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Operational Experience in Nuclear Power Stations [and Discussion]

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Operational experience in nuclear power stations

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From the first self-sustaining nuclear reaction to the present day represents a span of three decades: within that time large-scale generation of electrical power from nuclear energy has become acknowledged as economic, safe and environmentally acceptable. Within the U.K. 10% of electricity consumed is of nuclear origin. Some of the C.E.G.B. reactors have been in service for over 10 years.

The operating experience that has been gained shows how the original design concepts have been ultimately developed. Some of the difficulties encountered and the engineering solutions are presented. Operating experience feeds back to the design philosophy and safety requirements for future nuclear plant. In this way a foundation is provided for the further exploitation of what must become a major source of energy in the next decade.

1. The history of nuclear power in the U.K.

The equivalence of mass and energy which was established by Einstein at the beginning of this century was followed by the observation of energy release in radioactive materials and by element transmutation in the particle physics field. At that time the bombardment of nuclei by high-energy particles did not give any obvious lead as to how the energy released might be utilized. In 1938 it was established that fission of uranium was taking place in the natural state. The possibility of neutron release was realized and chain reaction appeared to be possible. The Maud Committee reported to the U.K. Government in 1940 its conclusion that it was possible to make a uranium bomb. The whole emphasis was on uranium-235 production, but it was soon recognized that plutonium could be used in weapons. The first chain reaction was set up by Fermi in the United States in 1942.

The post-war British effort was aimed at obtaining an independent nuclear deterrent and a working power programme. The U.S. approach to plutonium manufacture was to use water-cooled graphite-moderated reactors (Hanford) whose safety in U.K. conditions was questioned. Gas-cooled reactors seemed the best alternative, with aluminium-canned fuel. Although some empirical data on neutron absorption cross-sections were available they had to be checked and extended. Experimental reactors were therefore built at Harwell. This research yielded information that the data on the nuclear characteristics of magnesium were considerably in error and more favourable than had been reported so that its use as a canning material became possible. A series of magnesium alloys, generically known as 'magnox' was developed for fuel cans. Meanwhile, construction of the Windscale piles had taken place, using air-cooled aluminium-canned fuel. The Calder project, using magnox cans, was then initiated. During the whole of this period and up to the 1960s the lack of availability of enriched uranium dominated the scene so that no options were open to construct any reactors requiring enriched uranium such as light-water reactors. It was felt that the power programme would be based on the use of natural uranium fuel for a long time unless fast reactors could be quickly developed. To this end the Dounreay fast reactor was designed in the early 1950s. During the early period of Calder construction discussions took place between government and manufacturers and initially four consortia were set up to tender for the construction of nuclear power stations for the Electricity Supply Authority. The reactors could only be of the magnox type. As a result of the first round of tendering, the nuclear power stations at Berkeley and Bradwell were put on order.

2. The magnox programme

Berkeley and Bradwell went to power in late 1963 and since then six other magnox stations have been commissioned. The last set at Wylfa was commissioned in March 1973. All the magnox stations comprise two reactor units and associated turbo-generating equipment.

Design data for the C.E.G.B. magnox nuclear power stations are given in table 1 in chronological order of commissioning. Stations up to Sizewell utilized steel pressure vessels for reactor containment; Oldbury and Wylfa have steel-reinforced concrete pressure vessels. The number of coolant circuits has decreased but a minimum of four has been set. Turbo-generator capacity has also increased, although at Wylfa, with the much larger reactors, four generators of the proven size were installed.

During the magnox construction programme the aim was to reduce the cost per unit sent out at successive stations rather than to aim at operational advantage from replicated designs. Fuel rating, gas pressure and unit size were increased and the number of gas circuits reduced. Steam cycle efficiency was also raised under design conditions. This has meant that each station has incorporated some prototype design features giving rise to individual problems. Some examples are:

(1) Development work was required at most stations with on-load fuel handling equipment. Although fuelling chutes, which are introduced into the reactor only during the refuelling operation and are of fairly complex design, have performed satisfactorily with few exceptions, the more permanently installed pantograph and standpipe assembly components have required redesigned replacements at several stations. Fuelling machine availability has often been affected by poor performance of relays and electrical interlocking equipment, and marked improvements have been obtained during operation by substitution of small components with improved reliability.

(2) Although the testing of gas circulators during construction becomes prohibitively expensive as size increases so that rig tests must be confined to model tests on the larger sizes, their performance has been fairly good. At Hinkley Point 'A', part of a main gas circulator disintegrated during initial tests and all the circulators had to be strengthened and modified: performance since then has been good.

(3) Vibrations in gas circuits have been experienced but overcome by the provision of flow vanes at the elbow bends or by support improvement. Pressure-vessel insulation damage due to vibration at Wylfa involved temporary removal of a charge of fuel during the commissioning period; modifications to insulation mounting were carried out to prevent recurrence.

(4) Oil ingress via the gas circulator oil seals is serious because of its effects on the chemical reactivity of graphite and on the fuel-element heat transfer because of the formation of carbonaceous deposits. It has been a problem at several stations but has been largely overcome by further development of the rotating seals.

(5) Some developments have arisen from more demanding assumptions being introduced into economic and safety reappraisals, rather than by direct development of original designs. On-line delayed-neutron protection equipment is now installed at all stations with steel pressure-vessels to trip the reactor in the event of massive fuel-can failure.

TABLE 1. C.E.G.B. MAGNOX NUCLEAR POWER STATIONS OUTLINE DESIGN SPECIFICATIONS

basic data	Berkeley	Bradwell	Hinkley Point 'A'	Trawsfynydd	Dungeness 'A'	Sizewell	Oldbury	Wylfa
station s.o. capacity MW/reactor heat rating MW	275/558	300/531	500/971	500/860	550/840	579/948	600/892	1179/1875.5
mass of U per reactor/t	231.45	239	349	293	303.8	320.8	293	595.41
no. of fuel channels/no. of elements per channel	3265/13	2624/8	4500/8	3740/9	3932/7	3788/7	3320/8	6156/8
gas pressure (vessel inlet)/MPa	0.93	1.03	1.38	1.76	1.96	1.93	2.50	2.76
no. of boilers /gas circulators	8	6	6	6	4	4	4	4 sections/4
bulk gas outlet temp./°C	345	390	378	392	410	409.9	412	413.7
fuel element max. can temp./°C	432	440	437	435	452	453	450	451
fuel element max. rating/MW t^{-1}	4.1	3.98	4.37	4.97	4.58	4.74	5.1	5.03
total mass of machined graphite per reactor/t	1935	1811	2500	1972	2143	2200	2100	3735
type of gas circulator	induction motor, fluid coupling	induction motor, variable frequency	induction motor, variable frequency	induction motor, by-pass and throttle valves	back-pressure steam turbine	induction motor, vane control and gas by-pass	back-pressure steam turbine	induction motor, variable inlet guide vanes
h.p. steam/°C, at boiler s.v.	2.21/322	5.37/372	4.75/363	6.72/375	9.71/393	4.80/391	9.65/400	4.83/396 o.t.
l.p. steam/°C, at boiler s.v.	0.54/322	1.47/372	1.35/349	2.16/365	4.06/395	1.94/390	4·86/393 o.t.	—
no. of main turbo-generators × capacity/MW	4 × 83	6 × 52	6 × 93.3	4 × 145	4 × 142.5	2 × 324.75	2 × 312	4 × 333.6
no. of aux. turbo-generators × capacity/MW	—	3 × 20.25	3 × 33	—	—	—	—	—
emergency generators type, no. × capacity/MW	diesel 4 × 0.6	diesel 3 × 0.450	diesel 5 × 0.780	diesel 4 × 1.2	diesel 4 × 1.64	diesel 4 × 0.747	g.t. 3 × 2.5	g.t. 3 × 3
contractors	T.N.P.G.	T.N.P.G.	A.P.P.	U.P.C.	T.N.P.G.	A.P.P.	T.N.P.G.	A.P.P.

o.t., once-through boiler. g.t., gas turbine.

Table 2. C.E.G.B. magnox nuclear power stations operating results to 31 March 1973

station	end of commissioning, all turbines operational	net design electrical output MW	net maximum achieved electrical output MW	net accepted electrical output at 360 °C MW	days from end of commissioning to 31 Mar. 1973	total output up to 31 Mar. 1973 10^{15} J (10^9 kW h)†	cumulative load factor (%) against:	
							design output	accepted output
Berkeley	Nov. 1962	276	302	276	3789	72.1 (20.02)	79.8	79.8
Bradwell	Dec. 1962	300	325	250	3789	74.1 (20.57)	75.4	90.5
Hinkley Point 'A'	May 1965	500	531	460	2870	77.1 (21.42)	62.2	67.6
Trawsfynydd	May 1965	500	508	390	2872	71.6 (19.89)	57.7	74.0
Dungeness 'A'	Dec. 1965	550	551	410	2648	88.4 (24.58)	70.3	94.4
Sizewell	Sept. 1966	580	496	420	2389	68.2 (18.96)	57.0	78.7
Oldbury	Sept. 1968	600	555	400	1643	45.3 (12.59)	53.2	79.8
Wylfa	Mar. 1973	1180	843	840	12	0.61 (0.17)	49.5	69.6

† Units supplied since commissioning of last set at station. In assessing the total benefits and costs of the magnox programme, rather than the operational experience, the units supplied prior to commissioning the last set should also be considered. This would reduce these load factors.

(6) Secondary shutdown facilities by means of the injection of an absorber in the form of boron steel balls are now available. Provision is also being made for the manually controlled injection of boron dust should permanent shutdown be required.

3. STATION PERFORMANCE SUMMARY

Table 2 summarizes the operating results. The operational time and the units generated have been measured from the time when the last set was commissioned with both reactors operational. The load factor is then the actual generation as a fraction of the maximum possible generation if running continuously under design conditions. As a consequence of unexpectedly rapid oxidation of some steel components, gas-temperature limits have been imposed which have caused derating at all stations, except Berkeley, since 1969. The net output which can be expected from the stations under these limits with all plant available and with reoptimized parameters is known as the accepted output capacity. Load factors given in these terms are also shown in table 2. The magnox stations have very low operating costs, once built, and are therefore in demand for generation throughout the year since the minimum system load demand exceeds their aggregated capacity. The station load factor figures given in table 2 are therefore almost synonymous with station availabilities – availability being defined as the fraction or percentage of the time during which the plant item concerned was available whether used or not.

TABLE 3. PERFORMANCE DURING PEAK LOADING WINTER PERIODS (NOVEMBER–FEBRUARY 1962/3–1972/3)

station	net design electrical output/MW	winter electricity supplied (net) 10^{15} J (10^9 kW h)	winter days	cumulative load factor (%) against: design output	cumulative load factor (%) against: accepted output
Berkeley	276	26.3 (7.31)	1203	91.7	91.7
Bradwell	300	27.8 (7.71)	1203	89.0	106.8
Hinkley Point ‘A’	500	26.5 (7.36)	962	63.7	69.3
Trawsfynydd	500	28.8 (8.02)	962	69.4	89.0
Dungeness ‘A’	550	32.6 (9.06)	901	76.2	102.2
Sizewell	580	27.2 (7.57)	842	64.5	89.1
Oldbury	600	20.7 (5.76)	601	66.5	99.7

In the U.K., peak demands occur in the winter and the performance of the Board's plant is most critical at this time. The performance of the magnox stations during November to February inclusive is shown in table 3. The biennial consent to operate includes an assessment of the state of both reactors at a given station, assuming a further year of normal operation including 1 month of operating at an outlet gas temperature of 380 °C (20 °C higher than the normal gas outlet temperature). It is therefore possible to make use of this month during the winter period. This can result in the accepted output rising above 100%, as shown for Bradwell and Dungeness ‘A’. The high load factors shown in table 3 confirm the confidence placed in the magnox stations by the C.E.G.B.

Operational availability is shown in figure 1. In this presentation it has been found convenient to show operational time, planned outage time, and forced outages separated into external and internal causes. External causes are those arising from plant outside the reactor–boiler complex and internal causes those within it. Figure 1 shows that with the single exception of

Hinkley Point 'A' in 1970–2, the forced outage total due to both internal and external causes is always less than the planned outage time. At Hinkley Point 'A' a major turbine failure led to prolonged outages (Kalderon 1972; Gray 1972).

The length of planned outages in the magnox reactors is principally determined by the time taken to carry out the statutory inspections required. Each station must shut down one of its reactors each year for boiler gas-side inspection, for which man-access is made. Water-side inspection is also required although this can be carried out on load on individual circuits.

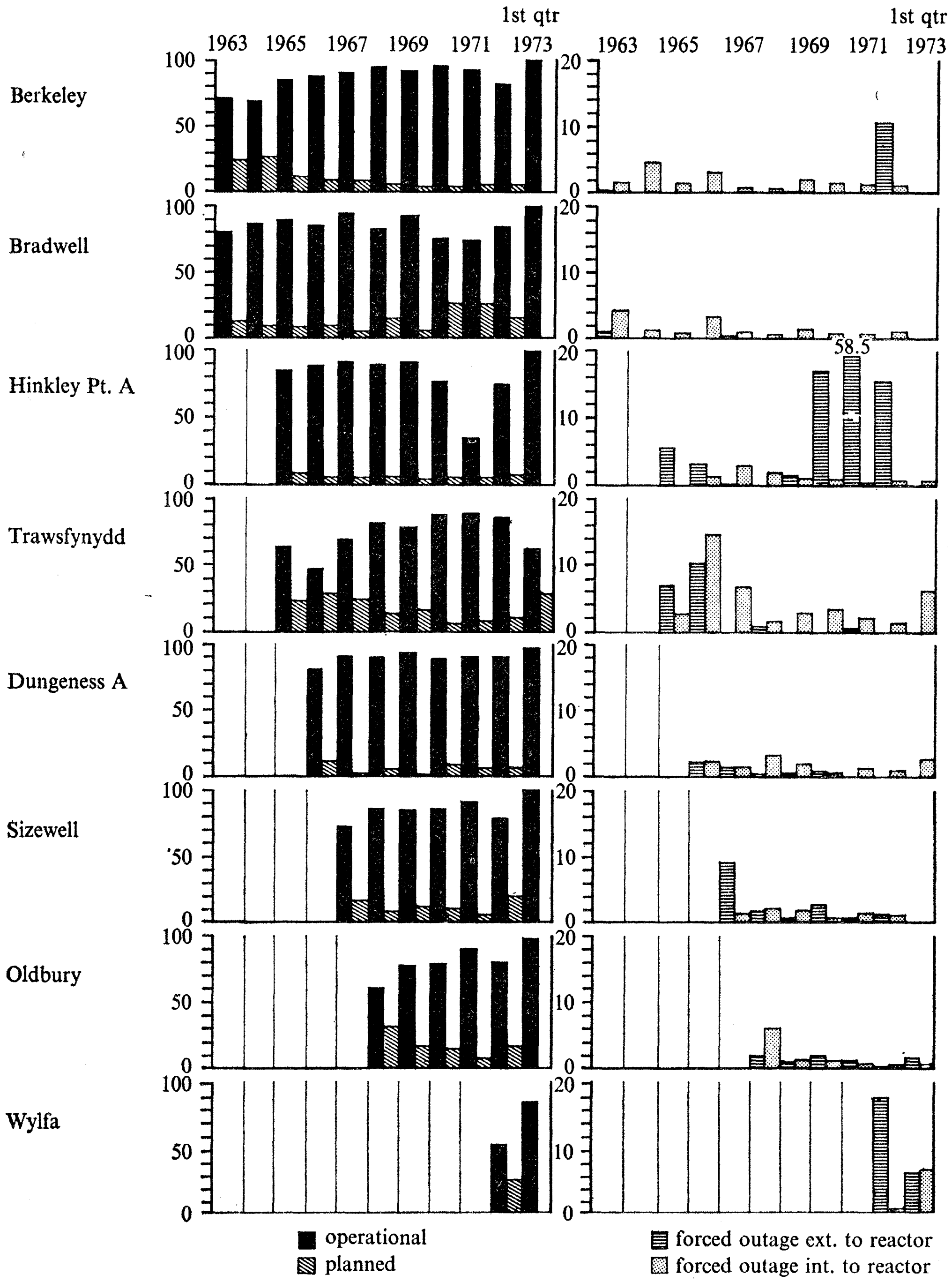

FIGURE 1. Percentage operational availability of C.E.G.B. reactors.

Reactor internal inspection is also a statutory requirement, carried out by a variety of techniques. The tendency is for planned outages to decrease in duration as operators improve performance through experience and forward planning: increased times may, however, occur as a result of increasingly onerous inspection requirements. The reduction of duration of planned outage times is generally the most profitable area for management concentration, and considerable efforts are directed to this end throughout the year.

Figure 1 also shows that the down time due to external forced outages generally exceeds that due to internal forced outages. These two components together with the planned down time add to the station operational availability figure to give 100%. The load factors which are shown in table 2 approach but cannot exceed the station operational availabilities. The causes of these outages have been further analysed in terms of plant items (Gow 1973). The figures speak for themselves and must be judged in comparison with the performance from other types of reactor or from other types of electrical generation. The high cumulative load factors and winter period figures indicate a satisfactory performance.

The running cost of nuclear generation in October 1973 was about one-third of the cost of generation at the best oil-fired and coal-fired stations. Appraisals of total costs per unit of electricity sent out depend on analyses of capital investments that were started up to sixteen years ago. Published figures (Hansard 1972, 1973) show that nuclear generation has been cheaper than at new oil and coal stations.

4. Operational problems encountered

No power-generation systems are without problems. Two of those encountered and dealt with in the magnox reactors are outlined.

Prior to the magnox programme, the technology of high-temperature gas cooling was investigated. Although large research programmes on material behaviour were started with the intention of covering the whole field, certain areas were not fully explored and this has led to problems in operation. The most important have been deformation of the fuel cans and mild-steel oxidation in hot carbon dioxide.

(a) *Fin deformation*

Reactor control is based on the measured heat transfer and pressure-drop performance of the fuel elements. Any fin deformation during service has serious implications since it may lead to a reduction in heat transfer and an increase in the pressure drop across the fuel element.

Some deformation has been produced by the stretching and buckling of the fins of high-temperature elements by an interaction between magnox and coolant gas (Harris 1972). This was a novel demonstration of creep produced by superficial oxidation stresses. In 1967 post-irradiation examination revealed significant fin deformation on Dungeness 'A' fuel elements at a channel average irradiation of only 10^{14} J/tonne (1200 MW d/t – megawatt days/tonne). Subsequently similar fin deformation was observed on fuel elements from other stations but in no case was the problem so severe as that at Dungeness. Fuel-element examination during discharge showed the axial and radial distribution of fin deformation in the reactor and hence the temperature-dependence of deformation.

Laboratory investigations defined the effects of gas composition and temperature and the effect of fin deformation on fuel-element heat transfer. All these results led to revised operating conditions. The proportion of hydrocarbons in the coolant was reduced by improvements in the efficiency of blower seals and the water content of the coolant was reduced by the use of dryers. At stations, such as Dungeness 'A', where the heat-transfer effects were significant, maximum fuel-element temperatures were reduced. Various design modifications were considered and a herringbone design of can, which is more resistant to fin deformation, was adopted for replacement fuel at Dungeness 'A'. However, before these design changes could be fully developed the effects of steel oxidation became apparent (Rutter 1972) and the temperature reductions which followed were sufficient to reduce the rate of fin deformation to a level which is not operationally significant.

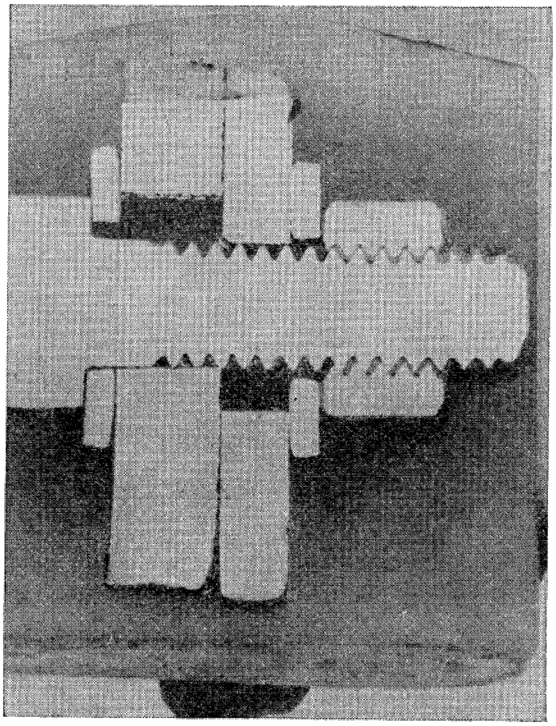

Figure 2.

(*b*) *Mild-steel oxidation in hot carbon dioxide*

The magnox reactors were designed for and originally operated at maximum bulk gas temperatures of up to 410 °C. It had been expected that oxidation of mild-steel components in carbon dioxide would be protective, with the rate decreasing with time as diffusion through the thickening oxide film became slower. In 1968 it was realized that 'breakaway oxidation' was occurring in some reactor components, with an enhanced and linear growth of oxide taking over from protective growth. If steel surfaces were originally covered with carbonaceous films then breakaway kinetics could be established at the outset. These observations led to decisions to limit maximum bulk gas temperatures to 360 °C to maintain an economic life for the reactors. Considerable research has led to better definitions of the major controlling parameters, temperature, wetness of the CO_2, and steel composition – and to the identification of a new oxidation mechanism (Rutter 1972; Gibbs 1973).

The most significant operational experience has been the straining and occasional failure of certain bolted assemblies, some of which include steels of low silicon content which are particularly susceptible to breakaway oxidation, some of which were coated with graphitic films during assembly, and some of which, because of the exigencies of constructional procedure in non-critical areas, include multiple washers and some misalinements. Growth of oxide between mating interfaces causes bolt extension (figure 2). Monitoring of the continued integrity of critical bolted joints is therefore essential, coupled with reliable forecasting of performance until the next scheduled reactor inspection. As there is no effect on oxidation of radiation, useful information can be obtained from boiler components. Means of inspection and sampling of reactor components are referred to in §5.

5. Reactor maintenance

(*a*) *General considerations for vessel work*

Conditions are met in nuclear plant which can create hazards different from those experienced in other branches of industry. Nuclear radiation is not detectable by any of the human senses, and working methods must therefore be controlled administratively with regard to instrument readings. Nuclear fuel continues to generate heat in a shut-down reactor because of fission-product decay heating. The carbon dioxide gas used in reactors is toxic and complete purging on shut-down may not be desirable or achievable.

All these circumstances show the necessity of breathing equipment for the man-access made to low-radiation zones in ducts and boilers associated with steel reactor vessels. Engineering requirements often dictate that access arrangements are difficult and working space is constricted. Provision for inspections should, wherever possible, be made at the design stage.

Concrete pressure-vessels, prestressed by tensioned steel ligaments, have been used for the later gas cooled stations. Their additional strength and accommodation of higher working pressures makes them suitable for urban siting. The reactors, boilers, circulatory and gas circuits are all contained within the pressure vessel as shown in figure 3. To gain access the carbon dioxide must be removed and replaced with air, and special air-cooled clothing has been developed because the temperatures cannot be easily reduced to atmospheric values with an integrated reactor boiler design. Under these conditions a man sweats approximately 0.5 kg water/h which is absorbed in the graphite. A graphite dry-out period of several days is required before start-up at the end of maintenance outages. Experience has been that circuits have remained clean and few problems have arisen with radiation dose or high levels of contamination within the boilers.

The cost of a shutdown of a magnox station in the C.E.G.B. system will vary between £20000 and £60000 per day according to its size, the time of year, and the availability of plant elsewhere. Downtime is therefore extremely expensive and all possible steps are taken to minimize it.

(*b*) *Television inspection and photography*

Reactor in-pile visual inspection equipment of several different types has been used, with emphasis on television inspection and photography rather than direct or mirrored viewing. Television viewing is suitable for general-purpose supervision because of the facility which it offers for immediate adjustment in position, focusing and zooming. It is also suitable for close-up work because of the ease of adjustment, and because in close-up work the definition may be adequate: for viewing a large area from a distance in detail conventional photography is used.

All stations have television equipment capable of being used to view the chargepans and reactor dome together with special television for inspecting the interior of channels.

For oxidation inspection, it is necessary to carry out very extensive photographic surveys at infrequent intervals, the surveys being planned in advance and occupying several days during reactor overhauls. In this way complete photographic surveys of reactor chargepans are carried out to identify any component movement or chargepan debris. The reactor top dome standpipe openings, pressure-vessel insulation and gas-duct openings have been similarly completely surveyed.

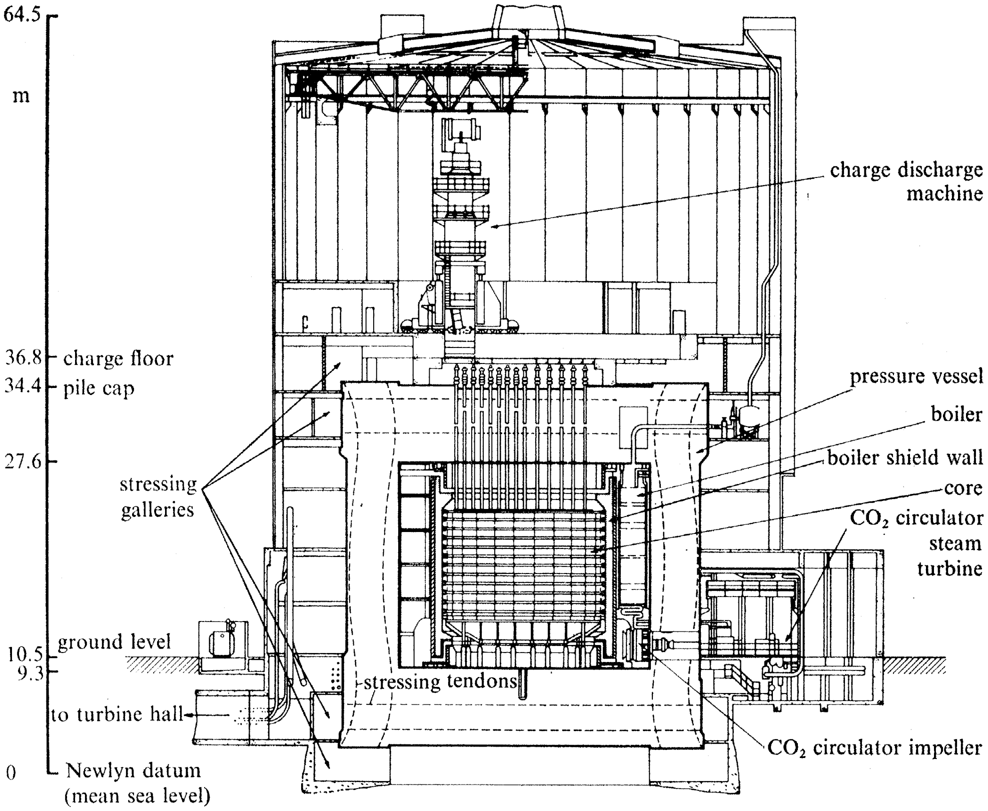

Figure 3. Oldbury: arrangement of reactor and prestressed-concrete pressure vessel.

(*c*) *Oxidation inspection*

When steel oxidation problems developed in magnox reactors it was necessary to increase the programmes of reactor inspection. Inspection is generally carried out in carbon dioxide with the reactors shut down, depressurized and cooled below about 70 °C. Attention is concentrated on those parts of the reactor which have been operated with carbon dioxide temperatures above 360 °C. Special manipulators have been developed for the handling of samples, tools and inspection equipment.

Ultrasonic testing has been successfully applied to bolts; impact and torque testing have also been used. Steel samples have been removed by grinding, trepanning and drilling. A pulsed laser technique is used for remote measurements of oxide thickness (Klewe *et al.* 1972).

(*d*) *In-vessel engineering*

There have been a number of reactor in-vessel component failures in this country and abroad of varying severity. Entries have been made to reactors containing large numbers of fuel elements. More particularly the development of remote-handling equipment and techniques have been accelerated and considerable experience has been gained. A problem arose at Trawsfynydd when a fuel chute could not be collapsed by the normal means. The chute was dismembered by remote tools and subsequently removed – an operation which took about 10 weeks to carry out. At Bradwell a steel sample basket was removed which had to be transported from the area at the top of the pressure-vessel down and out through one of the gas ducts. The most extensive work of this sort was the reinforcing of the top layer of the Bradwell core restraint. Twenty-four interlocking beams were lowered sequentially down standpipes and positioned around the top of the core to form an accurately mounted and tensioned polygonal garter. This work took about 4 weeks to complete and has now been done on each reactor. In work of this sort it is essential to manufacture a mock-up prior to initiating the actual work so that both the appropriate tools and the expertise of the staff can be developed.

(*e*) *Safety-circuit and control-rod testing*

The reactor is shut down in the event of accident by the insertion of control rods. These control rods are tripped in after the fault has been sensed by instruments which measure temperature, flux, pressure, and other relevant parameters. All reactor safety equipment must be engineered to a very high standard of reliability on a fail-safe basis. Redundancy is engineered into the equipment, usually in 2 out of 3 tripping logic. Maintenance of the reactor safety equipment must be to a very high standard and considerable effort is directed towards regular testing of this instrumentation.

Freedom of movement of control rods is of course essential and it is also necessary to be sure that their shut-down reactivity has not deteriorated and that they enter the core in the required time. Rod movement tests and rod timing tests are carried out on a routine basis. Rod reactivity may be inferred by other means but calibration tests are carried out from time to time if necessary, against xenon-135, which is a fission product whose absorption after shut-down is time-dependent. Analysis of control and instrument system maintenance performance is too extensive a subject to be covered here. The subject has been recently reviewed by Dixon & Jervis (1973).

6. NUCLEAR FUEL

The fuel elements used are of natural uranium, clad in a magnox can. The hottest fuel cans operate at peak temperatures of about 450 °C, with a peak centre uranium temperature of about 580 °C. Mean temperatures are considerably below these figures, the bulk gas outlet temperature being 360 °C.

(*a*) *Fuel operational experience*

The reactors each hold in total upwards of 20000 fuel elements. The residence time is 4–7 years, but is measured in 'burn-up' units of megawatt-days per tonne (MW d/t; 1MW d/t = 86.4 GJ/t). The fuel is changed on-load. Over one million fuel elements have been changed on-load, most of them at the end of normal life. About 0.1% of fuel elements have failed in service, mostly because of initial batch defects; and the present rate of failure is much less.

Fuel-element failure totals are shown in table 4 (Mummery & Hines 1973). Only 17 of these failures have resulted in any loss of output.

A considerable amount of development work has been necessary with fuelling machinery following first reactor start-up and changes in detail design of fuel elements themselves have required modifications during operation to refuelling machinery. The full capability of the fuelling machinery has not been realized at several magnox stations until several years of operation have elapsed, but despite these handicaps the plant load factor has been high.

Table 4. Totals of fuel element failures at 30 September 1973

	failure detection signal					
	start up and on-load charging	slow burst	rapid (1)	fast (2)	total	total fuel elements charged
Berkeley	20	129	17	3	169	297206
Bradwell	14	89	19	6	128	122156
Hinkley Point 'A'	65	84	12	3	164	180544
Trawsfynydd	10	52	6	5	73	154845
Dungeness 'A'	22	317	11	2	352	144298
Sizewell	12	503	2	1	518	131593
Oldbury	3	4	0	0	7	105388
Wylfa	0	3	1	0	4	109664
totals	146	1181	68	20	1415	1245694

Notes: (1) Signal doubles within 8 h. (2) Signal reaches saturation within 1 h.

(b) *Fuel development*

Twelve of the 16 C.E.G.B. reactors have now reached the end of the lifetime of the first fuel charge and equilibrium cycles have been established. The performance of the fuel has been assessed by a programme of fuel-element monitoring carried out jointly by the C.E.G.B., U.K.A.E.A. and B.N.F.L. The principal purpose of monitoring has been to underwrite the safe operation of the fuel but an additional objective has been to acquire information to enable improvements in the efficiency of fuel utilization to be made. At present some 7000 elements have been examined out of a total of about 1 million which have been loaded into the reactors. These examinations cover 'burn-ups' ranging to about 5×10^{14} J/t (5700 MW d/t) channel average irradiation.

As a result of this work the irradiation target for fuel has been progressively raised from 1.47×10^{14} J/t (1700 MW d/t), through 2.6×10^{14} (3000) and 3.1×10^{14} (3600) to 3.45×10^{14} J/t (4000 MW d/t). The principal problems encountered have been uranium-bar torsion, fuel-element bowing, and uranium swelling, the latter being caused by fission product gas build-up. These occur generally late on in the fuel life and provide an ultimate limit to operation. There were some unexpected problems with magnox cans arising early in fuel life. The most important of these were the occurrence of numerous can wall failures in certain batches of fuel elements and the fin-deformation problem already mentioned.

It appears that as the causes of fuel-element failures are understood and improvements in manufacturing and operating techniques implemented, the existing very low rate of failure will be maintained or even decreased further. The deformation of the fuel-element heat-transfer surface due to fin waving was unexpected, but solutions to this problem are available should a return be made to high-temperature operation. Neither torsion nor bowing of the fuel bar are likely to lead to difficulties and it must be inferred that the most probable life-limiting feature is the onset of breakaway swelling at very high discharge irradiation.

The ultimate objective of a fuel-element development programme is that the fuel is not discharged until it has reached its reactivity limit – that is, the point at which criticality can no longer be maintained. The fuel in the outer region of the core is already very close to this limit, but is capable of further burn-up in the central region. The axial or radial shuffling of fuel is being considered further to exploit the fuel utilization. A fuel element irradiation increase of about 50% is theoretically achievable. It is of course necessary to balance the economic advantages of more efficient fuel utilization against the possible penalties associated with the increased risk of reactor outrage if fuel were double-handled and its residence times further increased. Experiments on shuffling and on other dual residence schemes are being carried out.

(c) *Cooling ponds*

One of the major areas of difficulty has been in dealing with irradiated fuel discharge within and in the environment of the reactor cooling pond. The irradiated fuel resides in the pond for a period of about 3 months and is then returned to the fuel manufacturers (B.N.F.L.) for decanning and chemical processing. Radiological control is achieved by the application of appropriate safety rules within I.C.R.P. requirements. Radiation hazards arise from the fuel elements themselves and from any activity which may be present in the pond water or on the surface. Provided that the fuel residence in the cooling pond is not excessive and that failed fuel elements removed from the reactor are bottled there is small probability of activity building up in the pond water. However, practical difficulties at times preclude these objectives being achieved and damaged fuel elements may allow fission products to escape into the pond water. Clean-up plant is provided, consisting of filtration equipment and ion-exchange units.

7. ENVIRONMENT

(a) *Effluents*

The Board have a statutory duty to have regard to the effects on the environment in discharging any of their functions. Nuclear legislation requires that radioactive effluents, gaseous and liquid, arising from nuclear power stations are rigidly controlled to within authorized discharge limits. The principal criteria are:

(1) No member of the public shall receive more than one-tenth of the I.C.R.P. level for occupational workers.

(2) The whole population of the country shall not receive an average dose of more than 1 rad (10^{-2} J/kg) per person in 30 years.

(b) *Activity arising*

Reactor operation gives rise to solid, liquid and gaseous forms of activity. The storage and treatment of solid and liquid activity are determined by whether the activity is in the form of radiation or contamination. Dry storage of irradiated redundant reactor components in concrete vaults on-site is used. Contaminated solids can also be stored on-site in suitably constructed active waste areas. Activity occurs on filters and resins used for ion-exchange treatment. Resin regeneration gives rise to active sludges, and waste dumps are used on-site for this storage.

A considerable volume of low-activity waste accumulates in the form of packing paper, cleaning rags, overalls, etc.: some of this may be combustible. Reduction of volume of a considerable amount of this low-activity solid waste is possible by incineration, the greater part of the activity being retained in the ash. This method is used under careful monitoring at the stations for this purpose. Low-activity oil accumulates from rotating plant used in reactor equipment and is disposed of by combustion.

Transport of highly active materials is thus reduced to the carriage of spent fuel and to small quantities of fuel and other items which are sent to the laboratories for examination. Even so, the policy has been maintained of bringing laboratory facilities to the site wherever possible when large-scale special examination of active components is necessary.

Table 5. Activity discharged in 1972

	tritium liquids (Ci)		non-tritium liquids (Ci)		active aerosols (mCi)	
station	limit	discharged	limit	discharged	discharge	dilution factor at 0.5 km
Berkeley	1500	44.2	200	23.3	5.7	40
Bradwell	1500	251	200	119	3	40
			(5 ^{65}Zn)	(0.03)		
Hinkley Point 'A'	2000	38.6	200	147	43.4	40
Trawsfynydd	2000	46.0	40	31.4	33.9	15
Dungeness 'A'	2000	28.9	200	29	94.1	40
Sizewell	3000	53.2	200	14.6	79	35
Oldbury	2000	15.0	100	5.2	32	35
Wylfa	4000	82.7	65	0.3	3.2	40

Analysis of milk samples for iodine-131, caesium-137 and strontium-90, and dose measurements made outside the station boundaries, have demonstrated that the operation of the stations is causing no detectable changes to the environment. These monitoring surveys are presented to each nuclear station's local Liaison Committee with the object of keeping local residents fully informed. Activities discharged from the magnox stations in a typical year, 1972, are shown in table 5. The quantities of tritium released are very small, particularly in comparison with some water reactors (Richardson 1973)and the argon-41 activity in the shield cooling air decays rapidly. Fission product activity arising from failed fuel elements is minimal as these are discharged on-load as soon as failures occur and it has not so far been possible to correlate the observed district measurements on fission product activity with anything other than bomb tests. The zinc-65 limit at Bradwell has been set in view of the proximity of the beds of the local oyster industry. The aerosol figures are obtained by sampling through a filter paper: additional small quantities of sulphur-35 and tritium vapour were released. Gaseous argon-41 figures are not shown as this is not measured regularly: releases are of the order of 10^5 Ci per year per station, an insignificant figure for this isotope which has a short half-life.

(*c*) *Radiation dosages to the public and to workers*

Since Berkeley and Bradwell became operational in 1962 there has been no radiation exposure to individual members of the public exceeding the I.C.R.P. limits.

More than 5000 people are employed as radiation workers at nuclear power stations and particular importance is attached to radiological protection and monitoring. Radiation exposure is monitored by film badge for normal duties in normal radiation areas. These areas are such that full working residence in them could not result in acceptable dose rates being exceeded. When access is required to more active areas with higher radiation, individual dose meters are carried which give an immediate reading of the dose as it is integrated. When work is required in contaminated areas, precautions are necessary against ingestion through the body orifices. Precautions range from protective clothing to combat surface contamination to full enclosure with breathing equipment to combat air contamination. An annual medical test of classified workers is carried out, including blood tests.

8. Nuclear safety

Within the C.E.G.B. the Chief Nuclear Health and Safety Officer has direct responsibility to the Board, for the assessment of the safety of plant and the provision of advice on safety matters. His inspectors and technical staff stand apart from operational staff and constitute an independent line of surveillance.

The Chief Inspector of the Nuclear Installations Inspectorate (N.I.I.) advises the Minister and assesses proposals for new reactors and examines details of design and construction.

A site licence is necessary before construction can begin and this is issued by the N.I.I. after examination of comprehensive safety studies. The N.I.I. monitors the operation of stations through its own visiting inspectors and through receiving the formal proceedings of the Safety Committee which is appointed for each station.

The regulation of nuclear safety in England and Wales is by the Nuclear Installations Acts of 1965 and 1969 administered by the Secretary of State for Trade and Industry. C.E.G.B. sites are licensed by the Minister, who may attach special conditions relating to safety. The C.E.G.B. is entirely responsible for ensuring safe operation in respect of its own staff and of the public around the site. It must of course conform with the legislation and conditions imposed by the Minister and the immediate responsibility for this in each station lies with the Station Superintendents.

The Nuclear Safety Committee for each station is comprised of senior members of the staffs of the C.E.G.B., U.K.A.E.A. and B.N.F.L. Formal reports concerning safety matters are required and the approval of the Committee has to be obtained in circumstances where certain variations in operating procedures are proposed.

Outside the formal arrangements for day-by-day safety matters, the Minister is advised by a Nuclear Safety Advisory Committee whose members embrace all aspects of British nuclear experience. At individual station level, nearby communities and local authorities are kept informed of all relevant aspects of station activities through local liaison committees so that by this means a good understanding of safety issues can be achieved.

9. Conclusions

The whole of this paper has been based on C.E.G.B. experience. Against a world background, the cumulative total of nuclear electrical energy generated in the U.K. is 2.5×10^{18} J (694×10^9 kW h), about 37% of the world total.

During the next few years this percentage share will fall as other countries increase their nuclear capacity. In this country the advanced gas cooled reactors (a.g.r.) will be coming on line, the first of these in 1974.

The future of nuclear power generation lies with the breeder reactor, which offers the prospect of increasing the fission yield of natural uranium by two orders of magnitude.

Looking to the 1980s the C.E.G.B. is concerned that the next reactors shall be replications of proven designs. Important operational requirements are ease of inspection, access and maintenance, so that any necessary repairs can be carried out.

At the same time we need to accumulate operational experience of reactor types with future potential in demonstration sizes but would not expect to develop these entirely out of our own resources.

Society may have confidence that the nuclear power programme in this country will be soundly based on considerable operating experience and that the safety of staff and public will be assured.

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Discussion

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Dr Broom has shown that, recently, the annual total electricity generated by the C.E.G.B.'s nuclear power stations has attained a very high percentage of the 'accepted' output capacity of these stations. One suspects that this is not so much a measure of the reliability of nuclear-power technology as it is a credit to the C.E.G.B.'s judgement of what is safe when agreeing station acceptance ratings. To set this in proper perspective, perhaps Dr Broom, in the published form of his paper, would give the accepted percentage derating relative to the originally ordered electrical output capacity for these stations, both overall and (if trends exist) as functions of station size and date of ordering. A comparable figure for fossil-fuel stations over the same period would also be of interest.

T. Broom

The information sought can be derived from table 2. The net total derating is 23 %. In respect of those fossil fuelled stations which have had their last turbogenerators commissioned during the period November 1962–March 1973 their present total net electrical output is 23600 MW compared with a net design output of 24950 MW, a reduction of 5 %. Improvements to these ratings are still being acheived.

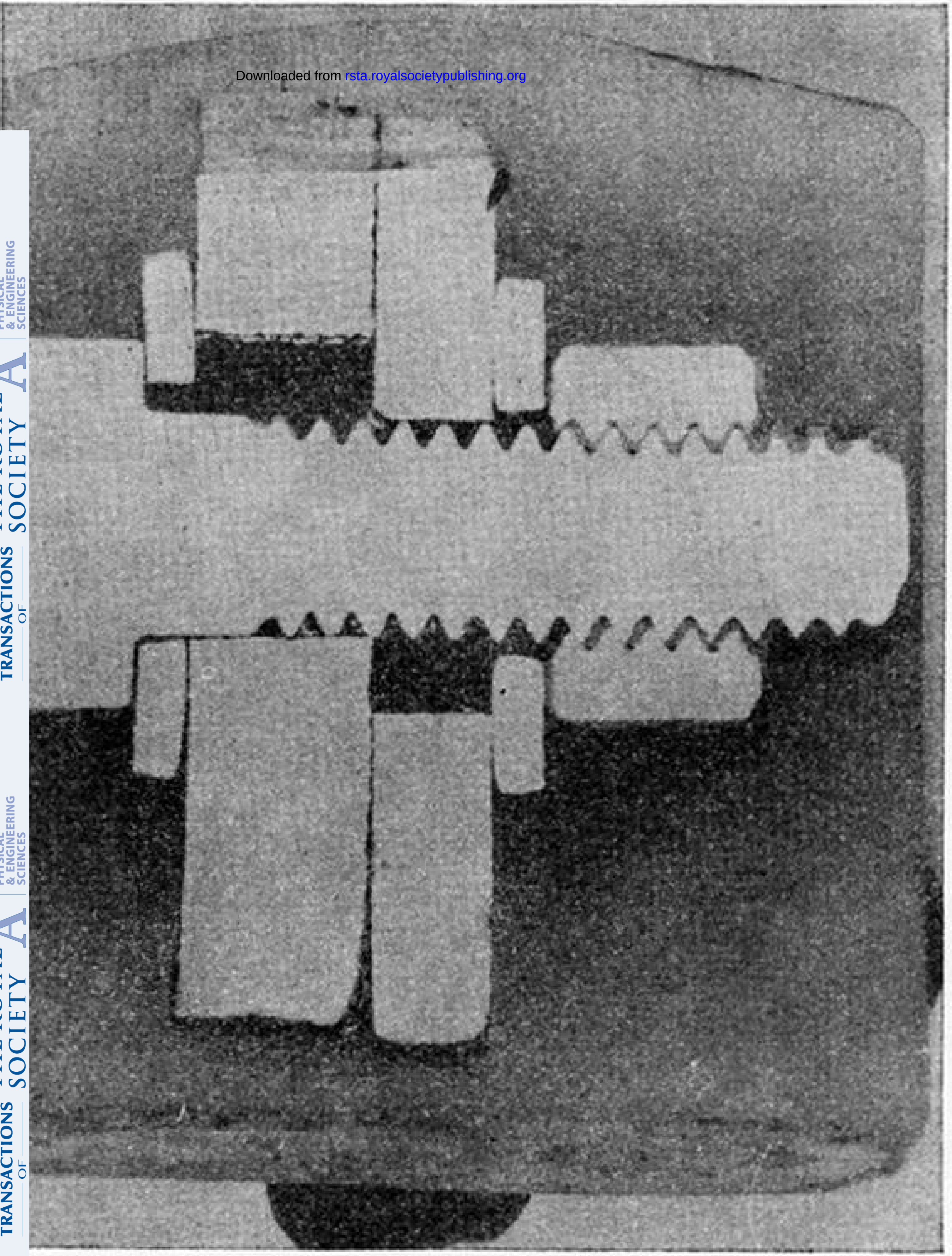

FIGURE 2.