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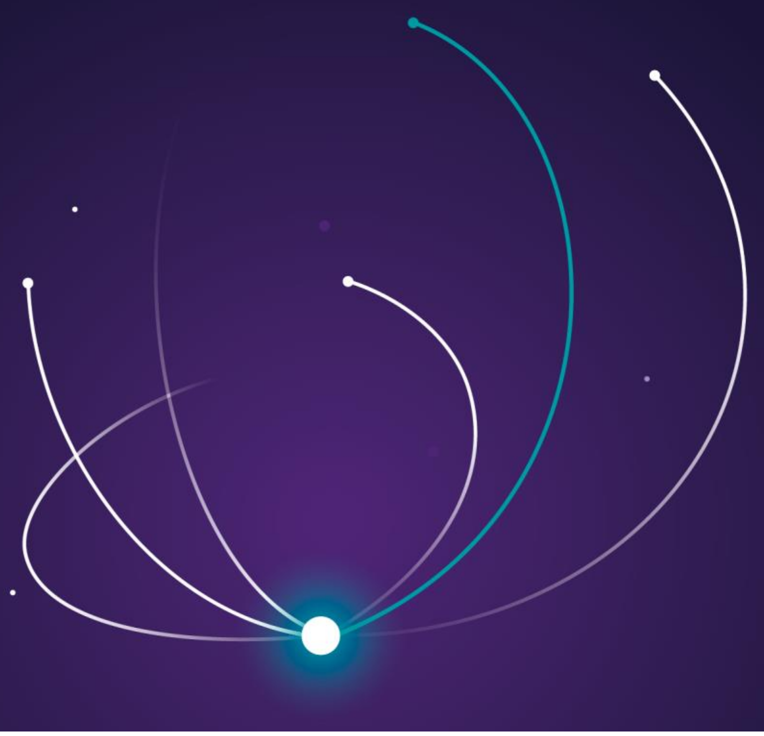
# History of the Benson license

1925 – 2018



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Iskenderun Power Plant – Turkey

Commissioned 2003
Installed capacity 1.320 MW

## 1. Introduction

On 1925-08-15, Siemens-Schuckertwerke AG (Siemens) concludes a license agreement with "Internationale Benson Patentverwertungs AG," of which Siemens and Benson Super Power Corporation each hold half the shares. Based on this, Siemens receives the exclusive license to the Benson patents, with the right to issue sublicenses. This contract marks the start of the success story of the Benson boiler license (Benson license), the license with the longest lifetime within Siemens.

Before concluding this agreement, Siemens becomes convinced of the feasibility of Benson's invention in the English test facility in Rugby. Siemens first secures the possibility of using the patents of Mark Benson in preliminary agreements - the first dated 1923-10-11.

Siemens' special contribution is the introduction of high-pressure technology to power plant construction with the Benson boiler, thus establishing the basis for cost-effective and flexible plants. The process developed by Siemens based on the Benson patent, known around the world as the Benson principle, has ultimately thwarted all attempts by boiler manufacturers to find an alternative solution. Currently, all manufacturers of once-through boilers use the Benson principle.

Over the lifetime of the Benson license spanning over 90 years, more than 1,360 fired Benson boilers have been constructed, with a cumulative capacity of 417,852 kg/s (1,504,265 t/h). The term of the current Benson license agreements for fossil-fired Benson boilers extends in part up to 2030.

This is supplemented by a total of more than 100 Benson heat recovery steam generators that have been ordered up to 2018 and the majority of which have also already been commissioned. The term for the current Benson license agreements for Benson heat recovery steam generators extends up to 2023.

## 2. Mark Benson and his patent

Mark Benson is born in 1890 in Schluchengau/Sudetenland as the illegitimate son of a Habsburg under his mother's maiden name of Müller. He studies chemistry and physics and finds himself in London on the outbreak of the First World War. To evade internment, he takes on the name of Mark Benson, immigrates to the USA and obtains American citizenship.

He is active in the chemical industry in the USA and files numerous patent applications. Through his activity in the American petroleum industry, Benson comes to address the topic of steam generation. Petroleum processing entails endothermic processes, and the necessary heat is supplied by low-pressure steam at temperatures of over 500 °C. Benson also travels to England for several years, where he is to establish a new oil processing plant in southern Wales for the Anglo-Persian Oil Company.

Damage in the evaporators of water-tube boilers, which Benson traces to evaporation phenomena, lead him to the idea of designing a once-through boiler in which the water is directly converted to dry steam. This is known to be the case at the critical pressure of 221 bar and above. Benson assumes that water and steam separate during the evaporation process and that the different physical properties of the two phases result in negative effects such as overheating of the tube walls, disturbances in equilibrium, hammer etc. This is the basic concept behind his invention.

Another version of Benson's invention is also portrayed in the literature (source unknown). The oil processing system requires steam at a temperature of over 500 °C, which can only be provided at the pressures of 7 to 8.5 atm(g) typical for that time. This requires highly expensive boilers. This induces Benson to search for more cost-effective ways of generating steam. He therefore first studies the thermodynamics of the steam process from the stand-point of "irreversibility."  In Benson's opinion, the greatest irreversibility apart from condenser loss lies in the heat of vaporization. This, Benson believes, is the cause of the poor efficiency on the order of 12% in power plants. He therefore decides to generate the steam at the state where there is no longer any heat of vaporization, i.e. at the critical state.

Benson submits his idea in a patent application; the first claim of which entails:

"[...]a method for generating usable process steam at any pressure from resources ... characterized by the fact that the pressure is regulated by special pressure generating devices in the first stage in which the resource is converted to vapor and by pressure-reducing devices in the subsequent stages such [...] that in each stage the separation of liquid and vapor is prevented“

A patent application in the USA fails. Application in England and Germany proves to be more fruitful. On 1922-07-18, the German Imperial Patent Office awards him patent No. 419766 for a "Process for generating usable process steam at any pressure."

In 1921, Benson sets about to construct a test plant to prove his theory. He forms a small company in London, the Benson Engineering Co., and he manages to garner the interest of the English Electric & Co. for his idea, which begins constructing the first test plant in Rugby for an output of 1000 kW.

While the test plant is under construction in Rugby, Benson publishes the theory of steam generation at the critical state in the American Journal Power Magazine through Philipp Swain, with the associated entropy diagrams and a description of the test plant in Rugby. The article is also published in the German VDI Zeitschrift. Based on these publications, the Benson Engineering Co. receives inquiries from Skoda Works, John Cockerill SA in Belgium, Siemens and other companies.

Siemens contacts Mark Benson and concludes a contract with him on 1923-10-11 that is intended to grant Siemens the option of using the Benson patents (see Section 4). Prerequisite for this is that the Rugby plant meets expectations.

After conclusion of the contract, the plant in Rugby (with a steam output of 1 kg/s, evaporator operated at supercritical pressure, superheater outlet condition 103 bar/420 °C) is completed and is taken over by Siemens. However, it does not operate reliably and fails frequently due to faults in the pressure control valve, the gaskets and the feedwater pump. As all tests for the first trial of the process are completed in 1925, the plant in Rugby is shut down and is only visited very rarely by Siemens employees until it is to be disassembled in the mid-30s.

Developments soon depart from Benson's original concept. A test boiler constructed in 1927 is first operated at subcritical parameters with a fully opened throttle valve in 1929. The second Benson boiler is operated without a pressure control valve in the Berlin cable works starting from 1930, at pressures of between 40 and 180 bar depending on the load. This is the birth of the principle of the modern sliding-pressure once-through boiler, which has gone down in power plant technology as the Benson principle. The original patent is no longer used, but the name "Benson boiler" is retained.

When Mark Benson is awarded a patent in 1922 for a "process for generating usable process steam at any pressure," he has no idea that his name will one day be associated with the most widely constructed once-through boiler in the world. This is especially remarkable since his invention proved to be worthless only a few years after the patent was awarded.

Based on statements from friends of Benson still living in the 1980s, he is an extremely intelligent man with a great character, although he can turn into a formidable binge drinker at times. After the Second World War, he remains in contact with Siemens, and maintains contact with his German friends until his death. In the meantime, he marries a movie star in Hollywood and, after a life of luxury, dies in 1959 as a destitute man who is finally forced to rely on welfare.

## 3. Siemens and Mark Benson's patent

Up to this point, Siemens has constructed only its own generators and switchgear for its Central Department (AZ). Karl Köttgen, chairman of the board of Siemens at the time, plans to have all of the main parts of a steam power plant (steam turbines, generators, boilers, transformers, switchgear, instrumentation and control, structures, power distribution systems) constructed in its own plants in the future. He begins negotiations with Thyssen for purchase of the Mülheim turbine manufacturing plant in Wiesenstraße, which Siemens acquires in 1927 for 12,000,000.00 Reichsmark. This plant constructs steam turbines for power plants and industrial plants based on the system of Prof. Röder. These are first characterized by reaction blading and the construction of large rotors with wheel disks bolted to the shaft and hollow drum rotors.

In the first twenty years of the last century, the state of the art in the field of boilers is characterized by small natural circulation boilers with steam outputs of 20 t/h, steam pressures of 15 bar and stoker firing systems, when, in 1911, Wilhelm Schmidt in Aschersleben constructs a highly-noted "high-pressure boiler" with an output of 7 t/h and for

HP steam conditions of 60 atm(g)/490 °C. The elevated HP steam level in this plant enables the heat rate of approx. 25,150 kJ/kWh common up to that time to be reduced to 16,370 kJ/kWh, a sensation for the time.

This induces development to focus increasingly on "ultra high-pressure steam", which, in the terminology of the day, corresponded to a steam pressure of over 30 bar. However, this development is brought to an abrupt halt by the outbreak of World War I. At the same time, the quality of boiler steel goes down due to the lack of alloy materials for steel manufacturing as a result of the war, and there is a dramatic increase in boiler damage and boiler explosions, especially due to embrittlement of the material and intergranular cracks, but also to the riveted drums. The high point of this series of boiler damage is the catastrophic boiler explosion in the Reisholz power plant on March 9, 1920. However, poor heat transfer in steam/water mixtures is suspected to be the cause of the many cases of damage.

With this background, the interest of Hans Gleichmann, Head of Steam Department AZ 7, is aroused by articles in Power Magazine and the VDI Zeitschrift in 1923 regarding Mark Benson's patent and the construction of a test plant in Rugby, England. Gleichmann recognizes the large development potential of this concept, also with regard to potential efficiency increases in the steam power process.

In this situation - expansion of the Siemens product spectrum to include all power plant components and the propagation of a completely new boiler technology by Mark Benson - Siemens believes it can exploit the Benson patent to place itself at the forefront of steam technology, as this boiler type is suitable for ultra-high pressures and temperatures and a higher thermodynamic efficiency of the steam process can therefore be achieved. Further advantages are promised by an inexpensive and space-saving design through the use of small-bore tubes with faster startup, high load change rates and explosion protection.

Following visits by Szilagi, the Siemens representative in London, Benson is invited to visit Siemens in Berlin. After ten days of negotiation, a contract is concluded between him and Siemens on October 11, 1923 that gives Siemens the opportunity to use the Benson patents worldwide (see Section 4).

Chairman of the board Karl Köttgen and Central department manager Hans Gleichmann visit the Rugby plant for the first tests in 1924. Despite the low steam output of 4.5 t/h from the small test boiler, the simply constructed Laval turbine can be started with steam at 108 atm/400 °C and a backpressure of 14 atm. The turbine and throttle tests reveal that the steam from the boiler was completely free from water.

On 1925-08-15, Siemens concludes a license agreement with Internationale Benson-Patentverwertungs AG giving Siemens the exclusive license to the Benson patents with the right to issue sublicenses.

In order to quickly achieve practical results, Siemens decides to construct a test plant in the Siemens Berlin-Nonnendam power plant in 1925. An existing 10 t/h inclined-tube boiler from 1903 is modified and is used as Siemens' own first Benson test boiler for fundamental investigations (operation from August 1925).

In the meantime, Siemens has established an office for developing the Benson boiler, subordinate to director Tonnemacher. Hans Gleichmann assumes technical management. He also assumes responsibility for promoting the interest of the professional technical world in the Benson boiler with many publications. The development work is performed especially by Martin Eule (engineering) and Heinz Rabe (calculation).

## 4. Mark Benson's Benson Super Power Corporation

It must first be noted that Siemens did not purchase the Benson patent, but rather only acquired the rights of use of the patent. The corresponding agreements commence on 1923-10-11 with the agreement between Siemens and Mark Benson to form a patent exploitation company and end on 1966-03-10 with the liquidation of the Benson Super Power Corporation founded by Mark Benson [61].

Mark Benson founded the "Benson Super Power Corporation" (BSPC below) in the State of Delaware, USA in 1922 to evaluate his inventions. Shares are initially $10,000,000, combined to $500,000 in 1940. Siemens is the sole contractual partner.

Negotiations between Siemens and Benson result in the first contract on October 11, 1923. It is agreed in this contract to transfer Benson's previous and future inventions and patents to a newly founded exploitation company that is to exploit the patents by granting licenses. However, the original Benson boiler is not defined here as a once-through boiler with a pressure control valve. This oversight is later to prove extremely expensive for Siemens.

The "Internationale Benson Patentverwertungs AG" (IB) is then founded in Zurich in 1924, with Siemens and BSPC each holding half the shares. Business management of IB is transferred to Siemens. On 1925-08-15, Siemens concludes a license contract with IB that grants Siemens the exclusive license to the Benson patents with the right to issue sublicenses. Siemens pays approx. 200,000 Gold Marks to BSPC for this. Siemens is also obligated to provide all results and intellectual property rights from further technical development of the Benson boiler.

In a special agreement that will significantly influence Siemens' later strategy, it is specified that the development costs incurred by Siemens will be charged to IB. By 1933, license revenues in the amount of approx. SFR 250,000 are offset by development costs in the amount of SFR 3,750,000. Siemens alone bears additional costs in the amount of approx. DM 3,500,000, incurred primarily for the Benson boiler test rig.

In the meantime, it is determined that a Benson boiler can also be operated at subcritical pressure. The Benson patent becomes less important. Siemens files for patents for subcritical once-through boilers. Based on this new development, Siemens considers exiting from IB. However, a corresponding decision is not taken, first because of the technical and legal difficulty of drawing the boundary between supercritical and subcritical Benson boilers as well as because the aforementioned development costs in the amount of SFR 3,750,000 would no longer be assumed by IB. Negotiations between Siemens and BSPC are concluded with a new contract dated 1933-03-29, that replaces the contract of 1923-10-11. Siemens now also contributes the development results for subcritical Benson boilers to IB and, after the Siemens prepayment is covered (SFR 3,750,000), the license profits are split 50:50 for supercritical plants and 85:15 (Siemens: BSPC) for subcritical plants. This agreement is to remain in force for as long as the patent rights; Siemens can only exit the contract by exiting IB.

Taxation and currency transfer issues result in a new contract on 1937-10-21 that provides for the dissolution of IB and a direct contractual relationship between Siemens and BSPC. It is agreed that Siemens will continue to conduct the Benson business as a trustee for both parties, the Siemens prepayments from previous years are fixed at 2,500,000 Reichsmark, Swiss law will apply and the contract will remain in force for as long as license fees are received.

In connection with the end of the Second World War, the London agreement dated 1946-07-27 on the handling of German patents specifies the confiscation of industrial property rights (patents, trademarks, brands). This also renders the Benson patents worthless. Unfortunately the Siemens Patent and License department neglected to terminate the contract with BSPC in this situation.

Until 1951-09-30, the Siemens prepayments in the amount of 2,500,000 Reichsmark were covered by royalties.

In correspondence dated 1955-03-01, Siemens attempts to terminate the contract with BSPC, as BSPC has made no further contribution beyond the provision of the Benson patents in 1923 and the patents had expired in 1940. This action resurrects BSPC, which had already been deleted from the US commercial registry. Its new chairman Wayne McAllister explains that the newer Benson boilers are all operated under supercritical conditions at full load and are therefore subject to licensing, and demands 15% of license profits. BSPC insists upon continuation of the contract and in 1960 requests court of arbitration proceedings in the Chamber of Industry and Commerce for invoicing and payment, to be conducted in Switzerland and in Rome. As it becomes evident that the arbiters are disinclined to follow Siemens' arguments, a settlement is concluded on 1962-05-24, as a result of which the contract of 1937-10-21 is continued. However, it is agreed to continue discussions with the objective of amending or terminating the contract from 1937.

In July 1963, meetings are conducted with Wayne McAllister in Erlangen over several days for amendment or termination of the contract. The Siemens recommendations for a scheduled termination of the contract or for a capital settlement are rejected. However, further meetings are conducted in 1964 to discuss a capital settlement. The starting point is a request from Wayne McAllister in the amount of DM 10,694,000 and an offer of DM 4,000,000 from Siemens. The negotiators are unable to come to an agreement.

Not until the meeting on 1965-09-14 to 1965-09-15 are two alternative proposals agreed upon:

First proposal: Siemens pays BSPC $400,000 as compensation for all claims accrued to the end of the 1964/65 fiscal year. A Swiss company assumes the contract from BSPC (with all future rights) for the payment of $1,150,000.

Second proposal: Wayne McAllister returns to the earlier proposal of selling back the BSPC shares at a price of $30.00 per share, but with the requirement that the sale be made not to Siemens but to a Swiss company.

The first Proposal is favored internally by Siemens. In the BSPC shareholder meeting on 1966-02-15, the shareholders vote for proposal 1 and the associated liquidation of the company. The contracts are handed over in New York on 1966-03-10 and the agreed sum in the amount of DM 6,510,000 is paid. On request by BSPC, the contract is first transferred for tax reasons to Swiss company Lothar AG, where liquidation then proceeds.

All contractual conditions dating back to the first contract with Mark Benson on 1923-10-11 are thus ended on 1966-03-10.

## 5. Siemens as a boiler manufacturer - a chronology

1925-08-15 Acquisition of worldwide utilization rights to the Benson patent by Siemens.

1925: Siemens' own first Benson boiler is constructed in the Siemens cogeneration power plant in Berlin-Nonnendamm by the modification of an existing 10 t/h inclined-tube boiler from 1903 and is used for fundamental investigations. The existing 13 atm boiler is raised and the piping packages for the Benson system are installed underneath. The existing boiler only serves as a flue gas heated feedwater preheater that heats the feedwater from 20 °C to 180°C. The feedwater is routed to the radiation evaporator and exits it as steam at approx. 225 bar/370 °C, is superheated to 400 °C and is then throttled to the operating pressure of 150 bar and again heated to 410 °C. It is supplied to a high-pressure turbine in this condition. With this plant (in operation since August 1925), Siemens also begins the development of pressure control valves, controllers ("indicator controllers") and startup valves (bypass to condenser). The test results are not yet convincing, as tube breaks are continually occurring at the end of the evaporator after a few days of operation. Improvements are achieved with blowdown valves in the individual parallel trains. However, this plant has proved itself in principle in operation with well-treated feedwater. This 10 t/h boiler remains in operation until 1928, when it is disassembled, delivered in a modified condition to Bitterfeld (Elektro-Süd power plant of IG Farbenindustrie AG) and is further operated until 1930.

1926: A first commercial Benson boiler with a steam output of 30 t/h and superheater outlet conditions of 182 bar/420 °C to 450 °C and reheat is planned for the Siemens cable plant in Berlin-Gartenfeld. This decision shows great courage, as this plant is to be constructed as a tower boiler for outdoor installation with pulverized coal firing. The boiler goes into operation in the fall of 1927 and has the following features:

- Cylindrical furnace to ensure uniform heat transfer by radiation.
- Cooled furnace walls with vertical tubing (16 parallel trains, medium flows upwards and downwards through 16 tubes each in sequence).
- Most uniform possible flow resistance in all trains.
- Pulverized coal firing with top-mounted burners and oil-fired ignition burners.

Tube breaks occur in the area of the flame cone; these are not limited to the end section of the evaporator. The opinion takes hold that the excessive salt content in the feedwater is the primary cause for the tube damage and an evaporator unit is constructed for the feedwater. The important result is also arrived at here that in the future, the so-called evaporation end zone must be configured in a flue gas area with moderate heating (transition section). A further cause is the lack of venting in the vertical furnace tubes connected in series. In a modification in 1929, the reheater is removed and the vertical tubing in the furnace is replaced by spiral tubing, which enables reliable venting and hence flow through the evaporator tubes. The boiler is also modified for sliding pressure operation. The boiler is finally dismantled in 1940 and is replaced with a new 50 t/h Benson boiler, which is again disassembled and sent to Russia already in 1945.

1927: Construction of a Benson test boiler for the Technical University of Berlin (Prof. Josse) with a steam output of 3 t/h, 230 bar/450 °C. In 1927, Prof. Josse makes the first attempt to operate this Benson boiler for approx. 14 days at subcritical conditions with the pressure control valve wide open, which is also fully successful. This also confirms, from the academic side, the experiences of the operating personnel of other Benson boilers that a Benson boiler can also be operated at subcritical conditions. On the one hand, this result renders the Benson patent worthless (it explicitly specifies the pressure control valve), and on the other hand Hans Gleichmann recognizes the opportunity and the large advantages of sliding pressure operation for power plants. Modification of the Gartenfeld Benson boiler therefore simultaneously includes reconfiguration for sliding pressure operation, and starting from 1930 both boilers are operated only in sliding pressure mode.

1927: The decision to construct a second Benson boiler in the Siemens cable plant is taken so early that the correct information on salt deposits in the evaporation end zone can no longer be implemented. The evaporation end zone is not moved to the second pass as a so-called transition section until a modification in 1931. This boiler is also constructed as an outdoor boiler in tower configuration. This boiler has a steam output of 37.5 t/h, 221 bar in the evaporator and 182 bar/465 °C at the reheater outlet. In the combustion zone, which has a square cross section in the lower area and a circular cross section above, the evaporator tubes are implemented in a spiral configuration with two sections. After 1932, this Benson boiler is also operated in sliding pressure mode without a pressure control valve.

1928: Construction of a 7.5 t h Benson boiler with a stoker combustion system with I.G. Farben in the Bitterfeld central power plant. Siemens assumes the costs for the parts exposed to water/steam. The pressure in the evaporator is 221 bar; superheater outlet conditions are 25 bar/400 °C. This system clearly demonstrates that the frequent tube breaks are caused by salt deposits. It also proves that the Benson boiler is also suitable for operation with stoker firing from a control standpoint.

1929: Construction of the Langerbrügge Benson boiler for the Société des Centrales Électricques des Flandres et du Brabant with a steam output of 125 t/h, 221 bar/450 °C at the superheater outlet and with reheat at 56 bar/450 °C. This boiler, constructed as an outdoor boiler in tower configuration, is among the largest plants of its time. The topping turbine is operated at a constant supply pressure. This boiler is also repeatedly modified. First the evaporation end zone is moved to the second pass. In 1934, the furnace tubing, which is implemented as double spiral-wound tubing, is modified to a vertical riser/downcomer system due to heavy slag formation in the furnace. The superheater pressure is also reduced to 160 bar.

Based on the results from Langerbrügge, the evaporator in the furnace is subsequently implemented as a riser/downcomer system with intermediate headers. This somewhat elaborate construction will later be long-retained by licensees as none dare to build a once-through evaporator design. All further development work for the operationally mature Benson boiler will also be performed by Siemens in subsequent years.

1929: Joint design and construction of a Benson ship boiler with Blohm + Voss for MV Uckermark. Steam output is 24 t/h, evaporator pressure is 221 bar, steam conditions downstream of the superheater are 69 bar/445 bar °C. The riser/downcomer system is implemented for the first time. The boiler is converted to subcritical pressure in 1934 by removal of the pressure control valve; the evaporation end zone is moved to the second pass. In 1937, the boiler is replaced with two new Benson boilers of equal capacity.

The previously described Benson boilers, with the exception of the boiler for the MV Uckermark, are all designed in what was then Siemens department AZ 7h and are produced in the Borsig shops (marine boilers at Blohm + Voss). It has been learned how a once-through boiler must be constructed if it is to operate reliably in continuous operation.

The expenditures for the various modifications have since cost the Benson account 2,500,000 Reichsmark. It is to the credit of Hans Gleichmann that he has successfully negotiated this financial dry spell with the board of directors.

1933: Siemens decides to cease the construction of Benson boilers in its own shops.

1933: Hans Gleichmann and his employees make every effort to secure the implementation of the Benson boiler in industrial power plants and electric power utilities.

| Year | Facility | Operator | Output t/h | Pressure bar | Temp. °C | Fuel |
|---|---|---|---|---|---|---|
| 1924 | Rugby test rig* | Siemens, Berlin | 4.5 | 103 | 420 | Oil |
| 1925 | Nonnendamm | Siemens, Berlin | 10 | 105 | 410 | Oil |
| 1926 | Cable works 1 | Siemens, Berlin | 30 | 190 | 450 | Hard coal |
| 1927 | Cable works 2 | Siemens, Berlin | 37.5 | 190 | 465 | Hard coal |
| 1927 | Berlin Technical University | Berlin Technical University, Berlin | 3 | 230 | 450 | Oil |
| 1928 | Bitterfeld | I.G. Farben, Bitterfeld | 7.5 | 221 | 380 | Lignite |
| 1929 | Langerbrügge/<br>Belgium | Société des Centrales Électr. des Flandres | 125 | 190 | 470 | Hard coal |
| 1929 | MV Uckermark 1 * | Hapag, Hamburg | 24 | 80 | 460 | Oil |

Benson boilers constructed by Siemens (* completion or jointly with Blohm + Voss)

## 6. Siemens as the licensor for Benson boilers

1925 to 1945

In 1925, Siemens obtains the exclusive license to the Benson patents with the right to issue sublicenses through the contract with "Internationale Benson-Patentverwertungs AG". Siemens issues the first sublicense to Steammotor on 1926-10-23. The background for the issue of this license is no longer known; Steammotor did not construct a single Benson boiler.
Siemens decides in 1933 to cease the construction of Benson boilers in its own shops, because the construction of steam boilers exceeds the scope of Siemens' manufacturing program. Boiler construction requires a completely different manufacturing process than that for turbines or generators. This may also have been influenced by the global economic crisis. The last order (Langerbrügge) is in 1929. Instead, Siemens now issues licenses to the boiler industry.

In 1933, Siemens issues a strategic license to Westinghouse Electric & Manufacturing Co., dated 1933-10-16. The background for this license is a framework agreement from 1924 regarding the exchange of information and a shared interest. One point in this shared interest is the delineation of areas of influence. For example, Siemens does not appear on the US market, therefore Westinghouse primarily leaves the European market to Siemens. This framework agreement with Westinghouse is renewed in the early '50s, until it is officially terminated in the early '60s. The Benson license expires in 1945; Westinghouse likely never intended to manufacture boilers.

The actual granting of licenses to boiler companies then begins in 1934. Up to the end of the war, 17 manufacturers have received a Benson license, including:

| Licensee | Contract start date |
|---|---|
| A. Borsig Maschinenbau AG, Berlin-Tegel | 1938-05-23 |
| Dürrwerke AG, Ratingen | 1934-06-30 |
| Blohm + Voss Kommanditges. auf Aktien, Hamburg | 1934-09-25 |
| Vereinigte Kesselwerke AG, Düsseldorf | 1935-10-08 |
| Walther & Cie., Cologne | 1936-11-09 |
| L. & C. Steinmüller GmbH, Gummersbach | 1937-03-15 |
| Friedr. Krupp Germaniawerft AG, Kiel-Gaarden | 1937-12-08 |
| Ansaldo S.A., Genoa | 1939-11-11 |

The license fee (e.g. at Dürrwerke AG) is initially 5% of the net price, not including shipping and packaging.

In 1935, the Siemens boiler design department produces a complete design for a Benson boiler incorporating all results regarding design and operating behavior. Main points include the furnace tubing with a riser/downcomer system and the boiler control. All new Benson boilers are operated at subcritical pressure, so that the original patent from Mark Benson becomes worthless. However, the termination of various contracts with Mark Benson and the Benson Super Power Corporation (BSPC) is inadvertently neglected.

This leads to  a protracted legal dispute with BSPC regarding license fees from the late '50s up to the mid-'60s.

A patent dispute between Siemens/Krupp Germaniawerft and Sulzer/Halberg is concluded with a settlement in 1940. The intent is to cease competitive activities between Siemens and Sulzer in order to promote the final breakthrough of the once-through boiler over the drum boiler. However, the Benson licensees actually accuse Siemens of promoting the Sulzer boiler, demand a reduction in license fees and even threaten contract termination.

Due to the chaos of war, the last Benson boiler for the duration is ordered in 1943. Up to this time, licensees have constructed 125 Benson boilers with steam capacities of up to 160 t/h and a cumulative output of 2,880 kg/s (10,368 t/h), of which 74 are constructed by Dürrwerke and Borsig alone. A large number of marine boilers are also constructed for the German Navy.

As a result of royalty payments received up to late 1944, the negative balance of the Benson account was reduced from 2,500,000 to 750,000 Reichsmark.

New beginnings after 1945

Towards the end of the war, the most important documents had to be rescued from the Red Army approaching Berlin. On March 12, 1945, part of the power plant engineering department is relocated from Berlin to Mülheim/Essen under the "West Group Directorate" to protect the employees and expertise from access by the Russians. All of the important planning documents and files are loaded onto two trucks with trailers and are also relocated to Mülheim.

In connection with the end of the Second World War, the London agreement dated 1946-07-27 on the handling of German patents specifies the confiscation of industrial property rights (patents, trademarks, brands). The Benson patents thus become worthless. The construction of steam turbines and boilers is also prohibited. Furthermore, there is no capital available for the construction of new power plants. Significant corrosion damage also results in existing plants due to inexperienced operating personnel. Tube breaks in the boilers repeatedly force shutdowns. The Benson boiler thus appears to have come to an end.

As the Allies transition from the Morgenthau Plan to the Marshall Plan, the necessary capital for the construction of power plants is again available. A series of orders quickly follows for the previously usual capacities of 160 - 200 t/h for installation in range-type power plants where the boilers deliver steam into a common header.

In correspondence dated 1950-05-15 to Mr. Schultes (successor to Hans Gleichmann), the patent department recommends that the Benson license business be discontinued since there are no more patents and the balance is still negative. However, the responsible engineers do not follow this recommendation; instead, the foundation for the future business success of the Benson license is laid with new patents.

The rapid economic growth beginning after the end of the war results in renewed and growing interest in the Benson technology among electric power utilities and boiler construction companies. The transition to higher unit capacities, unit-mode operation between the boiler and turbine and the implementation of ultra-high pressures enables high plant efficiency. Reheat is implemented as a standard feature and a series of plants with double reheat is constructed. The suitability of the Benson boiler for high pressures and a flexible operating mode with constant steam temperature across the entire load range meets these requirements especially well.

1950 to 1970

The license business soon recovers with the changing political and economic conditions, and well-known boiler manufacturers can again be acquired as licensees, including:

| Licensee | Contract start date |
|---|---|
| Deutsche Babcock & Wilcox Dampfkesselwerke AG, Oberhausen, | 1950-04-11 |
| Babcock & Wilcox Ltd., London | 1951-09-20 |
| Simon-Carves Ltd., Stockport | 1951-11-01 |
| Yokoyama Engineering Co. Ltd., Kobe | 1954-03-01 |
| Babcock & Wilcox, Barberton | 1954-04-29 |
| A/S Burmeister & Wain's Motor- e Maskinfabrik af 1971, Copenhagen | 1954-09.24 |
| Maschinenfabrik Augsburg-Nürnberg AG, Nuremberg | 1955-06-16 |
| Clarke, Chapman & Co., Ltd., Gateshead | 1956-04-24 |
| Koninklijke Maschinefabriek Gebr. Stork & Co., Hengelo, later Stork Ketels B.V. | 1959-09-10 |
| Babcock-Hitachi K. K., Tokyo | 1960-06-02 |

In 1951, the boiler department is transferred from Mülheim to Erlangen, the current company headquarters, and employee numbers gradually begin to increase.

In the '50 and '60s important innovations in the area of boiler construction are introduced:

- In 1954, many Benson boilers with slag tap firing are ordered. The evaporator tubing is designed with a meandering pattern to accommodate the geometric complexity of the furnace.

- In 1956, the first American Benson boiler without masonry and with walls welded gas-tight is constructed in the Breed power plant of the American Electric Power Corp. (output 450 MW, 1350 t/h, 240 bar/565 °C, double reheat 545/565 °C, manufacturer: Babcock USA).

- In 1960, Siemens introduces spiral-wound furnace tubing in large boiler manufacturing. The Civitavecchia plant (manufacturer: Ansaldo) still has a skin-casing design; the Rhodiaceta (manufacturer: VKW), Badalona and Fintinele plants (manufacturer: Dürrwerke) have boilers with enclosure walls welded gas-tight in tower configuration. Unfortunately, it was neglected to protect this innovation with a patent to extend the technical advantage over the Sulzer boiler for as long as possible. The differences from the spiral-wound tubing in the first Benson boilers in the '20s and from the AEG patent with a round slag-tap furnace (later acquired by Dürrwerke AG) are so great that the award of a patent would have been likely.

The Siemens boiler department works on the solution of the resulting design problems; many patents are applied for and granted. Licensee consulting is expanded in Germany and internationally. Emphasis in these years is clearly in the design area. Concepts are also developed to make the boilers safer and to improve operating behavior. Siemens becomes the leading power plant consultant in Germany since they are the sole manufacturer whose competency covers the technology of all the components in a power plant.

Order receipt for Benson boilers increases sharply. The fee is reduced for many licensees, as a defined order volume with higher license fees is soon exceeded.

After the once-through boiler has surpassed the drum boiler in Germany, competition between the Benson boiler and the Sulzer boiler becomes increasingly fierce and culminates at the 5th world power conference in Vienna in 1956. Mr. Juzi, the Sulzer representative, responds so unobjectively to a contribution to the discussion from Ruprecht Michel/Siemens that he is repeatedly warned by the president and must finally leave the podium amidst whistles from the audience.

However, it must be noted objectively that the success of the Benson boiler is due not only to its good and flexible concept and licensee consulting by the Boiler department, but that Siemens' market position as a leading power plant consultant in Germany also contributes to the growth of the Benson boiler. As a power plant consultant, Siemens also influences development in the field of boilers: For example, a boiler and firing concept is developed under the management of Siemens in cooperation with VKW and RWE enabling the first unproblematic combustion of coal with a high salt content (350 MW Buschhaus unit).

### 1970 to 1985

After the licensees surmounted the design problems associated with the introduction of the gas-tight tube wall with the help of Siemens, they believe that they have no further need of Siemens expertise to construct Benson boilers, and the interest of the German licensees in the Benson license undergoes a palpable decline. Furthermore, the importance of Siemens as an advisor for coal-fired power plants in Germany decreases with the penetration of nuclear power plants.

In this context, the German boiler manufacturers terminate the license agreements in June 1971. A meeting is held in Erlangen on 1971-10-20, in which the management of all German licensees participate and which is chaired by Siemens board member Hasso Leiste. They first offer to completely forego consulting by Siemens with the exception of the use of patents and to reduce the license fees accordingly. Siemens attempts to prevent the worst by proposing the construction of a new test rig and intensified research. The boiler manufacturers accept this proposal and a compromise is reached in which new contracts are agreed upon. The basis for calculating the license fees is also changed, from a percentage of the boiler price to boiler output (DM per t/h steam capacity), with separate calculations for oil/gas boilers and for coal boilers. A sliding price formula is introduced. This change obviates the consistently recurring and often somewhat embarrassing discussions between Siemens and the licensees regarding the boiler price to be used in determining the license fees.

A new test building and laboratory building then constructed on the Süd site in Erlangen (Building 64), which will accommodate the new Benson test rig. This starts operation in the fall of 1974.

With the completion of the Benson test rig, Siemens completely restructures consulting for its licensees: Siemens now defines research projects, agrees on these with the licensees and presents the results in annual licensee conferences. With this fundamental research, Siemens becomes the global leader in the areas of internal heat transfer and pressure drop in tubes. The same applies for the simulation work on the dynamic behavior of the boiler and the unit.

The focus of its licensee consulting shifts from design and configuration issues to questions of the thermodynamic and fluid dynamic design of the evaporator and the dynamic behavior of the boiler. The German licensees reward this by extending the license agreements.

Interesting discussions are held in 1973 regarding a merger between Sulzer licensee EVT and Benson licensee MAN. The new company is prepared to offer Sulzer boilers within Germany only in exceptional cases and to pay Siemens 70% of the license fee (corresponding to the market shares of MAN and EVT) for all new once-through boilers (Benson and Sulzer boilers) built by this company in Germany and internationally. However, when Walther suddenly changes the capital situation as a 40% shareholder of EVT, the merger in this form fails.

In the '60s and '70s, Japan is dominated by supercritical boilers of the American universal pressure and combined circulation designs. In the fall of 1979, licensee Kawasaki therefore organizes a round trip to the seven major Japanese EPUs, where Siemens holds presentations on Benson boilers. The Benson boiler then also achieves penetration of the Japanese market.

Due to the license payments, the German licensees frequently request preferential treatment from Siemens in the award of contracts for nuclear power plant components. Siemens therefore decides in the early '80s to allow the Benson license to expire. Research activities are to be drastically reduced and license contracts will not be extended. This decision, with which Siemens would have lost large license revenues and which would have damaged

Siemens' image in the future, especially internationally, is reversed in the face of growing interest by licensees in Siemens expertise. In subsequent years, they forego the usual termination notices to obtain changes in the conditions. Nuclear power plants soon lose their importance and therefore Siemens loses its importance as a customer: The decision thus peters out at the end of '80s.

1985 to 2000

For reasons of cost, licensees around the world decrease their development capacities on the water/steam side of the boiler, thereby increasing the technological lead of the Siemens Boiler department.

In the USA, rifled tubes are implemented increasingly in large once-through boilers as well as in drum-type boilers. Japanese Sulzer licensee Mitsubishi constructs three 700 MW boilers with vertical-tubed furnaces employing these tubes. Starting in 1990, Siemens therefore intensifies its fundamental research in rifled tubes. The research results lead to many patents (principle patent EP 0 581 760 B2) for furnace walls with vertical tubes and low mass flux. The area of application for this "low mass flux design" can be extended down to a boiler output of 350 MW.

In the mid '90s, Siemens wins a protracted patent suit against Sulzer, which violates a patent for an especially thermoelastic furnace suspension system. Sulzer has to pay SFR 250,000 to Siemens.

Public relations efforts are increased: With presentations at international conferences and with publications, the scientific work by Siemens and its significance for improving the competitiveness of the Benson boiler become known worldwide. The focal point of this activity is the future market of China. In many presentations and seminars in China, operators, licensing authorities and universities are familiarized with European power plant technology, focusing on Benson boilers. Penetration by European power plant technology succeeds in 1996 with the Waigaoqiao power plant, when Siemens is able to change the planning of three subcritical 660 MW American-designed units to two supercritical 900 MW units and to acquire the order for the turbines. However, the boiler order still goes to Sulzer licensee EVT. The Chinese market is subsequently dominated by the Benson boiler.

Further well-known boiler manufacturers are acquired as licensees over this period:

| Licensee | Contract start date |
|---|---|
| Foster Wheeler Energy International Inc., Clinton | 1996-08-20 |
| Bharat Heavy Electrical Industries Ltd., New Delhi, | 1999-07-01 |

A global gas turbine boom begins in the mid-'90s. Basic patent EP 944 801 B1 0 is awarded for a horizontal Benson heat recovery steam generator downstream of a gas turbine (unfired combined-cycle power plant). Expectations are fulfilled by a demonstration plant downstream of a 250 MW gas turbine in Cottam, England. This results in the conclusion of license agreements with many new boiler manufacturers starting in 2002, including Alstom, which has since acquired Sulzer and Combustion Engineering.

As consequence of the gas turbine booms, the construction of coal-fired power plants comes nearly to a standstill. Only 16 Benson boilers are ordered over the five years from 1995 to 1999. A financial dry spell can be delayed, as most of the contracts do not provide for payment of the license fee until after handover of the boiler to the operator.

2000 to 2005

While China still imports many coal-fired power plants over the '90s, even high-capacity power plants are now being constructed domestically with foreign technology. The decision-makers in China are apparently convinced of the advantages of Benson technology, with the result that several of the major Chinese boiler manufacturers obtain a Benson sublicense:

| Main Licensee | Sublicense |
|---|---|
| Babcock-Hitachi K. K. | Babcock-Hitachi Dongfang Boiler Co., Ltd. |
| Babcock & Wilcox Comp. | Babcock & Wilcox Beijing Company |
| Mitsui Babcock Energy Ltd. | Harbin Boiler Co., Ltd. (technology transfer agreement for 15 years) |

The Benson boiler thus also achieves domination in the world's largest current market for coal-fired power plants. For example, 48 boilers are ordered from these three manufacturers in 2003, corresponding to an over 70% share of the market in China. From 2004 to mid-2005 a further 38 Benson boilers for a unit output of 600 MW and above are ordered in China.

2005 to 2018

A focal point in the support of the Benson licensee over the years after 2005 is seen in the introduction of vertical-tube evaporators with low mass flux to the market [128]. Important elements of the new evaporator concept are what is known as the natural circulation characteristic (or positive flow characteristic) and the implementation of optimized rifled tubes in fired boilers with high heat fluxes in the furnace or the use of smooth tubes or standard rifled tubes in circulating fluidized bed systems with low heat flux. For heat recovery steam generators with a horizontal gas path, a concept for a once-through evaporator with vertical heat exchange tubes and a natural circulation characteristic was developed and patented already in the mid-'90s.

The first pulverized-coal fired system with a Benson low mass flux design is the boiler in Yaomeng 1 in China, commissioned in May 2002. This is a modification project in which large areas of the pressure section are replaced.

Following extremely positive operating results, the customer orders the modification of a second unit in 2007. The first new plant constructed with this evaporator concept and boxer firing is the supercritical steam generator in the Longview project in the USA, which can be handed over to the customer in 2011.

A further key application for the Benson low mass flux design entails boilers for firing anthracite and dry ash removal. The use of vertical tubing is nearly absolutely necessary due to the complex furnace geometry. The first project implemented is Jinzhushan plant in China, which is commissioned in early 2009. By late 2017, a total of 32 boilers for outputs between 600 MW and 660 MW have been ordered or are already in operation.

Vertical tubing with low mass flux is also used in supercritical plants with a circulating fluidized bed. Lagisza plant in Poland is commissioned and handed over to the customer in early 2009. The boiler in Baima, China is currently the largest operating circulating fluidized bed plant in the world, with an output of 600 MW. It is taken over by the operator in April of 2013. Many projects for 350 MW are ordered in China in the following years. By late 2017, the Benson reference list boasts a total of 26 supercritical CFB plants.

The first heat recovery steam generators with a horizontal gas path, vertical heat exchange tubes and a once-through evaporator is commissioned in 1999 in Cottam, UK. It remains the only heat recovery steam generator of this type until 2007. Only in this and subsequent years is it possible to successfully introduce this technology to the market with projects such as Hamm-Uentrop, Herdecke, Pego, Sloe Centrale etc.

50 Benson heat recovery steam generators of this design have since been commissioned and handed over to the customers. Further projects have already been ordered and are in the implementation phase.

Starting from 2012, the development of a once-through evaporator for a heat recovery steam generator with a vertical gas path is started in the Benson department. The basis for this development is basic patent EP 993 0 581 A1 from 1998.

The successful market introduction of this technology is significantly accelerated in 2015 by the order of 24 heat recovery steam generators of this design downstream of 400 MW gas turbines. 2018 is characterized by the commissioning of these heat recovery steam generators.

## 7. Further research and development by Siemens

The name of Siemens has long been associated with boiler development: Friedrich Siemens (1826 -1904), a younger brother of company founder Werner von Siemens and inventor of the regenerative furnace (1856), implements the radiation section in regenerative furnaces in 1879, where heat transfer from the flame to the wall is no longer through contact but rather by radiation. This procedure is also quickly implemented in steam boiler construction. In 1900, the Technical University of Dresden awards the first honorary doctorate to Friedrich August Siemens.

### Research and development from 1925 to 1950

The development activities at Siemens for Benson boilers start in 1925 with the implementation of the concept of Mark Benson in a completely new, competitive industrial boiler for power plants that has no precedent. Focal points of the development at that time:

- Furnace tubing
- Feedwater chemistry
- Configuration of heat exchange surfaces to prevent tube damage
- Boiler control

The development results are based on theoretical considerations, investigations in the test facilities in Berlin-Nonnendamm, the Technical University of Berlin and in Bitterfeld as well as the exchange of feedback with the power plants.

The vertical tubing of the furnace, comprising many tubes connected in series, is repeatedly subject to tube breaks due to a lack of venting. This tubing is therefore replaced by spiral tubing. However, this becomes so heavily fouled that the vertical tube configuration is again resorted to. The evaporator tubes are combined in individual systems with top-mounted outlet headers that can be vented and which are connected in series. The advantages of this riser/downcomer system are the small temperature rise in a system and good flow stability. This somewhat complex design is long retained, because nobody dares to implement an evaporator configuration without disruption.

Despite all precautionary measures, the two Benson boilers in Berlin Gartenfeld are repeatedly subject to tube breaks in the end section of the evaporator. In roughly 1929, it is recognized that the excessive salt content in the feedwater is responsible for this, and an evaporator system is therefore constructed for feedwater conditioning. Through a 5-fold evaporation, a salt content of < 10 mg/l can be maintained and the number of tube breaks is drastically reduced.

The problem of salt deposits is finally considerably mitigated in 1929/30 by configuring the end section of the evaporator in an area of low heat exchange surface loads. This results in what is known as the final evaporator zone. The boilers are also shut down roughly every 14 days and are flushed to the condenser via the startup line.

Roughly in 1927, the Benson boiler at the Technical University of Berlin is operated for the first time with subcritical pressure in the evaporator and with the pressure control valve wide open. This operating mode is also proven in other Benson boilers. Hans Gleichmann recognizes the advantages of the sliding pressure operating mode for unit operation, and he introduces this operating mode to power plant operation in the early '30s. The Benson patent thus proves to be worthless for further development.

A further focal point of development is the boiler control system. The long throughput time of roughly 2 to 10 minutes for the feedwater and the effect of the thermal masses make it extremely difficult to maintain a constant HP steam temperature. Not until the invention of the secondary heat exchange surface in the '30s can satisfactory control results be achieved, also in load following mode. Water heating is measured in an approx. 15 m long loop of piping configured in the upper section of the furnace and is used as a fast control signal

A Benson boiler that is wholly suitable for implementation and all aspects of which have been fully designed by Siemens is thus available in 1935. Until the mid '50s, boiler tubing is always configured based on the riser/downcomer system, until a spiral or meandering tubing system is again implemented based on new technical requirements.

Further important theoretical work follows. Rupprecht Michel prepares his dissertation on optimum feedwater temperature, which results in new knowledge for the design of the turbine cycle. Over the time up to roughly 1950, the Benson boiler design calculations are based primarily on the technical literature, supplemented and improved by Siemens' own measurements in power plants. The so-called "cookbook" with design instructions and diagrams is developed for Siemens employees.

Research and development from 1950 to 1975

In the mid-'50s, employees of the Boiler department and Siemens & Halske AG jointly perform extensive control investigations in Karnap power plant. The results obtained ensure Siemens & Halske AG a technological advantage over the competition that can be maintained for many years.

As the first fundamental theoretical investigation, the technical article on "Flow conditions in once-through boilers" is completed for Benson licensees in 1958 (Elmar Kefer). This investigates the stability and flow behavior of parallel systems of tubes as a function of mass flow rate, pressure, inlet enthalpy and heating and provides instructions for designing once-through evaporators. The extensive calculations are still performed by slide rule.

After the end of the '50s, Siemens activities are focused on the development of new boiler concepts and the solution of design problems such as:

- Spiral furnace tubing
- Transition from a masonry design to self-supporting, gas-tight tube walls, even for two-pass boilers
- Cost-effective startup systems
- Integration of the Benson boiler in combined gas/steam turbine processes.

Details of these design and process engineering development steps are described with appendices listed in Section 8, "Milestones in technical development".

Damage of Benson boilers in cases where the cause of the defect cannot be established unequivocally is the inducement for construction of the first Benson test rig in the Siemens Nuremberg transformer plant. This is commissioned in 1955. The electrically heated test rig is designed for a mass flow rate of 50 kg/h and steam conditions of 400 atm/700 °C. Tests for determining internal heat transfer are performed here that yield useful results within the bounds of the limited possibilities - only tubes with an inside diameter of 5 or 8 mm can be studied. The test rig is simultaneously used for chemical investigations. In early 1962, the Benson test rig is relocated to the Siemens Research Center in Erlangen. Phenomena such as the effect of magnetite deposits on heat transfer are researched there.

In the mid-'60s, Peter Mörk, an employee of the Siemens Boiler department, transfers to EURATOM in Ispra, Italy, where he constructs a test facility for studying internal heat transfer and pressure drop in tubes. The measurement results achieved there for tubes with an inside diameter of 10 and 20 mm are evaluated by Siemens. Together with the results of Siemens' research, these form the basis for the technical field of "internal heat transfer and pressure drop in tubes", in which Siemens is to later become a global leader.

A control manual is developed jointly with Siemens Karlsruhe from 1971 to 1974. This contains instructions for the design and analysis of Benson boilers to enable the optimum fulfilment of specified control requirements.

Research and development from 1975 to 2003

In 1971, German licensees want to allow the Benson license to expire, because they believe they can construct Benson boilers without Siemens' expertise. In the negotiations with German licensees, Siemens proposes to intensify research and development efforts, thereby achieving the conclusion of new contracts at relatively acceptable conditions. These contracts introduce a completely new phase of the Benson license: Siemens defines research projects and agrees on these with the licensees.

The contract negotiations in 1971 result in construction of the second Benson test rig on the Siemens Erlangen Süd site. Design data:

| | | |
|---|---|---|
| Pressure | 330 | bar |
| Temperature | 600 | °C |
| Mass flow rate | 4 | kg/s |
| Electrical heating power: | 2,000 | kW |

A new test building and a laboratory are constructed (Building 64) for this high-pressure test system, the 470 m² area of which also houses smaller test plants in addition to the auxiliary systems such as the demineralization system and the power supply. The costs for the construction of the test system (not including the building) are DM 3,346,000, paid for from Benson license revenues.

Three key development points are in the foreground in the design of this facility:

- Development of the design basis for heat transfer and flow processes.
- Testing and further development of design elements.
- Investigations for questions of feedwater chemistry with regard to the formation and retention of protective coatings.

The investigations on the Benson test rig will soon position Siemens as the global leader in several areas. Key results are as follows:

- Internal heat transfer in tubes: With the more than 148,000 measurements on smooth tubes (inside diameter 12.5 mm to 24.3 mm, status late 2004) over a wide range of parameters, well-founded relationships based on physical conditions are developed for the first time for predictive calculation of the heat transfer in the two-phase zone, thereby establishing a new design basis for evaporator heat exchange surfaces. The effect of dynamic processes (pressure change) on heat transfer is also new.

Induced by the use of rifled tubes in the USA and Japan, investigations with this tube type are started in the early '80s. Internal heat transfer is increased by 30% by optimizing the rifling geometry. By late 2004, more than 243,000 measurements are performed on rifled tubes (inside diameter 13 to 35 mm). In this area as well, Siemens takes its place at the forefront of global research; many tube manufacturers adopt the optimized rifling geometry. The results are provided to the licensees in the continuously updated manual "Heat transfer in tubes".

- Pressure drop in pipes: The effect of heating on pressure drop is determined in parallel with the heat transfer measurements. Pressure drop measurements are performed in a "cold water section" with pipes with extended exposure time that are subjected to repeated acid cleaning during the test period to enable the estimation of changes in pressure drop for boilers in operation and possible effects of the flow characteristic. The same test equipment is used to determine friction factors for flow restrictors. The results are provided to the licensees in the manual "Pressure drop in tubes".

- Water/steam mixtures: Tests with water/steam mixtures regarding segregation or uniform mixture distribution are complex and problematic from an instrumentation standpoint; the tests are therefore performed using water/air mixtures). Special emphasis must be given to the development of a simply designed centrifugal separator with a high separation efficiency that is configured in the startup and low-load system. The application for patent protection is unfortunately neglected, with the result that this separator is soon copied worldwide. The impingement plate distributor developed by Siemens for uniform distribution of the steam/water mixture is also proven in practice.

- Design elements: The transition of conventional power plants from base load operation to intermediate peaking duty requires a boiler with thermoelastic construction. The temperature distribution is therefore measured during non-steady-state temperature behavior in comb plates and support straps welded to a membrane wall in various ways in the Benson test rig. Comparative calculations using the finite element method provide information on heat transfer by radiation or contact at points that are not welded and at design-related gaps. These are used to elaborate boundary conditions and instructions for the construction of a thermoelastic support strap design for the furnace spiral tubing. Based on these documents, Siemens develops a special thermoelastic double-strap suspension together with licensee Balcke-Dürr, for which a patent is issued. Once-through boiler competitor Sulzer uses this patent and loses patent suit initiated by Siemens.

- Erosion corrosion and feedwater chemistry: Damage in the preheating and piping areas in nuclear power plants due to erosion corrosion leads to extensive investigations of this phenomenon in the Benson test rig. The results are also of interest for Benson licensees: high chromium content in flow restrictors and in water/steam separators drastically reduces the erosion rates.

The scientific importance of the work on the Benson test systems is evident from the many dissertations based on investigations on these systems.

| Name | Year | Title |
|---|---|---|
| Blank, Günter | 1963 | Measurements of enthalpy differences in steam at pressures of 100 to 400 bar and temperatures of 400 to 700 degrees Celsius |
| Thomas, Dieter | 1974 | Experimental investigation of the deposition of suspended magnetite in flow in boiler tubes and of the effect of magnetite deposits on heat transfer |
| Hein, Dietmar | 1980 | Model projections for rewetting through flooding |
| Köhler, Wolfgang | 1984 | Effect of wetting condition of heat exchange surface on heat transfer and pressure drop in an evaporator tube |
| Kefer, Volker | 1989 | Flow modes and heat transfer in evaporator tubes at different slopes |
| Zheng, Qinghao | 1991 | Frictional pressure drop in gas/liquid flows in smooth and rifled tubes |
| Griem, Harald | 1995 | Thermohydraulic investigations of rifled evaporator tubes |

The research projects are agreed upon with the licensee at the annual licensee conferences, which are introduced in 1975. In these conferences, the latest research and development results, especially from the Benson test rig, are presented to the licensees and information is exchanged about operating results and problems. Future projects are also presented and discussed. The presentations are then compiled in annual R&D reports.

These licensee conferences are initially held only in Erlangen with German-speaking participants. As the interest of international licensees increases, the annual information and exchange of experience is extended to Great Britain, Japan and the USA in the mid '90s.

The focus of further development and research is in the area of "internal heat transfer and pressure drop in tubes":

| | | |
|---|---|---|
| ● | Internal heat transfer in tubes | 25.5% |
| ● | Pressure drop in pipes | 12.1% |
| ● | Flow conditions in parallel piping systems | 10.8% |
| ● | Simulation of dynamic behavior | 7.6% |
| ● | Boiler and power plant concepts | 7.6% |
| ● | Design | 7.0% |
| ● | Miscellaneous | approx. 30.0% |

In the late '80s and early '90s, the split of KWU F (fossil-fired power plants) and KWU R (reactor department) is prepared, in which the test facilities at the Erlangen Süd site are also to be included. In connection with this, F management proposes that the Benson test rig be relocated to the Mülheim manufacturing plant. However, this fails under objection from the Boiler department, as this proposal would not only result in social problems (relocation of employees) as well as significant costs, but would also have entailed significant disadvantages for the Benson license due to the less straightforward connection between testing and implementation.

In the late '70s, Siemens develops a boiler design and calculation program that is initially used internally for licensee consulting. Only Babcock has a similar computer program in Germany. Steinmüller decides to perform calculations with the Siemens program. In the '80s, a completely new program family is then developed for boiler design, based on the latest knowledge ranging from furnace calculation up to determination of the internal heat transfer in the tubes. The DEFOS program for fossil-fired boilers and DEFA for heat recovery steam generators are used by multiple boiler manufacturers within the framework of the license agreements. Further design programs soon give Siemens - with the exception of structural stability analysis programs - computer programs that are at least on par with those of the experienced boiler manufacturers.

Because all previously known control theories for boilers are based on linear mathematical models but the processes taking place in the boiler do not follow linear dependencies, it is decided in 1976 to develop a nonlinear model for boiler dynamics. This is achieved in cooperation with the licensees (especially Steinmüller), Siemens Karlsruhe and the University of Karlsruhe under the management of the Boiler department. Joachim Franke authors his dissertation on this topic, "Investigation of the hydrodynamic stability of evaporator heat exchange surfaces by nonlinear simulation." The basic model development is completed in late 1981. New control concepts for Benson boilers with improved control quality result. The future-oriented model concept is publically recognized in 1987 by the award of the Heinrich-Mandel Prize to Joachim Franke by the Technical Association of Large Power Plant Operators (VGB).

The nonlinear dynamic model is subsequently continuously expanded. A program family is developed with DYNAPLANT for simulating power plant dynamics and DYNASTAB for stability investigations in systems of parallel tubes.

The '90s are characterized by many innovations, especially in the area of evaporator design: The number of patent applications is double that from previous decades.

In 1990, a patent (EP 0 439 765 B1) is filed for a Benson boiler with superimposed circulation. In 1992, tests are also performed with a test wall with vertical tubes in Oslavany power plant, Slovakia. The theoretical investigations are confirmed by the tests financed by Siemens. This technology enables measures such as the cost-effective conversion of existing subcritical drum boilers to once-through boilers.

The construction of Sulzer boilers with vertical tubes and an output of 700 MW in Japan by Mitsubishi causes Siemens to consider the development of a similar concept based on the measurements on rifled tubes. The result is an evaporator with the so-called "low mass flux design" (patent EP 0 581 760 B2). Mass fluxes in this boiler are so low that an increased heat input to individual tubes results in a higher throughput through these same tubes. This positive flow characteristic is verified by tests performed in the furnace of the Farge supercritical 350 MW Benson boiler in 1993 together with Babcock and Steinmüller. Because of the unwillingness of German licensees to take risks, it is not until 2000 that British Mitsui Babcock constructs the first furnace with vertical tube walls (Yaomeng power plant, China).

The low mass flux design concept is met with great interest worldwide: A protracted patent dispute with Sulzer/ABB/Alstom is not resolved in favor of Siemens until 2001. This patent bears crucially in the acquisition of new licensees Ansaldo and Foster Wheeler and extension of the license contracts with Babcock USA and Babcock-Hitachi.

A gas turbine boom begins in the '90s. The horizontal heat recovery steam generators for the gas turbine/steam turbine power plants are constructed nearly exclusively with natural and forced circulation systems. In 1997, Siemens develops a horizontal Benson heat recovery steam generator with nearly the same steam outlet conditions despite differing heat input for evaporator tubes configured in parallel on the water side and in series on the exhaust gas side (patent EP 0 944 801 B1). Many manufacturers of heat recovery steam generators acquire a patent license - even once-through boiler competitor Alstom.

A further key development is the fossil-fired boiler with a horizontal furnace (patent EP 1 086 339 B1). Its advantages lie in cost savings for the boiler frame, assembly and connecting lines between the boiler and turbine as well as ease of maintenance. This concept meets with great interest in the "700 °C power plant" research project.

In late 2004, Joachim Franke is honored as the "inventor of the year" for his contribution to the "success story of the Benson boiler". With this award, company management recognizes and emphasizes to the public the innovative activities of the Boiler department that have been increasing since the '90s and the resulting economic success.

### Research and development from 2004 to 2018

Further tube testing is performed in the Benson laboratory in Erlangen to close the last gaps in knowledge of heat transfer and pressure drops in smooth tubes and rifled tubes.

Extensive test series investigated heat transfer in smooth tubes at a slope of 18° from the horizontal typical for spiral tubing and with side heating from one side, the configuration of a furnace hopper tube with a 45° slope and heating on only one side from above and a vertical tube with minimum mass flux.

The test series are rounded out with tests on a highly optimized rifled tube and investigations of heat transfer and pressure drop in smooth tubes with inserts. Overall, more than 307,000 measurements of heat transfer and pressure drop in smooth tubes and more than 285,000 measurements on rifled tubes are available by late 2017.

The aforementioned inserts also represent a development in the framework of the Benson license. The angular momentum on the water side is generated by wire coils inserted in a smooth tube. The main advantage here is that the cold drawing process for producing the rifling is avoided. Cold-drawn rifling can only be produced in materials with a maximum chromium content of 5%. The inserts can be installed in smooth tubes of any material and result in an internal heat transfer equivalent to that in an optimized rifled tube.

A further focal point is of the investigations is the dynamic stability of evaporator flow. Starting in 2014, investigations in dynamic stability are performed in a test setup with three vertical smooth tubes connected in parallel. This setup enables the reproducible generation and observation of dynamic instabilities in vertically configured heated tubes with a geometry typical for Benson evaporators under laboratory conditions for the first time in the world. The purpose of the tests is to destabilize an initially stable flow in the tubes by changing a parameter and to generate a sustained mass flow oscillation. This stability threshold is investigated in many measurement periods with variation of the parameters of pressure, mass flux, subcooling at the inlet and superheating at the outlet.

The results from these tests are used for further validation of the dynamic stability programs.

All of the Benson programs are given modern interfaces and the software architecture is extended. The Stade program for calculating pressure drop in individual tubes gives rise to the StadeNet program for calculating pressure drop and the flow distribution in networks.

A further important development is the Wathan program for calculating stresses and the temperature distribution in evaporator walls. The code automatically performs an OpenFOAM calculation (finite volume method) for any fin and tube geometry and any operating conditions.

In the area of the heat recovery steam generator, the formulas for calculating pressure drop and heat transfer are integrated in the KRAWAL program. The DynaplantBENSON program grows out of the original Dynaplant. Both programs are given to licensees together with comprehensive design manuals in the framework of the Benson license for heat recovery steam generators.

The development of suitable control concepts takes on increasing importance in the area of the Benson heat recovery steam generator, also resulting in many patents.

## 8. Milestones in technical development

With the Benson boiler, Siemens has set many milestones in boiler development as well as in power plant development around the world:

| | |
|---|---|
| 1926 | World's first industrial once-through boiler in Siemens Berlin-Gartenfeld power plant field with pulverized coal firing as a tower boiler for outdoor construction. Steam output 30 t/h, 180 bar/450 °C, manufacturer: Siemens |
| 1926 | First operation of a Benson boiler at subcritical pressure in the test boiler at the Technical University of Berlin |
| 1927 | Introduction of spiral furnace tubing in boiler construction of Benson boiler 2 in the Siemens Berlin-Gartenfeld power plant. Steam output 37.5 t/h, 190 bar/465 °C, manufacturer: Siemens |
| 1929 | World's first Benson marine boiler on MV Uckermark. Steam output 24 t/h, pressure in evaporator 225 bar, superheater outlet 70 bar/445 °C. The boiler is converted to subcritical pressure in the evaporator in 1934 |
| 1929 | World's first high-capacity once-through boiler in Langerbrügge power plant, Belgium, this ranks among the largest plants of its time. Steam output 125 t/h, 190 bar/470/40 °C, manufacturer: Siemens |
| 1933 | Introduction of sliding pressure operation by Hans Gleichmann |
| 1949 | First once-through boiler in the world with maximum steam temperature of 610 °C in a power plant in the Bayer paint plant in Leverkusen. Steam output 125 t/h, 160 bar/610 °C, manufacturer: Dürrwerke |
| 1954 | World's first once-through boiler (Benson) with maximum steam conditions of 300 bar/605 °C and |

| | |
|---|---|
| | double reheat 565/565 °C in the Hüls chemical plants. Steam output 250 t/h. Manufacturer: Dürrwerke |
| 1954 | World's first once-through boiler for two units of 150 MW each in RWE power plant, Fortuna. Steam output 2 x 450 t/h, 181 bar/530/530 °C, manufacturer: Steinmüller/Walther |
| 1956 | First Benson boiler (UP) with gas-tight welded walls in Breed power plant of the American Electric Power Corp, Steam output 1,350 t/h, 181 bar/565/565/565 °C, manufacturer: Babcock USA |
| 1960 | World's first non-masonry once-through boiler with gas-tight welded staged spiral furnace tubing in Drakelow C power plant, England. Steam output 1,350 t/h, 255 bar/600/568 °C, manufacturer: Babcock London. This design remains unique |
| 1960 | World's first non-masonry once-through boiler with spiral furnace tubing (skin casing) in Civitavechia power plant, Italy. Steam output 660 t/h, 210 bar/540/540 °C, manufacturer: Ansaldo |
| 1962 | World's first once-through boiler in a coal-fired combined-cycle unit in Hohe Wand power plant, Austria. Steam output 215 t/h, 180 bar/535/535 °C, manufacturer: Waagner-Biro |
| 1962 | World's first once-through boiler in a $CO_2$-cooled nuclear power plant in Oldsbury, England, steam output 1,400 t/h, 105 bar/393/393 °C manufacturer: Clark, Chapman |
| 1963 | World's first oil-fired once-through boiler with gas-tight welded spiral tubing in Rodiaceta power plant, steam output 90 t/h, 115 bar/530 °C, manufacturer: VKW |
| 1963 | First high-output Benson boiler in Japan in Tokyo Denryoku power plant, steam output 590 t/h, 190 bar/543/540 °C. Manufacturer: Yokoyama |
| 1964 | First 1000 t/h boiler in Germany in Frimmersdorf power plant, 190 bar/530/530 °C, manufacturer: Deutsche Babcock with Buckau R. Wolf (Sulzer licensee) |
| 1966 | World's first coal-fired once-through boiler with gas-tight welded spiral tubing in two-pass design in Farge power plant, steam output 930 t/h, 250 bar/545/545 °C, manufacturer: Deutsche Babcock |
| 1968 | World's largest once-through boiler (UP) for the two 1,300 MW coal-fired units in Cumberland power plant, USA, steam output of 4,540 t/h (10,000 lb/h) each, 240 bar/540/540°C. Manufacturer: Babcock USA |
| 1969 | World's first high-capacity once-through boiler at a gauge pressure of 7 bar on the exhaust gas side in Lünen power plant. The boiler heat exchange surfaces are configured in the two combustors of a gas turbine. Steam output 312 t/h, 135 bar/525 °C, manufacturer: Dürrwerke |
| 1970 | RWE decides to implement Benson boilers in the six largest lignite-fired units in the world in Neurath, Niederaußem and Weisweiler power plants. Boiler height: 110 m with a combustion zone cross section von 20 x 20 m. Steam output 1,870 t/h each, 175 bar/530/530 °C, manufacturer: Borsig, Deutsche Babcock, Dürrwerke, MAN, Steinmüller, VKW and Walther |
| 1970 | Benson boilers for the six largest natural-gas fired combined-cycle units in the world in Firstinwerk and Lingen power plants. The exhaust gases from each 50 MW gas turbine serve as the oxygen carrier (18% $O_2$) for a boiler. Steam output 6 x 1,032 t/h, 190 bar/535/535 °C, manufacturer: Dürrwerke und Steinmüller |
| 1971 | Benson boilers for the two largest oil-fired units in Europe in Scholven power plant, steam output 2 x 2,120 t/h, 200 bar/530/530 °C. Manufacturer: Borsig und Steinmüller |
| 1972 | Benson boiler for the largest pulverized-coal fired unit in Europe in Wilhelmshaven power plant (720 MW), steam output 2,170 t/h, 190 bar/530/530 °C, manufacturer: Deutsche Babcock |
| 1982 | World's first once-through boiler with fluidized bed firing in Duisburg cogeneration plant, steam output 265 t/h, 160 bar/535/535 °C manufacturer: Deutsche Babcock |
| 1999 | World's first once-through heat recovery steam generator with vertical tubing and positive flow characteristic in Cottam power plant, England. Steam output 315 t/h, 190 bar/580 °C, manufacturer: Deutsche Babcock |
| 2000 | 1000th Benson boiler order received |
| 2002 | World's first once-through boiler with vertical tubing and positive flow characteristic in Yaomeng power plant, China. Steam output 936 t/h, 190 bar/540/540 °C, manufacturer: Mitsui Babcock |
| 2003 | World's first supercritical once-through boiler with fluidized bed firing and positive flow characteristic in Lagisza power plant, Poland. Steam output 1,295 t/h, 275 bar/560/580 °C, manufacturer: Foster Wheeler |
| 2007 | Order for the first supercritical Benson boiler with vertical tubing in Longview, USA.<br>First orders for supercritical Benson boilers with vertical tubing for firing with anthracite in China. |
| 2013 | Commissioning of the world's largest supercritical boiler with circulating fluidized bed in Baima, China at 600 MW |
| 2014 | Successful measurements of dynamic instabilities in a three-tube test in the Benson laboratory in Erlangen |
| 2018 | Commissioning of the first Benson heat recovery steam generator with vertical gas path in megaprojects in Egypt |

## 9. Spread of the Benson boiler around the world

After the Second World War, the Benson boiler quickly spread throughout the entire world, as can be seen in the table:

| Year | Country | Power plant | Output (t/h) | Manufacturer: |
|---|---|---|---|---|
| 1929 | Belgium | Langerbrügge | 125 | Siemens |
| 1939 | Italy | Genoa | 25 | Ansaldo |
| 1940 | CSSR | Banska Hutni Trinec | 62 | Walther |
| 1954 | Japan | Makiyama Works | 75 | Yokoyama |
| 1954 | USA | Philo | 306 | Babcock & Wilcox |
| 1955 | Austria | St. Andrä | 330 | SGP |
| 1956 | Great Britain | Margam | 110 | Simon-Carves |
| 1956 | Netherlands | Buggenum | 280 | Stork |
| 1957 | Denmark | Asnaesvaerket | 400 | Burmeister & Wain |
| 1957 | Poland | Blachownia | 240 | SGP |
| 1958 | Spain | Las Palmas | 8 | Deutsche Babcock |
| 1964 | Romania | Fintinele | 400 | Dürrwerke |
| 1966 | Korea | Pusan | 400 | Dürrwerke |
| 1967 | Philippines | Gardner | 742 | Babcock-Hitachi |
| 1967 | Yugoslavia | Sostanj | 860 | Deutsche Babcock |
| 1969 | Finland | Vaskiluoto | 510 | VKW |
| 1971 | Ireland | Tabert | 800 | MAN |
| 1971 | South Africa | Kriel | 1.585 | Steinmüller |
| 1971 | Sweden | Uppsala | 700 | Burmeister & Wain |
| 1972 | Argentina | Sorrento B | 515 | Babcock London |
| 1974 | Taiwan | Kaohsiung | 245 | Kawasaki |
| 1974 | Turkey | Afsin-Elbistan | 1.020 | VKW/Deutsche Babcock |
| 1975 | Iran | Mazandaran | 1.410 | Deutsche Babcock |
| 1978 | Australia | Northern Power Station | 990 | VKW |
| 1979 | China | Yuan Bao Shan | 1.845 | Steinmüller |
| 1981 | Brazil | Jorge Lacerda | 1.000 | Deutsche Babcock |
| 1984 | Greece | Megalopolis | 910 | VKW |
| 2000 | India | Neyveli | 735 | AE & E |

BENSON boilers in the USA

The average output of fossil-fired units increases sharply in the '60s and '70s, from approx. 200 MW (1960) to 600 MW (1970). The first 1,300 MW unit is ordered in 1967. A design for supercritical pressure is expedient for this increased capacity to prevent extreme increases in the diameter of the headers, lines, valves and turbine casing.

Maximum unit output increases by 200 MW every two years from 700 MW (1961) to 1,300 MW (1967). It is therefore impossible to account for operating experience in designing each successive unit size. The result is a drastic drop in availability of the supercritical units; cost-effectiveness drops in comparison with subcritical units. According to experts in the field, the low availability is not a result of the once-through boiler technology, but rather is caused by other factors, especially in the firing:

- Underdimensioned combustion zones with very high stresses in the burner rows result in heavy slag deposits, especially for coals from the Midwest
- The transition to pressurized firing, also in coal-fired boilers, necessitates plant shutdown already for small leaks in the enclosure walls

- High steam temperatures of 566 °C and double reheat require complex startup systems and long startup times
- Fixed-pressure operation places stresses on the turbine valves and results in maintenance issues

The operators therefore return to subcritical units with drum boilers, with the result that new orders for this power plant type increase from a share of 35% to over 80% in the '70s.

By 2005, 147 UP boilers are constructed in the USA. However, the European Benson boiler design with spiral tubing and sliding pressure operation cannot gain a footing in the USA.

### BENSON boilers in Japan

American boiler manufacturers introduce the American supercritical once-through boiler design in the early '60s:

- Babcock & Wilcox Co., UP boiler with Babcock-Hitachi K. K. as licensee. 24 UP boilers are constructed, most of which with gas or oil firing.
- Combustion Engineering Inc., the combined circulation boiler with Mitsubishi Heavy Industries Ltd. as licensee and
- Foster Wheeler Corp. the multi-pass-boiler with Ishikawajima Harima Heavy industries Co. Ltd. as the licensee.

The increase in nuclear power plants displaces fossil-fired power plants to the intermediate load range. However, the American plants, which are operated in fixed pressure mode and require long startup times, are less suitable for this. With the successful operation of the first supercritical Benson boiler with spiral tubing and sliding pressure operation in the mid '70s in the Tokyo Electric Power Ohi power plant, interest in European power plant technology increases in Japan, thus resulting in penetration by the Benson boiler in the '80s supported by Siemens Acquisition.

### BENSON boilers in China

Steinmüller constructs the first Benson boiler in China in 1979, in Yuan Bao Shan power plant. After several years of startup issues due among other things to the use of coals outside of the agreed range and the poor quality of parts from non-German suppliers, this boiler achieves the highest availability of all comparable plants in China in the mid-'90s

After Deutsche Babcock and Steinmüller receive further orders for Benson boilers in the intermediate output range in the '90s, the rapid industrialization of China necessitates the construction of many high-capacity coal-fired power plants. The decision falls to European technology for the new power plants: Once-through boilers with spiral tubing, sliding pressure operation and cost-effective startup systems. With the Chinese sublicensees of Babcock-Hitachi Dongfang Boiler Co., Ltd., Babcock & Wilcox Beijing Company, Harbin Boiler Co., Ltd. and with the direct license to Dongfang Boiler Group Co. Ltd. the Benson boiler also dominates the Chinese market.

## 10. The Benson marine boiler

The Benson boiler also proves itself as a marine boiler. A riser/downcomer system is implemented for the first time aboard the MV Uckermark in 1929; this will remain the preferred evaporator design up to the early '60s.

In addition to the 20 units for commercial vessels in the reference list with an overall steam output of 192 kg/s ([23], [26], [34], [44], [48], [50], [52], [80]) more than 60 Benson boilers are implemented in vessels of the German Navy. The number of Benson boilers verifiably constructed for vessels of the German Navy (all of the boilers are oil-fired) is based on two sources ([44], [63])

| Ship | Year | Manu-facturer | Steam output t/h | Press. bar | Temp. °C | Ref. |
|---|---|---|---|---|---|---|
| Destroyer Z9 Wolfg. Zenker | 1934 | Germania werft | 6 x 35 | 138 | 450 | [46], [66] |
| Destroyer Z10 Hans Lody | 1934 | Germania werft | 6 x 35 | 138 | 450 | [46], [66] |
| Destroyer Z11 Bernd von Arnim | 1935 | Germania werft | 6 x 35 | 138 | 450 | [46], [66] |
| Destroyer Z12 Erich Giese | 1935 | Germania werft | 6 x 35 | 138 | 450 | [46], [66] |
| Destroyer Z13 Erich Koellner | 1935 | Germania werft | 6 x 35 | 138 | 450 | [46], [66] |
| Destroyer Z14 Friedrich Ihn | 1935 | Blohm +Voss | 6 x 35 | 138 | 450 | [46], [66] |
| Destroyer Z15 Erich Steinbrinck | 1935 | Blohm +Voss | 6 x 35 | 138 | 450 | [46], [66] |
| Destroyer Z16 Friedrich Eckoldt | 1935 | Blohm +Voss | 6 x 35 | 138 | 450 | [46], [66] |
| Escort F7 | 1934 | Blohm +Voss | 2 boilers | | | [46], [66] |
| F7 class escorts (add.) | 1934 | Blohm +Voss | 4 x 2 boilers *) | | | [46] |
| Escort F8 | 1934 | Blohm +Voss | 2 boilers | | | [46], [66] |
| Escort G1 | 1941 | unknown | 3 boilers | 28 | | [66] |
| Total | 55 or 63 boilers *) | | | | | |

*) There is a discrepancy here between [46] und [66]: According to Franzen [46], six vessels of the F7 class are equipped with Benson boilers; according to Gröner [66] there are only two.

## 11. Competition for the Benson boiler

The Sulzer boiler

Sulzer evidently follows the development activities of Siemens, especially with regard to feedwater quality issues, and appears in public with a test boiler in 1929. This boiler differs from the Benson boiler in a key characteristic. It is equipped with a separator or water collecting vessel downstream of the evaporator, in which approx. 5% of the evaporator flow is blown down as water with a high salt content, as in a drum boiler. The Sulzer boiler thus loses two significant operating advantages of the Benson boiler. Because of the fixed evaporation end point, HP steam temperature is a function of the load, fuel, excess air and fouling condition of the heat exchange surfaces. Furthermore, operation is only possible at subcritical pressures. A second difference lies in the throttle valves at the inlet to the evaporator tubes to balance the throughput through the individual parallel tubes. Because the test boiler has only one evaporator tube, Sulzer henceforth uses the term "monotube boiler".

|  | Year | Benson boiler | Year | Sulzer boiler |
|---|---|---|---|---|
| Pilot plant | 1924 | Rugby | 1929 | Sulzer |
| 1st industrial boiler | 1926 | Berlin-Gartenfeld | 1931 | C. Weber |
| 1st boiler > 100 t/h | 1929 | Langerbrügge | 1938 | Mannheim |
| 1st gas-tight welded spiral tubing | 1963 | Rhodiaceta | 1966 | Vaesteras |
| Thermoelastic startup system with separate separators | 1964 | Badalona II | 1975 | Bremen |
| Number of boilers constructed (status 1995) |  | 977 |  | ≈ 320 *) |

*) The Sulzer reference list also includes more than 120 controlled circulation or combined circulation boilers that do not fulfill the criterion of a once-through boiler

The two boiler types differ in design of the furnace tubing up to the early '60s: In the Benson boiler, the riser/downcomer system is used, with meandering coil tubing in individual cases, while Sulzer uses only meandering coil tubing.

The Sulzer boiler becomes the main competitor for the Benson boiler. Initial licensees in Germany are KSG (Kohlenscheidungsgesellschaft GmbH) and Buckau R. Wolf, which becomes Walther & Cie. in connection with the acquisition of EVT (Energie- und Verfahrenstechnik GmbH) in 1975. These are followed later by Benson licensee MAN.

A comparison shows that Siemens always maintains a technological lead in the area of the once-through boiler:

In 1975, Veba Kraftwerke Ruhr AG forces boiler supplier EVT to abandon the Sulzer principle of a fixed evaporation endpoint for the 740 MW Scholven F boiler and to adopt the Benson principle of a variable evaporation endpoint. With this decision, the Sulzer principle also quickly loses importance for other power plant operators and is soon no longer used. Sulzer and its licensees adopt the Benson principle.

The Ramsin boiler

In the early '30s, an assistant from the Institute of Thermal Engineering at the University of Moscow (whose director is Prof. L. K. Ramsin) is employed in the Siemens Boiler department. After his return, he later designs and constructs the first once-through boiler in the USSR, which is called the "Ramsin boiler". Its design data are 200 t/h, 140 atm/480 to 500 °C/400 °C.

This boiler is commented on as follows in the journal "Archiv für Wärmewirtschaft und Dampfkesselwesen," Volume 9/1936:

- Th. Sauer: Advances have been made in Russian boiler design in recent years. This can be seen from the example of a special boiler constructed based on German development work.
- Siemens: ... the design is equivalent to that of the Benson boiler, which has apparently served as an example.

The UP boiler

The Universal Pressure boiler (UP boiler) from American Benson licensee Babcock & Wilcox Comp. is based on the original concept of Mark Benson for steam generation at supercritical pressure. However, in this case the supercritical pressure is chosen to prevent stratification at the entrance to the heat exchange surfaces in the three stages of the riser/downcomer system. The first UP boiler is constructed after conclusion of the Benson license agreement in 1954 in Breed power plant, USA. It represents a milestone in boiler development with its gas-tight welded enclosure walls.

In the '60s and '70s, the market for fossil-fired power plants develops rapidly in the USA; over 50% are ordered as supercritical units with once-through boilers. Unit size grows so quickly that it is not possible to account for operating results in each successively larger unit size. The result is a drastic drop in availability of the supercritical units. This is exacerbated by the advance of nuclear power; fossil-fired power plants are relegated to the intermediate load range. The importance of the UP boiler declines for this reason as well, since it is poorly suited to sliding-pressure operation. The last UP boiler is constructed in 1985 in Zimmer power plant, USA.

Babcock & Wilcox Comp. and its UP licensees Babcock Power Ltd. and Babcock-Hitachi K.K. have constructed a total of 171 UP boilers, including the world's largest boiler in Cumberland power plant, USA with an output von 4,540 t/h.

### The combined circulation boiler

The combined circulation boiler from Combustion Engineering Inc. is marketed as a combination of a forced circulation and once-through boiler, but in principle it is a supercritical forced circulation boiler. The licensee in Japan is Mitsubishi Heavy Industries Ltd. The combined circulation boiler is no longer constructed for the same reasons as the UP boiler.

### The multi-pass boiler

The multi-pass boiler from Foster Wheeler Inc. is based on the same technical concept as the UP boiler. The licensee in Japan is Ishikawajima-Harima Heavy Industries Co. Ltd. This boiler type is also no longer constructed for the aforementioned reasons.

## 12. License revenues

Only general data can be accessed for license income and expenditures up to the 1949/1950 fiscal year:

- Up to 1933, license fees totaling Sfr. 250,000 are offset by development costs in the amount of Sfr. 3,750,000. Approx. DM 3,500,000 are also used for construction of the Benson boiler in a power plant (probably Berlin-Gartenfeld).
- As a result of royalty payments received up to late 1944, the negative balance of the Benson account is reduced from 2,500,000 to 750,000 Reichsmark.

License fees are paid again starting from the 1949/1950 fiscal year. However, the balance of the Benson account remains negative until the mid '50s. Only after this does the Benson license begin to be a financial success for Siemens. However, the business result is always positive with the exception of two fiscal years in which construction of the second Benson test rig must be financed. This is further supplemented by orders for power plants and power plant components that Siemens receives due to its boiler expertise. However, these are not quantifiable.

## 13 Key persons

The following persons were or are active in responsible positions for the Benson license at Siemens over the past more than 90 years:

| | |
|---|---|
| Karl Köttgen: | General manager, takes the decision to build Benson boilers |
| Hans Gleichmann | Head of Steam department AZ7 from the start of Benson boiler activities in 1923 up to 1944 |
| Martin Eule | Head of design in the Boiler department from the start of Benson boiler activities in 1923 until the '50s(?) |
| Heinz Rabe | Head of heat engineering analysis in the Boiler department from the start of Benson boiler activities in 1923 up to 1942(?) |
| Rupprecht Michel | 1948 – 1973: Initially head of the Boiler department later division head for all mechanical engineering |
| Elmar Kefer | 1968 – 1973: Head of the Boiler department, died in 1973 at the age of 48 |
| Eberhard Wittchow | 1974 – 1995: Head of the Boiler department, later of the central Engineering department for conventional plants, consultant for steam power plants from 1995. Responsible for the Benson license over the entire period |
| Georg Lösel | 1974 – 1984: Head of the Benson boiler development department and licenses |
| Joachim Franke | from 1989: Initially consultant for Benson boilers, from 1995 head of the central department for conventional boilers, from 2001 senior consultant for Benson boilers |
| Rudolf Kral | from1996, consultant for Benson boilers |
| Jan Brückner | from 2010, responsible for the Benson license and technical development of the Benson heat recovery steam generator as principle expert in Benson technology |
| Martin Effert | from 2010, head of the Benson engineering department, which is continued as a process engineering group in global engineering from 2017. |

Heads of the Benson test rig:

| | |
|---|---|
| Karl-Rudolph Schmidt: | in the '50s and '60s |
| Dietmar Hein: | 1974 – 1982 (construction of the 2nd Benson test rig) |
| Bernhard Brand: | 1982 – 1989 |
| Wolfgang Kastner: | 1989 – 2001 |
| Holger Schmidt: | from 2001 |
| Wolfgang Köhler: | Advisor for the Benson test rig to 1999 |
| Oliver Herbst: | Advisor for the Benson test rig from 1999 |

Responsible for the Benson license in the Patent and Legal department:
Mr. Weller, Mr. Feist, Burghard v. Alvensleben, Peter Knorr, Thomas Bühlmeyer, Dr. Thomas Roth, Michael Schmid

## 14. Status of the Benson license in 2018

The interest of boiler manufacturers around the world in the Benson license remains unchanged.
This is based on use of the Siemens patents but also on its expertise. The current Benson license agreements extend in part up to 2030 (fossil-fired Benson boilers) or to 2023 (Benson heat recovery steam generators).

The following manufacturers currently have a license for fossil-fired Benson boilers:

| | |
|---|---|
| AC Boilers S.p.A. | Italy |
|  Ansaldo Caldaie Boilers India Pvt. Ltd. | India |
| Babcock & Wilcox Power Generation Group[*1] | USA |
|  Thermax Babcock & Wilcox Energy Solutions Pvt. Ltd. | India |
| Dongfang Boiler Group Co. Ltd. | China |
| Doosan Babcock Ltd. | Great Britain |
|  Doosan Heavy Industries & Construction Co. Ltd. | Korea |
|  Harbin Boiler Co. Ltd. | China |
| Sumitomo SHI FW | Finland |
| BHI FW Corporation | USA |
|  Shanghai Boiler Works Co. Ltd. | China |
|  BHI Co. Ltd. | Korea |
|  ISGEC Heavy Engineering Ltd. | India |
| Mitsubishi Hitachi Power Systems Europe GmbH | Germany |
|  BGR Boilers Pvt. Ltd. | India |
| Rafako S.A. | Poland |
| Riley Power Inc. | USA |
| Shanghai Boiler Works Co. Ltd. [*2] | China |
| PJSC TKZ "Krasny Kotelshchik" | Russia |

Direct license
 Sublicense
1: Main license ended, sublicense in force
2: Limited to CFB boilers

The following manufacturers currently have a license for Benson heat recovery steam generators:

| | |
|---|---|
| AC Boilers S.p.A. | Italy |
| CMI SA | Belgium |
| Amec Foster Wheeler Energía S.L.U. | Spain |
| IHI Corporation | Japan |
| Innovative Steam Technologies | Canada |
| NEM Energy b.v. | Netherlands |
|  GS Entec Corp. | Korea |
| Nooter/Eriksen Inc. | USA |
| Hansol SeenTec Co. Ltd. | Korea |
| S&T Corporation | Korea |
| Vogt Power International Inc. | USA |

Direct license
 Sublicense

## 15 Reference lists

The reference lists for fired Benson boilers as well as for Benson heat recovery steam generators are updated once a year. They are available for download in the internet on the homepage of the Benson license and Benson technology: http://www.siemens.com/benson

## 16 Steam capacity fired Benson boiler orders

| Year | Steam capacity per year (kg/s) | Accumulated steam capacity (kg/s) |
|---|---|---|
| 1926 | 20,00 | 20,00 |
| 1927 | 0,00 | 20,00 |
| 1928 | 0,00 | 20,00 |
| 1929 | 41,39 | 61,39 |
| 1930 | 0,00 | 61,39 |
| 1931 | 0,00 | 61,39 |
| 1932 | 0,00 | 61,39 |
| 1933 | 27,78 | 89,17 |
| 1934 | 0,00 | 89,17 |
| 1935 | 116,66 | 205,83 |
| 1936 | 165,28 | 371,11 |
| 1937 | 546,39 | 917,50 |
| 1938 | 611,78 | 1.529,28 |
| 1939 | 581,94 | 2.111,22 |
| 1940 | 123,89 | 2.235,11 |
| 1941 | 305,56 | 2.540,67 |
| 1942 | 17,50 | 2.558,17 |
| 1943 | 322,22 | 2.880,39 |
| 1944 | 0,00 | 2.880,39 |
| 1945 | 0,00 | 2.880,39 |
| 1946 | 0,00 | 2.880,39 |
| 1947 | 41,47 | 2.922,06 |
| 1948 | 88,89 | 3.010,94 |
| 1949 | 355,56 | 3.366,50 |
| 1950 | 80,00 | 3.446,50 |
| 1951 | 50,00 | 3.496,50 |
| 1952 | 395,28 | 3.891,78 |
| 1953 | 416,67 | 4.308,44 |
| 1954 | 1.536,94 | 5.845,39 |
| 1955 | 641,39 | 6.486,78 |
| 1956 | 2.458,33 | 8.945,11 |
| 1957 | 1.504,72 | 10.449,83 |
| 1958 | 1.957,22 | 12.407,06 |
| 1959 | 3.174,17 | 15.581,22 |
| 1960 | 4.359,72 | 19.940,94 |
| 1961 | 3.266,50 | 23.207,44 |
| 1962 | 6.033,89 | 29.241,33 |
| 1963 | 9.638,06 | 38.879,39 |
| 1964 | 7.815,56 | 46.694,94 |
| 1965 | 7.971,11 | 54.666,06 |
| 1966 | 8.473,33 | 63.139,39 |
| 1967 | 13.672,50 | 76.811,89 |
| 1968 | 15.772,50 | 92.584,39 |
| 1969 | 10.591,39 | 103.175,78 |
| 1970 | 7.549,67 | 110.725,44 |
| 1971 | 18.165,44 | 128.890,89 |
| 1972 | 8.101,94 | 136.992,83 |
| 1973 | 5.869,22 | 142.862,06 |
| 1974 | 3.036,22 | 145.898,28 |
| 1975 | 7.140,67 | 153.038,94 |
| 1976 | 5.608,61 | 158.647,56 |
| 1977 | 7.554,50 | 166.202,06 |
| 1978 | 729,44 | 166.931,50 |
| 1979 | 6.323,00 | 173.254,50 |
| 1980 | 1.902,50 | 175.157,00 |
| 1981 | 6.682,78 | 181.839,78 |
| 1982 | 1.953,06 | 183.792,83 |
| 1983 | 4.992,78 | 188.785,61 |
| 1984 | 2.821,89 | 191.607,50 |
| 1985 | 1.768,00 | 193.375,50 |
| 1986 | 1.657,00 | 195.032,50 |
| 1987 | 1.607,83 | 196.640,33 |
| 1988 | 899,94 | 197.540,28 |
| 1989 | 533,89 | 198.074,17 |
| 1990 | 416,94 | 198.491,11 |
| 1991 | 1.805,00 | 200.296,11 |
| 1992 | 2.926,94 | 203.223,06 |
| 1993 | 1.746,11 | 204.969,17 |
| 1994 | 2.864,89 | 207.834,06 |
| 1995 | 663,00 | 208.497,06 |
| 1996 | 833,00 | 209.330,06 |
| 1997 | 582 | 209.912,06 |
| 1998 | 834,00 | 210.746,06 |
| 1999 | 2.368,60 | 213.114,66 |
| 2000 | 2.054,00 | 215.168,66 |
| 2001 | 403,00 | 215.571,66 |
| 2002 | 1056,00 | 216.627,66 |
| 2003 | 27874,00 | 244.501,66 |
| 2004 | 14085,80 | 258.587,46 |
| 2005 | 10963,60 | 269551,06 |
| 2006 | 9776,80 | 279.327,86 |
| 2007 | 12951,30 | 292.279,16 |
| 2008 | 14001,40 | 306.280,56 |
| 2009 | 13699,92 | 319.980,48 |
| 2010 | 18482,66 | 338.463,14 |
| 2011 | 10172,00 | 348.635,14 |
| 2012 | 20324,00 | 368.959,14 |
| 2013 | 10288,80 | 379.247,94 |
| 2014 | 16805,17 | 396.053,11 |
| 2015 | 11349,10 | 407.402,21 |
| 2016 | 2879,10 | 410.281,31 |
| 2017 | 7570,60 | **417.851,91** |

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