18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18- S05_2

THE PRIMARY CIRCUIT OF THE DRAGON HIGH TEMPERATURE REACTOR EXPERIMENT

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ABSTRACT

The 20MWth Dragon Reactor Experiment was the first HTGR (High Temperature Gas-cooled Reactor) with coated particle fuel. Its purpose was to test fuel and materials for the High Temperature Reactor programmes pursued in Europe 40 years ago. This paper describes the design and construction of the primary (helium) circuit. It summarizes the main design objectives, lists the performance data and explains the flow paths of the heat removal and helium purification systems. The principal circuit accidents postulated are discussed and the choice of the main construction materials is given.
Keywords: Dragon Reactor Experiment, primary circuit, helium purification, materials, safety

1. INTRODUCTION

The Dragon Reactor Experiment in Winfrith/UK was a materials test facility for the early HTR projects like the German THTR pebble-bed reactor and the American Fort St.Vrain prismatic NPP. It was built and managed as OECD/NEA International Joint Undertaking. The DRAGON reactor operated successfully between 1964 and 1975, irradiating an increasing variety of experimental and prototype coated particle fuel as well as testing technological components and structural materials.
The successful operation of this experimental facility was described by myself at the "HTR 2002" Topical Meeting (2002) and in many earlier publications. This paper concentrates on the design and construction of the Dragon primary circuit.

2. MAIN CHARACTERISTICS AND DESIGN PRINCIPLES OF THE PRIMARY CIRCUIT

The main characteristics of the primary circuit were:

Thermal power	20 MW
Coolant	Helium
Coolant pressure	20 bar
Reactor inlet temperature	350°C
Reactor outlet temperature	750°C
Coolant flow rate	34 500 kg/h
Max. temperature at fuel element surface	1000°C
Average heat flux at fuel element surface	24W/cm²
Thermal power removed by natural convection	950kW

The design and construction of its primary heat removal system was governed by the following requirements:

- The helium coolant in the primary circuit had to be conducted on a flow path that avoided any contact of the pressure envelope with gas from the hot leg.
- The reactor inlet temperature should on one hand be low enough to prevent extreme creep of the material, but on the other hand should be high enough to limit radiation damage to a minimum.
- In case of a total loss of electrical power to the circulators and pumps the decay heat of the core had to be removed by natural convection. This requirement led to the design with six rising parallel coolant branches, which at their top carried the primary heat exchangers and the circulators.
- In order to accommodate the complete primary circuit within the bioshield, the heat exchangers had to be as compact as possible; as these primary heat exchangers also contained moving parts (by-pass valve) , they should also remain accessible for maintenance.
- In the event of a leak or a pipe rupture within the heat exchanger, radioactivity must not leave the containment; the amount of water entering the core had to be minimized to prevent a major chemical reaction with the red-hot graphite.

The proposed paper will expand on the design features of the circuit, the materials chosen for critical components and the overall performance during its operation.

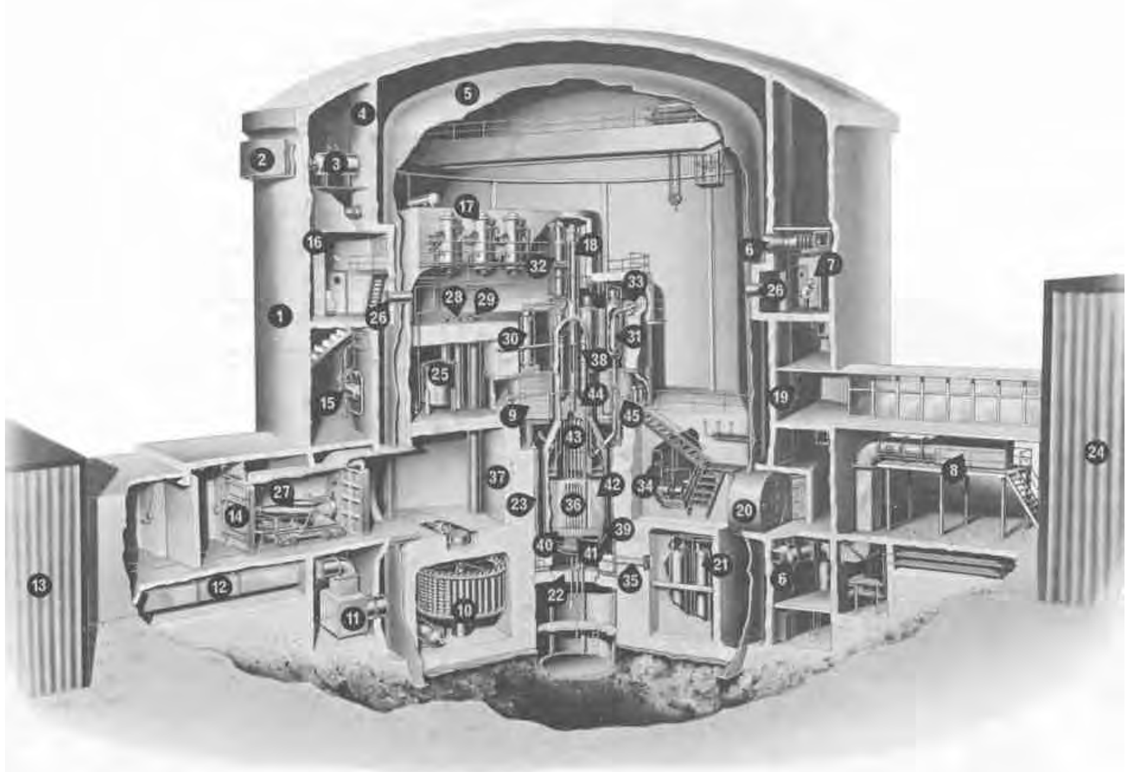
3. LAYOUT OF THE PRIMARY CIRCUIT

The emplacement of the main reactor components is shown in Fig. 1: The reactor pressure vessel [39] is a long, bottle-shaped steel construction divided vertically into two parts by the main shield plug [44]. The upper part contains the fuel handling area with the charge machine [18], the main entry valve and the control rod drives. This part of the vessel was under full reactor pressure, but kept at 130°C during reactor operation by cool helium from the coolant purification system.

The reactor [36] and reflector [42] rest on the core bedplate [40] in the lower (and wider) part of the pressure vessel. The hot reactor outlet plenum is constituted by the space between the main shield plug and the top of the core. In order to permit sufficient natural convection for the removal of decay heat in case of total loss of electrical power to circulators and secondary pumps, the six primary heat exchangers [31] and gas circulators [33] were placed on rising parallel coolant ducts.

4. MAIN CHARACTERISTICS

The heat produced by the 37 prismatic fuel elements is transmitted to a helium flow of 34 500 kg/h; in normal operation the average core outlet temperature is 750 °C. This hot coolant is divided among the six coolant loops and brought to the six primary heat exchangers through the insulated inner conduct. At the full power of 20 MWth the outlet temperature of the heat exchangers is 300 °C; the helium enters the one-stage main centrifugal circulator, which thrusts the helium flow back to the pressure vessel through the concentric outer duct of the coolant branch. Due to the compression and the heat transferred from the inner duct, the helium enters the annular inlet plenum in the pressure vessel at 350°C. The returning helium is then redistributed to cool the absorber rods, the shield plug, the reflector and the core bedplate, all of which are exposed to a strong neutron flux. The helium enters the core at 370°C and flows upward between the fuel rods to the outlet plenum.



1. Outer Concrete Containment
2. Shut Down Coolers
3. Water Storage Tanks
4. Inner Concrete Wall
5. Inner Containment Steel Shell
6. Circulating Ventilation Plant
7. Crane Control Room
8. Main Ventilation Inlet & Filters
9. Loose Shield Blocks
10. Fuel Element Storage Roundabout
11. Ventilation Exhaust Filters
12. Ventilation Exhaust to Stack
13. Active Storage Block
14. Vehicle Air Lock Entrance
15. Secondary Coolant Control Valve
16. Charge Machine Control Room
17. Secondary Heat Exchangers
18. Charge Machine
19. Personnel Air Lock Access
20. Emergency Air Lock Access
21. Helium Delay Beds
22. Bottom Biological Shield
23. Steel-Water Thermal Shield
24. Control Block
25. Secondary Coolant Dump Tank
26. Observation Windows
27. Transit Flask
28. Fuel Element Charge Chute
29. Fuel Element Discharge Chute
30. Canning Cell
31. Primary Heat Exchangers
32. Load Facility Transfer Flask
33. Primary Circulator
34. Compressor Room
35. Ion Chambers
36. Core
37. Neutron Shields
38. Seal Bung
39. Main Pressure Vessel
40. Core Bed Plate
41. Fission Product Pipes
42. Reflector
43. Absorber Rods
44. Main Shield Plug
45. Thermocouple (Helium Temp.)

Figure 1: The Dragon Reactor Experiment (section)

5. THE PRIMARY HEAT EXCHANGERS AND THE HEAT REMOVAL SYSTEM

In the six primary heat exchangers shown in Fig. 2 the thermal energy was transferred from the helium on the shell side to water inside the tube bundle. In order to prevent massive injection of water onto the hot graphite core in case of a tube failure, the pressure of the water in the secondary was only

15,8 bar, whereas the helium pressure was 20 bars. This may not be representative of a power reactor, but Dragon was not intended to drive a steam turbine. The water enters the primary heat exchangers at 200°C and leaves it with a steam content of 16,4 wt%. There are six completely separate secondary water loops each with its own secondary heat exchanger/ condenser. The latter are also equipped with emergency cooling tube bundles.

The main tertiary circuit operated at a pressure of 13 bar ; inlet – and outlet temperatures at the secondary heat exchanger are 50°C and 187°C respectively. In normal operation a bank of dry fin-fan coolers outside the containment cooled the tertiary water. In the case of a complete power failure, the decay heat of the core was evacuated by natural convection to the secondary loops and from there equally by natural convection via the emergency cooling tube bundles in the tertiary heat exchanger to a series of air-cooled shut-down coolers on outside of the container wall.

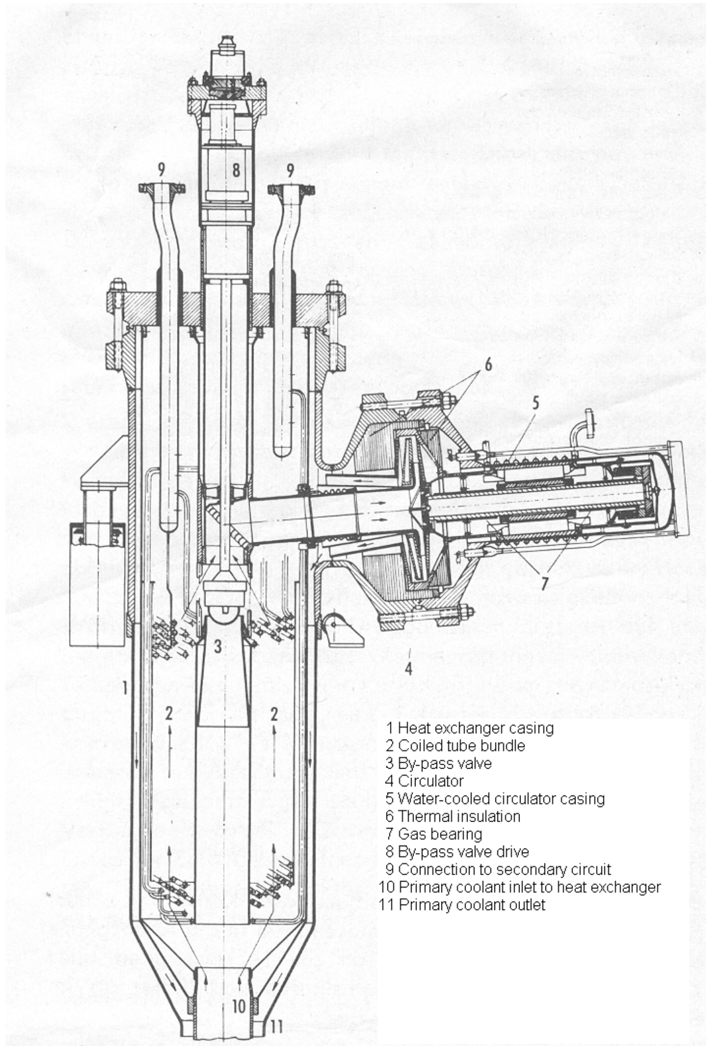


Figure 2: Primary Heat exchanger and Circulator

6. THE MAIN PRIMARY CIRCULATORS

The circulator (Fig 2, item 4) was a single stage centrifugal type blower driven by a 3-phase induction motor of about 75 kW fed by a variable frequency alternator from a Ward-Leonard set giving continuous variation of speed over the range of 1 300rpm to 12 000 rpm. The rotor shaft carried the impeller at one end and a gas lubricated thrust bearing at the other. This shaft was slightly off vertical to compensate for thrust and it was supported by two radial gas bearings.

The complete unit including the motor is sealed into the primary circuit. No moving parts intersect the circulator casing which is water cooled on the outside in the region of the driving motor. The principal dimensions of the circulator are:

Rotor shaft diameter:	100 mm

Impeller overall diameter: 400 mm

Distance between centres of bearings: 576.6mm

The circulator casing is fitted with thermal insulation around the concentric gas inlet and outlet ducts as well as around the impeller. Due to the water cooling the temperature at the bearings and in the electric motor does not exceed 95°C, although the impeller operates at 350°C.

Gas bearings were adopted for the circulators since they provide a simple means of making the primary circuit leak tight. These gas bearings have certain peculiar characteristics, which had to be studied extensively and required special precautions:

The hydrodynamic lubrication at operating pressure requires a minimum speed of rotation before it will support the weight of the circulator. Therefore the circulators were not routinely run below 1 300 rpm. Dry friction with oxygen-free helium in the bearings could lead to damage; this situation is avoided by pressing helium as jacking gas (hydrostatic lubrication) during starting and stopping. As a long the time would be taken for the circulator to stop spinning, electric braking through the motor is applied, once the shaft speed is below 1 100rpm primarily to economise on jacking gas.

7. TEMPERATURE CONTROL OF THE PRIMARY CIRCUIT

A fundamental design objective of the pressure vessel and external parts of the primary circuit was to assure that the pressure-bearing walls were not in contact with coolant from the hot leg of the circuit. During operation helium returning from the heat exchangers at 300 – 350 °C cooled down all external parts of the heat exchanger branches, the heat exchanger casings and the reactor pressure vessel under the shield plug. The returning coolant stream also kept the moderators, the absorber rods, the core shroud and the core bedplate from overheating. Fig. 3 shows the distribution of the coolant flow from the six branches to the core inlet plenum at the bottom of the RPV. It also shows the stream of relatively cold (50 - 100°C) helium (7,8 g/s) returning from the coolant purification circuit into the upper part of the pressure vessel. This relatively small flow of helium cooled the upper vessel and shield plug itself before continuing downward through an annular section along the pressure vessel wall. Due to the combined effect of cooling the

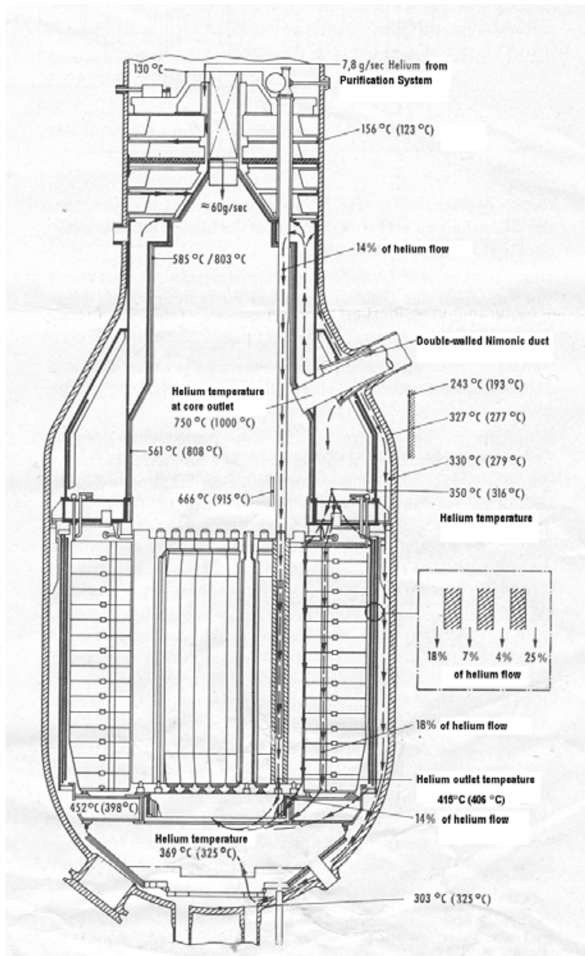


Fig. 3 : Coolant Flow and Temperatures in the Reactor at Full Power (Temperatures in Brackets are for Natural Convection after Emergency Shutdown)

inside wall with helium and transferring heat to water-cooled thermal shield all around the lower part, the temperatures in the vessel walls and the external walls of ducts and casings did not exceed 350°C during normal operation.

In the case of a complete power failure the reactor would trip and only the latent heat and the decay heat would have to be evacuated. The natural convection flow would amount to about 3% of the full circulator flow. In Fig .3 the resulting wall temperatures are shown in brackets; the maximum temperature of the RPV wall would not be affected, although the temperatures of the ducts and shrouds separating the hot leg from the cold leg of the circuit might reach 1000° C.

8. PRIMARY COOLANT PURIFICATION

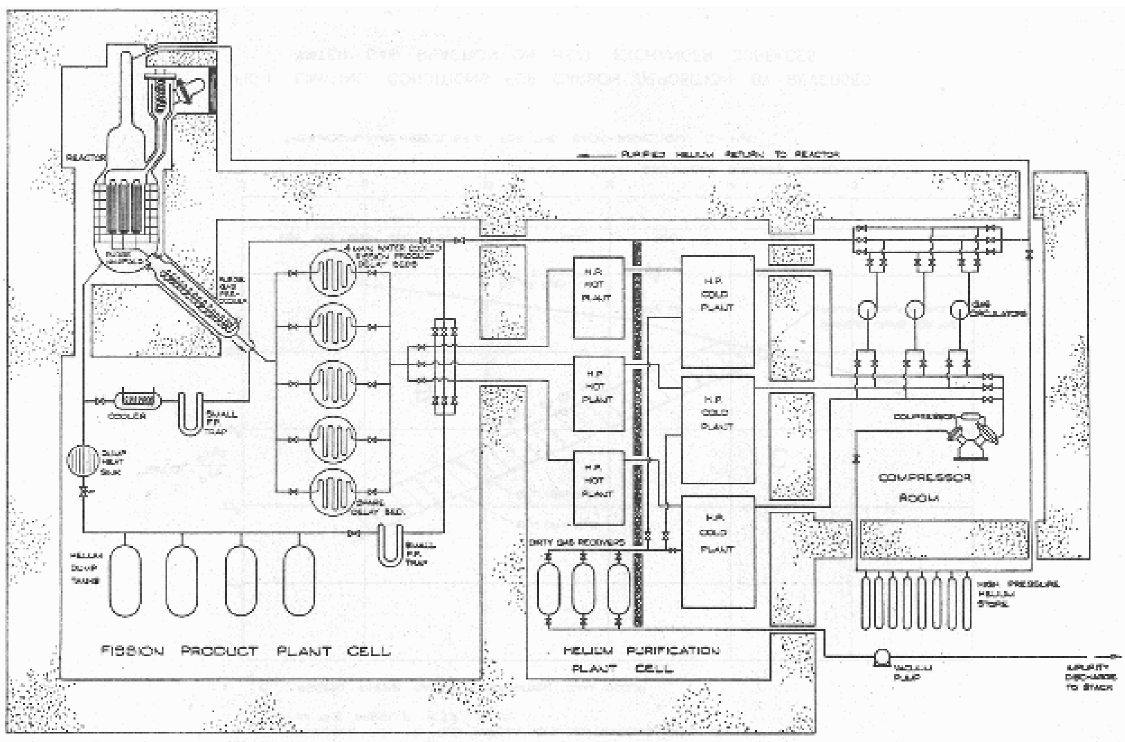


Fig. 4 : Dragon Fission Product Trapping and Helium Purification System Simplified Flow Diagram

When the helium purification plant for Dragon was designed, a relatively high release of fission products from fuel elements was anticipated. The individual purging of fuel elements was therefore required in order to prevent FP build-up and plate-out in the primary circuit. The invention and development of the coated particle by the Dragon Project resulted in release rates amounting to a small fraction of the originally forecast activity. Normally the purification by-pass stream would be drawn from the purge lines at the bottom of each fuel element. This feature provided an individual sampling facility for each fuel element, which gave reliable data about the rate and nature of fission product release for the various fuel element designs and operating conditions. The purification flow from the purges (total 7.8g/s) turned over the helium inventory approximately every 6 hours. A simplified flow sheet of the Dragon fission product trapping and helium purification system is shown in

Figure 4. All components except the control valves of this system were located in a series of shielded vaults inside the main containment (s. items 36 and 24 in Fig.1). Starting from the purged fuel elements, the main purge gas stream is collected in a manifold under the core support grid and routed via a precooler to a set of water-cooled, charcoal filled fission product delay beds. The precooler reduced the helium temperature from 350°C to 100°C; the delay beds removed the decay heat (max 70kW) of short lived fission products and their daughters and cooled the helium to about 35°C. Each of the five delay beds contains approximately 3 m³ of charcoal in a series of "U"-tubes surrounded by cooling water. Four of the five delay beds were normally used in parallel, the fifth acting as spare. They were designed to delay xenon for 200 h and krypton for 15 h, thus eliminating plate-out of longer-lived daughter isotopes.

Downstream of the delay beds, the gas passed to the (chemical) purification plant. Three basically identical trains of purification plant were provided in parallel, permitting several duties of coolant cleanup to be performed simultaneously, while one is undergoing regeneration. The function of the purification system was to remove both the chemical (H^2, H^2O, CO, CO^2, CH_4, N^2) and radioactive impurities, leaving only extremely pure, inactive helium to be returned to the primary coolant circuit. As the precision of the release measurement for the experiments depended on the activity background level, the designers and operators aimed at complete decontamination of the gas returning from the purification plant. A coolant analysis during routine operation measured the following impurities:

Table 1: Chemical impurities in Helium coolant in vpm

O_2	N_2	CO	CO_2	CH_4	H_2O	H_2
0.1	0.05	0.05	0.02	0.1	0,1	0.1

Each purification train consisted of a high temperature section or hot plant followed by a low temperature section. In the hot plant, carbon monoxide and hydrogen were oxidized by a bed of CuO at about 350°C, while any oxygen present were removed by pure copper at the end of the bed. In the low temperature section the gas was progressively cooled down to –180 °C in a freezer heat exchanger, on which H_2O and CO_2 plate out as solid deposits. A small cold delay bed, in which charcoal – filled thimbles were surrounded and cooled by boiling liquid nitrogen, then removed all remaining radioactivity except 85-Kr. Impurities leaving the cold delay bed were readsorbed on 300 litres of charcoal in a cold adsorbtion trap (this latter trap generated no decay heat; it could therefore be kept cool by the gas from the preceding krypton delay bed). The purified gas passed through a tube coil immersed in the boiling liquid nitrogen of the cold delay bed and was then used to cool down the incoming gas in the freezer heat exchanger. This raised the purified helium stream to room temperature before it was returned to the reactor by small gas bearing centrifugal circulators running at 24 000 rpm.

9. HELIUM MANAGEMENT

The helium inventory of the Dragon primary coolant system was about 355kg of which, during operation 175 kg were kept in reserve stores and the dump tanks. Of the other half, 68 kg were flowing in the main heat removal circuit, the rest slowly moved through the Fission Product Removal

Plant (36kg), the Helium Purification Plant and the Transfer chamber at the top of the Reactor Pressure Vessel. The heat sink contained the remaining 10kg.
For refuelling, the reactor was shut down and the coolant from the primary circuit was pumped back into the storage and dump tanks before the vessel was opened to air at atmospheric pressure. Helium losses of 20-30 kg were registered at each refuelling shutdown due to this practice. The other main reason for helium losses was the frequent sampling of helium for the monitoring of experiments, which did not exceed 1kg per operating day. Maintenance work and “spillage” during insertion and operation of experimental probes and general leakage were considered “unaccountable losses”; these on average amounted to 0.2 kg/day or 0.12% of the circulating inventory. In 1974 however these unaccounted losses rose to 2kg/day. After months of searching, the leakage was traced to small-bore stainless steel piping in the Hot Purification System. The leaks, almost invisible pores and crevices in otherwise healthy lengths of pipe were caused by chloride corrosion: all leaks occurred exactly at sections marked with colour-coded PVC tape during the commissioning phase. During normal operation some of these tubes reached at temperatures between 80°C and 120°C. At this temperature the tape decomposed slowly, leaving gaseous HCl trapped on the tube surface. Once the 200 tape markings were removed and all suspect piping replaced, the average unaccounted helium losses dropped to 0.2 kg/day.

10. DESIGN ACCIDENTS

The rupture of the primary circuit by a complete separation of one of the main coolant branches was postulated to verify the effectiveness of the containment. In this MCA the usual assumptions concerning release of radioactivity from the core were applied: 100% of gas, 100% of volatile FP (fission products) and 25 % of all other FP are released from the core to the containment.
In this unlikely case the dose rate at the perimeter fence (about 100m from the containment centre) would be 150 mr/h.
The release of helium from the circuit and the direct transport of heat from the core to the gas mixture in the containment would result in an increase of the containment pressure of 0,16 bar (2.3psi) at a gas temperature of 85°C. The containment was designed and tested to support 0,7 bar.
If a tube failure in the one of the heat exchangers were to release the entire capacity of one secondary circuit, 320kg of water might react with the graphite core, the water gas ($CO + H_2$) resulting from a complete reaction would raise the pressure in the containment by 0,625 bar, but would not breach the containment. The really dangerous case would arise, if the water gas on escape from the primary circuit could ignite. After combustion, the remaining gas mixture would have reached a temperature of 575 °C and a pressure of 2,2 bar. It could however be shown, that even under conservative assumptions there could not be sufficient water gas in the mixture to ignite.
The case of a complete loss of electrical power to all circulators and pumps the primary, secondary and tertiary circuits were designed to operate by natural convection. As the reactor would immediately scram, only the latent heat and the decay heat from the core had to be removed to the emergency

coolers. These systems were tested and a full rehearsal of the incident showed, that the core temperatures rose only slightly for about 5 minutes before beginning a slow decrease.

11. PRIMARY CIRCUIT MATERIALS

All pressure components of the primary circuit with the exception of the vessel penetration flanges were designed to British Standards 1500(1958):

"Fusion Welded Pressure Vessels", Class I Standard.

The joint flanges conformed to the "Taylor-Forge" design specifications. All vessels were designed and built to the requirements of Lloyd's rules for "Category A" vessels for use in land based nuclear installations. For all pressurized components the following modes of failure were considered:

Creep, fatigue, fast fracture, brittle fracture, corrosion and tensile stress.

A large number of material tests were performed and two particular measures were applied to avoid failure of the circuit: To demonstrate that critical cracks were not present after comprehensive non-destructive testing, the circuit was subjected to a pressure of 25 at overpressure at 350°C, well above the design values of 20 bar. Regular inspection for even minute cracks was made during the entire operating period.

The second specific measure resulting from the analysis of the circuit was to fit electric heaters to the coolant duct elbows in order to maintain these tube walls at a temperature between 80°C and 100°C. The duct elbow materials were suspected of having less than 50% fibrosity at room temperature, but would retain their ductility even after irradiation to 5*10E18 n/cm² at the higher temperature.

The main incertitude was the possible increase of the N.D.T. or nil ductility temperature due to the accumulation of neutron irradiation. For unirradiated steel the N.D.T was 5°C and after extensive irradiation tests it was concluded, that if the vessel wall would receive an integrated (>1.O MeV) fast neutron dose of 10 E19 n/cm², the N.D.T. would not rise above 25°C.

Cylindrical steel samples placed in the reflector were recovered at predetermined integrated doses and impact-tested. When the reactor was shut down, the remaining samples had received less than 10E19 n/cm².

The steel used for the reactor pressure vessel was a carbon manganese steel with an aluminium addition for grain refinement, specified as MARWE 426MA by its producers, Mannesmann (Germany); its composition in % is given in Tab. 2:

Table 2: Reactor Pressure Vessel Construction Material MARWE 426MA:

C	Si	Mn	P	S	Al	Total Ni + Cr + Mo	Co	Cu	Fe
0,16 max.	0,30 max.	1,0 to 1,5	0,16 max.	0,30 max.	0,12 max.	0,30 max.	0,025 max.	0,18 max.	balance

The coolant ducts were made of the normal silicon killed boiler tube material to the German specification St 35.8 with guaranteed heat resistance. The primary heat exchanger and circulator casings were made from Altom 44 (Voest /Austria), which has practically the same composition as the MARWE 426MA used for the pressure vessel.

The use of carbon steel is precluded for the containment of gas at temperatures beyond 750°C. The hot gas duct to the primary heat exchangers and the inner face of the upper plenum chamber were lined with two layers of 1.6mm thick Nimonic 75 alloy sheet (s. Table 3) and the control rod tubes were entirely made of this alloy

Table 3: Limiting Chemical Composition of NIMONIC 75 Alloy in%

C	Si	Mn	Ti	Cr	Fe	Cu	Ni
0,08-0,15	1,0 max.	1,0 max.	0,2-0.6	18,0-21,0	5,0 max.	0,5 max.	balance

This alloy combines the inherent oxidation resistance of nickel chromium alloys with improved mechanical properties at high temperatures.

12. SUMMARIES AND CONCLUSION

During its operation from 1964 to 1975 the Dragon Reactor Experiment tested a great variety of fuels and coated particle configurations. The purge system allowed to monitor each fuel element individually and also prevented contamination of the helium inventory by releasing fuel experiments, thus providing high accuracy analysis. The design of the pressure vessel and the six heat exchanger/circulator branches permitted a safe and reliable heat removal under all conditions. The fission product removal and purification system kept the helium in the circuit extremely clean without releasing active waste. Among the postulated accidents the simultaneous breach of the primary circuit and a primary heat exchanger tube was considered the most dangerous, as it resulted in the discharge of inflammable water gas into the containment. The concentration of Co and H2 in the containment however would not exceed the limit of flammability.

The mechanical properties of the construction materials were not affected by irradiation or high temperature and the only one minor case of corrosion attack was recorded. The Dragon Reactor Experiment has shown, that international cooperation can be very effective and has proven, that the melt-down proof ceramic core, the coated particle fuel, the negative temperature coefficient, the non – corrosive coolant and the ability of natural convection decay heat removal of the HTR concept result in a clean and inherently safe reactor.

ACKNOWLEDGEMENTS

This paper should not only draw the attention of the present generations to the relevant results of yesteryear, but also remind the audience of the excellent work accomplished by the highly dedicated and competent team of the O.E.C.D. High Temperature Reactor Project.