

## Thermonuclear Power Plant Model

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### Introduction

Scale models may be very useful aids to science teaching or divulgation. This paper describes an eye-catching 85cm x 40cm N scale (1:160) model of a thermonuclear power plant with electrical substation (Figures 1 and 2) built for educational purposes. It has been successfully used in classes and in science-fair events. Section 2 lists the main materials used to build the model.



Figure 1. Thermonuclear power plant model

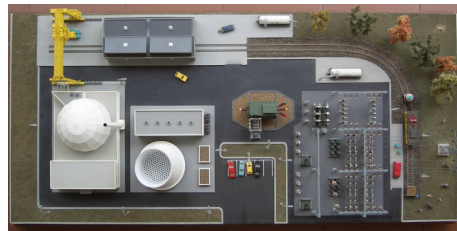


Figure 2. Top view of the model

Section 3 presents the model components and gives a brief technical explanation on the main components of real-world nuclear power plants and electrical substations. Section 4 gives some details on an operational railroad integrated in the model. Section 5 contains the conclusions of the paper and a list of references is given in Section 6.

### Materials Used to Build the Model

The main materials used to build the model were the following:

1 *Heljan* nuclear power plant kit, ref. 1718; 1 *Revell* transmission substation kit, ref. 2018; 1 *Revell* power transformer kit, ref. 2015; 1 *Brawa* metallic high voltage towers set, ref. 2659; 1 *Peco* train shed unit kit, ref. NB-80; 1 *Vollmer* container crane kit, ref. 7905; 1 *Kibri* diesel oil filling station kit, ref. 7430; 1 *Fleischmann* N scale electric locomotive, ref. 7968; 1 *Seuthe* smoke generator, ref. 100; 6

*Fleishmann* N scale model cars; 1 *Fleishmann* N scale van; 1 *Busch* transfer traffic symbols, ref. N 7197; 1 *Preiser* set of 6 N scale workmen, ref. 09105/79105; 1 *Preiser* set of 6 N scale cows, ref. 09155/79155; 16 nuclear waste containers; 1 loudspeaker magnet; 1 *Bachman* N scale bogie; 1m of *Peco* N scale flexible track; 1 N scale railroad sandbox; 2 reed relays; 6 switches; 15cm of brass tube with diameter 0,95cm; 5 sets of 3 *Viessmann* N scale brass street lamps, ref. 6690; 5 sets of 3 *Viessmann* light bulbs (16V, 30mA,  $\phi$ 1,8mm), ref. 6228; 8 miniature 12V light bulbs; 6 LEDs; 7 N scale trees.

Other materials include a wooden base, balsa wood, plastic glue, white glue, enamel and acrylic paints, cardboard, light cardboard, double-sided adhesive tape, green and multi-coloured sawdust, electric wire, a power transformer and the electronic components used in the circuits that monitor and control the train movements.

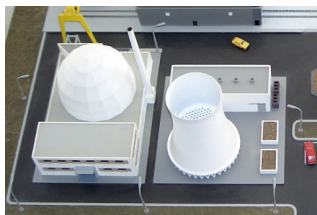
### **Model Components and Real-World Nuclear Power Plant Components**

The model has a main building with nuclear reactor, an electric generator house, a cooling tower (Figure 3) and an electrical substation (Figure 4). It also includes facilities such as an operational railroad, a train shed, a container crane (Figures 5 and 6) and two diesel oil filling stations (Figure 7).

The main building has its own interior illumination and a smoking chimney that actually works. The original plastic chimney was replaced with a brass one equipped with a smoke generator. The train shed and the cooling tower bottom also have interior illumination. Street lamps illuminate the other facilities and a red signalling lamp lies at the top of the crane.

The substation is very detailed, with a three-phase power transformer, section breakers and other components. A *Brawa* metallic high voltage tower (Figure 8) was used to hold the outgoing main power line of the substation.

Some workmen, cars, a van, nuclear waste containers, trees and even a few cows complete the environment.



**Figure 3. Main building with nuclear reactor (left), generator house and cooling tower (right)**



**Figure 4. Electrical substation**



**Figure 5. Train shed and container crane in the foreground**

The rest of this section contains a brief technical explanation on the main components of real-world nuclear power plants and electrical substations.

### **Nuclear Power Plants**

Nuclear power plants are thermal power plants that convert heat produced by nuclear fission into electricity. They contain a nuclear reactor, where nuclear fission takes place; a heat transfer system, which heats water until it is converted into steam; a steam turbine mechanically connected to a synchronous generator, used to convert steam pressure into rotational movement, thus producing electricity; and a steam cooling system, to convert steam into water again. Overall efficiency of these power plants is between 30% and 40%, due to inherent low efficiency of thermal machines [1].

**Nuclear reactors** are devices where controlled nuclear chain reactions occur, generating heat that will be converted into electricity. There are several types of nuclear reactors.

The **Pressure-Water Reactor (PWR)** is the most common type of reactor in power plants around the world [2]. Water is used as a coolant and neutron moderator under such a high pressure that it does not form steam. Some reactors use light water (ordinary water,  $H_2O$ ). The others use heavy water (water with deuterium isotope,  $D_2O$ ). Two cooling circuits are used: in the primary circuit, the coolant is kept at very high pressure, transporting heat from the nuclear core to a heat exchanger and a pump keeps the coolant flowing; in the secondary circuit, another pump inserts water in the heat exchanger, where it turns into steam, which will be conducted to the steam turbine. Then, the steam coming from the turbine is condensed into water again.

PWR reactors have some advantages: they are very stable, because they have the tendency to produce less power as temperature rises; they may use natural uranium dioxide as fuel, although heavy water must be used in this case; the turbine is unlikely to be contaminated by radioactive materials, because it is in a secondary cooling circuit; and control rods are inserted from the top, making them easy to insert in the reactor if power fails. On the other hand, there are also some disadvantages: the primary coolant circuit must be kept at very high pressure, raising the risk of accident due to a fracture in the circuit; most of these reactors can't be refuelled while in operation; a sudden coolant temperature descent would raise power production, causing emergency shutdown of the reactor.

**Steam turbines** are used to convert steam pressure differential into mechanical rotation movement. They consist of a high-pressure (HP) turbine, a medium-pressure (MP) turbine and a low-pressure (LP) turbine, usually mounted on the same shaft, connected to an electric generator. Each turbine has many radial blades that deflect the steam, producing torque. The size of the blades (and, therefore, the diameter of the turbine) depends on the steam pressure: the blades of LP turbines are the longest and the blades of HP turbines are the shortest.

The **condenser** is responsible for diminishing low-pressure steam temperature until it condenses into water again. Enormous quantities of fresh water are needed to

carry the heat away from the condenser. The cooling water may be driven from a river, or from a cooling tower, and its temperature typically increases 5°C to 10°C.

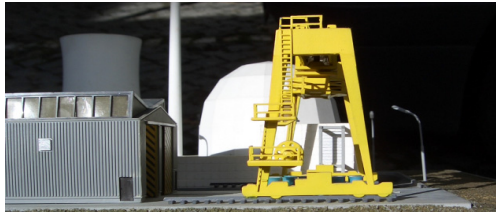


Figure 6. Side view of the container crane and part of the train shed

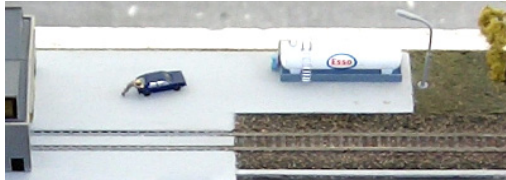


Figure 7. Diesel oil filling station

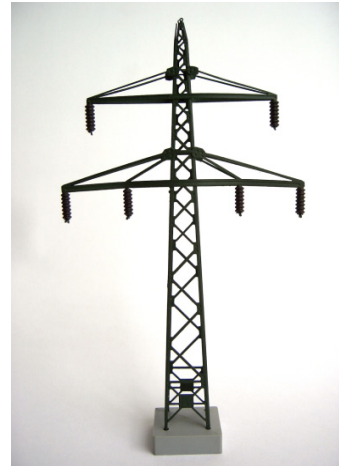


Figure 8. Metallic high voltage tower

**Cooling towers** are needed when the power plant is located in a dry region, or when the heating of water streams is undesirable. The cooling towers freshen up the condenser by means of evaporation. The circulating water is exposed to the surrounding air by means of creating an artificial rain inside the tower: the hot water coming from the condenser is fed to the top of the tower where there are lots of small pipes with holes; then, the water is dropped on an open reservoir placed on the tower's bottom, where water may be pumped to the condenser again. A small part of the water is lost in the process, but can easily be replaced from a stream.

### Electrical Substations

An electrical substation is the part of an electrical energy system where line voltage and current levels are modified using power transformers, in order to diminish system installation and operation costs. There are three types of substations, along and electrical energy system: the generating substation, the transmission substation and the distribution substation.

Electrical power plants generate electricity by means of synchronous machines working as generators, called alternators. For technical reasons, these machines output voltages are limited to a few kV (18kV, for example). So, it is necessary to raise the generated medium-voltage to the high-voltage levels necessary to transmit the energy economically. This transformation is accomplished by **power**

**transformers** existing in generating substations. The model described in this paper has a substation of this type; however, all types of substations are similar. Besides power transformers, substations usually contain the following equipments: circuit breakers, air-break switches, disconnecting switches, grounding switches, surge arresters, current-limiting reactors, grounding transformers, and measurement transformers [1]. The model contains some of these elements (Figures 9, 10 and 11).

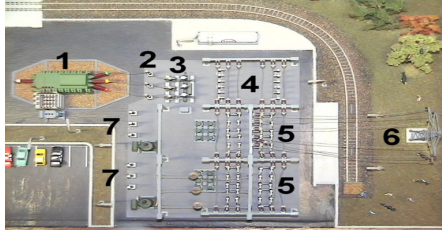


Figure 9. Electrical substation layout: 1 – main transformer with underground feeder; 2 – measurement transformers; 3 – main circuit breakers; 4 – main bus; 5 – main bus air break and disconnecting switches; 6 – outgoing main power line; 7 – outgoing secondary lines (not mounted)



Figure 10. Close-up on main transformer (left) and circuit breakers (right)

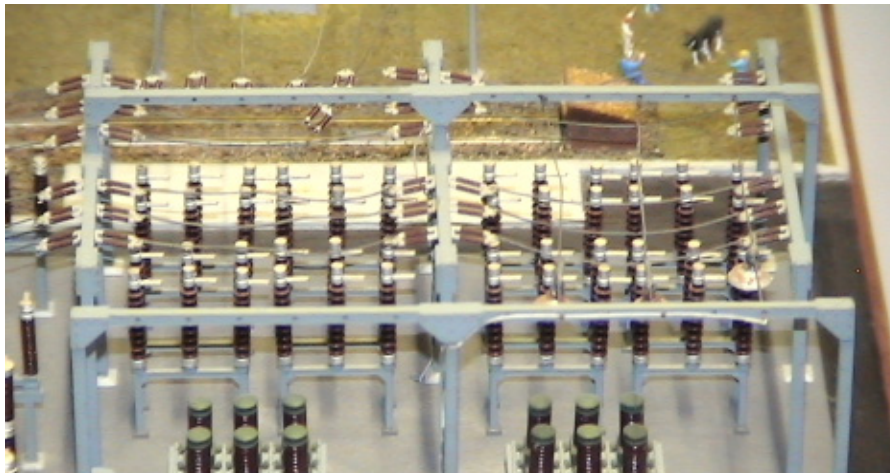


Figure 11. Close-up on main bus air break and disconnecting switches

**Circuit breakers** are designed to interrupt normal or short-circuit currents. They may be remotely operated by a human supervisor, and they automatically open when electric parameters (current, voltage, etc.) become off their limits. There are

five types of medium/high-voltage circuit breakers: oil, minimum oil, air-blast, sulphur hexafluoride and vacuum circuit breakers. Each type has some advantages and some disadvantages.

Oil circuit breakers have a steel container and their moving contacts are immersed in insulating oil. When a fault occurs, a spring is released, and the contacts are opened. An electric arc is produced, which volatilizes the oil around the contacts, producing a turbulence that renews the oil around the contacts, thus extinguishing the arc. These circuit breakers are relatively simple, but have the danger of explosion and use oil that is very aggressive to the environment.

Minimum oil volume circuit breakers use the same working principle, but they have an explosion chamber around the contacts and moving pistons, which inject high pressure fresh oil in the chamber where the arc is formed. They are more efficient than the first type and require lesser quantity of oil, reducing environment hazards and explosion risk.

Air-blast circuit breakers have the moving contacts inside a chamber where very high-pressure air is blown into when the contacts open, causing the arc to be extinguished. The high-pressure air is stored in containers, near the circuit breakers. This type of circuit breakers has enormous cutting power and is used in the highest voltages. However, the noise of operation is so loud that exhaust systems are required and they cannot be used near residential areas.

Sulphur hexafluoride (SF<sub>6</sub>) circuit breakers are totally enclosed, having their moving contacts sealed inside arc chambers filled with insulating gas SF<sub>6</sub>. They usually have moving parts, which renew the SF<sub>6</sub> in the arc extinction chamber when the contacts open. This type of circuit breaker is usually used when space is critical, because they are the smallest type. Operation noise is also relatively reduced.

Vacuum circuit breakers use a working principle that is different from the one used by other types of circuit breakers: their arc chambers and moving contacts are sealed in vacuum, instead of some insulating material. They need very little maintenance, as the contacts never become polluted, and they are also very silent. However, their maximum rated voltage is about 30kV. They are used in places of difficult access, for example in underground distribution systems.

**Air-break switches** have a moving blade that engages a fixed contact, both mounted in insulating supports, operating in free-air. These switches are able to cut transformer excitation currents and line no load currents. They have arcing horns, where electric arc is formed when they are opened; the arc moves upward, becoming longer, and eventually extinguishing itself.

**Disconnecting switches** are similar to air-break switches, but they can't interrupt any current at all: they must be operated only when no current flows through them. Disconnecting switches are intended to provide visible isolation of other components (transformers, circuit breakers, lines, etc.). These switches are constructed in the most simple and reliable way, without springs or other complicated mechanisms. When they are opened, gravity tends to maintain them that way.

**Grounding switches** are devices used to assure that lines are definitely connected to the ground (for maintenance security, for example). They have a moving blade



similar to a disconnecting switch, for each phase. Obviously, they are operated only when line voltage is zero.

**Surge arresters** are intended to protect several devices – namely, transformers – from over-voltages that may occur due to thunderstorms or switching surges. They are connected to the ground and provide a low impedance path for discharging surges directly to the ground, avoiding any damages in other more sensitive equipments. At normal voltage operation, they should remain with high impedance.

**Current-limiting reactors** are connected in series with the power lines, in order to increase short-circuit impedance and control short-circuit current gradient. The voltage levels involved are very high and overall impedance is low. So, without current-limiting reactors, the short-circuit currents would be enormous and circuit-breakers wouldn't be capable of cutting them. That would result in severe damages in many expensive and slow to repair components of the power grid.

**Grounding transformers** are used when it is necessary to create a neutral wire on a three-phase, three-wire system, transforming it in a three-phase, four-wire system. Usually, these transformers are three-phase autotransformers connected in zigzag, with the middle point connected to the ground. This helps keeping system balanced in the case of connecting single-phase loads between one line and the neutral.

**Measurement transformers** are used to reduce voltage and current to safer levels, in order to measure or monitor voltages and currents on the transmission lines and to provide electrical isolation between measurement and power lines. There are two types of measurement transformers: voltage transformers, whose primary winding is connected in parallel with the lines, and current transformers, connected in series with the lines.



Figure 12. Locomotive with container carrier

### Some Details on the Model Railroad Construction and Operation

The model railroad is used by a locomotive that pulls a container carrier (Figure 12). This latter was built by fastening a loudspeaker magnet to a model coach bogie (Figure 13). Two reed relays (Figure 14) placed on each extremity of the track

(Figure 15) are connected to a logic and timing electronic circuit (Figure 16). This circuit controls a locomotive motor drive [3] connected to the rails. The motor of the locomotive is powered via its wheels. When the container carrier passes over a reed, its contacts close; the logic and timing circuit makes the train stop for a few seconds; then, the train sense of motion is reversed and the train is set to move again.

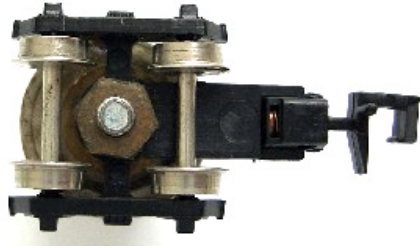


Figure 13. Bottom view of the container carrier



Figure 14. A reed relay

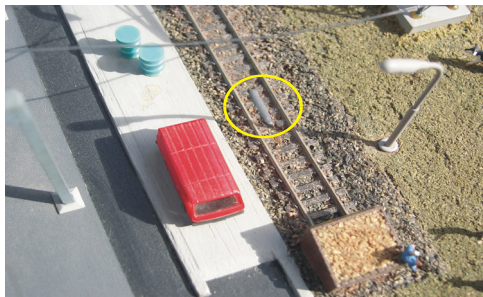


Figure 15. Reed relay placed between the rails

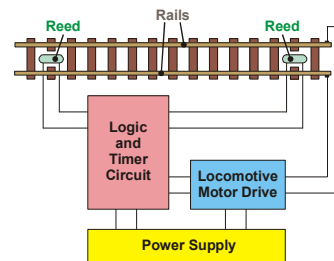


Figure 16. Train control system

## Conclusions

A model of a thermonuclear power plant with electrical substation, built for educational purposes, has been described. Some construction details were explained. A brief technical explanation on the main components of real-world nuclear power plants and electrical substations was also given.

The model is very eye-catching and most suitable for classes or science-fair events. It has been successfully used in both kinds of activities.



## References

- [1] Wildi T, Electrical Machines, Drives, and Power Systems, Prentice Hall International, 1997.
- [2] [http://en.wikipedia.org/wiki/Pressurized\\_Water\\_Reactor](http://en.wikipedia.org/wiki/Pressurized_Water_Reactor)
- [3] Mennis R, Comando bidireccional de motor, Elektor Electrónica, 79/80: 79-28, 1991.

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