

# Nuclear power plant's water thermal plume assessment by satellite remote sensing data

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**Abstract** — The main environmental issues affecting the broad acceptability of NPP (Nuclear Power Plant) are the emission of radioactive materials, the generation of radioactive and heat waste, and the potential for nuclear accidents. Satellite remote sensing is an important tool for spatio-temporal analysis and surveillance of environment, thermal heat waste of waters being a major concern in many coastal ecosystems involving nuclear power plants, as sharp changes in water temperature can significantly affect the distribution and physiology of aquatic biota and contribute to global warming. The thermal plume signature in the NPP hydrological system in TIR (Thermal Infrared) spectral bands of Landsat TM and ETM TIR band 6 as well as ASTER TIR bands time series satellite have been used for WST (Water Surface Temperature) detection, mapping and monitoring. As a test case the methodology was applied for NPP Cernavoda, Romania during period of 1990-2010 years. Thermal discharge from two nuclear reactors cooling is dissipated as waste heat in Danube-Black -Sea Channel and Danube River. If during the winter thermal plume is localized to an area of a few km of NPP, the temperature difference between the plume and non-plume areas being about 1.5 °C, during summer and fall, is a larger thermal plume up to 5-6 km far along Danube Black Sea Channel, the temperature change being of about 1.0 °C.

**Keywords** — Nuclear power plant environment, thermal plume, satellite data: Landsat TM, ETM; ASTER, Cernavoda Romania.

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## 1 INTRODUCTION

At the present time in Romania there is one operational Nuclear Power Plant (NPP), located at Cernavoda, in Contanta county, South-Eastern part of the country. The plant was designed to comprise five CANDU 700 MWe units. NPPC Unit 1 started operation in 1996, Unit 2 in 2007. There are under construction NPP Cernavoda Unit 3 and 4. Cernavoda NPP Units 3 and 4 will each have 720 MW gross electrical capacities. Each unit consists of a CANDU-6 Pressurized Heavy Water Reactor (PHWR). The construction period is estimated to be 64 months, commissioning is scheduled for 2013 and 2014 respectively. The design life for the nuclear units is 30 years [1]. Both the Cernavoda Units 1 and 2 are well designed for the meteorological conditions specified for the site (normal and extreme values for ambient temperature, wind speed, amount of precipitation -rain and snow) and level of humidity). The Cernavoda site grade level has been established higher than the highest credible flood water level, so there is no danger of flooding from either the Danube Black Sea Channel or Danube River, as well as to resist the effects of earthquakes. The CANDU reactors are of the surest types in the world. Radioactive emissions are low under normal conditions of function, but the main radioactive waste products, in gaseous and liquid status, are associated with tritium and carbon-14 emissions that can, in time, accumulate in the trophic chain and finally in humans. Together with colder

water, emissions of heavy tritiated water (HTO) arrive in the Danube River. The environmental advantages of nuclear energy technology over alternative means of large-scale energy production are many. The lower production costs of 36 EUR/MWh for Cernavoda Nuclearelectrica, covering almost 6% of Romania electric power generation is one of the main reason [2].

Non-radioactive pollutants of the atmosphere like as release of greenhouse toxic gas and toxic atmospheric emissions are insignificant in comparison with fossil fuel and biomass burning at thermo power plants. The main environmental issues affecting the broad acceptability of nuclear power are the emission of radioactive materials, the generation of radioactive waste, and the potential for nuclear accidents. All nuclear fission reactors, regardless of design, location, operator or regulator, have the potential to undergo catastrophic accidents like have happened at Chalk River (1952), Chernobyl (1986), Fukushima (2011) NPPs involving loss of control of the reactor core, failure of safety systems and subsequent widespread fallout of hazardous fission products. While such accidents are infrequent, the consequences are severe and involve effects on human health, the environment and the economy. Risk is the mathematical product of probability and consequences, so low-

probability and high-consequence accidents, by definition, have a high risk.

Environmental concerns about nuclear power plants are mainly attributed to radioactive pollutants which are released in the environment (atmosphere, water, soil and vegetation) with effects on the population living in the neighborhood. Nuclear risk in any geographical area is connected with the nuclear sites, i.e. milling and mining facilities, fuel fabrication factories, reactor stacks or nuclear fuel reprocessing plants, in many areas. The Fukushima and Chernobyl accidents showed that the scale of impacts can be very severe over remote distances on the Earth. Besides radioactive waste release into the environment, nonradioactive aspects must be also be considered. Nuclear power plants convert heat resulted from fission nuclear reactions into electrical power generating steam, which feeds a turbo-generator system with a conversion efficiency of about 30-40%. The remaining 70-60% of the produced heat is dispersed into the aquatic environment through a cooling system [3].

This paper will consider only non-radiological aspects of the thermal water emissions in the environment.

## 2 USE OF GEOSPATIAL DATA

Several advanced space-borne TIR (Thermal Infra Red) sensors with different spatial, spectral and temporal resolutions provide data for monitoring and assessment of the thermal aspect of aquatic systems in the neighborhood of nuclear power plants. Of these, satellite Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper+ (ETM+), Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration (NOAA) satellites and Advanced Space-borne Thermal Emission And Reflection Radiometer (ASTER) on board the Terra satellite as well as Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on board both the Terra and Aqua platforms are well-suited for thermal plume patterns monitoring of Water Surface Temperature of hydrological systems around nuclear power plants.

### 2.1 Water Surface Temperature (WST)

Global-scale SST (Sea Surface Temperature) sensors (e.g. GOES, SeaWiFS, MODIS, and AVHRR) effectively observe sea-ocean-basin scale dynamics [4] but cannot resolve river stream or coastal and estuarine features finer than a few kilometers. Due to the potential for contamination from land, these sensors cannot reliably acquire data for water bodies less than 3 km in width, or less than 2 km from the shoreline. In addition, these broad-scale sensors cannot resolve fine-scale WST (Water Surface Temperature) gradients important in some inland

hydrographical systems [5]. Sensors with spatial resolutions appropriate for such systems and coastal zones are limited by infrequent observations (e.g. 16-day repeat for Landsat TM/ETM) or are costly (e.g. airborne sensors). Thus, detailed water thermal plume near nuclear power plants have not been developed due to the difficulties in obtaining both the high spatial (< 1 km) and temporal resolution (daily or 10-day interval decades) data required to observe WST anomalies and seasonal dynamics. In this paper, have been used in situ corrected Landsat TM/ETM Thermal Infrared (TIR) scenes which provides water temperature measurements at a spatial resolution of 120 m and can be effectively used for tracking small scale thermal patterns in stream and coastal waters. Water Surface Temperature is an important indicator of water quality, particularly in regions where aquatic ecosystems are sensitive to elevated water temperature. Regional assessment of water temperatures from the ground is limited by sparse sampling in both space and time, so remotely sensed thermal-infrared (TIR) images are able to make spatially distributed measurements of the radiant skin temperature of waters. Satellite thermal imagery can provide the opportunity to explore how much can be learned about nuclear power plants cooling system dynamics and thermodynamics for a limited amount of ground truth data. Many researchers have combined remote sensing data, numerical modeling and in situ measurements to understand the processes that dominate transport of pollutants and natural constituents of different surface water systems. anthropogenic heat flux may influence regional climate projections and contemporary chemistry-climate studies [ ].

## 3 STUDY AREA AND DATA USED

### 3.1. Test area

The Cernavoda NPP Site is located in Constanta County, latitude 44.3 °N and longitudes 28.01 °E in the Dobrogea Region (Fig. 1). The nuclear facility lies about 2 km southeast of the town of Cernavoda, in the lower Danube region, near the Black Sea. The site is located between the Danube River and the Danube-Black-Sea (DBS) Channel. The Danube River, the second largest river in Europe, (1,075 km length bordering Romania) drains the whole of Romania and completes its 2857 km course through nine countries in Romania's Danube Delta ) to its mouth on the

Black Sea. In the 1970s, a new dam raised the Danube's level and eased navigation through the Iron Gates. The river has become an important source of hydroelectric power and of irrigation water for farming. Romania's rivers are mainly tributaries of the Danube.



Fig. 1. Cernavoda NPP Site on Quickbird satellite image 05/10/2007

The Danube-Black Sea Channel (64.2 km long), between Cernavoda and Agigea-Constanta was opened to traffic in 1984. Danube River waters temperature depends on the climate of the various parts of the basin. In the Romanian sector summer temperatures vary between 22 ° and 24 °C, while winter temperatures near the banks and on the surface drop below freezing, but the Danube never freezes entirely, because the current is turbulent. During severe winters the lower courses, however, become icebound. Between December and March, periods of ice drift combine with the spring thaw, causing floating ice blocks to accumulate at the river islands, jamming the river's course, and often creating major floods. The natural regime of river runoff changes constantly as a result of the introduction of stream-regulating equipment, including dams and dikes. The mineral content of the river is greater during the winter than the summer. The content of organic matter is relatively low, but pollution increases as the waters flow past industrial areas. The river's chemistry also changes as city sewerage and agricultural runoff find their way into the river. The NPP gets its cooling water from the DBS Channel. Most of the time the cooling water is returned to the Danube River, but in winter it can be released into the Channel, so that the warmed cooling water can be

used to avoid freezing at the intake [ ] . Some of waste heat is lost to the atmosphere via evaporation, convection of sensible heat and thermal radiation. Correct prediction of temperatures in the cooling Channels requires accurate meteorological data for calculation of energy losses to the atmosphere. In the vicinity of the NPP diverse industrial and other hazardous activities (pipelines for petroleum and natural gas) are going on. The climate is continental with a Mediterranean-like influence from the Black Sea. Summers are hot and dry and winters are moderate, with some snow.

The major aquatic ecosystems in the Cernavoda area are the Danube River, the Danube-Black Sea (DBS) Channel, and a series of ponds and lakes. These interconnected systems are characterized by complex trophic structures, starting with primary producers, through primary and secondary consumers, to decomposers. The most important primary producers are algae and aquatic macrophytes. The primary consumers are zooplankton (rich in rotifers), invertebrates (including zebra mussels), and some plant-eating fish, such as carp, bream and roach. Primary consumers also include several species of water birds. Some invertebrates act as secondary consumers, as do predacious fish, such as pike, perch and sheat fish, which is a native species of large catfish. The same is true for various species of frogs, snakes, birds and mammals that feed on aquatic animals. Among the most important decomposers are benthic invertebrates, fungi and bacteria, which make nutrients available for recycling. All the systems have been heavily influenced by human activity, having been settled by the ancient Greeks, the Romans and successive civilizations. The terrestrial environment near the NPP Site is dominated by simple agricultural ecosystems interspersed with some more complex semi-natural systems.

### 3.2. Data used

The surface water temperature (SWT) of NPP Cernavoda hydrological system was examined between 1990 and 2010 period using Landsat TM/ETM and ASTER satellite imagery, both missions with recurrent cycle of 16 days. Have been used the following time series satellite data:

- Landsat TM: 12/08/1990; 16/07/1997; 20/07/1998;
- Landsat ETM: 20/08/2002; 18/07/2003, 08/08/2004; 13/08/2006; 16/07/2008; 20/07/2009; 12/08/2010;

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- ASTER: 31/07/2002; 16/08/2004; 28/08/2006; 12/07/2008;
- Quickbird satellite image: 05/10/2007.

This imagery have been selected cloud-free scenes (< 25% cloud cover over water bodies). We got Landsat TM Band 6 products acquired at 120-meter resolution, but resampled to 60-meter pixels till February 25, 2010 and after February 25, 2010 resampled to 30-meter pixels. Landsat ETM+ Band 6 products acquired at 60-meter resolution have been resampled to 30-meter pixels after February 25, 2010. Due to limited width of Danube river (150-300 m) and Black Sea-Danube River Channel (90 m) in Cernavoda area only TIR satellite remote sensing Landsat TM/ETM and ASTER having proper spatial resolutions could be used in our study. ASTER data used were characterized by surface kinetic temperature (Level 2B03), surface spectral emissivity (2B04), VNIR surface spectral reflectance (2B05V), SWIR surface spectral reflectance (2B05S), and relative digital elevation model (DEM) (4A01). The images have been divided in several sub scenes, chosen as study areas, covering Cernavoda area. Some in situ-monitoring meteorological data and ENVI 4.7, IDL 6.3 and ILWIS 3.1 softwares have been also used.

#### 4. METHODOLOGY

Landsat TIR TM/ETM data were obtained by the satellite at approximately 12:30 GMT (14:30 AM locally). Land pixels were masked based on a threshold of TM band 5 from a clear-day image. Radiances ( $W m^{-2} \mu m^{-1} sr^{-1}$ ) in TM band 6 (high gain on ETM+) have been calculated from digital numbers (DN) using standard NASA equations to correct for gain and offset at the detector. In TM and ETM+, band 6 captures the radiant thermal energy of  $10.4 \mu m - 12.5 \mu m$ , at the atmospheric window between  $O_3$  and  $CO_2$  atmospheric absorptions [6]. The at-sensor radiance,  $L_{sat}$ , is a function of surface temperature ( $t$ ) and emissivity ( $\varepsilon_\lambda$ ), but is modified by transmission and upwelling irradiance between the ground and the satellite sensor. This analysis started by assuming no atmosphere, and invert Planck's Law to convert radiance to apparent temperature [7]. Ideally, the precise surface temperature can be determined by correcting for atmospheric interference directly. This can be written as:

$$L_{sat} = T_a(L_\lambda + [1 - \varepsilon_\lambda]L_{a\downarrow}) + L_{a\uparrow} \quad (1)$$

where  $L_{sat}$  is the actual radiance received at the satellite,  $L_{a\uparrow}$  and  $L_{a\downarrow}$  are, respectively, the upwelling and downwelling radiance from the atmosphere,  $T_a$  is the atmospheric transmission, and  $L_\lambda$  is the actual radiance of the surface. Since emissivity of water is very high ( $\varepsilon_\lambda = 0.975$ ) in the detection limits of

Landsat's TIR wavelength region,  $L_{a\downarrow}$  is negligible [8].

Water surface temperature WST was estimated from Landsat-TM and ETM+ TIR channels through the following methodology: a) the thermal infrared band was extracted from TM and ETM+ image data and geo-referenced to a standard datum and projection; b) was done the conversion of DN value (digital number) to radiance and then to brightness temperature in the Thermal Infrared channel-6. Water surface temperature was computed from water surface emissivity and its brightness temperature [9]. Computation of water surface temperature from the TM and ETM+ TIR channels consists of two steps:

1) the original pixel values (Digital Number) have been converted to at-satellite radiance ( $L_\lambda$ ) as:

$$L_\lambda = \frac{L_{min} + (L_{max} - L_{min}) \times BV_{ijk}}{C_{max}}$$

(2)

where  $L_{min}$  and  $L_{max}$  are calibration constants for the sensor,  $L_{min}$  is the lowest radiance measured by a detector,  $L_{max}$  is the radiance measured at detector saturation,  $BV_{ijk}$  is the brightness value of a pixel ( $i, j$ ),  $C_{max}$  is the maximum digital value for the image (e.g., 8-bit sensor – 255) [10];

2) the effective at-satellite temperature was then computed by using the calibration coefficients  $K_1$  and  $K_2$  [11]. The conversion formula is given as follows:

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \quad (3)$$

where  $T$  is the effective at-satellite temperature in Kelvin degree ( $K^\circ$ ) and  $L_\lambda$  is the spectral radiance in  $Wm^{-2} \mu m^{-1} sr^{-1}$ . The computed at-satellite temperature in Kelvin degree from Landsat-5 TIR channel was then converted to Celsius degrees ( $C^\circ = K^\circ - 273.15$ ).

Was selected a valid data range with upper and lower limits to identify pixels that were within a normal temperature range (non-plume pixels), and those that were warmer than normal (designated as plume pixels). Land pixels were flagged with values of zero and excluded from the analysis. The average temperatures were calculated for pixels in the water plume and non-plume areas. The number of pixels in

the plume was used to estimate the areal extent of the plume assumes. We demonstrate that Landsat TM and ETM, and ASTER satellite remote sensing images can be used to determine warm water discharge from Cernavoda NPP. Was also analyzed the seasonally variability of the thermal plume by using satellite data and in-situ data measurements. The classification of surface water temperatures was obtained from two operational classification standards and a combination in order to be most suitable when remote sensing data is used. In most cases, the classification is possible even without concurrent ground truth data. This indicates that operational classification with remote sensing data is possible. The classification accuracy ranges from 76% to 90%. The main advantage of remote sensing over the traditional surface water monitoring method based on water sample collection is its good spatial and temporal coverage. Monitoring can be carried out several times per year and rivers not included in the traditional sampling can be also monitored. River waters require a specific algorithm to take into account the differences in water constitute and their optical properties at different locations and times. These differences are caused by several factors such as fluctuations in winds, river discharge, sediment load, primary production and phytoplankton species type. As a result, *in-situ* data must be required at the same time as the satellite overpass to calibrate algorithm specific to the site. The algorithms developed for a specific site will not be accurate for other geographical locations. However, the method of algorithm development also used. can be applied anywhere. Were developed the algorithms for specific site of Cernavoda NPP area waters, but with different times between satellite overpass and in-situ measurements.

The resulting surface waters temperature maps retrieved from the imagery after application of the statistical algorithm show detailed information on the variation in temperature in the Black Sea- Danube Channel and the inflow in the Danube River. The limited amount of in-situ measurements also influences the result of statistical approach.

## 5. RESULTS

The present study focused on characterizing the thermal plume in Cernavoda, South-East of Romania hydrological system stream waters using satellite infrared data. These waters undergo dramatic changes in their physical, chemical and biological from discharge of large quantities of waste warm water from Cernavoda NPP. TIR satellite data are used to demonstrate the spatial and temporal characteristics of the thermal plume signature around the Cernavoda area using Landsat-TM and ETM+ and ASTER TIR image data.

In Cernavoda NPP area, all waste heat resulting from 2 CANDU reactors cooling system enter in

hydrological channels nearby, and some of heat is lost to the atmosphere via evaporation, convection of sensible heat and thermal radiation. Correct prediction of temperatures in the cooling channels requires accurate meteorological data for calculation of energy losses to the atmosphere. Verification of the temperature predictions requires direct water temperature measurements, which are also used to verify satellite temperature retrievals. Nearby surface temperature of water and upper-air meteorological data are used to compute energy losses to the atmosphere. The thermal inertia of large bodies of water such as the channel system makes the computed temperatures insensitive to hourly fluctuations in air temperature, humidity and winds. Hour-to-hour variations in wind speed and direction produce some changes in thermal plume movement and dimensions. Warm waste water discharge from NPP Cernavoda could have consequences on the ecology of Black Sea –Danube Channel and Danube River. Regarding fishery presence in the hydrological network in the Black Sea – Danube Channel and Danube River. Water temperature distributions captured in thermal IR imagery have been correlated with meteorological parameters. Additional information regarding flooding events and earthquake risks is considered. Before the operation of the Cernavoda NPP, by numerical modeling was predicted that the power station could affect the region 5 km from the power station. Under normal functioning of the power plant, in the immediate vicinity of Units 1 and 2, the water temperature plume can register an increase of 9° C. During the winter, the thermal plume is localized to an area within a few km of the power plant, and the temperature difference between the plume and non-plume areas is about 1.5 °C. During the summer and fall, there is a larger thermal plume extending 5-6 km far along Danube Black Sea Canal, and the temperature change is about 1.0 °C. During summer, the stratified waters confine the warm thermal plume in the upper few meters of the water column. The discharge of the warm water further increases the surface water temperature, which enhances stratification. Variation of surface water temperature in the thermal plume was also analyzed. The strong seasonal difference in the thermal plume is related to vertical mixing of the water column in winter and to stratification in summer. Hydrodynamic simulation leads to better understanding of the mechanisms by which waste heat from NPP Cernavoda is dissipated in the environment.

Studies on the environmental impact of warm water discharge have been undertaken for many power plants, being reported that thermal discharge increased water temperature of the body water reservoirs. The influence of the thermal plume on phytoplankton growth should also be further investigated. Before the operation of the Cernavoda NPP, by numerical modeling was predicted that the power station could affect the region 5 km from the power station. Principal Component Analysis (PCA) based on Landsat TM/ ETM satellite data for Cernavoda test area have been done to identify the temperature and turbidity changes in the hydrological system (Fig.2).

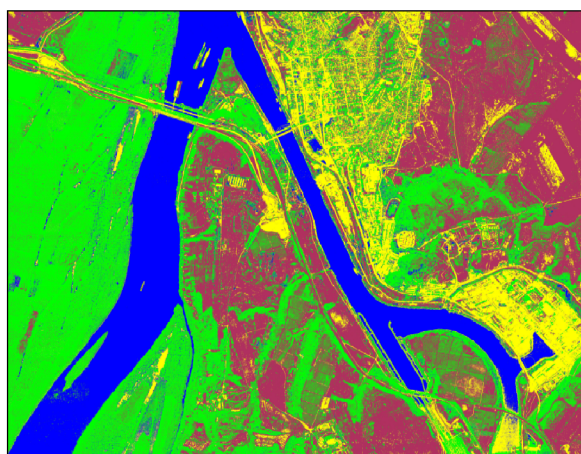


Fig.2 PCA classification on Landsat ETM image 12/08/2010, hydrologic network Cernavoda NPP

Fig.3 shows a water temperature map of Cernavoda hydrological network derived from ASTER TIR 12/07/2008 image.

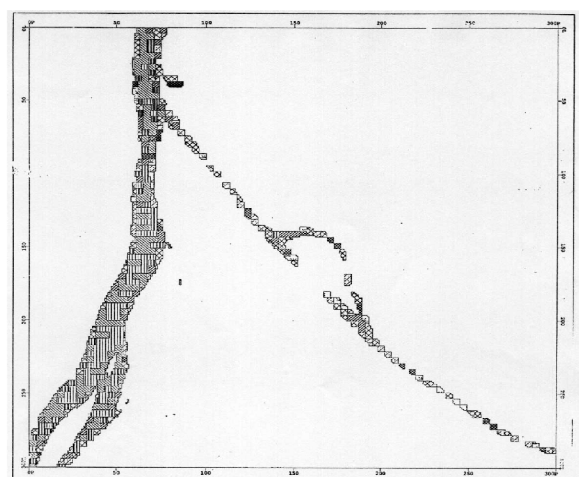


Fig. 3 . Water temperature classification map for NPP Cernavoda hydrographic network area , ASTER TIR 12/07/2008

The combination of high-resolution thermal imagery and hydrodynamic simulation models must lead to

better understanding of the mechanisms by which water waste heat from nuclear power plant cooling systems is dissipated in the environment.

The retrieved at-satellite temperature from the TM and ETM+ and ASTER thermal infrared channels were found to be comparable with the in situ temperature.

## 6. CONCLUSION

This study shows the utility of using a multi-year record of the Landsat TM/ETM and ASTER thermal imagery to monitor spatial thermal plume water surface temperature (WST) of hydrological system in NPP Cernavoda area.

Regional assessment of water temperatures from the ground is limited by sparse sampling in both space and time, so remotely sensed thermal-infrared (TIR) images are able to make spatially distributed measurements of the radiant skin temperature of waters, with best applications in nuclear power plants environment. The condenser cooling water discharge has the potential to cause several environmental effects. The most serious of these is related to heat stress resulting from increases in water temperatures caused by the discharge, which could adversely affect entrained fish and other organisms and those aquatic biota located downstream of the cooling water discharge.

The impact of large amounts of waste heat disposed into the local environment from nuclear power plants are also contributing to global warming due to increased trapping of TIR (thermal infra-red radiation) directed outward from the Earth. Some of waste heat is lost to the atmosphere via evaporation, convection of sensible heat and thermal radiation. Correct prediction of temperatures in the cooling channels requires accurate meteorological data for calculation of energy losses to the atmosphere. Satellite thermal infrared data become very useful for detection of thermal waste discharges from nuclear power plants in the environment, to be used in global climatic models and global warming monitoring. Generally, water bodies shift temperature gradually with seasonal change, so large magnitude departures from the trend may be considered anomalous.

Thermal effluent from the Cernavoda nuclear power plant disperses mainly on the Danube – Black Sea Channel surface around the outlet due to its higher water temperature than the ambient coastal water, and affects the biota around the power plant. Therefore the quantitative prediction of the dispersion of

thermal effluent from the power plant is very important for the successful environmental assessment and management associated with the construction of new UNIT 3 and UNIT 4 reactors for power plant, planned to be operational around 2015 year.

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