlights: Reactor technologies and engineering. *India: BARC.*

Blanchette. (2007). A hydrogen economy and its impact on the world as we know it. Energy policy .

Ciferno, & Marano. (2002). Benchmarking biomass gasification technologies for fuels, chemicals and hydrogen production. *U.S. Department of Energy.*

Conte, Iacobazzi, Ronchetti, & Vellone. (2001). Hydrogen economy for a sustainable development: state-of-the-art and technological perspectives. Journal of Power Sources .

Csik, K. (1997). Nuclear power applications: supplying heat for hoime and industries. *IAEA.*

EASAC. (2007). A study on the EU oil shale industry. *EASAC.*

Finan, Miu, & Kadak. (2005). Nuclear technology and Canadian oil sands: integration of nuclear power with in-situ oil extraction. *Cambridge: Department of nuclear science and engineering.*

Forsberg. (2006). High-temperature nuclear reactors for in-situ recovery of oil from oil shale. Proceedings .

Forsberg. (2008). High-temperature reactors for underground liquid-fuels production with direct carbon sequestration. Proceedings .

Forsberg. (2003). Hydrogen, nuclear energy, and the advanced high-temperature reactor. International journal of hydrogen energy .

Forsberg. (2009). Sustainability by combining nuclear, fossil, and renewable energy sources. Progress in nuclear energy .

Forsberg, & Peddicord. (2001). Hydrogen production as a major nuclear energy application. *U.S. Department of Energy.*

Hedges. (2005). A Brief Introduction to CANDU9 – A New Generation of Pressurized Heavy Water Reactors. *From Canteach: http://canteach.candu.org/library/20054416.pdf*

IAEA. (2007). Advanced applications of water cooled nuclear power plants. *Vienna.*

IAEA. (1997). Floating nuclear energy plants for seawater desalination. *Vienna.*

IAEA. (2000). IAEA TECDOC 1184 - Status of non-electric nuclear heat applications: technology and safety. *IAEA.*

IAEA. (2006). IAEA TECDOC 1487 - Advanced nuclear plant design options to cope with external events. *IAEA.*

IAEA. (2007). IAEA TECDOC 1584 - Advanced applications of water cooled nuclear power plants. *IAEA.*

IAEA. (1997). IAEA TECDOC 953 - Method for the development of emergency response preparedness for nuclear or radiological accidents.

IAEA. (2002). Market potential for non-electric applications of nuclear energy. *IAEA.*

IAEA. (2005). Meeting report of the first research coordination meeting (RCM) of coordinated research project (CRP) on small reactors without on-site refuelling. *IAEA.*

IAEA. (2003). Method for Developing Arrangements for Response to a Nuclear or Radiological Emergency (Updating IAEA TECDOC 953). *IAEA.*

IAEA. (1998). Nuclear heat applications - Design aspects and operating experience.

Kirchsteiger. (2006). Current practices for risk zoning around NPPs in comparison to other industry sectors. Journal of Hazardous Materials .

Komabe, Hanaoka, & Fujimoto. (2007). Co-gasification of woody biomass and coal with air and steam. Fuel .

Kutznetsov. (2008). The Technical and Economic Principles and Lines of Development of Nuclear District Heating Cogeneration. Thermal engineering , 55 *(11), 926-938.*

Levin, & Chahine. (2009). Challenges for renewable hydrogen production from biomass. Hydrogen energy .

Maioli. (2006). EPZ History and background.

McKendry. (2002). Energy production from biomass (part 3): gasification technologies. Bioresource Technology .

Minchener. (2005). Coal gasification for advanced power generation. Science Direct .

Mozaffarian, Zwart, Boerrigter, & Deurwaarder. (2004). Biomass and waste-related SNG production technologies. Rome.

NRC. (1998). NUREG 0654 - Criteria fro preparation and evaluation of radiological emergency response plans and preparedness in supporto of NPP. *NRC.*

NRC. (1988). NUREG 1140 - A regulatory analysis on emergency preparedness for fuel cycle and other radioactive material licences. *NRC.*

NRC. (1990). NUREG 1150 - Severe accident risk: an assessment for five US nuclear power plants. *NRC.*

NRC. (1998). PEP. *From Nuclear Regulatory Commission: http://www.nrc.gov/about-nrc/emerg-preparedness/images/10-mile-EPZ-map.jpg)*

NRC. (1998). Regulatory guide 4.7 - General site suitability criteria for NPS. *Retrieved 2010 from U.S. NRC: http://www.nrc.gov/reading-rm/doc-collections/reg-guides/environmental-siting/active/04-007/*

NRC. (1962). TID-14844 Calculation of Distance Factors for Power and Test Reactor Sites. *NRC.*

NRC. (2003). Title 10 - Energy, Volume 2, Part 100 - Reactor Site Criteria. *NRC.*

NRC. (1950). WASH-3. *NRC.*

OECD/NEA. (2004). Non-electricity products of nuclear energy. *OECD.*

OECD/NEA. (2003). Short-term Countermeasures in Case of a Nuclear or Radiological Emergency.

OPG. (2009). Site boundary consideration for new nuclear - Darlington. *From Canadian Environmental Assesment Agency: http://www.ceaa.gc.ca/050/documents_staticpost/cearref_29525/0105/ai-sb.pdf*

Ots. (2007). Estonian oil shale properties and utilization in power plants. Energetika .

RAND. (2005). Oil shale development in the United States: prospects and policy issues. *U.S. Department of Energy.*

RENAEL. (2004). Vademecum sulle tecnologie del risparmio energetico: teleriscaldamento. *From http://www.renael.net/public/documenti/181/Teleriscaldamento.pdf*

Ro, Cantrell, Elliott, & Hunt. (2007). Catalytic Wet Gasification of Municipal and Animal Wastes. *From ACS Publications: http://pubs.acs.org*

Schultz, Brown, Besenbruch, & Hamilton. (2003). Large-scale production of hydrogen by nuclear energy for the hydrogen economy. *San Diego: General Atomics.*

Stiegel, & Maxwell. (2001). Gasification technologies: the path to clean, affordable energy in the 21st century. Fuel processing technology .

Turn. (1999). Biomass integrated gasifier combined cycle technology III: application in the sugar cane industry. Int. Sugar Journal .

WNA. (2009). Generation IV nuclear reactors. *From WNA: http://www.world-nuclear.org*

WNA. (2009). Nuclear power in Italy. *From WNA: http://www-world-nuclear.org*

WNA. (2010 йил 12-March). Nuclear power in Russia. *From WNA: www.world-nuclear.org*

World Energy Council. (2007). 2007 survey of energy resources. *London: World Energy Council.*