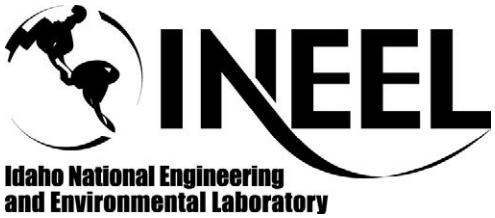

INEEL/CON-04-01526
PREPRINT

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April 25 – 29, 2004

ICONE 12

Proceedings of ICONE 12:
Twelfth International Conference on Nuclear Engineering
April 25-29, 2004 Arlington, Virginia

ICONE12-49380

LESSONS LEARNED FROM GEN I CARBON DIOXIDE COOLED REACTORS

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KEYWORDS

Carbon dioxide, gas cooled reactors, Magnox, AGR

ABSTRACT

This paper provides a review of early gas cooled reactors including the Magnox reactors originating in the United Kingdom and the subsequent development of the Advanced Gas-cooled Reactors (AGR). These early gas cooled reactors shared a common coolant medium, namely carbon dioxide (CO_2). A framework of information is provided about these early reactors and identifies unique problems/opportunities associated with use of CO_2 as a coolant. Reactor designers successfully rose to these challenges. After years of successful use of the CO_2 gas cooled reactors in Europe, the succeeding generation of reactors, called the High Temperature Gas Reactors (HTGR), were designed with Helium gas as the coolant. Again, in the 21st century, with the latest reactor designs under investigation in Generation IV, there is a revived interest in developing Gas Cooled Fast Reactors that use CO_2 as the reactor coolant. This paper provides a historical perspective on the 52 CO_2 reactors and the reactor programs that developed them. The Magnox and AGR design features and safety characteristics were reviewed, as well as the technologies associated with fuel storage, reprocessing, and disposal. Lessons-learned from these programs are noted to benefit the designs of future generations of gas cooled nuclear reactors.

INTRODUCTION

Gas cooled reactors have had a long and varied history which dates back to the very early days of nuclear energy development. Most of the early development centered on low temperature systems using a graphite moderator, metal clad metallic fuel and carbon dioxide coolant. Commercial deployment of such systems started in the mid-1950's, primarily in the United Kingdom and France, with the natural uranium fueled Magnox stations, followed by higher temperature, low enriched uranium fueled advanced gas cooled reactor stations, solely deployed in the United Kingdom, starting in the mid-1970's. Although these two pioneering programs have now concluded, experience from the over 1000 reactor-years of operation comprises a very valuable database for ongoing development and design programs on higher temperature gas cooled reactors.

From the very beginning, it was recognized that greater benefits of gas cooling (in particular, at that time, the ability to attain modern fossil fired steam conditions permitting, thereby, more highly efficient electricity production) would accrue if higher gas temperatures could be achieved. It was this goal, coupled with the vision that such higher gas temperatures might also lead to even broader applications of nuclear energy such as providing industrial process heat, that motivated the development of the high temperature gas cooled reactor with its characteristic reactor core of graphite moderator and ceramic fuel and its use of a gas as coolant.

As of the end of 1988, a total of 52 electricity generating, carbon dioxide cooled reactor plants had been placed in operation worldwide (37 Magnox, 15 AGRs). A list of the reactors is given in Table 1 [1, 2,3,4].

Table 1. Carbon Dioxide Cooled Reactors

Country	AGR FACILITY	Number of reactors	Max. & (derated) output (MWe)	Operation start year	Shutdown year
UNITED KINGDOM					
	Calder Hall-A, -B (prototype)	4	220	1956, 1958	2003
	Chapelcross -A, -B (prototype)	4	200	1958, 1959	2005 (est.)
	Berkeley 1, 2	2	276	1962, 1962	1988, 1989
	Bradwell	2	300 (250)	1962, 1962	2002
	Hunterston-A1, A2	2	320	1964, 1964	1990
	Trawsfynydd 1, 2	2	500 (390)	1965, 1965	1993
	Hinkley Point-A	2	500 (460)	1965, 1965	2000
	Dungeness-A	2	550 (410)	1965, 1965	2006 (est.)
	Sizewell-A	2	580 (420)	1966, 1966	2006 (est.)
	Oldbury	2	600 (400)	1968, 1968	2009 (est.)
	Wylfa	2	1180 (850)	1971, 1972	2010 (est.)
FRANCE					
	Marcoule-G2, -G3	2	80	1959, 1960	1980, 1984
	Chinon-A1,-A2,-A3	3	750	1964, 1966, 1967	1973, 1985, 1990
	St. Laurent-A1, -A2	2	995	1969, 1971	1990, 1992
	Bugey-1	1	540	1972	1994
ITALY					
	Latina	1	150	1963	1986
JAPAN					
	Tokai-1	1	159	1966	1998
SPAIN					
	Vandellos	1	480	1972	1989
		37	8360		
ADVANCED GAS REACTOR					
UNITED KINGDOM					
	Windscale (prototype)	1	32	1963	1981
	Hinkley Point-B	2	1250	1976, 1977	2006 (est.)
	Hunterston-B	2	1250	1976, 1977	2007 (est.)
	Dungeness-B	2	1200	1984, 1985	2013 (est.)
	Hartlepool	2	1250	1984, 1985	2014 (est.)
	Heysham-1	2	1250	1984, 1985	2014 (est.)
	Heysham-2	2	1320	1988, 1988	2018 (est.)
	Torness Point	2	1320	1988, 1988	2024 (est.)
		15	8872		

GENERAL DESIGN CHARACTERISTICS OF MAGNOX AND ADVANCED GAS REACTOR'S

Magnox reactors operate with natural uranium metal fuel, and utilize carbon dioxide coolant; the moderator is graphite, with fuel and coolant being located in coolant holes in the graphite in a lattice arrangement. The term Magnox comes from the name of the magnesium alloy used to clad (or can) the metallic/uranium fuel elements. The core power density of these reactors is nominally about 1 MWth·m-3, so the core physical size is relatively large. The low power density and high heat capacity of the graphite in the reactor combine to give relatively small changes in graphite temperatures if the core power level were to increase with time, which enhances the reactor safety characteristics. Graphite itself can operate at extremely high temperatures; however, the internal temperature of the Magnox fuel elements must remain below ~ 650°C to avoid unit cell deformation in the uranium crystal lattice. Also, the steady state clad temperature is limited to about 500°C (design value) to avoid loss of strength and of cladding integrity. As a result, the bulk average gas temperature leaving the reactor was originally limited to 414°C with plant thermal efficiencies being about 31%. Subsequently, high oxidation rates of some mild steel structural components were observed; to reduce these rates to acceptable values, the outlet coolant temperature was lowered to 360-380°C giving thermal efficiencies of about 29%.

To increase the practical physical size and power level of Magnox reactors, the UK and France pioneered the use of prestressed concrete pressure vessels (PCPVs), which were also known as prestressed pressure reactor vessels (PCRVs) and steel reactor pressure vessel (RPV). The vessels were constructed in sizes large enough to house the entire reactor system, including the steam generators. The vessels also increased the operating pressure of the coolant gas and the power` levels in the Magnox and AGR units. The PCRVs are kept in compression at all times by a network of redundant, tensioned steel tendons that can be monitored and retensioned or even replaced if necessary. Tightness against leaks was provided by a steel liner affixed to the inside of the PCRV, which acts only as a membrane seal to contain the coolant. The liner and the walls of the PCRV are cooled by water circulating through tubes that are welded to the outer surface of the vessel. PCRVs were subsequently adopted for all French and British gas-reactor systems. The high degree of safety afforded by the concrete vessel contributed to the British decision to construct a second generation of reactors known as the advanced gas cooled reactor near urban sites [5]. Early Magnox reactors were shut down early primarily due to the lack of a robust safety case associated with steel reactor pressure vessels.

The low core power densities and the limitations in fuel and fuel cladding temperatures in Magnox reactors placed limitations on their economic performance. To improve performance, the UK developed the AGR. Like the Magnox units, AGRs employ graphite moderator and carbon dioxide coolant; however, the fuel is low enriched uranium oxide contained in stainless steel cladding. The AGR fuel increases the permissible fuel temperature to higher than 2000°C; more effectively limiting is the cladding temperature, which increases to a design value of 882°C. As a result, the average core power density is increased to a nominal value of 2 MWth·m-3. The higher core power density and associated smaller physical size also permit an increase in coolant pressure. The bulk fuel channel outlet gas temperature at the top of the fuel stack is increased to about 640°C; plant thermal efficiencies of about 40% are obtained. With the higher operating temperatures, the AGRs were able to burn more of the uranium 235 in the fuel before refueling became necessary. With higher temperatures the efficiency of electric-power generation was raised from about 30 percent to a little more than 40 percent. Table 2 provides a summary comparison of the Magnox and AGR reactors.

Table 2. Comparison of Magnox and AGR Design Characteristics

Reactor Type	Fuel Element Temp	Clad Temp	Output Temp	Efficiency
Magnox	< ~650℃	500℃	414℃	29-31%
AGR	~ 2000℃	882℃	640℃	~ 40%

The AGR plants also experienced problems with oxidation and have experienced other problems, which precluded on-line refueling in the early years of operation. Development work has resulted in the ability to progressively raise the outputs to more than 97% of the originally designed gross electric output and thermal ratings to greater than 100% of design. On-line refueling was able to commence in 1982 but with the power outputs temporarily reduced to 30-40%. The operation of the last set of AGRs (Heysham-2 and Torness) has been satisfactory. However, some AGRs remain unable to refuel online (e.g., Dungeness B).

SAFETY CHARACTERISTICS OF MAGNOX AND AGR'S

A key safety characteristic of Magnox and AGRs is the negative power coefficient of reactivity due to the reactor fuel heating at a much higher rate than the graphite moderator during a power increase transient, which stabilizes the reactor. The addition of steam to the core (following failure of steam generator tubes) does not lead to a reactivity increase. If cooling of the AGR were deliberately stopped, the fuel would heat up about 30°C per second and the graphite 0.2°C per second; the negative temperature coefficient of the fuel would dominate reactivity changes and shut down the reactor system. Control rod insertion is assured on the basis of engineered or 'active' systems and can be accomplished by either primary or secondary shutdown systems (which also are redundant); under these circumstances, the fuel cladding would not approach melting temperatures. These features result in benign plant behavior under steady state and transient conditions.

The advantageous safety characteristics of Magnox reactors and AGRs are due to:

1. The inherent negative power coefficient of reactivity of the core;

2. The high heat capacity, the high temperature capability, and the good thermal conductivity of the core graphite;

3. The low power density of the core;

4. Long times (minutes to hours) for operators to take needed actions;

5. The "loose coupling" between the various plant systems, such that a fault (accident) in one system does not react in a significant way with other systems;

6. The chemical compatibility of the fuel, coolant, and moderator;

7. The single-phase nature of the carbon dioxide coolant;

8. The excellent retention of fission products with the metal cladding of the fuel under operating conditions;

9. The use of PCPVs, which are highly redundant in their strength characteristics;

10. The ability to cool the reactor following loss of coolant and other postulated accidents.

The barriers preventing the release of radioactivity into the atmosphere are the fuel itself, the fuel cladding, and the integrity of the primary circuit. Experience has validated that excellent quality fuel elements are produced, with the cladding retaining essentially all fission products during normal operations as well as expected transient conditions [3,6].

MAGNOX AND AGR FUEL STORAGE, REPROCESSING AND DISPOSAL

The technologies for gas cooled reactor fuel storage, reprocessing, and disposal were developed by the U.K. and France.

The Magnox reactor fuel elements consist of natural uranium metal fuel, Magnox cladding, and assembly hardware. The ability to store and cool such elements is relatively great since the fuel exposure attained in Magnox reactors is only about 5.5 GW d/tonne, leading to a relatively low rate of decay heat production. Storage of such elements is easier than that of LWR fuel elements. The reprocessing and fuel conversion technology for Magnox fuel elements is well established (Magnox fuel was recycled for over 30 years, and about 15,000 tonnes of recovered uranium has been recycled in UK reactors).

AGR fuel elements consist of low enriched oxide fuel having stainless steel cladding; they are exposed to about 24 GW d/tonne in the reactor. These elements are very similar, in general, to LWR fuel elements; their lower fuel exposure tends to simplify some of the fuel storage and fuel reprocessing steps. The storage, reprocessing, and disposal of Magnox fuel also applies to AGR elements.

The Magnox power station decommissioning program consisted of three stages:

Stage 1, the fuel is removed from both reactors and sent to British Nuclear Fuels for reprocessing.

Stage 2, follows shortly after the completion of stage 1, covers the removal of all plant and buildings outside the biological shields surrounding the reactor.

Stage 3, involves the complete removal of the reactor structures comprising the graphite core, the steel pressure vessels and the reinforced concrete biological shields.

Each of the three stages was originally expected to take 5 and 7 years to complete [7]. Currently, the Magnox decommissioning process is expected to last from 50 to 100 years.

MAGNOX DESIGN

The United Kingdom (UK) has considerable experience with gas-cooled reactors. The first commercial gas-cooled reactor began operation in 1962; and an extensive program was undertaken to build Magnox reactors for electricity production. Twenty-six Magnox reactors and fourteen AGR's were placed in service. The British were early pioneers in the field of gas-cooled reactors and made significant contributions to HTGR development, especially in the areas of fuel, core and heat transfer technology.

The Calder Hall nuclear power station is located on the southeast side of BNFL's Sellafield site on the Cumbrian coast. Calder Hall was the first of the Magnox type reactors, and was touted by the British as the world's first, large, central-station nuclear power plant. The first Calder reactor went critical in May 1956, where it generated 100 MWth or 28 MWe. This reactor was followed by three more at Calder Hall and four at Chapelcross, with the final reactor going into service in 1960. They were the prototypes of all the later Magnox reactors. Although their original purpose was to manufacture plutonium with electricity as a by-product, the design was essentially a prototype for commercial electricity generation. The basic design was very conservative with large factors of safety, small sizes, and low ratings making for simple operation but with low thermal efficiency. Improvements in fuel design, improved temperature assessment techniques and plant uprating, enabled output to be increased to 260-270 MWth [8,9].

The Chapelcross nuclear power station is situated near the town of Annan, between Dumfries and Carlisle on the north side of the Solway Firth. The first reactor was commissioned in 1958 and the other three in 1959. Its design and specification are similar to those of the Calder Hall station. The main differences between the layouts of the two stations are the orientation of the reactors and the arrangement of the turbine halls. Calder Hall has two turbine halls, each serving a pair of

reactors, whereas Chapelcross has s single turbine hall serving all four reactors.

The Calder Hall and Chapelcross nuclear reactors consist of a large graphite moderated thermal-neutron reactor that uses natural uranium clad in magnesium alloy as fuel. The reactor used a CO_2 coolant, where the coolant enters the base of reactor at 0.69 MPa (100psi) and 140°C (284°F), and leaves at 336°C (637°F) in four parallel and identical circuits. Each includes a heat exchanger in which heat is removed from CO_2 to raise steam for turbines, and a main coolant pump in the low-temperature leg.

The primary reactor coolant is CO_2 gas that is supplied from a dedicated liquid storage and evaporation plant. The original storage plant consisted of eight 5 tonne tanks, augmented later by four 15 tonne tanks, and a distribution system providing all four reactors with CO_2 from two separate supply routes. In 1979 the CO_2 supply station was extended when an additional four 53 tonne tanks and six 2 tonne/hour evaporators were installed. This increased the CO_2 storage capacity from approximately 100 tonnes to 280 tonnes to provide a contingency against disruption of the delivery of liquid CO_2 to the site. During 1985/1986 the original CO_2 storage station was removed and two more 52 tonne tanks, along with evaporators and refrigeration units, were installed with interconnections to the existing tanks [10].

Unlike the later Magnox reactors, refueling requires the Calder Hall and Chapelcross reactors to be shutdown and depressurized.

The operational history of Calder Hall is a testament to the robustness of its original design and construction and to the professional manner in which it has been operated and maintained. In 1997, the Nuclear Installations Inspectorate awarded Calder Hall a permit for fifty years of operation, subject to annual revisions and back fitting to the current state of the art [11,12,13].

Hunterson A has two Magnox reactors that are graphite moderated and CO_2 cooled. The Magnox reactors use natural uranium contained in magnesium-oxide-clad cans. Each Hunterson A reactor is enclosed within a 70-ft-diameter steel sphere pressure vessel and surrounded by concrete shielding. Each reactor core has more than 3,200 vertical fuel channels loaded with 10 fuel elements each. The fuel elements stand on top of one another in the channels. Their weight is transmitted down through their graphite sleeves to a graphite reflector sleeve (a radiation shield) and then to a support member that incorporates a flow control gag (in a set position that can be changed only during refueling).

The South of Scotland Electricity Board (SSEB) closed the Hunterston A station due to insufficient electricity demand in Scotland. The lower cost AGR's coming on line at Torness showed higher outputs than originally expected. However, the Hunterston A was among the leaders in performance after 25 years, with a life-time load factor of 81.7%. All the Magnox station operating costs in the U.K. increased markedly in the late 1980's, particularly because of higher charges for spent nuclear fuel reprocessing [14,15].

The oldest Magnox reactors, the first generation of gas cooled reactors, were in operation for more than 47 years [16]. These reactors are fueled with natural uranium metal, clad with Magnox (a magnesium-aluminum alloy), and use CO_2 as the coolant. The early Magnox plants had steel pressure vessels while the later, higher output versions at Oldbury and Wylfa use prestressed concrete reactor vessels. In the UK, the higher power output versions had to be derated by approximately 20% following the discovery of a steel oxidation problem in 1969. In general the Magnox reactors showed steady improvement in capacity factor over the years.

The French developed a version of Magnox reactors in the 1960s. The Marcoule and Chinon had external CO_2 systems, while the St. Laurent and Bugey reactors are of an "integral' type, where the whole of the main CO_2 system is included inside the pressure vessel. Although these head exchanges were of very unique design, no special trouble was encountered during design or construction phases of the CO_2 circuits. France had successful experience with their eight prototype Magnox gas cooled reactors. However, because of their high operating costs compared to the pressurized water reactors in France, the reactors were eventually shut down.

In Japan a single, small (160 MWe) gas cooled Magnox plant, Tokai-1, was built in the 1960s as a demonstration plant. In recognizing that process industries in Japan required large quantities of high temperature heat (35% of total energy consumed is used to provide heat between 300°C and 900°C) and that future needs for coal gasification and thermochemical water splitting would require process heat at temperatures of 900°C or higher, Japan foresaw the very high temperature gas cooled reactor (VHTR) to supply industrial process heat as the most promising application of HTGR technology.

The Vandellos plant was built and operated by a French-Spanish company (Hifrensa). The plant was shutdown in 1989 after an alternator fire accident [17].

AGR DESIGN

After the very successful introduction of the Magnox reactor stations to nuclear power generation for the UK utilities, the search for a more compact design that could make use of the standard 600 MWe turbine generator sets, which were being developed for contemporary coal and oil fired stations, began in 1957. These requirements were met by the AGR, which can be regarded as a development of the Magnox system. The 33 MWe test bed AGR at Windscale, in Cumbria in 1962 ushered in the next generation of AGR systems for commercial use.

The essential concept of the 1200 MWe station was to use twin graphite moderated, CO_2 cooled reactors, with stainless steel clad fuel elements containing enriched UO_2 cylindrical pellets, to provide the necessary higher temperatures to match the fossil

fuel station steam conditions, enabling standardization on the bigger turbines that had been developed.

Prestressed concrete pressure vessels, pioneered in France, and a feature of the later UK Magnox stations, were adopted for the AGRs, together with provision for changing fuel on-load. On-load refueling has proved to be a successful feature of the Magnox stations. There are two types of design for the concrete pressure vessel. One uses a single-cavity vessel to encapsulate the core and the boilers, and the second adopts a "podded" style of vessel where the steam generators are housed vertically in separate cavities in the wall of the pressure vessel, with the gas circulators located vertically below them.

The power station at Dungeness B was the first commercial venture with the AGR concept, and in this design the basic vessel layout of the Oldbury Magnox station was used in association with those features now characteristic of the AGR. The features included: the highly-rated fuel, handled in long strings; the internal dome to provide re-entrant flow of the coolant gas in the core; high temperature carbon dioxide coolant; and steam at a temperature of 565°C.

Hinkley Point B has all the features of Dungeness B except that steam temperatures were reduced to 541°C. Also the fuel cycle and engineering features were further developed in the interest of economy or security. For example, the gas pressure was increased from 3.3 MPa (34 kg/cm2) to 4.2 MPa (43 kg/cm2) in order to reduce the pumping power. The gas circulators were designed so that they could be removed for maintenance while the reactor is under pressure. The shield wall between the core and boilers was completely new in concept to achieve a reduction in vault dimensions [4,18].

The reactor units and turbine house are combined in a single complex with a central block for control and instrumentation. The twin turbines are arranged side by side on the same centers as the reactors in order to shorten the steam pipe runs. The two reactors are served by one refueling machine operating within a common charge hall. The reactor itself has a heat output of 1,500 MW and delivers carbon dioxide gas at 654°C to four steam generators, which raise steam at 16.7 MPa (170 kg/cm2) and 541°C. The layout is similar to Oldbury and Dungeness B, with boilers in an annulus surrounding the core and upward flow of coolant gas through the fuel channels. The gas circulators are located beneath the boilers at a level convenient for access and maintenance.

The reactor core is a 16-sided stack of graphite, connected at the periphery to a steel tank restraint structure. The bricks are interconnected by graphite keys to provide stability of the assembly and to maintain the vertical channels on their correct pitch. The core contains 308 fuel channels arranged in a square lattice. The control rods and other facilities are located in interstitial, i.e., off-lattice positions. Access to the boilers and all plant other than the core within the pressure vessel is possible during reactor shut down by a radiation shield wall surrounding the walls and top of the core.

The fuel elements consist of 36 pins containing 14.5mm diameter uranium dioxide pellets, the pin cluster being contained within a graphite sleeve of 190mm inside diameter. Eight such elements, each 1039mm long, are linked together by a tie bar to a fuel unit extending to the top of the refueling standpipe and terminating in a pressure closure. The lower part of the plug unit is a sealed hot-gas duct which carries the channel outlet gas through the region below the gas baffle and discharges it above the baffle. The design of fuel assembly is an essential feature of an on-load refueled re-entrant core system since the fuel elements themselves, together with the lower plug unit, form the fuel channel. Fuel and control rods are replaced on load because of the savings associated with reduced outage time and with a continuous fuel cycle are likely to be much greater than the cost of extra equipment for this facility.

Coolant gas leaves the reactor at 665°C and flows into the boilers. Gas is drawn from the bottom of the boilers by the circulators and discharged into an annular duct. Before re-entering the fuel channels, part of the coolant flow passes up the annulus between the gas baffle and the shield wall, and into the domed space above the core, where it then divides, half returning down between the tubes of the shield wall and the other half passing through the core in the passages between the graphite bricks. The temperatures of the gas baffle, boiler shield wall, core restraint tank, and graphite bricks are thus maintained at values essentially those of the cool inlet gas. On each reactor there are eight gas circulators of centrifugal type with constant-speed electric motor drive. Variable inlet guide vanes will control coolant flow. Each circulator, complete with motor and control gear, is a totally enclosed unit located in a horizontal penetration at the bottom of the vessel wall. The motor runs under full coolant pressure [4].

Hunterson B has two advanced gas-cooled reactors that are graphite moderated and CO_2 cooled. The AGRs have slightly enriched uranium oxide in stainless-steel-clad pins. AGR cores have a higher power density and operate at a higher coolant temperature and pressure than do Magnox cores. Both AGR and Magnox reactors are designed for on-load refueling, but the later have been more successful at being able to refuel at 100 percent power. Operational constraints have limited AGRs to lower levels of power while refueling.

The two Hunterston B reactors are each contained in a cylindrical prestressed concrete pressure vessel. Each core has 308 vertical fuel channels and 81 control rod channels. A fuel element has 36 pins containing hollow pellets of enriched uranium dioxide clad in stainless steel. There are three levels of enrichment across the core. Each pin cluster is contained within a double graphite sleeve. A fuel assembly is composed of a fuel stringer (eight stacked fuel elements) topped by a plug unit. During refueling, the fuel stringer hangs from the plug unit by a tie bar. (The tie bar is not stressed when the fuel sits in the core.) With the fuel assembly installed in the core, the plug unit extends upward to the top of the refueling standpipe and terminates in a pressure closure.

The coolant passes upward through the fuel channels, between the outside of the pins and the inside of the sleeve, picking up heat from the fuel. (The coolant also is circulated in other pathways to cool the core.) Each fuel channel has an individual

gas flow control, remotely operated from the control room to optimize thermal generation. Heat is transferred from the coolant to water in 12 once-through reheat boilers (located inside the reactor), arranged three to a quadrant around the core, to create steam. Eight centrifugal gas circulators, grouped two to a quadrant, drive the coolant. Each reactor drives its own turbine. Fueling is done from the top of the reactor, with direct access to each channel. A single charge machine is used for both reactors. This machine also handles control rod assemblies. On-load refueling is currently conducted periodically in groups of about eight fuel channels and is limited to a power level of about 30 percent.

The Heysham-1, located on a site near Morecambe on the northwest Lancashire coast of England, is graphite moderated and carbon dioxide cooled. The two AGRs at Heysham-1 are rated 625 MWe. Each Heysham-1 unit has eight gas circulators; eight helically wound, integrally finned pod boilers; and 324 fuel channels [14].

Some of the last developed AGRs, such as Heysham-2 and Torness Point, used a single cavity vertical cylinder design of concrete pressure vessel with helical multilayer prestressing tendons in the walls, so arranged that no tendons are required across the top and bottom slabs. The inner surface of the vessel has a steel liner, insulated and cooled to 50-70°C to limit the concrete temperatures. Concrete pressure vessel penetrations are also lined, insulated and cooled so that there is a continuous membrane over the whole of the inner surface of the vessel.

The use of enriched uranium dioxide fuel pellets in stainless steel cans enables CO_2 gas outlet temperatures up to 670°C to be obtained, with a maximum permissible fuel clad surface temperature of 825°C. The graphite moderator is constructed of individual blocks, with vertical channels, about a quarter of which contain absorber rods of boron steel and the remainder, clusters of fuel pins within graphite sleeves. The reactor core is a 16-sided stack of graphite bricks, connected at the periphery to a steel restraint tank.

The core stands on a support diagrid, and both are enclosed in a domed, cylindrical, steel gas baffle, which segregates the core from the boilers and which is welded to the pressure vessel liner floor to prevent movement in the event of an earthquake. The gas baffle enables the graphite moderator and other core structural components to be adequately cooled during normal operation. The external surface of the baffle is thermally insulated from the coolant leaving the fuel channels. Gas circulators draw cooled CO_2 gas from the bottom of the boilers and supply a flow of gas to the plenum beneath the core, where it is divided into two streams. One stream (approximately 70% of the total flow) takes the cool gas up the inside surface of the gas baffle, around the perimeter of the core to cool the restraint system and on reaching the top of the core it is directed down to the bottom of the core again through paths in the graphite to cool this core material. The coolant then joins the second gas stream (the remaining 30%) and flows directly up the fuel channels to collect heat from the fuel as it passes over the surface of the fuel elements. The hot gas leaving the top of each fuel channel is then, passed in guide tubes through the dome of the gas baffle, and is combined in the hot gas plenum above the gas baffle, before flowing down through the boilers, giving up heat to raise steam for the turbines.

In the Heysham-2 and Torness designs, which are based on Hinkley Point-B and Hunterston-B stations, the fuel assembly consists of a fuel stringer and a fuel plug unit. At Heysham-2, each reactor has eight gas circulators, 12 once-through boilers, and 332 fuel channels. The fuel stringer comprises eight 36 pin fuel elements (each 1 m long) stacked one above the other and suspended from the fuel plug to make them more robust for on-load fuelling. The fuel plug unit incorporates controls for the coolant flow through the fuel stringer, and adjustments to gas flow can be made during reactor operation. This is achieved by resetting the gag at the top of the fuel stringer using a motor drive mounted on the fuel assembly plug unit.

The primary system for control and shutdown of the reactor comprises 89 control rods and drives. These are made up of black and gray rods, with a number of the latter used as a safety group that is withdrawn to provide trip protection when the reactor is shut down. A secondary shutdown system is also provided. Fast shutdown is achieved by injecting nitrogen, and long-term hold-down by injecting boron glass beads into the core.

Eight gas circulators deliver CO_2 gas at about 4.33 MPa (43.3 bars abs.) and 298°C into the plenum below the diagrid. Heat is transferred to the gas from the fuel raising its temperature to about 640°C. Four boiler units are arranged circumferentially in the annulus formed by the gas baffle and the reactor pressure vessel liner. Each boiler has high pressure and reheat sections with separate feed and steam penetrations through the outer cylindrical surface of the pressure vessel. The main boilers and gas circulators are physically divided into four separate quadrants by division plates at the circulator inlet plenum below the boiler seal. The boilers are of the once-through type so that the number of pressure vessel penetrations can be minimized. Separate tube banks, below the economizer section in the main boiler casing, comprise the decay heat boiler, which provides a diverse route for shutdown cooling of the reactor. The eight induction motor driven gas circulators are located in pairs in each boiler quadrant. Each circulator and drive motor, complete with motor cooling circuit water heat exchangers, is a totally enclosed unit located in a horizontal penetration below the main boiler.

During normal operation, feed water is supplied to the boilers at about 157°C and 17.0 MPa (170 bar abs.), giving steam temperatures of about 541°C. The gas circulators are driven directly from grid supplies at 11kV and 50 Hz. Gas flow control is achieved by adjusting the angle of guide vanes at the inlets at each circulator. Steam raised in the boilers is passed to one 660 MWe turboalternator per reactor (2 x 660 MWe per station).

The AGR became the mainstay of the British nuclear reactor program in the 70's but continuing controversy over the economics of the AGR system led to an extensive evaluation of the pressurized water reactor (PWR) and the decision to turn to PWR for the next program.

OXIDATION OF MATERIALS

When steel is exposed to carbon dioxide at temperatures in the range of 350°C to 450°C, a thin protective coating of magnetite (Fe_3O_4) is formed. This coating thickens at a slow rate and ultimately cracks whereupon local pimples and excrescences form, permitting more rapid oxidation.

At the design stage the evidence suggested that oxidation rates were moderate even on exposed surfaces. The first gas-cooled reactors were, therefore, constructed from mild steel and the use of the more expensive stainless steel was restricted to essential applications. If this had not been done then construction costs would have been enormously increased and nuclear power stations would not have been commercially attractive [14].

In the Calder Hall reactor research program they identified problems involving the corrosion and oxidation of the can (believed in most cases to be Magnox alloy – a magnesium-beryllium alloy), and of the steel shell in a wet CO_2 atmosphere. Other canning methods were pursued including zirconium and beryllium alloys.

The oxidation affects from CO_2 samples tested at 400°C, 0.8 MPa pressure, and varying moisture contents, are shown in Table 3.

Table 3 – Oxidation of Materials in Carbon Dioxide

Material	Oxidation
18/8/1 stainless steel, Commercial A1 Sintered A1 powder	*Excellent* (no attack after 5 months)
Pure Mg ***Magnox C*** Mg alloy AM503 Al alloy RR58	*Good* (0.1 mg/ cm^2 / 5 months)
Al alloy RR57 Mg alloy ZT1 Mg alloy ZRE1 Magnox E Alloy steel (Jessops G1) Mild steel (0.05% C) Sintered Mg powder Pressure-vessel steel	*Moderate* (0.15 – 1.11 mg/ cm^2/ 5 months)
Cast iron	*Poor* (2.72 mg/cm^2 / 5 months)

Test results indicated that moisture almost doubles the corrosion rate.

Significant oxidation of structural materials occurs from CO_2 at the operating temperatures of the Magnox reactors. It was not until the Bradwell and Berkeley reactors were operated for some years before it was appreciated that inadequate account had been taken of the effects of corrosion of certain types of mild steel. At the design stage the evidence indicated that in general mild steel would undergo protective oxidation and this material was widely used in the fabrication of reactor components.

Although adequate allowance was made for metal loss due to oxidation during reactor life in the design of the strength members, the extent and significance of interface corrosion was not properly appreciated. This shortcoming was exacerbated by the fact, which emerged from continuing experimental work, that under some conditions of temperature, moisture content etc. the time to onset of accelerated or "breakaway" corrosion could be much shorter than had been anticipated, particularly in the case of rimming steels. In the case of the breakaway oxidation, once it is established it will remain [1].

The net result of these developments was that it became apparent that unacceptable strains could occur in bolted fastenings, imperfect weld etc., due to build up of oxide at interfaces and that failure of the fastenings might occur. A broken bolt in the core of one of the Bradwell reactors provided operational evidence of this problem. It was deduced that the bolt had fallen from a container designed to hold steel samples for monitoring purposes in the hot gas region above the core, and removal of the container confirmed the cause of the trouble. These findings precipitated an extensive inspection of the mild steel components of operating reactors and intensification of the allied research programs. The main conclusion showed that oxidation rates were predominantly influenced by operating temperature and that these rates doubled for each 25°C increase in temperature. The type of steel was shown to be important, high silicon steels resisting oxidation more than those with a low silicon content. The effect of oxidation on ordinary free surfaces was negligible. No significant weakening of steelwork occurred through loss of metal itself. The effect of oxidation on the trapped surfaces between nuts and bolts and the surfaces held together by them was more serious. When steel is oxidized the oxidation product occupies a volume about two to three times greater than the original metal. In accommodating this increased volume the bolt is stretched and when the process is sufficiently advanced, failure of the bolt may occur. As a preventative measure, it was decided to set reduced upper limits on the temperature of the coolant, a step that involved derating some of the reactors [19, 20,21].

A number of different canning materials were investigated. Physical properties of possible canning materials were investigated. The most important requirements are:
- low thermal-neutron cross section.
- good resistance to coolant attack.
- compatibility with U under operating conditions.
- good sealing characteristics.
- resistance or accommodation to stresses imposed by the fuel during operation, which implies good ductility combined with adequate strength.
- good thermal conductivity and extended coolant surfaces for heat transfer.

The physical properties of possible canning materials are shown in Table 4:

Table 4 – Physical Properties of Canning Materials

	Be	Mg	Zr	Al	Nb
Thermal neutron absorption cross section 10^3 □ abs. cm^2/cm^3	1.23	2.54	7.65	13	59.9
Melting point, C	1,284	650	1,860	659	2,415
Thermal conductivity at 125 C, BTU/hr ft F	80-64	95.76	10.08	133.56	32.76
Vapor Pressure	Low	High	Very low	Very low	Very low

Much of the early work had been done on the use of aluminum for canning materials. The Windscale reactor fuel elements were Al clad. Oxidation tests on magnesium, however, indicated the possibility of satisfactory operation up to 400°C in air. As can be seen from Table 4, the nuclear properties of Mg are substantially better than those of Al, with only a very small decrease in thermal conductivity. Even though satisfactory operation of pure Mg canning in CO_2 appeared possible without fire hazard, it was felt that an alloy that would be oxidation–resistant at temperatures up to and including the molten state would be a substantial advantage. Magnesium alloys containing 0.05% Be, 0.1% Ca, and 1.0% Al were developed; they are remarkably oxidation-resistant. Tests in wet CO_2 with Magnox E alloy showed no failures in 2,500 hr at 615°C.

The alloy finally selected for reactor canning was Magnox C, in which the Ca was omitted. Difficulties in welding due to cracking and poor penetration were relieved by the omission of the Ca, and the loss in oxidation resistance was insignificant in CO_2.

A very important characteristic of Mg alloys is, however, that they do not form any intermetallic compounds with U metal, and consequently no barrier between the U and the Mg is required. This property simplifies the canning process enormously and consequently resulted in a substantial reduction in fuel-element-fabrication costs.

CARBON DEPOSITION

Operational experience with carbon dioxide cooled reactors showed the need to optimize carbon monoxide (CO) levels, created by radiolysis in the reactor, to balance radiolytic corrosion of core graphite with carbon deposition on the stainless steel fuel pins.

Carbon deposition on some fuel pins in the two Hunterston B reactor cores necessitated reductions in gas outlet temperatures of some channels – and consequently, reduced power levels (15-30MWe)-because of the impaired heat transfer capability of the affected fuel pins. This reduction was slowly reversed as new fuel replaced the fuel having the carbon deposition.

It was found that methane injected (to a level of 270 ppm) into the coolant could stop graphite corrosion. However, too much CO creation (assisted by catalytic nickel from the gas bypass plant, the reactor coolant processing system) will cause carbon deposition. Methane injection was used at Hunterston B to reduce the level of CO production. However, a consequence of the reduction in CO level was a reduction in core life. Because CO helps to stop core graphite corrosion, the station operators had to seek a balance between carbon deposition and core life.

At Hinkley Point B, the CO level was higher than at Hunterston B, and Hinkley Point B was the first station to experience very high carbon deposition levels on the clad – thickness up to 300 microns. Station operators had to impose fairly severe heat transfer impairment. Tests indicated that the carbon deposition at Hunterston B was greatest at the gas bypass plant, which conditions the gas and has catalytic nickel coming from construction materials. Keeping the gas bypass plant hot all the time reduced the effect of the nickel in promoting carbon deposition. They were able to minimize the heat loss penalty by focusing on the bypass quadrant [14,22].

CHOICES OF REACTOR COOLING GASES

Since the early days of nuclear reactor design, a large number of coolants has been proposed. A wide choice still remains, including: liquid metals, mainly sodium or NaK; organics; water in its various forms (liquid, saturated, and superheated steam); and other gases. Among the gases, carbon dioxide has been mostly used in France and in Great Britain, while helium is used in the United States. Other gases, such as air, nitrogen, neon, argon, and hydrogen, have also been used for special applications such as gas turbines (closed or open cycle) and nuclear rockets.

Gas cooled nuclear power reactors cover a large spectrum of reactor types, from the early dual-purpose plants, such as Calder Hall and Marcoule, to the advanced Magnox reactors, such as most British and French civilian power reactors, to the advanced gas-cooled reactors. Several reasons are advanced by the proponents of gas cooling for reactors-the possibility of decoupling high temperatures from high pressures and the low macroscopic neutron absorption cross section being among the main advantages. Safety considerations are sometimes offered as an added attraction, since a catastrophic reactor accident appears to be extremely remote, especially with an integral reactor inside a prestressed concrete pressure vessel.

Nuclear, thermal, mechanical, and metallurgical design of the core is greatly influenced by the type of coolant gas. The choice of primary coolant also affects several parts of the system, such as the pressure vessel, the piping, the heat exchangers, and the compressors, besides the core. Mechanical problems, such as design of seals or grid plates, vibration

problems, design of turbo machinery, and selection of system materials are all affected by the choice of gas. In addition, the coolant gas should be chemically and neutronically inert, cheap, and readily available. It should have good heat transfer and transport properties and should for instance, also be a good insulator (to keep the pressure vessel cool), a good conductor (from fuel rod to cladding), and a good natural convector (in case of loss of coolant and for removal of shutdown heat). Obviously, there is no such ideal gas. The three main contenders as reactor coolants are water, sodium, and the gases. Helium, CO_2, and steam represent virtually the only closely evaluated alternatives. Meaningful intercomparison of all these coolants suffers from the impediment that different classes of reactors have different requirements and, indeed, some kinds cannot use some coolants at all [20,23]. Among the most important of the features of gas cooling are:

1. pure single-phase operation, meaning not only freedom from all concern about local boiling or voiding, and absence of necessity to deal with condensable coolant vapors;
2. low neutron absorption and moderation;
3. inertness, both chemical and radioactive, including, in the case of helium, compatibility with water, air, and fuel;
4. transparency;
5. total coolant loss is impossible – only depressurization; and
6. low total stored energy.

Gas cooling allows full utilization of the most modern steam plant development, with substantial advantages to plant cost and efficiency. It also makes feasible the integral PCRV type of construction [19, 24].

In the Magnox and AGR reactor designs, other gases were considered as an alternative to CO_2. Nitrogen and carbon dioxide are relatively poor gases as far as thermal conductivity is concerned. Helium has good heat-transfer properties and good chemical properties, but was not domestically available in the UK in the quantities necessary. Hydrogen has excellent heat-transfer properties but essentially unknown chemical properties. There is no single gas that is the best coolant under all possible conditions. The ultimate criterion in choosing a gas coolant for a power reactor should be the lowest overall power cost [20,21,25].

EVOLUTION OF HTGR'S

The continuing evolution of gas reactor technology in Europe and the U.S. led to a convergence in at least two important particulars in the development of gas-cooled reactors. Helium replaces carbon dioxide as a coolant and the reactor core is charged with nuclear fuel in a unique system that dispenses with the need for a metal cladding. The two features were demonstrated at Peach Bottom, Fort St. Vrain and two European reactors [26].

In the 21st century, with the latest reactor designs under investigation in Generation IV, there is an interest in developing a Gas-cooled Fast Reactor (GFR) that could use CO_2 as a coolant. The GFR system is a fast neutron reactor operating at high temperatures (>800°C) using a direct gas-turbine (Brayton) cycle without use of a heat exchanger. The reactor would be designed at a 288 MWe capacity and use passive safety features. The fuel is a 8-10% enriched U-235 Uranium Oxycarbide.

Several potential schemes are being considered for the GFR coolants. Helium and carbon dioxide are currently being considered. CO_2 is considered to be a better convective coolant for decay heat removal, than Helium. One concept is to use Helium gas for the primary system and CO_2 on the secondary cooling system. An advantage cited for using a Supercritical CO_2 cycle (20 MPa) would be the possible efficiencies of up to 45% at 550°C.

CONCLUSION

This paper has provided a review of early carbon dioxide cooled reactors including the Magnox reactors originating in the United Kingdom and the subsequent development of the Advanced Gas-cooled Reactors. This paper has provided historical perspectives regarding the 52 reactors and the reactor programs that developed them. The Magnox and AGR design features and safety characteristics were reviewed, as well as the technologies associated with fuel storage, reprocessing, and disposal.

The paper also addressed several problems/opportunities that arose from the use of carbon dioxide as a reactor coolant. Reactor designers learned to consider the material properties because of concerns of oxidation at high temperatures. Also carbon deposition on fuel pins created a need to evaluate reactor construction materials that promoted carbon deposition. Reactor designers successfully rose to these challenges.

It is very interesting to note that Calder Hall, the very first Magnox reactor, was shut down on March 31, 2003, after 47 years of operation. The decision to close was not due to faulty design, but due to the depressed price of electricity. The operating license actually allowed Calder Hall to continue operations for 50 years! The Magnox and AGR designs have withstood the test of time. Potentially, we may see CO_2 gas cooled reactors again, perhaps this time developed in the United States.

ACKNOWLEDGEMENTS

Work supported through the INEEL Long-Term Research Initiative Program under DOE Idaho Operations Office Contract DE-AC07-99ID13727.

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