Huntorf CAES: More than 20 Years of Successful Operation

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1. Introduction

The basic idea of CAES (Compressed Air Energy Storage) is to transfer off-peak energy produced by base nuclear or coal fired units to the high demand periods, using only a fraction of the gas or oil that would be used by standard peaking machine, such as a conventional gas turbine.

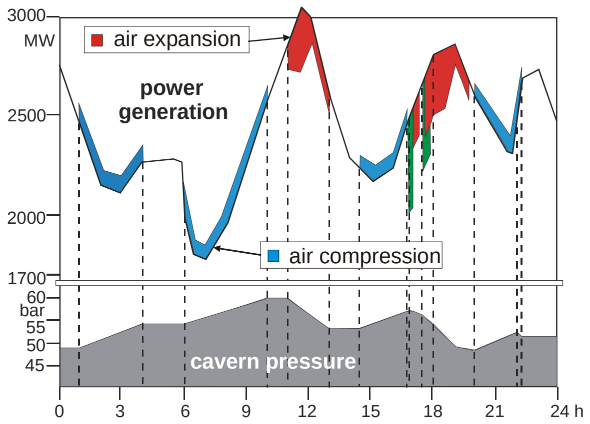

Fig. 1: Example of power production during a single day

So far, there are only 2 CAES plants in the world: the 290 MW plant belonging to E.N Kraftwerke, Huntorf, Germany, built in 1978, and the 110 MW plant of AEC (Alabama Electric Corporation) in McIntosh, Alabama, USA, commissioned in 1991.

Because of the intended shut down of large power generating capacities in Germany, the importance of the "minute reserve" is expected to grow in the near future (the minute reserve refers to power station output that can be made available within a few minutes). Another argument in favour of CAES is found in the steadily rising capacity of wind power, which creates less precise short term predictability of necessary power production.

The aim of this article is to briefly describe the CAES plant in Huntorf (concentrating on the subsurface facilities) which has been successfully operated for over 20 years, and to report on the practical operating experience gained over this period. This looks in particular at the critical components of compressed air storage caverns:

- Production casing (risk of corrosion due to wet compressed air)
- Thermodynamics (heat exchange between the air and the surrounding salt)
- Long-term stability of the underground storage

2. Principles behind a CAES plant

A CAES plant mainly consists of (1) compressor train, (2) motor-generator unit, (3) gas turbine and (4) underground compressed air storage; see fig. 2.

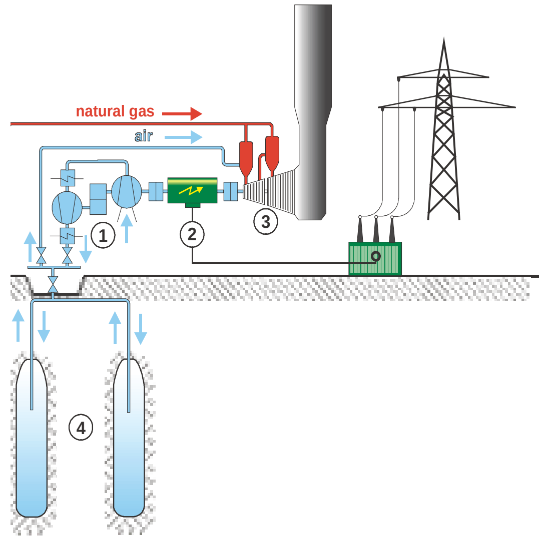

Fig. 2: Main components of a CAES plant

During low-cost off-peak load periods, a motor consumes power to compress and store air in the underground salt caverns. Later, during peak load periods, the process is reversed; the compressed air is returned to the surface; this air is used to burn natural gas in the combustion chambers. The resulting combustion gas is then expanded in the 2-stage gas turbine to spin the generator and produce electricity.

In a pure gas turbine power station, around 2/3 of the output are needed for compressing the combustion air (100 MW net output + 200 MW compressor consumption = 300 MW gross output). In a CAES power station, however, no compression is needed during turbine operation because the required enthalpy is already included in the compressed air. This has 2 advantages: (1) during off-peak periods cheaper excess power can be used for compression; (2) the gas turbine can generate 3/3 (or 300 MW in the above mentioned example), instead of 1/3 (= 100 MW).

The main type of underground storage suitable for this purpose is the salt cavern. Alternatives are also being considered: a CAES project in Norton, Ohio, USA, is currently in the planning stage and the underground storage in this case is a 10 million m^3 limestone mine; aquifer structures (water filled underground reservoirs) are another type of feasible storage and were investigated in detail in the 80s.

3. Huntorf CAES (planning and construction)

Key data: The Huntorf plant, located in North Germany, was commissioned in 1978 as the world's first CAES plant. Fig. 3-1 shows an aerial photograph of the plant. The plant has been extended in the meantime with an own 300,000 m^3 natural gas cavern to supply the gas turbines with higher economic efficiency.

The following table lists the key data of the Huntorf plant.

Table: Specifications of the Huntorf CAES plant

output ➢ turbine operation ➢ compressor operation	 290 MW (≤ 3 hrs) 60 MW (≤ 12 hrs)
air flow rates ➢ turbine operation ➢ compressor operation air mass flow ratio in/out	 417 kg/s 108 kg/s 1/4
number of air caverns	2
air cavern volumes (single) total cavern volume	≈ 140 000 m³ ≈ 170 000 m³ ≈ 310 000 m³
cavern location – top - bottom	≈ 650 m ≈ 800 m
maximum diameter	≈ 60 m
well spacing	220 m
cavern pressures ➢ minimum permissible ➢ minimum operational (exceptional) ➢ minimum operational (regular) ➢ maximum permissible & operational	 1 bar 20 bar 43 bar 70 bar
maximum pressure reduction rate	15 bar/h

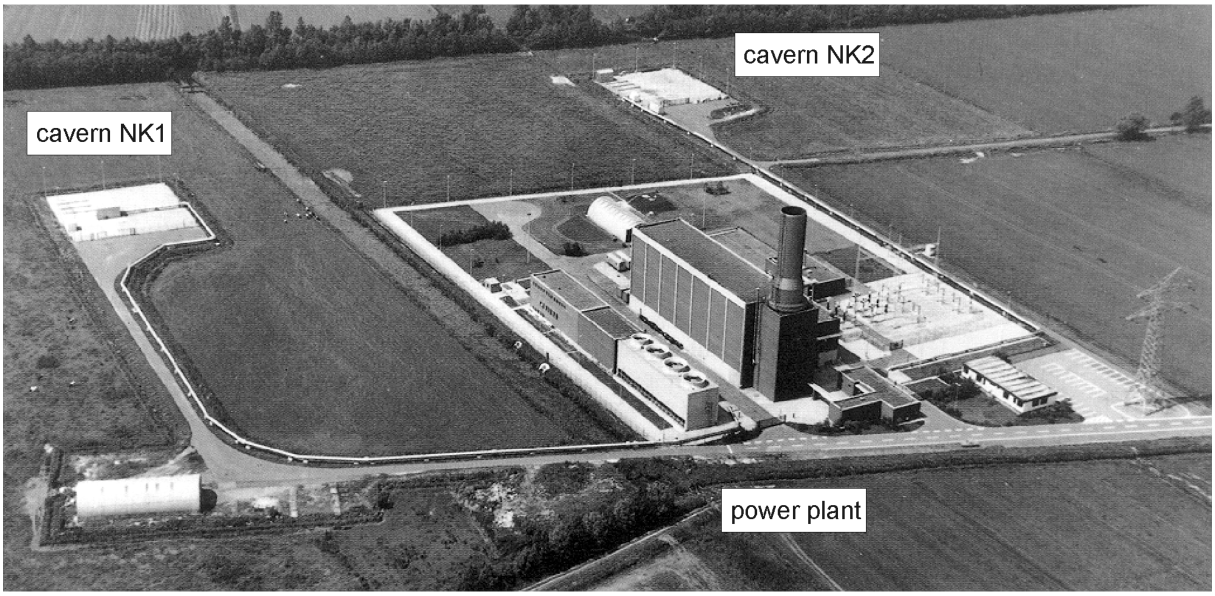

Fig. 3-1: Aerial picture of Huntorf plant

General design: The total volume of approx. 310,000 m^3 corresponds to the specified operating pressures and the stored air mass (rate * time period); an important aspect here is taking into consideration the thermodynamic effects in the cavern during injection and withdrawal.

Two caverns were planned for various reasons even though the total volume could easily have been realized in just one cavern:

- Redundancy during maintenance, cavern shut-down
- Easier cavern refilling after drawing down the pressure in a cavern to atmospheric pressure.
- Start up procedure for plant compressor requires a minimum pressure of 13 bar in at least one of the caverns.

The depth of the caverns (see fig. 3-2) was selected to ensure stability for several months at atmospheric internal pressure, as well as to guarantee the specified maximum pressure of 100 bar.

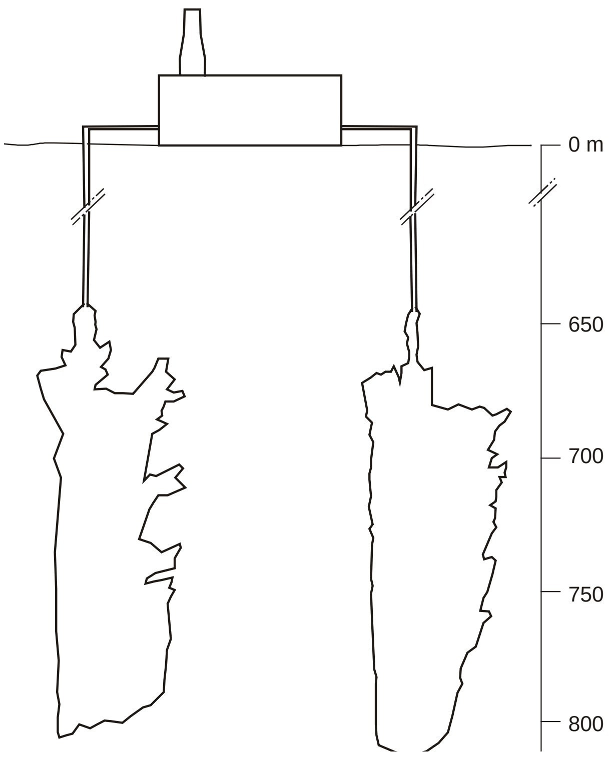

Fig. 3-2: The 2 caverns and plant on the same scale

Cavern wells: A critical aspect when designing the cavern wells was the specification for extremely high withdrawal rates of 417 kg/s combined with low pressure losses. This required a 20"/21" production string and thus a 24 1/2" final casing. Because of the absence of a packer to fix the production string in the final casing, there was a danger that the final casing could be corroded by the moist air penetrating the annulus. This is counteracted by the injection of dry air into the annulus.

Brine evacuation: In natural gas caverns, the brine is usually displaced by gas during first-fill. In this case, the brine was withdrawn using a submersible pump because the plant compressor had an inadequate maximum pressure and an excessively high air flow rate resulting in unacceptable air velocities in the production string.

Completion: The completely water-saturated compressed air is a very corrosive medium. To reduce costs, the production string was initially made out of normal structural steel with extra thick walls. The spirally welded production strings with welded joints hung approx. 80 m in the cavern without support. This was planned to prevent the entry of salt dust via the cavern throat into the turbines.

First-fill of first cavern: Because of the need for minimum back pressure for the plant compressor, the first cavern was first filled up to 7 bar by a mobile compressor. The plant compressor then cut in. This involved controlling the volume of air via a by-pass to ensure that the flow velocity of 20 m/s was not exceeded in the production string.

4. Practical experience in operating the Huntorf CAES

Starts per year: The Huntorf plant has now been operated successfully for over 22 years. Fig. 4-1 shows the number of starts per year: since 1978. The number of starts made by the plant has fluctuated widely during this operational period. This is attributable to (1) connection to a larger network in 1985 which added pumped hydro capacity, (2) the CAES plant's primary role as an emergency reserve in case of unplanned failure of other power plants and (3) the CAES plant's role as an alternative option to purchasing expensive peak load from outside suppliers.

The power station is typically used today as a minute reserve: medium load power stations (coal) take 3 – 4 hours to generate full capacity before they can provide short-term power – the intervening time is preferentially covered by CAES plant. Another typical use is for peak shaving in the evening, when no more pumped

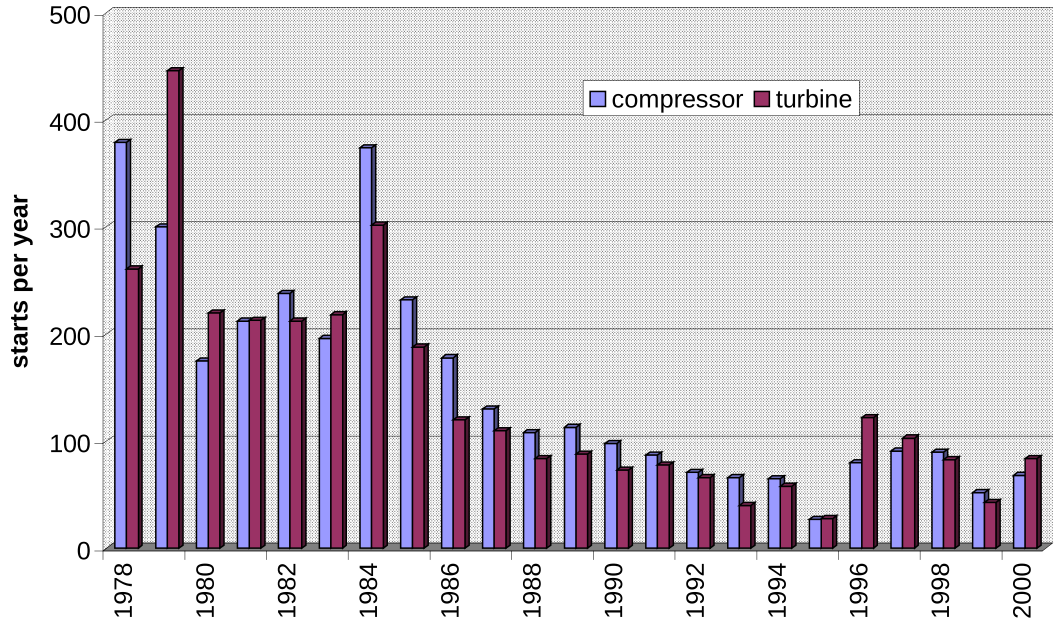

Fig. 4-1: Number of starts per year

hydro capacity is available. An additional application is associated with the strong increase in the number of wind power plants in North Germany in recent years: because the availability of this type of power cannot be reliably forecast, the plant in Huntorf is able to quickly compensate for any unexpected shortage in wind power.

Thermodynamics: During first-fill and later trial runs, extensive measurements of pressure and temperature were carried out. The subsequent numerical simulation of the thermodynamic behavior revealed that the heat exchange with the rock only took place in a peripheral zone around one meter thick. Thus, the very irregular shape of the caverns had the advantage of increasing the heat exchange between the air and the cavern walls, which in turn led to a significant increase in storage capacity.

An interesting effect occurs when the air is expanded to atmospheric pressure: the pressure drop initially results in the expected cooling of the air, but after reaching a minimum, the temperature rises again, see fig. 4-2.

Stability / cavern convergence (survey results): Important aspects when operating CAES caverns are the stability of the surrounding salt and the volume losses due to convergence. Compared with conventional gas caverns, CAES caverns are operated with higher withdrawal rates and thus higher pressure reduction rates (up to 15 bar/h). In addition, it is sometimes necessary to run the pressure in the cavern down to atmospheric pressure to allow work to be carried out on the well heads and the production strings. In the latter

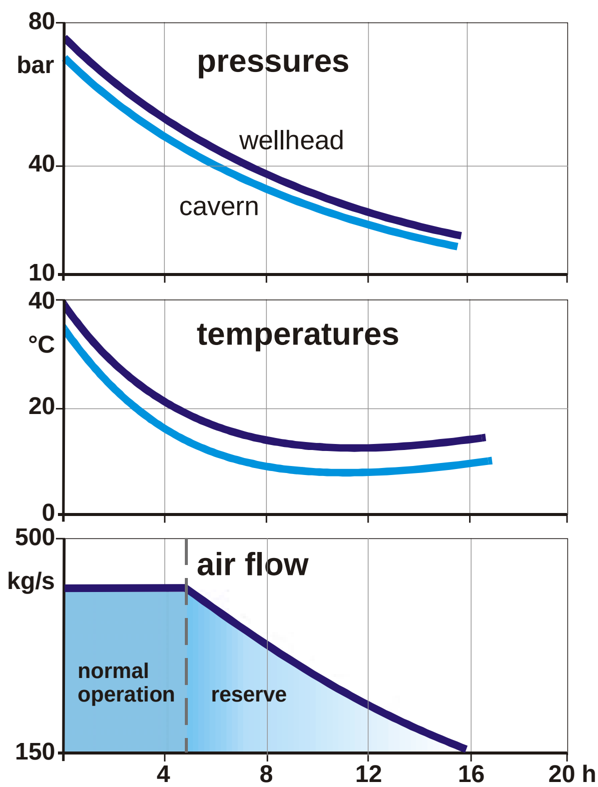

Fig. 4-2: Pressures, temperatures and air flow when emptying the cavern

case, problems with the insulation of a new FRP (fiber glass reinforced plastic) string in one case required the caverns to remain at atmospheric pressure for approx. 12 months.

To monitor the stability, regular surveys of the sump using a sonar tool are carried out – evaluation over the whole operational period shows practically no changes that can be attributable to roof falls, etc.

Surveying the contours of the cavern has proved to be difficult because the usual ultrasonic tools used in gas caverns have an inadequate range in the CAES caverns and because of the humidity of the compressed air. Regular laser surveys carried out as an alternative also usually prove ineffective because of the fog in the cavern and the condensation of moisture on the lens.

When cavern NK1 was expanded to atmospheric pressure at the beginning of 2001, a survey was possible with a *heated* laser tool (see figure 4-3). The evaluation of this survey after over 20 years of operation showed practically no deviation compared to the original conditions (fig. 4-4).

Production string: As already discussed, an uncoated, spirally-welded steel string was initially used. However, after only a few months of operation, serious corrosion problems became apparent with the appearance of high levels of rust in the filter upstream of the gas turbine. This caused shut-downs shortly after the start up of the power station.

The following alternatives were investigated to solve the problem:

- coated subsurface strings
- lined steel strings
- stainless steel strings
- synthetic strings

After detailed investigation, FRP (fiber glass reinforced plastic) was selected at the beginning of the 80s for reasons of costs and ease of installation. The specially produced casing was designed according to specifications with respect to abrasion resistance, collapse resistance (stress directly beneath the well head during maximum air withdrawal) and vibration behavior of the free-hanging 80 m section at the top of the cavern (air velocities up to 35 m/s). The casings were threaded and glued. The 58 casing sections were installed within 12 days using a 40 t workover rig.

Fig. 4-3: Heated SOCON laser probe

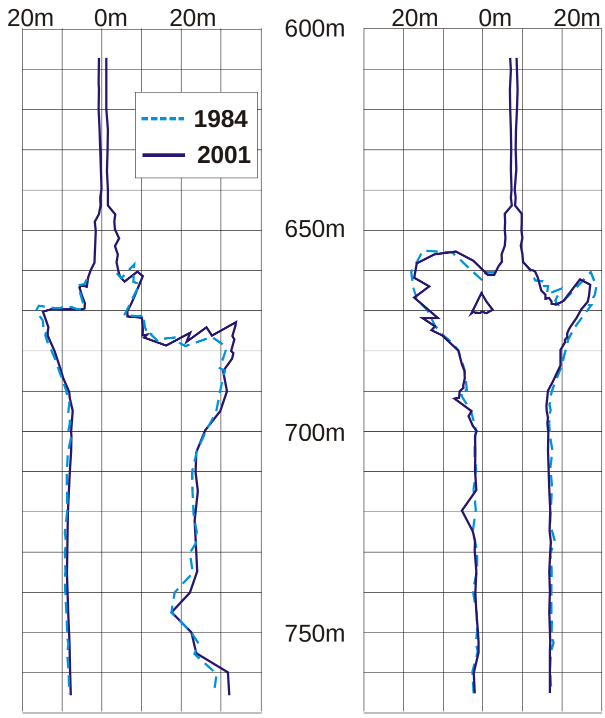

Fig.4-4: Comparison of sonar survey for NK1 in 1984 and laser survey in 2001

After over 20 years of problem-free operations, material problems are now occurring in some of the pipe sections resulting in partial destruction of both FRP strings. Fig. 4-5 shows the point of fracture.

Fig. 4-5: Point of fracture of FRP string

Investigations are currently being carried out on replacing the pipes. After over 20 years since the last investigation on the material and installation alternatives, technological advances now require a completely new evaluation.

Last cemented casing (24-1/2"): Unlike the production string, the last cemented casing cannot be replaced. The corrosion protection was therefore taken into consideration right from the start by injecting a protective gas – nowadays, dry air is used – in the casing /FRP string annulus.

After removing the damaged FRP string, the cemented casing was first cleaned using the Hydroblast technique. The casing was then inspected for any potential corrosion damage. After detailed analysis, the METT (Multifrequency Electromagnetic Thickness Tool) from SCHLUMBERGER was selected for the non-destructive measurement of the wall thickness. Because of the large casing diameter, the tool was used outside of its usual measuring range extending up to 13-3/8" casing. Moreover, there was no reference measurement. However, the evaluation of the log run reveals that the corrosion protection measures were successful and that there has not been any surface corrosion or pitting.

Salinity: Gas turbines are sensitive to the salt in the combustion air. Measurements during 2 cycles at withdrawal rates of up to 365 kg/s revealed salt contamination of less than 1 mg (salt)/kg(air). This positive result was confirmed by inspection of the turbine blades.

Design for 2 independent caverns: Over 20 years of practical operational experience confirmed the choice to build two independent caverns. For various reasons, it was necessary on several occasions to drop the pressure in one or other of the caverns down to atmospheric. As already described with reference to the first-fill, refilling the caverns is costly and time consuming because of the need to start the process using mobile compressors and then the plant compressors.

As mentioned before, the start up procedure for the plant compressor requires a minimum pressure of 13 bar in the cavern. It is very easy to satisfy this condition by partially filling the cavern involved from its neighboring cavern.

Moreover, during repair work, one replacement cavern is always still available for power generation, albeit at a reduced storage capacity.

5. Conclusions

The Huntorf plant is the first compressed air storage / gas turbine power station in the world – an unprecedented feat of engineering. The plant started operations after a short commissioning period and exceeded the design parameters (operational turbine period). After replacing the original steel production strings after a few years with FRP strings, the cavern plant continued to be operated for over 20 years without problems. Maintenance was limited to work on the well heads and the associated valves.

After the production strings fractured as result of material failure, analysis is now being carried out to identify the best replacement alternative in terms of materials and installation method. After installation of the new strings, the Huntorf CAES plant will continue its successful operation.