Special report

Reliability engineering

by T. Demler and W. Issler*

Nuclear power plants have now accumulated more than 3000 reactor-years of operating experience with individual lifetime availabilities as high as 80%. It may therefore be claimed that their safe and economic operation, on the basis of existing regulations and design principles, is possible. Nevertheless, the optimization of design and materials technology, including quality assurance and repeated in-service inspection, is an important prerequisite if continued safety and reliability are to be guaranteed.

An International Symposium on the Reliability of Reactor Pressure Components, organized by the IAEA in co-operation with the Staatliche Materialprüfungsanstalt (MPA) at the University of Stuttgart, was held in March 1983 (a report appeared in the *IAEA Bulletin*, Vol.25 No.3, September 1983). An exhibition was arranged concurrently with the symposium with the aim of acquainting participants with operational experience of technologies and methods which further enhance safety and reliability. The exhibition focused mainly on manufacturing and repair techniques, and methods of non-destructive testing. Fifteen exhibitors from the Federal Republic of Germany, France, the United Kingdom, and the United States of America, took part. Some especially interesting exhibits are reviewed here.

Shape welded vessels

Nine years ago, plans were formulated for constructing components of any dimension and shape, using only weld metal. Instead of casting and forging or rolling, a multilayer weldment may be produced by the submerged

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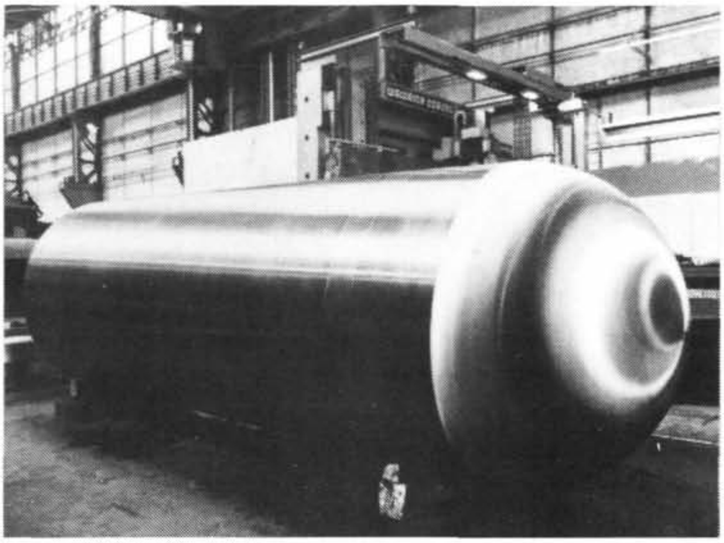


Figure 1. Shape-welded vessel.

arc welding (SAW) process. This method, called "shape welding" for brevity, has specific advantages for the manufacture of thick-walled components having properties such as high strength, and creep and corrosion resistance. Shape welded components are expected to meet the most stringent safety requirements and be cheaper than those produced using conventional methods.

A principal advantage of the process is that for the first time yield and tensile or creep strength can systematically be varied by using differing materials within a thick-walled component. Inherent problems of stress and toughness distribution as well as stress or stress-assisted corrosion cracking and erosion can normally be solved by using optimized filler types. Preliminary tests have also shown that shape welding has some advantages over conventional methods in, for example, the fabrication of vessels with an inner stainless steel cladding.

The use of shape welding in the manufacture of complex components is still in the development phase. Figure 1 shows a shape welded 58-tonne pressure vessel with a dome fabricated of 10 MnMoNi 55 filler material without a weld joint. The outside diameter is 1811 mm, the length of the cylindrical part is 4575 mm, and the overall length is 5482 mm.

Safety valves and the Basis Safety Concept

The Federal German Basis Safety Concept puts a special emphasis on materials. The basic safety of a component is determined by:

- use of high-quality materials having good characteristics, in particular toughness
- conservative limitation of stresses
- avoidance of stress concentrations, by optimizing design
- guarantee of the use of the best possible technology
- knowledge and judgement of faults.

If these requirements are met the "basis safety" of the components is assured; their failure as a result of faults in the manufacturing process is excluded.

Functional testing on test stands is also required. Before manufacturing begins prototype safety valves are tested under realistic conditions of pressure and temperature, mass flow, etc. The results obtained have to be evidenced again in further tests on fittings of the manufactured series. At the same time, the initial values for repeated inspection and function tests to be carried out later when the fittings are in service are ascertained.

Figure 2 illustrates a safety valve with spring washer and pneumatic control unit, type SIZ-DN 200 X 250 for a set pressure of 65 bar steam at 550°C, and a flow rate of 200 tonne/hour, demonstrated at the exhibition.

Remote-controlled welding and grinding machines

Impulse-welding technology has reached such high standards that pipe welding operations can now be performed successfully at any location. The introduction of transistorized power supplies has had a beneficial effect, since they assure exact repeatability of welding parameters.

For use in "hot" regions of the reactor, equipment must also be designed to be serviceable remotely as far possible. Welding equipment shown at the exhibition (Figure 3) comprised:

- power source with programme control
- surveillance system
- welding head
- manipulator for guidance of welding head
- cooling device
- annealing device (for pre-heating purposes).

Welding parameters may be different at each position around a circumferential weld, and to achieve a constant layer a process-control programme is necessary. The orbital head shown, guided along a taut strip by means of a manipulator, can weld pipe of up to 120 mm outside diameter. The head is fitted with TV cameras which allow precise surveillance of the welding process.

Increased safety requirements call for non-destructive examination of pressure-retaining welds during in-service inspection of nuclear plants, using techniques such as ultrasonic and X-ray examination. If ultrasonic examinations are performed on unprepared weld surfaces, misleading indications may originate from weld imperfections such as root sagging or shrink. If the root areas of circumferential welds welded from one side only are machined, root crack initiation is considerably reduced. It is now possible to grind the inside diameter (ID) of piping to such a standard that the definition of indications originating from the weld root region is quick and accurate.

A machine designed for this purpose is now being used successfully during the initial construction and subsequent replacement of pipework at all power plants from one manufacturer. A so-called "teach in" control system is used when it is necessary to grind bent weldments. More than 3000 welds have now been ground on site, most of them at locations almost inaccessible by other means.

This pipe ID-grinding machine has been adapted for use as a welding head carrier and positioning device for

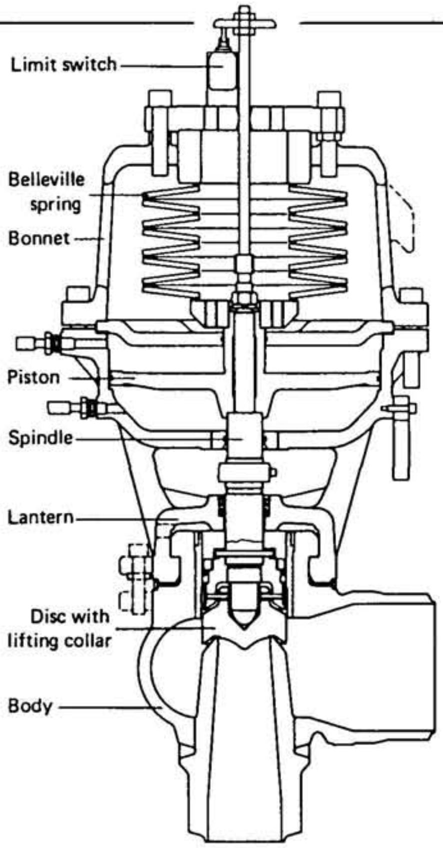


Figure 2. Safety valve with spring washer and pneumatic control unit.

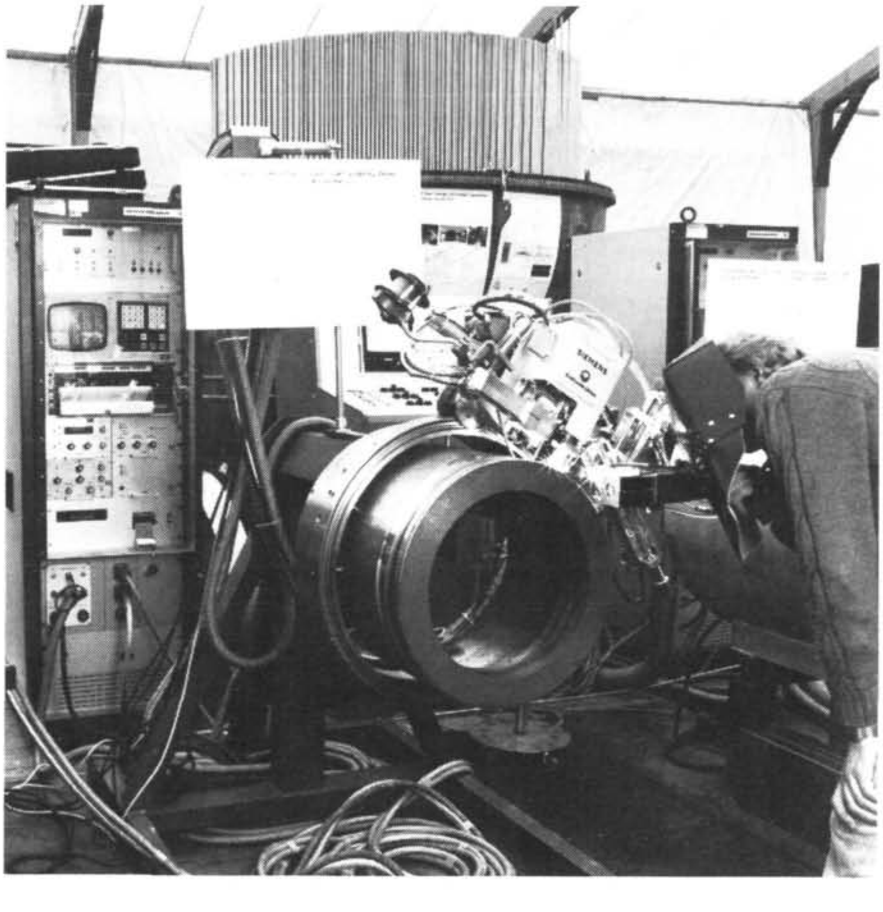


Figure 3. Remote-controlled welding machine for welding of pipe joints.

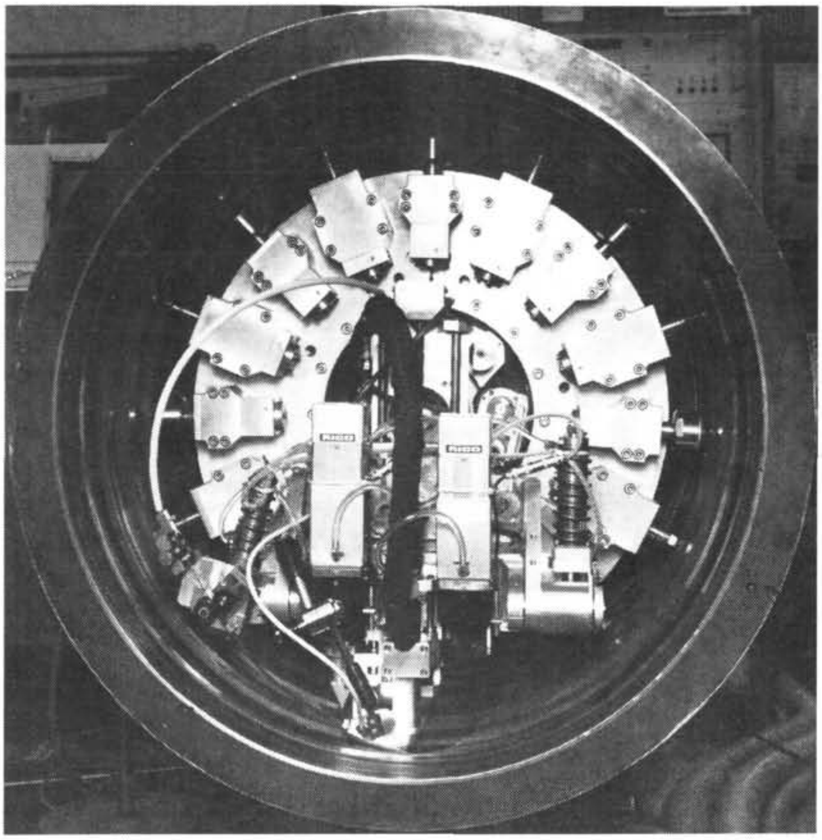


Figure 4.
Welding machine for pipe internal cladding.

the remote-controlled internal cladding of piping, and for pipe repair. The welding gear, shown in Figure 4, consists essentially of the same equipment as is used for external welding, but also comprises a TV system for monitoring of the welding process and for positioning. Its first use was during the construction of the Philippsburg 2 nuclear power plant, where 20 on-site welds of the primary piping were clad under remote control.

Repair of steam generator tubes by sleeving

In *Pressurized-Water Reactors (PWRs)* the steam generators are the interface between the primary and the secondary system. Operating experience over extended periods has shown that steam generator tubes may be susceptible to corrosive attack causing leakages due to denting, wastage, and intergranular stress corrosion cracking.

Periodic in-service inspections to determine the condition of the tubes are mandatory. Decisions whether to keep the tubes in service or to plug them are based on the results of these inspections. Excessive plugging, however, reduces the efficiency of the nuclear plant, and a "sealable sleeve" was therefore developed specifically for the repair of tubes. Figure 5 shows a sealable sleeve schematically. It consists of a heat-treated Inconel-600 tube plated with Ni-200 with a wall thickness of approximately 1 mm. After cleaning, the sleeve is inserted into the defective tube and attached at the top by gold alloy brazing. The brazing area is first expanded by explosive expansion to establish contact between the sleeve and the tube. The brazing alloy is retained in two shallow grooves on the sleeve; heat is applied by an induction heater inserted into the sleeve. The lower portion of the sleeve is joined to the tube by explosive welding. The alternative method, mechanical expansion, was rejected since its use might give rise to residual stresses higher than those resulting from explosive welding or hydraulic expansion.

Sleeving steam generator tubes has a number of beneficial features:

- reconstitution of the structural integrity of the steam generator
- preservation of the entire heat-exchange capacity
- restoration of the theoretical steam generator lifetime
- rapid and qualified performance.

A manipulator which may be used as a universal tool for inspection of steam generator U-tubes at low radiation exposure levels is shown in Figure 6. It may be used for:

- non-destructive tests, e.g. eddy current inspection, ultrasonic testing, profilometry, visual inspections
- plugging of tubes with explosive plugs, removable mechanical plugs and welded plugs
- repairs, e.g. sleeving of tubes and removal of leaking plugs
- pulling of tubes for subsequent examination.

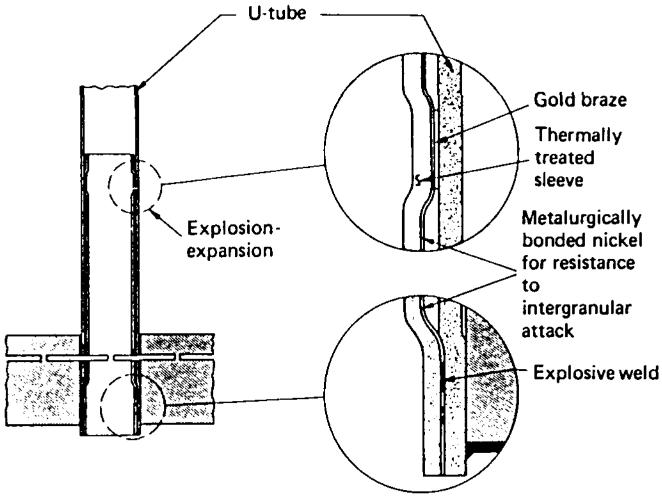
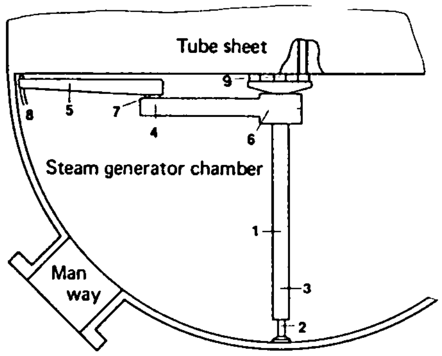


Figure 5. Tube sleeving.



1 Manipulator leg with drive shaft
2 Pneumatic cylinder
3 Motor for vertical movement
4 Head arm
5 Probe arm
6 Motor for head arm
7 Motor for probe arm
8 Probe
9 Camlock

Figure 6. Remote-controlled manipulator for inspection and repair of steam generator tubes.

Full-size reactor pressure vessel

The main attraction at the exhibition was a full-size reactor vessel. The experience gained in the baseline and periodic non-destructive examination (NDE) of reactor pressure vessels (RPVs) is of limited applicability, since those which are in operation only rarely contain cracks and, in general, manufacturing defects are repaired. Within the scope of a research project for the Federal German Ministry of Research and Technology a full-sized vessel with a large spectrum of defects was made available to MPA Stuttgart. The defects it contains are being used to qualify and evaluate the efficiency of NDE procedures which are in common use.

The *Boiling-Water Reactor (BWR)* pressure vessel has an inside diameter of 5875 mm and a wall thickness of 146 mm in the cylindrical part. The top dome thickness is 88 mm, the bottom dome is 202 mm thick, and the total height is 17 500 mm. It consists essentially of A508 Class 2 material and contains various material and defect states as well as nozzles of different shapes (Figure 7).

The main purpose of the project is to demonstrate and verify the effectiveness of various conventional and newly developed NDE methods in conjunction with the use of automatic manipulator systems under simulated operating conditions. The testing procedures and concepts will be optimized on the basis of a defect and system analysis. The major test areas are shown in Figure 7.

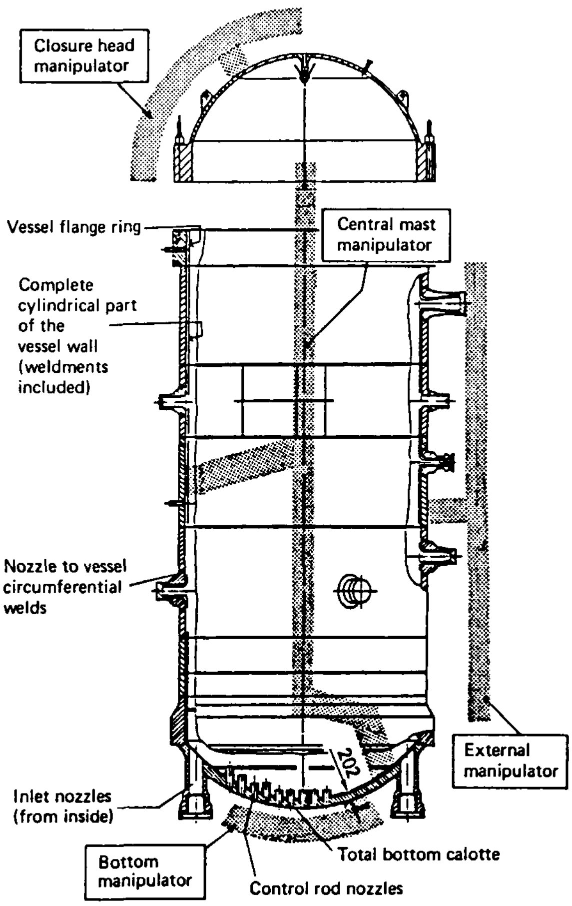


Figure 7. Testing areas in the full-sized vessel.

Central mast manipulator

A central mast manipulator has been designed for the interior ultrasonic inspection of reactor pressure vessels. Special emphasis was put on maximum flexibility in terms of applicability to pressure vessels (mainly PWR) of various sizes. For inspection, the central mast manipulator is placed on an auxiliary bridge. The mast

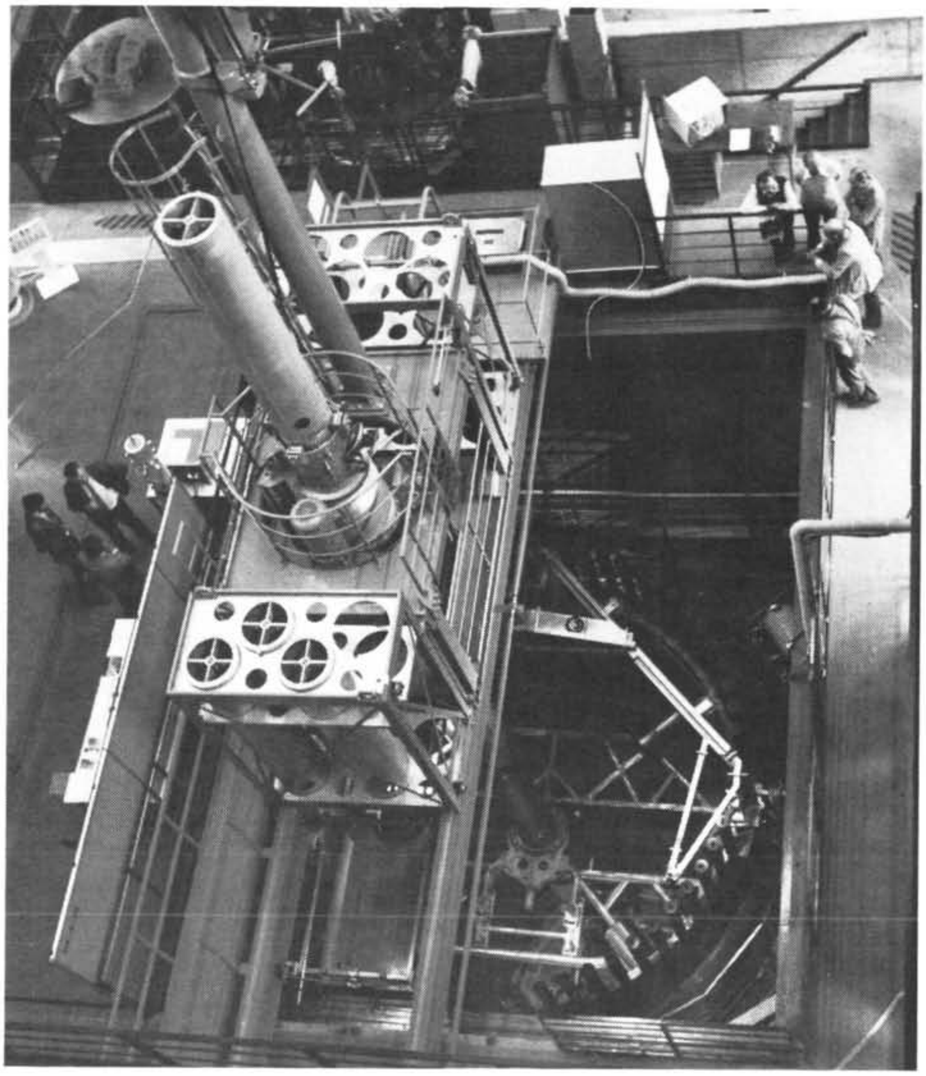


Figure 8.
Central mast manipulator adapted to the full-sized vessel.

consists of a number of cylindrical columns centred on a device at the level of the studs. The lowest part carries the inspection arms (one horizontal for the cylinder and nozzle inspection, one pivoting for the bottom). An integral crane makes the manipulator independent of the building crane.

For the interior inspection of the full-size BWR vessel the manipulator was adapted to larger dimensions (Figure 8). The centring device can be fixed at various heights within the vessel, enabling 100% inspection.

Universal manipulator for BWR-RPV inspection

The universal manipulator moves on fixed vertical rails in the inspection gap between the RPV and its insulation. A complete inspection of the cylindrical part of the BWR-RPV and of the nozzles including their radii can be carried out. A special arrangement of the nozzles on the RPV, and an optimized design of basic carriage of the manipulator plus a limited variety of extension arms adapted to the various geometries, were called for.

Figure 9 shows the universal manipulator on a RPV mock-up with a 1 : 1 piece of rail and a simulation of the limitations of movement by a nozzle. The multiple-probe system can be seen clearly above the nozzle simulation.

Manipulator for inspection of ligaments in bottom closure

For remote guidance of probe modules in performing the compulsory periodic inspection of reactor pressure vessels it has become common practice to use standardized inspection manipulators which, equipped with all necessary accessories, are designed for scanning of the inspection zones. In addition, it is frequently necessary to use manipulators of special design to inspect particular zones or components, especially when inspection from the outside surface is required. A manipulator developed for the inspection of the ligaments in the bottom closure is one of these tools; it is designed to guide probe modules on the outside of a BWR (Figure 10).

Figure 9.
Universal manipulator on an RPV mockup.

The manipulator incorporates a multiplicity of individual components: track rails, probe car, probe module mounts, transfer car, and electric and pneumatic control console. The probe car, equipped with various exchangeable probe modules depending on specific needs, moves on a system of curved rails permanently installed in the lanes between the ligaments. The inspection car and probe module mount are moved by remote control from the electric and pneumatic control console, their instantaneous positions being transmitted back for indication and recording (together with the test results). A transfer car is used to transfer the probe car from one rail to the next.

The rails are in the form of a channel section, open at the top, with an integral gear rack to drive the probe car and to monitor position. The rail system is supported by rigid-mountings and slip-fit bearings to render it independent of thermal expansion. Beyond the area of the bottom closure the rail system is extended to permit the probe car to be mounted outside the zone of high irradiation, where it is also possible to perform all

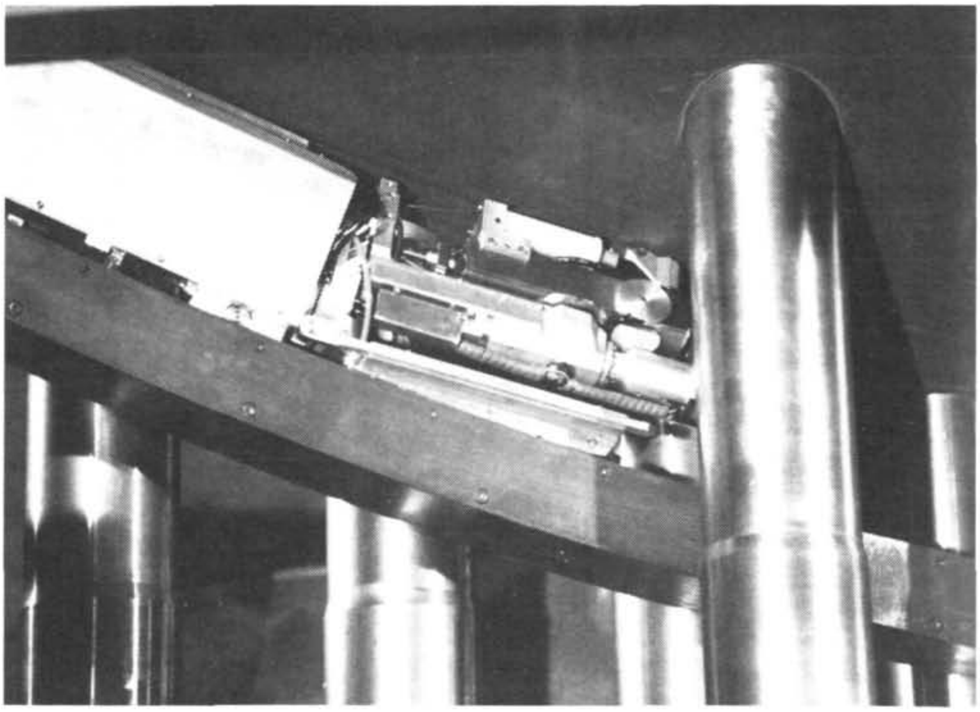


Figure 10.
Manipulator for the inspection of ligaments in the bottom closure.

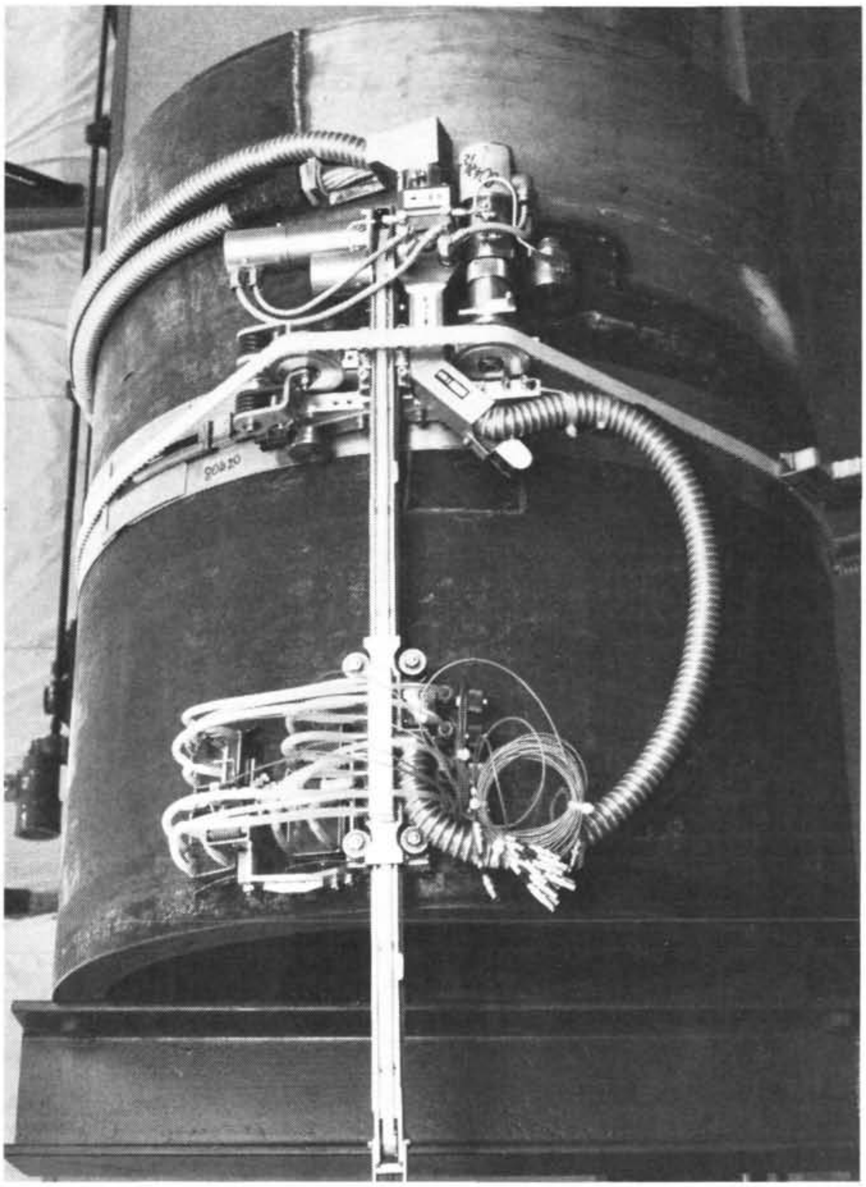


Figure 11.
Belt manipulator for piping inspection.

necessary maintenance work and change the probe modules. The probe car is self-propelled by a motor drive and guided on the rails by a rack-and-pinion system. It is designed to carry the following probe modules, which are connected by articulated joints and can be exchanged according to requirements: a multi-crystal probe unit; a cantilever bracket which permits the probe to travel perpendicular to the direction of the lanes; a module with three single probes; a TV camera and lights; and a measuring boom for dimensional data acquisition.

Manipulators for piping inspection

The field of in-service inspection of piping is covered by various manipulator "packages" of modular basic equipment. Each set of manipulators corresponds to a modular ultrasonic testing device and data processing system.

Figure 11 shows a belt manipulator. A guide belt is mounted around the pipe near the area to be inspected. A carriage with a variable extension arm allowing movement perpendicular to the belt carries the probe system allowing meandric movement. The height of the manipulator is relatively small (ca. 120 mm), and it can therefore be used at plants already in operation. The range of pipe diameters to be examined extends from 160 to 1500 mm.

Eddy-current examination of steam generator tubing

Periodic inspection of the integrity of the heat exchanger tubes in steam generators is required, to guarantee that no radioactive coolant can enter the secondary circuit through leaks. As radioactivity is present in a steam generator, giving rise to an associated risk of radiation exposure of maintenance personnel,

Figure 12.
Primary chamber head mockup with eddy current equipment.

the examination required has to be executed rapidly and extremely reliably by means of remote-controlled devices.

Eddy-current testing is used to find possible defects. Special analytical procedures can be used to describe any defect in terms of its position, magnitude, and origin. Changes in the physical properties of the tubes due to damage are ascertained from the resultant of two superimposed alternating magnetic fields. One is generated by a test probe, which induces eddy-currents in the tube. These in turn produce an alternating magnetic field opposite in sense to the initiating field. It is necessary to use several test frequencies at the same time in order to ensure that neither the tube layout nor electrically conductive deposits on the tube-sheet interfere with the flaw signal and, therefore, the flaw perceptibility.

Using this examination procedure any reduction in wall thickness of greater than or equal to 20% can be reliably recognized and distinguished as either an outside or an inside defect. In addition, the level of any sludge in the secondary side can be determined during the tube examinations.

To carry out an eddy-current examination the following equipment is essential:

1. manipulator, consisting of positioning unit, feed device and control device;
2. multiple-frequency eddy-current testing device, including test probe;
3. data acquisition and data processing equipment;
4. instrument container and control equipment.

Figure 12 shows a primary chamber head mock-up with the eddy-current test equipment, as exhibited.

Phased array system

This system was developed by the Fraunhofer-Institut für zerstörungsfreie Prüfverfahren (IzfP) for basic and in-service NDE-inspection of reactor pressure vessels. The system consists of 24 microcomputer-controlled channels. Charge-coupled devices (CCDs) are used to delay the transmitted and received pulses. By changing the clock frequencies the time delays can be varied. Each CCD chip contains two channels. The first channel delays appropriately the sine-wave bursts which excite, after linear amplification, the array probe elements. The preamplified echo signals are delayed in the second channel of the CCDs, summed, and displayed as an A-scan or B-scan presentation. The clock frequencies are generated by synthesizer modules. The calculation of the clock frequencies and the control of the time basis of the x-y display is performed by the microcomputer. The centre frequency can be varied from 0.5 to 5 MHz and the pulse length between 1 and 20 cycles. By appropriate phasing, longitudinal, transverse and surface waves may be generated; and by suitable excitation of the array probe elements the ultrasonic field can be steered, focused and formed. Fast electronic beam forming by phased arrays offers new possibilities for defect reconstruction and classification. Basically, three approaches may be distinguished:

- at a fixed probe position the defect may be scanned with a narrow sound beam (sector scan);
- the probe may be moved by a manipulator and, at each position, a sector scan performed. On a storage display all sector scans are superimposed (compound scanning);

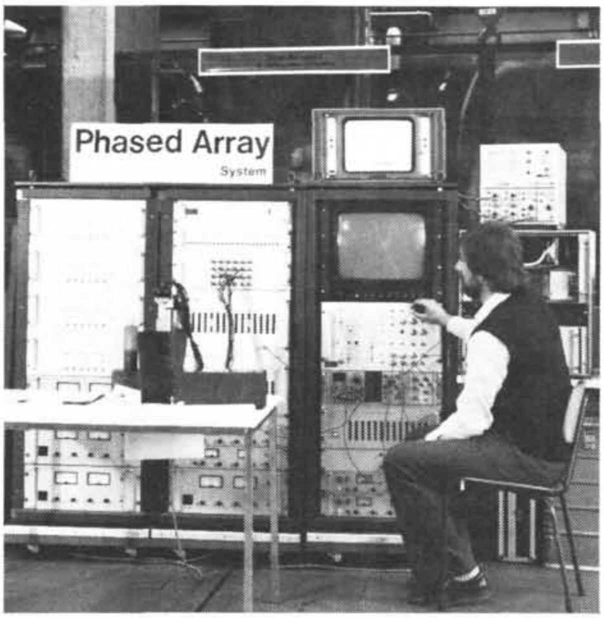


Figure 13. Phased Array System.

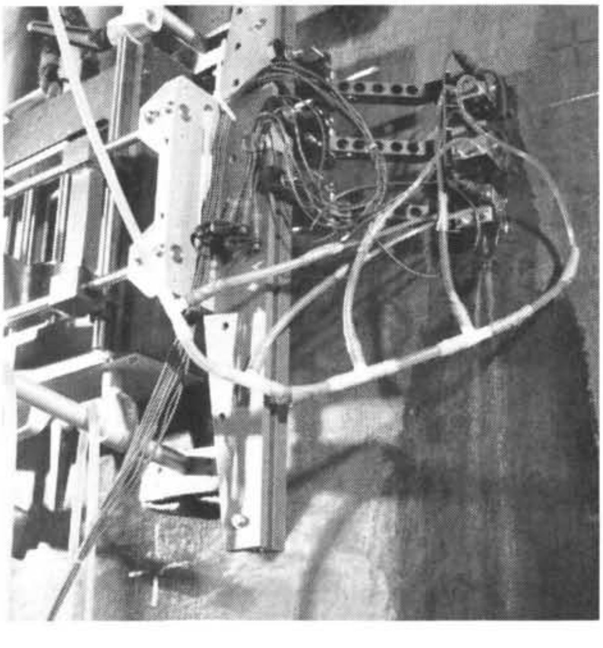
- at each probe position a sector scan may be performed with open beam, and the maximum echo height in the azimuthal direction recorded. The resultant compound scan amplitude locus curve represents directly the defect orientation.

Figure 13 shows the system configuration prepared for an examination on a test piece.

ALOK (Amplitude – Time of flight – Locus curve) system

The ALOK system was designed by IzfP for in-service inspections of pressure vessels and reactor components as a defect detection system with high detection capability and resolution. It has as well an inherent capacity for defect characterization. Figure 14 shows the ALOK probe system and manipulator mounted on the full-size vessel. A transmitter system employs HF-multiplexers at the entry units which transfer all test signals to a signal processing system. The determination of the peak value of the HF-signal is performed in a compactor system. Transit time, giving flaw depth, is measured; simultaneously, the compactor monitors the status of the flaw depth counter and performs the data reduction.

Figure 14. ALOK probe system with manipulator.



The local co-ordinates of the probe system and amplitude/transit time values are collected in data blocks. After reaching a certain block size the data are transferred to the computer or to the mass storage. The main steering device co-ordinates the whole system. During examination the A-scan of the single test functions can be obtained on a display, with their linear or logarithmic amplitude curves.

In the ALOK technique a flaw signal is stored if a certain number of half waves before and after the maximum are equal or smaller than the maximum. The decision depends on the signal shape of the transducer used. By means of this technique all signals, even certain noise information, are stored depending on the transit time; relevant indications can be separated from the stochastic background noise and, by pattern recognition, from geometrical effects.

Acoustic linear holography

Acoustic linear holography is a means of analysing a detected defect by determining its dimensions. The defect is "illuminated" by an ultrasonic probe with a divergent beam. Amplitudes and phase information are measured, stored, and numerically superimposed on a reference wave. The hologram formed as a result of this procedure may be used as the basis for reconstruction of the ultrasonic field in the half-plane below the aperture line.

For planar defects with orientations perpendicular to the surface a tandem technique is most suitable. In Figure 15 a measurement on a large vessel test-block at one of approximately 120 inserted defects is shown. A special analysing manipulator (with high accuracy and position resolution better than 1/10 of the wave length) is necessary for the measurement. This can be mounted on the central mast manipulator or the primary circuit manipulator.

Remote visual inspection of advanced gas-cooled reactors

British commercial nuclear reactors are designed for working lives in excess of 25 years. One of the methods used by the Central Electricity Generating Board to confirm continuous integrity is a periodic visual inspection of the reactor interior during shutdowns. The modular TRIUMPH TV camera (Figure 16) is used to carry out the majority of visual inspections. It has an overall length of 1000 mm, is gas-cooled and is deployed by a variety of hoist units and manipulators. It has been used in ambient temperatures of 120°C. The viewing range is up to 6 m. A prism in the front module can tilt over a 105° range. Behind this module is a 6 : 1 motorized zoom lens assembly which incorporates an extended focusing range for viewing objects very close to the camera using the front lighting. The TV camera module uses a 16 mm low-light level tube. The rear module houses the main lighting which can be tilted as required. The complete assembly can be rotated by ± 180°. All camera, lens, and lighting functions are remote-controlled.

For Hartlepool and Heysham I advanced gas-cooled reactors, additional cameras and manipulators have been developed to inspect the boiler top closure region and the boiler tubing. As shown in Figure 17, each boiler closure region has been fitted with two permanent circular rail systems; a compact 16 mm camera assembly fitted with its own lighting may be transported around the rails using a series of trolleys. The camera has remote focusing, rotates over 180°, and is gas-cooled.

When a gas circulator has been removed the boiler tube viewing TV camera is guided through the 25 mm gap between the concentric tubes (Figure 18). The camera has a cross-section of 43 mm X 18 mm. It has remote focusing, rotates over 360°, and is gas-cooled.

Extension rods are added to the front camera section as it is driven up the gap between the tubes. A sideways viewing mirror in front of the camera can be moved out of the field of view to allow for forward viewing. A photographic camera utilizing the same cross-section has been developed.

The need for remote visual inspection above the gas baffle dome has resulted in the development of the Links Manipulator (Figure 19). This manipulator is capable of positioning a TV camera in a variety of orientations. It can be extended up to 7 m by using a reactor access hole only 260 mm in diameter. It is being further developed to allow visual inspections to be carried out below the gas baffle dome and in the pressure circuit peripheral regions.

Heavy-duty manipulators for remote operations

The examples of non-destructive testing methods mentioned reveal the success which has been achieved in flaw detection and sizing, coupled with a reduction of the radiation exposure of testing personnel by using automatic manipulator systems.

For further tasks such as necessary repair work on vessel cladding or the eventual dismantling of the pressure vessel, when a manipulator system capable of handling different automatic tools in a highly radioactive environ-

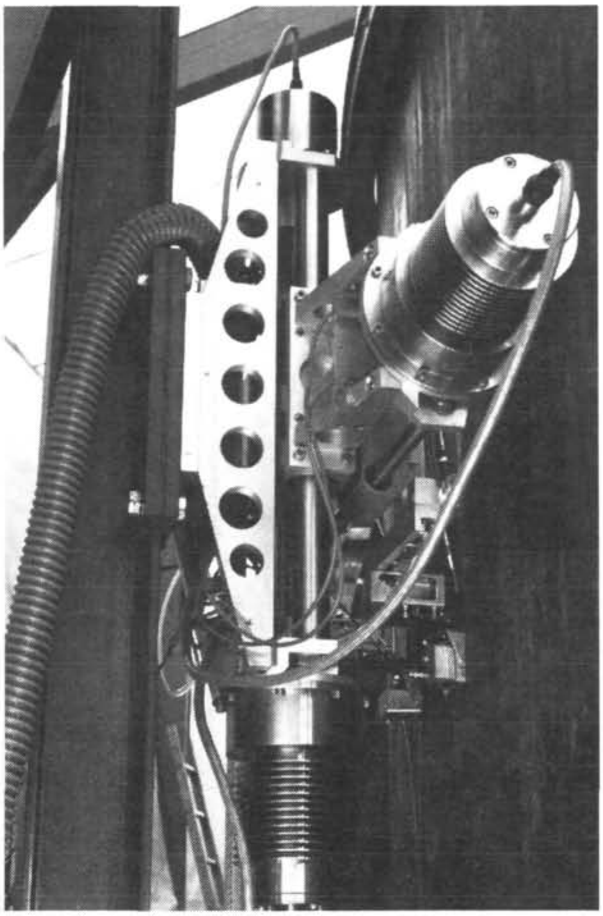


Figure 15. Analysing manipulator for acoustic linear holography

Figure 16. TRIUMPH assembly 70 mm diameter.

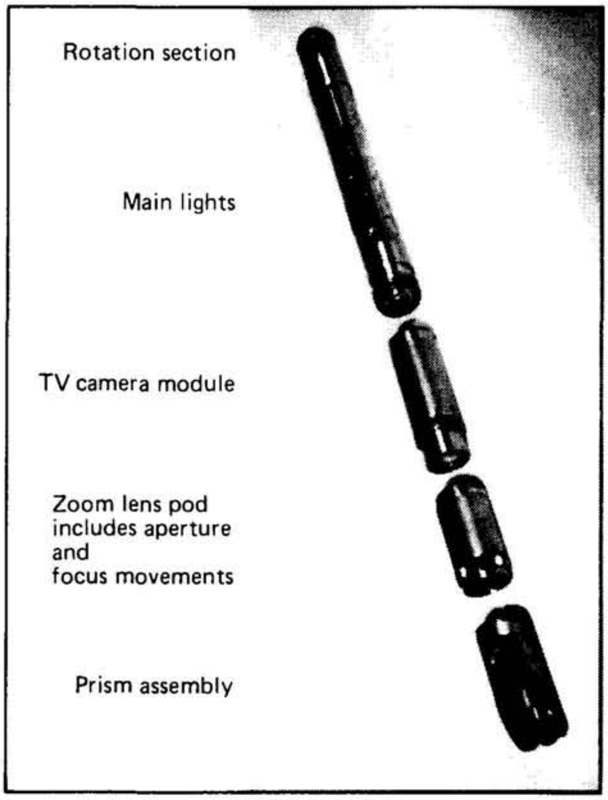
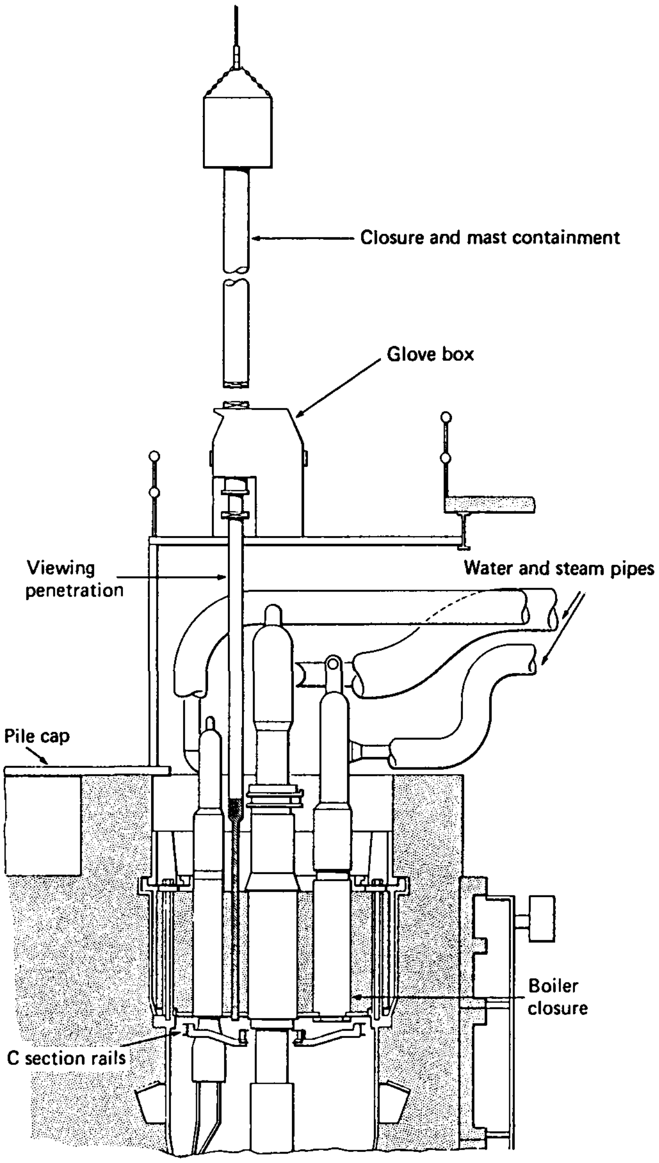


Figure 17. Boiler closure viewing equipment.



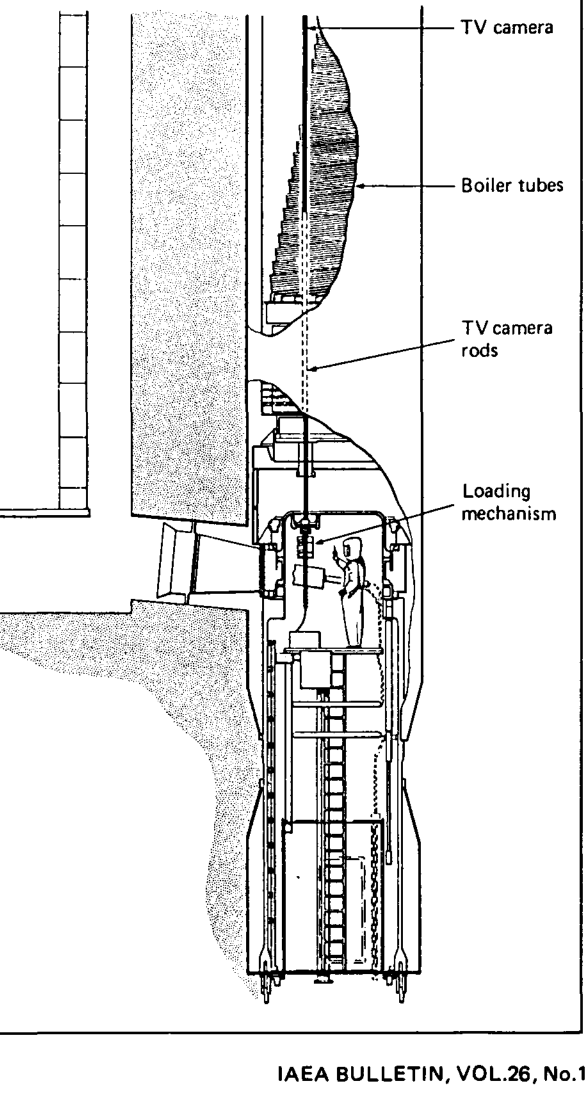


Figure 18. Boiler tube viewing equipment.

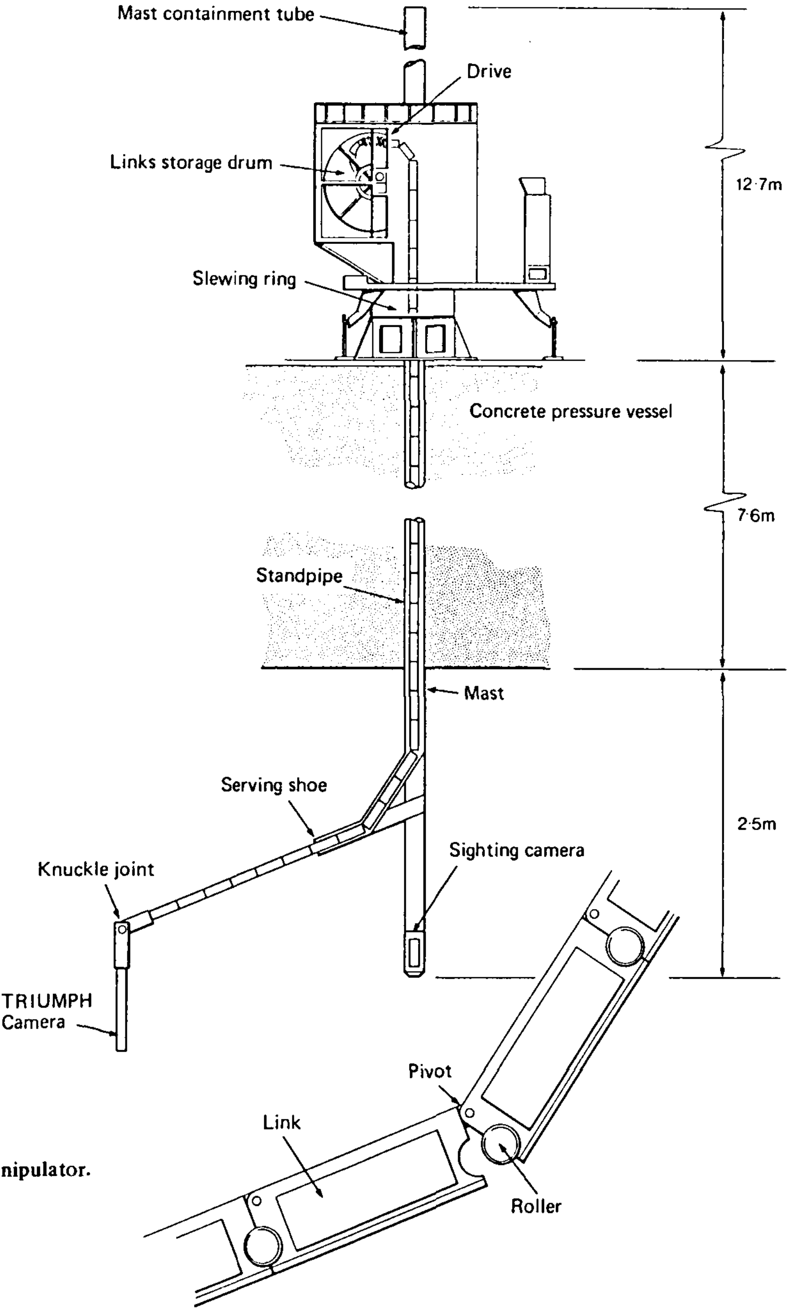


Figure 19. Schematic of LINKS manipulator.

ment and of lifting or holding heavy equipment will be required, a remote-controlled heavy-duty manipulator system and a number of adaptable automatic tools for mechanical and thermal machining of carbon or stainless steels have been developed. A first industrial application of such a manipulator system will be the remote dismantling of an activated pressure-tube reactor as part of a turnkey project for the total decommissioning of the nuclear power plant at Niederaichbach.

Figure 20 shows a 1 : 15 scale fully operational model of such a manipulator system, installed in a model of the Niederaichbach plant.

The multidirectional movements of the manipulator comprise a 380° rotation of a ring girder, shown as the manipulator support structure positioned in the original bearing of the fuel element handling machine on the upper floor of the reactor (Figure 21), upon which an eccentrically-arranged horizontal slide operates. The manipulator mast, which also rotates up to 380°, is placed in the horizontal slide. A vertical slide, equipped with a universal gripper and adapter unit for special tools, moves up and down the mast. There is a distinct position where the vertical slide can pass from below the ring girder to the top of the mast. The system thus has a special

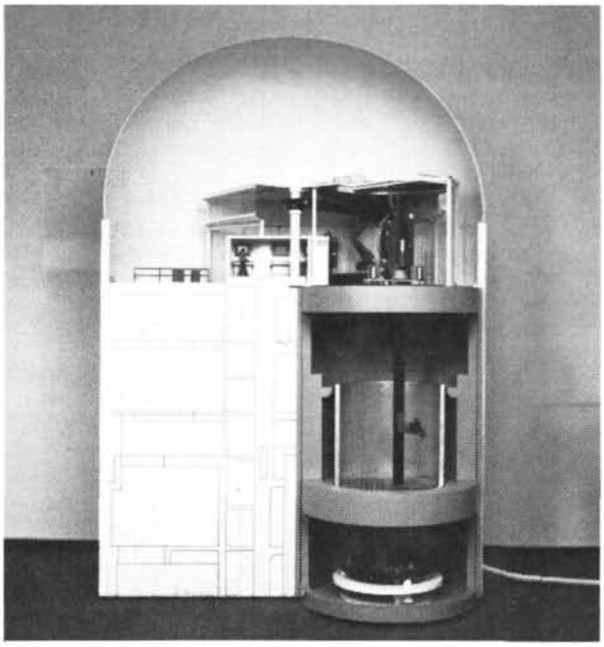


Figure 20. 1 : 15 scale operational model of a remote-controlled heavy duty manipulator system.

Figure 21. Top view of the heavy duty manipulator system showing the rotating ring girder opening.

advantage with respect to transferring parts or adapted tools from the upper floor down to the operating area inside the reactor vessel or vice versa.

The system has a large operational cross-section, equal to the ring girder opening, and requires no additional linkage inside the vessel for stabilization. As designed, the construction is capable of lifting three tonnes.

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