Upgrade of the FRIGG test loop for BWR fuel assemblies

ABB Atom in Sweden has been carrying out full-scale tests on BWR fuel assemblies at its FRIGG fuel test facility since the mid-1960s. A recent upgrade of the test loop has boosted its thermal power to 15 MW and brought improvements that include a new loop control system, a new powerful data collection system and a new control room. FRIGG has been modernized to meet present-day and future requirements for measuring void distribution, transients and the stability of the fuel assemblies.

Following its US$ 5 million modernization of the FRIGG BWR test loop, ABB has a fuel test rig at its disposal which can hold its own with the best in the world 1. The upgraded FRIGG facility is used to carry out tests and simulations which are a necessary part of the development of new fuel concepts, and thereby increase their acceptance by power plant owners and authorities. The upgrading of FRIGG is also a testimony to ABB's commitment to nuclear energy and to the company's determination to remain a leading supplier of nuclear fuel.

The decision to upgrade the FRIGG test facility was taken in 1994 after several alternative solutions had been thoroughly evaluated. An important factor in the decision was the condition of the systems and components of the test rig, which were still in good shape after 30 years of operation. The rig's test loop is made of conventional carbon steel, and the long-term corrosion behaviour of this material has proved to be remarkably good.

Thermal power rating is increased to 15 MW

The increase in thermal power to 15 MW required, among other things, a new 20-MVA transformer for the Tegnér industrial site at ABB's factory in Västerås. In addition, it was necessary to install four new thyristor rectifiers and a new heat-exchanger, while the cooling-water supply system also had to be enlarged.

In all, ten smaller and four larger rectifiers in a 12-pulse arrangement for a maximum voltage of 400 V and a total current of maximum 55 kA are now available for tests.

The test rods used to simulate the fuel rods of a reactor are now indirectly heated by means of a spiral resistor. Due to the good experience with these simulator rods, which have been used for almost ten years in the FRIGG facility, it was decided to continue using them after the upgrade.

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At the same time, a system for the single connection of 100 individual rods to the different rectifiers was realized 2. Each rod has water-cooled top and bottom electrodes, plus instrumentation with up to eight thermocouples that warn of local overheating. A new, more practical connection system has been fitted which is suitable for all the required coolant pipes and instrument cables.

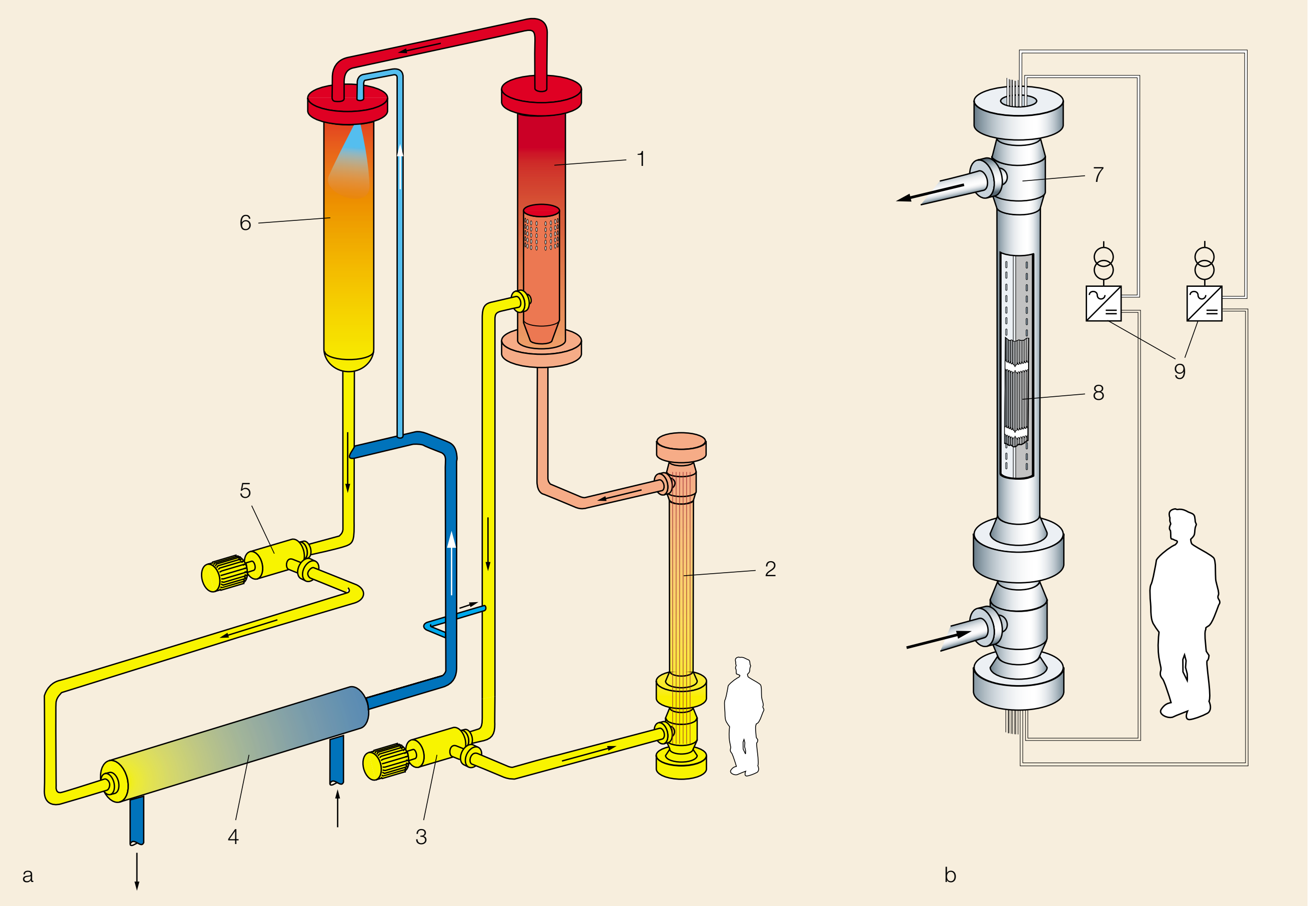
Upgrading and modernizing the test loop

As already mentioned, the part of the test facility under pressure was still in good shape, and following the upgrade it is once again fully operational. In addition, the performance of the cooling system has been improved and the piping adapted to the new conditions in the test section of the rig. Measures have also been taken to allow exact control of the inlet temperature, and the transient capability has been improved by installing fast-acting valves. The installation of ABB Master, which has been modernized and extended, has also added considerable control capability to the test loop. With the new data collection system, 830 measured values can be recorded as often as 25 times per second.

The temperature of the rods is carefully monitored, the power control being linked up to an automatic alarm and protection system for this purpose. Also, a considerably larger and more modern control room is now available for supervision of the tests 3.

Void measuring system

An important parameter for the fuel assemblies of boiling-water reactors (BWR) is the so-called void distribution. A unique void measuring system was developed, based, like the earlier system, on penetration of the test section by gamma rays.



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Basic arrangement of the modernized FRIGG BWR test facility (a) and detail of the test section with size comparison (b)

Main data		
Pressure	MPa	10,0
Temperature	˚C	311
Thermal rod power	MW	15
No of rectifiers		14
Material	carbon steel	
Measuring system	830 measuring points, 25 times/s	

1 *Steam separator*
2 *Test section*
3 *Main circulation pump*
4 *Heat-exchanger*
5 *Recirculation pump for coolant loop*
6 *Condenser*
7 *Pressure vessel*
8 *Test bundle*
9 *Rectifiers (max 14)*

What is new, however, is the much improved three-dimensional resolution of the measurements in the upgraded facility.

The new system consists of a measuring table with caesium preparation (700 GBq Cs137)[1] and 16 scintillation counters, plus the radiation protection and collimators **4a**. The measuring table is brought into the required position with the help of an ABB industrial robot **4b**. Numerous transilluminations of each layer are carried out in different directions. A specially developed test section is used for the first measurements.

Calculation software does not replace testing

The test facility upgrade has meanwhile been concluded. Already before the official inauguration, tests were started with complete fuel assemblies with 96 rods, based on the advanced fuel concept SVEA-96+, to verify operation with a highly non-uniform power distribution. This had not been possible in the past.

Tests are currently being carried out in connection with the next generation of fuel, as fuel assemblies for boiling-water reactors continue to have a large development potential. Even today's most advanced computer programs have not eliminated the need for full-scale testing of fuel assemblies. They are necessary on the

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[1] Bequerel is the SI unit of radioactivity:
1 Bq = one disintegration per second.
The unit 'curie' has often been used in the past,
1 Ci being equal to 3.7 · 10^{10} Bq

one hand to confirm the calculations, while on the other they support the development of a so-called Computational Fluid Dynamics (CFD) program for BWR fuels. Before this program can be introduced, a comprehensive series of tests with large amounts of recorded and evaluated data are necessary. This work alone will ensure that the FRIGG test facility is fully ‘booked’ for some time to come.

The goal is to be able, in several years, to accurately predict the results of modifications to fuel design and data and to be able to verify these through tests in reference cases. Although this should allow the number of tests for a particular application to be reduced considerably, it will not completely eliminate the need for tests. Because of this it is likely that good use will be made of the FRIGG test facility's capacity well into the future.

A proven tool for fuel development

The significance of the recent upgrade is perhaps best explained by a brief look at the central role FRIGG has played in the devel-opment of ABB BWR reactors and their fuels.

Work on the FRIGG test loop began in the early 1960s [1]. The goal then was the full-scale simulation of fuel assemblies under operating conditions. The first tests to be carried out were performed with fuel assemblies for the heavy-water reactor of the Marviken nuclear power plant, a state-owned test facility which never went into operation for a number of reasons. Shortly afterwards, efforts were concentrated on the development of a boiling light-water reactor which was completely independent of foreign licences; this was used for the first time in the Oskarshamn nuclear power plant in Sweden.

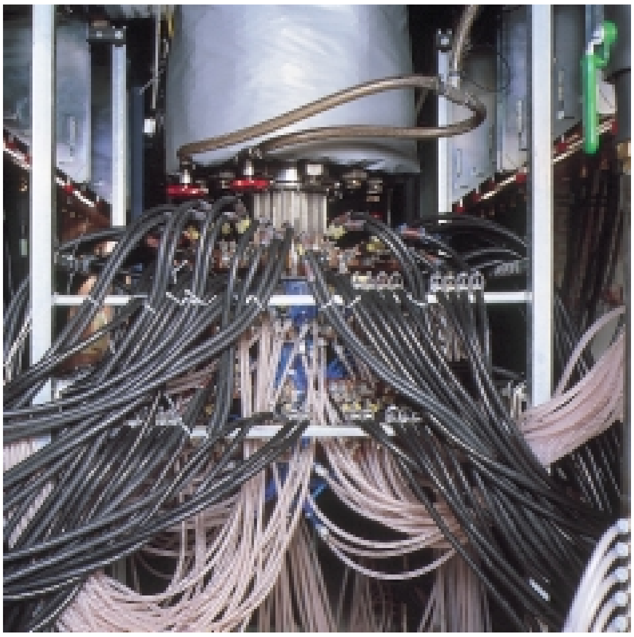
The work represented a major challenge, in particular the simulation of the high power density of a fuel assembly by means of electrical heating. To gain time and test the technology, a smaller test facility, named FRÖJA, was first constructed. This had the same basic structure as the FRIGG facility.

When the FRIGG test loop became operational at the end of 1966, two years of operating experience with the FRÖJA test rig were already available. This had been used to carry out measurements on long, normal fuel assemblies, although the tests had been limited to six heated rods. FRÖJA also helped the rig operators overcome many difficulties encountered during testing, and provided experience which could be put to good use in FRIGG. For example, tests in which the rods were heated with alternating current were given up in favour of tests with direct current heating.

Conditions in a nuclear reactor are simulated

The objective with FRIGG was to design a loop with characteristic data that would approach as closely as possible those of the primary loop of an actual nuclear reactor. With its maximum thermal power of 9 MW, the capacity of the test loop built in the 1960s was sufficient for the fuel assemblies at that time. In those days,

Bottom terminal for the electrical energy and coolant for a test section with 96 rods (SVEA-96+) **2**



New control room at the FRIGG test facility. Control is by means of ABB Master. The rod temperatures are monitored on the screen on the right. **3**

FRIGG could also boast of being the highest-power test facility of its kind.

A special, if lesser objective involved the capability for testing the hydraulic stability with both natural and forced circulation. FRIGG was furthermore equipped with excellent systems for measuring the axial and radial void distribution.

Up until 1970, three test sections with fuel assemblies of heavy-water design and three with assemblies of BWR design were tested, in each case with different radial and axial power distribution. The rods were heated directly, the required power distribution resulting from the different material thicknesses used for the heating tubes. Low voltage and high current were used. BWR tests with 64 rods in a 8x8 arrangement required a current of 80 kA. The technical problems encountered during the experiment were considerable, not least because of the high currents, which quickly caused overheating of the connections to the heated rods. In addition, the high currents produced strong electromagnetic forces.

Successful example of North-European cooperation

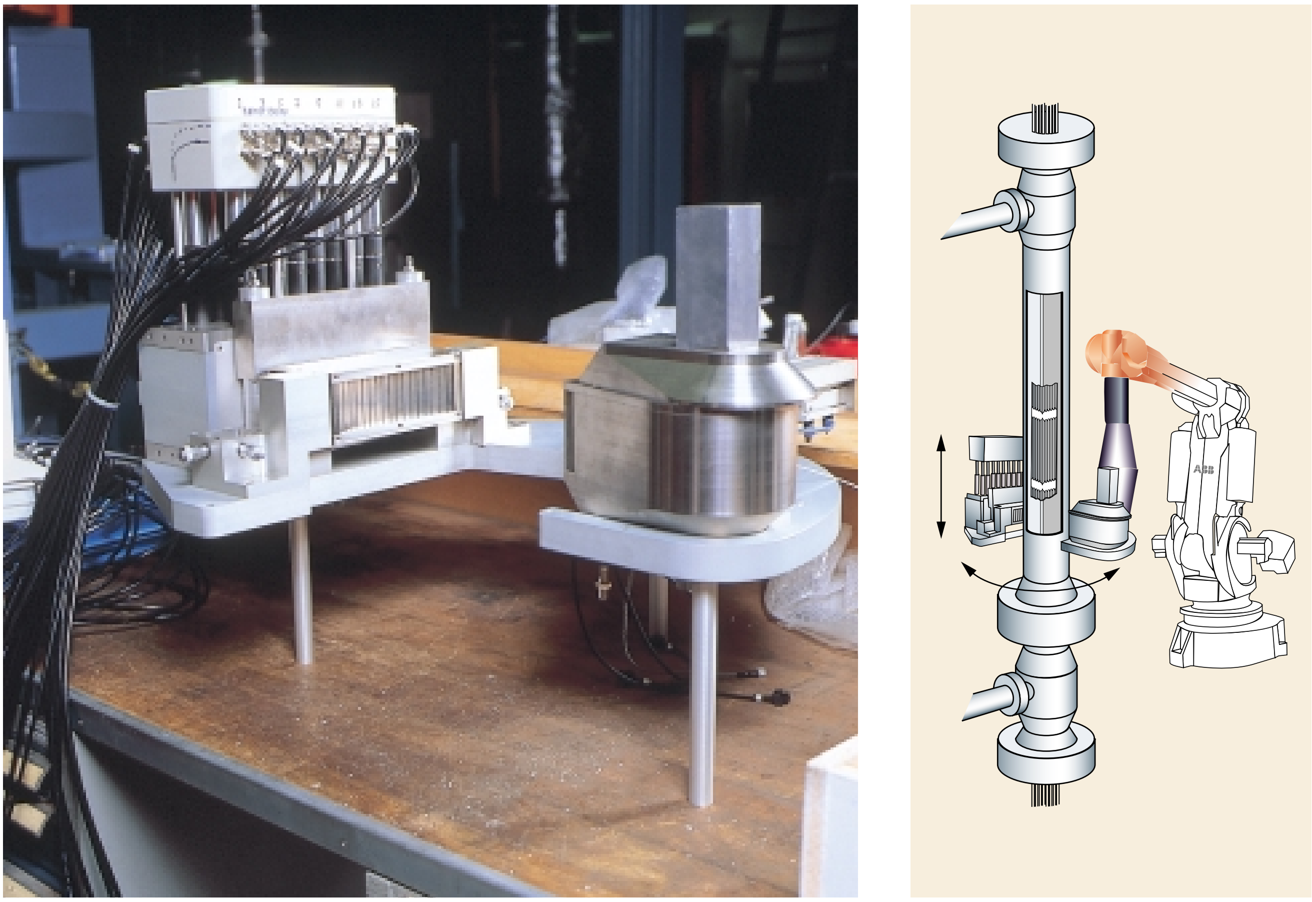
The tests were carried out in close collaboration with research centers at Studsvik in Sweden, Risø in Denmark and Kjeller in Norway. This northern-European cooperation turned out to be very successful.

The problems that did arise could be solved one by one, and each test section was utilized to the full for different fuel assembly measurements. Primarily, it was determined where the thermohydraulic limits at the maximum power lie under defined conditions. These limits are characterized by the start of local overheating due to the critical boiling state, known as the dryout limit, or by diverging oscillations in the coolant flow, the so-called stability limit. Also measured were the pressure drop distribution and the void distribution, ie the relative steam volume. Transfer functions were used for the measurement of the different transients. The tests were carried out with both natural and forced circulation and took account of changes in pressure, inlet temperature and coolant flow. Another important factor was the testing and adjustment of the sensors and instruments for five advanced test fuel as-

Tomographic measuring equipment for determining the void distribution **4**

a *Measuring table with gamma ray source and radiation protection (on right), scintillation counters (left, back) and collimators (left, front)*

b *Positioning of the measuring equipment relative to the test loop with the help of an ABB industrial robot of type IRB 6400*



semblies which had been installed in the Oskarshamn 1 nuclear power plant and used for commissioning.

Basis for future development work

The measurements were evaluated and systematically documented. The database they provided formed a basis for the future development of BWR technology and two-phase flow (steam/water), not only for Sweden but also for the international community. ABB's void distribution data were unequalled until recently, when measurements were also carried out in Japan.

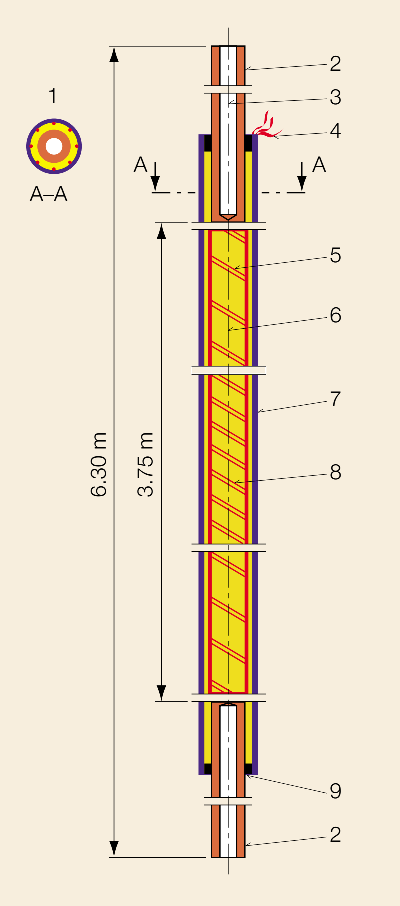
The stability data obtained with the FRIGG facility also have outstanding qualities, and they are still used very often today for international benchmarking of calculation software. In fact, ABB Atom still receives enquiries mentioning the meanwhile almost 30-years old FRIGG test reports from all over the world.

The tests showed that the design of Oskarshamn 1 had included a large margin of safety. A newly prepared dryout correlation (AA69) was the first for BWR fuel to be based on full-scale fuel assembly tests. The main competitor, General Electric, followed suit several years later with its ATLAS test rig and afterwards also changed to 8 × 8 fuel.

Critical boiling state

The critical boiling state, referred to today as 'dryout', was at that time termed 'burnout'. This name reflected the fear then that if this limit were exceeded the rods would, in effect, burn out. This view was based, among other things, on experience with smaller-scale tests.

With the first BWR test section, ABB demonstrated that slightly higher, stable temperatures constitute no risk of burnout, and that they are conceivable for powers far above the so-called burnout limit. This subsequently became highly significant for the evaluation of short-time limit violations, eg due to possible, but unlikely transients in the reactor.



Design structure of the indirectly heated rods for the FRIGG test facility. The outer diameter of the rods is about 10 mm. **5**

1 *Typical arrangement of thermocouples*
2 *Terminal electrode*
3 *Cooling channel*
4 *Thermocouple terminals*
5 *Heater spiral with steep slope for low power*
6 *Insulation*
7 *Encapsulating tube*
8 *Heater spiral with slight slope for high power*
9 *Seal*

The tests also showed that the design of the spacers between the rods plays a very important role in the effectiveness of the cooling. Recognition of this was to open the door to power increases through improved spacer design.

First upgrade of the FRIGG test facility

The FRIGG test facility was upgraded for the first time at the beginning of the 1970s. This was also done to be able to perform vibration measurements and endurance tests on actual prototype fuel assemblies under realistic BWR conditions.

A jet pump system for recirculating the steam and water enabled long-term tests with a steam flow and quality corresponding to the full power rating, however with only a fraction of the power consumption otherwise needed.

Over the following years, the increased capability was used extensively for testing many new designs. A new six-point spacer was one of the first innovations to be tested. This spacer design was used first for the 8x8 fuel and later, after further development, in the following SVEA concepts. The SVEA concept is characterized by the arrangement of the rods in a configuration with four sub-bundles which are divided by a so-called water cross [2-4]. With this arrangement, certain properties of the fuel assemblies can be considerably improved.

Development of new nuclear fuels

The installation of the first four SVEA fuel assemblies in Ringhals 1 nuclear power plant in the autumn of 1981 was preceded by intensive development work. Verification of the fuel design relied mainly on the tests carried out on the FRIGG facility. Further development work performed up until 1984, when the first reload of SVEA fuel in the Ringhals 1 plant became due, was also accompanied by tests on the FRIGG loop. These included measurements of the pressure drop as well as dryout and stability tests in an arrangement with complete fuel assemblies, with and without communicating openings for pressure equalization between the sub-bundles.

The dryout tests showed that there was close agreement between the sub-bundle and full-assembly measurements, but showed also that the available 9 MW of power was no longer adequate for the verification of the complete fuel assemblies at higher coolant flow rates. The stability tests confirmed the favourable influence of the communicating openings.

Verification of the behaviour of the emergency spray cooling

FRIGG also played an important role in the verification of the emergency cooling behaviour of SVEA fuel. This behaviour can be described as the ability to maintain cooling even in the event of an assumed serious accident with loss of coolant. Older reactor designs that rely on emergency spray cooling by means of nozzles fitted above the reactor core have to satisfy special demands in this respect. Spray cooling tests were carried out in special test units which had been connected up to the FRIGG test loop.

The spray cooling tests, which were performed with a full-assembly configuration and 500 thermocouples, confirmed the superiority of the emergency cooling behaviour of the SVEA fuel: it was verified that the maximum rod surface temperature was about 200 °C lower than with the older 8x8 fuel.

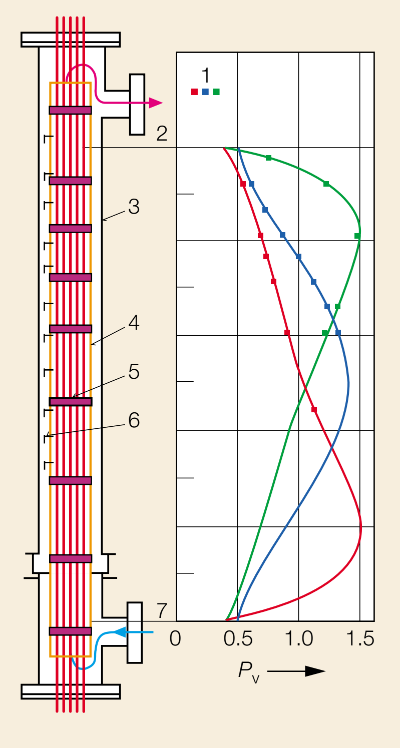
Changes to FRIGG necessitated by the SVEA-96/100 fuel

The first-generation SVEA fuel was based on the earlier 8x8 fuel and had 64 rods. It was therefore given the name SVEA-64. Further development of the SVEA fuel versions with a 10x10 arrangement (SVEA-100 and SVEA-96) made it necessary in the 1980s to make further modifications to the FRIGG facility, in particular with respect to the power supply system.

Due to the rods now being slimmer, serious proplems, such as deformation of the bundles, were being caused by the magnetic forces. Following change-over to indirectly heated rods of the kind developed at Stern Laboratories in Canada to overcome the stresses occurring during dryout tests, it was possible to use considerably higher voltages and correspondingly lower currents, resulting in reduced magnetic forces **5**.

Test loop with a sub-bundle of SVEA-96+ fuel. The spacers in the upper part of the fuel assembly are mounted closer together to improve the dryout behaviour of the fuel. The variation in axial power distribution P_V is achieved through rod changes. **6**

1 *Thermocouple measuring points*
2 *End of heated length*
3 *Pressure vessel*
4 *Flow channel*
5 *Spacer*
6 *Nozzle for measuring pressure drop*
7 *Beginning of heated length*



The indirect heating of the rods also solved the insulation problems in the test section, while the supply of electrical energy to the indivual rods or small groups of rods allowed the radial power distribution across the rods to be varied.

In the meantime, a new power supply system with 10 smaller rectifiers had been installed. The maximum power output was 4 MW, which was not only sufficient but included a good margin of safety for a SVEA sub-bundle.

Improved predictions and power capability

A comprehensive database, covering variations in the cross-sectional geometry, different distances between the rod center lines and different spacer distributions and designs, was created for the SVEA-100 and SVEA-96 fuel arrangements.

The radial power distribution was investigated for many variants in each of the test sections. Tests were also carried out with different axial power distributions **6**.

With the help of the results from these tests, the employed methods of prediction, which had been shown to have major deficiencies during the first tests, provided a good correlation with the actual values.

Also interesting is the increase in dryout power which has been made possible over the years by the new fuel concepts. Compared with the old 8 × 8 arrangements, for example, the dryout power with the advanced versions of SVEA-96 has increased by almost 40 percent **7**.

Full-assembly tests called for upgrading of FRIGG

The possibility of limiting the measurements, which provide highly realistic results, to a single quadrant, ie just one rod sub-bundle, is unique to SVEA and has significant benefits for the tests. The limiting to tests with sub-bundles has led, however, to situations with considerable power differences and a resulting flow exchange between the sub-bundles having to be computed. Many electric utilities therefore considered it worthwhile to also simulate events with strong local differences in power during full-assembly tests. Such events do occur, and under certain circumstances can represent a power limitation.

Full-assembly tests also allow the probable potential for an optimized interaction of the assembly parts in terms of dryout and stability to be taken into account.

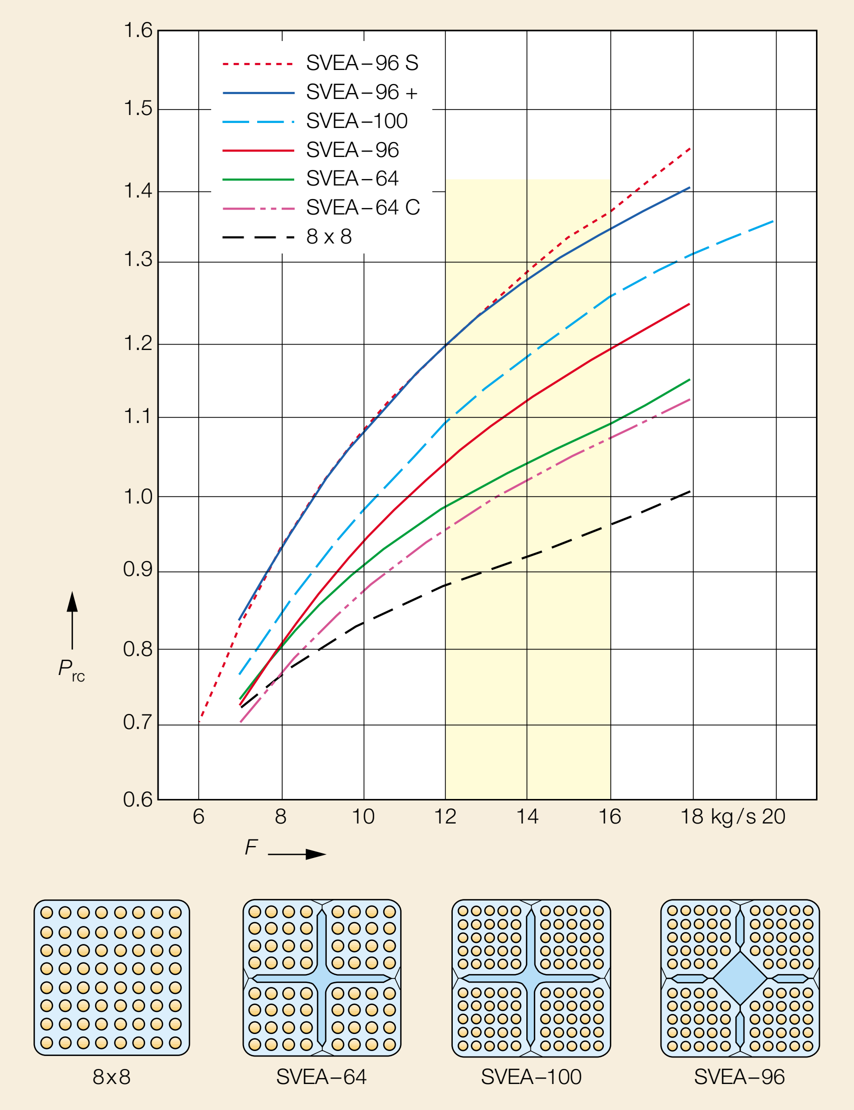
Another important wish of the utilities was for the void distribution measurements to be carried out again. This is because of the uncertainty involved in extrapolating measured void data from the 1960s and using the results for today's geometries.

Moreover, the fast development of detailed methods of calculating fluid flow behaviour also prompted a need for void measurements with high 3D resolution for the purpose of comparison.

These new requirements, together with the desire to modernize the test loop, led ultimately to the decision being taken in 1994 to upgrade FRIGG once more.

Outlook

The FRIGG test facility has provided valuable support during the development of BWR fuel at ABB Atom in Västerås, Sweden, for more than 30 years. Following completion of the most recent upgrade, FRIGG is once again at the technological forefront in its field. The new rig is already being used to test the next generation of SVEA fuel, and will help ABB Atom maintain its technical leadership in the BWR fuel market in the future.



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Progress made in the dryout power of 8×8 fuel up to the latest versions of SVEA-96. The tests and verifications were carried out on the FRIGG test facility.

P_{rc} *Relative critical power*
F *Flow rate*

Yellow *Normal operating range*

References

[1] **O. Nylund:** Full-scale loop studies of BHWR and BWR fuel assemblies. ASEA Research 10 (1969), 63–125.

[2] **O. Nylund, Ö. Bernander:** SVEA fuel leading the market for boiling water reactors. ABB Review 1/95, 14–21.

[3] **O. Nylund:** New SVEA fuel assemblies for boiling-water reactors. ABB Review 3/88, 11–16.

[4] **O. Nylund, B. Fredin, A. Johansson:** SVEA – a new generation of BWR fuel assemblies. Asea Journal 3/84, 4–7.

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