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The H.T.R. - B.N.D.C.'s Latest Design and Supporting Development in the United Kingdom

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SUMMARY

British Nuclear Design & Construction submitted a tender to the U.K. Central Electricity Generating Board in April 1971 for a nuclear power station based on an H.T.R. Since that time B.N.D.C. has made improvements to its design, including the gas circuit arrangement, boilers, and steam cycle. This paper describes some of these improvements, as well as an alternative fuel element design for which the reactor is suited. An outline account is given of supporting fuel and materials development work being carried out in the United Kingdom.

1. INTRODUCTION

British Nuclear Design & Construction submitted a tender to the Central Electricity Generating Board of the U.K. in April, 1971, for a nuclear power station based on a single helium cooled ceramic fuelled reactor (H.T.R.). This station was for an output of 750 Mw(e), but an alternative with an output of 907 Mw(e) was also offered. Some details of these designs have been publicised at the 1971 Geneva Conference and other Conferences.

Though these offers have not yet been taken up by the C.E.G.B., B.N.D.C. has continued design work on the H.T.R. system, which it believes has great promise for the future. Several improvements have been incorporated. Some of these, relating to the gas circuit arrangement, and the main boilers and steam cycle are described here. The first part of this paper is concerned with these improvements which will lead to reductions in cost, complexity, and technical risk of the H.T.R., and with important features of fuel, core, and emergency cooling arrangements. The second part outlines some major aspects of the supporting fuel and materials development programme in the U.K.

2. BASIC PRINCIPLES OF B.N.D.C. REACTOR DESIGN

In preparing H.T.R. designs B.N.D.C. has placed particular emphasis on the following principles:

(i) Simplicity of the general concept and of component design.
(ii) Ease of operation in normal and fault conditions.
(iii) Minimisation of moving parts and stressed steel components in the reactor gas outlet stream.
(iv) Reliable means of protecting reactor components when faults occur, both for safety and to safeguard the purchaser's investment.
(v) Maximum replaceability of reactor components.
(vi) Ensuring maximum value is obtained from previous B.N.D.C. design, manufacturing, and construction experience.
(vii) Design for rapid construction.

Though some of these principles tend to conflict in some areas, it is B.N.D.C.'s contention that in its design these principles are very successfully embodied. The way in which this has been achieved is decribed below, in relation to several features of this design.

3. OUTLINE DESCRIPTION OF DESIGN

Figure 1 illustrates diagrammatically the general arrangement of B.N.D.C.'s H.T.R. The design described here produces 915 Mw nett electrical output.

The reactor is contained in a cylindrical prestressed concrete pressure vessel, having boilers and gas circulators housed in vertical pods within the side wall. This arrangement is very similar to that of four 660 Mw(e) gas cooled reactors now being constructed by B.N.D.C. Access for refuelling is through an array of penetrations through the upper cap of the vessel. Helium coolant flow is downwards through the core. The reactor is designed so that it can be refuelled on load, in accordance with the C.E.G.B. specification.

The coolant circuits external to the reactor core, and the steam system, are split into two parts, termed the "main system" and the "auxiliary system". About 81% of the reactor coolant flows through the main circuits and 19% through the auxiliary circuits. Both circuits operate continuously during normal operation producing steam which passes to an 800 Mw(e) main turbine-generator and to two 80 Mw(e) auxiliary turbine-generators respectively. There are four main boiler pods and four auxiliary boiler pods.

The auxiliary system is used in the starting up and shutting down of the reactor, and to give continuity of electrical supplies during faults. The reasons for its adoption will be given later. Station output control is normally effected through the main system.

The reactor core consists of 235 hexagonal graphite columns containing fuel, surrounded by radial and axial reflectors and shields. Each core column contains 5 fuelled blocks 0.5m across flats and 1.0m long, and axial reflectors and shields totalling a further 4m. The columns, other than the outer radial reflector ring, are carried on graphite struts, which in turn are carried on a bed of ceramic insulating blocks set on the vessel bottom liner. The space spanned by the support struts forms the reactor coolant outlet plenum. This is closed circumferentially by a continuous graphite skirt, which also acts as a support for the outer ring of radial reflector columns.

Eight pairs of concentric ducts connect the reactor vault with the eight boiler pods, the inner duct carrying reactor outlet gas from the outlet plenum to the boiler inlet, and the outer duct carrying gas circulator outlet gas back from the boiler pods to the reactor vault. In the vault this gas passes upwards alongside the graphite stack and then downwards through the core. In the main boiler pods the reactor outlet gas passes upwards over the boiler tubing to the gas circulator inlet, then downwards between the boiler casing and pod liner to the concentric duct outer annulus. In the auxiliary boiler pods the reactor outlet gas passes downwards over the boiler surface, upwards through a central tube to the circulator inlet, then downwards between the tube and the pod liner to the concentric duct outer annulus.

This coolant gas circuit arrangement ensures that all the vessel insulation except that beneath the graphite stack (which is replaceable) is swept by helium at reactor inlet temperature.

4. PERFORMANCE DATA

Helium pressure	45 bar
Reactor inlet temperature	264°C
Reactor outlet temperature	704°C
Reactor heat output	2331 Mw
Reactor coolant flow	1030 kg/sec
Total coolant pressure drop (main)	1.036 bar
Reactor pressure drop	0.661 bar
Main circulator power	7.0 Mw each
Auxiliary circulator power	1.75 Mw each
Mean fuel burn up	80 GWD/Te
Core power density	8.5 Mw/m^3
Mean feed fuel enrichment	7.7%

	Main system	Auxiliary system
Feed water temperature	182°C	157°C
Superheat steam temperature	538°C	510°C
Superheat steam pressure	160 bar	86 bar
Superheat steam flow	2.19×10^6 Kg/hr	0.57×10^6 Kg/hr
Main turbine (gross)	800 Mw	
Auxiliary turbines (gross)	2 x 80 Mw	
Nett station efficiency	0.393	
Nett station output	915 Mw	

5. ASPECTS OF REACTOR CORE DESIGN

The main design requirements for the graphite stack were:

(i) To devise a satisfactory on load refuelling scheme, in which blocks could not become jammed in the graphite stack during withdrawal or replacement.

(ii) To achieve mechanical stability of the stack.

(iii) To ensure that there will no leakage paths allowing an excessive bypassing of fuel by the coolant gas.

(iv) To accommodate enough control rods and secondary shut down absorber in uniform arrays.

(v) To achieve uniformity of components with maximum simplicity and symmetry.

Downflow cooling of the core was chosen for several reasons, the primary ones being: to have the control rod and fuelling mechanisms operating at the lower temperature end of the stack; and to avoid the reduction in mechanical stability of the graphite stack which upthrust due to upward gas flow would have given, particularly during refuelling on load.

Core column pitch is 520 mm, and the columns abut each other over short lengths in the top and bottom reflectors where Wigner damage is insignificant. The abutments in the bottom reflector, together with the skirt surrounding the outlet plenum, form the gas seal against core bypassing. Between the abutment levels the column diameter reduces so that there is a 20 mm gap between columns, which is capable of accommodating bowing due to Wigner, thermal, and machining tolerance effects without the columns touching. This gives geometric freedom for removing the blocks during fuelling without risk of jamming, and also avoids gaps opening between end faces of fuelled blocks which would cause coolant to bypass the fuel channels. The blocks of the upper abutment plane carry a patented spring device designed to eliminate problems of interference with adjacent columns and possible resultant jamming.

To permit free movement of the columns between abutment planes, the lower reflector contains a special pivot and gas seal arrangment. To ensure that the columns between butting planes are mechanically stable a large column diameter, 0.5 m across flats, has been selected. With this diameter none of the forces occurring during refuelling or at any other time will cause the columns to break open at the joints. The columns are mounted so that both gravitational forces and coolant pressure drop act to hold the columns together in the abutment planes.

Each of the 235 core columns contains a 110 mm. diameter central hole which can accommodate either a control rod, or secondary shut down absorber in special emergency. These central holes are also used to accommodate the fuelling machine lifting grab. All the fuelled blocks in the core are exactly the same.

6. ALTERNATIVE FUEL ELEMENT DESIGNS

Figure 3 shows the fuel block design used by B.N.D.C. in its tender to the C.E.G.B. This utilises the reference tubular interacting fuel pin developed in the United Kingdom, shown in Fig. 2. Each pin contains 9 pressed annular compacts of coated fuel particles in a graphite matrix. Each fuel block contains 24 fuel channels of 75.8 mm diameter, and the central 110 mm hole. There are 2 fuel pins in each channel, and the coolant passes down through the centre of the fuel pin as well as through the annulus between the fuel pin and the channel wall.

In addition to this style of fuel element, BNDC has studied the form of element shown in figure 4. In this arrangement the fuel is in the form of cylindrical pellets of the same composition as the compacts of the tubular interacting pin. The pellets are set in 144 vertical holes in the block, closed at either end. An interspersed pattern of 300 coolant channels pass through the block. The 110 mm. central hole is retained. The behaviour of fuel blocks of this general type, but different detailed geometry will be demonstrated when the Ft. St. Vrain reactor constructed by G.G.A. is operated.

It had at one time been believed that the type of element shown in figure 4 would not be suitable for the low enrichment uranium cycle, but B.N.D.C.'s studies have shown that the two types are likely to yield almost equal generation costs. Thus the choice of type would most logically be made on the basis of general robustness, magnitude of internal stresses in normal and in power cycling operation, corrosion by small concentrations of water, and fission product retention characteristics. It should be noted that the U.K. reference fuel pins has successfully undergone extensive testing, as outlined in section 11 of this paper.

Both types of fuel element are suitable for use in B.N.D.C.'s reactor.

There is evidence, not yet confirmed in numerical detail, that both types may also be used economically in conjunction with the uranium/thorium cycle. Further studies covering the use of uranium or thorium as fertile materials, and uranium or plutonium as fissile materials, are in hand or proposed in the U.K.

7. STEAM CYCLES

In order to simplify the boilers to the maximum extent, no reheaters are included in the pods. The main and auxiliary steam cycles are illustrated in figure 1. In the case of the main system, steam leaving the intermediate pressure cylinder is reheated by steam bled from the exhaust of the high pressure cylinder, before passing to the low pressure cylinders. This is similar to arrangements in operating B.N.D.C. stations. Condensate from the reheater vessel is passed to the deaerator. The moisture level in the L.P. exhaust is 8.8%, and in the I.P. exhaust 4.5%.

The reheater vessel is sited close to the main turbine. The quantity of plant enclosed within the reactor vessel and subject to radioactive contamination and repair and maintenance difficulties is reduced. Though the efficiency of this cycle is about 2½% less than that of the usual reheat cycle where the reheater is in the primary circuit, the saving in pipework, boiler and reheater plant more than outweighs this.

The auxiliary steam passes to two standard single cylinder turbines through condensers, feed heaters, and deaerator, to the feed pumps. This is a simple non-reheat cycle.

8. BOILER DESIGN

Each main boiler is mounted on a central tubular spine which extends from the base of the pod to the top of the heat transfer surface. The heat transfer tubing is wound helically around the spine, and is carried through hangers from brackets attached to the top of the spine. Feed tubes enter the reactor vessel through a vertical penetration below the spine, and pass up the spine. The water then flows down through the helical tubing, and emerges as superheated steam at the lower end. The superheater tail pipes are collected into four bundles which pass out of the vessel through four separate penetrations disposed round the feed penetration.

This very simple arrangement is made possible by having downflow of water through the boiler tubing. This does not lead to water flow instabilities because, firstly, the angle of the tubes to the horizontal is only about 6^{o}, and, secondly, the main boilers never have to operate steaming at below 20% of full load. Experimental work has confirmed the stability.

9. EMERGENCY COOLING ARRANGEMENT

The reactor has a negative temperature coefficient, the fuel (of both types described) transfers its heat to the moderator very readily, so that faults do not cause large fuel temperature increases quickly, moreover the fuel is able to withstand large temperature increases without general failure. Consequently the first concern of the emergency cooling arrangements is not to control the fuel temperature, but to safeguard the boilers and gas circulators so that they will not suffer damage, and will continue to be available to remove heat.

The downward gas flow in the core dictates a minimum flow following reactor trip, of about 8%, to prevent flow instability and reversal which would overheat components above the core and eventually the gas circulator. Because the core behaves as a large heat store in close thermal connection with the coolant, the heat removed initially, following a reactor trip, is proportional to the gas flow.

It is, therefore, imperative that the balance between gas and feed flows is maintained within close limits, to avoid wide fluctuations in boiling level and steam and metal temperatures in the boilers. This requirement would demand a low turn down ratio for the main boilers, and good control and flow stability at these low loads, following a reactor trip. The requirement would apply to a broad range of faults and initial conditions.

To avoid these difficult design requirements for the main boilers, and to give continuity of feed water and helium flow, B.N.D.C. proposes to stop both gas and feed water flow to the main boilers following reactor trips, and to continue cooling with the auxiliary system. By this means the main boilers and circulators are protected from rapid temperature changes, and do not have to operate producing steam below 20% load, thus avoiding flow stability problems.

The auxiliary system is capable of producing power from reactor after-heat for some hours. Immediately following a fault it continues to operate without need for major adjustment, and only after some time has elapsed need the gas flow be reduced; the auxiliary feed flow is controlled to match the gas flow in both normal and fault operation.

Because of the small size of the units, the auxiliary system is provided inexpensively with a good redundancy of components such as feed pumps, etc. The auxiliary boilers and turbines are designed and chosen for simplicity and reliability. Two out of the four auxiliary boilers and one of the auxiliary turbines is adequate for provision of emergency cooling in all faults with reactors at pressure, and the system is designed so that no special action is required if up to half the system fails to operate. Furthermore, the safety of the station does not depend on quick starting of prime movers, because the auxiliary system is always in operation when the station is in operation, it being given the start up and shut down role. A small diesel installation is provided for longer term cooling in case electric power supply from the grid is unavailable.

The auxiliary system pays for itself by contributing to station output, and its inclusion permits great simplification of the main boilers, as well as improving safety and reliability.

10. REPLACEABILITY OF COMPONENTS

During the refuelling cycle, the whole of the reactor core, upper reflector and shield, and the inner half of the lower and radial reflectors, are removed. The parts not containing fuel may also be renewed if required. In addition, the whole of the graphite stack, its support columns, and the ceramic insulation layers resting on the vessel liner, below the core and inner radial reflector, are designed within the basic hexagonal geometry of the core columns. All these parts are removable using the fuelling machine with an extended reach tool, should they be damaged or a fault suspected. The boilers, gas circulators, and hot gas ducts are all designed to be replaceable should it ever prove necessary. All the insulation of the boiler pod is replaceable. Vessel prestressing cables are replaceable. The specification of shielding and fuel respecting fission product release has been aligned with access requirements to permit this extent of replaceability.

The only components not easily replaceable are the reactor vault side wall and ceiling insulation, the outer ring of the graphite stack, the graphite stack peripheral location steelwork, and the reactor vessel structure.

11. FUEL MANUFACTURE DEVELOPMENT AND TESTING BY BRITISH NUCLEAR FUELS LTD AND THE U.K.A.E.A.

The U.K. reference fuel particle comprises an 800 μ diameter UO_2 kernel with PyC and SiC coatings. The kernel is specified to have porosity for accommodation of swelling and gaseous fission products. Coated particles are overcoated with a graphite/resin mixture and pressed into annular compacts. The packing factor of particles in the compacts is chosen to give 0.8 gm/cm^3 uranium density, with particle damage rate not greater than 1 in 10^4, the latter figure being determined from consideration of fission product release.

The aim of the fuel manufacturing development programme has been to establish that the specification can be met in a commercial plant. This has progressed well, several tonnes of coated particles and tens of thousands of compacts have been satisfactorily produced, and the process for particle manufacture successfully scaled up.

The feasibility of meeting the specification has been demonstrated on prototype capacity plant at Springfields. Sufficient quantities have been produced to enable plant reliability, inspection techniques and reject statistics to be properly assessed, and more accurate estimates of fabrication costs to be made.

In fuel irradiation tests, fuelled compacts have been irradiated in the Dounreay Fast Reactor to the fast neutron dose of 3×10^{21} n/cm^2(EDN); no obvious deterioration of particles or matrix has been observed. Particle irradiations continue in U.K.A.E.A. M.T.R.s and the O.E.C.D. 'Dragon' reactor, to study performance, statistical behaviour, etc. Complete fuel pins are being irradiated in Dragon and other reactors. Nearly 50 pins have been discharged for examination after about half target burn up, and none show any evidence of failure, even though some suffered more severe stress conditions than anticipated in a power reactor, including very large single imposed power excursions. Thermal cycling experiments on reference type fuel pins are proceeding in Dragon, and simulate the most severe power cycling conditions forecast for power reactors.

12. STEEL PROPERTIES TESTING PROGRAMME IN THE UNITED KINGDOM

Although helium is chemically inert, the behaviour of steels in an H.T.R. system has been found to depend on the concentrations and ratios of impurities present. These arise from impurities in helium as supplied, from assumed rates of steam and hydrogen ingress from boilers, and from reaction with reactor materials, especially graphite. The precise composition will determine whether the environment is oxidising or reducing, carburising or decarburising. Experiments suggest that oxidation is primarily determined by the H_2/H_2O ratio, and carburising by the $(CO)^2/CO_2$ or $CH_4/(H_2)^2$ ratio.

The steels testing programme has been conducted in the laboratories of the U.K.A.E.A., the industrial companies, and at Oslo on behalf of Dragon. Early work covering a wide range identified the main problems and preferred materials. The current programme concentrates on provision of comprehensive data on selected alloys at appropriate temperatures up to 800°C in representative helium atmospheres. One contains $H_2/CO/H_2O/CH_4$ at partial pressures of 500/500/50/50 μ ats., and represents a maximum moisture level tolerable for appreciable lengths of time on account of graphite corrosion; others have proportions 50/50/5/5 μ ats., and 200/10/2/20 μ ats., and represent the probable range within which the average long term environment will fall.

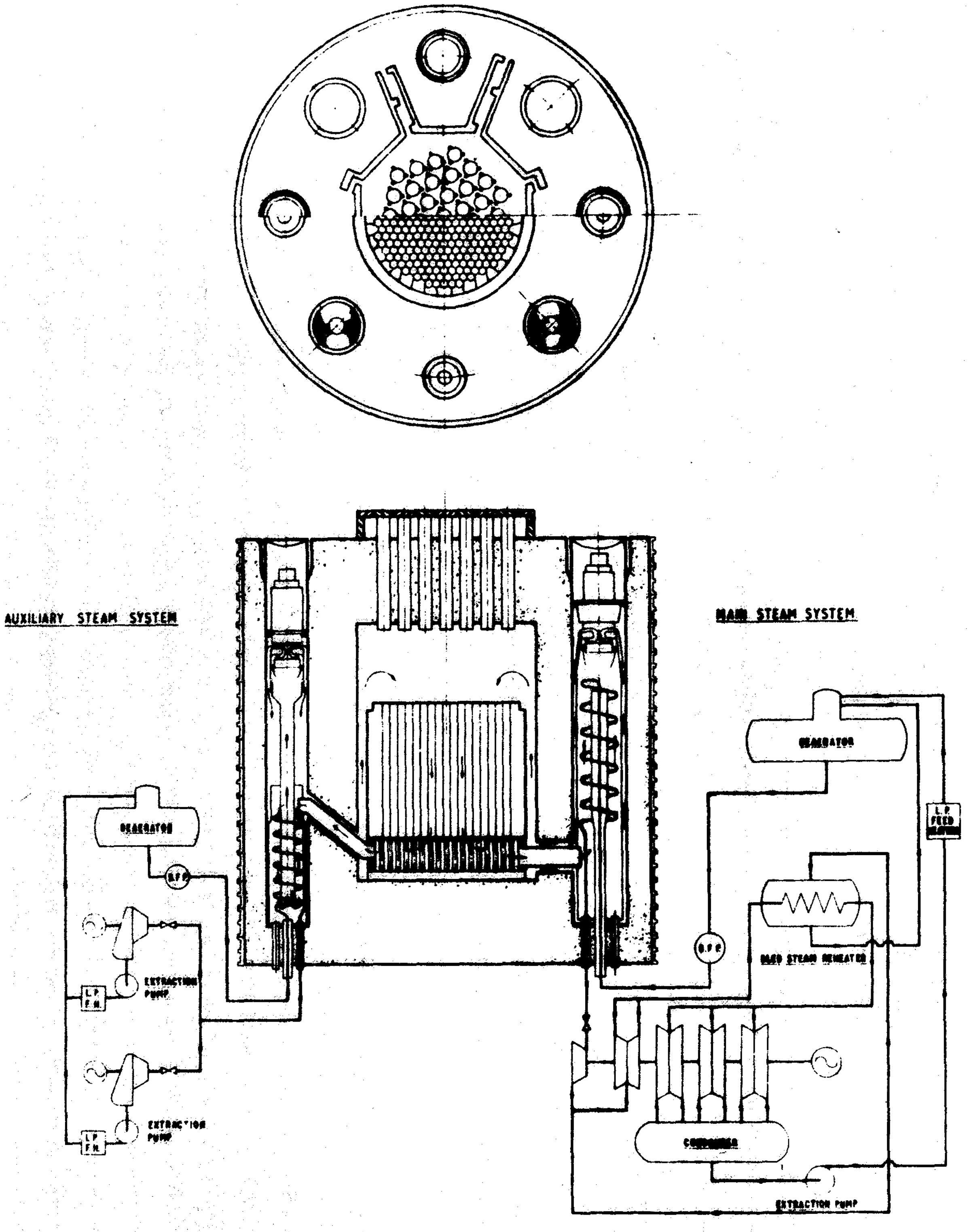
Materials selected include mild steel, low alloy Cr Mo steels, austenitic stainless and nickel-based steels, of direct interest to B.N.D.C.'s system. Briefly, experiments indicate that H_2/H_2O ratios not exceeding 10 give oxide film formation on mild steel up to $400^{\circ}C$ and possibly decarburisation above this temperature, and with low alloy steels at 500 - $550^{\circ}C$ oxidation of chromium but not iron, with some indication of slight internal oxidation and a marginal decarburisation situation depending on Cr content and stabilising elements. High temperature materials at 700-$800^{\circ}C$ exhibit oxide film formation due to reaction with CO_2 and H_2O, but carburisation may occur if CH_4 is present and where oxide films cannot form, as in crevices.

The mechanical properties and tribology programmes include experiments in representative environments to obtain data for selected materials on axial and tubular creep rupture, high-cycle and high strain fatigue, adhesion between metallic couples, fretting, and friction and wear rates particularly at higher temperatures and where there is insufficient oxide film to prevent severe adhesion.

The magnitudes of the corrosion effects in B.N.D.C.'s design are small. Proposed materials include mild steel and $2\frac{1}{4}$ Cr. Mo. steel in the lower temperature range; type 316, Alloy 800, and Sandvik 12R72 are candidate materials for the temperature range 600-$704^{\circ}C$. The helium clean up plant is designed to maintain the H_2/H_2O ratio below 10. This value is based on thermodynamic considerations and may be pessimistic. Peach Bottom experience indicates that much higher ratios can be tolerated. Loss of metal due to oxidation of mild and low alloy steels is not expected to exceed 125 microns, and internal oxidation of the high alloy steels is not expected to have an effective depth greater than about 250 microns, at maximum boiler tube temperature, and 500 microns at $700^{\circ}C$, in the design life of 30 years.

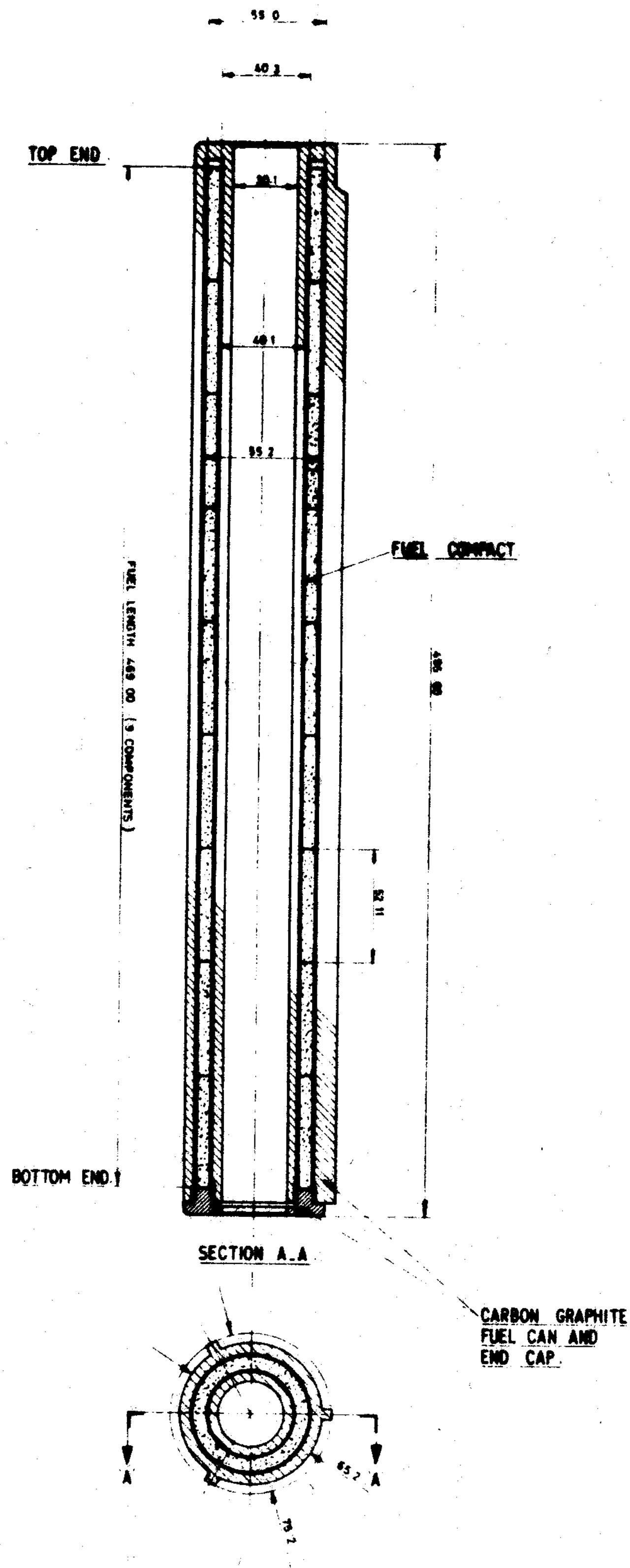
13. CONCLUSION

B.N.D.C. had great confidence in its H.T.R. System, of which some features have been described. The supporting development work has provided a very satisfactory design basis. Continuation of the development programme in the U.K. will provide further support for the design described, and the basis for extension of the H.T.R. principle to gas turbine generating plants and process heat provision for chemical or steelmaking plant.



REACTOR GENERAL ARRANGEMENT AND STEAM CYCLE SCHEMATIC.

FIG. 1.

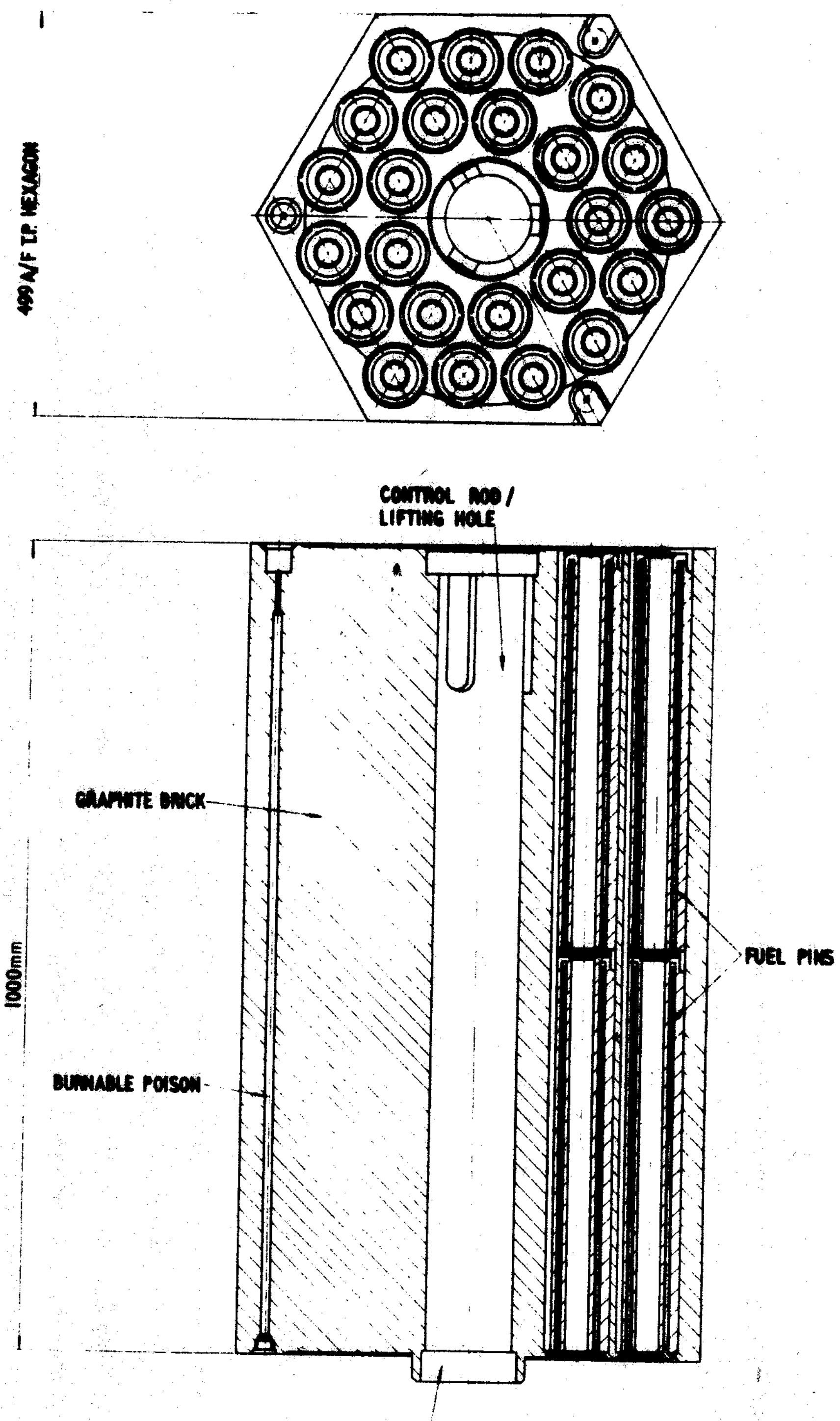


TUBULAR INTERACTING FUEL PIN.

FIG. 2.

ALL DIMENSIONS IN MILLIMETRES

BRITISH NUCLEAR DESIGN & CONSTRUCTION LIMITED



FUEL ELEMENT WITH INTERACTING
FUEL PIN

FIGURE 3