High-Pressure Test Facility - 25 Years of Operation*

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Introduction
A high-pressure test facility which is installed in an accredited laboratory at Framatome ANP in Erlangen, Germany and is unique throughout the world due to its wide range of operating conditions – called the BENSON test rig – is now celebrating its 25th anniversary. This is an exceptional event for any test facility and marks a good occasion for taking a look at the tests and research work that have been performed at the test rig in order to demonstrate its broad range of applications. The results of this work have frequently served as a basis for developing design tools as well as for finding solutions to issues related to power plant operation. As the name of the test rig implies, its main purpose is to investigate topics associated with the operation and further development of BENSON boilers. In addition to this, the test facility is also used for issues related to power generation using nuclear and renewable energy sources. However, before details are given of examples of past projects, a brief description of the test rig will first be presented below.

A High-Pressure Test Facility – The BENSON Test Rig
In its role as a licensor for BENSON boilers, Siemens Power Generation responded in 1973/74 to the need for supplementary research and development work in this field by making the foresighted decision to set up a new test facility with wide-ranging capabilities. The BENSON test rig – in operation since 1975 – has been used for investigating numerous topics and has been continually adapted to new developments in science and technology. Its range of operating conditions is based on the service requirements of BENSON boilers and raw-gas heat-recovery steam generators. The test rig’s design data are:

- System pressure: 330 bar
- Temperature: 600 °C
- Mass flow: 28 kg/s
- Heating capacity: 2000 kW.

The test facility mainly comprises – see Figure 1 – a water supply system, the object to be tested, a pressurizer and a cooling system. In the water supply system, demineralized and deaerated water or boiler feedwater to which chemicals have been added to obtain the required water chemistry is provided in a feedwater tank. This water is injected into the test loop by a piston pump. To minimize flow oscillations caused by the pump’s six pistons, a damping vessel is installed in the pump discharge line.

![Flow diagram of BENSON test rig](image)

Fig. 1: Flow diagram of BENSON test rig

The water is heated in a main heater to establish the thermodynamic flow conditions required at the inlet to the test object. This coil-type heater is designed for direct electric heating; i.e. an electric current flows through the wall of the coil which acts as a resistor and is thereby heated. The advantage of this heating method is that it allows precise control of the heat added to the fluid. This is particularly important in connection with the development of heat transfer and pressure drop correlations. Experiments using other methods such as radiation heating (performed perhaps directly in a power plant) are less suitable for such tasks since precise determination of fluid enthalpy or of actual heat input is more difficult.

After the fluid has passed through the main heater it enters the test section, which is likewise equipped for direct electric heating. Here the flow and heat transfer conditions are simulated and monitored. Depending on the task in hand, the test object can consist of various kinds of tubes and vessels. Further details will be provided when the applications for which the test rig has been employed are described below.

Installed downstream of the test object is a spray-type condenser for condensing the steam fraction and subcooling the fluid. The subcooled fluid then passes to a circulation pump which recirculates part of the flow for cooling the spray condenser. Condenser cooling water is taken from the main flow immediately downstream of the pump as well as from the main cooler which is supplied on its secondary side with water from a wet cooling tower (trickle cooler).
System pressure is adjusted by a large thermal pressurizer and a throttling valve (pressure-reducing valve) downstream of the test object. Assurance of a constant pressure is particularly important for investigations performed near the critical pressure since pressure fluctuations can affect heat transfer conditions in the test object.

If the mass flow exiting the test loop is smaller than that supplied by the piston pump, the level of water inside the pressurizer initially rises. This does not, however, lead to any increase in system pressure since the steam cushion provided inside the pressurizer is compressible. The rise in water level is, however, used as a process control variable to open the pressure-reducing valve at the end of the test loop.

If large mass flows are required for certain investigations, the test rig can be operated in the recirculation mode. In this case the water is not injected into the test loop by the piston pump, as when the test rig is operating in the once-through mode, but is recirculated by the circulation pump instead.

The entire test facility is made of austenitic stainless steel and is thermally insulated by means of an approximately 50-mm-thick layer of rockwool. Figure 2 provides a view of part of the test facility and some of its major components.

The BENSON test rig as well as the test object are instrumented in such a way that all relevant parameters such as temperature, pressure and flow can be measured.

Data acquisition and process visualization play a key role for recording and monitoring the individual experiments. The diagram in Figure 3 shows the equipment and procedure employed for data acquisition and processing.

The data measured throughout the test rig and at the test object are recorded by state-of-the-art data acquisition systems. A description is given below of the temperature measuring instrumentation as an example.

The thermocouples measure the temperatures and convert them to analog signals in units of millivolts. These signals are passed via a connector board to an instrument amplifier in which they are amplified to a level of 0 to 5 volts. The amplifier then transmits them to an analog/digital converter (ADC). The digital signals output by the converter can subsequently be further processed in SI units at a PC and stored.

A similar procedure is used to record absolute pressures and differential pressures. The frequency with which these signals are recorded and the way in which they are processed at the PC are based on the specific needs of the tests being performed, although a frequency of 5 Hz has proven to be adequate for a large number of applications. Following conversion the measured data are processed using user-friendly programs and corresponding analyses are carried out. The data are stored in databases to ensure that they can be retrieved at any time in the future.
The tests themselves are continuously monitored at two screens (Fig. 3). Process visualization is performed using the most suitable software for the task in hand. The screen displays ensure that the operator has a clear picture at all times of how each test is proceeding. One screen shows the BENSON test rig along with the component being tested and thermal-hydraulic conditions while the other displays the data currently being measured at the test object.

Spectrum of Applications

The applications for which the high-pressure test facility can be used cover a wide spectrum of topics ranging from fossil-fired, nuclear and solar thermal power plants through wet steam piping networks for thermally enhanced heavy-oil recovery to issues related to water chemistry, etc. (see Table 1). A few examples of these, which are highlighted in color in the table, will be briefly addressed below.

Example 1: Optimization of Fossil-Fired Once-Through Steam Generator Design and Operation

In a once-through steam generator – unlike in other types of boilers – the water fed to the boiler tubes is completely transformed into steam while passing only once through them. During this process, varying conditions of heat transfer arise in the waterwalls, something which must be accounted for in the design since they have a major effect on tube wall temperatures during operation and thus on the availability of the waterwalls for heat transfer.

The process of heat transfer inside a boiler tube is not constant. Just as the flow through the tube undergoes a transition between different flow patterns during evaporation, so too do the regions of heat transfer vary. This is illustrated for a uniformly heated tube in Figure 4. Boiler design is therefore primarily focused on two basic questions (see also /1/):

- At what location, i.e. at what steam quality, does the boiling crisis occur (critical steam quality)?
- What maximum wall temperatures are reached after occurrence of the boiling crisis (i.e. in the post-dryout region)?

When the inside surface of the tube is no longer wetted by water, a boiling crisis occurs and heat transfer drops, usually quite sharply. This results in an almost instantaneous increase in wall temperature. As shown by the example in Figure 4, the wall temperature decreases in the subsequent post-dryout region as steam production increases. This can be attributed to more efficient convective cooling resulting from the higher velocity of the two-phase mixture. The highest wall temperatures are therefore usually reached immediately after onset of the boiling crisis.

At the test rig, work concentrated first on determining the design bases for BENSON boilers with spiral-wound furnace tubes. In this type of boiler, smooth tubes are predominantly employed.
### Table 1: Spectrum of applications for BENSON test rig

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<tr>
<th>Topic of Investigation</th>
<th>Special Test Features</th>
<th>References</th>
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<td><strong>Fossil-Fired Power Generation</strong></td>
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<td>Combination of venturi tube and gamma densitometer; pressures up to 220 bar</td>
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<td></td>
<td>Complex test setup; pressures up to 115 bar; gaps of 1 to 10 mm</td>
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<td>Complex test setup with elevations scaled 1:1; 600 kW/m², ≤ 40 kg/m²s, ≤ 1.35 bar on secondary side</td>
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<td>Test object with real cracks (bending stress, fatigue); pressures up to 160 bar; 0 to 70 K subcooling</td>
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<td>* Cladding tube temperatures in fuel assembly with various spacer grid designs</td>
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<td>Testing of production-type components under realistic PWR conditions</td>
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<td>* Influence of fouling on secondary-side heat transfer in a steam generator tube that has been in service</td>
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<td></td>
<td>Testing of production-type components under realistic PWR conditions</td>
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<tr>
<td></td>
<td>* Leakage rates from real cracks</td>
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<tr>
<td></td>
<td>Testing under realistic conditions; comparisons with archived tube and chemically cleaned tube formerly in service</td>
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<tr>
<td><strong>Power Plant Concepts for Direct Solar Steam Generation</strong></td>
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<td>30-m-long test tube, tube diameters of 50, 65 and 85 mm, pressures up to 100 bar</td>
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<td></td>
<td>* Forced-flow once-through concept</td>
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<td>* Injection concept</td>
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<td>* Recirculation concept</td>
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<td><strong>Thermally Enhanced Heavy-Oil Recovery</strong></td>
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<td>Diameters of 25 and 50 mm; up to 100 bar</td>
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<td>* Robust measuring techniques for application in the field</td>
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<td>Gamma densitometer, venturi and pitot tubes</td>
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<td><strong>Water Chemistry</strong></td>
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<td></td>
<td>BENSON boiler conditions</td>
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<td></td>
<td>Transient conditions</td>
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<td></td>
<td>* Behavior of protective layers in the event of thermal shocks</td>
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<td></td>
<td>Conditions of fossil-fired boilers and nuclear plant secondary cycles</td>
<td>14, 15, 16</td>
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<tr>
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<td>* Material loss due to erosion corrosion</td>
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<tr>
<td></td>
<td>Conditions of fossil-fired boilers and nuclear plant secondary cycles</td>
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<td></td>
<td>Steam generator tubes made from Inconel 690, Incoloy 800; PWR conditions</td>
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<td>Traction motor heat exchanger for electric multiple unit trains</td>
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<td></td>
<td>Steam generator tubes made from Inconel 690, Incoloy 800; PWR conditions</td>
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* Highlighted topics are addressed in greater detail in the following.
The tests revealed that safe operation requires mass fluxes above 2000 kg/m$^2$s during operation at full load. If the mass flux is reduced while keeping heat flux at the same level, the wall temperatures initially increase only slightly and then rise disproportionately as the mass flux decreases further. Figure 5 illustrates this relationship for a case in which the heat flux was maintained at a level corresponding to full-load operation while the mass flux was reduced in stages. This figure also indicates that there are two main reasons for the disproportionate increase in wall temperature:

- The deterioration in heat transfer occurring in the post-dryout region, and
- The reduction in the critical steam quality.

Figure 5 illustrates this relationship for a case in which the heat flux was maintained at a level corresponding to full-load operation while the mass flux was reduced in stages. This figure also indicates that there are two main reasons for the disproportionate increase in wall temperature:

- The deterioration in heat transfer occurring in the post-dryout region, and
- The reduction in the critical steam quality.

The effect of this is twofold:

- The location of the boiling crisis is shifted to areas of high steam qualities, i.e. to the end of the evaporation zone. The high steam velocities prevailing at this location result in good tube wall cooling.
- Heat transfer in the post-dryout region is significantly higher in rifled tubes than in smooth tubes.

Figure 6 shows an example of the superior heat transfer performance of a rifled tube compared to that of a smooth tube (for further comparisons, see /4/).

Fig. 5: Effect of mass flux on inner wall temperature of smooth tube

Fig. 6: Wall temperatures in smooth and rifled tubes

At pressures near the critical pressure – namely, around 200 to 220 bar – it is not possible, even with rifled tubes, to keep the inside surfaces of the tube walls in the evaporation zone wetted at all times. This is connected to the problem of surface wetting that generally arises at pressures just below critical. In both smooth tubes and rifled tubes, the location of the boiling crisis can be seen to shift towards areas of low steam qualities as the pressure approaches the critical pressure /5/. This is caused by a drop in the so-called Leidenfrost temperature to the value of saturation temperature when the critical pressure is reached. Consequently, above a pressure of approximately 210 bar, only a small increase in wall temperature is sufficient to result in a transition from boiling with a wetted tube surface to so-called film boiling with an unwetted surface. Figure 7 shows the relevant curve of the Leidenfrost temperature for forced convection as a function of pressure /6/. Although wetting problems also arise in rifled tubes at pressures near critical, the effects on the rise in wall temperature are much smaller than in the case of smooth tubes. This applies particularly to those cases in which tubes with an optimized rib geometry are employed.
In steam generator design, the topic of pressure loss plays just as important a role as heat transfer. Not only does it have an influence on feedwater pump capacity, but knowledge of this parameter is also essential, above all, for calculating flow distribution in the parallel tubes of a boiler. The total pressure loss occurring in a boiler tube is made up of friction loss, static head loss and acceleration loss. In most cases, however, the pressure loss due to acceleration is negligible compared to the other components.

When once-through steam generators are operated at high mass fluxes, it is the pressure loss due to friction that is the dominant component. This is primarily influenced by tube diameter, pressure and mass flux. Moreover, smooth and rifled tubes exhibit different pressure losses. For example, the dependence of friction pressure loss on mass flux differs considerably in smooth and rifled tubes. To illustrate this a comparison is presented below of experiments performed on unheated vertical tubes. Figure 8 (left-hand side) gives an example of the strong dependence of the two-phase multiplier of smooth tubes on mass flux (the two-phase multiplier is defined as the ratio of the friction pressure loss of a two-phase flow to that of a saturated water flow). Here, as the mass flux increases, the two-phase multiplier decreases, something which is attributable to the reduction in the thickness of the liquid film on the wall that is observed to accompany the increase in two-phase velocity. The thinner the liquid film, the smaller the pressure loss due to friction. In the case of rifled tubes, however, mass flux has only a small effect on the two-phase multiplier (see right-hand side of Fig. 8).

In steam generator tubes, the state of heating surface wetting – in other words, the location of the boiling crisis – also has a considerable influence on friction pressure loss. The sudden drop in friction pressure loss to be seen in Figure 4 at the location of the boiling crisis can be attributed to the disappearance of the water film on the heating surface.

Fig. 7: Leidenfrost temperature for forced convection as a function of pressure

Fig. 8: Effect of mass flux in smooth and rifled tubes
Investigation of these briefly outlined design aspects for fossil-fired steam generators required – as illustrated in Figure 9 – extensive experiments on tubes with different geometries, modes of heating and orientations over a wide range of operating parameters. The system pressures and mass fluxes were chosen such as to envelop the entire operating range of a steam generator from full load to extremely low part load. In connection with tube heating, conditions that arise in so-called "hot spots" were also accounted for. Furthermore, the tubes that were investigated had inside diameters of the kind found in both once-through and recirculating steam generators. Data from 100,000 measurements taken on smooth tubes as well as 140,000 measurements on rifled tubes (as of the end of 1999) have been compiled to form an extensive database on wall temperatures and pressure losses which serves as a basis for developing software for the fields of thermal hydraulics and fluid dynamics.

<table>
<thead>
<tr>
<th>Tube Heating</th>
<th>Smooth</th>
<th>Rifled</th>
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<tbody>
<tr>
<td>Uniform</td>
<td><img src="image1" alt="Uniform Smooth" /></td>
<td><img src="image2" alt="Uniform Rifled" /></td>
</tr>
<tr>
<td>One-side</td>
<td><img src="image3" alt="One-side Smooth" /></td>
<td><img src="image4" alt="One-side Rifled" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Pressure</th>
<th>Mass flux</th>
<th>Heat flux</th>
<th>Tube inner diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25 ≤ p ≤ 280 bar</td>
<td>100 ≤ m ≤ 2500 kg/m²</td>
<td>9 ≤ q ≤ 950 kW/m²</td>
<td>8 ≤ d ≤ 70 mm</td>
</tr>
</tbody>
</table>

**Fig. 9:** Overview of heat transfer tests

The BENSON test rig was also used to conduct investigations of the behavior of membrane waterwalls with integral supports under transient loading conditions. In these tests, measurements were taken of the time-dependent temperatures and stresses arising in sections of the membrane waterwalls with their supports. The results of these investigations serve as a basis for calculating the thermal stresses induced in these components during boiler startup and shutdown.

Another series of tests carried out at the BENSON test rig that is also worthy of mention concerned a new compact measuring system, basically consisting of a venturi tube and a one-beam gamma densitometer (see Fig. 10), that can help improve feedwater control in once-through steam generators.

Up until now it has been common practice to use the steam enthalpy – some manufacturers also use the steam temperature – downstream of the boiler section as an input variable for feedwater control. However, in order to be sure that these measurements are always taken in a superheated steam environment, even during dynamic processes, the instrumentation for this control variable must be located in the primary superheating section, e.g. between the high-pressure superheaters. The disadvantage of this is that response is slower to changes in heat input inside the furnace and thus to changes in primary superheater steam enthalpy. Processes of heat storage and heat removal occurring inside the boiler section cannot be monitored.

The measuring system developed by Framatome ANP measures not only the pressure and the temperature but also the mass flow and the steam quality of wet steam. The system can be installed at the end of the boiler section (upstream of the moisture separators or even between individual boiler sections) for either full-flow or part-flow measurement, and supplies data on all variables needed for feedwater control. The measuring system tested at the BENSON test rig and later also in a power plant is characterized by the following features:

**Fig. 10:** Wet steam measuring system
• Compact and operationally safe design which is simple to use,
• Easy interpretation of measured data, and
• Wide range of measurement.

Compared to the conventional method of enthalpy measurement, the wet steam measuring system also provides the following advantages:

• Only a small delay between changes in heat input inside the furnace and the consequences of such changes in the steam, condensate and feedwater cycle, thus making feedwater control response extremely fast.
• Processes of heat storage and heat removal occurring inside the boiler section can be monitored. The measured data can be quickly processed and used as inputs for attemperator control.

When this wet steam measuring system is installed near the end of the boiler section, faster rates of load change are possible (while at the same time preventing excessive stressing of the HP superheater materials) than when traditional methods for measuring enthalpy or temperature at the high-pressure superheaters are used.

Example 2: Contributions to the Safety of New and Operating Nuclear Power Plants

The high-pressure test facility can be employed not only for topics associated with fossil-fired power plants but also for safety-related tasks for new nuclear power plant designs or nuclear plants already in operation. Tests have been performed, for example, to measure the influence of fouling on secondary-side heat transfer using part of a steam generator tube that had actually been in service. Another project involved determining the cladding tube temperatures of simulated fuel assembly segments using spacer grids equipped with different swirl vanes.

Recent investigations have shown that, under certain boundary conditions, light water reactors possess safety margins in the event of a beyond-design accident which have not previously been taken into account. Until now, no one had been able to properly explain why, during the accident at Three Mile Island (TMI) in 1979, the wall of the reactor pressure vessel (RPV) did not start to melt even though around 20 tons of molten core material had slumped into the lower plenum and a corresponding amount of decay heat required removal.

What had already been verified was that the molten core material formed a crust when it came into contact with the water still present inside the RPV, resulting in gaps arising between the porous crust of the molten material and the RPV wall. Thanks to the experiments carried out at the BENSON test rig, however, an explanation has now been found: namely that, in a case such as this, the intensive cooling effect provided by evaporation of the water is sufficient to remove enough of the decay heat so that overheating of the RPV wall does not occur /8/.

For experimentally verifying the phenomenon of gap cooling, a specially designed test replica was integrated into the test facility (Fig. 11). This allowed the width of the gap between the simulated debris crust and the RPV wall, as well as the system pressure, to be varied within the ranges applying to this accident.

Fig. 11: Test setup to simulate heat removal during TMI accident
In order to determine the maximum amount of heat that could be removed, the heat input coming from the simulated core material was steadily increased using electrical heaters until the rise in the temperature of the heat-transfer surface signaled the onset of the boiling crisis. It was found that, even with very small gaps, large quantities of heat can be removed by the water (see Fig. 12). As the simulated RPV wall continued to be efficiently cooled, it can be concluded that – provided the gap is submerged in water – this cooling mechanism can prevent overheating of the RPV wall in the event of a core melt accident.

**Fig. 12:** Validation of heat removal from molten debris during TMI accident

In connection with the development of new pressurized water reactor designs, investigations were also carried out for a passive, secondary-side residual heat removal system. The main component of such a system is a so-called safety condenser (SACO) in which heat from the secondary side of the steam generator is removed by evaporating water under practically atmospheric pressure conditions. Water is fed to the SACO by gravity flow.

In a SACO of once-through design such as that shown in Figure 13 (left), steam is condensed inside the tubes (hereinafter called the secondary side), while the water fed to the SACO is evaporated on the outside of the tubes (hereinafter called the tertiary side). Heat transfer to the water is characterized by the following data:
- High heat fluxes (up to 600 kW/m²),
- Very low mass fluxes (≤ 40 kg/m²s),
- Low pressures (≤ 1.35 bar).

For these conditions, an initial series of tests was conducted on a 3 x 3 tube bundle with forced feed. The tests demonstrated that under these operating conditions most of the water fed to the tubes evaporates, thus assuring adequate heat removal. However, since the occurrence of oscillations cannot be ruled out in the case of gravity feed, the results of the first tests were verified in a second series of experiments in which this form of water supply was simulated.

**Fig. 13:** Investigation of integration of safety condenser into secondary cycle of pressurized water reactor
In order to simulate all hydrostatic effects realistically, all system elevations such as the elevation of the water storage tank, the relative elevations of the water feed line inlet and outlet, and the active height of the SACO were scaled 1:1. The final test setup is shown in detail on the right of Figure 13. Whereas the tertiary side, in which atmospheric pressure conditions prevail, operated as a function of differences in hydrostatic pressure, the secondary side of the SACO was connected to the high-pressure side of the BENSON test rig. The heat coming from the steam generator was simulated by electrically heating the tube bundle with a heat input of 1.3 MW. The following aspects were investigated:

- The performance characteristics of the SACO, i.e. its heat-exchange behavior as a function of secondary-side pressure, water feed rate and exit resistance
- Its heat-exchange characteristics for various initial conditions.

In this steam condenser, which operates according to the once-through principle, the heat-exchange behavior is primarily governed by the occurrence of the boiling crisis. If the boiling crisis should already occur in an area of low steam quality, a large proportion of the water fed to the condenser will pass through the heat exchanger without absorbing heat. The reason for this is that film or transition boiling occurs in the region above the zone with a wetted heating surface (subcooled boiling and saturation boiling), resulting in much less heat being transferred per unit of heat-exchange surface. However, if the boiling crisis should not occur until an area of high steam quality is reached, most of the water will be evaporated, thus assuring good heat removal. As was shown by the experiments, the latter of these two cases applies to the SACO. The tests also verified that heat transfer performance is not affected by the method of water supply (Fig. 14).

If the heat-exchange data measured at the 3x3 tube bundle are extrapolated to apply to the entire SACO, then it can be expected to have a heat-removal capacity of 50 to 55 MW at secondary-side pressures starting from 25 bar and nearly 30 MW at a pressure of 5 bar /9/.

Thus the tests verified that a safety condenser operating on the once-through principle meets the requirements stipulated for such a component as regards adequacy of heat removal.

Another safety-related contribution has concerned leak detection in nuclear power plants using acoustic leakage monitoring systems. To reliably detect the presence of ruptures and thus prevent further damage to the ruptured component itself or to components in the immediate vicinity, it is necessary to be able, on the one hand, to calculate the anticipated discharge rates and, on the other, to correlate these with signals from leakage monitoring systems. Calculating such discharge rates using the models available in the literature is problematical since most of the underlying investigations were not performed on real cracks but on openings of a predefined geometry, such as orifice plates. In addition, model validation has been lacking in the range of parameters that is of interest for engineering processes, such as high pressures. For these reasons, tests using water and steam were carried out at the high-pressure test facility with the aim of obtaining, for a wide range of parameters, information on discharge rates as a function of stagnation pressure and temperature as well as hydraulic resistance (crack opening geometry, surface roughness, etc.).

In addition, measurements of noise were taken during the experiments using a variety of different sensors in order to determine the relationship between discharge rate and leakage noise and thus document the applicability of acoustic leakage monitoring systems /10, 11/.

Example 3: Power Plant Concepts for Direct Solar Steam Generation

One of the options for integrating solar thermal technologies into the power plant market in countries of the sunbelt can comprise the following concept. A fossil-fired power plant (e.g. a combined-cycle plant) is used for base and intermediate load service. When solar radiation is sufficiently high, the sun’s rays are concentrated by a trough collector and used to generate steam for cutting down fuel consumption or meeting mid-day peak demand.

Up until now, thermal oil has been heated in absorber tubes and steam has been generated in a heat exchanger installed in a separate circuit. However, economical solar steam generation can only be expected from systems in which the solar energy is used to directly evaporate water...
inside the absorber tubes. Three different concepts could be used for this: a forced-flow once-through concept, a recirculation concept and an injection concept. The last of these seemed to be particularly suitable since each absorber section would only be supplied with as much water as could be evaporated by the solar radiation. This would avoid problems associated with ensuring steady, stable operation – even in cases of highly intermittent solar availability (see Fig. 15).

To investigate the functional capabilities of these individual concepts, corresponding tests were carried out at the BENSON test rig. For these tests a 30-m-long tube was installed (Fig. 16). The BENSON test rig supplied the required inlet flow conditions, while heat input from solar radiation was simulated in the three-part test tube by means of electrical heating. In terms of the most important parameters:

- Mass flux
- Steam quality
- Heat flux
- Heating profile (sun in morning/evening or mid-day position)
- Tube diameter

the test results (see Fig. 17) showed that direct solar steam generation is technically feasible from a heat-transfer viewpoint in the case of all three concepts. On the basis of the experimental results a mathematical model was developed for the thermal-hydraulic design of a solar field for direct steam generation (see /12/).

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**Fig. 15:** Concepts for direct solar steam generation

**Fig. 16:** Test setup for direct solar steam generation investigations
Example 4: Wet Steam Piping Networks for Thermally Enhanced Heavy-Oil Recovery

One of the methods employed for recovering heavy oil – for example, in Venezuela – is that of injecting steam into the oil reservoir. The steam, which is injected through boreholes, increases the reservoir pressure and lowers the viscosity of the oil. This enables oils of originally high viscosity to be recovered from oil sands and oil shale.

The piping networks used to distribute the steam to the injection boreholes suffer considerable heat losses due to their sometimes extremely long pipe runs (> 10 km). As a result, a portion of the conveyed steam condenses inside the pipes, producing a two-phase flow. For this type of flow, the pressure drop occurring in the various piping components and the flow distribution at, for example, connecting tees are much more difficult to calculate than those of a single-phase flow. However, precise knowledge of these parameters is essential for ensuring optimum steam injection and thus oil recovery. Investigations carried out for this purpose also included tests at the BENSON test rig performed on piping systems comprising straight pipes arranged in vertical, inclined and horizontal configurations as well as pipe bends of various bending radii and orientations /13/. The test setup, which contained pipes of two different diameters (25 and 50 mm), is shown in Figure 18.

Figure 19 gives examples of the results of the pressure loss measurements as a function of steam quality for a horizontal pipe, an inclined pipe and a pipe bend. The diagram clearly illustrates that the pressure drop increases as the steam content increases, until a certain maximum level is reached. The drop occurring at very high steam qualities results from the progressive dryout of a near-surface film of water in the test objects.

These tests – extended to include, for example, connecting tees – were supplemented in field experiments conducted in Venezuela by pipe diameters of 100 and 150 mm in order to be able to investigate scaling effects. The results were used as a basis for a computer program for designing wet steam piping networks.

In the course of such tests, valuable information was also obtained for the selection of robust measuring techniques for application in the field, including power plant operating conditions. One example is the compact mass flow and steam quality measuring system, already mentioned above, which had originally been developed as a multi-phase...
measuring device for oil, water and gas flow and content in offshore oil production systems and was later tested under power plant operating conditions for use in once-through boilers.

Example 5: Effects of Water Chemistry on Protective Surface Layers and Investigations of Component Materials

Via the chemical dosing point shown in Figure 1 it is possible for any desired water chemistry to be established in the BENSON test rig which is made entirely of austenitic material. This option was used for a variety of experimental tasks related, for example, to:

- Formation of protective magnetite layers inside tubes
- Behavior of protective layers in the event of thermal shocks
- Material loss due to erosion corrosion.

The last of these topics is briefly addressed below.

Erosion corrosion can be defined as the loss of material from solid surfaces through corrosive dissolution under the convective action of single-phase liquid flows /14/. It is characterized by the corrosive dissolution of protective surface films or parts thereof. In addition to this, it requires the presence of a turbulent, single-phase liquid flow adjacent the surface which is, however, also possible in wet steam regions, e.g. in areas of annular flow (ring of water at pipe wall and steam at the core of the flow) or of partial steady-state wetting. Erosion corrosion is a phenomenon restricted solely to metals whose resistance to corrosion depends on the formation of protective oxide layers such as magnetite.

![Wall thinning due to erosion corrosion](image)

**Fig. 20:** Wall thinning due to erosion corrosion (effects of thermal-hydraulic and water chemistry parameters)
To investigate the parameters influencing the process of erosion corrosion, tests were conducted on the BENSON test rig on various objects (flat plates oriented in the direction of flow, tubes, bends, reducers and increasers) under conditions of water and steam-water flow /15/. The material loss caused by erosion corrosion was determined by different measuring techniques. In addition to weighing and direct wall thickness measurement, the so-called Thin Layer Activation (TLA) technique was also employed. This method allows continuous measurement of material losses at a layer of the surface that has been activated through irradiation with radioisotopes.

The tests focused in particular on investigating the effects of flow velocity, fluid temperature and water chemistry (pH and oxygen content). In addition, the resistance of various materials (around 15) was compared and the resistance of protective magnetite layers to erosion corrosion was investigated. The results of these extensive investigations – some examples are shown in Figure 20 – were used to develop a computer program which can be employed in power plant design to ensure that no significant damage due to erosion corrosion will occur during the plant's design service life. The program can also be applied for existing power plants to identify locations on components at which the wall thickness should be monitored, meaning that the scope of in-service inspections can be reduced to cover just those locations at which measurements are absolutely necessary. Finally, the program can also be used to optimize aspects related, for example, to materials, design or water chemistry regimes for component repair or replacement activities that might become necessary /16/.

In addition to the above, it should be mentioned that the test rig can also be employed for determining the material properties of components. One example has been tests carried out to determine the thermal conductivity of materials for nuclear steam generator tubes.

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