ATOM HARVEST

TO THE MEMORY OF MY FATHER

ATOM HARVEST

A BRITISH VIEW OF ATOMIC ENERGY

by

Leonard Bertin

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Introduction to the American Edition

By JOHN PFEIFFER

"ATOM HARVEST" presents—for the first time to American readers—one important version of the course of Anglo-American relations in developing atomic weapons and atomic power, during and after World War II. It is a frank and outspoken book. It indicates quite explicitly the existence of some bitterness among British scientific leaders, a bitterness which could not be expected to appear in diplomatically impersonal official statements.

According to Leonard Bertin, joint efforts went smoothly for nearly two years, when scientists in Great Britain and the United States were engaged in relatively small-scale activities. Full cooperation and exchange of information was the rule while they were simply exploring the possibility of achieving a chain reaction. As soon as the possibility became a probability, however, things began splitting at the seams. The $2-billion Manhattan Project was born, under the military leadership of Major General Leslie Groves, and British scientists often found themselves barred from information and access to laboratories.

Early in 1943 the situation had reached a point where Churchill sent a strongly worded cable to the White House. The gist of the cable was that if atomic data were not shared fully, Britain would be forced to make a "somber decision" and organize a program of separate research. One result of this message was an agreement, signed by Churchill and Roosevelt in Quebec, involving the postwar exchange of information on weapons and power production. But three years later the agreement was kept secret from Congress while it passed legislation prohibiting the release of such information to any nation—legislation which deprived America "of any right to share in subsequent British achievements".

Mr. Bertin elaborates on his thesis in some detail, using facts which have not previously been brought together in one publication. Many American authorities will interpret the same facts differently, but they are hardly likely to ignore "Atom Harvest". While the book is by no means an official statement, it is based on interviews with members of Britain's Atomic Energy Authority, among others—and presumably reflects the personal feelings of some people in high places. It is reasonable to expect that when the full story of international cooperation is told, the British version will be taken into account.

"Atom Harvest" is far more than a contribution to the history of atomic energy, however. We may hope that the airing of past difficulties will help shape policy in the future. The broad problem of science and secrecy will not be solved for some time to come. It involves the generally accepted notion that certain information must be kept secret in the interest of national security, particularly information concerning specific weapons and countermeasures. But the laws of nature, the basic discoveries upon which all applications depend, are not so readily amenable to security regulations. Sooner or later, and usually sooner, they become known wherever original research is under way. Furthermore, there is always the matter of sharing the information we have decided to classify. Should it be kept secret from all nations or only from those that are unfriendly? Do the advantages of sharing outweigh the risk of "leaks" to potential enemies?

Such questions rarely have simple answers, and even the first approximations to answers may demand an apprcciable degree of sophistication in things scientific. Yet nonscientists, including the public and its elected representatives, are being called on increasingly to consider legislation affecting the conditions under which scientists work. The more completely we are informed, the wiser our decisions will be—and the more effectively democracy will function. Granting that there are at least two sides to every question worth bothering about in the first place, books like "Atom Harvest" are one way we can keep ourselves informed.

Incidentally, it would be a pity if the controversial political aspects of the book obscured its value as a first-rate example of how science can be explained to laymen. Sometimes the professional science writer assumes that his job is finished when he obtains the facts and expresses them clearly. Indeed, this is probably the most common mistake of the scientist who tries earnestly and occasionally to communicate with laymen, and may subsequently wonder why his message did not get across. As every politician knows, even the most important and interesting facts will not make a permanent impression unless they are presented vividly and in human terms.

But there are many ways of "making an impression". It can be done by sensationalizing, breaking confidences, and indulging in the sort of personal remarks commonly found in gossip columns. Such tactics are less popular than they once were, although they have not disappeared entirely. In any case, they do little to improve relations between science and the press. Mr. Bertin plays the game fairly, and is none the less readable for that. His chapters include conversations and anecdotes which not only make scientists come alive, but help us understand points of particular significance.

Finally, I feel that W. H. Freeman and Company deserve special recognition for making this book available to the American public. The influence of publishers in bringing science to nonscientists cannot be emphasized too strongly. The viewpoints presented in "Atom Harvest" are more widely known abroad than in the United States, and the free flow of opinions about scientific policies is fully as important as the free flow of technical information itself.

New Hope, Pa.
April, 1957.

Foreword

WHEN the war ended, America possessed a virtual monopoly in the atomic energy field. With the encouragement and substantial aid of many foreign and foreign-born scientists she had pushed the frontiers of knowledge far beyond the stage required for the manufacture of atomic bombs. She possessed a diverse collection of atomic reactors that provided stepping-stones into vast new fields of application. That knowledge was hers to give away or to keep. She kept most of it.

There is no attempt here to belittle the American achievement. The world has never seen the like of it before and it has been well publicised. The aim of this book, instead, will be to tell a little more about the British contribution to that war-time effort and something about the way in which, in the years after the war, she built up her own atomic industry, worth hundreds of millions of pounds, in the face of American legislation which excluded her from any fair share in the fruits of their war-time collaboration.

CONTENTS

LIST OF PHOTOGRAPHS

LIST OF DIAGRAMS

Author's Preface

IN WRITING this book I have drawn freely from a large number of sources, both living and on the bookshelf. I have endeavoured to acknowledge as many of them as possible below and I would beg pardon for any inadvertent omissions.

I am particularly grateful to the United Kingdom Atomic Energy Authority for the tremendous amount of help I have received in my task. That help was freely promised by members of the Board without any strictures except those of national security long before even the author had any idea of the way in which the book would be written. It goes without saying that neither the Board of the Atomic Energy Authority, nor any of its employees, nor any of the many other persons whom I have consulted, are in any way associated with the views that are expressed, or the inferences drawn. In fact, it is only fair to say that in the matter of Anglo-American relations in the atomic field the Authority do not agree with many of the conclusions I have drawn.

Very early on in my researches I discovered how much had been forgotten already about events of great national importance, even, in some cases, by people who took a major part in them only ten years previously. It has been my common experience to find two eminent persons, both closely associated with a particular happening, who have held widely differing opinions, even on matters of fact. The task of weighing one against another has not always been easy and compromise has been made.

The book contains criticisms of American policy. They have not been made in a spirit of bitterness or unfriendliness, and would not have been made at all had it not been felt that the future has lessons to learn from the past in these matters. In the aircraft industry and in a number of other spheres including several realms of atomic energy there is now a large measure of collaboration between Britain and the United States. We should be careful to see that such collaboration does not extend over the whole sphere of fundamental science where Britain and the Continental countries have always thrived, and end at the stage where these ideas are ready to be exploited industrially. It is in the field of technology that the Old World has most to learn from the New. Britain is already paying too many American companies for the right to use ideas that we were initially responsible for developing.

The present American Administration, under the enlightened leadership of President Eisenhower, has recently made a number of very important steps towards fuller collaboration in atomic matters. The "Atoms for Peace Plan", the 1954 Atomic Energy Act, the initial offer of fissile material and of assistance in building research reactors, the new agreement with Britain signed in June, 1955, the International Conference on the Peaceful Uses of Atomic Energy in Geneva in August of the same year, are all landmarks along the road that could lead to a new Golden Age in which there are endless sources of energy at man's disposal.

In this flush of new magnanimity in atomic matters it should not be forgotten that European scientists, among whom were many Britons, played the major part in unravelling the secrets of the atomic nucleus. The United States, which were destined by fate to reap the first technological results of this endeavour, have delayed in releasing all-important technological material and any share in stocks of vital materials until a moment when it is abundantly clear that countries like Norway, France and Russia are capable of reaching the same objectives on their own and when Britain has achieved a leading role in the industrial atomic power field and in the sphere of nuclear weapons development.

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Sourcebook of Atomic Energy, Samuel Glasstone (Macmillan & Co.). *Atomic Energy*, H. D. Smyth (H.M. Stationery Office). *Report on the Atom*, Gordon Dean (Alfred A. Knopf). *The Atom*, Sir George Thomson (Oxford University Press). *Power and Prosperity* (Central Electricity Authority). *Power, To-day and To-morrow* Dr. Sherwood Taylor (Frederick Miller). *Nature* (Macmillan & Co.). *Discovery* (Jarrold & Son, Ltd.). *Medicine Illustrated* (Harvey & Blythe, Ltd.). *Atomic Scientists Journal* (Taylor & Francis, Ltd.). *Research* (Butterworth's Scientific Publications).

My thanks are also due to the Editor of the *Daily Telegraph* for permission to write this book and draw on some of my previously published material.

L. B.

[I]

Through the Looking-glass

WE live in a new era. We have walked, as it were, through a laboratory looking-glass into a strange new world in which the very smallest things, atoms and sub-atoms, have become suddenly more important than all the big things. It is an epoch when, to quote Sir Winston Churchill, a quantity of plutonium less than would fill the famous dispatch-box in the House of Commons, "would suffice to produce weapons that would give indisputable world domination to any Great Power which was the only one to have it".

That is the sombre side of the picture. There is a better one. The ancient box that stands on the table before the Speaker's chair is two feet long, and the three cubic feet of plutonium needed to fill it would weigh a ton and a half. If put to useful purpose, it could in theory do the work of nearly five million tons of coal.

There, in a nutshell, we have the whole problem created by the discovery of nuclear fission. Like fire and the aeroplane, atomic energy can be used for man or against him. Factory processes can be speeded up or turned into a tangled mass of wreckage. Lives can be saved by the life-giving properties of energy under control or they can be blistered and burned by the bomb's heat or poisoned by rays they can never see.

Atomic radiation can be used to produce new varieties of disease-resistant corn, but it can just as effectively store up deformity, both mental and physical, for future generations. That is the atom. All its shame and all its glory.

The great hope for mankind lies, perhaps, in this very paradox. The great promise it offers to a world dedicated to peace may still provide man with the inspiration to improve his lot. In the last resort, knowledge of the disastrous results that would attend its use in war may yet supply the one sufficient deterrent.

Britain has given her own answer to this challenge. The position she intends to take in the new atomic era has been stated in two momentous declarations made within days of each other.

The first of them, on February 15, 1955, announced the decision to go ahead at once on a programme of full-scale nuclear power station construction, the first in the world, that would provide electricity for industrial and domestic purposes at a cost lower than that realised by the most modern coal-burning stations.

The second, on February 17, 1955, made known the Government's decision to manufacture the hydrogen bomb.*

However unpleasant that latter decision must have been, it was as essential to the nation's security and future in 1955 as was the equally unpleasant decision taken ten years earlier that Britain, no longer able to hope for collaboration from the Americans, must go ahead on her own to make the ordinary atomic bomb and to catch up ground lost in the sphere of peace-time applications.

That Britain should have had to walk that track alone after all that the two nations had shared and suffered together was an unhappy comment on those few in charge who were aware of the true nature of the war-time partnership and a misguided attempt to weigh dollars spent and dreams of future political power and industrial wealth against certain intangible commodities, things like honour and respect, that are absent from any table of equivalence.

The battle of peace was, after all, as important to win as the battle of war. When the question of the bomb first arose the Americans were very happy to obtain from the British all the help they could and the British were only too glad to give it. When the cessation of hostilities once more permitted British scientists to leave subjects like radar for more productive work and released engineers from the task of making munitions, it would have helped so much if missions from the United King-

* The first two British hydrogen bombs were successfully exploded on May 15 and May 31, 1957.

dom had been allowed to visit the great factories at Hanford and Oak Ridge where atomic explosive and fuel was made.

No sooner had the great body of public opinion in America learned of the new developments than it began to feel possessive about the atom and jealous of rivals. People were worried lest the new monster they had helped to produce might be turned against them. Only four days after the formal Japanese surrender on August 14, 1945, a newly elected senator from Connecticut, Brien McMahon, had introduced a Bill for the domestic control of atomic energy.

President Truman's own views were stated on October 3, 1945, in a message to Congress. "The first and most urgent step", he told them, "is the determination of our domestic policy for the control, use and development of atomic energy within the United States." He proposed that Congress declare it to be unlawful to produce or use the substances comprising the source of atomic energy or to import or export it except under conditions prescribed by a commission. Mr. Truman went on to say that he would initiate discussions "first with our associates in this great discovery, Great Britain and Canada, and then with other nations in an effort to effect agreement on the conditions under which co-operation might replace rivalry in the fields of atomic power". He rightly prophesied that "the difficulties of working out such arrangements are great".

The day the President delivered his message to Congress a Government Bill was introduced into both Houses for the domestic control of atomic energy by a commission to which service officers on active duty would be appointed. The Bill was unpopular. The country was not keen to see such a promising and important development left in the hands of the military. The battle began to rage between opposing groups, the protagonists of military and civilian control. The scientists, as might be expected, threw in their lot with the civilians.

On the precise day that in Britain an announcement was made of the establishment of an atomic energy project the American Government set up its own atomic energy committee, with McMahon as chairman, "to make a full, complete and continuing study and investigation with respect to problems relating to the development and use of atomic energy". The

British Cabinet already guessed the outcome would not be in their favour. By August of the following year, when the U.S. Atomic Energy Bill, better known as the McMahon Act, received Presidential assent, engineers of Britain's newly established atomic energy production group were already planning how to build on their own the first reactors.

The strictures of the McMahon Act created a fantastic situation in which the United States completely slammed the door on her British friends. This fact was recognised to their credit by many prominent Americans. In a very fair book, *Report on the Atom*, Mr. Gordon Dean, himself for three years chairman of the American Atomic Energy Commission, wrote: "Few people who have thought about the problem at all believe that it makes very much sense for these two great and traditionally friendly countries to go their separate ways in the new and challenging field of atomic energy". Gordon Dean blamed British security methods for the lack of co-operation. Many people felt, he said, that "until British security methods are tightened, at least to the point where a Bruno Pontecorvo cannot merrily wing his way from Harwell to Russia without some kind of restriction, we cannot afford to be full partners".

The statement, however, reflected shortness of memory, for the Americans, too, had had their embarrassments in the way of atomic and non-atomic spies. It paid no attention either to a point of view that is quite as strong over there as any security consideration. Most of those Americans who are aware that British scientists made any contribution to the bomb at all rate such contributions meagrely when striking a balance. It is something that cannot be calculated in dollars and cents, and for lack of a monetary yardstick is apt to be shelved completely.

Senator McMahon tried to shelve it when he once discussed the matter with me. There was the matter of security, too. There were doubts about people like Fuchs, who when working for Britain gave away secrets of the bomb. But McMahon's condemnation here was clearly tempered by what he knew of defections and suspected defections of many Americans. He seemed to pay far more attention to another aspect. He chose a simile from the life he knew at home when he tried to explain it to me one night in a Strasburg hotel.

McMahon saw America in the same light as a wealthy and benevolent owner of horses for ever distributing largesse among his many servants and dependents as reward for their loyalty, coming to their assistance when they were in trouble, paying the hospital bill when the wife had trouble with a new baby. "Wouldn't you feel a bit resentful", he asked me, "if one of those you had helped a great deal turned round one day and demanded a share in the stable?"

But the matter was obviously one that he was unhappy about, and he answered my questions about the war-time agreement between Sir Winston Churchill and the American President with a brusque "No comment!" "Next question?"

He was reported as saying afterwards in the United States on one occasion that he would never have supported the McMahon Act in the form it took had he been aware at the time of the nature of that war-time agreement. It is difficult, in fact, to believe that any Congress aware of its terms would have done so.

America's unilateral termination of collaboration had two effects. It deprived her of any right to share in subsequent British achievements and it gave to Britain on the other hand the satisfaction of knowing that all she has done she has done on her own.

[2]

The H-bomb Our Shield

THERE were four good reasons why speedy development of atomic energy was essential to Britain. The first was military, the second was economic, and the third was the straightforward matter of prestige. The fourth was less tangible but something still quite fundamental to humanity, the impelling urge to devil out fresh secrets from nature, backed by the knowledge that there can be no standing still. Man must march forward or he will certainly be forced to retreat.

In the matter of prestige the inception of the atomic era has brought with it a new criterion of greatness. It was no exaggeration after Hiroshima to say that a nation without atomic weapons could not remain a first-rank power in world politics, That position has now been stretched still further. There are those countries WITH the hydrogen bomb and those WITHOUT it.

Nations without this devastating means of defence and reprisal must always rely on "protector" countries. Even Britain would have been relegated in the councils of the nations to the status of a second-rate power had she not gone ahead with her own atomic weapons project in 1946. Her new decision to proceed with the development of the H-bomb will lend immeasurable weight to her influence, and, just as her possession of those great weapons constitutes a new badge of greatness in the sphere of power politics, so her achievements in the field of atomic energy development for civil purposes give her a special position in the more constructive world of peaceful endeavour.

The military reasons are self-obvious but there are several aspects of them that deserve more careful analysis. Sir Winston

Churchill, always a man of great prescience in such matters, asserted that during the immediate post-war period it was possession of the bomb that kept the Russians out of Western Europe. The true nature of Russian intentions at that time must remain for the present, and may ever remain, a matter of conjecture. The deterrent was certainly there, and the Russians, through their agents, were in a good position to know that the Americans could have gone on dropping atomic bombs at the rate of several a month as new material was produced.

Many will think that it was undesirable that any one country should have been placed, as America was, in the position of a "super-power" possessing a weapon that would have allowed her to impose her wishes on the rest of the world. We may certainly be glad that this power was not placed alone in the hands of our enemies.

There is no doubt that when the Russians, too, had the bomb, Britain could not afford to remain sandwiched and powerless between two great nations of such widely differing ideologies. Without atomic weapons, her fleet, her air force and her, by conventional standards, well-equipped army were a sheer waste of money. They were too big for policing duties but too small to constitute a major deterrent.

The successful testing of the first British atomic weapon in the Monte Bello Islands in 1952 was an event of the greatest importance, notwithstanding attempts that were made in various parts of the world to overlook the event or to play it down. It immediately placed Britain in a new category. Because of the effective way in which she had prevented other nations from learning the real extent of her potential, it gave, at least in theory, a single one of her aeroplanes the hitting and deterrent power of a whole score of her 1,000-bomber raids over Germany. I say "in theory" because there was still a long way to go between the explosion at Monte Bello of an infernal machine the size of a suburban bathroom and the development of a reliable atomic weapon of reasonable dimensions that could be dropped from our fastest aeroplanes, fired possibly from long-range guns of our field armies and battle fleets, and carried to targets many hundreds of miles away in the war-heads of guided missiles. There was a long way to go, too, between the extraction of sufficient material from a single bomb and the manufacture on an industrial scale of quantities sufficient to equip our armed forces. Exactly how far Britain has progressed along that road, and the Russians too for that matter, is as uncertain as the undeclared hand of an astute poker player. The position with regard to the hydrogen bomb is still more obscure.

The Statement on Defence published in February 1955 confirms that the United Kingdom has the ability to produce such weapons and "after fully considering all the implications of this step the Government have thought it their duty to proceed with their development and production".

The British weapon designers, we have been told by Mr. Gordon Dean, one-time chairman of the United States Atomic Energy Commission, "are of the very best" and they are backed by an equally efficient production organisation. True, their operations have been limited in scope by the smaller resources that Britain could afford. But tests at Monte Bello and Emu indicate that a great deal of progress has been made and much money saved by intelligent improvisations.

It is typical of the change in strategy brought about by the H-bomb that its use as a deterrent has almost completely effaced the question of its application as a field weapon, although, in fact, field armies have never been backed up by or had to face so devastating an arm. The effect of the fission bomb on field operations should not be exaggerated. While it would undoubtedly achieve complete annihilation of troops and installations at ground zero, the point on the ground nearest the explosion, its effects on a well-dispersed army would be limited to a few brigades in the immediate area.

There are no such limitations when the H-bomb is used. It would need to be equated, not against brigades, but against divisions and army corps. Large regions, tens of thousands of square miles, of combat area would be temporarily paralysed for friend and foe by the need for exploratory operations to detect the extent of lethal contamination.

Nevertheless, its effects on battle operations fade into insignificance when compared with those of its use as a deterrent or retaliatory weapon against the home base.

I asked Professor Joseph Rotblat of St. Bartholomew's Hospital, London, what the use of such a weapon on a British target would mean. Rotblat, a Pole by birth, was a member of the British war-time atomic weapons team at Los Alamos. At the end of the war he dropped weapons work to devote himself to the peaceful exploitation of atomic energy.

"Just imagine an H-bomb bursting over London", he told me, "and translate to Britain the information gained by the Americans about fall-out, that is the settling of explosion debris, in the 1954 Bikini thermonuclear test". He paced up and down a relatively large study that nevertheless looked small by reason of the vast number of books and periodicals and gadgets that filled it. "If such a weapon exploded over London when a wind from the south-east was blowing, cities like Birmingham and Coventry would be showered with radioactive dust that would amount to a lethal dose within two and a half hours from the time that fall-out started."

Rotblat explained the implication of figures collected by boats, aeroplanes and balloons in the Pacific. "It doesn't end there", he went on. "In Liverpool and Manchester about ten per cent of all the people exposed in the open for thirty-six hours or more might die."

He emphasised that the figures applied only to people who did not take shelter. The walls of an ordinary building, he told me, would cut down radiation level by one-half, and a basement shelter with about two feet of earth covering it might reduce the dose to one-hundredth for people who were prepared to remain inside for a day or so.

For them, however, as for everyone else, there would always be hazards other than from radiation outside. Particles of contaminated matter could be inhaled or ingested and some would inevitably concentrate in organisms of the body, particularly in the thyroid gland or bones, where they might stay for a long time.

Rotblat broke off for a moment to answer one of the bank of four telephones at the edge of his desk. "Excuse me a moment," he said, and went into his workroom next door where two white-coated girls were slowly turning the delicate micrometer screws on the turntables of powerful microscopes. A research worker had come in to query with him a matter concerning a new atom-splitting machine, known as a linear accelerator, the most powerful of its kind in any hospital in the world, that had been installed at his suggestion in a new and heavily protected underground laboratory in the building next door.

"Where were we?" he asked, as he apologised for the interruption. I reminded him that we had spoken of contaminated material that might enter the body by eating and breathing. "Plants and animals breathe and eat, too", he went on. "Everywhere over an area of thousands of square miles will be covered in a thin layer of radioactive ash. We may not see it, and the soil in any case will soon absorb it, but the story will not end there for plants will soon be feeding on it. Contamination from this source might reach us either directly or via meat or milk from grazing animals or through fish caught in an area of contaminated sea." The latent effects of these internal radiations are likely to be far more serious, he told me, than any of the immediate ones. Since prevailing winds at high altitude are from the west, the fall-out effects on London might be equally disastrous if a bomb burst as far away as Bristol.

The Defence White Paper has stated what this may mean in terms of daily life. Large tracts would be devastated and rendered uninhabitable. Essential services and communications would suffer widespread interruption. In affected areas central and local governments would be put partially or wholly out of action, and industrial production, even where plant and buildings remained, would be gravely affected by the disruption of power and water supplies and by the interruption of the normal interflow of materials. There would be serious problems of control, feeding and shelter. Public morale would be most severely tested. "It would be a struggle for survival of the grimmest kind."

These ghastly results of thermonuclear warfare are now well known. The better known they are, the less likely, perhaps, countries will be to court war. But the annihilating and catastrophic effects of such weapons on any Power, however great its potential, provide at the same time the greatest argument for their surprise use by a Power without scruples. The might of these weapons is such that in any war the outcome of the first exchanges would be of critical importance, and tremendous advantage would accrue from the first use. For an enemy who is determined that he could gain most from war, the argument in favour of their use to initiate hostilities is obvious.

We have to face the fact that such an enemy, remembering the tremendous success the Japanese achieved at Pearl Harbour, might well decide to try and profit from the weapon of surprise and attempt to deal at the outset and without warning a blow that would cripple our deterrent forces. It therefore becomes the task of the Allied Strategic Air Force to satisfy themselves and at the same time prove to the rest of the world that their power to hit back could not be effectively interfered with.

We have to plan for the contingency that might arise if the fear of deterrent failed, as fail it might if an enemy thought that a sudden and severe blow could sweep away the deterrent force. We have to be sure that if aggression of this sort did take place, we would still be in a position to deal a crippling counter-blow at capital cities and other centres of communication and mobilisation, at concentrations of industrial power and ports, and be sure that we could do this in the face of any anti-aircraft measure that might be used against us.

Britain's defence policy is based, too, on the fact that we must be prepared to go one step further and demonstrate that we have both the will to survive and also the power, with our Allies, to achieve victory. In this important aim nuclear weapons have a further importance to Britain as an "equalising factor". Ours is a country which, for both reasons of manpower and economics, must rely on the efficiency and high fire-power rather than on quantities of weapons. Neither our financial position nor our industrial potential permits us to pay our way in the competitive peace-time world, and still maintain vast fleets of aeroplanes and ships and great land armies.

The countries controlled by the Communists, in addition to the new weapons, atomic and H-bombs, and long-range rockets that they are now developing, have, of course, vast conventional forces. They have a large and growing navy, vast numbers of aeroplanes of high quality, and land forces numerically far stronger than anything we have ourselves. British intelligence sources estimate that the Soviet Union, with its Eastern Europe satellites, have some six million men under arms, backed by numerous reserves. On the German front the Soviet army could be increased to well over a hundred divisions within thirty days. Against such a numerical preponderance nuclear weapons offer the West a unique and indispensable answer.

If war were forced upon us, and God forbid that it should be, then our forces, and in particular our land armies, could only operate in conditions which forced the enemy to disperse and limit his numbers. It is hard to imagine how a large land army could operate and be maintained and supplied in the field in the face of nuclear bombardment. It is hard, too, to imagine great air fleets ever attempting attack in the face of atomic anti-aircraft weapons.

While this use of atomic weapons in an anti-aircraft role has still to be further explored, it has certainly been considered seriously in the United States. British and Canadian experts were allowed to witness the testing of such a weapon in Nevada in April 1955. The threat of H-bomb weapons has brought the employment of atomic anti-aircraft weapons much closer. Were it only known that a particular plane or formation of planes was carrying against us an H-bomb, capable of eliminating in one blow an area the size of London and of contaminating an area of country width, there would seem to be no doubt that use of atomic weapons to destroy it would be a gamble well worth while. Single intruder aircraft should fall an easy prey to guided missiles, however, and one of the most useful roles of an atomic anti-aircraft weapon may easily be that of forcing an enemy to forsake formation attacks and adopt tactics that are more favourable to guided-missile defence.

There is, of course, even in the weapons field an economic factor to be taken into consideration. The late Senator Brien McMahon in an historic address to the U.S. Senate some years ago, while he was chairman of the Congressional Atomic Energy Committee, told them that atomic bombs and shells would soon be produced more cheaply than tanks and would be a better economic proposition than conventional explosives, having in mind their greater destructive power. He saw them being employed by ships, by artillery men of land armies, in guided missiles both defensively and offensively, and, of course, as a means of propulsion. He prophesied that atomic weapons used in this way would be far cheaper than their well-known counterparts, the conventional explosives RDX and TNT.

Senator McMahon, of course, had all the facts at his disposal and undoubtedly knew what he was talking about. But even the layman, who knows nothing of the cost of producing fissile material needed for a single weapon, can form a pretty good idea of the wisdom of the Senator's statement when he considers other factors that are inextricably related to the argument.

Let us for argument's sake suggest that an atomic bomb produced on an industrial scale costs the exaggerated sum of £1 million and try comparing it with the cost of thousands of four-engined bombers that would be needed to deliver an equivalent blow. Imagine not only the cost of the petrol or kerosene they would use in the journey there and back, but also the cost of all the fuel used in training flights of the crews beforehand; the effort of training the men not just to fly their planes but right through their schooling; the cost of ammunition fired by them in their own defence on the way over; the cost of men who never come back.

Compare it, instead, if you like, with the cost of thousands of guns that would normally be required to deliver a crippling blow against armies massed for battle in the field, of the 25-pounder cannon placed wheel-to-wheel in the British desert assault on the German and Italian lines at El Alamein, backed up by hundreds of medium and heavy guns and a continual stream of light and heavy aircraft; consider the men and materials that needed to be distributed along the coast of Britain to meet the possible invasion by Hitler during World War II at a time when those forces were so badly needed elsewhere.

In thinking of the uses of nuclear anti-aircraft weapons, consider, too, the fact that German heavy anti-aircraft guns during the war brought down on an average only one aircraft for every 50,000 shells fired by their land batteries.

It is always difficult to place a monetary value on any new development, particularly when it is of a military nature. Dr. Hafstad, director of reactor development in the U.S. Atomic

Energy Commission, once told the Institute of Aeronautical Sciences there that it was as difficult to place a current value on the atomic bomb as it was to place a value on a single Spitfire in the Battle of Britain. Hafstad did a calculation that suggested an order-of-magnitude estimate of its worth at the time of Hiroshima. At that time America's daily war expenditure was over £100 million a day. If the use of atomic weapons had shortened the war by only ten days, he reckoned, the value of over £500 million could be put on each of the bombs used over Japan, thus providing a figure sufficient to write off the total incurred cost of the war-time Manhattan District Project.

When we begin to assess the military value of the atom bomb in terms of its human life and real estate destructive power, the situation becomes out of hand. An ordinary atom bomb might destroy six square miles of city. While no reliable values are available, and they would in any case vary tremendously from place to place, it can be seen that in atomic weapons we have something which on purely economic grounds is far more significant than anything in the past.

It would be a mistake, however, for any Power to assume that development of such weapons by the West infers a desire and intention to attempt a conquest of the rest of the world. The H-bomb is a punishing weapon, a damaging weapon. It can hope to deter, and if it fails in this object it can retaliate and neutralise lines of communication. It could wipe out an invasion force before it left the enemy shore and could certainly make a sea crossing impossible, but it could never occupy a country and it has no power to consolidate advantages gained or damage done.

Nor should we lull ourselves into feeling that we have and will always have a better bomb than those of the enemy. It may well be that at present we have, but complacency of this sort should be tempered with the memory that it was probably the Russians and not the Americans who produced the first "dry" H-bomb, and that the American fusion weapon now used almost certainly follows certain important principles first put to the test by Russia.

The Americans have demonstrated their ability to mass-produce quickly the ideas of the scientists, and the effort they have devoted to the development of nuclear weapons has almost certainly placed them in the position of temporary superiority. The next stage is one of saturation, where the mere numerical superiority of one side over the other in the possession of these weapons becomes of purely academic interest in face of the power even of the weaker side to deliver a crushing blow.

To assume that the present weapon designs represent the ultimate, the final result of man's destructive genius, would be to ignore history. We would be just as blind, if we did that, as would have been the people living in the days of the Black Prince, had they assumed that gunpowder and leather-barrelled cannon represented the acme of human achievement.

[3]

Energy Spells Prosperity

PEACE-TIME applications of atomic energy are, if anything, of greater importance to Britain than those of the military field. In the latter case she has always in the United States a stout ally to rely upon, but in the competitive industrial field she and the rest of the Commonwealth countries at present stand alone. There is little doubt that our prosperity in the decades ahead will depend just as surely on atomic energy as that of our grandfathers and great-grandfathers depended on coal and the steam engine.

From the earliest days of the industrial revolution steam allowed coalmines to be drained and deepened. It lifted and carried the products of those mines to the towns and cities. It speeded up land travel, led to a revolution in shipping, permitted mechanisation of the mills and the birth of heavy industry. Gradually in Britain as in other countries throughout the world people became used to having steam to do their work for them, either directly in the provision of motive power or indirectly by the generation of electricity that could be piped alike into home and factory. The industrial productivity of a nation is directly related to the amount of energy in one form or another which the individual worker can call upon in the performance of his daily tasks. It has been called the "Age of Power".

There is no doubt that in coming decades we shall hear more and more of a further factor in industry known as "automation" or automatic control. Most of us have seen examples of this already. Many of us have gas or electric stoves in our homes that are controlled by thermostats that regulate heat to provide predetermined temperatures. We have seen street lights turned on automatically at predetermined hours, and we may have seen fruit canning, even complicated evolutions of car manufacture, carried out by extensions of the same principle.

All are examples of automation and all provide instances of how energy is being turned on and off to carry out tasks for man and allow him extra time in which to employ his energies elsewhere. They all point to one important tendency of the present age, the use of more and more energy per head of population. Some idea of how steep that increase is may be gained from the Central Electricity Authority's own figures. They show how yearly consumption jumped from ninety units per head in 1920 to 520 in 1940 and 1,100 in 1953.

There is, too, another factor we have not yet reckoned with, but one which is vitally important to future generations, and that is the fact that coal, oil and natural gas are all important starting-points for the synthesis of materials needed in every field of our daily life. Dyes, medicines, plastics, including artificial textiles and hundreds of thousands of other substances that we take for granted, are all manufactured from by-products of the purification of one or more of these three raw materials. To burn them is to squander irrevocably a valuable and irreplaceable heritage that we should hold in trust for our children and children's children.

In Britain's own case, where there is little hydraulic power and only minute quantities, as yet, of oil or natural gas, our economy at present inevitably turns on coal. We use it at present to run the greater part of our railways, to drive our electric power stations, to heat our homes and to provide gas for lighting and heating, alike for domestic and factory use, and as coke it is an essential commodity in the production of another vital commodity, steel. All our life, in fact, revolves around coal in one way or another.

In the world as a whole there is no apparent shortage of it. Figures assembled for the World Power conference held in London in 1953 placed world resources at well over 6,000,000 million tons, and consumption at somewhere in the neighbourhood of 1,500 million tons a year. On such a basis it would appear that we had about 4,000 years' supply ahead at the present rate of consumption.

The trouble is that these resources are not all where they are most needed, and some countries that are sorely in need of it have none at all. Thus, only fourteen nations produce as much as 20 million tons of coal a year, and many of the countries that have least need it most because of their rapid expansion of industry and the urgent requirement to improve their living standards.

Even those nations that have plenty are not without their problems in getting it from the ground, as we in Britain know only too well. There are probably more than 40,000 million tons of workable coal lying underneath the ground in this country and yet we still have difficulty in obtaining each year the coal that we need for domestic purposes, for industry and for the generation of electricity and gas.

Since the war the production of coal from deep mines has increased from 175 million tons in 1945 to 214 million tons in 1954, but the demands of expanding home industries have been rising even faster. In 1954 we were reduced to the point where we had to buy 4 million tons from America. It was not, of course, that the coal was not there. It was due partly to a new attitude of mind but primarily to the fact that every year the coal is harder to get. In the old days, very naturally, coal-mining companies tended to exploit the richest deposits and those that were nearest to the surface. As these deposits were exhausted, the miners had to go deeper or, alternatively, the consumer had to be content with poorer grades of coal. Among the worst sufferers in this last respect were the power stations that supply the country with electricity, which have had to make do with progressively inferior qualities of coal fuel.

In some cases a modification of plant will permit this poorer coal to be used economically, but there is one disadvantage of using poorer coal which Sir Francis Simon has stressed and that nothing can overcome, and that is the fact that because it has a lower heat value more of it is needed to do a specific job. Poorer coal, of course, is not cheaper to transport than the better varieties and it costs at least as much and often far more to obtain initially from the mine and to handle. Thus, as the quality of the coal goes down, so the price goes up and the cost of electricity and gas goes up with it.

Energy is such an important factor in industry that any increase in its price and availability is likely to be reflected all the way along the line, until it shows up inevitably in an increased cost of living for every one of us. Even if such increases in cost were acceptable, the estimated reserves in Britain only amount to about 200 years' supply.

There is another factor to be reckoned with. As man is forced to go deeper and deeper to win the coal he needs, so the task of attracting labour to the mines gets even more difficult. There is no disguising the fact that, notwithstanding all that has been done to improve the lot of the miner, the job is not popular. Incentive wages have to be offered and then the price goes up again.

Even under ideal conditions coal is never burned economically. The best of our power stations only enable use to be made of less than one-third of the available energy. In 1953, 7·3 per cent of British power station capacity was wasting more than 80 per cent of the energy in the coal in the process of turning it into electric current. Even after taking into account the most modern stations, the average wastage of energy was still well over three-quarters of the whole.

As far as the immediate future is concerned, the same efficiency limitations will apply to nuclear power stations, since atomic reactors must be regarded merely as furnaces used directly or indirectly either to boil water or to heat a gas. The hot steam or gas then gets rid of its energy by turning the rotors of a turbine which in turn drives a dynamo.

The efficiency of this process depends, broadly speaking, on the difference in temperature of the steam or gas when it enters and leaves the turbine. This is another way of saying that it depends on the amount of heat the gas has been able to use up in its passage through the turbine.

The first nuclear power station to be built in Britain will operate at only 20 per cent efficiency. This rather low figure is partly because generating efficiency has been sacrificed in favour of the overriding need for nuclear explosive.

The first of the strictly civil reactors, those built by the

Central Electricity Authority, will be a considerable improvement on this and will operate at 25 per cent efficiency. This is still well below that obtained in the latest coal-burning stations. There are two reasons for the discrepancy. The first is that, for metallurgical reasons, it is not possible to run the atomic furnaces at the high temperatures operating in coal furnaces. The present fuel rods would not stand up to it. The second reason is that it is not convenient at present to boil the water within the reactor, and an intermediate cycle has to be introduced to transfer the heat from the pile itself to a point outside the reactor where the water is turned into steam.

Now both these reasons are temporary limitations and there is no doubt at all in the minds of nuclear engineers that it will be possible soon substantially to raise the temperature within the atomic furnace and also that it will be possible, by one method or another, to get more of this heat transferred to the turbine where it has to do its work. Costing is based to a certain extent on a somewhat fictitious price for the by-product plutonium. It is worth noting that, if the White Paper figures can be accepted, then an atomic power station at 25 per cent efficiency can still produce electricity slightly more cheaply than it can be produced by coal-burning stations working at higher efficiencies.

The advantages of atomic fuel are tremendous. Its volume and weight are negligible compared with coal, while the heat that can be produced in an atomic reactor is only limited by the efficiency of the means of removing it, so that a pile no bigger than a forty-gallon drum can easily deliver continuously over a long period the energy needed by a small city.

Then again it is difficult to imagine the difference that wide-scale use of atomic energy instead of coal would make to the life of a country whose industrial areas rarely know the meaning of a really clear atmosphere. Some of us may still live to see a Britain completely devoid of "smog", in which trains, factories and homes will all be powered, heated and lit by electricity from power stations that receive their fuel, not daily in barges or train loads, but in small covered lorries that drive up once a week to deliver new elements and take away old ones for processing.

Although atomic power stations will undoubtedly replace in the end the conventional central stations with their ugly heaps of coal waiting to be burned, there is a factor that will prevent this from happening for many decades. This is the rapidly increasing demand for more power. The consumption of electricity in Britain is likely to be three and a half times the 1955 level in twenty years' time, and to meet this demand installed generating capacity will have to be increased from 20 million to 60 million kilowatts.

This rate of increase is far greater than that at which industry can design and build nuclear power stations in the initial period, and the present atomic energy programme is unlikely to meet much more than a quarter of this total generating requirement by 1975. The contribution of these stations will, however, be far more important to the country's economy than this fraction suggests, for these stations will all be used to meet the "base load", that is to say, they would, except for periods of maintenance, be operating continuously and thus displacing many coal-burning stations to the subsidiary role of running for short daily periods to meet peak requirements.

Without nuclear power, consumption of coal for electricity generation would, having in mind increased efficiencies that are now being aimed at, increase two and a half times over the next twenty years and reach 100 million tons yearly in the 1970's. The Government's nuclear power programme should now enable the demand for coal to level off, instead, at between 60 million and 70 million tons a year by the middle 1960's.

It will thus be seen that, as far as Britain is concerned, the developments in the atomic energy field have come just in time. Had we waited for America to release information on the peaceful utilisation of atomic energy, we would have been ten years too late.

[4]

The Atom is Split

THE chances of putting atomic energy to work in the service of man were not very bright in the years previous to 1939 if the published statements of the nuclear physicists themselves were anything to go by.

It is true that as far back as 1904 the eminent British astronomer Sir James Jeans had talked of the destruction of matter to produce energy, and Prof. Einstein a year later had calculated correctly the formula that would govern such a process. It is also a fact that Sir Arthur Eddington, another great theoretician, after talking to the British Association in 1920 of the way in which the stars obtained their heat, went on: "We sometimes dream that man will one day learn how to release and use it for his service."

In the early 1920's, Aston's work had provided data from which it was possible to calculate the energy released or absorbed in a nuclear change, although at the time he did it the change could not be achieved experimentally. Had anyone entertained the idea, it should have been clear from this work that enormous amounts of energy would result from the splitting of uranium or thorium.

Nevertheless, Lord Rutherford, the greatest of all the nuclear physicists, the "father of atomic energy", had argued as late as 1925 that "the outlook for gaining useful energy by artificial processes of transformation does not look promising", and in 1937 he reiterated this view. He based his argument then on the fact that the only transformations which had been obtained until that date, while each individually providing more energy than was used to secure them, happened so rarely that when you took into consideration all the energy that had been expended in unproductive reactions, in "near misses", the total balance sheet was well "in the red".

He was not alone in his view. Dr. E. O. Lawrence, one of the greatest American physicists, and a man who was destined to take such a prominent part in later work, said in a lecture in 1938: "The fact is that, although we now know that matter can be converted into energy, we are aware of no greater prospect for destroying nuclear matter for power purposes than of cooling the ocean . . . and extracting the heat for profitable work."

Then came the proof of nuclear fission, a process attended by the liberation of large amounts of energy, and the picture changed overnight. It was not so much the amount of energy released by this process that was important, as the fact, soon to be confirmed experimentally, that it was accompanied always by the ejection of at least one and sometimes as many as three neutrons, bulky neutral components of the atomic nucleus, each capable of provoking further fissions in other atoms. In this fact lay the possibility of the "chain" reaction. Such a process would be able to sustain itself and spread like fire. It was in this respect quite unlike the early "atom-chipping" by Rutherford of substances like lithium which produced only helium, a substance incapable of provoking any further reaction.

The literature suggests that the uranium atom was first split artificially in Rome by Enrico Fermi in 1934, without his being aware of the fact, when he bombarded this substance with a stream of neutrons. He then reported that the products of this bombardment emitted rays of at least four different kinds, suggesting the production of at least four new substances. Had his instruments been more sensitive he would almost certainly have discovered that there were many more products of the reaction, but the work he was doing was already well in advance of its time. As it appeared to him then, and there were some good reasons for his argument, the newly produced activity was due to the formation of heavier elements than uranium, the ones we now refer to as the "transuranic" elements, by a building-up process of neutron absorption.

Unfortunately, the techniques of the day were primitive and the substances they were trying to identify were only produced one atom at a time as a result of individual atomic collisions. The amounts present were infinitesimal.

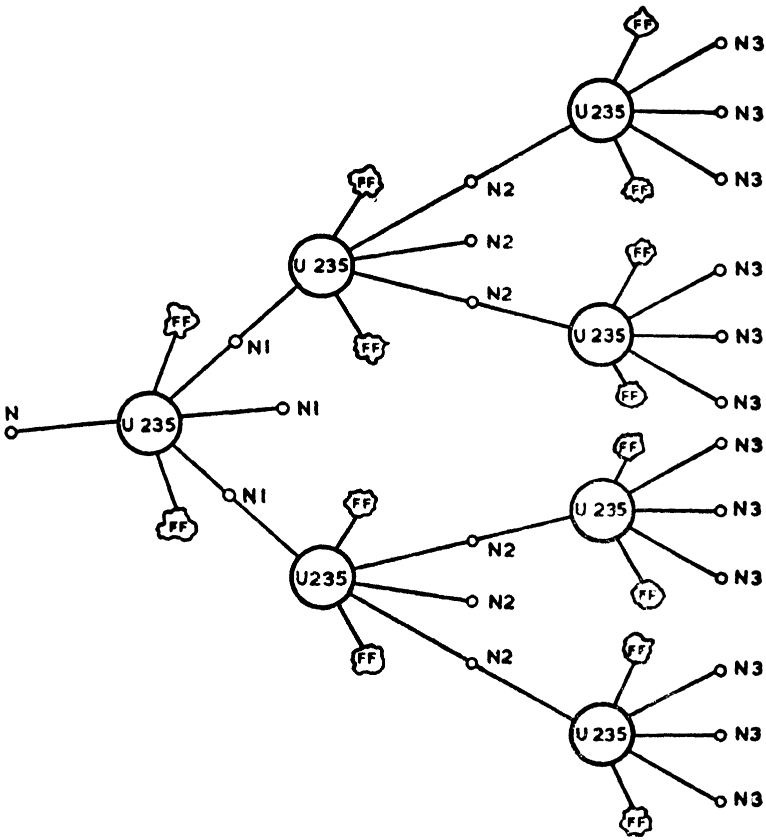
Fermi's results were studied and repeated by workers in other countries, especially in the 1937 period, when there was a great recrudescence of interest. Prof. Otto Hahn, working with Dr. Lise Meitner in the Kaiser Wilhelm Institute in Berlin, tried to identify the new products. So, too, in Paris, did Prof. Joliot and his wife Irene, the daughter of Marie Curie. In the Cavendish Laboratory Dr. E. Bretscher, a senior research worker from Switzerland, and Dr. Norman Feather and others were working on the same problem.

"It was a shocking thing that physicists did not tumble to fission before they did", said Dr. Feather, now professor of physics at the University of Edinburgh. "It was perfectly clear on the basis of measurements made by Aston, certainly in the middle thirties, that the ordinary uranium nucleus was fat enough to come apart and break into two fragments, nuclei of roughly equal size. It was there, staring us in the face. The facts were there, in the tables, for anyone to take note of. The sad story is that no-one grasped it.

"The fact of the matter is, and it was discovered by two Russian scientists in 1940, that if you leave uranium completely on its own, shielded from any form of outside bombardment, it will still undergo the same splitting process sooner or later spontaneously. It is a very slow process, however, and for every five million atoms that decay in the normal way only one undergoes spontaneous splitting. Everyone knew about the normal process of decay, by which uranium loses a small fraction of its mass, and no-one thought of looking for anything else."

Dr. J. V. Dunworth, who now leads the Reactor Physics Division at the Atomic Energy Research Establishment, Harwell, and who shared a laboratory with Dr. Bretscher in those days, told me how Dr. Bretscher, now a naturalised British subject and head of the Nuclear Physics Division at the same establishment, was bombarding uranium with neutrons. His object was to discover evidence of element number 93 which had never yet been shown to exist but which everyone thought

ought to be formed by a building-up process when the neutrons hit the uranium.



The fission, or splitting, of one uranium 235 atom by a single neutron (N) produces between two and three fresh neutrons (N1), any of which may cause further fissions in other uranium 235 atoms to produce yet another generation of neutrons (N2). As each uranium 235 atom splits into two more or less equal parts (FF) these " fission products " fly apart and tear their way through adjacent materials. It is the friction needed to bring them to rest which produces the heat exploited in atomic power stations.

Dr. Bretscher, who was well known in those days in the Cavendish for his predilection for extremely short trousers, was mystified, Dunworth recalls, by the fact that he was finding traces of barium and iodine in his target. "The fact that they should have been there at all made him very excited." We now know that these two elements, each about half the mass of the uranium atom, are among the commonest products of fission.

Another story which Cavendish workers of the period tell at their own expense, and one which undoubtedly had its parallels in many other famous laboratories elsewhere, is that of a ray-detecting device, known as a counter, which "misbehaved" itself. Counters, popularly known nowadays as "Geigers", are used to detect rays produced when atoms break up or decay as a result of collision or some natural process. The emission of each burst of radiation causes a "pulse" of electricity to flow.

In the thirties the counters being used were still fairly primitive and were constantly being modified by workers to meet their own needs. The story goes that in one room in the Cavendish there was a research worker who, when he bombarded his specimens of uranium with neutrons, periodically obtained from his counter much larger responses than usual. In the light of later knowledge there could be only one explanation of this violent reaction. It was caused each time by the fission of an atom of uranium.

The abnormal response was an indication of the exceptionally large energy release that takes place when the atom splits in half. To the worker concerned, who is now a physicist of great eminence, the abnormally large pulse was a troublesome phenomenon that interfered with the experiment. The counter, so I am told, was quickly and effectively modified so that large pulses could no longer be recorded!

The desire to interpret everything that was observed in terms of the existing framework of knowledge was leading other workers into trouble too. Prof. Otto Hahn and Dr. Fritz Strassmann, working in Berlin in 1937 and looking for new heavy elements, argued on the basis of their chemical analysis that four of the mysterious substances obtained by the bombardment of uranium were various forms of radium, a heavy element of much the same weight as uranium. They based this on the discovery of residues that behaved like barium, an element chemically rather similar to radium.

Mme Joliot-Curie and a fellow worker, P. Savitch, who were carrying on similar research in Paris, wrote a paper saying that they thought that the chemical properties of the residue included those of lanthanum, another element, of about half the weight of uranium, but they too, trying to interpret their results in terms of then-held theories, concluded that this element must in fact be actinium, a substance chemically similar to lanthanum, but much nearer in weight to uranium.

The Germans, who had all the time been expecting to find elements formed that were heavier than uranium, were amazed. "You can readily imagine Hahn's astonishment", we are told by L. G. Cook, a Canadian radiochemist who was working in Berlin at the time. "I well recall the day when he received the French paper. His reaction was that it could not be and that Curie and Savitch were very muddled up."

Hahn, however, drew the obvious conclusion. If one of the ray-emitting substances turned out afterwards to be lanthanum, the 57th element in the table of the elements, then it must have been barium, the 56th element in the table, before it emitted the ray that changed its identity. They went over their work again and to their great surprise they discovered that this was so. "We have come to the conclusion", they wrote, "that our 'radium isotopes' have the properties of barium." But they still would not take the plunge and draw what to us now might seem to have been a clear inference.

"As chemists", they said, "we should replace the symbols Ra, Ac, and Th in our scheme (symbols, respectively, for the heavy elements radium, actinium and thorium that they thought they were producing) by Ba, La and Ce . . ." (symbols for barium, lanthanum and cerium, elements of round about half the weight of the uranium they had been bombarding). But there was no precedent for such an idea in classical thought, and apparently no theoretical justification, and they would not accept it. "We cannot", they wrote, "decide to take this step in contradiction to all previous experience in nuclear physics."

The explanation, although no-one apparently recalled it at the time, had been provided in 1934, shortly after Fermi's original experiments. A German woman chemist named Ida Noddack, discussing Fermi's work, had suggested a "new type of nuclear disintegration brought about by neutrons". It was conceivable, she argued, that in the bombardment of heavy atomic nuclei like uranium "these nuclei break into several large fragments".

The world of science seemed reluctant to draw conclusions that are now destined to change the pattern of peace-time industry and way of life as thoroughly as they have already swept away all our older concepts of war. Ida Noddack's explanation was dismissed as the rambling of a sceptical chemist who just did not want to believe the physicists.

When the explanation did come, it was not from Berlin but from two scientists who had taken refuge from the Nazis abroad. The first was Dr. Lise Meitner, who had for many years shared with Hahn the direction of the radio-activity section of the Kaiser Wilhelm Chemical Institute in Berlin and who had gone a few months previously to Stockholm. The second was her nephew, Austrian-born Dr. Otto Frisch, now Jacksonian Professor of Natural Philosophy at the Cavendish. Frisch had left Germany in 1933 and, after a short spell at the Imperial College of Science in London, had accepted a post in Prof. Niels Bohr's Institute of Theoretical Physics in Copenhagen.

Frisch was spending the Christmas of 1938 with his aunt in Sweden, he tells me, when a letter arrived from Hahn telling her of his results. Frisch, a short curly-haired man of fifty with a serious demeanour that hides a live and typically Austrian sense of humour, confesses that "it took my aunt a little while to make me listen" as she started to tell him all about Hahn's work. Eventually they got to arguing about the meaning of it all. Up till then it had been accepted that you could, by bombarding an atomic nucleus like that of uranium, either chip little bits off or add bits on. Very gradually it dawned upon them that what was happening to the uranium nucleus in this case was something quite different.

Frisch told me: "It looked as if the absorption of the neutron had disturbed the delicate balance between the forces of attraction and the forces of repulsion inside the nucleus. It was as if the nucleus had first become elongated and then developed a waist before dividing into two more or less equal parts in just the same way that a living cell divides."

The striking similarity of that picture with the process by which bacteria and other organisms reproduce themselves caused Frisch to seek out an American biologist friend as soon as he got back to Copenhagen to ask him what technical term was used to describe this process. He heard that it was called "fission" and immediately applied the same name to the newly discovered nuclear phenomenon.

The importance of fission, as Frisch and Meitner were quick to realise, lay in the fact that the combined weight of the products would be less than that of the original uranium nucleus. If mass vanished, then, as Einstein and Aston had shown, it could only result in the production of vast amounts of energy.

The task of composing a report of their discovery for publication was complicated and delayed by the fact that further discussions between Frisch and Lise Meitner had to be conducted over the long-distance telephone between Copenhagen and Stockholm, and it eventually appeared in the British scientific journal *Nature* on February 11, 1939.

A great deal had been happening in the meantime, and with bewildering speed. Niels Bohr was in America attending the Washington meeting of the American Physical Society when the Hahn and Strassman paper arrived. On January 26 he told his friends there about it, and told them too of the picture which Meitner and Frisch had formed to explain the German results and about which Frisch had told him in Copenhagen.

The effect was electrifying. Some physicists went immediately to their laboratories, a few of them even before Bohr had finished speaking, to gain experimental proof. It took only a few hours to demonstrate the large energy pulses produced by the fission fragments.

The conclusions of Meitner and Frisch, arrived at over Christmas, had been reported to *Nature* in a letter dated January 16, which appeared in the correspondence columns under the usual editorial disclaimer on February 11. There were no such delays in announcing to the world what appeared to be the first experimental confirmation of their conclusions. The daily press in America carried them within days.

It was not until a week or so later that Bohr received a letter from one of his sons in Copenhagen which reported that Frisch had obtained similar experimental confirmation several weeks earlier. "I had not written to him myself", says Frisch, "because I wanted to make sure and to follow up various questions. I had, however, told Bohr's son of my results."

Bohr himself went to a great deal of pains to persuade the American newspapers of his own laboratory's priority of discovery, and it was probably as a result of that fact that Frisch first became known in the United States as his son-in-law. As Frisch himself points out, Bohr had no daughter and he was himself unmarried.

The most immediately interesting feature of the new discovery was the amount of energy released. It meant that a single nucleus, so small that about one million million could be packed side by side on a space one inch long, was releasing, when it split, enough energy to make a small grain of sand do an easily perceptible hop.

Several scientists were quick to point out that, when the uranium atom split, some of the neutrons would find no home with the fragments. There would be too many of them. Von Halban, Joliot and Kowarski in France, and Anderson, Fermi, Hanstein, Szilard and Zinn in the United States, confirmed it. The big question now was whether these neutrons would be produced fast enough and in sufficient numbers to split further uranium atoms and keep the process going. If they were, then a veritable "chain reaction" would be the result, and every time a neutron split an atom it would produce a vast amount of energy in the form of heat and radiation.

There were various methods of finding out. The French team were first off the mark and took for convenience a uranium compound that would dissolve in water and placed it in a large vessel. In the centre they put a source of neutrons, and round it they placed a number of devices that could detect the presence of neutrons and count them as they were formed. Then they substituted for the uranium solution another that was very similar but contained no uranium.

The results were conclusive. There were many more neutrons in circulation, they found, when the neutron source was placed in the solution of uranium. After making all the necessary allowances for absorption and loss of neutrons in different ways, the French team came to the conclusion that for every neutron that splits a uranium atom, between three and four additional ones are produced in the splitting process.

Confirmatory tests were carried out elsewhere and soon showed that the French results, though basically correct, were unduly optimistic. There was in fact no fixed number of neutrons produced by fission.

It took several years of painstaking work in many laboratories to discover that the average number of neutrons produced in each fission of uranium was 2·5. The results already obtained were enough for the French workers. They showed that if you bombarded uranium with slow neutrons you produced a new generation of fast ones. The French scientists knew that graphite, heavy water and beryllium could be used to slow these down. With commercial acumen that is rare in pure scientists on this side of the Atlantic, they produced designs of both heavy water and graphite reactors* to be used as sources of power and hurriedly made the first application for patents of chain-reacting piles, not very different in general principle from those now operating in many parts of the world.

As may well be imagined, their action disturbed the tranquillity of the scientific world. It was so out of keeping with the slow, precise and disinterested traditions of the very international nuclear "club" that many thought they had been precipitate and a little unsporting. "After all," as one eminent scientist told me, "no-one, including the French, knew that it could work. There were many vital facts to be found out and several years of hard and expensive work before anyone could know the answer." The French reply to this was, that you don't need to prove that a patent will work the day you make initial application for it. That obligation only follows later on.

The French action did not immediately drive the atom "underground". Scientists continued to meet and correspond and publish their results in the rapidly expanding field, until by general agreement publication of results ceased in the interests of the Allied war effort. This was to deprive the enemy of any benefit he might otherwise derive from them and to prevent him from seeing the way in which the Allies were thinking and working.

* See page 81.

The initiative in this move came primarily from a group of foreign-born physicists working in America in 1939, and it was at first only partially successful. Leading British and American physicists agreed, and so did Niels Bohr. Joliot of France, however, did not, and refused at first to co-operate, partly, perhaps, because of the publication in the American *Physical Review* of a paper that had been submitted before the agreement had come into force. There is little doubt that the French were even at this stage anxious to protect their commercial interests. It was not going to be an easy field in which to apportion credit or rights.

It has often been argued that some particular event, like the first deliberate splitting of any atom by Rutherford in 1919, the discovery of the neutron by Chadwick in 1932, the splitting of uranium in 1938 by Hahn and Strassmann, the conclusions of Meitner and Frisch, or the construction of the first chain-reacting pile by Fermi in 1942, was the individual agent responsible for triggering off the great succession of scientific discoveries and technological achievements that have now provided us with atomic bombs and nuclear power stations.

The truth is very different. Admittedly it was the good fortune of Britain, with men like Dalton, to play a leading part in the early formulation of atomic theory which continued up to the end of the century, and to have made an outstanding contribution through men like Rutherford, Chadwick, Soddy, Aston, Cockcroft, the two Thomsons, Walton, Blackett, Powell, and so many others who have continued that work in the current century. But a glance at the scientific textbooks and periodicals, so scrupulous in giving credit to earlier work, will show that teams everywhere were engaged on these problems, all the leading countries vying in friendly competition and comparing notes and often asking or giving advice. Many times the experimental results or theoretical ideas of one would only achieve fruition through the complementary conclusions of another team in a different country.

The German invasion of France soon changed all this, however, and in the interests of the general war effort work on the subject was concentrated in America, and it was the privilege of the United States, aided by scientists from Britain

Canada, France, Italy and Germany, to make the outstanding contribution to the great scientific discovery and technological achievements of the war and immediate post-war period.

The part played by European scientists is not sufficiently well known in America, and although a great deal of lip service has been given to that help in official statements and in scientific journals in America, the great proportion of the general American public remains ignorant of the facts. Mr. Gordon Dean, three years chairman of the United States Atomic Energy Commission, was not exaggerating when, in his book *Report on the Atom*, he wrote: "I sometimes think that we in America are a little inclined to believe that each atom bears the inscription 'Made in the U.S.A.' except those that have been stolen from us. In those cases the U.S.A. has been scratched out and the letters 'U.S.S.R.' have been etched on."

"The myth", he said, "would run something like this: Atomic energy was discovered and first developed in the United States in secret during World War II. Although we are still ahead in the field, the Russians, with the help of traitors, successfully stole enough of our key secrets during the war to develop a programme of their own and are now hot on our heels. Our Allies, the British, because some of their scientists came over to help us with our war-time programme, also know something of these matters, but are actually running a very poor third."

There was a time when I would have thought this story far-fetched. An experience I had one night in a Los Angeles drugstore taught me that it is probably an understatement and that the world of an American can be just as circumscribed and self-sufficient as that of any Russian. The girl behind the counter asked me how long I had been in the States. I told her "Three days". She wanted to know where I came from, and I told her I was from London. "You speak English very well after only three days here", she told me.

So much for the English language. What about the atom? Let us ask Dean. "Under no circumstances can it be said that the atom is native-born American", he tells us. "The most that can be said is that it is an immigrant of mainly European lineage that has taken out its first papers over here." The precise date when the atom immigrated to the United States would be placed by Mr. Dean at January 16, 1939, the date when Niels Bohr told them Hahn and Strassmann had split the atom.

In the light of subsequent events it is difficult to believe that it was not in great measure due to the prestige of scientists working in Britain and their confidence in the feasibility of the bomb project that the American Government were persuaded to embark on the programme when and on the scale that they did. By the time that decision was taken, scientists in Britain had already calculated within near limits the critical mass of fissile material needed for such a bomb and had worked out the outlines of the two main methods later used to produce atomic explosive, that is to say the method of separating uranium 235 by the system of gaseous diffusion, and production of plutonium by the process of transmitting uranium 238 in an atomic pile.

That work, as we shall see, had been started by a British Committee under the chairmanship of Sir George Thomson, now Master of Corpus Christi College, Cambridge.

[5]

Transatlantic Partnership

THE College of Corpus Christi is an ancient and distinguished foundation. Its Gothic windows, battlemented tower and friendly court of closely cut green grass date back to 1352. Although the college borders on the town's main street, its quiet exterior gives no hint of the industry within its many rooms nor boasts the many distinguished scholars that have left it to take their places among the country's honoured men.

In this self-effacing quality the college has much in common with its Master. Always willing to help, ready with pencil and paper to worry out a problem or test a theory, Sir George Thomson nevertheless shuns personal publicity, but he will willingly spend half an hour explaining to a layman in the simplest language the significance of some scientific discovery about which he has been consulted.

In 1939 Sir George was Professor of Physics at the Imperial College of Science and Technology in the heart of London. Like others working in the field, he had quickly grasped the significance of the news from Germany. It was a situation, he realised, that required immediate action.

There is nothing normally conspiratorial about him, as the reader may have guessed, but even the quiet Sir George (he was plain G.P. for George Paget then) said afterwards that he felt "like a character in a third-rate thriller" on the day when, early in 1939, having thought it all out and talked it over with Sir Henry Tizard, head of his college, he went to the Air Ministry and asked officials there for a ton of uranium oxide. Of course, they wanted to know why. "G.P." told them of the

Berlin work, of the conclusions of Meitner and Frisch, and of a letter that had just appeared in *Nature* telling of the experiment of Halban, Joliot and Kowarski with the tank of uranium solution and how they found they got out more neutrons than they put in.

The discovery, he told them, might be of the greatest military importance. There were two possibilities, he said, from the military point of view. The first would be the establishment of an endless chain reaction, releasing energy in perhaps controllable amounts as a source of power; the second was to make the process to be so rapid that, to use his own words, "a considerable fraction of the available energy is released before the whole contrivance is blown to the four winds". The second possibility would be an atomic bomb.

G.P. wanted the ton of uranium oxide, he told the Air Ministry, because the data available was far from complete and it would enable him to carry out experiments with Professor Moon and others in the college. They would have liked uranium metal, but at that time such a thing existed only as a chemical curiosity.

G.P. got his uranium oxide all right, but the first experiments were disappointing. They appeared to indicate that the chain reaction, the first objective, could not be achieved at all with uranium oxide unless large supplies of heavy water were available. There was hardly any heavy water in Britain. With ordinary water or paraffin, the next best things, the reaction would not work at all, they found, because all the neutrons were absorbed by these substances before they could achieve their effect. This seemed automatically to rule out the second possibility, that of a bomb.

"If this conclusion now seems disgraceful blindness," says Sir George, in retrospect, "I can only plead that to the end of the war the most distinguished physicists in Germany thought the same."

It was from Prof. Sir James Chadwick of Liverpool University and from two refugee scientists from Germany that the first workable idea for an atomic bomb came quite independently. In March 1940, Dr. Peierls and Dr. Frisch, who had both come to Britain from Germany, came to see Sir Henry Tizard, chairman of the Committee for the Scientific Study of Air Warfare. Dr. Peierls, now Professor of Theoretical Physics at Birmingham University, and Dr. Frisch pointed out that while there were objections to a bomb made out of ordinary uranium, the same objections would not apply if the lighter uranium 235 were used. A sub-committee of scientists was formed to go into the matter and G. P. Thomson was put in charge of the investigation.

Every committee must have a name by which it can be recognised, and the same applies even if it is only a sub-committee. It must be a name which, especially in a case like the present one, tells no-one what it is up to. Most committees take their names from their chairmen, but Thomson's name might have given the enemy a clue. The "cover name" chosen for the uranium sub-committee would have defeated even the historians. Its members christened it "Maud".

Sir George tells me that it all started with a telegram that Dr. Frisch had received about that time from Niels Bohr in Copenhagen. Denmark had just been overrun by the Germans. The latter part of the telegram ran, "TELL COCKCROFT AND MAUD RAY KENT". Frisch knew of no such person, nor did John Cockcroft. Between them they concluded with great but misguided ingenuity that, allowing for a certain amount of garbling, the words MAUD RAY KENT might be an anagram for RADIUM TAKEN and have been intended to warn the British that the Germans had confiscated the country's stocks of that valuable and significant commodity.

"Years after the war", says Sir George, "I happened to mention this to Niels Bohr and he told me the message had had nothing to do with radium. There was, in fact, a lady of that name who had stayed some time in Copenhagen before the war and he wanted word sent to her friends." Needless to say the message never reached them.

The ingenuity of a later generation of Civil Servants went one better. Sir George heard afterwards that in the absence of any other explanation the initials had been interpreted tentatively as "Military Application of Uranium Detonation"!

There were a number of problems that the MAUD Committee needed to sort out. Uranium as it is found in nature is a mixture of two kinds of atoms weighing, respectively, 235 and 238 units. Wherever it is found, whether as hard, dense grey rock called pitchblende in the Belgian Congo or as bright yellow carnotite in Colorado, the metal itself, whatever is in combination with it, will always contain these two sorts of uranium atom. They will always be, too, in the same fixed proportions of about 99·3 per cent of the heavier 238 variety and 0·7 per cent of the lighter 235 form. Because they behave in exactly the same way chemically, there is no hope of separating them by any method of chemical reaction.

But the bomb suggested by Chadwick and by Frisch and Peierls demanded that only the lighter, rarer variety be used. Unless the two forms could be separated on an unheard-of scale there could be no bomb of uranium 235. Dr. Peierls offered to tackle this problem with Dr. Francis Simon.

A team under Professor Haworth of Birmingham University undertook to investigate related chemical problems, and the help of Imperial Chemical Industries was enlisted. Chadwick agreed in the meantime to go carefully into the fundamental physics, while another team, with Prof. N. Feather and Dr. E. Bretscher, worked at the Cavendish Laboratory in Cambridge. One thing they had to find out was whether, even if the right ingredient could be manufactured in quantity, the reaction would proceed fast enough to achieve the desired effect and not just result in a "fizzle". They needed, for example, to calculate what the chances were of the neutrons escaping from the mass of atomic explosive before they had had a chance to collide with one of the other nuclei of uranium.

They knew that if the right amount of nuclear material were present it only needed one neutron to start a chain reaction which would result in an atomic explosion. Perhaps the greatest problem of all was that of discovering just how much uranium would be required in the bomb.

The nucleus itself occupies a minute fraction of the whole space taken up by each atom, and they knew that if the amount of uranium used were too small the neutrons formed by early fissions would probably escape to the exterior through the open spaces in surrounding uranium atoms without ever encountering another nucleus in which to provoke further fission.

As the radius of any sphere gets bigger, it is a simple mathematical fact that the volume grows more quickly than the surface of the sphere. This meant that a smaller proportion of the neutrons would be able to find their way out through the surface of a large sphere than would through the surface of a small one. If the sphere were too small the leakage would be too great to permit a chain reaction to build up; if it were too big, one stray neutron would suffice to set off a chain of reaction that would result in a full-scale atomic explosion.

To make a bomb that would be quite safe until the moment of detonation it would be necessary to calculate theoretically the "critical" mass needed to provide an explosion, and then make up this amount in two or more fractions that would only be brought together at the vital moment.

While this work was proceeding in Britain, the French had been carrying out experiments of their own on the non-explosive applications. When the Germans invaded France their work would have been brought to an end but for the timely activities of a modern edition of the "Scarlet Pimpernel" in the person of the late Earl of Suffolk.

As scientific attaché in Paris, he had compiled a list of 150 French scientists and technical men who ought to be smuggled to Britain if Paris became endangered. Among them were Halban (Joliot preferred to remain) and Kowarski. With them they carried what must have been strangest of all the many things salvaged from France at the time. It took the form of thirty-six gallons of heavy water which they nursed like the best Napoleon brandy.

It was a valuable consignment, well worth saving, for it comprised most of the then stock of the entire world. Its loss to the Germans was as important as its gain to ourselves. The Earl of Suffolk was killed afterwards in a courageous attempt to render harmless a German infernal machine. It was from Prof. Halban that I heard the story one night in a dimly lit Mayfair eating club.

Because of congestion on the roads and interrupted communications, and also the reluctance of some of them to leave France, only about forty of the men on the Earl of Suffolk's list reached Bordeaux, where arrangements had been made for them to embark on an 8,000 ton collier, the *Broompark*. The cargo was a motley one, says Halban. It included £2½ million worth of industrial diamonds and every British vehicle they could get aboard.

Plans were immediately made to save the most valuable items if the ship were sunk on its way across the Channel. The heavy water, which had been ordered from Norway and flown to France at Joliot's request in March 1940, was in twelve sealed aluminium cans. The Earl, a romantic figure who had once in his youth run away to sea and signed on as a ship's carpenter, built a raft and the heavy water and diamonds were lashed on top.

Halban tells me that the Earl of Suffolk and Kowarski then drew up with him a "solemn agreement", which they all signed, to the effect that if the ship were mined or bombed and were in danger, any of them who survived would cut the raft adrift and remain with it. If the ship were attacked by submarine, since it was believed that the Germans were already looking for them, they would see that the raft remained tied to the *Broompark* when it sank. To increase their own hopes of survival they donned the inner tubes of tyres stripped from vehicles they had saved.

The *Broompark*, as fate would have it, reached Falmouth in safety, although a neighbouring ship went up on a mine. Halban and Kowarski, after preliminary negotiations to safeguard their rights to any new discoveries, were installed with a young British research worker, Fred Fenning, in an annexe to the Cavendish Laboratory in Cambridge, where Prof. Feather was in charge. From that time on they took a leading part and were a constant inspiration in the reactor side of the new project.

In July 1940 the Americans were advised of British progress. The information was passed on to them by Dr. R. H. Fowler, a distinguished scientist then heading a mission in Washington. Sir George Thomson tells me it was agreed that he should be given all the data that had been collected up to that date so that he could communicate it to the American Government. The precedent so formed was followed, and the minutes of MAUD were sent to Fowler on a number of occasions to be communicated to the Americans, who by this time had their own committee under Dr. Wyman J. Briggs, head of the Bureau of Standards, and with Dr. George B. Pegram of Columbia University as vice-chairman.

John Cockcroft came back early in 1941 from a visit to America with an account of their work. It was mainly concerned with the separation of uranium 235 from the unwanted 238. It was very much along the same lines as our own, he reported, but perhaps not so well advanced. Fermi had just started investigation of a pile system that depended on graphite instead of heavy water, and was to operate two years later and provide the world with the first chain-reacting pile in history.

The French team in Cambridge had meanwhile made an important discovery. Using a suspension of uranium oxide and heavy water in a spinning sphere that kept the powder well mixed with the fluid, they performed late in 1940 an experiment which provided for the first time clear evidence that in a sufficiently large system a chain reaction would be possible. Between three and six tons of heavy water, they found, would be needed.

Their findings were reported to the United States, where they were immediately pooh-poohed. Some of the criticisms were quite childish. If the mantle of the late Lord Rutherford had fallen on anyone's shoulders, it had fallen on those of Prof. Chadwick. He was the man whose opinion would not be doubted, and the Americans asked him to go down to Cambridge to check the French claims. He reported that though the accuracy might not be as high as was suggested, the general import was quite convincing. It was not until eighteen months later that foreign-born scientists, working in America, were able to provide similar evidence, using graphite, and in America due credit has never been accorded to the French for this work. The Smyth Report, for example, makes no reference to it whatsoever. It was not without effect, however. The National Defence Research Committee soon afterwards gave an order for the design of a factory to produce heavy water in quantity.

About this time members of the British Mission in the United States were invited to attend some of the meetings of the N.D.R.C. sub-committee dealing with uranium, and the

Americans in their turn attended meetings of MAUD. It was arranged that Dr. E. O. Lawrence, a Nobel prize winner, should carry out certain experiments on his atom-splitting cyclotron, and that Dr. A. O. Nier should help by providing a sample of separated uranium 235.

French interest in the chain-reacting pile was based on its use as a source of energy, but a discovery by two American scientists, McMillan and Abelson, published in 1940 for all the world to see, gave the clue to a further possibility. It suggested that a new element, plutonium, heavier than uranium, would be formed when uranium 238 absorbed neutrons. This building-up process, by competing with the fission process for available neutrons, was obviously one of the reasons why it had been so difficult to get a chain reaction to take place, but to Cockcroft, Feather, Bretscher and others in Britain it suggested a further atomic explosive, as good as uranium 235, which, because it was chemically different from uranium, might be far easier to separate out and purify than were two substances that were chemically similar.

By the summer of 1941 the work of Sir George Thomson's MAUD Committee was sufficiently advanced for an historic report to be made. There were two main findings. The first dealt with the possibility of a bomb made of uranium 235, and the second with the production of power and plutonium in a heavy water reactor. It also included designs for a separation plant to produce uranium 235, with a rather optimistic estimate of the cost of a full-scale plant to produce a bomb a week.

The work on the large-scale isotope separation was in the hands of Sir Francis Simon, now Professor of Thermodynamics at Oxford, who was responsible for the laboratory side, and Professor Peierls in Birmingham, who was in charge of the theoretical aspects. Both groups worked in very close collaboration.

When Simon was asked to prepare a cost estimate for a full-scale diffusion plant, he had to base it to a large extent on guesswork. A gaseous form had to be used. The only known volatile uranium compound, the hexafluoride known for short as "hex", was only available in very small amounts, just enough to measure its physical and chemical properties. There could be no question of running an isotope separation on these amounts, quite apart from the fact that no compressors or barriers had at that time been developed for this highly corrosive gas. The separation experiments had to be carried out

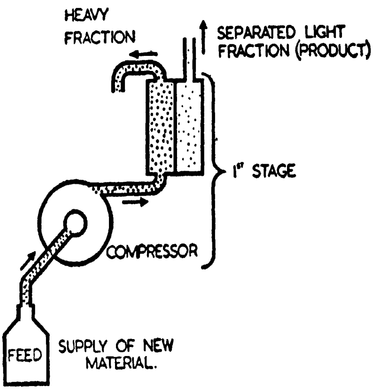


Diagram A

Diagram A, illustrating the principle used in the process of gaseous diffusion employed at Capenhurst to " enrich " uranium by increasing the proportion in it of the lighter isotope, uranium 235.

A single " stage " of the plant consists of a rotary compressor, or pump, and a box divided by porous membranes, the "holes of which are so small that there are several million of them to every square inch of material. The U235 atoms, being lighter than those of U238, move faster and tend to pass more quickly through the membrane. Because the separation is very imperfect it must be repeated several thousands of times. The effectiveness of the separation is further increased by " re-cycling " as shown in diagram B.

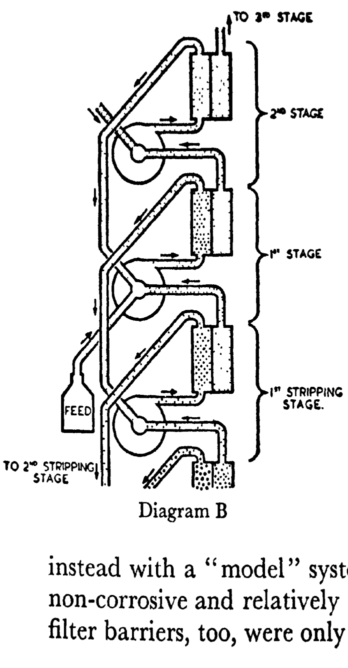


Diagram B

instead with a "model" system, a mixture of two heavy gases, non-corrosive and relatively easy to separate and analyse. The filter barriers, too, were only in the early stages of development and guesses had to be made about what might be possible later on.

These experiments, however, left the isotope separation group confident that the diffusion process would be the best one to separate the uranium isotopes on a large scale. It was also clear that such a plant, with its thousands of stages, was going to be extremely expensive, and it was probably the first time that physicists had ever had to accustom themselves to the sum of a million pounds as a unit of cost.

Sir Francis confesses that when it came to estimating for the full-scale plant he was in a quandary. The possible spread of costs was enormous owing to many uncertainties that were unavoidable at that time; indeed, he thinks that, if he had cautiously given figures approaching the upper limit, it would have killed the diffusion project immediately. "I felt justified in putting forward the lowest estimate which, under favourable circumstances, might, in my opinion, have been achieved in practice," he tells me, "and I am glad that I did so."

The MAUD Report went to the Hankey Committee, the highest committee in the land on the military applications of science. At the end of August, Lord Cherwell, whose duty it was to keep the Prime Minister informed on all these and other technical problems, reported the substantial progress that had been made.

The general responsibility for scientific research under the various technical committees lay with the then Lord President of the Council, Sir John Anderson, later to become Lord Waverley. Having this in mind, the Prime Minister on August 30 wrote the following minute:

Gen. Ismay for Chiefs of Staff.

Although personally I am quite content with the existing explosive I feel we must not stand in the way of improvement and I therefore think that action should be taken in the sense proposed by Lord Cherwell and that the Cabinet Minister responsible should be Sir John Anderson. I shall be glad to know what the Chiefs of Staff think.

The Chiefs of Staff replied recommending immediate action with the maximum priority. A decision was taken in favour of building a pilot plant for uranium production in Britain, with, if possible, a full-scale plant in Canada.

Sir John Anderson, who had now the ministerial responsibility for putting this decision into action, had had a most distinguished and varied career, but there was nothing on the face of it to suit him for his present task. Born in July 1882, and educated at George Watson College and the University of Edinburgh, he had gone to the Colonial Office in 1905, where his ability was quickly appreciated. His first big responsibility came with his appointment to the Ministry of Shipping in the vital period towards the end of the First World War when our food supplies were almost at the mercy of the German U-boats. In 1932 he had been appointed to the Governorship of Bengal, and when he returned in 1938 he successfully stood for election as Member of Parliament for the Scottish Universities and was made a Privy Councillor.

The most relevant item in Anderson's career, however, was a period about which few people except Mr. Churchill knew. It lay in the world of science. By a curious coincidence Anderson had played his own part in the early nuclear investigations at the very start of the century, when the excitement first began.

In 1903, after gaining his Edinburgh degree, he went to Leipzig to do post-graduate research under Professor Ostwalt in the Physical Chemical Institute.

Professor Ostwalt himself had become alive to the interesting possibilities opened up by the work of Becquerel, discoverer of radioactivity, and the Curies just before the close of the century. He wanted to start up work in his own laboratory and he asked Anderson to initiate and take charge of this work.

That early experience of the special problems involved in atomic energy work, and the special "feel" that it gave Anderson for the scientists' point of view, were going to stand Britain in good stead in the years that lay ahead, and it explained why, when the time came soon afterwards for the Cabinet to be reorganised, for Anderson to become Chancellor of the Exchequer, and for another minister as Lord President to take over the general responsibility for science, he was asked by Mr. Churchill to continue his responsibility for the atomic bomb project.

Wanting to know more about those early days, I went to see Lord Waverley. As chairman of the Port of London Authority controlling the largest expanse of docks in the world, he occupies a finely panelled and beautifully furnished office in their headquarters on Tower Hill, overlooking the Tower of London and Tower Bridge. In an ante-room nearby, where I waited, there were large painted metal maps of the port showing where every ship, represented by small magnetic models, was berthed in the many basins.

Waverley himself was dressed in a rather old-world fashion, quite unfamiliar in the atomic age. He wore a jacket of black doeskin cloth and stiff white winged collar. A pearl tiepin held his finely checked grey tie in place. The tempo of our conversation was set by the slow and measured tones with which he himself spoke all the time, emphasising each word carefully. On every occasion when he mentioned the names of foreigners or used foreign words, he pronounced each syllable with the greatest possible care and correctness.

He seemed to recall his early Leipzig days with a great deal of pleasure. "We were, of course, only interested", Lord Waverley told me, "in the scientific aspects of nuclear research. Our interest was chiefly in the newly discovered phenomenon of radioactivity. What they had asked me to do was to investigate the various forms of radioactivity associated with uranium."

The work involved a good deal of chemical separation. One of the processes which Lord Waverley used in those early days was due soon to achieve a new significance in the British post-war programme. It was the method of extracting uranium by dissolving its compounds in ether. This method was adopted, as we shall later see, in preference to one of precipitation which had been favoured by the Americans in the production of plutonium.

I asked Lord Waverley what his first reactions were on being asked to take over the new task. He had shown, it seems, immediate interest in the idea. "My first act", he told me, "was to appoint a consultative council." This was composed of Sir Henry Dale, President of the Royal Society, Lord Hankey, and later Mr. R. A. Butler, chairman of the Scientific Advisory Council of the Cabinet, Sir Edward Appleton, Secretary of the

Department of Scientific and Industrial Research, Lord Brabazon, Minister of Aircraft Production, and Lord Cherwell, who was Mr. Churchill's personal adviser on scientific matters.

"The next move was to appoint someone to take executive control", he went on in his slow, measured speech. "On the advice of members of my council I decided to ask the late Sir Wallace Akers, who had been concerned with the secret work that I.C.I. had been doing for the Government in connection with the problem of isolating the active 235 component of uranium."

Akers, an industrialist of outstanding ability with a gift for understanding and getting on with people and a wide knowledge of research techniques and plant construction, had just been elected to the main board of I.C.I. as director responsible for research. I.C.I., who were destined to supply the project with a dozen or more of its senior men later on, and had already lost many to the munition factories, generously gave up Akers and allowed him to take Mr. M. W. Perrin as his chief assistant and deputy.

Although Perrin was to take a leading part in the war-time programme and continued as scientific "chief-of-staff" to Lord Portal in the four formative years of the project immediately following the war, he was never a man to seek the limelight. There must be few people in the country, however, who have not used domestic articles made of the hard, waxlike and almost incorrodible polythene that he was in great measure responsible for developing while at I.C.I.

To ensure that Akers had at his disposal all the laboratory facilities and services that he needed, the atomic project was made into a new and, to all intents and purposes, autonomous division of the Department of Scientific and Industrial Research.

The normal procedure within the Civil Service, of course, is for a division of that sort to deal with the responsible minister only through the Permanent Secretary. Akers and Perrin resisted this procedure successfully and, right from the start, were given access to the Lord President in all matters concerning the project, so that there was continual movement between their office in 16 Old Queen Street, which was then the headquarters of the Department of Scientific and Industrial

Research, and Lord Waverley's office round the corner in Whitehall.

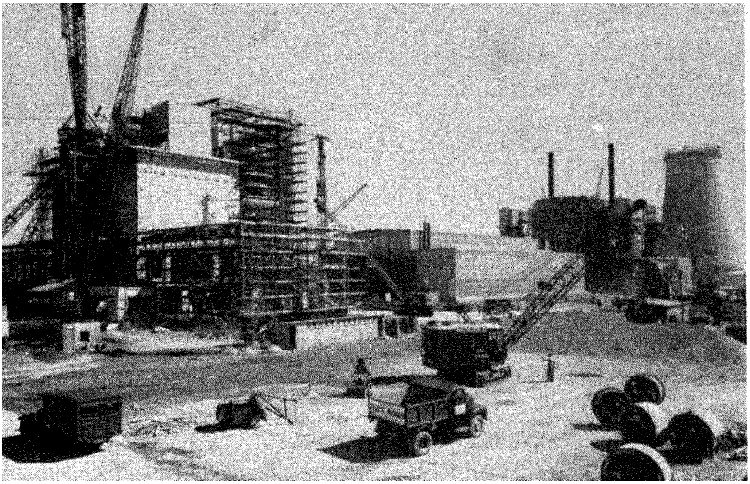
The new division had to have a name and was rapidly christened the "Directorate of Tube Alloys", or "T.A.". The name soon became so firmly associated with atomic energy work that in America many scientists and engineers talked of "tuballoy" as a code word when they meant uranium. Perrin, who is now chairman of The Wellcome Foundation, told me how the division came to get its name. The story reflects the sound judgement that Lord Waverley showed in so many directions.

Akers and Perrin had been discussing the question of a name together. They wanted one that gave away nothing but was high-sounding and urgent enough to impress the firms with which they had to deal. It was at a time when the outstanding success of the German armoured divisions a year before in France had suddenly made the country extremely "tank conscious". They hit upon the name "Tank Alloys".

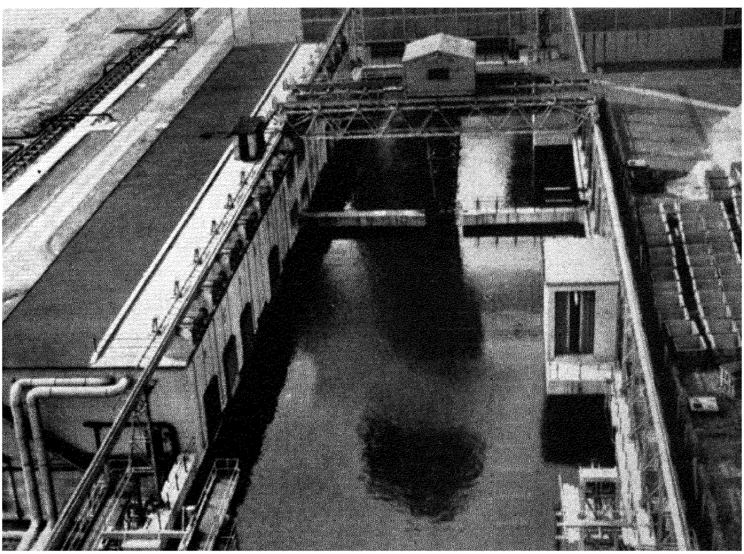
Shortly afterwards Sir Wallace Akers went to see Waverley and asked him what he thought of the name. "At that time we had pinned our faith on the diffusion process for the separation of uranium 235", he says. The plant required involved a great agglomeration of tubes made from a special alloy capable of resisting the corrosive effect of 'Hex'. It was for that reason that I suggested Tube Alloys as a generic term."

The new directorate was set up in September 1941, and at the same time a technical committee was set up under the chairmanship of Akers on which sat scientists who were directing the various spheres of work. Its members at the start were Sir James Chadwick, Professor Peierls, and Drs. Halban, Simon and Slade. Later they were joined by Professors Oliphant, Cockcroft and Feather.

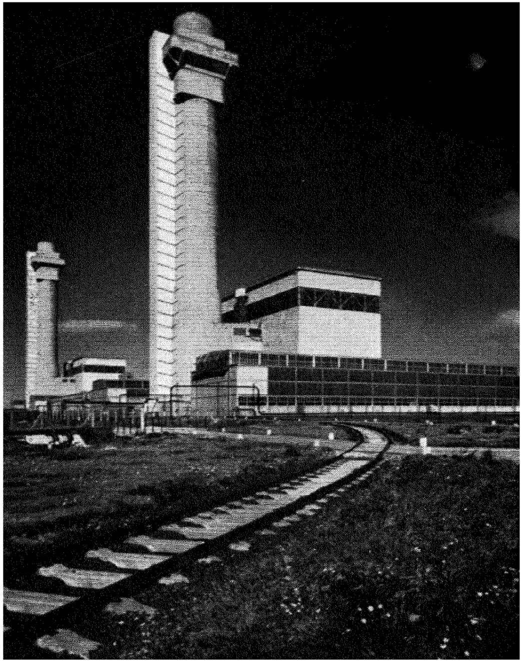
By this time there had been a good deal of reorganisation in Britain. The immediate needs of the war effort—radar, telecommunications, precautions against mines, the development of better tanks, anti-tank guns, and of course aircraft—had made a heavy call on scientific and industrial resources, and a large proportion of the physicists were already engaged on the various tasks. In the atomic field a choice clearly had to be



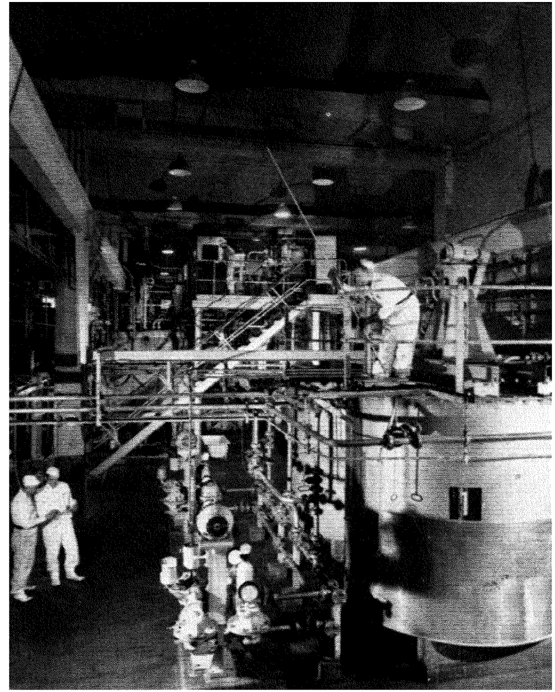
4. Calder Hall, the world's first large-scale atomic power station nearing completion. On left and nearest the camera is one reactor. The common hall for generating equipment is in the centre and beyond are the second reactor and a water-cooling tower.



5. The "cooling pond" at the Windscale plutonium factory where fuel elements, highly radioactive after being used in the reactors, are allowed to remain for some months to lose some of their activity.



6. The two giant reactors of the Windscale atomic explosives factory. The long low building is one of the four halls housing fans used to cool the reactors. Resultant hot air is expelled through the 410-ft.-high chimneys. Service lifts run in the oblong-shaped tubes to the left of each chimney.



7. Uranium purification plant at Springfields, Lancs, where crude ore from places like the Belgian Congo and Australia, and other raw materials from South Africa, are fabricated into fuel elements of the pure metal.

made and the decision was taken to concentrate on a few "super priorities". They were:

Obtaining essential nuclear physical data.
Theoretical investigations into the chain reaction in an atomic bomb and the dimensions and design of the bomb and its blast effect.
Development of prototype plant for the enrichment of uranium 235 explosive by gaseous diffusion.
Investigation of atomic reactor systems, especially those using heavy water.
Manufacture of the uranium fuel elements and the heavy water that would be required by such reactors.

The Americans, as has been said, had been kept fully informed of the British progress and views on the atomic bomb project. As far back as December 1940, Fowler had passed over to E. O. Lawrence a letter from Cockcroft in which the view, already put forward by Feather and Bretscher in Cambridge, was expressed that plutonium could be used as an alternative explosive to uranium 235 and pointing out that it might be easier to manufacture.

Professor Bainbridge of the American National Defence Research Committee (NDRC) had come over to England in April 1941, and Professor Lauritsen, also a member of NDRC, in July of the same year. Their visits had been on general scientific matters, but both had, in the spirit of share and share alike, been invited to attend meetings of the MAUD Committee.

They had been told, too, of Professor Chadwick's strong conviction that a bomb of great destructive power could be made from uranium 235 and of the opinion of the whole British group that the separation of uranium 235 on the necessary scale was feasible.

The British had emphasised the urgency of the project by pointing out that the Norwegian heavy water plant at the Norsk Hydro was capable of producing several quarts of heavy water a day, and also the fact, learned by our intelligence department, that the Germans had given orders for considerable quantities of paraffin, a highly significant substance, to be manufactured from the heavy hydrogen thus obtained.

There was no doubt that the considered opinion of the MAUD Committee, which included almost all the leading physicists in Great Britain either as members or consultants, greatly impressed the Americans. It strengthened the hands of those who already believed in the project and was useful in persuading men in authority that they ought to take the matter seriously.

Up till late 1941 the American National Academy of Sciences had made two reports on the uranium problem. Neither of them was very cheerful. The first, in May 1940, mentioned radioactive poisons, atomic power, and atomic bombs, but placed emphasis on power. The second had stressed the importance of the new work on plutonium as an alternative source of nuclear energy, but was not specific about the military possibilities.

Before the Academy could make its third report, in November 1941, Dr. Bush had raised the whole matter again with President Roosevelt and Vice-President Wallace. He summarised the British views. The President agreed that the American programme ought to be recognised and broadened with the aid of funds from a secret source, and also decided that it was a matter on which there should be a complete interchange of information with the British. On October 11, 1941, he wrote a letter to the British Prime Minister suggesting that any extended efforts on this important matter might usefully be co-ordinated or even jointly conducted.

"The proposal commended itself to us", Lord Waverley told me, "because our resources were very heavily mortgaged and we were in a very vulnerable position. We thought that the job would go on far better on the other side of the Atlantic and that there was where our people should be, apart from a few like Akers and his personal assistant, Mr. Perrin."

The Americans then sent over to Britain Prof. Urey and Dr. Pegram of Columbia University, two of their top men, to make a closer study of the theoretical and experimental work that was going on in Britain. A special meeting of the newly formed Tube Alloys technical committee was called to review the whole field of progress, and Urey and Pegram were of course told everything.

It may be a measure of American faith in their own project that up till then less than £60,000 had been committed, and that this was in fact the first visit that the Americans had made to Britain specifically in connection with the uranium project. It left them with a deep impression of optimism which contrasted with the more conservative report soon to be made by the National Academy of Sciences.

Perrin, deputy director of Tube Alloys, who had taken over his task only a few days before the visit of Urey and Pegram in November 1941, tells me that he took advantage of their visit to make a first tour of the various universities and industrial establishments where work was being done. He sat in at all the talks they had with people like Chadwick and Frisch at Liverpool, Peierls and Simon at Birmingham, Feather and Bretscher and the French team at Cambridge, and saw progress by Imperial Chemicals up at Widnes on the extraction of metallic uranium. "There was no doubt of the effect it had upon them", he told me. "The fact that men of this calibre had similar ideas and had in many cases been thinking ahead of them certainly gave them courage to talk firmly when they got back to America."

There were in fact many scientists within the American ring of consultants, including probably Fermi himself, who were no more convinced that the bomb could be achieved at this stage than they were in 1940, but the fact that the British and apparently the Germans, both grimly at war, thought the problem worth undertaking, together with the fact that a good deal of progress admittedly had been made, swung the balance.

There had been also, as we are told in the Smyth report, a "change of the whole national psychology". Although the attack on Pearl Harbour was still to come, the impending threat of war was being felt more keenly than before. Expenditures of money that would have seemed enormous in 1940 were being taken for granted by 1941.

The American decision to go ahead with an "all-out" programme was announced to the uranium section, known as "S-1", of the Office of Scientific Research and Development, on December 6, 1941. On that occasion they were also told of the complete reorganisation of the group, which would be under Dr. Conant as representative of Dr. Bush.

A British mission led by Akers and composed of Halban, Peierls and Simon went over to the United States early in the New Year. They were able to report that the Americans were now fully engaged on a programme which planned to make the fullest use of the country's enormous resources both in the universities and in industry.

They had by this time come round to the British conclusion that the bomb was definitely feasible. There was still a great deal of uncertainty about the best way of producing the fissile or explosive material, and four methods had been recommended. One of these was the production of plutonium in a graphite pile, and the others were various methods of separating uranium 235, including the electromagnetic and the gaseous diffusion methods on which work had been done in Britain.

In May 1942, Perrin went over to Canada with a two-fold mission. The first was to sound Mr. Mackenzie King, the Prime Minister, and Dr. C. J. Mackenzie, head of the National Research Council, about transferring to Canada Dr. Halban and the rest of the team working on the reactor side, so that they would be nearer to Fermi and his team in Chicago; the second was to persuade them of the desirability of acquiring control of the Eldorado Mine in the far north, where uranium was mined as a source of radium and for industrial purposes that, up till then, had nothing to do with atomic energy.

Perrin passed through the United States on his way home and talked the whole matter over with Bush, who was still running the American project. Bush saw the different methods of producing fissile material then under review rather like four horses in a race. They were all good beasts and all well backed. The British, he thought, had a good horse, too, but it was not well enough supported. With proper resources behind it, Bush thought the British horse had at least a chance of winning out in the end. He wanted to see all run in the same race with an equal degree of backing. He favoured the move to Canada.

In June the decision was taken in America to go ahead with a major industrial project, and on August 13 a special group of the Corps of Engineers known as the Manhattan District was officially established for what was known for security reasons as "D.S.M.", or the Development of Substitute Materials. One month later Brigadier-General L. R. Groves, a dynamic young engineer officer who, as a major, had built the gigantic Pentagon building outside Washington, was put in complete charge of the project.

About the same time the advance guard of the British team, under the leadership of Halban, arrived in Canada and established themselves in the laboratories of the National Research Council in Montreal. The plan was a good one, for it enabled work to continue in far greater freedom and with greater resources than would have been possible in a Britain which, by that time, was severely harassed by bombing. It should have led to a much closer relationship with work in the United States.

[6]

The Partnership Breaks Down

BY THE autumn of 1942, however, something had gone definitely wrong with Anglo-American relations as far as the atom was concerned. It was all tied up with the change in status of the project from that of an interesting scientific possibility to a military probability. Having once become a military matter, with a military man or commercial contractors in charge and with industrial firms transforming fundamental scientific theories into large-scale technological processes, United States officialdom adopted at once a completely new attitude towards the matter of co-operation.

British scientists who, with full approval of their Government, had been ready to provide the Americans with all the data they wanted, suddenly found doors closed upon them. There is a popular but mistaken belief that this breakdown in co-operation occurred after the war with the passing of the McMahon Act in 1946. It would be truer to say that it started the day the Americans were persuaded that, despite their own misgivings, the production of atomic weapons before the end of the war was possible.

It is difficult to create barriers, however, between scientists who have been accustomed to working together for decades, and there were still some interchanges between Fermi's group in Chicago, who by December 1942 had got the world's first atomic pile to work, and the now reinforced British group in Montreal.

Churchill had discussed the bomb with Roosevelt in their Hyde Park meeting in June 1942. To Harry Hopkins, the President's personal aide, he cabled afterwards: "My whole understanding was that everything was on the basis of fully sharing the results as equal partners. I have no record, but I shall be much surprised if the President's recollection does not square with this."

The matter had been further discussed at Casablanca in January 1943, when, according to Harry Hopkins's own diary, the Prime Minister expressed concern because the previous Anglo-American co-operation and full exchange of information and experimentation seemed to have ended. Hopkins had promised to look into the matter on his return to Washington.

Churchill, having heard no more from Hopkins, telegraphed him again on February 16: "I should be grateful for some news about this as at present the American War Department is asking us to keep them informed of our experiments while refusing altogether any information about theirs."

Hopkins replied: "I have been making inquiries as a result of your request to me in regard to Tube Alloys. It would be a help to me to have Anderson (Lord Waverley) send me a full mem by pouch of what he considers is the basis of the present misunderstanding, since I gather the impression that our people feel that no agreement has been breached. I should like particularly to have copies of any recorded conversations or references or memoranda which would reveal the nature of the misunderstanding."

Churchill, who was sick at the time, sent by cable a long record of Anglo-American dealings since the first exchanges of 1940. He expressed the conviction that this record proved that, on the grounds of fair play, he could justify his request for the restoration of the policy of joint work in developing the joint resources of the two countries. "Urgent decisions about our programme both here and in Canada", he said, "depend on the extent to which full collaboration between us is restored and I must ask you to let me have a firm decision on United States policy in this matter very soon."

In a later cable to Hopkins Churchill was forced to the point of saying that, if the full pooling of information on the progress in nuclear fission were not resumed, then Britain would be compelled to go ahead separately in this work and that that "would be a sombre decision". Hopkins took the matter up with the President, with Mr. Stimson, Secretary of War, and with Dr. Bush and Dr. Conant.

A cable from Bush to Hopkins on March 31 revealed what the Americans were up to. "The adopted policy", he wrote, "is that information on this subject will be furnished to individuals, either in this country or in Great Britain, who need it and can use it now in the furtherance of the war effort, but that, in the interests of security, information interchanged will be restricted to this definitive objective."

There was nothing new or unusual in this policy, the note went on. "It is applied generally in this country and elsewhere. To step beyond it would mean to furnish information on secret military matters to individuals who wish it either because of general interest or because of its application to non-war or post-war matters. To do this would decrease security without advancing the war effort."

Since the British were not, under the joint agreement, supposed to be engaged in the production of uranium 235 or plutonium, this amounted to a cold refusal to hand over to Britain any "know-how" about the fabrication of fuel elements, the design of reactors, the processing of resultant plutonium, or about other methods of producing fissile material such as the gaseous diffusion of uranium. It was a sufficiently good excuse to last until the end of the war when there could always be an Act of Congress to make such exchanges illegal.

The Americans adhered to this policy to such an extent that even in the matter of the separation of uranium 235 by the process of gaseous diffusion, for which the British team worked out both scientific and technological details, no scientist or engineer was ever allowed to enter the plant at Oak Ridge and our men were not even told whether the ideas that they had developed had worked satisfactorily.

The excuse made for this action was that of security. Subsequent events indicated quite clearly that the question mainly at stake was that of the post-war development of atomic power. Mr. Churchill rightly objected in his correspondence with Hopkins that the stand taken by the Americans gave them exclusive possession of the fruits of joint research, including the subsequent use of atomic energy for industrial purposes. The technique of accusing someone else of what you are in fact guilty of doing yourself seems to have been singularly applicable in the present case.

Tube Alloys had been divided into two groups, T.A.1 and T.A.2. The first dealt with fast neutron studies directly applicable to the process of fast fission that takes place when an atomic bomb explodes. The second concentrated on slow neutron work, that is to say, the atomic reactors in which plutonium could be manufactured if this form of explosive were used.

From a security point of view it was considered that the work of T.A.2, concerned chiefly with getting a reactor to operate, would serve as a useful cover for T.A.1 if the story leaked out, and would deflect interest away from the bomb itself.

Mr. Stimson came over to Britain himself in the early summer of 1943, soon after some further cabled exchanges. He represented to Mr. Churchill that the impression was gaining ground in America that the British were interested in the atomic bomb project primarily for the economic advantages that might accrue. The Americans, he said, could not see the fun of spending billions of dollars to find out things for someone else to use in a competitive post-war world.

The discussion between Mr. Churchill and Mr. Stimson on this matter was a very personal, informal affair. Stimson had come over to discuss a number of different matters. There were very few members even of the War Cabinet who knew anything of the atomic bomb project, so carefully had the secret been guarded.

When the atom bomb question cropped up, Lord Waverley was naturally called in. No others were present. Waverley explained how completely wrong was the point of view that Stimson had put forward. Stimson pretended to be unconvinced. It was then, it appears, that Mr. Churchill, in his characteristically magnanimous way and as a supreme gesture of good faith, put forward the proposition, later to be formalised in the Quebec agreement, that full collaboration should be reopened and the matter of post-war applications be left entirely to the discretion of the American President.

Instead of getting better, matters got worse after the Stimson talk.

"We were greatly worried", Lord Waverley told me, "because the basis for exchange that we had previously had was clearly in the process of being withdrawn." It got to the point where the President telegraphed Churchill suggesting that he should send over one of his top men to sort the matter out. Waverley agreed to go and immediately got in touch there with Dr. Bush and Dr. Conant and General Groves, the head of the Manhattan District Project. Waverley took with him as personal adviser Mr. Gorell Barnes from the Cabinet office. Together they framed the heads of the agreement that was signed in Quebec a month later.

The agreement, typed out on Citadel notepaper, showed how far Great Britain was prepared to trust her American allies. In the cold light of history it may seem a little naïve. Its phraseology is revealing. "Whereas it is vital to our common safety in the present war to bring the Tube Alloys project to fruition at the earliest moment," it starts, "and whereas this may be more speedily achieved if all available British and American brains and resources are pooled; and whereas owing to war conditions it would be an improvident use of war resources to duplicate plants on a large scale on both sides of the Atlantic and therefore a far greater expense has fallen upon the United States; . . ."

It was agreed never to use the weapon against each other nor against third parties without each other's consent nor to communicate any of the information gained to third parties without mutual consent. The fourth clause, and from some points of view the most important, stated that in view of the great burden falling on the United States the British Government recognised that any post-war advantages of an industrial or commercial character should be dealt with as between the United States and Great Britain on terms to be specified by the President of the United States. The Prime Minister expressly disclaimed "any interest in these industrial and commercial aspects beyond what may be considered by the President of the United States to be fair and just and in harmony with the economic welfare of the world".

In exchange, the Quebec agreement arranged for the setting up of a Combined Policy Committee on a fifty-fifty basis to keep all sections of the project under constant review and to settle any questions that might arise on the interpretation of the agreement.

It specified that there should be "complete interchange of information and ideas on all sections of the project between members of the Policy Committee and their immediate technical advisers".

In the vital field of scientific research and development there was to be a "full and effective interchange of information and ideas *between those in the two countries engaged in the same sections of the field*". The italics are my own and are there to emphasise a clause that was to give the Americans their excuse to exclude the British from information on all vital production techniques. If the Americans were producing the nuclear explosive, they were to argue later in justification of their action, then there was no need for the British to produce any, and if the British were not engaged in production, then there was nothing in the Quebec agreement to authorise the passing over of information.

Lest there should be any doubt in this direction, the last clause of the agreement specified that in the field of design, construction and operation of large-scale plants, interchange should be regulated "by such ad hoc arrangements as may, in each section of the field, appear necessary or desirable if the project is to be brought to fruition at the earliest moment". Any such agreements had to be approved by the Combined Policy Committee which, on the American side, consisted of Dr. Bush, Dr. Conant and the Secretary of War, Mr. Stimson, who had already shown himself to be unhelpful in this respect.

The agreement was signed by President Roosevelt and Mr. Churchill in the Citadel of Quebec on August 19, 1943. It was essentially a war-time agreement. Between two allies both acting openly and in good faith it provided the basis of an effective partnership.

There were many good arguments in favour of the doctrine of "compartmentalisation" which the agreement recognised. It is a sound security tenet, recognised on both sides of the Atlantic, that highly sensitive information should not be disclosed to any person who does not need it in the performance of his duty.

The effectiveness of the doctrine stands or falls on the way in which it is implemented. With her limited manpower Britain herself could not afford to create a vast number of completely watertight compartments and it would not have been economic to do so. In America there were many examples where a tremendous amount of effort was wasted by compartmentalisation, because of barriers which prevented information acquired but not needed by one department from flowing freely to other departments where it would have been invaluable.

Its effectiveness, on the other hand, is demonstrated by the fact that many men in Britain carried out important research work for people like Professor Chadwick without ever knowing the purpose for which that work was intended. In America, at Los Alamos, many workers who fondly believed at the time they were working on the uranium or plutonium bombs only discovered years later that their calculations had been quite clearly required and used instead on development of the hydrogen bomb.

It could, however, be exploited to extract the maximum information from the British in the scientific fields where they were working, without conveying any obligation whatsoever on the Americans to pass to the British the technological information they would need to develop an atomic energy project of their own, either for defence or to set her peace-time economy on a permanently stable basis in the post-war world.

It is interesting to speculate on what would have happened if Mr. Roosevelt had lived. The agreement was a secret one and was only made public by Sir Winston Churchill in April 1954. Americans, of course, abhor secret treaties. They cut right across the powers of the legislature to question and amend or approve. It is most unlikely that formal agreement, open to such debate, could ever have been reached in terms as favourable to Britain. By mid-1943 the Americans had really sucked most of our ideas. The basic anatomy of the project, even of the bomb itself, was known. The Americans had an enormous construction programme under way to put these findings into effect.

While the Quebec agreement has been criticised by some in Britain because it depended entirely on good faith and on what a President of the United States considered "fair and just", it must not be forgotten that its terms have been much criticised and would have been equally unpopular in some quarters in the United States.

The story goes that General Groves was only informed of the final text of the agreement shortly before it was due for signature, and sent one of his staff officers to Quebec by air in an effort to have it amended. He was too late. As General Groves was the man who had to put the agreement into effect in wartime, this was not a good start and it is perhaps to his credit that he helped as much as he did.

By the time the war came to an end, of course, Mr. Roosevelt was dead. Mr. Truman, a man relatively unknown to the American public, had taken his place, and the Democrats had another election campaign ahead of them. The decision was taken not to publish the text of the Quebec agreement. The Smyth report, "a general account of the development of methods of using atomic energy for military purposes under the auspices of the United States Government", published in August 1945, gave no hint of its terms.

In the year that followed, two Bills on the control of atomic energy were debated by a Congress completely unaware of the terms of the agreement with the British and Canadians by which they were at least morally bound. The McMahon Act, forbidding the passing of information on power production or weapons or the transfer of fissile material to any other country, was drafted, debated, passed by Congress and signed by Mr. Truman.

Senator McMahon, who had drafted the Atomic Energy Act, to his great embarrassment, was only shown the text of the Quebec agreement after he had accepted chairmanship of the Joint Congressional Committee on Atomic Energy. The same applied to Mr. David E. Lilienthal, who was appointed chairman of the newly established Atomic Energy Commission.

Why did Britain keep quiet herself and watch in silence an Act passed by Congress which made no distinction between countries like Britain and Canada and our late enemies or those with whom at the time we were engaged in a cold war? It might well have been argued that the terms of the Act about to be passed by Congress so shamefully cut across the spirit of the agreement that they rendered its terms null, including the British obligation to secrecy.

Against this were the equally strong arguments that there was still a peace to be won and that Britain was in no position to win it on her own. The world depended more than ever before at that time on a show of Anglo-American co-operation. There was also the fact, undoubtedly to be taken into consideration, that if any row over secret treaties had blown up it might have helped isolationists into power in America with inevitable repercussions in Europe and the world at large.

One of the provisions of the Anglo-Canadian-American agreement was for the sharing of uranium supplies from the Belgian Congo. The story of how these supplies came to be available at all has never been publicised.

Belgium, itself, of course, was occupied by the German armies. Its exiled Government was operating from London. The Congo uranium is mined by what is known as the Societé Minières de Haute Katanga. The general manager of this company, M. Sengier, who was in the United States on a visit, was approached by the Americans, who wanted to acquire the total output. As a senior official said at the time, "they tried to pull a fast one". M. Sengier would have none of it. When he returned to Britain, Lord Waverley approached him with little more success.

Waverley then appealed to the exiled Belgian Government and invited the late Mr. Winant, the American Ambassador, to join the discussions. Winant said he would leave the matter entirely to Waverley. The outcome of the talks was extremely satisfactory, and Sir (then Mr.) Anthony Eden signed with M. Spaak, the Belgian Foreign Minister, and M. de Cleeschauwer, the Minister for the Colonies, the agreement under which the Manhattan project got the bulk of its supplies.

One happy result of the Quebec agreement was the closer and fruitful co-operation that sprang up between the British and the Canadians. During the initial period Waverley had got the Americans to agree that the British side of the Combined Policy Committee should include a Canadian and that Canada should be considered as sharing the British side of the agreement.

Mackenzie King, the Canadian Prime Minister, viewed the idea, I understand, with mixed feelings when it was first suggested to him. Waverley had put to him that atomic energy was a big and coming thing and had offered to make the Canadians equal partners. The suggestion was that Britain should supply a large proportion of the scientists and pay their salaries, while the Canadians would be expected to pay for the expenses locally incurred by the work.

Mr. Mackenzie King was inclined to be suspicious at first, and so was his ministerial colleague, Mr. C. D. Howe, and both were reluctant to commit themselves to an enterprise that no-one could see an end to. In the end they agreed, however, and the Anglo-Canadian co-operation in this sphere matured and the joint establishments in Montreal and at Chalk River, 120 miles from Ottawa, grew into installations of very great importance that were to play a vital part in the birth of Britain's own post-war project.

As a further result of the Quebec agreement, teams of scientists started moving over from Britain to the United States so that they could make a more direct contribution to the main bomb project. Professor Chadwick was established in Washington as scientific adviser to the British members of the Combined Policy Committee. His staff was joined by Niels Bohr, who, under the code name of "Mr. Baker", had been smuggled first to Sweden and then to Britain.

To Berkeley, California, one of the principal centres of nuclear research in America, went Oliphant, Massey, Allibone and Wilkinson. Emeleus and Baxter went to work on a plant for the separation of uranium by an electromagnetic method, while Frisch and Bretscher went to the weapons research establishment at Los Alamos, New Mexico, where they were joined later by Peierls, Penney and, from time to time, by Professor Sir Geoffrey Taylor, the ballistics expert, and by Chadwick, leader of the group, who spent a great deal of his time in Washington.

The effect of these transfers and others that were made to the project in Montreal was to close down almost entirely all work in Britain on nuclear physics. In the British view the decision was the only proper course to take in view of the decision to give the highest priority to the production of the bomb.

[7]

Nuclear Monopoly

BY THE time the war ended the Americans had built no less than nine atomic reactors. They were, as far as we know, the only atomic reactors in the world. One of them, the very first, had already been dismantled after Fermi had used it to prove that the idea of a "self-sustaining chain reaction" was feasible, using a graphite system.

To be strictly accurate, even this was not the first "pile" of all, for the name itself derived from the fact that Fermi and his co-workers, in their earlier studies, had used piles of graphite blocks heaped one upon another to measure the extent to which the neutrons, the life-blood of the chain reaction, were wastefully absorbed by impurities in the various materials. They had already assembled nine such heaps of uranium and graphite over a period of more than a year, before their measurements told them in July 1942 that it would be worth while trying to build an actual graphite reactor.

When they did so, in a disused squash court beneath the stands of the playing fields of the University of Chicago, it was almost inevitable that this reactor, which worked for the first time on December 2, 1942, should be named by officialdom "C.P.1" (Chicago Pile One).

C.P.2, like C.P.1, was a simple affair. Because there was still hardly any uranium in the metallic form, they both used as fuel the commoner, powdered, compound of the element known as uranium oxide. The heat generated inside C.P.2, ten times as much as in its predecessor, was still only equivalent to that of a single large domestic electric fire. Air was blown through the structure to cool it. Others like it, all of low power, were built at Oak Ridge and at Hanford, Washington, where the first three giant production piles were later located.

Two other research reactors were completed before the war ended; one, C.P.3, was at Chicago, of course. The other was at Los Alamos, where the first atomic bombs were designed and built. It would be most inappropriate to refer to either of these reactors as "piles", however, because in both of them the reaction was conducted not in a heap of graphite blocks but in a tank of heavy water, so called because it is water in which the hydrogen atoms are twice as heavy as normal hydrogen.

It is worth digressing for a moment to see why a "moderator" or operating medium of heavy water or graphite should be needed at all. It will be remembered that natural-occurring uranium had been ruled out early in the war as a possible atomic explosive, because neutrons produced by the fission of the lighter uranium 235 component were gobbled up by uranium 238 before they had a chance to reach another atom of uranium 235. The neutrons, in fact, were absorbed by the uranium 238, which was in turn transmuted by several stages into a new element, plutonium.

Investigations soon proved that the extent to which the neutrons were gobbled up depended on the speed at which the neutrons were travelling. Neutrons of certain speeds were absorbed easily, but when slowed down sufficiently to what are known as "thermal" energies, the absorption was less important.

It became apparent that what was required was some form of system in which neutrons, immediately they had been released by one fission, would leave the mixed uranium fuel elements until such time as they had been slowed down to speeds where they would no longer be absorbed by the uranium 238 and would have a chance of bringing about further fission of uranium 235 atoms that formed less than 1 per cent of the natural metal.

A lattice design suggested itself in which pieces or rods of the metal or of purified oxide were interspersed in some medium that would slow down neutrons by a succession of ricochet collisions. The substances best able to do this would be those containing atoms of the same weight as the neutrons.

The reason for this will be apparent if we think of a neutron for a moment as a perfectly elastic ball. If such a ball, travelling at a great speed, is allowed to collide with a stationary ball of the same size and weight, the energy of the fast-moving one will be shared equally with the other and half the energy of the first one will be lost. The same process would be expected in each successive collision. If instead the fast-moving ball had hit another of many times its own weight it would have bounced off again as if from a hard floor at much the same speed as before and without having any effect on the object it hit and without losing energy in the process.

Neutrons have mass equal to one atomic weight unit and the only other thing that weighs the same amount is the nucleus of the ordinary hydrogen atom. That would have meant using as a "moderator" to slow down the neutrons a substance containing plenty of hydrogen, such as water or paraffin. The difficulty there, scientists soon found, was that ordinary hydrogen itself tends to absorb neutrons of low energies. There is, however, another form, known as heavy hydrogen, or deuterium. This occurs in nature in heavy water, that forms in turn approximately one part in 4,500 of all water in the world, whether it be rain, in the sea, in lakes or rivers, or in the human body. Tests had shown that heavy hydrogen, which already contains one neutron, did not absorb more.

The proportion of heavy water in ordinary water can be increased by a number of different processes which take advantage either of the fact that this substance boils at a temperature slightly higher than ordinary water, or of other slight differences in physical properties. All these processes are expensive and there was only one such plant in the world at the beginning of the war, the Norsk Hydro in Norway, where the process was carried out on a commercial basis.

A number of other light elements were considered at the time. Helium, the next element in the list and weighing four units, was ruled out because it was a gas and formed no solid or liquid compounds. Lithium, the third element, and boron, the fifth, excluded themselves automatically because they absorbed neutrons. This left beryllium, the fourth element, weighing approximately nine units, and carbon, the sixth, weighing twelve. Beryllium was rarely used for anything at that period except in very small quantities in fluorescent lamp tubes and there was little hope of obtaining quickly a sufficient quantity. Carbon instead, in the form of graphite, had many properties to recommend it and it was used in most of the early American piles and also in the British ones that followed.

Heavy water, however, had many advantages, Not only did it "moderate" or slow up the neutrons far more effectively than the bulkier carbon atoms of graphite, thus permitting much smaller reactors with a corresponding smaller investment of fissile material. It was also liquid and needed no careful machining to shape with special expensive tools. It was easier to purify and could easily be cooled on exit from the reactor by passing it through a "heat exchanger", or series of cooling tubes. The first reactor of this sort using heavy water as a medium was C.P.3 (Chicago Pile 3), which operated at very low energy.

The use of liquid moderators offered a further and very important possibility which the Americans tried out for the first time in an experimental reactor known as the Los Alamos "Water Boiler". In this reactor, which provided vital data for the bomb project, the atomic fuel used was a soluble compound of uranium containing more of the 235 form than usual. This for reasons that will be apparent later, permitted ordinary water to be used in place of the more expensive heavy water. The working solution was known as "soup", and it was contained in a stainless steel cauldron in which it was free to bubble or boil.

Even more important technical developments were in the offing, for in 1946 a reactor named "Clementine" was brought into action which was bound to have direct bearing on many of the peace-time problems of producing atomic power. Clementine used pure atomic fuel of "weapon grade". This, for various technical reasons, meant that it could operate on fast neutrons and therefore needed no moderator to slow them down. Lastly, it used for the first time a liquid metal coolant, mercury.

It will be seen that America thus finished the war with a formidable start over the rest of the world in the race for atomic power. Their installations continued to yield valuable information to scientists and engineers during the succeeding years while other nations were groping in the dark.

This American monopoly of atomic energy was short-lived, however, for no act of national legislation could hope to bar the general march of scientific progress. All it could do was to slow it down and cause bitterness between friends.

With the possible exception of Russia, about which there is no precise information, the first country outside the United States to build a reactor of her own was Canada. It is a matter of great pride for Britain that her own scientists took a prominent part in the design of both this first reactor, known as ZEEP (Zero Energy Experimental Pile), completed in autumn 1945, and in its much larger and more important successor NRX (National Research Experimental, finished in 1947. The scientists and engineers did their job so well in fact that for five years or more NRX was the richest source of neutrons and the most powerful research pile in existence anywhere in the world.

Canada's association with nuclear physics, of course, dated back to the days when Rutherford, from New Zealand, and Soddy, discoverer of isotopes, had spent a period at the University of Montreal. Interest had been renewed in the early days of the war when men like Laurence and Sargent in 1942 started performing experiments with graphite and uranium. NRX was to a certain extent an Anglo-American-Canadian project. This sprang from the fact that the fuel for it had to be made available by the Americans.

Canada in fact provided the "hot laboratories" specially suited for work with dangerously radioactive materials during the post-war period, while a similar laboratory was being constructed at Harwell, and ZEEP, the first Canadian reactor, was invaluable in making measurements of the properties of various materials that were being considered for the first British reactors.

Other countries were interested in atomic energy, too. The war-time teams in Canada had, of course, included a number of French scientists, including a team of physicists under von Halban and the chemists under Gueron. Dr. Lew Kowarski, one of the physicists, played an important part in the design of ZEEP. After the war he returned to France to head the reactor division of the newly formed C.E.A., the atomic energy commission of France. To direct the commission the French Government chose Joliot.

Joliot, as most of those who know him will avow, is a born leader. He is also a good business man, as may be judged from the speed with which his pre-war team took out patents for atomic reactors, along much the same lines of some working today, a year or so before Fermi got the first Chicago pile to work. But Joliot was passionately devoted to Communism and his commission soon became full of Communists. When, in 1950, two years after he had been sacked by his Government because of his political views, I visited the atomic energy establishment at Fort Chatillon on the outskirts of Paris, there was still not a room in the old Napoleonic fort that had not its photograph of "our director".

In those early days France had already made great strides. At Le Bouchet, thirty-five kilometres south of Paris, in a disused government explosives factory, she had set up a well-run establishment for processing ore from her uranium mines in the Massif Central and converting it into ingots of pure metal. At Saclay, nearer to the capital, in the open fields, the foundations were being laid of a model research establishment which, but for its size, would have vied with any in the world. The foundations were already laid for P-2, a much more powerful pile capable of producing significant quantities of the atomic fuel and explosive, plutonium.

True, there were no signs of the giant atom-smashing machines of the British and American universities and atomic establishments, but there was the enthusiasm and a great scientific tradition pervading the work, which promised well for the future if the material means were not lacking. With two piles in action, one of zero energy and another of 4,000 kilowatts, she has the useful basis for further steps forward. Two plutonium-producing reactors, one due to be finished in 1957 and the second in 1958, will, after a "cooking period" of several years, provide her with the sizeable quantities of fissile material that she will need for advanced industrial reactors and for weapons should she decide to direct valuable supplies in that direction.

Post-war development in the atomic energy field are not limited to the four major participants in the war-time project, and Russia. Almost every civilised country in the world formed its own atomic energy organisation after the war and many of them have made considerable progress. If Britain, Canada and France, who after participating in one way or another in the giant war-time atomic bomb project still felt in the dark when the war ended, it may well be imagined that things were far more difficult in countries like Norway and Sweden, Holland and Belgium and Denmark.

Two of these countries, Norway and Holland, decided to tackle the problem together by setting up a joint project at Kjeller in Norway, in 1950, under an astrophysicist, Dr. Gunner Randers. They completed their first reactor, known as JEEP, in the following year, using heavy water made by the famous Norsk hydro plant at Rjukan, and uranium that Holland had purchased from Belgium for the purpose in 1939. Setting a fine example to other countries, they declared that none of their work would be secret and at once invited scientists from Italy, Sweden, Switzerland, Yugoslavia, Norway, Holland and the United States to join them. The task of all these countries and also that of Germany has been considerably improved by recent British and American decisions to make available both information and supplies of fissile material.

It is now apparent that not all the smaller countries are content to make their entry into the atomic energy field for peaceful purposes alone. The Commander-in-Chief of the Swedish Army, General Nils Svedlund, on November 1, 1954, announced that during the next ten years the Swedish forces would be modernised and equipped with tactical atomic weapons and robot weapons. About £36 million, he said, had been reserved for the new weapons, increasing Sweden's arms expenditure to £189,300,000. Costs, he claimed, would be cut down by reducing the army's share from 41 per cent to 34 per cent, and the navy's from 20 per cent to 17 per cent. The air force's share would go up from 32 per cent to 37 per cent. Heavier armament and greater fire-power, especially in the anti-aircraft equipment, were promised.

The announcement is interesting for a number of reasons.

First of all, the boast that armament would include tactical atomic weapons clearly shows that such weapons are no longer the prerogative of a few countries with a great deal of research and development facilities at their disposal. The Americans had given the impression that the tactical or lightweight, easily delivered weapons that they had developed depended on a succession of atomic tests of which there have been to date more than fifty. We have no precise information of the nature or the efficiency of the American weapons, but it is of significance that a small country like Sweden should boast its ability to produce such weapons before ever it has made a test at all.

It is possible to go a little further than the announcement by General Svedlund and to say that it would be no surprise at all if Sweden and any other small country like Sweden were to announce their intention of making hydrogen or super-bombs as well. Experts with whom I have spoken tell me they see no reason why improved thermonuclear weapons, easier and cheaper to make, such as are now being produced in the United States, Britain and Russia, should not in time be made and used equally successfully by the Swedes or any other country with comparable scientific and industrial resources.

[8]

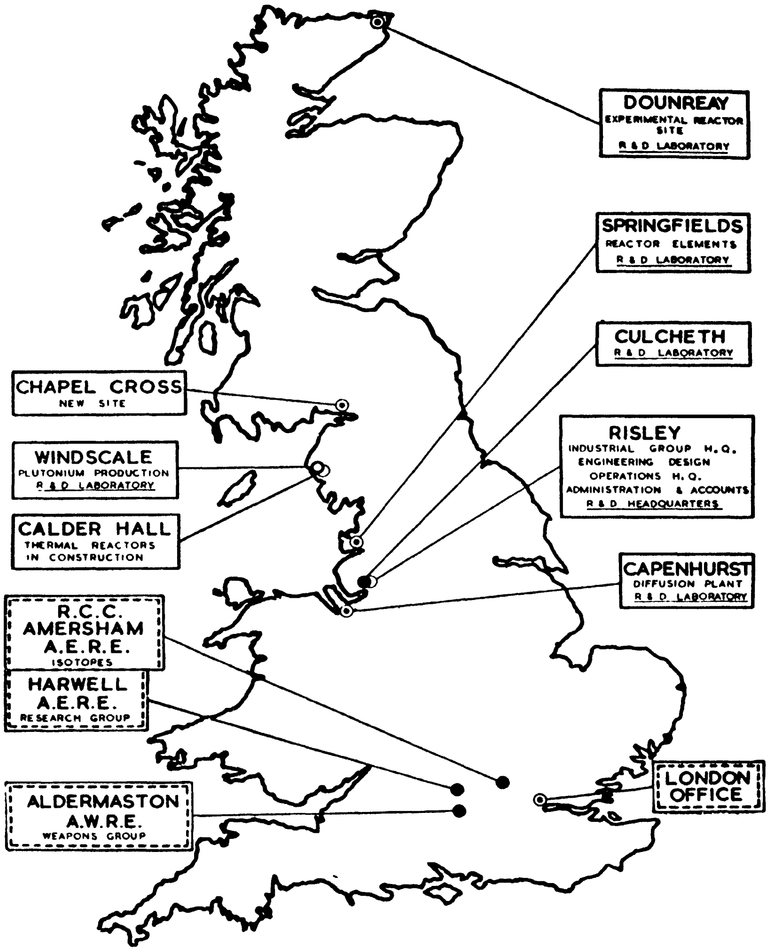
Harwell is Born

IT WAS clear long before the war ended that Britain would need to have an atomic energy project of her own at the close of hostilities. She could not continue to depend entirely on the laboratories in Montreal and Chalk River. The idea of setting up a British establishment was first mentioned, according to Sir John Cockcroft, at a discussion in Washington in November 1944. Akers, director of the whole Tube Alloys project, had come out from London. Chadwick, head of the mission in Washington, was there. Cockcroft himself, who had replaced Halban as chief of the Anglo-Canadian project, had come over from Montreal, Peierls from Los Alamos, Oliphant from Berkeley.

The first requirement, they all agreed, was a research establishment. Their plans were not extravagant and afforded little justification for American suggestions that the British were only interested in post-war commercial developments.

"We thought we would set up an establishment on a modest scale with a pile and a Van de Graaff machine (an atom-splitting device) and a few other tools of nuclear physics", Sir John wrote later. "The recommendation was passed to Sir John Anderson and his consultative council and during the summer and autumn of 1945 the plan was further elaborated in England.

"We considered the desirable conditions for the future establishment", says Sir John. "It had to be not too far from London; there should be easy access to a major university; there should be some degree of isolation, and lastly, the country-side should be pleasant to live in."



Atomic research or production establishments are bringing new traditions to widely scattered towns and villages in Britain. Some of them, like those of Windscale and Dounreay, are in sparsely populated areas with few industries. Others, like Risley, have had to be placed near existing industrial centres.

It was obviously desirable that they should start with a prepared site, with roads, services and some permanent buildings, and Lord Cherwell suggested they should look for a suitable R.A.F. airfield. So, in a hurried visit to England in the autumn of 1945, Professor Oliphant and Sir John Cockcroft looked at airfields. Most of those suggested had very temporary buildings and offered little advantages over open sites. "We were left with a short list of Duxford, near Cambridge; South Cerney, near Cirencester; Benson and Harwell. Duxford, in spite of the great advantages of proximity to Cambridge, was voted to be too inaccessible to most universities and there was not enough water available. South Cerney was an attractive airfield but somewhat too isolated."

In the end they asked for Harwell, Sir John tells us, and "on a windy day of February 1946, on a flying visit from Canada, I was able with Skinner and Fisher to look closely at our heritage".

Those who, like Cockcroft, Skinner and Fisher, remember their first reconnaissances of that lonely aerodrome in Berkshire, must find it hard to reconcile their memories with the establishment that now occupies the same ground and contains equipment of variety and complexity that few if any would then have dared to contemplate.

Within the 300 or so acres now occupied by the establishment, there are known to be six atomic piles. There may well be others that have never been talked about. But atomic reactors only tell one small fraction of the whole story.

There are nineteen divisions altogether at Harwell, and between them they range over the whole field of nuclear research and technology. They include departments of chemistry and of engineering, of electronics, chemical engineering, health physics, isotopes, medicine, metallurgy, and various divisions of theoretical and applied physics. Many of these divisions are the size of large university research schools and each is under a head who enjoys status comparable with that of a university professor. Side by side with the atomic energy establishment, but outside the security fence, there is the Radiobiological Research Establishment of the Medical Research Council, which investigates the effects of nuclear radiation and a thriving atomic energy instructional establishment that is attended by students from almost every country in the world.

The first glimpse the visitor catches of Harwell, if he knows what to look for, is the tip of the 200-foot chimney of BEPO, the biggest of the establishment's reactors. It can be seen over hills and houses when you are still five miles or so from the establishment. On drawing nearer, the buildings suddenly come into view as an untidy and motley cluster of prefabricated houses and huts, one-time aeroplane hangars, and the typical brick buildings of a modern aerodrome. Here and there, in sharp contrast, can be seen pleasant new buildings of modern and more enlightened design which will blend well later with the well-kept lawns and shrubberies and 10,000 or more trees that have been planted in the grounds since the scientists arrived.

Harwell was officially taken over from the R.A.F. on New Year's Day, 1946 by an administrative Civil Servant, Mr. A. B. Jones. The only officially allocated member of his staff, he tells me, was an extremely competent secretary named Betty Hillen. From the R.A.F., however, he inherited four drivers, a carpenter and a handful of labourers. Days later he found he had one more man on the roll, a watchman on a nearby dump who had been completely forgotten about at hand-over time. There was no transport and no cash.

Every now and again a lone aeroplane, ignoring the large white crosses painted on the landing strips, would alight on the airfield and its pilot would express great astonishment at finding the place "gone to the boffins". When building began in earnest and the public came to hear of the new developments at Harwell, so many pilots landed with trumped-up and at times quite fantastic excuses about engine trouble and the like that the security men began reporting them to the Ministry of Civil Aviation and asking for disciplinary action.

But at this stage of the proceedings the really interesting work was going on 4,000 miles away at Chalk River and in Montreal, for it was on the teams in Canada that Britain had to depend for the early planning of her own atomic energy project.

At Chalk River the joint team was already engaged in designing the large heavy water pile, NRX, and in working out the complicated chemical techniques that would be necessary. After the Washington meeting, and immediately the decision was taken to set up a post-war research establishment in Britain, a new group was set up to design a large graphite reactor for the British project.

Those early days in Canada, when telegrams were whizzing backwards and forwards across the Atlantic in an effort to make arrangements for the new establishment, were not without their lighter moments. The fine establishment that now stands at Chalk River, 100 miles from Ottawa, was still in those days a Red Indian settlement. Accommodation at Deep River nearby was primitive, and the only people who could be persuaded to work there were the British and French, a fact which was quickly ascribed by them to the lack of central heating and other facilities to which the Canadians were accustomed.

The prefabricated bungalow where the small team lived, which served as a night stop for visitors, was christened the Ipswich Arms in recognition of the fact that its "curator", Fred Fenning, one of the reactor physicists, came from East Anglia. At that time the entire staff at Chalk River were able to travel to and from work in a single station wagon. The team soon grew, however, and the number of bungalows increased as men from Canada, New Zealand and more from Britain arrived on the new site.

An anonymous writer in *Harlequin*, the Harwell magazine, tells how some of the scientists bought what for Canada was an ancient Pontiac of 1934 vintage. It was "a trifle passée but every inch a lady" and was christened Priscilla. The tyres had seen better days, it was true, and the transmission suggested that at least a part of its life had been spent as a taxi. The door by the driver's seat had a habit of opening at unexpected times, but, the writer tells us, as the opening of a door is commonly used over there as a signal for turning, it merely looked as though the driver was proceeding in an agony of indecision.

The decision that the first pile to be designed by the Anglo-Canadian-French team would be a heavy water reactor, NRX, was only taken after a great deal of discussion. Auger, the French scientist, who is now chief of the science department of UNESCO and a member of the French Atomic Energy

Commission, had wanted to build a graphite one. Other members of the team favoured one of heavy water but they could not get enough. By this time, however, the heavy water plant established by the Americans had come into production. The Americans were consulted. They had no large heavy water pile of their own at the time and were glad to have the joint team explore the project. An agreement was signed between the United States, Canada and the United Kingdom whereby the Americans agreed to supply heavy water, the Canadians provided money and Britain provided scientists.

The design team worked fast, and construction of the reactor started on the Chalk River site in 1944. In the meantime, in order to have a reactor ready as soon as possible, work had started on a much smaller pile, ZEEP, and by the time this was finished in the summer of 1945 the main NRX pile was largely built, but because of a whole host of minor engineering troubles it was to take a further thirty months to make it work. NRX functioned remarkably well until December 12, 1952, and enjoyed undisputed pride of place as the most powerful research reactor in the Western world. An accident occurred on that day and the reactor had to be dismantled. The task of making good the damage and reassembling the reactor took two years. It provided most valuable experience on the repair of radioactive plant, and when the task was completed the reactor was considerably more powerful than before.

In part at least responsible for difficulties with NRX was the fact that Britain was by then forming her own atomic project and there was a continual change-over of personnel in the British component of the Commonwealth team. So far as the British project was concerned the choice of an initial reactor was limited to the question of whether it could be a small one or a big one. There was no likelihood of getting more heavy water from the Americans and there was no other source large enough. It was therefore decided to go ahead with the design of BEPO (British Experimental Pile), an air-cooled graphite-moderated pile large enough to supply the various radioactive materials needed for scientific research for industry and medicine.

The men entrusted with the task included Newell, now back at I.C.I., Volkoff, now a professor in British Columbia, Kowarski, the French scientist, Pryce, now a professor at Bristol, and Guggenheim, together with Tongue, Dunworth, Rennie, Bunemann, Whitehouse and Fenning.

From the point of view of designing processing plant to deal with the used fuel, the most troublesome complications arose from the presence of the highly active fission products than from any chemical difficulty. There were several processes that could be used for separating the uranium and plutonium. The question that had to be decided was, which of them would be the most efficient under the conditions of remote control that would have to operate for the protection of personnel. It was known that the Americans had favoured a method known as "precipitation", but they had jealously guarded the details. A chemist named Dr. R. Spence was given the task of finding the answer.

Spence was a young man, he must have been forty at the time, a good chemist and full of enthusiasm. Because there were no "hot laboratories" in those days of late 1945 in Britain, he worked in Canada, first in the laboratories at Montreal, where much work had been done throughout the war by a mixed team of British, Canadian and French scientists and later at the Chalk River laboratories.

My first meeting with Dr. Spence provided me with a big surprise. I had gone down to Harwell to see him and had been warned to expect a shy man.

His office was in a new brick building that faced out across a barbed-wire fence and overlooked the old airfield. A great aluminium chart picked out with coloured lights met me in the entrance hall. It was the elaborate but rarely used "hot" laboratory alarm system. I found another just like it in Spence's own anteroom. On it was shown a floor plan of the entire laboratory, each room picked out with two electric lamps, one red for fire, another blue to indicate an accident involving radioactive materials.

Spence came out to meet me as I hesitated on the threshold, flung out a large hand and gave me a welcoming handshake. "Well," he queried, "what can I tell you?" It was a good start, and I told him I was curious to know how any team could design a chemical plant worth £20 million or so on the basis of experiments done with an almost invisible quantity of plutonium. "It was not easy", he told me. "But that was all we had so we made the best of it."

It would be hard to exaggerate the difficulties of the separation process that would be needed to extract plutonium from the slugs of uranium once they had been irradiated in the atomic piles. Pure plutonium is very much like pure uranium, and both look very much the same as nickel or silver. While they are different chemically from each other, they are too much alike for the process of separation to be anything but a very complex one. It was, as the Smyth Report on the development of atomic energy for military purposes stated, "a problem of separating at a daily rate of, say, several grammes of plutonium from several thousand grammes of uranium which was contaminated with large amounts of dangerously radioactive fission products comprising twenty different elements". The problem was especially difficult because the degree of purity required was very high indeed, and the cost and importance of the material meant that wastage must be cut down to an absolute minimum.

The Americans, instead of telling the Canadians the methods they used, offered instead to pass over a limited number of uranium fuel slugs that had been irradiated in the pile at Clinton. The idea, from their point of view, was a good one. There were still no final ideas on the best method for separation and there was always the chance that the teams in Canada might produce something better than they had. The Anglo-Canadian team, for their part, were grateful. The supplies from Clinton, though meagre, were just enough to allow the Montreal laboratory to work out the necessary chemistry. The amount of plutonium in a fuel element depends always on the amount of time that it has been irradiated. In those early days the period was necessarily short, and often only two or three thousandths of a gramme could be extracted from a single "slug". It was a small but valuable amount and it provided the basis for working out a process.

Dr. Spence told me of the extreme lengths to which they went to conserve these stocks. "By the time the U.K. team was ready to start on its own project", he told me, "we had assembled enough for our purposes. We did this by deputing four of our little team exclusively to the job of initially extracting the plutonium from the fuel elements by a fairly straightforward process, and then, after we had finished with it, of extracting it again from the many different sorts of residue resulting from our experiments."

"We used to work in such a way that we ran through our process in the same time scale and with the same concentrations we hoped to use in the British plant. The amount present in the Clinton slugs, of course, was far less than we hoped to have after long periods of irradiation, so we had to concentrate it and work with very small volumes in order to cut out at least one of the many sources of error in our work."

The British workers had altogether for their work only twenty-five thousandths of a gramme of plutonium, not more than would cover a pinhead. They used about half of this in "one run".

The Americans learned through their liaison officer at Chalk River that the British had developed methods different from their own. "We thought it would do quite a lot of good for them to know we could master the problem on our own and that this might make them more ready to collaborate with us", said Dr. Spence. "They, in their turn, saw that we had a process and thought it would be profitable to learn more about it."

As a result, collaboration in the chemical field, which had ceased in 1942, reopened just a little in 1948. The Americans invited the British and the Canadians to join them in a conference on processing at the Argonne National Laboratory.

"The exchange showed that in general principles the flow sheets were amazingly similar although in detail quite different. The exchange was valuable to us, too, but it was and still is limited to discussion on chemical and chemical engineering principles up to and including the pilot stage. It does not include major chemical engineering processes."

Back in London at Shell-Mex House, home of the Ministry of Supply, a small nucleus of workers were submerged in drawings, plans and schedules, research contracts inherited from the old Tube Alloys organisation, and by streams of letters, telegrams, phone calls from men and women enquiring about chances of working in the project. Mr. D. R. Willson, the secretary at Harwell, whose writings in *Harlequin* are a mine of information on those early days, records how the rising tide of applicants, in fact, threatened almost to engulf the organisation as it struggled to place new men while sorting out the future of others who were by now returning from America and Canada. Grades and salaries had to be fixed and accommodation in many cases had to be arranged.

Harwell, it must be remembered, was in the "wilds" of Berkshire. You could not just plant a few thousand scientists, engineers, secretaries and the like at the side of the road and leave them to make their own arrangements. In February 1946 a conference was summoned to talk the matter over and to try and make some sort of assessment of the accommodation and other administrative requirements, and numbers of prefabricated houses were ordered. There were such things as stores to be thought about, also, where people could do their shopping, and transport to get them to the nearest village some miles away.

By the autumn of 1946 the site had already been transformed. R.A.F. blocks were being turned into laboratories, hangars were being adapted to house large instruments and machine tools, and everywhere there were deep trenches being dug to house the various service pipes and drains, so that travelling within the perimeter became a continual hazard. The security fence was at that stage more symbolic than functional.

Martin Fishenden, now head of the Division of Scientific Administration, recalls a day during that period when, as a visitor, he called on the establishment and filled in the various passes and forms at the police post near the main gate. He passed the night with friends working at the establishment in their prefabricated bungalow outside the fence. The following morning, having become initiated into the domestic secrets of the establishment, he made an informal entry through a hole in the fence.

As Wing-Commander Henry Arnold, the establishment's chief security officer, pointed out, a scientifically qualified

Russian spy could have found out very little at that time about their intentions if he had toured the establishment.

Arnold, the man who was instrumental in unmasking Fuchs, the spy, is a man whose extreme restlessness picks him out at once. Thin and wiry, his eyes are always alert and he has a good sense of humour and lives up to his belief that the secret of being a good security officer is to be a good mixer. His father was a professor of the violin at the Royal Academy of Music in London and used to like playing the cello and the piano, too.

Arnold went early into the Bank of England in 1911, but when war broke out he joined the Royal Flying Corps as a scout, the early equivalent of a fighter pilot, in 32 Squadron at Ypres. He was shot down in 1917 and went back as an instructor afterwards until the end of the war. He returned to the Bank of England on general tasks of auditing the bank's accounts, and when the war broke out again was senior superintendent of the bank's audit department. In World War II he went into Intelligence and became chief security officer at the Ministry of Aircraft Production and in addition had the task of covering the preparations for the bombing of the German dams. Afterwards, he returned to the Bank of England and while there was asked if he could suggest names for a chief security officer for Harwell. He put up several but the Ministry of Supply finished up by asking him if he would undertake the job himself, and he agreed to do so.

Arnold has no regrets. He likes working with the atom men, he tells me, and from what I could gather the atom men like working with Arnold. They have in him a man who quietly, tactfully but quite firmly perseveres at his task without causing bad feeling or an undue feeling of restriction.

* * *

I saw a lot of Martin Fishenden. As chief of scientific administration he accepted the task of making arrangements whenever I asked to meet one of the scientific staff. His task at Harwell is an extremely responsible one. He is also personal assistant to the director.

Fishenden's mother is a "don" at the Imperial College of Science in London, working on heat-transfer problems. His father compiles *Penrose Annual*, journal of the printing trades. Martin himself is married to an artist of some distinction who is responsible for several paintings in riotous colour that break up the dreary Ministry of Works distemper on his office walls, and they have two children, a boy and a girl. He came to Harwell from radar work at the Telecommunications Research Establishment, Malvern, in the rather ordinary grade of senior scientific officer. He wears sports jackets, hates being quoted, and to the outsider gives the impression of continually striving to be just like everybody else.

He has straight black hair and is somewhat dark-skinned. Although he is in his middle thirties and often wears a heavy frown, there is a suggestion of the schoolboy in his face that is emphasised when he grins. He loves fast cars, had an Aston Martin at T.R.E. and now drives a 1½-litre Riley that runs away with most of the prizes in cross-country races arranged by the establishment staff. One of his secret "vices" is said to be that of standing for long periods on railway bridges noting particulars of passing engines, and his colleagues are much amused by cryptic postcards that reach him from friends travelling abroad and tell enthusiastically of record runs in continental expresses.

One of the men that Fishenden took me to see was Glasgow-born Dr. H. M. Finniston, forty-two-year-old chief of the Metallurgy Division. The group of untidy-haired, serious youths in the early twenties who were discussing a point with him over cups of tea in his roomy office when we arrived might have been any tea-break group of graduate students in a university research department. Finniston's full Glaswegian tones could easily be heard above the rest. He motioned me to a seat at a boardroom-sized table and swept away the cups in one wide gesture of his large hands. Several of the group tried to pin him down to a time for further discussion of one of their problems but he deftly evaded the move.

"One of our chief problems here", he said, turning to me, "is that everybody in Atomic Energy is extremely hard-driven. We are trying to compress the time-scale in which everything is being done. If you consider that in something like ten years we have moved from the point where we had nothing at all to one where we are introducing plans to spend £300 million you can see we are moving something. I think, sometimes, that we should stop and think whether we are backing the right horse or not. Mind you, I think we shall succeed, but we may be rushing too quickly on the grounds that we are largely ignorant of what is round the corner. And by taking the easiest and more obvious path we may be side-tracking ourselves from the main stream on which it will develop in ten years' time."

At that moment he caught my eye searching the wall for the customary clock that adorns the wall of almost every Harwell room. "I won't have a clock", he told me, shaking his head of curly, greying black hair. "Clocks are nothing but a nuisance. I told them to leave my office without one. You cannot time work of this sort."

One of Dr. Finniston's big headaches is the devising of fuel elements for reactors that will permit longer periods of irradiation and higher working temperatures.

"The problem that you are faced with is this," he told me, "that you start with a piece of uranium metal that consists of two sorts of atoms, one of which splits into two new atoms when fission takes place. These new atoms or fission products go hurtling through the solid metal disrupting the lattice and creating a disorder which has profound effects on the material. Although the new atoms are each only about half as heavy as the original atom, they still occupy approximately the same space, so that even when they come to rest the problem still remains that you have got to find space for two atoms where before there was only one."

Finniston went to his blackboard and drew on it what looked like a lot of closely packed cells in a honeycomb, to demonstrate how the fission process set up stresses within the fuel rods.

"The new atoms that you now have are a very different type of atom from the ones you started off with", he went on. "You are in fact forming a very complex alloy. In some cases, where the newly formed atoms are gases like xenon and krypton, you have a further complication." There may be so much gas trapped in the uranium that a given piece occupies 40 per cent more volume than before.

Uranium and plutonium have the further peculiarity that they are "anisotropic" in certain ranges of temperature. That is to say, they may have different physical properties in different directions. Uranium may expand in one direction, for example, when it gets hot and contract in another, which is a most unusual phenomenon. Even these properties are not consistent over the whole of its solid state, since each of these metals passes through a succession of phases in which it behaves quite differently.

Uranium goes through three such phases, the alpha, beta and gamma phases. Plutonium, instead, has six, and within each of these separate brackets the behaviour of the metal is completely different. Both metals are extremely reactive with the atmosphere and with water when they are hot.

"What you have to do, if you are using solid fuel, which is the usual form, is to put the uranium into a can with which the fuel itself will not react and which will not burst under the various radiation effects. Over short periods of irradiation this problem is being solved, but when you begin to consider long burning periods the problem of radiation damage becomes one of the first magnitude. To find out more about this we have to leave rods in for varying periods under careful observation and then examine them to see what has happened.

"You see how big our task is and why I talked about rushing it, when I remind you that we are carrying out here a thorough investigation of the properties of six metals new to technology and of phenomena new to engineers and metallurgists. No normal industrial organisation would be asked to carry out such a task. There are research organisations that concentrate on iron and steel, on aluminium or copper. The task we have is that of investigating the properties of at least two sorts of uranium, of plutonium, zirconium, beryllium, niobium, vanadium and, of course, any other metals that physicists or engineers think may improve reactors."

Finniston warmed to his subject. "Just think of the conditions under which we work. Before you can examine a metal specimen under a microscope in a normal laboratory you need to machine it and polish it and probably etch it with acid. Throughout all these operations you have every opportunity of easy manipulation.

"Many of our specimens are so toxic that before we can work with them at all we have to wear special protective clothing from head to foot and operate in sealed boxes through gloves. Remember, Bertin," he went on, "it can be dangerous if we swallow only a tiny speck of plutonium dust. Once a specimen has been in the pile we can no longer deal with it directly.

"Machining, polishing and etching must all be done under the most trying conditions of remote control behind ten-inch-thick lead shields. Any man who attempts to examine such specimens through a microscope would lose his eyes."

At Harwell they use television instead for such work. Again, where a research scientist in a conventional laboratory would examine the properties of a metal with the aid of equipment mounted on the usual laboratory bench, experiments on metals used in the construction of atomic piles have to be carried out at the bottom of a hole forty feet deep and only four inches wide that reaches down into the very heart of the reactor and down which you cannot look directly.

To meet the needs of some engineers to inspect these centres Ronald Coleman of Pye, who designed the underwater TV camera which first located pieces of the Comet off Elba, produced a new form of remote-controlled camera with an "eye" that can be made to look in any direction. The whole unit was only four inches in diameter. With the aid of such a device the most searching inspection could also be made of structures right inside the pile.

[9]

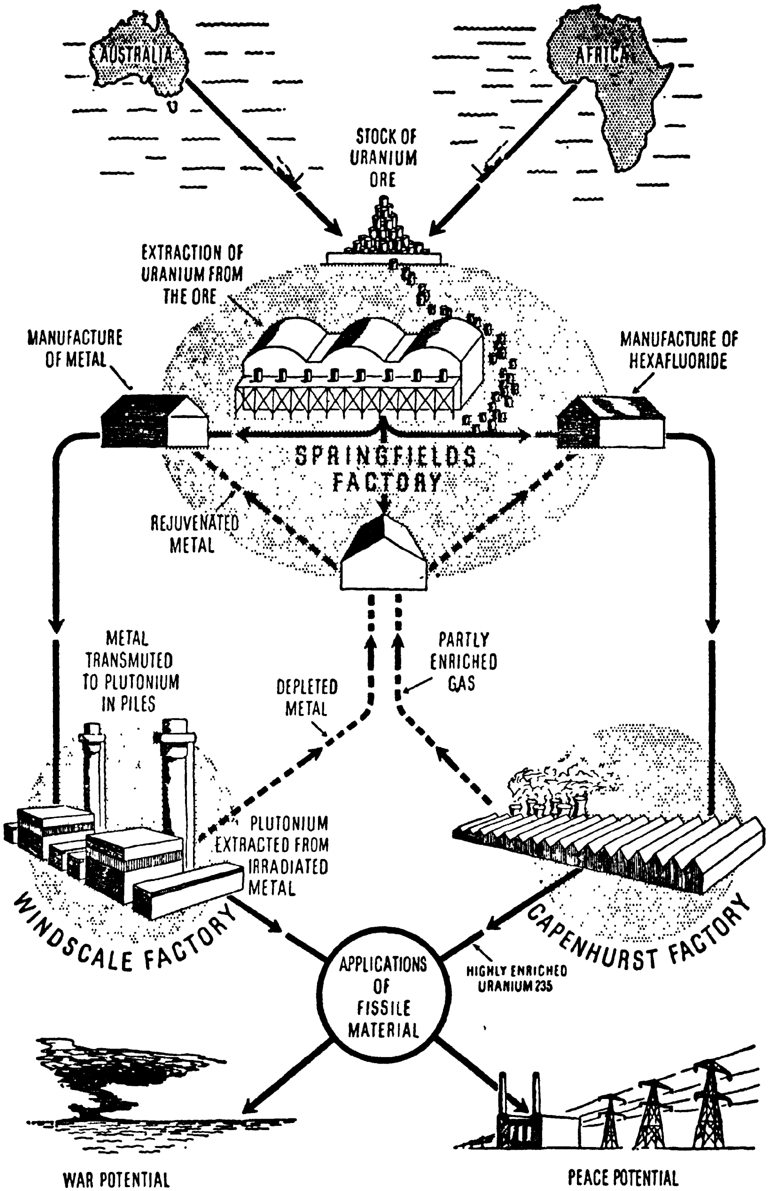
Factories are Planned

IT IS difficult, more than ten years afterwards, to appreciate what it meant in the immediate post-war years to start building a whole new industry. There were shortages of labour and of scientists and engineers, of steel, coal and generating equipment, and of almost all the materials that industry needed. There were restrictions on building in order to give the housing programme a chance, and even hospitals and schools had to wait years for permission to make good the scars of war.

Industrial firms that had been compulsorily confined to the manufacture of weapons and other strategic equipment throughout the war years were busily trying to recruit all the good men they could in an attempt to regain their old markets and find new ones. Overcrowded universities were unable to cope with their insatiable demand for more engineers and scientists.

In the midst of all this industrial reorganisation, on January 29, 1946, came an announcement of the Government's decision to build up a great atomic energy organisation capable of manufacturing nuclear explosive on a large scale. It was an objective that could clearly only be attained at the expense of a vast drain on resources. Firms would have to interrupt newly established production lines to satisfy small orders, unlikely to be repeated, of special machines and unusual materials, and all to unheard-of specifications.

The decision taken was a courageous one and it has since paid dividends, but it is fair to say that no-one at that time had the slightest idea how hard the task was they had set themselves. Basically, it meant, in addition to the setting up of the research



Crude uranium ore must be carefully processed before it can be used as fuel in reactors. The journey is much longer and more complicated when the final product needed is for explosives or as pure fuel for more advanced types of reactor.

establishment at Harwell, the erection of a number of factories where ore from the Belgian Congo would be processed into uranium metal, made into fuel elements, transmuted into plutonium and then made into bombs. On the face of it, and at least to many uninitiated politicians, it seemed as if the whole process had been set out quite simply in the newspapers.

The fact that the initial task of supplying plutonium for bombs was completed on schedule and that the firm basis was laid in record time for peaceful exploitation of atomic power depended to a great extent on a few engineers like Sir Christopher Hinton and Mr. Leonard Owen, his deputy, who provided a driving force that never flagged.

It is, in fact, true to say that the industrial applications of atomic energy in Britain are as inseparable from the name of Hinton as are atomic research from that of Sir John Cockcroft and atomic weapons from that of Sir William Penney. Sir Christopher, who, as one of the Atomic Energy Authority's "five knights",* directs the industrial group, has been associated with the organisation almost from the moment the British Government took its first decision to set up the project.

His fine brain, coupled with a tremendous and unrelenting driving force, have been the main factors in the birth of a great organisation worth hundreds of millions of pounds. No man is entitled to more credit than he for the magnificent and courageous programme of nuclear power production on which the country has now embarked.

Hinton, at the outbreak of war, had been borrowed from I.C.I. by the Ministry of Supply and made deputy director-general of the great Filling Factories organisation, which in six years built up to the point where nine very big factories and seven smaller ones were employing 135,000 people. These factories took empty shells and explosives made by others and filled the cases, preparing all the ammunition, including the big blockbuster bombs, for the three Services. It was a terrific task and Hinton showed himself more than adequate for it.

* The "five knights", the five full-time directors of the United Kingdom Atomic Energy Authority, are: Sir Edwin Plowden (Chairman), Sir Donald Perrott (member for finance and administration), Sir John Cockcroft, Sir Christopher Hinton, and Sir William Penney.

In the latter half of 1945 one of the big jobs of the filling organisation was to run the factories down. It took some doing. As usual with Sir Christopher, it was done to a programme, and this programme let him out of the organisation at the end of 1945.

The Ministry of Supply, however, was already looking round for someone to build up the new chain of factories for the manufacture of atomic fuel and explosives. Sir Christopher, who keeps his own diary, could find no record when I queried him about the first approach that he received. "I think that at the time it must have been too secret to record", he told me. It seems, however, that it was probably in October 1945.

He remembers that he showed interest in the idea. The first entry that referred to formation, still unannounced, of the British production organisation was on December 13. On that day he saw the Director of Establishments at the Ministry of Supply to arrange about starting a London office. Five days later he had his first technical meeting.

The discussion was with Mr. Perrin, who had been personal assistant to Sir Wallace Akers in Tube Alloys throughout the war and was later to carry on the same task for Lord Portal of Hungerford when he was appointed Controller. With Perrin, he went through all that was known of the various processes.

Hinton had still said nothing to Owen, his engineering director and close friend. They were both due to leave the filling factories a few days before Christmas. Owen, who worked at Westminster House in Horseferry Road, recalls the day when he loaded his personal belongings into his car for the last time and drove round to Shell-Mex House in the Strand where Hinton worked. "I gave him a hand to get his stuff into the car and while I was in his office the telephone bell rang", he says. "It was Wilmot, Minister of Supply at the time, asking to see Hinton. After about half an hour he came back and told me we had both been offered a new job. He said it was to build atomic energy factories. I asked him: 'What the hell is atomic energy?' says Owen and he replied that he was not so sure that he knew himself."

Owen recalls how all his reactions were against the idea at first. "We had both had a very strenuous war and we were looking forward to going back to industry."

As they drove from London to their homes in the North, they discussed the matter together. Hinton, who had already had a chance to go into the matter more deeply, says he was already sold on the idea. The one thing he had insisted upon was that he should not be limited in scope to purely military applications.

"What I felt", Sir Christopher told me in retrospect, "was that the Government were obviously setting extreme importance on the development of atomic energy from the defence point of view, and I felt that if on top of that we could put enough skill and energy into it, we could go further. I had asked for and received an assurance that it was not intended that work should be confined to the defence industry alone and that we should be able to build up an industrial organisation. It was always in my mind from the outset that on a sufficient scale it might be of immense importance for the country. I was always out to break into the industrial field, but I think I had certainly realised that it was going to be a hell of a struggle."

In the middle of January a meeting was arranged between Cockcroft, Hinton and Owen. "We were still not keen enough about it all to come down to London," says Owen, "so the meeting was arranged half way on neutral ground in a hotel near the main station at Crewe." To those who know the place as it was then no comment is necessary. Circumstances could not have been less auspicious, but Cockcroft was full of enthusiasm. "He brought out the newness and pioneering nature of the job," says Owen, "which was something that appealed to Hinton and myself."

A few days later the Prime Minister announced in Parliament the setting up of the production organisation under the leadership of Lord Portal of Hungerford. Sir Christopher Hinton (he was still plain "Mr." then) was given the job of designing, building and operating the necessary factories.

"We did several things very quickly indeed", Owen told me. "One was to take this office at Risley. It was one of the biggest of the filling factories. Most of its 1,300 acres had been signed over to the Admiralty for use as their main storage depot in the North. We were just in time to place a caveat on this one corner, a few acres or so. We could have chosen London but office accommodation was not easy to find. Risley had in its favour the fact that it was in the middle of the heavy chemical and heavy engineering industry. We put our claws on the place.

"The next move was immediately to get in touch with some of our old staff. Kendall jumped at it. People like Disney, one of my chief engineers now, jumped at it. Men were also taken on in two or three junior grades. By February 1946 this band of about a dozen moved in here and started looking round for paper and envelopes and the like. Luckily we had food laid on from a Ministry of Supply canteen."

When Owen met Cockcroft he had asked him about literature. Cockcroft told him that he would get a pretty good idea about it all from the Smyth Report. Hinton and Owen examined it together. They both agreed that it was a masterly work. It told them nothing, however, about the way to design the plant they needed.

Owen himself is a Liverpool man. Right through his life his hobby has been sailing boats. He first learned on the Mersey while he was at Liverpool College. Later he was to sail on the "flashes" of Cheshire formed by rivers overflowing into subsidences caused by salt-mining.

When the First World War broke out, Owen joined the Liverpool Regiment. Afterwards, he went back to Liverpool and gained a City Scholarship to the university, the best of the sort that could be got. He secured first-class honours in engineering and went to I.C.I., "taking my sailing with me".

I met Owen first in his office in the atomic energy industrial group's headquarters at Risley. They are a spartan set of buildings, the remains, as Owen said, of one of the filling factories. Most of them were prefabricated huts. There was one single-storey brick-built structure. With a second storey later to be added, it served the senior officers of the group right through until the end of 1955.

Owen's office, like all the rest, had few trappings. The furniture was of the very simplest and there was a water-colour or two on the wall done by architects of the Ministry of Works during the construction stages of the production piles at Windscale. By his table was a group photograph of engineers associated with the first days of the project.

Owen himself was a round-faced man in his middle fifties. He wore heavy horn-rimmed glasses and during the interview smoked continually. "It has been an enthralling job for the engineers who have had the opportunity of building this thing up," he said, "and, while on the subject of engineers, let me tell you, it is a lot of bunk talking of atomic energy as so many people do in the Press and elsewhere as if it was something exclusively scientific. I am not being derogatory about scientists. This sort of thing all started with people like Lord Rutherford, and the whole conception of atomic structure was the result of masterly scientific work, but once you have got past that point it is the engineer, the industrial chemist and the operator who give you the material.

"I will have nothing said against the scientists," he went on, "but the people this country needs most today are the men who can understand what the scientist's idea is and put it into practice in brick, mortar, iron and steel. These are the chaps we are trying to get here, and they are in awfully short supply. We are always trying to get more engineers of the sort who can discuss all the different aspects of the many specialisations, the operations side under Ross, the development side under Rotherham, the scientific side with teams at Harwell, and can chat with the secretarial and administrative types about Treasury considerations and with the doctors about health. Your design engineer takes all this into account. He then takes a decision on how to build whatever is wanted.

"I think you should realise how engineering men like me tick", Owen went on. "Any B.F. can do a job given enough time and money, but the engineer that I am after is one who can build a factory as quickly as possible and as cheaply as possible, and that will produce the goods at an economic cost. He must be able to complete his task within the estimate given to his boss of what it was going to cost and of the time it was going to take."

That statement of Owen's represented the "credo" of the production group. "Anyone who breaks these 'musts' here", he told me, "is in for considerable trouble. I gather people around me who believe in them."

He instanced the task he had been given early in the project of building a factory to produce uranium metal as fuel for the first reactor. "I put a first-class fellow named Turner in charge with the title of Chief Engineer and made him responsible for completing the Springfields factory. The remit received from the Ministry of Supply was to take ore from the Belgian Congo and turn it out as cartridges suitable for the pile.

"The development work was done by chemists of the general chemical group of I.C.I., who were doing the laboratory work. That was in April 1946. Within a month or two, using their chemical flow-sheet, we had got out the first engineering flow-sheet and the first estimate of cost. That was the start. The estimate then went to the Treasury, and said in effect: 'To build this sort of uranium factory we need so much money'. Under me, my chief engineer was entirely responsible, and when I say 'entirely' I mean it."

One of the biggest problems at the time, Owen told me, emphasising the point already made by Dr. Finniston at Harwell, was that of making suitable cartridges for canning the uranium in a way that would protect it from corrosion and would make it last a really long time. The problem still remains. "Give me a good uranium cartridge", he told me, "and I will give you a pile. It is almost as easy as that. The cartridge is one of the main problems of the moment in atomic energy. It is one that we are gradually solving."

Owen said one of their greatest difficulties was getting men. "There are two sorts of good man", he said. "Some have come up the hard way, and some the easy way. The hard way is the working-class home, followed by the serving of an apprenticeship and attendance at night school; the getting of the National Certificate, and then a start in a junior position."

He quoted examples of the two extremes. "Take Harry Cartwright. He got his First in the Mechanical Sciences Tripos at Cambridge, spent several years with the Royal Air Force during the war, and afterwards took a pupillage with English Electric. He came here in the lowest grade of design engineer but quickly showed great aptitude and is now carrying very considerable responsibility."

Owen's face showed obvious pleasure as he told me of a typical example of "the other way". It was that of Jack Tatlock, a thirty-one-year-old "E.1", or Engineer 1st class, who had already gained an M.B.E. for work with the project. Tatlock is a Bolton man, tactiturn and shy, and not at all keen to talk about himself. He came to Risley straight from apprenticeship as a draughtsman in the early days. He worked well and studied hard, putting the job first and his own prospects second.

Tatlock now works under Kendall, the engineer who built the Windscale piles and is engaged now on a far more tricky task, the breeder reactor at Dounreay. He had quickly gained professional qualifications as an engineer, and, says Kendall, "is now one of my best designers". Among his many duties he is secretary of a "design committee" consisting of senior engineers, research and development people and production men. "When the discussion has been getting a bit wordy, I've seen him quietly drive straight into the conversation and sum up the position," Kendall told me.

Tatlock is by no means an isolated case. Owen told me there were many others like him. "The opportunities in this growing organisation far outnumber the men ready to take advantage of them, and the chances of promotion are unlimited."

Owen believes in pushing his men hard, as does Sir Christopher. "If you get the right sort of chaps and form the right sort of team, they will, I think, be quite hurt if you are not pushing them hard. The happiest times", he said, "have always been those when there was far too much to do."

The big complaint now is that the organisation is getting too big. Owen is a firm believer in leadership. "Hinton is an ideal leader with his eye firmly fixed on a star," he said, "but personal leadership can only go through so many people and after that it inevitably becomes a bit remote to some. There was a time in 1946 when we were only about a hundred strong and we all knew every draughtsman and the names of his children. Now, instead, we are growing into one of the biggest industrial organisations in the country and it is no longer so. It just couldn't be."

From Owen I learned more of those early days about which so little has ever been committed to paper. With Kendall's help he pieced together the story of the famous first meeting of "the twelve apostles". The story goes that on February 4, 1946, twelve men of all ranks, forming the nucleus of the Production Division, arrived in Risley from the four corners of England and moved into their new headquarters for the first time. "Of this group only one man knew anything about atomic energy", says the official report. "The first thing done was to call a meeting of the whole group and ask the one informed member, who had spent some time at the Canadian project, to tell the rest in simplest terms what atomic energy was."

Memories, I found, were short and it was some time before I was able to collect the names of those present. There were, it seems, thirteen of them, but one more or less at that stage made very little difference and no-one then or later was disposed to regard the meeting as unlucky. Apart from Sir Christopher, Owen and Kendall, there were, I was told, Harold Disney and Dennis Ginns, Leslie Cole, Donald Mackey, Johnny Farthing, Bill Parsons, John Antwis, Robert Hart, Ken Sheard and Charles Turner.

They all had a simple lunch in a canteen formerly used by the filling factory staff and then filed into a tiny room, almost devoid of furniture, that is now used as a library. There was a small table there and a few folding chairs. The proceedings were very informal. The one knowledgeable man was Dennis Ginns. He was an engineer who had been in Canada designing heavy water reactors but had been taken ill and returned to Britain. While he was recovering, I.C.I., from whom he had been seconded, agreed to his helping the atomic energy project with his knowledge for a year or so.

"We asked Ginns to tell us exactly what a reactor was, or at least something of the principles involved", says Owen. "Dennis did this, telling us about the Canadian reactor, of the possibilities of using heavy water or graphite, and why we needed these substances at all. He talked, I suppose, for an hour or so."

"That is all very well," said Owen in his blunt way at the end of the discourse, "but what makes the ruddy thing start to begin with?" He was used, he said, to industrial plant where you had to turn valves or push a switch down, but was baffled by a device that seemed to have no need of them.

Ginns explained that there was always the "odd neutron kicking around in the atmosphere" that would start off the reaction. Other questions were asked about the purity of the heavy water or graphite and other components that would be required.

"We had at that time", says Owen in retrospect, "very little realisation of what we were in for. The first task, having got some idea of what a reactor was, was to set up an organisation to start the job off. We had many hectic meetings at the time to discuss the remit that we had from the Ministry, including that part of it which required us to build a water-cooled reactor along the lines of the ones at Hanford, used by the Americans to produce plutonium."

The British knew nothing of Hanford. The Americans just would not let our engineers see the piles there, so that there was a good deal of groping in the dark. One thing was quite clear, and that was that a factory would be needed to start off with to refine uranium, and Charles Turner, now Chief Engineer, responsible for chemical plant, was asked to study this.

Hanging over their heads was the great immutable date, the day on which they had to hand over to Sir William Penney the plutonium he needed for the Monte Bello test.

Meanwhile, with the exception of Sir Christopher Hinton, Owen, Turner, Disney and Ginns, all of whom had homes in the Northwich area, the whole team were accommodated in primitive conditions in the nearby Newchurch Hostel used by miners. They slept on wooden plank beds with three "biscuit" mattresses apiece. "The men there were an extremely good lot", Kendall told me, "and you would not have placed the majority as miners at all. A few of them were pigs, though. They deliberately came into the dining-rooms wearing their pit muck."

Kendall recalled that, when he first heard from Sir Christopher, he thought it was part of a leg-pull by colleagues. It was in war-time and Kendall was in Southport. The message asked him to meet Hinton in London nearly 200 miles away. The meeting took place at 10 o'clock one Sunday morning. Owen was there. Kendall was offered an engineering post in the filling organisation and accepted it.

"I found Hinton at first a bit difficult to get used to", he told me. "I think it was his voice, which is a little high, a little hard and metallic; an impersonal sort of voice. I soon began to realise that the impression was a purely superficial one", he said, and told me a story to show how human Sir Christopher could be. "We were doodle-bugged at the Ministry, and I had the job of clearing up the mess. There was no labour to be had for the job and I had to bring in men from the filling factories. The job took some time.

"The doodle-bugs, of course, were coming in across Sussex and many were falling short. My wife and daughter were living there at the time and Hinton knew that I was worried about them. One day, without a word to me, he obtained their telephone number and himself invited them to stay with his wife in the North. They stayed first at the Hinton home and then at the Owens'." One of Jennifer Kendall's most vivid memories—she was very small at the time—was when Hinton, who was 6 ft. 4 in., picked her up sometimes when he was at home and swung her "round the Maypole" at what to her seemed an enormous height above the ground.

There were many sides to Hinton. One Sunday morning, when both Kendalls were spending a weekend break at the Hinton home, Sir Christopher suddenly asked Kendall: "What do you do about your churchgoing, James?", to which Kendall, a little taken aback, replied after a moment's hesitation, "I usually delegate it to my family". "Oh, well," replied Sir Christopher, "that's all right, because my family usually delegates it to me." So off went Hinton to church with the Kendalls while James himself peeled the potatoes for Lady Hinton.

Hinton at home was one thing. Hinton at work was another. The team were working to a deadline and he was determined that they should meet it. With Owen he had laid out a pattern for the job.

Owen told me how they drew up their plans. "Every year Hinton gets out a long-term programme. It is in effect a 'master' programme. After discussion it is adopted and at once becomes one of our 'Bibles'. It may have only a couple of lines on each job but it does give us a date. Without this method of programming we would not succeed. We did this when we were in the I.C.I.'s Alkali Division. Sir Christopher started it there. It is one thing drawing up a programme, however, and quite another thing meeting it. It must obviously have been drawn up judicially. There is no question of arbitrary fixed dates. Only one date was arbitrary in the atomic energy programme and that was the date on which he had to hand over the plutonium needed by Sir William Penney. This was a political decision. We had to accept or reject it. Once we had accepted the date we had to get out our programme. Inside that date, once agreed upon, nothing was arbitrary. It all fitted together like a jigsaw puzzle."

Getting the bits from industry, while the country was working on a sellers' market, was a difficult proposition in the early years of the programme. The essential part was to have a really good progress department. "Right from the start this department goes into partnership with the industrial concerns", said Owen. "It gets to know their difficulties, makes sure they have licences, and if they are short of men helps them out. They have to see that right from the start there is no excuse for missing the date."

[10]

A Knight in a Duffle Coat

THE first thing that strikes one about Sir Christopher himself is undoubtedly his height, and there is little wonder at that for he is reputed to have been the tallest member of the Ministry of Supply during the war-time period. His high domed forehead and piercing eyes give one immediately the impression of a man of great intellect, and when he starts to move his innate vigour is at once apparent. He is clearly a man who never does things by halves. Whenever I have seen him out of doors, he has almost always been striding along in dynamic fashion. In cold weather he often wears a duffle coat that emphasises, as I later found his home did, too, the essentially functional nature of his attitude to life.

In his spacious and tastefully furnished office at Risley he rarely remains for long seated behind his large and highly polished desk. He paces up and down in a most deliberate fashion, tracing out imaginary patterns with his feet on the thick carpet with tremendous care, hesitating here and there between a left or right turn as if planning some new factory. He emphasises his points with expressive gestures, sometimes flinging his arms out wide and slowly bringing them together in a squeezing motion as if he were playing a concertina. Occasionally he will gaze out of the window as if in search of inspiration. I several times followed his gaze. There were no lovely pastoral scenes like those outside his own home; just a couple of prefabricated grey buildings and a cloud or two in the sky above; but they seemed to supply him with the words that he was searching for and he would quickly return to his point.

One of the dominating features of his life, I had already found, is the doctrine of the immutable deadline. A promise must be kept. Another is a scorn of established procedures, which he has learned by long experience. It is typified by his attitude towards the use of pilot plant to test a process before plans are made to use it on a major scale. The normal procedure in the chemical industry is one of caution. When a procedure has been shown to work in the laboratory it is tried out on a larger scale. If it still works the scale is increased.

"I believe, in the light of six years' experience in the atomic energy business", he told me, "that the construction of pilot plant can be a mixed blessing. The pilot-plant designer tends to take the line that he need not be particular because it is, after all, only a pilot plant. When the work is picked up by the designer of the full-scale plant he then tends to argue that the pilot plant may be inelegant, but at least it has been shown to work and therefore it would be unwise to make modifications. If instead the designer of the full-scale plant has to go ahead from scratch, he really has to think for himself, and I believe that although one is taking a heavier risk by doing things that way better results are often achieved."

In support of that doctrine Sir Christopher quotes the case of the plutonium extraction plant at Windscale, worth many millions of pounds, that was designed solely on the basis of experiments done in the Canadian laboratories by Dr. Spence with no more plutonium than would cover a pinhead. "It is an interesting fact", he told me, "that this has been our frequent experience with atomic energy plant."

One of his chief worries, he told me, was the task of finding senior engineers, especially in the design field. "Given time we could bring our own engineers along, and that is what we are trying to do. There are no senior engineers within the organisation that have not gone up two or three steps since they came and virtually all our senior posts are filled in that way. Unfortunately we have been expanding so rapidly that it has been virtually impossible to bring men on fast enough. The worst shortage of all is of design engineers capable of earning £1,000 to £1,700 a year."

One of Sir Christopher's many interests is architecture. He had a lot to do with the designing of the fine administrative buildings of the Capenhurst factory and with the great six-storied office buildings that will soon make his Risley head-quarters a symbolic island in the flat and dreary Lancashire plains and be far more in keeping with their status than is the grim accommodation they now occupy.

Hinton has often been blamed by his staff for the fact that, while the factories enjoyed priority in the provision of amenities and good buildings, the people at the centre of the organisation get nothing at all.

The trouble, as his Yorkshire-born personal assistant, John Dixon, pointed out, has been that the Risley organisation itself had no sense of permanency until atomic energy established itself as an economic proposition. The Risley staff were there to plan factories and they never knew what would happen when the factories were finished. The other disadvantage was that, through starting in an old ordnance factory, they always had something there already that they could use. "If we had had no canteen we could have built ourselves a new one, but since there was one already there, never mind how shoddy, there was not much we could do. It was the same with the offices. The building industry was already overstretched and our people thought they would be quite unjustified in lashing out and building palaces."

Now there is no alternative. The Risley establishment is encircled by an Admiralty stores depot and both organisations have built right up to the dividing fence. Apart from an old spoil heap now being built on, there was no room for extra buildings. The only thing to do is to go upwards. As each new block goes up, so a few of the hutments will be pulled down to make way for new buildings.

Sir Christopher sets the date at which atomic energy really came into its own as 1952. In that year the first British atomic weapon was tested and the design studies were completed for the first economic nuclear power station. "It was not until that year", he says, "that we really began to see our way through."

One of Hinton's less direct ways of placing atomic energy on the technological map was the Nuclear Engineering Society, which he was instrumental in forming as far back as 1946, and which has since grown to countrywide proportions. The present chairman, Mr. Harry Morris, a forty-two-year-old Yorkshire-born engineer with three lots of letters behind his name, told me: "It was the brain-child of Sir Christopher and he has always been the president. The original object was training. We had just started a new industry and were recruiting staff from many different walks of life, each bringing their own specialised knowledge to serve the new field of atomic power. They had to be shown the other side of the house; electrical engineers to learn something of chemistry, for example, and chemists to learn something of the mechanical side. To give them this training we had meetings once a fortnight and regularly brought down celebrities to address us."

Sir Christopher often attends meetings himself, and now that the society has grown in scope, membership and responsibilities he is helping it forward in an important new step, that of seeking incorporation as a private company.

Both Sir Christopher and Lady Hinton take part in the Risley organisation's less formal activities, including the annual dinner and dance, and both are a little sorry, I think, that the general set-up there, and the dispersion of the homes of staff over a wide area, do not favour community spirit to the same extent as in some of the Authority's other establishments.

The Hintons were kind enough to invite me over to their own home, "Sandyway", at Tarporley, twenty miles from Risley. It is a pretty little cottage which they designed themselves. As you approach it along a neat drive, well-chosen items of highly polished antique metalwork immediately catch the eye. Most of them, like the antique furniture, and brightly coloured china that adorn the walls, are relics of earlier days when Sir Christopher and Lady Hinton (they were "Mr. and Mrs." then) used to love wandering round antique shops. "We never get time to do that sort of thing now", said Lady Hinton, as she showed me into a cosy drawing-room that looked out over newly ploughed fields ("We love the pastoral scene"), to the bunched pines, oaks and birches of the Petty Pool woods. "Just look at that fine old Italian tray that we picked up, dusty and covered with grime, in a poky little shop."

"My husband lives a quiet homely life and loves walking", Lady Hinton told me. The fine, well-kept garden was all his own work. He loves flowers, and a collection of colour transparencies of the herbaceous borders, which we looked at through a collapsible viewing device, paid tribute at once to his ability as a gardener and in his newly started hobby of colour photography.

Hinton loves tennis and sometimes plays badminton and golf at the nearby Winnington Hall Club, which belongs to I.C.I. (Alkali), of which he was once a director.

The house, Lady Hinton told me, was their own idea. They planned it together during that early post-war period when floorspace and cost were severely restricted. Between them they had clearly squeezed the utmost out of the regulations. It was a most lovely house all over, but the pride of it was certainly the kitchen. Well lit, long and wide, with a seven-yard array of factory-made kitchen furniture, stainless-steel sink, time-controlled electric stove, and several arrays of lovely china to lend brilliant colour to the plain, light walls.

Lady Hinton says that the house is so easy to run that she finds she can do most things herself. She is naturally proud of her kitchen. She pointed out a large and useful plate-warmer just inside the kitchen side of a wide service hatch. "We pass everything through", she told me, "so people can see inside if they want to, but then you don't mind if you have a kitchen like this one."

At that moment a bell rang and Lady Hinton went to open the front door to new visitors. I made my departure, still marvelling at the way in which a man who works as intensely as does Sir Christopher could find time to lavish on his home.

I heard of yet another side of Sir Christopher from Daphne Whailing, a pretty, dark-haired Authority driver, who took me back to Risley. "I always used to think of him as a bit of an ogre, going by what some people said of him," she told me, "until I was told one day to put on a new uniform to show him because the girl for whom it was made was away. I went in fear and trembling when I heard I had to show it off to Sir Christopher."

It was a neat grey affair, not really like a uniform at all, and with a lovely round hat of the sort that some air hostesses wear.

Hinton spent a good twenty minutes looking at it and commenting on the design. He explained that he did not think it would be much fun for drivers wearing something that looked definitely like a uniform when they had to put up in some hotel at night on a long trip. "It does make you feel conspicuous and uncomfortable, it is true," she told me, "but I never expected Sir Christopher to think about a little thing like that."

[11]

A Taste of Trouble

WHILE Turner was planning and building the Springfields factory to process uranium ore with the advice of I.C.I. and information gained by the old Tube Alloys group, Kendall was told to cut his teeth on the design of BEPO, the first big British experimental reactor. A group in Canada were hard at work on this project but there was still not much information available. All they had to work on, in fact, at Risley were three pile drawings and four or five full sketch sheets of specifications. Shielding at this stage was providing quite a problem and in May 1946 Kendall went over to Canada to chat with physicists there.

"A most curious correspondence ensued", says Kendall. "Many silly questions were put to John Robson and other physicists there. It was the process of learning." Kendall chuckled, as he rustled through faded and flimsy sheets of airmail paper. One of the letters started: "Dear James, Here are some results of further calculations on the shield . . ."and ended abruptly after five or six pages of highly mathematical equations with the sentence "Your trousers were despatched from Deep River (the cantonment adjoining the Chalk River plant) on May 23rd and should reach you in two or three weeks' time. I hope they will fit."

Kendall does not recall whether the trousers fitted or not. The important thing was that they solved their shield troubles, which were mainly concerned with the fact that it could not be a complete casing of concrete around the pile but must allow instead for continuous access to the pile face to change fuel elements and to insert and withdraw substances that needed to be irradiated in the pile for varying periods.

BEPO was built in the form of a cube with sides each 26 ft long. Twenty-eight thousand blocks were used. Although the standard dimensions were 7¼ in. by 7¼ in. by 29 in., there were so many minor variations in shape to allow for cooling, for control rods of one sort or another, for various irradiation cavities and for the fuel elements themselves, that 1,500 different shapes of block were needed. They rested on a steel floor six inches thick based on a central concrete plinth. The steel, which also surrounds the pile itself, was thus able to protect the concrete from the damaging effects of the neutron irradiation.

The problem of producing the graphite blocks was alone enough to daunt the most enthusiastic engineer. When the project started, there were few tools that would stand up to the abrasive effect of this very hard form of carbon, and new forms of tungsten steel, harder than any previously known, were developed for the purpose. The task of machining the blocks to an accuracy of nearly a thousandth of an inch, a quarter of the thickness of a normal sheet of paper, was tremendously complicated by the fact that it had to be carried out in conditions of cleanliness that rivalled those of a hospital operating theatre. Even one part in one million of some impurities would have rendered the product useless.

Workers, we are told, had to strip to the skin before entering tke machine shops and put on specially laundered clothes, and no-one who left could enter without going through the whole process over again. When made, the blocks were stacked inside the sealed-off concrete shield. Workers entering the vault had to do so through a series of airlocks which ensured greater pressure within the shield than without to keep out dust.

The whole of the 26-ft cube had to be completed to an accuracy of 0·015 of an inch, the thickness of a heavy postcard, and this was done by carefully selecting over- and undersized blocks. There are 1,760 horizontal channels, but only the central 888 of them are loaded with uranium and they form the central reacting core, 20 ft long and 20 ft in diameter. The remaining graphite serves to reflect back some of the escaping neutrons.

The "biological" shield surrounding the pile is 6 ft 6 in. thick and is made of concrete that weighs 40 per cent heavier than ordinary concrete. The inner 6-in.-thick steel plate absorbs most of the neutrons. The purpose of the concrete is to absorb the gamma radiation, that is fast X-rays, emitted during the chain reaction and also produced when neutrons hit the steel shield. There had to be, of course, a hole through this shield for each channel in the pile, and the two holes had to be exactly in register. When the pile is in use these tubes are plugged. Other exits, known as "thermal columns", are plugged with graphite and permit neutrons of thermal, that is low, energies to reach the exterior when needed for experimental purposes.

Cooling air is sucked through the channels and the pile by electric fans and discharged up a 200-ft-high chimney stack. The slightly reduced pressure within the pile caused by this suction process ensures that there will be no leak of radioactive material from the shield into the room outside. The temperature of the air after leaving the pile was about 80–90 degrees Centigrade, that is well below the temperature at which water normally boils.

After the pile had been in operation for some time a water-heater was installed in the hot air outlet duct. This was normally capable of handling 2,000 kilowatts and producing water at 72 degrees Centigrade that was used to heat buildings of the Research Establishment. In its own small way this was quite an historical feature, for it represented the first attempt in the world to make use of the heat from a nuclear reactor.

A month before Kendall was able to complete the building of BEPO, he was switched to the job of building the big production piles at Windscale. The completion and start-up of BEPO was handed over to a Harwell engineering group.

All the time that the Harwell establishment was growing the Risley team had been working like mad on the Windscale complex. Hinton, although few knew it, had been given a deadline. The remit from the Ministry, a closely guarded secret at the time, had specified that Sir William Penney must have his plutonium by August 1952 for an atomic weapon to be tested the following October. That was the great immutable date around which the whole of the atomic energy programme revolved.

Inside that date and working back from it the Springfields factory had to be built and producing the uranium metal, the plutonium piles had to be constructed and run for a sufficient period to transmute the necessary amount of uranium into plutonium, and a separation plant had to be designed, built and operated which would enable the few ounces of plutonium thus produced in every ton of fuel to be extracted on a commercial scale and delivered in the required state of purity.

There was no changing the deadline, and it is to their credit that the production organisation never suggested such an idea.

Early on, the design engineers had learned that construction and operation of the giant atomic production reactors was only one aspect of the problem. The chemical treatment of the fuel elements after they had been irradiated for a period had proved to be a problem of the first magnitude, and the construction of plant for the purpose a task comparable with that of building the piles themselves.

Charles Turner, who had designed the ore-processing factory, was now asked to plan a separation plant for plutonium. The more urgent task, however, was that of constructing the reactors themselves. For security reasons full details have never been given of these two great production reactors at Windscale but a few outsiders like myself have had the privilege of seeing them, and the general principles on which they work are now well known.

The original request from the Government had been for graphite-moderated, water-cooled piles, "like the Hanford ones" which the Americans had used for their own bomb project. At that time Dr. Erastus Lee was head of the technical engineering section, and with Dennis Ginns and James Kendall was given the job of planning them. They gave a great deal of thought to the request for water-cooled piles and did a great deal of work on the subject. Kendall tells me he still uses a piece of aluminium water-piping, once intended to cool these piles, as a sheath for the electrical resistance of his Canadian-made electric razor.

An argument in favour of water was that its use as a coolant permitted much more heat to be removed and consequently allowed the piles to operate at a higher activity rate. The argument against ordinary water, as we have already seen, was that it absorbs neutrons more rapidly than graphite does and that if for any reason the supply of water failed the removal of this source of neutron wastage would at once increase the scale of the chain reaction.

It was true that the Hanford piles had been run for some years without serious incident, but they had only run for twelve months initially when they had to be shut down and modified for safety reasons. The consequences of a "runaway" might be serious, leading to the release of fission products and contamination of the surrounding countryside. It was all very well for the Americans to build such reactors in remote sites hundreds of miles away from cities; it was quite a different thing to consider building one anywhere in Britain.

The alternative was a gas-cooled pile. Du Ponts, the big American chemical firm which built the Hanford piles, had, we knew, recommended against gas cooling. "They thought", said Kendall, "that in gas cooling the pumping power required was far too great to make it a practical project. We were not accepting that. We adopted the line that we could, by using extended heat-transfer surfaces, that is to say, by fitting fins to the fuel elements, by pressurising the system to make the gas more dense and by injecting it into the centre of the pile where heat was greatest, divide the power needed for pumping by a factor as great as 27."

Lee and his team wrote a paper on the subject. By this time there were quite a number of people at Harwell who had come back from Canada, and one of them, Jack Diamond, now head of the engineering department of Manchester University, suggested that by using only one of these effects, the fin-shaped fuel elements, gas cooling could still be a practical proposition. Because of the urgency of the task and the desire to avoid any more complications than were absolutely necessary, it was decided to build the Windscale piles with fin-shaped fuel slugs and to leave for later piles like the PIPPA reactors at Calder Hall more complex developments like pressurisation.

In most essential respects the Windscale piles were much like BEPO, the first of the large Harwell reactors, but this research reactor had had a heat rating to start off with of only 6,000 kilowatts, equivalent to the same number of single-bar domestic electric fires. The building of the two Windscale production reactors, each producing heat equivalent to the furnaces of a large electric power station, was quite another matter. Although safety considerations had seemed considerably simplified by the decision to use gas and not water cooling, it was still undesirable to have these, the first big piles in Britain, on the outskirts of a large city.

Safety requirements were in fact thought to be much the same as those of an ordinary explosives factory and the obvious thing to do was to look round for just such a factory which was no longer being used. There were two available on the West Cumberland coast. The better of them was at Sellafield. This site had many advantages. It was near the sea and its use for industrial purposes was consistent with long-term planning in the area. There was water available, office buildings and railway sidings, and these facilities probably reduced by a year the time taken to complete the factory. The name Windscale was given to the new factory, and work on laying out the site started in September 1947.

Some idea of the size of the factory can be gained from the fact that 300 professional men, architects, surveyors, engineers and the like, and up to 5,000 construction workers were needed for the task. Apart from the two atomic piles with their enormous chimneys, each 415 ft high, and the many-storied chemical processing plant, all the normal factory services had to be built, boiler-house, offices, stores, workshops, surgery, fire station and the rest. By November labourers from Ireland were brought in, and gangs were opening up and clearing the 300-acre area and buildings, hutted camps, canteens, and other amenities for some thousands of workers who had to be brought in to supplement the local labour force.

In the case of plutonium production piles, of course, there needed to be no facilities for experimentation and this immediately simplified the task of constructing the biological shield. Firstly, it reduced the number of channels that were required. Secondly, it meant that, where at Harwell radiation from the pile to the exterior had to be reduced to a point where it would have no effect on delicate instruments used for experiments just outside the shield, in the case of the production reactors it was quite sufficient to reduce escaping radiation to a level where it would do no harm to workers.

The graphite and uranium core of the reactor itself weighed many thousands of tons, and by the time the foundations, the fan-houses and the 3,000-ton chimney had been added in, the total weight of each pile was 57,000 tons. A great deal had to be known about the terrain that was to bear a weight of this order and holes had to be drilled to discover its exact nature and the way it would react when subjected to a heavy load.

Engineers decided that the best way to deal with this problem was to put each pile, complete with all its related equipment, chimneys and the like, on to a great reinforced concrete mat, 200 ft long, 100 ft wide and 10 ft thick. The various structures upon it were carefully planned to counter-balance each other and to ensure that there was no chance of a subsequent tilt. It meant that the heaviest loads needed to be positioned with an accuracy of inches. In the concrete work errors were not allowed of more than half an inch in 100 feet, and tubes running through the shield had to be placed with the same accuracy.

The major item, of course, was the cooling system. Each of the piles would produce continuously energy equivalent to that used by a small city and it all had to be extracted. The blower houses at Sellafield are an impressive sight. The fans used are like huge, multi-bladed paddlewheels and are totally encased. The principle used is similar to that of windmills lately devised by the Dutch to pump water from reclaimed land. They are driven by powerful electric motors which consume enough current between them to run a large motorcar factory; the great hall trembles, the air vibrates, and one feels for all the world as if the great motors had put out an invisible hand to grasp one's inside and shake it violently. In periods with "little ships" in the Royal Navy, I have satisfied myself that I am not the sort of person who is easily seasick, but I dreaded every moment during my visit to the fan-houses that I was going to disgrace myself and longed for the time when my guide would press on to the next section.

There are two of these fan-houses for each pile, to secure a balanced airstream, and they pump air through a subterranean channel into the bottom of the pile core. Since any particles of dust entering with the air would be radioactivated by passage through the pile, most stringent filtering arrangements are necessary on the air intakes, and further precautions must be taken before the heated air can be allowed through the chimneys into the air above. Filters of this sort must be strong to stand up to such an airstream. How strong they need to be can be imagined from the fact that when the fans were first switched on the fall of pressure in the fan-houses caused even the great steel doors of the building to belly inwards several inches.

There were many worse trials than that for the engineers. While the first of the great chimneys was still in an elementary stage, some tens of feet only from the ground, a message came from Sir John Cockcroft, who was in America, warning that experiments there had shown unexpected risks of leakage of radioactive material from the fuel elements.

If the deadline were to be satisfied, there would be no time to take the chimney to pieces again and install further filters, nor could modifications be introduced into the second one, shortly to be started. The expensive decision was taken to make the whole of the 415-ft chimney a parallel tube in each case instead of a tapered one as had originally been intended. The filters would be housed at the very top and would, incidentally, make the chimneys unique.

Another trial for the engineers came in the early days of testing. When the blowers were worked, they found the chimneys got wet inside. There was only one quick way to find out, they decided, and one of the engineers volunteered to stand in a steel sentry box fixed in the airstream at the base of one of the chimney stacks. As the blowers were switched on, his task was to watch and see what happened through a small reinforced-glass window. For hours he waited in the hurricane of cold, damp air as the fans gained momentum and then, after the test, gradually slowed down. But he found the cause of the trouble.

Operation of the pile is normally controlled, of course, under far more reasonable conditions. The control room, insulated from the thunder of the great fans, is lined with many dials and devices that provide a continuous record of operating conditions. Operation of the whole complex is conducted from a single grey steel control desk in the centre, which contains all the essential indicators and controls, including the master shut-down switch that can in a moment of emergency release the sixteen great safety rods so that they come crashing down into the pile and prevent further reaction. Another switch operates the twenty-four normal control rods that vary the degree of activity within the pile and move in and out in response to the slightest pressure of a finger. One of the most important devices in the control room is the bank of lights that indicate immediately the position of any fault that may develop in any of the controls.

Uranium fuel rods, once they have been "cooked" for a sufficiently long period in one of the piles, have to be extracted again and transferred to the chemical plant. This provides quite a problem of remote control. Each fuel element is a foot or so long and they are all fed into the channels one after another until it is full. When they have been in the pile for the appropriate length of time the new slugs are fed in and these push the irradiated slugs out at the far end of the channel, where they fall into trucks, which are run through a shielded tunnel under water to the "cooling pond".

Because of the intensely radioactive state they are in when they first come out they are left in this pond, which is like a large open-air swimming bath, for a period of up to three months. This period enables the intense activity of substances like radio iodine to die down and cause less contamination of the chemical plant. Before the cooled cartridges can pass on, the can must be removed, a task that is done under water by remote control by a machine with 18-ft-long aluminium arms.

The first stage of separation, known as the "primary stage", results in the production of four liquids of which the most important is that containing plutonium. There are only a few pounds of this liquid for every ton of fuel elements, and it is handled with the greatest care and economy. The second is a large quantity of rather impure uranium solution, and the third a large amount of dirty solvent that can be distilled and used again. The fourth and most troublesome is composed of a great deal of intensely radioactive fission products, all in solution.

It goes without saying that the whole of the primary separation process has to be carried out by remote control from behind concrete walls many feet thick, and this added enormously to the difficulties of design and operation.

There appeared in the early days to be no possibility, either, of reaching the plant to correct faults or to mend leaks or adjust pumps once it had started to operate. The designers had to plan it in such a way that it would last for scores of years without needing to be maintained. Only one material could be relied upon to meet such a remit and that was the finest stainless steel, which would have to be welded throughout and then submitted to the most searching X-ray examination. Every one of these X-ray plates, more than 50,000 of them, was filed away for future reference.

To avoid the need for maintenance it would have to be a plant in which fluids could move from one point to another without any pumps, filters or valves. There would just be columns, tanks, and miles and miles of connecting pipes, all stowed away in an enormous concrete box, but so designed that process men would always know the nature and condition of substances, rate of flow, and temperature, at any point within the system.

[12]

Secret Deadline

THE prospective visitor to Britain's first plutonium factory will not find the name "Windscale" in any railway time-table nor yet in a gazetteer. The name came, it appears, right out of the blue, just like the wind that often moans and whistles round the great filter-rooms perched 415 feet up on top of its massive chimneys.

Geographically speaking, Windscale is in the village of Sellafield, and although there are few houses in evidence there is a tiny railway station, no more than a halt really, that bears this name a hundred yards or so from the factory's main gate.

The nearest place of any size is Seascale, famous for its golf-course, five minutes' run in a train to the south, but this is only a village with a population of a thousand or so, and many shoppers go northwards to Whitehaven, or to Barrow-in-Furness, further south.

The last few hours of the journey northwards from London are a dreary business. The train stops at most stations on the way, although several of them must have done very little business since war-time factories closed down. On the left are great stretches of flat sandbanks covered at high tide. To the right pleasant rolling country with the hills of the Lake District, when you can see them, further east.

The observant traveller will catch sight of the Windscale chimneys, unique in the world for their shape, a minute or so before the train arrives, and as he climbs the winding, dusty road the two atomic reactors, each the size of a super cinema, and the ten-storey chemical plant make an impressive sight.

As you walk up the neatly laid-out approach to the factory gates, guarded by armed police, you catch a glimpse of well-kept gardens inside. On the miles-long security fence that surrounds the plant are prominent but futile notices at short intervals warning that photographing of the factory is forbidden, as if the world of tiny but effective miniature cameras and telephoto lenses and the like had stopped still while the atomic age went marching on.

They are a mixed lot, the men who travel up in the train to work at Windscale each day and who had gradually filled the carriage as it made its way up from Barrow. A few of them talked and joked, but many of them sat quietly, talking to no-one, as if they lived and worked in a world apart. There are 3,000 workers altogether on the payroll at Windscale, including 800 scientists and engineers. Two thousand of them, mainly industrial, come from Cumberland.

The job of recruiting the industrial grades for the new work fell to the factory's senior labour manager, Miss Mitchell, a tranquil, friendly woman with stylishly waved grey hair and a strong Scottish brogue. She would be, I would say, in her middle fifties; she used horn-rimmed spectacles and wore a neat grey costume. The men around the plant would say, I think, that she "definitely has class".

She told me she used to be with Coopers, the provision people, in Glasgow as welfare supervisor for a number of years, but at the beginning of 1941 joined the Ministry of Supply and went to an ordnance factory at Bishopton in Renfrewshire. It was a large place, making all sorts of explosives and employing about 23,000 people. She was labour officer, then labour manager, and finally senior labour manager. After a period when the Ministry of Supply was scaling down its factories and depots, Miss Mitchell was asked to go to Windscale "on loan" for a period of six months. It has developed already into seven and a half years.

Glasgow-born, she went to Paisley Grammar School and then to a commercial school called the Athenæum. She speaks a bit of Spanish, French and Italian. At first, she tells me, she wanted to be a foreign correspondent in some company but later changed her mind and went into personnel management.

"It was interesting coming here. It is a chance in a million for a person in my line to get the job before anyone has passed through the gates.

"The first year was spent in steadily interviewing people in conjunction with the local labour exchange. While we hoped to get all the semi-skilled and unskilled labour locally, we had very little chance of finding skilled men. This meant going for them to Barrow and Workington. The trouble here was that the transport position was such that, even if people had wished to study and take technical training, it would have been just about impossible. We had to bring people in. We had a nucleus of men from ordnance factories like Drigg, which by now was on a care and maintenance basis.

"The story of Cumberland is a sad one", she told me. "There were many mature men in the thirties to fifties who seemed to be completely overwhelmed by the county's history of industrial depression. In Glasgow I had been used to the more militant types, people who had had almost as bad times as the people of Cumberland but who had gone marching with red flags. Here they had been submerged by the influence of bad times. They were inclined to sink back and you had to jolt them out of it. In the war they had the ordnance factories, of course, and actually war-time had not been at all bad. But they had in their memories the pre-war days of slump and the fixed idea that these days would come back again. Some had migrated to America, only to be hit in time by the slump there too. They had no faith.

"Every day a number of them were up for medical examination. Our first recruitment was for the graphite shop, and graphite to them meant coal, and coal in turn meant pneumoconiosis and T.B. Unless they had been handled humanly it would have been no good attempting to persuade them. Here the humanity and tact shown by the doctors helped so much. Word had got round that we were X-raying them and many were afraid. Then some of them came back new people from the surgery, after they had been X-rayed and shown to be in good health. Men who had been many years in the mines and thought they 'were bound to be dusted' and their lungs diseased were new men when told there was nothing wrong with them.

It worked like a most marvellous tonic. What did strike me about all of them was the consistent honesty. We had to do a lot of checking up and not once have I found that they were bluffing."

As the factory expanded they had to bring in more men from outside. Vickers Armstrongs were in a slack period and were contacted. "'We are getting a lot of applications from your men', I told them. 'Do you mind if we take them?' They were confident that they would get all the people they needed when the time came but they warned me that we were unwise in taking too many men from Barrow. There is a saying 'Barrow sticks to Barrow'. Shipyards, they thought, would get busy again and the men would leave. That was only true to a very limited degree.

"There were others who came from Tyneside, Teeside, Merseyside, Portsmouth and Plymouth. Many of them were fitters, born in Cumberland, who had migrated to other cities to get work and who were quick to take advantage of the chance of coming back to Cumberland again. They now have enormous faith that they will be absolutely all right here. I would say that at the beginning they did not realise the immensity of it all, not until the first pile began working. It was not only people in the works that had to be disabused about this. A very great deal was done by the boss in talking to farmers, unions, rotary clubs, chambers of trade and commerce and the like. The importance of that work could not be overestimated."

The "boss" to whom Miss Mitchell referred was Henry Gethin Davey, the forty-six-year-old Welsh works general manager, who is a chemist, physicist, engineer, schoolmaster and local politician, all rolled into one. Davey, a short, serious man with a way of getting what he wants, has been in charge since the Windscale project started. He was born near Cardiff in 1908. At school he earned a scholarship to Cardiff University. After graduating with first-class honours in chemistry, physics and mathematics he took a master's degree.

"My first job", he told me, "was really a teaching one in a place called Treforest, Glamorgan. It was run by the South Wales coal-owners and ultimately was taken over by the county authority and became known as the Glamorgan College of

Technology. The war came, and being a chemical engineer I was sent to explosives work. After a training period at Pembrey, West Wales, I was transferred to Drigg, an ordnance factory in Cumberland, built for the manufacture of T.N.T. I helped to start it up."

By 1942 Davey was managing chemist there and two years later was made deputy superintendent of a group of three factories, Drigg, Sellafield and Bootle, under Hines, who now manages the Atomic Energy Authority's Capenhurst factory. When the war ended, Sellafield closed down, but Bootle and Drigg continued to operate. Bootle was a "breaking-down" factory which extracted the metal from unwanted ammunition.

In April 1947 when Hinton visited the area he asked Davey to take charge of the Windscale factory. Although Davey by then was a chemical engineer, the physics and mathematics of his original degree now came in handy. "It meant that I had a reasonable knowledge of atomic structure and radioactivity. I had, like you, of course, been brought up on Rutherford's conception of the atom and a great deal had happened in the meantime. There was a great deal to be learned and much studying to be done and I spent some weeks at Harwell."

Davey is married but has no children. "I used to play games," he told me, "but I scarcely ever do so now. My chief interests outside the job are gardening and music. I am essentially a listener. I am not one of those people who think that playing the harpsichord is like stroking a parrot's cage with a toasting-fork, and I like Beethoven, Handel, Mozart, Bach, Purcell and Byrd."

Davey reckons that the background of explosives work that many of his men had was a great help. "We were very conscious of the need of things like operating manuals, emergency instructions and house rules of conduct within the plant, and these were drawn up before ever it went into operation. It was, however, an attempt to adapt known techniques to unknown problems, and time had proved that in some ways it was the wrong approach.

"The original conception was of a works divided into groups. The general group, in which there would be no radioactive hazard and in which people would work in their own clothing;

and a chemical and pile group, in which there would be hazard and people would have to remove all their clothes and put on special garments. After much thought we felt that this was fundamentally wrong because it gave the conception of clothes for the protection of the individual. From the beginning we set out to make modifications to the plant that would confine the radioactivity so that there would be less and less need for special clothing. In my own opinion this is the right approach and in fact it increases safety to a substantial degree.

"The idea at first was that radioactive material would get outside the plant anyhow and that protective clothing would be needed to prevent the individual from becoming contaminated. The new conception is that shielding should be made to perform its proper function and therefore personnel will be free to use their own things. The extent to which we succeeded can be measured by the small amount of protective clothing that we now wear."

He had a bit of a job at first putting the new idea over to his men. "In this part of the world one tends naturally to draw analogies from the collieries. One illustration that I used was that of coalmines where gas is a substantial hazard. 'Men do not wear masks day and night', I would tell them. 'All necessary steps are taken, instead, to ventilate the colliery. In emergency, however, rescue teams wear full protective clothing and carry canaries or rats in cages.' That was something that they could understand."

Nowadays at Windscale they have reached the stage where most personnel entering the chemical group change only their shoes and put on outer garments. The number of men making a complete change has now dropped from 800 to 300 and the tendency is expected to continue.

"Support for our methods", Davey told me, "is provided by the number of cases of contamination. Since Windscale started up we have been involved only once in serious contamination. In the early days there were a large number of minor cases. Now, instead, cases of contamination are quite exceptional and relatively light."

The "serious" case Davey had mentioned was of a craftsman involved in a spill of radioactive material. He suffered more from the scrubbing down, the doctors say, than he did from the radioactivity. People soon learned that it was better to avoid contamination than to suffer the remedies.

To get the men accustomed to the idea of radioactivity Davey had a "mock-up" plant built. "It contained all the usual things that a chemical plant needs, vessels, pumps, tanks, valves, filters. Although this plant only manufactured ammonium nitrate we pretended that the whole thing was radioactive and process men were taught operations under simulated radioactive conditions and were drilled in the precautions that were necessary. Engineering personnel had to maintain the plant and again we pretended that it was radioactive. The ammonium nitrate ended up as fertiliser on the factory lawns."

* * *

Nuclear engineers don't talk about an atomic reactor "starting to work". They say it has "become divergent" or "reached criticality". In each case, however, it means that there is enough nuclear fuel within the pile when the safety plungers and control rods are out to allow the chain reaction to work. There is, as the pundits would say, "spare k".

This stage was reached in the case of the first of the Windscale reactors on a cloudy July day in 1950, when, even if the reaction did produce any vapour, which, of course, it did not, no-one would have noticed it leave the tall chimney. At that time, Davey tells me, there was nothing but grass and a few holes here and there on the site where the ten-storey primary separation plant would later be built to receive irradiated fuel elements from the pile. It was a case of taking first things first.

There were, he explained, still eighteen months to run before the first fuel elements would need to be removed prematurely from the pile to meet the urgent need for plutonium. The normal economic period would be much longer.

To meet the Government's original remit for purified plutonium in August they were taken out of the reactor in December 1951. Towards the middle of February, with only six months to go, the slugs were still at the bottom of the "cooling pond" losing some of their radioactivity. On February 17, when Sir Winston Churchill told Parliament of plans to test a

British atomic weapon at Monte Bello in the autumn, the huge primary separation plant where the irradiated fuel elements would be initially processed had still to be tested. Not even "tracer runs", token quantities of radioactive material, had been passed through the many vats and miles of piping. "Although everything was still proceeding to schedule, we shuddered", Davey told me, "when we heard of the Prime Minister's public announcement."

It was all very well to know that the secret programme required the delivery of material by a certain date. It was quite a different matter to have the whole world know of that commitment before they could be absolutely sure of the fact themselves.

"If ever a man earned a decoration," says Miss Mitchell, "it was earned by Mr. Davey on the day he took the final decision to let the contaminating fluids enter the plant."

Davey himself admits it was the biggest decision he had ever had to make. "People kept on talking of modifications that might have been done. Others were asking us if the plant was safe and satisfactory. Finally came a day late in February when we said that we had done everything that we could for safe and satisfactory operation. 'We have tested the plant and shown it to be liquid-tight, first by inactive operations and then by trace runs', I told the staff, 'and now we are starting up'."

Davey admits that he did not sleep much that night. He took his plant to bed with him, and all night through he could see the individual vessels, and imagined the fluids passing through the pipes. "In eight hours", he told me, "we had reached the point of no return. The plant had become so radioactive that no further modifications could be made. The first part of the plant was too 'hot' to touch. If I had not taken that decision when I did there were people who with the best intentions would have kept us going with further modifications for weeks."

Luckily, all went well. The plant worked precisely as it was meant to do and Penney got his plutonium on the date specified.

[13]

Calculated Risk

WITH only a couple of months to go before the date already announced for the first test, Sir William Penney's team had no time to waste. Britain had had a fairly large team at Los Alamos under Sir James Chadwick. There were Peierls, Fuchs and Penney on the mathematics side, and Bretscher, Frisch, Marshall, Moon, Poole, Rotblat, Titterton and Tuck and others in the various physics departments. Some, like Frisch, who after the war went to Cambridge, had actually performed experiments in America that meant bringing together quantities of materials that would have exploded under the right conditions.

One of the methods that Frisch used in Los Alamos, he told me, was to take a lump of atomic explosive large enough to form a bomb, but which had a cylindrical hole drilled through the centre, place a boron counter close to this lump to measure the "flux" of neutrons produced, and then, when all was ready, he would drop through the hole a plug of fissile material just sufficient to fill it.

The combined mass was slightly "over-critical". That is to say, there would be more than enough fissile material present between the two lumps to bring about a spontaneous atomic explosion. Frisch, who has a predilection for telling jokes or recalling what are really quite sensational stories with a completely deadpan look on his face, explained to me that "it was quite all right" because the flux of neutrons would take several thousandths of a second to build up enough for an explosion, whereas it was calculated that the plug, as it passed through the hole, would only be in the most favourable position for one thousandth of a second. In the short instant that it was there the neutrons multiplied very rapidly, but before they could do any harm the plug had gone through and everything died down again.

Frisch and his co-workers for this experiment were behind a thick concrete wall and he reckons that they were well shielded. There was one occasion on which he admits there was some danger. "I was doing an assembly", he told me, "to discover the critical size in the absence of a neutron reflector. I had overlooked the fact that the body itself is a reflector of neutrons." One of the counters was clicking rather irregularly, and an assistant, who thought it had gone wrong, pulled it out to change it. "Leave it where it is," shouted Frisch, leaning forward, "I'm just going critical." As he spoke he saw through the corner of his eye that the flickering neon lights that recorded units, tens and hundreds of neutrons passing into the counter had ceased to flicker. There were so many neutrons about that the counter could no longer distinguish them and the light remained on continuously.

It turned out that the flux had multiplied many thousands of times purely because Frisch had leaned forward. Had he allowed this process to proceed two seconds longer he would have been killed, as two others were in similar experiments. Instead, he quickly removed one block of uranium and stopped the reaction.

Frisch adopts a casual attitude about it all. "In these small reactors (the name they give to such assemblies of fissile material) you know exactly what they will do. You can go as near to an explosion as you like with safety. There is no danger at all so long as the experiment is controlled. In many cases", he explained, "the system had been so adjusted that the flux of neutrons took over fifteen seconds to build up from nothing to a dangerous level, and then shut off in complete safety".

"An atomic bomb", he summed up, "is a very dangerous beast that is always under control so long as you do not make any mistakes, so much so that after a time it is difficult to realise that if you make a mistake you have had it."

Like Frisch, most of the British team had been engaged on obtaining fundamental data about the bomb process. They were not engineers or technicians. None of them had had direct responsibility for the really practical problems of making the bomb, the engineering, the metallurgy, handling of plutonium or actual weapons assembly; and by 1952 most them had left the project to join universities in purely academic work. At the Weapons Research Establishment itself at Fort Halstead near Sevenoaks, Kent, and at the Woolwich Arsenal, neither Penney not any of the other members of his staff had ever handled a sizeable lump of plutonium.

Sir William will tell you that the credit for the fact that the British bomb went off on the specified date goes to the whole of the team, but the team point back to Penney. The man who had shouldered this great responsibility was a thirty-year-old assistant professor of mathematics at the Imperial College of Science when war broke out. With his boyish face, blue eyes, tousled, sandy hair and ingenuous smile he looks the last person in the world to develop a fearful weapon of destruction. He fell into his present job quite accidentally and without any of his own contriving.

Penney had been working at the college on very fundamental and abstruse problems concerning the nature of matter, and, like most other scientists when war broke out, his name was on a central register of scientists that had been prepared for the purposes of national emergency.

"I was naturally willing to do anything that I could," he told me, "but I had no idea of what that could be. Then, one day, after several months of hearing nothing, I met Sir Geoffrey Taylor, a world authority on fluid mechanics, and he told me he was being asked by Government departments lots of questions about explosions and that sort of thing. He could not deal with all the questions and therefore asked me to have a go at the pressure wave caused by an explosion under water."

Sir William (he was Dr. Penney then) got down to the problem at Imperial College and within a few months had gained what he called a "reasonable understanding" of what happened. He did not do it by firing torpedoes at old hulks or anything dramatic like that. Penney's tools were pencil and paper. His method was to take phenomena like sound waves that were already well understood in the laboratory, and use pages and pages of formulæ to extend this knowledge to the problems under study.

His way worked and his theoretical predictions fitted so well the measurements that the Admiralty made with actual explosions that Sir Geoffrey Taylor, who at that time was studying what happened inside an explosive when it went off, asked Penney if he would try and find out more about what happened in the air outside. First he dealt with very fundamental stuff, and then he began to consider what blast waves did to various structures, ships, houses, windows and the like. Just when he was beginning to get a firm grasp of the matters, another urgent job came along. Plans were starting on the Normandy landings and the Admiralty wanted advice on what the wave patterns inside the Mulberry harbour were going to be and what stresses the various structures would have to withstand. Penney's findings, a classic piece of research, are now preserved in the annals of the Royal Society.

While British and American troops were preparing for the Normandy invasion, a most distinguished collection of scientists were studying at Los Alamos, in New Mexico, the question of how to make an atomic bomb. Very little was known at that time about how it was to be designed and assembled. They thought that a crude device could be made by firing one bit of fissile material into another, in a totally enclosed system rather like a gun-barrel, but there were better ways than that and they depended on the compressibility of fluids and shock waves and all the other things that Penney had handled so easily in Britain.

The Americans knew of Penney's work and invited him to Los Alamos in June 1944, a few days after D-Day. At the beginning he worked as one of the team of mathematicians and physicists that already included many from Britain. As matters became clearer concerning the bomb, it was decided that a test would have to be made. Before this could be planned and the instruments positioned and scaled, the scientists had to have some idea of what the explosion was likely to do. Not many of the workers at Los Alamos had ever seen an explosion at all, never mind an atomic one, and Penney soon became a general consultant.

The first explosion of an atomic weapon took place in the deserts of New Mexico at a place called Alamagordo on July 16, 1945. It was so successful in fact that many of the instruments failed to stand up to the unprecedented pressures. Published accounts tell of how some were crushed and others were torn loose and thrown considerable distances. There was one sort of instrument, however, that thrived on this sort of treatment. It was devised by Penney.

To quote from one official American record:

"He made the daring guess that the humble tin-can can prove to be one of the best 'instruments' for measuring the terrific pressures produced by atomic bomb explosions. He soon showed his guess to be correct. He demonstrated that whenever a gasoline can was partially crushed by a sudden pressure wave the degree of the crushing depended on the exact intensity of the pressure wave. For example, an over-pressure of only a few pounds per square inch might reduce the can's volume to 80 per cent of the original volume, but a more extreme over-pressure might reduce its volume to 10 per cent. Cans are cheap, hundreds may be used and the average effect may be measured with accuracy. (The decrease in the can's volume could be measured simply by filling the can with water and weighing it and making a comparison with the weight of the uncrushed ones.) Many other instruments were equally ingenious."

Preparations for the atomic attack on Japan were already well advanced. Teams of scientists were leaving Los Alamos for the Mariana Islands. Penney was sent as a member of one of these teams. Another, Group Captain Leonard Cheshire, V.C., was sent as British Service observer.

The devastation caused by the atomic bombs in Japan is now a matter of history. Manhattan District immediately sent parties of doctors and scientists into Hiroshima and Nagasaki to survey damage. Penney's talent came to the fore again.

"We did not know at that time", he told me, "how big the explosions were or what sort of blast accompanied them. There were theoretical estimates, but even in the case of the Nagasaki bomb, which had been tested beforehand at Alamagordo, these only gave large limits."

While other members of the party were busy asking questions and taking elaborate photographs Penney went about matters in his own, very personal, way. "There were squashed petrol cans there too," he told me, "and flagpoles bent over by the wind, panels that had given way under load, bits of concrete and bent tubing. I thought I could tell later what sort of loading had caused the damage and brought them back to England with me."

Penney normally looks a bit like a mischievous schoolboy who is enjoying a secret joke, but the twinkle in his eye turns to a broad grin that spreads right across his face as he remembers the day when he finally arrived back in Britain by Clipper. The £450 excess that he had to pay on his "collection" immediately made him a focus of interested attention among the Customs Officers at the airport, who, in 1945, knew little about atom bombs and nothing of Dr. Penney.

"A Customs man asked me what I had to declare and the chap just would not believe me when I told him the bags were full of old pipes and concrete and things", said Penney, with a chuckle. "He asked me to open them up and had a good look at the whole collection before finally deciding that I really must be crazy."

Dr. Penney went back to his old room in Imperial College and carried out his tests, obtaining the results he had anticipated. All the time he was thinking how pleasant it would be to become a professor again. The Ministry of Supply were not so keen to lose him, however, and after putting a good deal of pressure on him, directly and indirectly, they offered him the job of Chief Superintendent of Armaments Research. From being a junior professor he had suddenly sprung, overnight almost, into the head of a great mass of research and development establishments scattered over the length and breadth of the country.

Success did not go to his head. People who work with Penney find two words to describe him. "He is naturally democratic", one of his closest colleagues told me. "He does not attitudinise, either by conscious informality or heavy dignity. Meetings are conducted round a table and attention paid to what is said rather than to personalities. Sir William or anybody else may go to the blackboard to illustrate an argument or to draw a diagram, but certainly not with any idea of achieving dramatic emphasis.

"In a scientific establishment," he went on, "it is an advantage when the man in charge concentrates entirely on the subject under discussion, is explicit, economical and objective in his views, and invites comment in a matter-of-fact manner whether the subject is of a highly technical or general nature. Explicitness is a difficult thing to achieve, especially in highly technical matters that are frequently of a mathematical nature. It needs a remarkable mind to break through all the complications and to be able to define the fundamental difficulties or the broad conclusions that can be reached and that will determine whether a good deal of detailed work is worth doing or not."

Penney's ability to bring out the main lines of argument are very strikingly shown in mathematical analyses of physical problems, but atomic bombs involve many other sorts of problem as well, chemical, metallurgical and engineering, to name only a few, and Penney shows the same clarity of explanation in discussing all of them.

In the early days after his appointment he was to have little chance to visit his new domain, however, for no sooner had he said "all right" than the Americans decided to stage the first great Bikini tests, one of them intended to determine the effect of an air burst on ships and ground establishments and the second an underwater burst to discover the effect on a fleet at anchor. The Americans gave him the title of Co-ordinator of Blast Measurement and asked him to take charge of a large group known as the "Pressure Group (Cans and Drums)".

The name, perhaps, gives the wrong impression. There were many other gauges too, but all of the same crude sort. One type resembled a line of organ pipes or a harp and consisted of many tubes of graded width and length. The idea was that when the pressure wave hit the pipes the long, thin ones would bend most and the short, fat ones the least.

The Bikini test had been organised on a fantastic scale. There were 42,000 men taking part, 242 ships, 156 aircraft, 750 cameras, 5,000 pressure gauges, 25,000 radiation recorders, 204 goats, 200 pigs and 5,000 rats. The first of the bombs, dropped by a B29 with the finest bombsights, was intended to burst several thousand feet above the target fleet.

Blast waves are sound waves, and it is just as important to put a sensitive blast-recorder at the right place as it is to stand the right distance from a microphone when talking into it. For reasons that have never come to light the bomb landed, instead, several thousand feet from the point that had been selected. Some of the more complicated blast-recorders that had been carefully positioned beforehand were too near to the burst and the scales were quite inadequate to record such violence, whilst others were too far away and showed nothing. The "Cans and Drums" brigade not only proved the accuracy of the Hiroshima and Nagasaki blast deductions; they gave invaluable data on the new explosions.

One of the things that worried everyone who saw or studied the second Bikini test, where the bomb was exploded under water, was a phenomenon known as "base surge".

"The explosion threw an enormous quantity of water up into the air", Sir William explained. "The water broke into fine drops, so that after the explosion there was an enormous cylinder of water drops in the air with a cloud at the top. The average density of the air and water in the cylinder was higher than that of the air outside so that it quickly fell down again under the action of gravity. Then it went rushing outwards across the surface of the sea like a foggy, contaminating gas. Its movement was for all the world like a thin pancake mixture spreading as it is poured into a frying-pan."

The base surge was of great practical importance, because the column of collapsing fluid was thought to contain most of the deadly fission products after the explosion. When Penney got back to England, he set his men to work immediately on a series of experiments to try and determine at as little cost as possible how much water would be lifted into the air by such an explosion, and how it would behave.

In Britain, an island power depending on its sea-routes and ports, we badly needed to know the full extent of the danger. The way in which the answer was found demonstrated once again Penney's genius for improvisation and his way of seeing a problem in its simplest terms. "We made a glass tank", he told me, "and filled it with water. Inside the tank we put an open vertical waxed paper cylinder the inside of which was filled with coloured water laden with salt to make its density greater than that of the water. The cylinder was then pulled up and the column of coloured water at once began to spread over the bottom of the tank just as the column of wet mist or spray spread from the explosion over the Bikini Lagoon."

By varying the conditions of the experiment it was possible to match in the model the rate of spread of the Bikini base surge as published by the United States and thus discover the weight of water thrown up as mist at Bikini to be about 150,000 tons. Much later Britain was able to add to this information by full-scale tests.

[14]

The First Fruits

BRITAIN's first atomic weapon exploded in the Monte Bello Islands on October 3, 1952. It was not until three weeks later, on October 23, that the world learned from Sir Winston Churchill that a 1450-ton frigate, H.M.S. *Plym*, had been vaporised by the blast.

"When the planning began," Sir William Penney tells us, "a lot of thought was given to deciding which type of explosion would provide information and experience of the greatest value. Purely scientific measurements are most easily made when the weapon is placed at the top of a high tower, but there were other weighty considerations. The civil defence authorities in this country badly needed more data about atomic explosions and accordingly the test was planned to get as much novel information as possible for civil defence. The decision was thus taken to explode the weapon in a ship moored near land, thus simulating an explosion in a port."

The Ministry of Supply at once sought the help of the Deputy Chief of Naval Staff, Vice-Admiral E. N. Evans-Lombe. A committee was formed among the Ministries concerned and in May of the following year Rear-Admiral A. D. Torlesse was chosen to take command of the operation.

The ship, he was told, would not only have to carry the bomb. It would also have to function as an automatic transmitting station that would relay to a safe spot outside the range of the explosion a vast number of measurements from instruments distributed all over the ship until the moment when they, too, were vaporised by the atomic explosion.

A ship could undoubtedly be found among the vast number left over from the war. A bigger problem was where to hold the test. Out came the Admiralty charts. What was wanted, if the test were to be of real value, was a piece of water that resembled the estuary approach to a typical British port. It was no good choosing another Bikini or Eniwetok. They would have been of little use in solving a very English problem. In any case, many of the results of the Bikini test were already known. It was no good, either, choosing a place that would involve expensive and unpopular transfers of population or where winds might afterwards drive the poisoned clouds over inhabited areas.

Navy men who knew the western coast of Australia reckoned that a group of islands known as the Monte Bellos would take a lot of beating. They lie about ninety miles north of the tiny town of Onslow and there are about a hundred of them, surrounded by shallow and sometimes rocky waters. The largest of them are Hermite, Trimouille, North West and the Alpha Islands. On the west they are bounded by a coral reef. No-one lived in or anywhere near them and the only animals on the islands seemed to be rats, brought there probably by some ship that had been wrecked on the coast.

The Australian Government were consulted. They sent H.M.A.S. *Karangi* to make a preliminary survey of the area. When the survey proved the islands to be entirely suitable for the test, the Australians, ever ready to co-operate to the full, generously gave permission for the trials to be held there, sent H.M.A.S. *Warrego* to make a detailed survey of the treacherous waters, and offered substantial help in preparing the site and supplying food, water and everything else that was needed.

By August 1951 ships of the Royal Navy that were to take part had been chosen, refits planned, and even the dates of departure from Britain and arrival in the test area had been settled. They were adhered to almost exactly.

The ships chosen were the aircraft-carrier *Campania* (base ship and flagship of Rear-Admiral Torlesse), the "weapon ship" *Plym*, and three tank-landing craft. Refit in the *Campania*'s case meant doubling the wardroom and cabin space to house scientists who eventually outnumbered naval officers by four to one; the provision of specially fitted workshops, large stores, extra boats, extra plant for distilling water, and stores for the civil engineering works, the huts, towers, shelters, and the like that would be needed on shore. There were aircraft, too, three helicopters and two amphibians.

The tank-landing craft had plenty to carry as well on their long journey across the world. To start off with there were 800 men of the Royal Engineers and all their stores, building material and plant, besides quantities of technical stores for the scientists. They carried seventeen smaller landing craft with Royal Marine crews who had learned their job on the Normandy beachheads.

The secret had been well kept. The first news of the test came on February 17 of the following year when the Prime Minister, in a seventy-two word announcement, told of the test and assured the country that there would be no danger whatsoever from radioactivity to the health of people or animals. The Prime Minister's announcement had still given no details of the plans, however, and when, two days later, the first two ships of the squadron, the landing ships *Zeebrugge* and *Narvik*, sailed out of Portsmouth under Captain G. C. Colville, few knew of their connection with the operation. They arrived on April 26 and, helped by the Australians, work started at once on the task of preparing the site for the test.

To many the testing of any sort of bomb, even an atomic bomb, must seem a relatively simple affair, a little more complicated maybe than the annual expedition into the home garden on the night of the Fifth of November to set off the family fireworks, but certainly not a major operation costing millions of pounds. To scientists who still had only an insignificant quantity of nuclear explosive to show for the scores of millions of pounds that had been spent in Britain on the bomb's development, the position was very different. Nothing must be missed. Every scrap of scientific information that could be extracted from the test would be carefully recorded and analysed in relation to the rest of the data.

Electronic gadgets, Sir William Penney tells us, were the basis of nearly all the measurements and there were more than 300 of them, many grouped together in half-dozens and dozens.

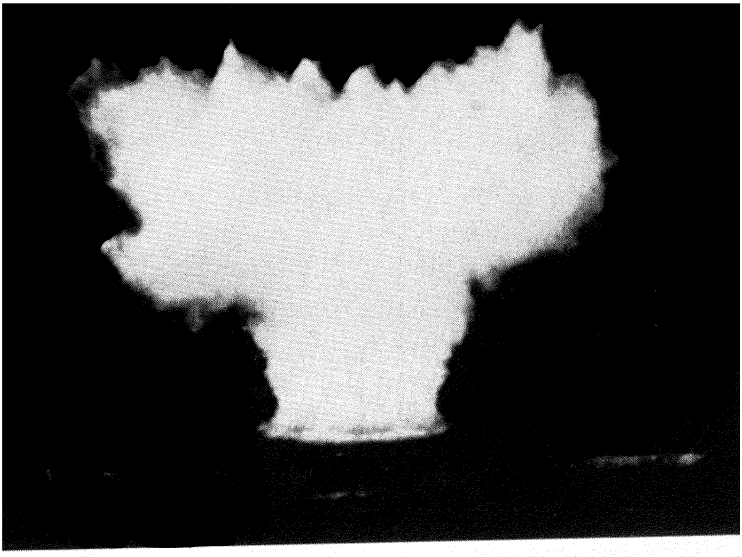
Some of them looked like television sets, but instead of a viewer watching a picture on a screen a camera was used to photograph the record. Many of the readings made by the instruments were radioed automatically to a control recording office in one of the ships.

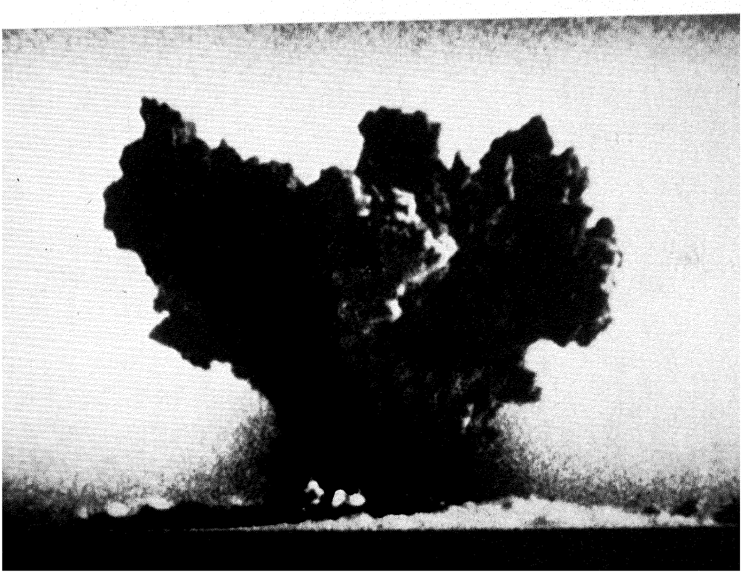
Cameras of all sorts surrounded the *Plym*, many of them very straightforward affairs, some to take still-pictures, others to provide a cinematograph record. When an ordinary bomb of T.N.T. bursts, the temperature produced is around 5,000 degrees Centigrade. In the case of an atomic bomb it is nearer a million. The pressure is of the order of hundreds of thousands of times greater than that of the atmosphere we breathe. When you think that a pressure of one single atmosphere more than normal will blow down a house like a pack of cards, you get some idea of the effect achieved by an atomic bomb when it bursts in the belly of an unarmoured frigate. It would not take long, certainly less than one-thousandth of a second. In one-tenth of that time the incandescent ball of gas would already be 100 feet in diameter.

It was those early moments that the scientists were most anxious to capture. The average cine camera takes 300 times as long to get a single photograph, so that would not do. Nor would more specialised apparatus already designed by scientists for split-second work. The atom men had to set to work and design their own.

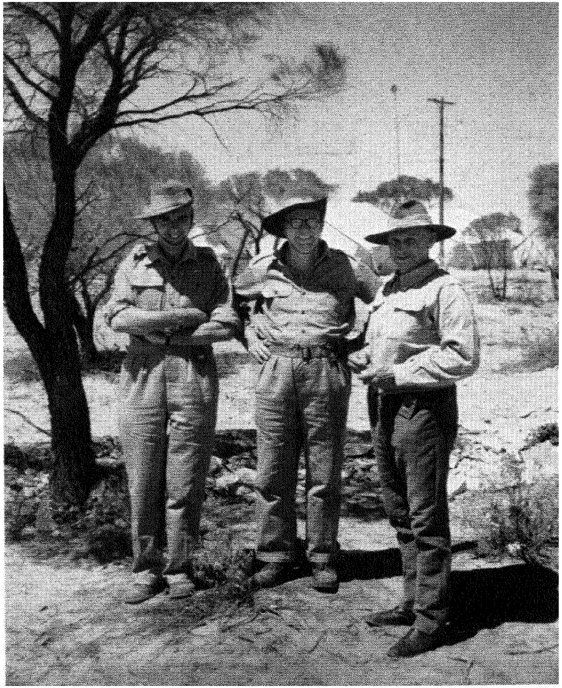
But young scientists in Britain have always been encouraged to make shift for themselves when novel apparatus is required, and the ability to devise the right gadget and then produce it has become a traditional part of the research worker's training. The museums of the Cavendish Laboratory, of the Clarendon and of the Royal Institution and so many others are full of such ingenious devices. The answer that the scientists of Sir William Penney's team produced for their new problem was worthy of earlier tradition. It was a camera which was capable of taking nearly 100 separate high-quality photographs in one ten-thousandth part of one second. The exposure time of each photograph was one ten-millionth of one second.

Such a camera is required to get pictures of the early stages of the explosion of an atomic bomb on a tower. The Monte

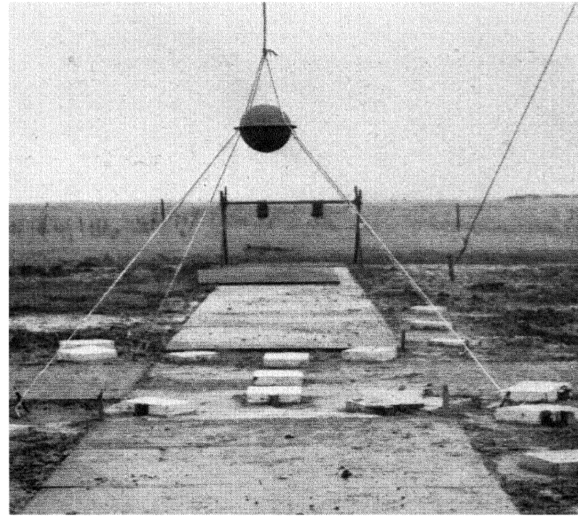




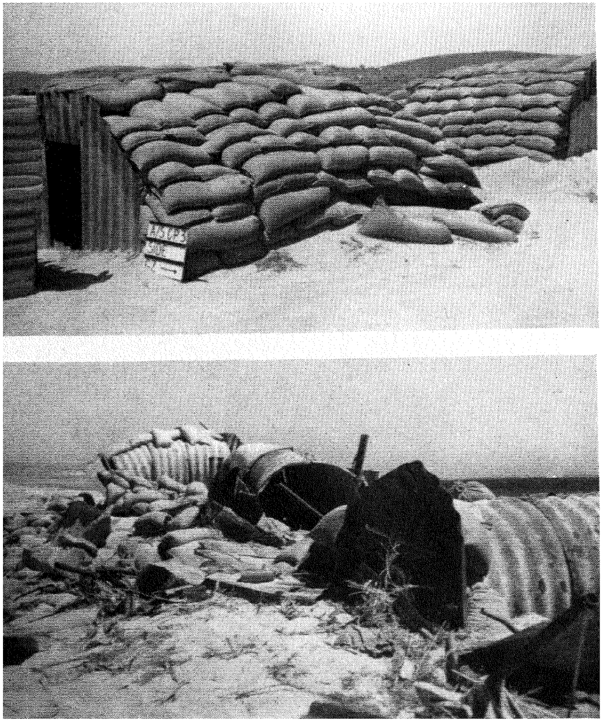
8 and 9. The detonation of a small spoonful of conventional high explosive in a laboratory water tank under properly controlled conditions enabled Sir William Penney and his team to anticipate accurately the effects of exploding an atomic weapon in the hull of the frigate PLYM near the Monte Bello Islands. *Above:* the laboratory experiment. *Below:* the full-scale explosion.



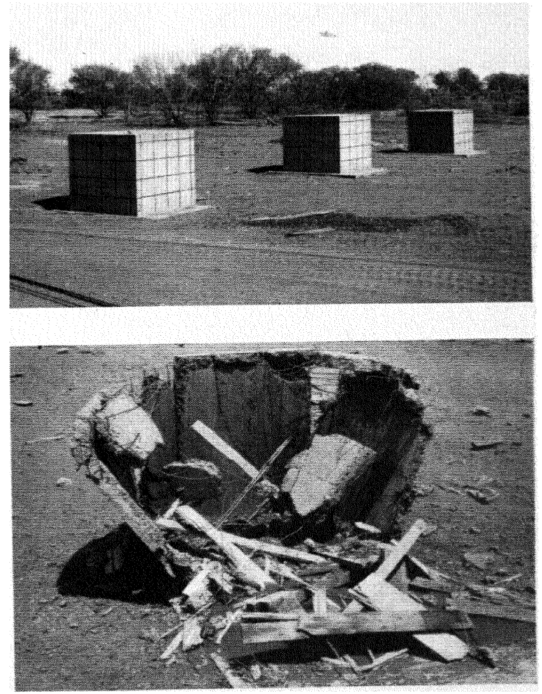
10. Mr. C. A. Adams, who directed the atomic weapons tests at Emu Field, in the Central Australian desert in 1953, with Sir William Penney, F.R.S., and Brig. Lucas, the military commander. Mr. Adams is now Chief of Research at the Atomic Weapons Research Establishment, Aldermaston.



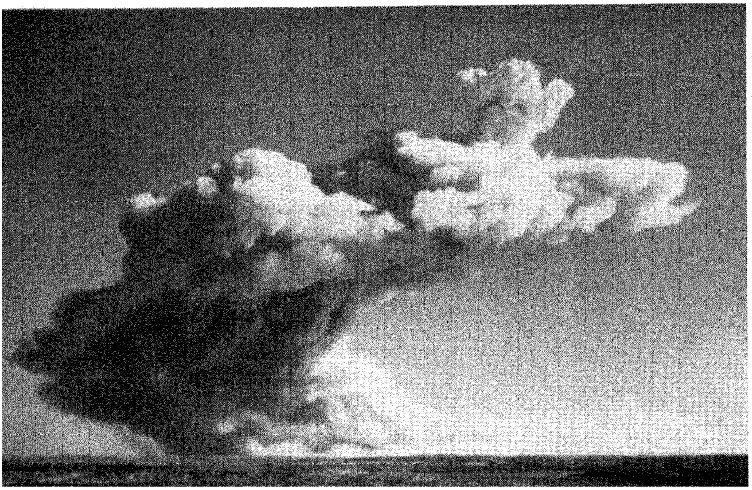
11. A large charge of conventional explosive is detonated over specially built concrete models on an island off the Essex coast to discover what the effect would be on the Admiralty Citadel in Whitehall of an air-burst atomic explosion. This photograph and those on the opposite page are here released for the first time.



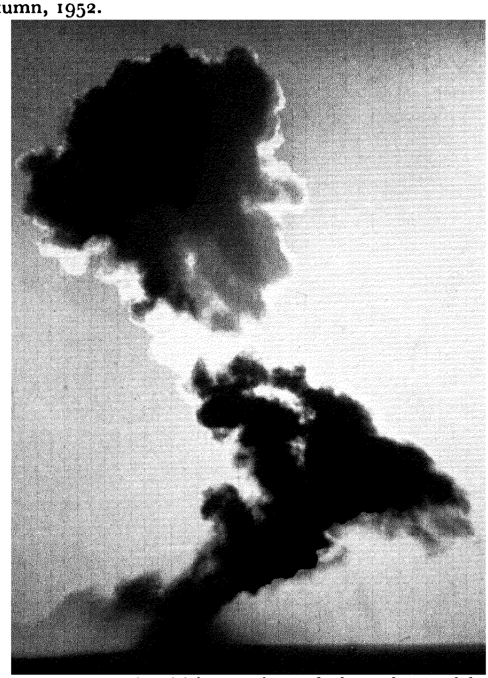
12. Typical sandbagged Anderson shelters before and after the Monte Bello explosion.



13. Carefully constructed models using scaled-down reinforcement and concrete ballast, before and after the desert explosion.



14. Cloud produced by the first British atomic explosion in the Monte Bello Islands in Autumn, 1952.



15. The second British atomic explosion witnessed by the author one year later in the Central Australian Desert produced a much smaller cloud, chiefly because of the lack of local moisture.

Bello explosion, however, did not need such rapid photography because the ship covered up the very early stages. The camera was therefore run at one-tenth of its maximum speed.

Men of the Royal Engineers and the Ministry of Supply had the job of installing all these devices. There were concrete emplacements and shelters to be built, jetties, power stations, stores and accommodation, mainly tented, for the men who would have to spend nearly a year on the site. The majority of the engineers themselves, to their credit, continued to live in the landing craft in the most spartan accommodation that had been intended to be occupied for a few hours only by invasion troops during the journey from their main base to their objective. With them too were a small nucleus of men from the R.A.F., doctors, scientists and those responsible for ferrying equipment between Britain and the Monte Bello site.

When the frigate *Plym*, already bearing the means of its own swift end, arrived off the Monte Bellos on August 8, 1952, escorted by the aircraft carrier *Campania* and the landing craft *Tracker*, warships of the Royal Australian Navy were already patrolling a great stretch of ocean. The same day the whole area was declared a danger to shipping. On shore security men were busy checking newcomers to the tiny port of Onslow, protecting activities at the naval dockyard of Fremantle, further to the south, and keeping a close eye on all aircraft movements to make sure that a ban on flying over the area was not broken.

While all these preparations had been going on, meteorological experts, including two Australians from Melbourne, were busy sorting through past records of the area to assist them in their task of predicting a suitable day for the test. Weather was one of the big worries. An engineer and a scientist between them can legislate for most things, but they still cannot control the winds. Weather, in fact, provided the planners with some of their most anxious moments. One of the worst of these came right on the eve of the test.

In order to have winds in the right direction at that time of the year, winds, that is, that would blow the fission products, contaminated salt spray and explosion debris far to the north, where they would scatter and lose their potency long before they struck human habitation, the planners had to choose a period of strong winds both on D-Day and D—1, the day before the test.

They were strong all right. So strong, in fact, that even the navy men began to wonder whether the scientists would be able to go round to the various islands beforehand to set their many instruments. It was touch and go, but the sailors and the marines between them managed it and by nightfall the scientists, soaked to the skin, were able nevertheless to report to base that all their many devices were ready.

There was still one more worry. Would the weather hold? Would the winds, now southerly, remain long enough to blow the deadly products northwards out of harm's way, or would the test after all have to be put off? They need not have worried. The weather-men were dead right, as time showed, and the following morning, after the area had been completely evacuated by all but the firing party, the time clock was started.

Penney was on the deck of *Campania* with Admiral Torlesse and most of the ship's company. They faced away from the *Plym* as the last few seconds were counted out over the loudspeakers. Then there was a great flash that reached the far horizon. Even Dr. Penney, who had witnessed the first historic atomic cataclysm in the desert at Alamagordo and later seen a bomb burst over Japan, described the scene as "terrifying" as he turned round to find the frigate *Plym* had vanished and to see a great greyish-black cloud shooting up thousands of feet into the air and ever growing in size. Over the islands a great dust-storm suddenly sprang up.

It took the noise of the explosion a minute to reach the party on *Campania*. They were ready for the first bang. The second, which came several seconds later, took them completely by surprise, and then came the peculiar sensation in their ears of making a sudden descent in a lift. They were feeling the suction wave that follows a great blast. And fourteen miles away the great black cloud moved steadily upwards to form after ten minutes the shape of a great letter "Z" as strong winds, blowing in quite different directions at different heights, pulled the column of smoke into a great twisted spiral.

The bomb had worked. The hundreds of instruments distributed around the different islands had worked. The records had flowed steadily into the radio rooms of the *Campania*. A later analysis showed that the record was complete and would provide invaluable data to those who were planning to protect food supplies in war and the lives and health of the men and women working in the many ports and harbours that form a vital part of the nation's lifeline.

The double bang immediately prompted many to suggest that a hydrogen bomb had been used to blast the *Plym*. The real explanation, as Dr. Penney later confirmed in his broadcast to the world on November 7, 1952, was a much simpler explanation. The first bang had reached them by the straight and quicker path. The second was provided by a shock wave that had travelled upwards and been bent down again by a layer of warmer air some two miles up.

[15]

The Project Grows

NEITHER the scientists at Harwell nor the engineers at Risley had been content to confine their thoughts to simple, air-cooled reactors suitable exclusively for the production of nuclear explosive. No sooner had each of the establishments made adequate dispositions for the GLEEP and BEPO piles at Harwell and the two production reactors at Windscale than they formed small groups to discuss other possibilities for the future.

At an early stage in the North when they were really hard put to find engineers to deal with more immediate jobs on their hands, Kendall, then in charge of the Windscale piles, had still argued that "if we are so desperately short of designers that we cannot afford to maintain a mixed squad of ten people to work on more advanced ideas, we might as well chuck in our hand".

Permission was given for them to go ahead and they went down to Harwell to talk the matter over with Dr. Dunworth, head of the Reactor Physics Division, and Compton Rennie and others who were already engaged on similar studies. "We have nothing that we actually have to do," they told the Harwell men, "but we want to keep thinking."

The American war-time project had already demonstrated that many different types of reactor were possible and suggested a number of profitable new lines of exploration but it did not disclose details. Britain's resources were a good deal more limited, however, and it was important to choose carefully the types of reactor on which to concentrate the available effort. The selection depended clearly on what each reactor was required to achieve and on the fuels and structural materials likely to be available.

The first reactor ever built, Fermi's pile in Chicago, had one purpose only, that of proving that such a thing could work at all. More since then have been built to manufacture explosives, to test structural materials, to manufacture ray-emitting radio-isotopes needed for medicine, research or industry, to generate electricity, to propel submarines and to facilitate the designing of atomic bombs. Others are being designed at present in various parts of the world to do the same jobs in a different, more efficient way. At least two are being designed to drive aeroplanes, others for rockets, and a number to propel such large ships as aircraft-carriers and ocean-going liners.

The design requirements in each of these cases are very different. In one, lightness would be essential; in another it would be of no importance at all; in another vast amounts of heat would need to be extracted, while in some types so little heat is produced that no special arrangements need be made for removing it.

GLEEP, the first British pile to be completed, was strictly a research and materials-testing reactor. If the suitability of a particular metal for use in a later pile were in doubt or its purity were in question, it was only necessary to place a specimen inside GLEEP to find out immediately its effect on the chain reaction. Impurities in some cases of only one part in a million were easily detectable.

Piles of this sort, based on natural uranium, inevitably needed very large cores to cut down the effect of neutron escape to the exterior. GLEEP, for example, had a core in the shape of an octagonal prism 17 ft long and nearly 19 ft in diameter.

The total quantity of graphite used was 505 tons. The blocks were stacked in forty layers, each layer being arranged like a parquet floor. The whole assembly was based on a fundamental distance of 7¼ inches between rods of fuel that were carried in diamond-shaped channels in the graphite.

Because of the shortage of uranium metal at the time when the pile was built, metal itself was only used in the centre while uranium dioxide was used in the outer portion. The metal was in rods or "slugs" a foot long and 0·9 inch in diameter. These were sprayed with a thick coating of aluminium to prevent corrosion and escape of fission products that might otherwise be ejected from the bars by the force of the fission process.

The uranium dioxide was pressed into pellets wrapped in paper containers and packed in aluminium tubes. The pile contained altogether twelve tons of uranium metal and twenty-one tons of uranium dioxide.

In the Canadian reactors, of course, the slowing down of neutrons was achieved even more effectively by the use of heavy water. The water had to be "heavy", it will be recalled, because hydrogen atoms of ordinary water, although ideal in size for the slowing-down process, have the defect that they absorb neutrons at slow speeds before they have a chance of reaching other atoms of uranium 235. The exception to this is when enriched fuel is used.

In one of the latest American reactors, that intended to power the submarine, *Sea Wolf*, a compromise has been struck between hydrogen, of atomic weight 1·0, and graphite of weight 12, by using the lightweight metal beryllium (9·013 units). This metal is in many ways better suited to the task than graphite, and engineers would have used it before, both as a moderator and also as a protective sheath for fuel elements. They were prevented from doing so in the early days by the difficulty of obtaining sufficient quantities, by lack of data about its properties, and because of doubts about using a substance known to be extremely poisonous.

In the other American atomic submarine, the *Nautilus*, ordinary water was used as a moderator. The fuel was enriched in uranium 235 content to make up for losses of neutrons in the water. Piles using ordinary water either as a moderator or as a coolant are very attractive from many points of view but are, as has been seen, inherently dangerous, in that if for any reason the supply of water fails, or is turned to steam, a source of neutron wastage has been removed and the reactor might heat up. It might become "super-critical" and destroy itself, releasing fission products over a wide area.

During the early years of the British project the shortage of weapons-grade or enriched fuel meant that much of the design work had to be concentrated on bulky slow neutron reactors and at a very early stage initial studies were completed of a reactor of this sort for submarine propulsion. The project was shelved when it was found that a reactor based on natural uranium, the only fuel available, would be far too large for the sort of submarine that the Navy had in mind. While it would probably have done for an aircraft-carrier, there was not at the time considered to be sufficient call for an atom-powered carrier to justify the effort needed.

The whole design position changed the moment it was decided to extend the gaseous diffusion factory for the enrichment of uranium already under construction at Capenhurst. This factory was at first intended only to rejuvenate uranium already once used in reactors and to provide small quantities for use in research.

With the promise of enriched fuel ultimately being available, it was possible to contemplate a completely new range of reactors, smaller in size, lighter in weight, and using construction materials like steel, and coolants like ordinary water under pressure or molten metals like sodium or potassium. This represented an enormous step forward.

The size of the reactor core could in extreme cases be reduced from something the size of GLEEP or BEPO to that of a football or a four-gallon petrol tin, if very pure fuel were used, or of from six to twelve feet across if the fuel employed were only partially enriched.

The new technical possibilities were obvious to all, but atomic energy planning was still dogged to a certain extent by the conviction that power generated in this fashion would be far more expensive than that generated by conventional methods. However, a few at Harwell saw the future in a different light and among them was R. V. Moore, a young engineer in the group that had taken over BEPO from the Risley organisation.

Moore, I am told, is a typical example of the young university-trained engineer in the atomic energy set-up, one of those whom Owen had described as coming up "the easy way".

A pleasing young man in his middle thirties, with wavy brown hair, he speaks with a friendly cultured accent, looking often at his fingernails but never biting them. Like most of the atomic energy set, he is firmly addicted to the blackboard habit.

He uses it as his diary, and reminders, in blue and white chalk, to take home frozen peas to his wife mingle with power curves and a list of letters he has to write.

Moore served an engineering apprenticeship in the electrical supply industry and at the same time studied for his degree at London University, attending the firm in the morning and going to lectures at the Battersea Polytechnic and King's College in the afternoons. He graduated just before war broke out and was with the Navy until he joined Harwell in 1946.

After the completion of BEPO he worked with others on the submarine-propulsion study for a bit, but in his spare time he gave a lot of thought to the economics of nuclear power. At that time the outlook was not particularly bright. "It is difficult to give you now the feeling of the time", he told me. "A lot of people had the idea then that it would only be of military significance for tasks like the propulsion of submarines and the like."

Moore wrote a paper in which he considered the question in the light of information then becoming available from the operation of the Windscale production piles. It suggested that power stations could be built to produce energy at prices comparable with those of conventional generating plants and caused quite a stir at the time among the few people in the secret. A big conference was called soon afterwards to discuss progress that had been made to date. All the important people were there. British Electricity Authority engineers were invited for the first time. There were many university people who had been acting as consultants on various aspects of the programme, and some, too, from industry.

The meeting was a sort of symposium. There were other papers read, too, which looked into the possibility of what sort of reactors could be built, but it was Moore's paper that caused real excitement. It was decided that Harwell men should proceed at once to design studies for such a power station, which Moore had called PIPPA.

Mr. B. L. Goodlet, another engineer, and Moore, with the co-operation of many of their Harwell colleagues, spent two years on their basic studies and by February 1952 completed their drawings and estimates of cost, performance and time scale.

Completion of this work, as it happened, coincided with a request from the Joint Chiefs of Staff for the production of more plutonium, and Sir Christopher Hinton, after discussing the matter with Sir John Cockcroft, asked to see Moore.

"I went up to Risley with all my papers," he tells me, "and Hinton and Owen spent two days going over them together in the greatest detail. At the end of the second day they made their decision to build two of them." Moore moved to Risley as deputy to Cunningham, and when Cunningham became seriously ill, took effective charge of a project which was destined to provide the world with its first large-scale atomic power station, the one at Calder Hall.

"There was nothing really scientifically new about the PIPPA piles at Calder Hall as far as the British project was concerned, but many engineering problems had to be solved before a definite design could be evolved. The fuel elements of the Windscale production piles had been fin-shaped, instead of simple rods, to make cooling easier and cheaper, but the cooling air was passed up a high chimney to dissipate the heat into the atmosphere to save the extra time that would have been needed to provide a more efficient but necessarily more complicated system."

In the PIPPA piles the cooling gas, carbon dioxide under pressure instead of air, is recirculated through the pile after passing through boilers or "heat-exchangers" where steam is raised to drive the dynamos that provide electricity.

The scheme employed is extremely simple in principle. In each pile the fuel rods are arranged vertically in a honeycomb of graphite blocks built up within a vertical steel cylinder known as the "pressure vessel".

The cooling gases leave from four exits around the side of the dome-shaped top and are conducted to four "heat-exchangers" which are really vertical boilers. Inside are many dozens of water pipes around which the hot gases circulate on their way down. The water thus cools the gas and gets boiling hot in the process. The more efficient the design of the vessel, the more effective will be this exchange of heat. The gases can then be pumped back into the pressure vessel while steam produced is used to propel turbines of precisely the same sort as are used in a conventional coal-burning power station.

Nuclear power stations of this sort have been referred to by Harwell scientists as "Model T" ones, recalling the simple but very reliable early Ford motors. Their "thermal efficiency", that is to say, the proportion of the heat that they can turn into usable electric power is expected to be only 20 per cent, as opposed to the 30 or more per cent realised by a modern conventional station. The figure could be at least 25 per cent were it not for the fact that the need to produce plutonium is still of paramount importance to national defence, and sacrifices have been made in thermal efficiency to produce the maximum yield of this nuclear explosive.

The Calder Hall station is, of course, an experimental one and much may be learned from its operation. Although the PIPPA piles are the first of any size in the world to be used to generate power, they may still be considered to be of fairly conventional design because they embody theories and techniques that have all been individually well proved.

Of far more interest both to scientists and engineers is the advanced type of reactor now under construction at Dounreay near Thurso on the north-east coast of Scotland. This, to start off with, is a "fast" reactor, which means that the neutrons are not slowed down by any moderator. To make this possible it will use fissile material, plutonium or uranium 233 or uranium 235, of a high degree of purity. The size of the core is, as a natural consequence, very much reduced in size and will in fact be a cylinder two feet in diameter and two feet deep.

The problem of removing the heat from such a small core is tremendous. Sir Christopher Hinton has stated that from every square centimetre of surface, the area of an average fingernail, the amount of heat to be continually extracted is equivalent to that produced by a single-bar domestic fire. To do that liquid metal must be used, and this must be cooled in turn by heat-exchangers outside the pile.

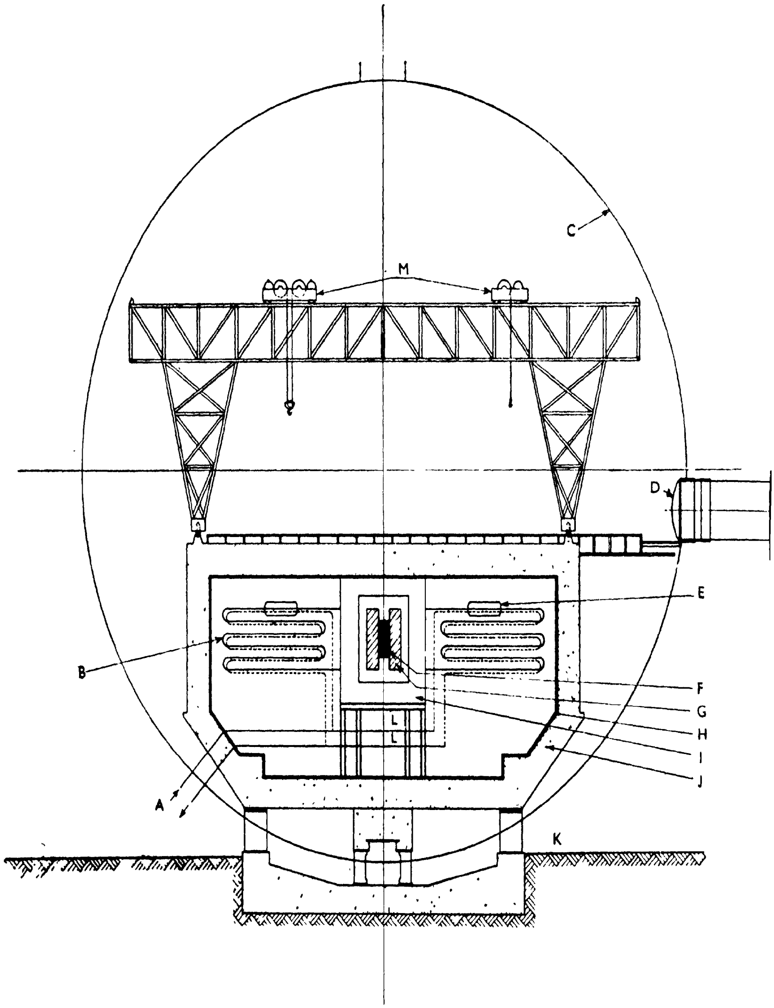
Potentially the most interesting part about the pile is that it is designed in such a way that surplus neutrons produced by the chain reaction will be absorbed by a blanket of "fertile" material to produce new atoms of primary fuel. In early experiments the fuel used in the core will be uranium 235 and the fertile material in the outer blanket will be uranium 238. This is purely because more is known about these materials than is known of others like plutonium and thorium. It is most unlikely, however, that the filling will be the same in later and more advanced models.

The fact that "breeding" is feasible has already been proved to be so by experiment, first in the United States and then with the aid of a fast neutron research reactor of zero energy, known as ZEPHYR, at Harwell. Not many months after both American and British scientists had announced with some pride that this breeding process had produced one new atom for every atom of fuel consumed, the United Kingdom Atomic Energy Authority was able further to announce to the Geneva International Conference on the Peaceful Uses of Atomic Energy in August, 1955, that on a purely experimental basis they had been able to *double* the amount of fuel produced and generate two new fuel atoms for every atom burned up.

The design of the Dounreay reactor core represents a compromise between the views of physicists, who, ideally, would like to keep the investment of fissile material as low as they can by using the smallest possible core, and those of the engineer, who, while equally keen to economise in fissile material, must find room for structural materials and coolant and needs a more dilute core.

Even in such a small core the amount of fissile material used is very great, for a cubic foot of uranium weighs well over 1,000 lb and would suffice for many atomic weapons. The concentration of the energy source within such small dimensions inevitably brings with it a new hazard. All is well so long as the liquid-metal coolant flows according to plan and is in its turn cooled by the heat-exchangers. If the cooling system should fail, however, there is the possibility that the heat within the reactor core will rise to such an extent, in spite of various safety and emergency shut-down measures, that the fuel slugs will become badly damaged, if not vaporised.

To take care of this possibility a great gas-tight sphere of two-inch-thick welded steel plate, nearly as big in diameter as the dome of St. Paul's Cathedral, is to be erected around the reactor. There is little doubt that this extra safety measure will take care of any contingency and prevent the scattering of



An advanced type of atomic reactor at Dounreay which is designed to produce more nuclear fuel than it consumes, while at the same time providing substantial quantities of heat energy for the generation of electricity. As an additional safety measure it is enclosed in a great sphere of steel made of plates one inch thick.

Arrangement of the Dounreay Fast Reactor Shield.

A. To secondary heat exchangers
B. Primary heat exchangers
C. Steel sphere
D. Airtight door
E. Electro-magnetic pump
F. Reactor core
G. Breeder blanket
H. Thermal shield
I. Inner shield
J. Biological shield
K. Ground level
L. Coolant pipes
M. Hoist

radioactive materials over the surrounding countryside if anything went wrong.

Dounreay is one of eleven nuclear reactors completed or under construction within the United Kingdom Atomic Energy Authority establishments. A further six PIPPA reactors are on order for the Authority, and at the time of writing sixteen reactors are planned by the Central Electricity Authority for their short term industrial power programme.

This represents a formidable achievement in a period of ten economically-difficult years. The importance of the reactor programme (listed below) lies not so much in the numbers as in the diversity of ideas employed and the basis they provide for further advances.

Reactors completed or nearing completion on January 1, 1956

GLEEP (Graphite Low Energy Experimental Pile). Natural uranium metal. The first atomic pile in Britain. (August 1947.)

BEPO (British Experimental Pile O). A research pile of moderate energy (6,000 kW), graphite-moderated natural uranium, air-cooled, heats buildings. Prolific source of radio-isotopes. (July 1948.)

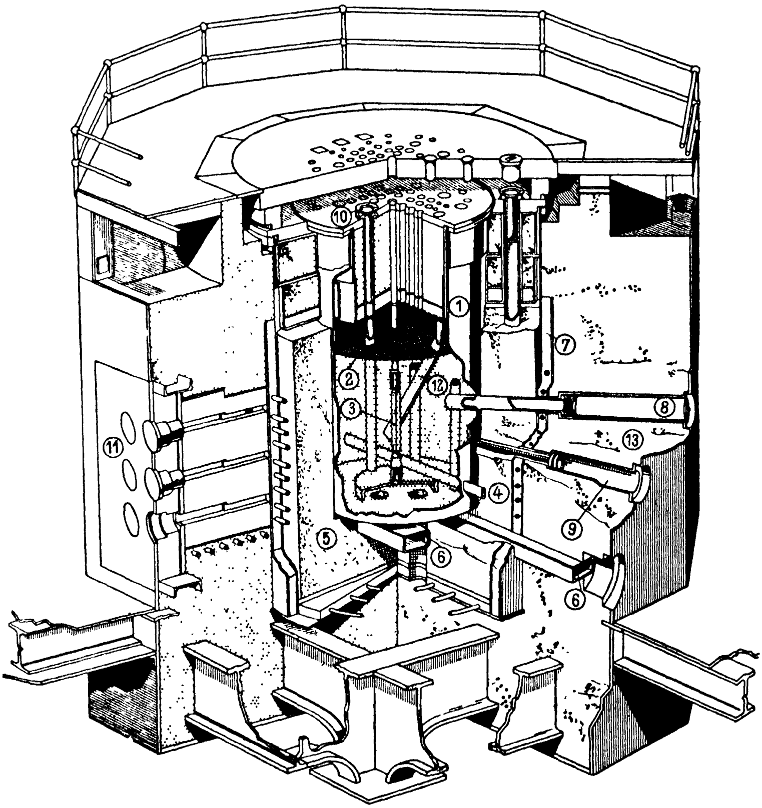
WINDSCALE. Two full-scale plutonium-producing reactors, air-cooled. Built for military purposes. Output never disclosed. Completed 1950.

DIMPLE (Deuterium-moderated Pile Low Energy). First of the British heavy water piles built as pilot to further, larger neavy water reactor.

ZEPHYR (Zero Energy Fast Reactor). Built to investigate materials and general problem of breeder and fast reactors and to pave the way for Dounreay reactor.

Two PIPPAS at Calder Hall, Cumberland. Britain's "Model T" industrial piles providing steam for a power station, the first full-scale industrial plant in the world, with turbo-alternators for electricity generation comparable in size with those of conventional coal-burning generating stations.

DIDO (E443) at Harwell. A full-scale high-flux heavy water research reactor and for isotope production. Completion date 1956. 10,000 kW.



A sectional view of the heavy water reactor Dido at the Atomic Energy Research Establishment, Harwell. Jobs which took a year to do in earlier British reactors can be performed by Dido in a fortnight.

1. Reactor aluminium tank containing heavy water
2. Level of heavy water
3. Fuel element
4. Experimental hole
5. Graphite reflector
6. Experimental holes
7. Water-cooled thermal shield
8. Experimental hole entering heavy water
9. Experimental hole entering graphite
10. Vertical experimental hole
11. Thermal column of graphite to provide beam of thermal neutrons
12. One of six control arms
13. Concrete biological shield

DOUNREAY. A fast neutron reactor using no moderator and designed to breed more fuel than it consumes while at the same time providing sizeable amounts of heat energy in the form of steam for power generation. Provisional rating, 15,000 kW of delivered electricity. Completion due in 1958.

ZEUS (Zero Energy Uranium System). A full-size pilot model of the Dounreay fast reactor but operating at zero energy. Built at Harwell to gain information on fast reactor problems.

PLUTO (RE775) at Harwell. A full-scale high-flux heavy water research reactor intended for testing out complete units and assemblies under high flux conditions. Completion due 1957. A duplicate of Pluto is being built at Dounreay.

* * *

In the days when the plutonium factory was planned it was assumed that the atomic reactors and the primary separation plant, which is the most active area, would be run until there was a serious breakdown and then they would have to be discarded and others built.

One of the biggest achievements of the Windscale team, in Davey's opinion, was the way they demonstrated that this need not be true. The discovery was due in great measure to a young London University chemistry graduate, Mr. Tom Hughes, who runs the primary separation plant. After some initial operating experience he inevitably saw means of modifying and improving parts of the plant if only this were possible. Ultimately he expressed the conviction that if the plant were washed out repeatedly so that solid matter like sludge could be removed, it would be possible to enter and stay for a short time under carefully controlled conditions.

Hughes talked the matter over with Mr. Donald Fair, manager of the Health Physics and Safety Department, and together they worked out details of what later became regularly known as a "planned entry". They then put their idea to the test. It worked as they had forecast, and overnight changed the whole economics of atomic factory planning. Subsequent work showed that most of the chemical plant could be entered for short periods if the right rules were observed.

Davey could not tell how many planned entries had been made. They have become now a matter of routine. No man goes in without holding a personal clearance that states what work has to be done, the precautions that have to be taken, the special clothing that has to be worn, and the time that he is permitted to stay on the job. This certificate is filed at the end of the job. No-one can instruct him to stay longer than the time stated. It is a very specific document and even a senior engineer would not go inside without one, nor would any man dream of telling another that he could stay five minutes longer than the document stated.

As part of this work, even cutting of plant, which is all stainless steel, and re-welding has been done. They have, for example, drilled a hole in the top of a plutonium evaporator and examined it, and then, when they were satisfied, sealed it up again. Three years ago it was considered quite impossible to do work in a plutonium plant.

The clothing first used for such work was of thick rubber and very much like a frogman's suit. Nowadays, instead, they wear what looks like an inflated polythene bag with a great "tail" through which air is pumped. Made of transparent, paper-thick plastic, it is so light that the body does not feel enclosed. A man is much more comfortable, and by totally enclosing him there is the guarantee that he cannot breathe even an infinitesimal amount of plutonium. The material is tough and has stood up well to many tests.

Just how much the planned-entry system has meant to the atomic energy industry may be judged from the fact that a chemical process plant to serve the nuclear power station on the nearby site at Calder Hall would, in Davey's estimation, have cost £7 million or more. As a result of modifications to the primary separation plant at Windscale over the past two years the "through-put" has been considerably increased so that it can deal with all the fuel elements from Calder Hall. Further modifications now planned may enable Windscale to cope in addition with irradiated fuel from many of the reactors to be built under the £300 million nuclear power scheme.

[16]

Capenhurst—an Engineer's Dream

ONE of the most secret and rapidly expanding establishments in the British atomic energy project, outside the laboratories and factories where weapons are designed and made, is the great factory at Capenhurst in Cheshire, where uranium 235 is separated from the heavier and less useful uranium 238 by the process of "gaseous diffusion".

Long after everyone interested in atomic energy knew what this establishment was intended for, officials still refused to confirm the fact. Even now they adopt a subtle change of tone when they discuss the factory, as if they are afraid of being overheard.

Harwell has been described a little inadequately as a paradise for physicists, and Springfields and Windscale, with equipment unrivalled anywhere in the country, represent the ultimate in chemical engineering. Long before I was ever allowed to visit the Capenhurst factory, I heard top men in the atomic energy project describe it as the "mechanical engineer's dream". With its diversity of finely finished mechanical pumps and compressors and remote controls that have to operate for a year or so continuously without overhaul, it is certainly something that the mechanical engineers may be proud of, but the story does not end there. There are ample problems for physicists and chemists, too.

Capenhurst is situated on the long peninsula between the rivers Mersey and Dee known as the Wirral. To the north and south of it along Merseyside are a long succession of oil refineries, detergent factories, shipyards at places like Birkenhead, Port Sunlight and Ellesmere Port. Further north and to the west are the seaside resorts of Wallasey, New Brighton, Seacombe and Hoylake. Some say the area is damp and bad for the chest, but others are just as prepared to swear by its health-giving properties. To the visitor it is like a piece of well-cultivated delta country with a long succession of factory chimneys along the northern skyline.

The factory has two main purposes and its two plants cover an area four times the size of Paddington Station. The first is for the rejuvenation of the depleted uranium that has been used as fuel in the production piles at Sellafield. As fuel only slightly enriched in uranium 235 is required for the production piles, this plant is comparatively small. The second plant carries on the enrichment process until it is nearly 100 per cent when the separation of the two isotopes is nearly complete.

There are two calls for this extra-pure uranium 238. The main one is the supply of weapons-grade explosive and the second is the production of fuel for fast reactors of the Dounreay type. The process used is the same in each case. It depends on the fact that if you have a mixture of two gases in contact with a porous membrane, the lighter gas will leak or diffuse through the pores of the membrane more easily than the heavier one. In an ideal system of this sort the speeds at which the two gases pass through the barrier will be directly related to their weights by a simple mathematical formula. Many other factors influence the efficiency of the process, however. The pressure on each side of the membrane will obviously have great effect, and so will temperature.

In the case of uranium separation there are several additional difficulties to be faced. There is for a start the fact that it only forms one suitable gaseous compound under reasonable operating conditions of temperature and pressure. This is known as hexafluoride, or "hex", and is formed by the combination of one atom of uranium with six of a highly toxic, incendiary and corrosive gas known as fluorine. Metals and other substances normally considered to be stable and unreactive, react violently in the presence of fluorine. Normally fireproof substances like asbestos burn fiercely when they come into contact with it, others react with it to form compounds that explode spontaneously.

The general principles of the separation process have been known since the early years of the nineteenth century when the physical laws governing the passage of gases through a porous barrier were first described. The explanation of the phenomenon is simple. It is that at any given temperature the molecules of a lighter gas move faster on an average than those of the heavier gas. From this it follows that molecules of the lighter one will pass through pores more quickly than those of the heavier. The method was used for the first time to obtain a partial separation of two isotopes of the element neon in 1913 by the British physicist Aston.

Another problem in the case of uranium is that the difference in weight is only 3 parts in 238 for uranium itself, and in the case of the hexafluoride gas is only 3 parts in 352, or less than one per cent. It means that even in theory each filtration will only enrich the mixture by 4 parts in 1,000. In practice this theoretical separation factor is never reached.

Ten-fold enrichment at this rate could only be obtained by filtering the gas 1,800 times in succession, while the nearly 100 per cent enrichment required for weapons purposes calls for about 4,000 successive stages.

An added complication was the fact that "hex" is a solid under normal conditions of temperature and pressure, and as pressure is used to force it through the membrane the tendency to solidify is further increased.

For this reason gaseous diffusion factories are bound to be large. The one at Capenhurst is about half a mile long and composed of 400 or more heat-proof "cells" each containing a number of units. Cells of this sort contain many compressors and pumps to keep gases circulating. The whole cell must be kept at tropical heat. No man can work for long in such a temperature. The compressors and pumps require such a large amount of electricity that the factory calls for the complete output of a large modern central power station.

The man responsible for designing and ordering the equipment of this great enterprise was Mr. Harold Disney, a shy man in a lead-grey suit, who told me, with obvious sincerity, "I find it more difficult to talk about my work than I did to do it".

Disney is one of the many men in the Atomic Energy Authority who have come up the hard way and in doing so have gained a rich and broad experience. He went to school in Ilkeston, near Nottingham, and was articled as an apprentice to Messrs. G. R. Turner Ltd. at Langley Mill. He went to evening classes at Nottingham University College and, after qualifying, joined the Alkali Division of I.C.I. During the war, he told me, he went over to the Royal Ordnance Factories, and when the atomic energy business started up, Sir Christopher Hinton asked him to join it. "The main problem for me", he went on, "was that we faced the building of a huge factory with a short target date and after limited development work. To this was added the difficulty of recruiting staff. No-one could have had any experience because the job had never been done before in this country.

"We had to produce a flow-sheet from scientific data, bearing in mind that the gases we were dealing with were highly corrosive. We had to try and foresee what sort of engineering problems would arise and evolve techniques to deal with them. In an entirely different job there was the problem of teaching the meaning of cleanliness in our particular context. There was, too, the big problem of getting uniform quality of material. The super priority was always the necessity of keeping everything so clean that nothing could happen subsequently to block up the pores, of which there are several million to every square inch of membrane separating the various cells."

Cleanliness was something which I was to hear a great deal more about later on when I visited the factory. Ralph Lyon, the labour manager, told me it was something which many of the men found it difficult to understand and some found irksome. There was, for example, the scaler and red-leader who had come from a neighbouring shipyard. "He came to us on a Monday", Lyon told me, "and gave in his papers on Wednesday because he found the job too clean and too quiet. That was an extreme case, but some effort is often necessary before a man from an everyday job or even from a chemical works can acclimatise himself to the standards required at Capenhurst."

Even the engineers had to get used to completely new standards. To most engineers a casting is clean by the time it has been machined and polished. Before it can be used in a gaseous diffusion plant, however, it must go through a whole series of special cleaning processes.

The difficulties of the diffusion process are increased by the fact that it must be partly conducted in a state of vacuum that was previously approached only on a small scale in the electric bulb industry. If there is any leakage of air or moisture into the system the effect may be disastrous.

Designing the factory and building it was a big-enough problem, but it was only the first of many. The next was that of getting it to work. Many names were associated with that achievement, but two of them became almost a legend. The first was that of the general manager, Mr. S. F. Hines. The other was that of Mr. Robert Alexander, the works engineer.

Hines, a forty-eight-year-old Londoner, who went to St. Albans school and the Imperial College of Science, is by training a chemist, but his main interests right from the start were in industrial management. He graduated during the slump period of the early thirties and took a research job but did not like it. Soon afterwards he applied for an appointment at the Royal Gunpowder Factory at Waltham Abbey, near London, and was soon running an experimental plant making T.N.T. by a new method. By the end of the war he was superintendent of a group of three ordnance factories up in the North.

When the atomic energy business started, Hines became general manager of the factory at Springfields, where they were processing crude uranium ore and turning it into finished fuel elements. In 1950, when work started at Capenhurst, he was asked to take charge.

The speed at which work was pushed on soon provided Hines with plenty of problems. "Because designs of plant compressors, pumps and the like were being modified more frequently than would normally be the case," Hines told me, "assembly commitments were transferred to our own workshops. It was a good thing in many ways because it gave us experience in techniques which would be encountered in plant maintenance. This gave my engineers more insight in matters of design, but to do this we had to build up quite a sizeable engineering team. There was also, of course, all the scheduled maintenance to be done all the time and 'crash' work when anything went wrong."

Hines reckons that his present task is the most interesting job he has ever come across. He has constantly to call upon the services of specialists in many different fields, chemists, physicists and engineers. Capenhurst probably employs a higher percentage of physicists than normally obtains in industry, and like the rest the majority of them come straight from school. There are relatively few who have had experience and all the time Hines has to concentrate on building the staff up. "In the main", he told me, "we recruit people in junior grades and these are people we look to to fill vacancies in more senior positions. I pay a great deal of attention to the question of training youngsters, and do a lot of it myself. I regard it as one of my most important jobs."

Teamwork, he believes, counts as much as anything else, and he pays a lot of attention to industrial morale. "If the management is working as a team it gives the labour force an example. A sense of unity is one of the first things that one must try to achieve. We do the same thing for the industrial labour force. We constantly try to get them to realise that we regard them as responsible individuals. In this part of England the industrial grades normally have the fixed idea that management is going to exploit them. That attitude takes a lot of breaking down. You must be continually at pains to show them that there is no question of exploitation."

To illustrate his point about the need for *esprit de corps* and teamwork in the factory Hines told me of a typical case where all had pulled together to meet an emergency. "There was a particular heavy maintenance commitment", he told me in his typical unemotional factory jargon. "It required all possible effort to be concentrated on the job. The work had to be completed without interruption of the process going on within the plant. My maintenance men", he told me proudly, "without exception carried on right to the end."

[17]

The Second Bang

AN ATOM bomb explosion, even when seen from a safe distance, is something not easily forgotten. I'd hate to see one from near at hand. The one that I was privileged to witness was the testing of Britain's first operational weapon. It took place on a remote claypan in the Central Australian "desert" shortly after dawn in November 1953. Even in the Southern Hemisphere, where the seasons are reversed, it was unmistakably cold, in spite of the extra clothing that we had all been warned to wear.

There was an eerie atmosphere about it all In spite of the fact that the world by then was used to atomic bombs and about forty had been exploded in one part of the world or another, we still had, all of us, a strong feeling of awe. We felt that we were part of a great conspiracy to brave nature. Even James Cameron, the veteran foreign correspondent of the *News Chronicle*, who had seen two tests before, shared our feeling of being in a world ringside seat on a great occasion.

The events of the past few days had contributed strongly towards it. The sense of the unusual had mounted steadily since the moment when the group of newspaper correspondents had reported to the Australian Government Office in Melbourne from places as far apart as Sydney, London, Singapore and Korea. The Australian authorities confessed that they were worried about us. They knew that some of us were personal friends of scientists taking part in the test and their orders had been to ensure that there was no contact between us beforehand. Half of the security officers of Australia, it seemed, had been detached to guard the bomb itself, secure enough as it was in its desert fastness; the other half, disguised thinly at first as guides, catering officials and "government historians", had been told to watch the press corps.

We were billeted in what were intended soon to be the women's quarters of a military aerodrome then being established in the old ammunition factory at Salisbury, sixteen miles from Adelaide. There was barbed wire all around the camp and there were sentries at the gates. Every morning during the days that we waited for weather to favour the explosion we were called together at breakfast-time by our "guides" and asked what we wanted to do that day. By remarkable and carefully arranged coincidence that surprised us at first there was always a police car about to go in the very same direction, and since none of us could afford too often to call in a cab from Adelaide we were usually very glad to accept the offer of a lift, even when it entailed an escort.

For our guides, who were the kindest and friendliest lot of security men I ever hope to meet, it was a problem of persuading us to stay in groups as far as possible and not to go in a dozen different directions. It meant fewer men to keep an eye on us and gave a few of them the chance to take time off. The task of suggesting activities that would appeal to us got steadily more difficult. We visited the local distilleries, the wine fields, the fruit canneries and the local beauty spots. One enterprising group even allowed themselves to be sent fishing for the day in the bay to the great contentment of Bill Worth, the ex-R.A.A.F. security chief, who felt at last that he had some of us well out of harm's way. Wherever we went, of course, the Australians showed us the warmth of their hospitality and we soon came to know and appreciate the many fine wines and liquors that are made in that area.

Every night, however, we had a stern reminder of what we had really come for. We had to be in our isolated wire-enclosed billet by 6 p.m. At that time each night we would learn what the chances were of a test the following day and once we had that information we were not allowed out again that night. Such delays were hard on the entertainment funds of the Commonwealth Security Organisation and each morning one of their cars took back to Adelaide a melancholy load of empty bottles. We soon began to feel that any further delays might prove disastrous for the national economy.

We were waiting, of course, for the right sort of wind. It was not just a matter of direction. The velocity counted, too, and there were many different wind-levels to be considered. The famous "Z" cloud in the Monte Bello Isles after the test the year before had shown vividly how directions could vary between different points of the compass at different heights. It was no good having a wind at ground-level that would blow the cloud away from spectators if the effect were reversed at 10,000 ft.

The bomb was to be exploded at an undisclosed point some hundreds of miles north-west of Adelaide and north of the transcontinental railway that circles the Great Australian Bight. It would have been ideal, of course, to have had a steady wind drive the explosion debris slowly north-westwards along the deserted Empire rocket range that stretches 1,500 miles from Woomera to the western coast. Nobody expected the winds to be as helpful as that.

When the site was first chosen little was known about the meteorology of the Australian continent apart from the thin belt of inhabited coastline. This made things difficult, for weather is essentially something that needs to be studied on a statistical basis over a long period, and examination of the records of a year or so will very rarely give a true picture of what is to be expected. Planners decided to collect all the information they could and meteorology immediately assumed an important priority among other scientific preparations for the test.

Weather-men were, in fact, among the first to be flown in to the lonely desert site, later to be known as Emu Field. A weather and forecasting station was set up and round-the-clock observations were made by radio-sonde balloons that wirelessed to earth automatically the conditions that they met on their way upwards into the stratosphere. Similar data was collected from all existing Australian stations and radioed to Emu to be filed and analysed at frequent intervals each day. The exact geographical location was ascertained of all known settlements, native camps, missions and other inhabited areas.

Choice of the Emu Field site dated back to a time in 1950 when a reconnaissance expedition from the Long Range Weapons Establishment at Woomera went out exploring the desert for its own purposes. They found typical red plain country covered in red bush, blue bush, spinifex, mulga and sheoak. There were large expanses of sand dune and drift but the terrain was quite often hard enough to permit landings by heavy aircraft. Heavily scarred with claypans, it looked from the air like the cratered surface of some dead planet. No aborigines lived anywhere near it and it was far too barren to attract white men.

The need for such a land test area had been realised for a long time. The Monte Bello Island site was ideal for the purposes of the test held in October 1952. It gave the experts just the information they needed about an explosion in one of our shallow British harbours. That was not the sort of experiment that needed repeating, however, and for the general purpose of weapons improvement a wide expanse of flat terrain well out of harm's way was much more the sort of thing that was required.

Sir William Penney visited the site during the Monte Bello test period. With him went two scientists, a radiologist, a meteorologist and a signals officer. Penney said the site was just what he was looking for. It was in the middle of an 80,000 square mile prohibited zone set aside for testing war materials. In December the British Government officially asked the Australian Government if they might use the site and received an immediate assent.

To prepare the site for the test was no simple task. It is surrounded by hundreds of miles of "gibber" plain, flat country littered with small and large flat stones that make most unpleasant going for motor vehicles. It was also waterless. Major-General J. E. S. Stevens, formerly Secretary of the Australian Department of Supply and then chairman of the Australian Atomic Energy Commission, took over the task and appointed short, tough and wiry Brigadier Lucas to command the party of 150 R.A.A.F. airfield-construction men, army engineers and civilian specialists who were to start preparing the site. The fact that a second atomic test was to take place was still only known to a very few people in Australia. Most of the officials in Melbourne were unaware of the purpose of their work and men on the site imagined that they were working on some job connected with the guided weapons range.

For the men in this early task force it was a seven-day-week job like many they had tackled on active service. Every vehicle of the convoys that set out from Woomera had to be equipped with water, stores, petrol and camping facilities sufficient to last twice the time normally needed for their trip across the trackless desert. With the early convoys went bulldozers and other earth-moving equipment needed to prepare the landing-strip and the many miles of high-speed motor-roads required in the test area. But 80 per cent of all the equipment needed, jeeps, refrigerators, boring plant for artesian wells, food, nissen hut frames, water-piping, cement, heavy timber and other equipment, was carried by Bristol freighters and four-engined Yorks belonging to the R.A.A.F. and R.A.F., formed under Australian command into what was known as No. 34 (Communications) Squadron. They made six or seven flights a day and were serviced round the clock.

To narrow the security risk and minimise the terrific supply problems every man chosen had to be expert in two or more jobs and they worked a seventy-hour week. One of the British scientists said of them: "They are simply terrific and their enthusiasm quite superb." One day when they were working under the most primitive conditions Brigadier Lucas called them together. "Men," he told them, "I have no good news for you. You will continue working ten hours a day, seven days a week. Water will be short. There will be no leave for anybody. I will try to get amenities for you, but I can only promise a life of hard toil." His remarks were greeted with a cheer and day by day a chart in his office recorded the progress they were making.

Wells were drilled for water, but it came up brackish and a distillation plant had to be set up. That meant less water, and there was no beer to make up for it. The ration was "one bottle per man per week". But the work went on and the men slept at night under six blankets to reduce the demands on fuel. The only recreation was the collecting of dingo scalps, for which there was a premium in the form of a State reward.

One of the strangest tasks carried out in those early days was the collecting of "guinea-pig" equipment for the test. Many items of equipment used by the modern army were to be assembled in the target zone around the tower on which the weapon would explode. The idea was to enable scientists to study the effect of the explosion on battle equipment, ammunition of all kinds, radio and radar equipment, service uniforms, vehicles and prefabricated huts. Much of this equipment did not need to be placed in position until shortly before the test.

There was one item on which there could be no delay, however. This was the request by the British Ministry of Supply that six obsolete fighter aircraft should be dispersed over the area.

When the Australian Government started looking round for planes to meet this requirement the best thing they could find were some war-time Mustang aircraft, which were quickly rescued from a dump of unserviceable aircraft. Experts reckoned they could be made "flight-worthy" if the job were done without delay but warned that the planes were deteriorating so rapidly that it might be impossible to get them into the air at all at a later stage. Puzzled ground-staff were set to work on the aircraft to make them serviceable enough for this last flight.

Equally mystified were the officers, a group captain, two wing-commanders and a squadron-leader of the R.A.A.F., who were told off to fly them to a secret destination from the airfield at Tocumwal on the New South Wales side of the Murray River. Because of the absence of landmarks on the arid desert they had to find their way by dead-reckoning, that is by plotting their course on the basis of known speed and direction with the aid of a compass. They were told the job was so secret that they must not use their radios in case by doing so they gave any indication of the direction in which they were flying.

Obeying their orders, they landed their planes at the Emu Field site and returned to Adelaide by the next transport plane without discussing their unusual mission. It is unlikely that they would have learned much if they had done so, because at that early stage the construction force still did not know what they were building the base for.

No doubt in the early days when the site was chosen the administrative officials had in mind the hope that the work would be of permanent use, but the difficulties arising from the remoteness of the site and lack of water soon made it clear that the first series of tests there in October 1953 would also be the last. There were to be two atomic explosions and ten other minor ones involving conventional explosive about which we were told nothing. It was fair to assume that these minor explosions were aimed at testing various forms of detonating mechanism. These devices rely on lens-shaped discs of conventional high explosive faced with fissile material. Their geometry is important because it determines the path this thin coating of fissile material will take when the explosive goes off. The idea is very similar to the cone-shaped "hollow charges" used during World War II as anti-tank weapons. These cones were lined with steel. The effect of the explosive was to concentrate this hard lining into a thin pencil of molten metal that could drive its way through armour.

The same principle was used in bombs to concentrate the fissile material, but tests invariably resulted in the dispersion of quantities of highly poisonous plutonium or uranium. It was not the sort of thing that could be carried out at Aldermaston in Berkshire, at the Woolwich Arsenal site south of the Thames, or on islands off the east coast of Essex, where so many test explosions take place. It had to be done somewhere remote and unlived in.

Newspaper men had only been invited to one test, the first of the two big atomic explosions, and there is nothing quite like a job which means travelling 24,000 miles to see and report something that is going to be over and finished with in about one second. All through my mission, from the moment when I set out from London on my five-day journey in a commercial airliner that was already a day behind schedule, and read in a normally reliable newspaper that the test was to happen in three days' time, I had an awful feeling that something might happen to render the whole journey vain. A missed plane or mechanical delay, a sudden illness, the failure to be on the spot at the crucial moment, to all this had to be added the problem of uncertainty of getting the story back to London in time. In our messages from the site itself we were, by agreement, rationed to 200 words, about eight sentences, that had to be handed in within half an hour of the explosion. We were then to fly several times over and around the spot where the bomb had gone off before returning to Salisbury in our Bristol freighter. Once on the ground at Salisbury again we would have to make a mad dash by car through congested roads to Adelaide, fifteen miles away, to deliver the remainder of the story to the cable office in the middle of the city.

We did not know, of course, how much we were going to be told by the authorities and how much we would have to guess for ourselves. In preparation for the test I had visited a shop in the Strand and bought myself a military oil compass and a tiny and easy-to-operate device known as a clinometer that is used by artillerymen to calculate the angle of elevation to nearby obstructions. The compass I knew would tell me the direction of the wind. The clinometer would tell me the height of the cloud.

The calculation was simple. It depended on the well-known method for telling how far away lightning or a flash of gunfire is by timing the interval before the sound arrives. With the distance of the explosion known, it would be easy with the aid of a slide-rule to calculate from all this data the height of the cloud. Even a layman should then be able to judge whether it was a "very big bomb " or a "very small one" or something way in between. To assist me further I had drawn myself a bookful of geometric graphs that would enable me to read this answer straight off and that took account of the specially high speed of sound during the early stage of the shock wave.

As things turned out I could have saved myself this trouble, for the experts unexpectedly came to our rescue with a great deal of information about the test. The weapon we were going to see exploded, we were told, would be one with a relatively small content of fissile material. That in itself would tend to make the column of smoke a relatively low one. A second factor that always determines the height of the cloud is the amount of water vapour in the air around the explosion. When there is plenty of it about, as in the case of many of the earlier atomic explosions, a great deal of this vapour is carried up with the rising fireball.

As the cloud rises, cold air is mixed in and the cloud expands due to falling pressure. Soon the temperature falls sufficiently to make the water vapour condense out into droplets, giving the atomic cloud the appearance of an ordinary one. Water vapour in the act of condensation releases, however, a great deal of heat, and this in turn warms the cloud and gives it an extra push upwards so that it may rise very high and often reaches into the stratosphere, 40,000 feet or more up.

At Emu, we were told, there would be very little water vapour at all in the air around the site. That meant two things. First of all the cloud would not go very high, possibly only 10,000 feet or so. Secondly, the cloud would not be nearly so well defined as many of those to which we had been accustomed. The type of cloud effect we would see would, in the absence of water vapour, be mainly characterised by the grey particles formed from condensation of material that had formed the tower, and by upswept dust particles from the ground. Its form would be further picked out by the presence of nitrogen peroxide, a reddish-brown gas formed by the combination at great temperature and in the presence of nitrogen and oxygen in the air itself.

Events the following day were to confirm this prophecy of the experts. But before the test we had a long journey through the night ahead of us. First to an aerodrome in police cars, but not to the one we had normally used. To prevent the secret of the test from leaking out beforehand and in case anyone were watching at the nearby airport, which planes habitually used, extravagant measures had been taken. We found ourselves being hustled out to a military aerodrome some miles away that none of us had visited before. Our Bristol freighter had been blacked out with curtains so as not to disclose the latter part of our route, the location of the test and the layout of the test site.

Early in the morning we landed at the airfield of the Woomera Long Range Weapons Establishment, several hundred miles to the north. I had been there before and saw nothing new there now to suggest that anything unusual was afoot, except the food and drink that awaited us in a prefabricated shed on the corner of the field and the fact that several of the planes of the "atom fleet" were no longer there. There were specially sealed Canberra jet-bombers standing out of sight nearby ready to take off just before the test and measure radioactivity in the atmosphere around the site. One of them, with Group-Capt. Dennis Wilson, a radiologist attached to the R.A.F. Central Medical Establishment, would fly straight through the cloud minutes after the test to collect the first sample of its contents.

After a quick "breakfast" we were ushered back into our curtained plane for the last lap of our journey. There was still an hour to dawn when we landed on the short, make-shift airstrip at Emu. Brigadier Lucas came up to welcome us with a friendly "Hallo" and shake of the hand and invited three of us to join him in his jeep for the quick run to a piece of slightly elevated ground a short distance from the field. Although probably only a matter of a few feet above the rest of the plain, it still enabled us to see across the flat forest of twisted mulga trees, quondongs and sheoaks that looked like some ancient petrified forest and separated us from the spot far on the horizon where the bomb stood ready on its steel lattice tower.

The names of the planets had been used to label the final stages of the Monte Bello test a year before. On this occasion they used instead the names of some of Australia's many unique animals. Early stages carried out during the night had been referred to as DINGO, the native dog; EMU, the clumsy Australian bird that cannot fly, GOANNA, the lizard; KOALA, the little bush bear, and KOOKABURRA, the laughing jackass.

As we arrived at 6 a.m. the experts were carrying out duties that bore the code word OPOSSUM, the final preparation of the weapon. Twenty minutes later we heard the name PLATYPUS, that of the duckbilled mammal, come over the loudspeaker. It meant that the lonely tower on the horizon was finally being evacuated by an unnamed scientist who had completed the last circuit and had taken away with him the key without which those in the control tower could proceed no further.

It was clear that not everyone felt the same tension in those last moments that we did; certainly not some of the Australians who had done the real hard work of preparing for the test. With plenty more hard work ahead of them and no immediate part to play, they were having an extra hour in bed, it seemed. An accident possibly on the part of the switchboard operator on one occasion put through to our loudspeaker system remarks that were clearly not intended for our consumption and we heard "lazy bastards" being exhorted to get up and "show an eye" or they would "blank well know what for".

The last moments before the test were heralded by a form of drill that has now become a familiar part of such explosions. Capt. Pat Cooper, a former naval officer, now technical secretary to Dr. Penney, counted out the seconds before the bang.

Observers had been told beforehand they could watch through the extra-dark welder's glasses that had been provided for the first part of the explosion. They were warned that if they did they would miss many of the brilliant effects of the succeeding stages on account of their eyes not becoming at once accustomed to the change in brightness when they removed their dark glasses.

The alternative, however, was to turn our backs on the initial flash, as observers had done at Monte Bello, but this idea did not appeal to any of us and we decided to watch through our goggles, which were so black they almost obscured the bright orb of the rising sun, and to whip them off at the first sign of the explosion.

There were two masts on the distant horizon, one of them enclosing the bomb and the second held ready for a further explosion. From our position fourteen miles away they looked like those of ships but with very large crows' nests showing distantly upon the skyline. Each was some hundreds of feet high; the one on the right we knew would soon be the site of a blazing inferno.

There were about thirty-five in our desert "grandstand", eighteen were reporters and photographers, mainly from Australia. Only two of us had come from Britain for the test. Most of the others present were senior members of the construction team that had prepared the field and the site and the many roads to the area, together with the ever-present security officers, who now carried heavy pistols in bulging leather holsters slung over their shoulders.

There were now only seconds left before the weapon was due to explode. As they passed, the sense of suspense was tremendous. Deserts are rarely noisy places, and even when the promise of food has attracted the eagles or carrion crows their dismal squawkings only accentuate the unearthly stillness below. The sound of each second, counted out over the loudspeaker, now had the same eerie effect, and not even the photographers, eagerly poised over their long-lensed cameras, made a sound as we waited. The intervals between one second and the next appeared to grow longer and longer. "Five . . . Four . . . Three . . . Two . . . One. . . ."

We all had our own ideas of what to expect, based in some cases on various full and vivid technical descriptions that we had studied beforehand. But the more we had studied, I think, the more we were stunned by the speed with which things actually happened and were over. In dealing with an atomic explosion the scientist uses as his unit of time the millisecond or a thousandth part of a second.

The human brain, however, takes much longer to appreciate what it sees and having registered the sight retains it for a good twentieth part of a second more. Some idea of the inadequacy of the human element in observing such explosions will be realised by the fact that as each one-hundredth of a second passes, the scene changes radically for something completely new. Within one second the whole thing would be over and the fireball of incandescent air and explosion debris would be on its way upwards at a speed of between 100 and 200 m.p.h.

The explosion took place at 07.10 hours precisely according to textbook. As Capt. Pat Cooper began to mouth the word "Zero" a bursting, blinding ball of light appeared on the skyline and the flash shot outwards towards the horizon in every direction at a rate of 186,000 miles a second. We had been warned that it would be brighter than the sun and through my own special welder's screen, which enabled me to watch while still keeping my eyes accustomed to daylight, it seemed as if the surrounding desert were momentarily ablaze.

Earth fused and boiled in a blazing vortex which became every moment more confused as it mingled with smoke and dust, turned violet at the edges due to the compression wave, and mixed with the deadly poisonous and peach-coloured oxides of nitrogen. Most of us found our senses were paralysed. Then the great and expanding mass of dirt and smoke was suddenly sucked inwards and upwards in the wake of the rapidly rising ball of fire until, at several thousand feet, it hesitated for a few moments and bulged slightly on meeting a level of different temperature before shooting upwards again in a long great curve to form a characteristic mushroom shape several miles to northward. Some saw in this great pillar of smoke, sometimes dull grey and at other times a peachy pastel shade, the typical fuzzy head of a great aboriginal Australian, but it looked most of all like the thin smokestack of some early steamship surmounted by its drifting column of smoke.

It had taken away our breath for a moment, but it was not impressive in any real sense. The absence of any noise ruled that out. The whole succession of events had followed through in an eerie silence that made the whole affair seem almost unreal. I realised, probably for the first time, how one's assessment of any occurrence depends on a combination of many senses and the effect that absence of any one of them to which one is accustomed can have. I had never realised before the extent to which one relies on sound. Without it now there was something definitely wrong.

The flash could have been the bursting of a much smaller bomb closer at hand and the solid column of hot gas poised uncertainly over the desert reminded one of burning supply dumps in Lybia during one of the great retreats. I wondered for a moment whether any of us would have thought a great deal about it had we not known of the cataclysmic nature of the forces let loose and of the historic milestone which the successful development of a practical atomic weapon meant to the Commonwealth. It left one with an odd feeling of detachment. I must confess to having felt at the time an acute sense of disappointment and anticlimax. It was all so small, so far away, that I am sure I have derived far more excitement in the past from the explosion of a halfpenny "demon" in a milk-bottle, an orange or a bowl of blancmange.

A minute passed before we were suddenly brought to our senses by the bang. The sound reached us in the form of two shattering shock waves which brought home to us all at once the truly catastrophic violence of the process we had witnessed. Had it been a mine or a conventional bomb or shell that had gone off thirteen and a half miles away the noise would have reached us as a dull "boom", blurred by distance. The noise we heard, instead, was as sharp and incisive as if it had been caused by a high-velocity gun a short distance away, fired straight at us. It came like two stunning slaps in the face that seemed to hit both ears twice in quick succession. And then the double crash reverberated round the desert like a quite unearthly thunder.

It reminded me for a moment of the sound of cannon fire echoing round the mountains of India's North-West frontier, only its magnitude was so much greater and there had been no mountains within sight to provoke it. Sound waves and shock waves are one and the same thing, and after an initial period during which the exceptional conditions of an atomic explosion cause the wave to travel outwards at more than the normal speed of sound the noise travels outwards in all directions at a speed which, under average conditions of temperature and pressure and other atmospheric conditions, would be 1,086 feet per second. The waves travel on until they hit something and then they are reflected, unless the material is absorbent.

Sound waves can be reflected by solid objects like houses, trees, mountains, and can be bent downwards by layers of air of differing densities. Such reflections from the upper atmosphere account for the fact that an explosion may often be heard sixty or seventy miles away and yet not be heard at all at some points much nearer to the source. It accounts for the remarkable fact that the saluting guns in London at Queen Victoria's funeral were heard in Edinburgh, nearly 400 miles away, whilst during the First World War it was not at all uncommon to hear gunfire from the Western Front in London and the Southern Counties.

It was a variation of the same effect that caused observers twenty miles or more from the Monte Bello explosion to hear two sharp bangs, which were then wrongly interpreted by some as an indication that a hydrogen weapon had been exploded. The second bang, which we also heard ourselves, is not always due to reflections from above, however. Big explosions of any sort produce a very complex shock picture that often defies accurate analysis, and which may result in two or even more separate bangs. With conventional explosives they may follow too quickly for the ear to separate them. The bigger the explosion the longer is likely to be the time interval between them, so that in an atomic blast they may be seconds apart.

Bangs of that sort take a bit of getting used to, but on this occasion we were given no such chance. While the crash was still thundering round the desert like hell let loose, security men were already touching my elbow and telling me that there was a breakfast ready of "curried beef and whiskey". The suggestion brought me quickly to earth and the realisation that I only had twenty-nine minutes in which to write and file my report. Needless to say I ate no breakfast, and still without time for reflection was reminded by Brigadier Lucas that I had better jump into his jeep if I wanted to catch my plane.

Although we all had a pretty good idea of how long it would take us to travel thirteen miles and we all thought we knew exactly where we had seen the bomb go off, the task of identifying the site from our plane was no easy one. The claypan was scarred everywhere with the marks of smaller explosions used in the testing of instruments.

Then, suddenly, I saw the spot. It was nothing but a circle of burnt clay, black in the centre and elsewhere dark brown. From its centre, slightly excavated by the explosion, radiated innumerable scored rays over the area that, from our low flying plane, appeared to have a radius possibly of 600–700 yards. Except in the blackened centre, perhaps 200 yards across, the scorings were not deep enough to erase tracks used by constructors' vehicles going to and from the central point where the tower bearing the weapon had been. Of the tower itself there was no sign.

Beyond the outer circle of dark brown earth it was difficult to detect any effect at all. The ancient Mustang fighters that had been flown out earlier to the area and placed at intervals along the road radiating from the tower were apparently little damaged, although several appeared to be well within the mile of ground zero, the point directly below the explosion. The same could be said of vehicles, radio equipment, military stores and nissen huts.

What little time we had for careful examination did disclose, however, a litter of small objects, probably torn from equipment and scattered over the area. The absence of craters was no surprise as many larger American weapons did not cause craters when exploded from a height more than 250 feet above the ground. Just how high the tower had been in the present case was a closely guarded secret, but engineers told us that it would have been technically possible to have constructed one almost 1,000 feet high had they wanted to do so.

One of the most surprising facts was the almost complete absence of the well-known incendiary effect of flash outside the area of the main explosion. Although both vehicles and planes had been left with full petrol tanks, none of them had been set on fire, and the only sign of burning that I noticed outside the immediate area of the explosion was some thousands of yards away and might well have been the smoke from generators purposely set off to enable instruments to follow the blast effect on surrounding air by its displacement of the column of smoke.

We heard from Capt. Cooper that troublesome low-level winds had been the cause of the test's repeated postponement. On the day of the explosion low-level winds were present, but at 10,000 feet there was a steady S.S.W. wind, which did not, however, prevent the activity from the explosion being wafted later eastwards towards the coast of New South Wales, although by the time it reached there it was far too diffuse to do any harm.

Thus forty hours later when I visited the laboratory in Canberra of Professor Oliphant, the eminent physicist, counters that he had dispersed above the ground were registering the passage overhead of the cloud and indicating activity due to X-rays fifteen times higher than that normally present due to the natural radioactivity. The level, which was well within safety limits, nevertheless indicated quite clearly the presence of radioactive explosion debris in the clouds overhead.

[18]

How Many Bombs?

HOW many atomic weapons and how much fissile material can Britain now produce? The answer to these questions is one of the country's most closely guarded secrets. Without any access to unpublished and classified information, however, it is possible to arrive at certain interesting conclusions without in any way contravening the Official Secrets or Atomic Energy Acts.

Let us take the facts as they are generally known. Every time an atom of uranium is split it produces, on an average, two and a half neutrons. One of these is required to split another atom of uranium and keep the chain reaction going. A percentage is bound to be wasted by escape from the exterior walls of the pile or in absorption by impurities, including fission products of earlier reactions. It is reasonable for the purposes of our present calculation to assume that there will, on an average, be one neutron taken up by uranium 238 for each fission and that this neutron will convert one gramme of uranium 238 into plutonium. We may expect, therefore, plutonium at the rate of an atom per atom of fuel used. This is an optimistic statement of the position but it is near enough.

A fairly simple calculation tells us that if a reactor burns one gramme (one twenty-eighth part of one ounce) of uranium 235 a day the heat produced continuously will be of the order of 1,000 kilowatts and approximately one gramme of the new fuel, plutonium, will be produced. Now no-one has ever stated what is the heat output of the two British production reactors at the plutonium factory at Sellafield in Cumberland, but it is generally known that the three American piles built at Hanford for a similar purpose were of about 300,000 kilowatts each.

Assuming that the designers, with general knowledge but no detailed technical information about these reactors, aimed at a similar output for the Sellafield piles, we could then place their combined daily output at somewhere in the neighbourhood of 600 grammes of plutonium a day *within the reactor.* The efficiency of the extraction processes is secret knowledge, but if it is of the order obtained in some comparable commercial processes one might expect almost 100 per cent of this amount to be extracted in fairly pure form, that is 600 grammes or 1·3 lb a day.

Translating this figure into bombs is a little more difficult. With only the early information to go by provided for us in the Smyth Report, the United States report on the development of atomic energy for military purposes, one would have to place the figure for each bomb as being between 2 and 100 kilogrammes, that is between 4½ and 225 lb. Within these limits our production of bombs might vary between one hundred bombs and two bombs every year if we had only the Sellafield factory to depend on.

The critical mass of uranium or of any other fissile material will obviously depend on the amount of impurities present. If our bomb were made of uranium it would depend to a very great extent on the amount of the greedy-for-neutrons 238 that was still left behind by the diffusion process. It would obviously depend, too, on the efficiency of the reflecting shield that enclosed the bomb.

There is one further way in which the critical mass may be reduced, and that is by the method of "implosion". An implosion is, one might say, an explosion turned inside out. It makes use of a fact known for some years but only really exploited in the latter stages of the Second World War. It is that if a block of any normal explosive is machined or moulded to the shape of a concave or hollow lens and detonated, the explosive force will be focused to a point in much the same way as light rays would have been focused had they been passed through an ordinary magnifying lens. There have been many recent applications of this knowledge, the best known of which is probably the hollow-charge bomb used against tanks on the battlefield. In atomic weapons, as the man in the street first learned from the trial of the American atomic spy Greenglass, who passed to Russia plans of the detonating mechanism, the same principle can be used to produce suddenly a mass of plutonium or uranium of extremely high density.

This is done by surrounding a central core of the atomic explosive, itself too small to explode spontaneously, by a whole series of lens-shaped charges of conventional explosive. If each of these lens surfaces is lined with further amounts of plutonium or uranium the effect of detonating the charges will be to propel these additional amounts of uranium or plutonium simultaneously into the central mass, thus both adding to the total quantity and increasing its density by the compressive effect. This would do two things. First it could make the central mass suddenly far greater than the critical size needed to bring about spontaneous chain reaction. Secondly, by compressing the whole mass, it would naturally bring each of the atoms of the nuclear explosive closer to its neighbour and would reduce the chances of neutrons reaching the surface and escaping before they had caused further fissions.

The science of implosion, to which Sir William Penney himself made important contributions, was only in its infancy when the first atomic weapons were being developed at Los Alamos, New Mexico. "The *obvious* method of very rapidly assembling an atomic bomb", as the Smyth Report said, "was to shoot one part as a projectile in a gun against a second part as a target." The projectile mass, projectile speed and gun calibre required were not far from the range of standard ordnance practice. There is no doubt whatsoever that it is a method that has long been superseded by that of implosion, and we may assume that it very much reduced the minimum amount of fissile material required for the manufacture of an atomic bomb.

Bearing this in mind, and also our knowledge that the energy released by a "nominal atomic bomb", one equivalent to twenty kilotonnes, was equal to that made available by the fission of one kilogramme of plutonium, let us assume that because of losses and the inherent inefficiency of the system about four times this quantity, i.e. four kilogrammes or nine

13

pounds, of fissile material will be required. We then see that the yearly production figure we took would suffice for more than fifty atomic bombs.

That figure, no more than a guess, is based on an assumption of what might be done with the two Windscale reactors, the only source of plutonium in Britain likely to be producing plutonium on a large scale until 1957. It takes no account of the Capenhurst factory, where uranium 235 is produced, or the production from the many other reactors scheduled to make substantial and growing contributions in the next few years.

The term "atomic bomb" is used loosely above. Each one of these bombs might well be used as the detonator of a hydrogen bomb. They could be something much worse, a weapon that Professor Rotblat has called the "fission-fusion-fission" bomb. Let us take the first suggestion.

It is no secret that the first American hydrogen "bomb" was far from being a droppable affair. It needed a barn to house it and depended on a refrigeration system to maintain the hydrogen in its liquid state (it boils at about minus 270 degrees Centigrade). It became known as the wet bomb. It is no secret either that reports of the first Russian hydrogen bomb indicated that it was, instead, a "dry" one, far more easy to handle and quite conceivably portable. It has been widely suggested, and it is very generally believed by scientists both in the United States and in Europe, that this great advance in the technique of bomb-making was realised by the use of hydrogen in a solid, stable form, that of a chemical compound of hydrogen and a particular form of the lightweight metal, lithium.

To see how this could be of use let us go back for a moment to the wet bomb. The idea here, without going into too many details, was to make heavy hydrogen, known as deuterium, fuse with more heavy hydrogen to form helium, the next element in the list. To do this all that was required was heat—much more heat than could be produced by the explosion of an ordinary atomic bomb.

To bridge this gap a tinder was employed. The ingredients proposed were deuterium and a further, super-heavy and very rare form of hydrogen known as tritium. Deuterium and tritium will fuse together at a temperature well below that needed if deuterium is used on its own and that temperature can be obtained from a well designed uranium or plutonium bomb. Thus, the "wet" bomb used an ordinary atomic bomb as the spark, a mixture of deuterium and tritium as the tinder, and deuterium on its own, as much as anyone cared to pile on, as the main fuel.

Although tritium, like deuterium, occurs in nature, the amount is so small as to be insignificant, and in the quantities needed for nuclear weapons it had to be obtained in atomic reactors by the expensive process of bombarding the metal lithium with neutrons much needed already for the production of plutonium.

The "dry" bomb had a much easier way out than all this. It combined the two processes together by using a solid substance, lithium deuteride, and performed the operation while the bomb was bursting. Talking broadly and taking some liberties with scientific terminology in the interests of simplicity it might be said to have worked like this. First the atom bomb goes off. This produces an enormous surplus of neutrons. These neutrons are absorbed by the lithium to form tritium. The tritium then reacts with the deuterium to form helium. The tremendous heat produced by this reaction provides the "tinder" needed to start fusion of the remainder of the heavy hydrogen. The violence of the explosion would then only be limited by the amount of heavy hydrogen available in solid form.

We spoke of one further possibility. At the time I write it has never been mentioned in public before. It is based, however, on analyses by leading nuclear physicists of the known results of certain other explosions.

The deuteride bomb had become known as the "cheap" hydrogen bomb, because it avoided the use of the expensive tritium and led to great simplification in design. But it still required large quantities of heavy hydrogen, which is made from the very expensive commodity, heavy water. There might be an even cheaper way.

It will be remembered that when atomic reactors were being discussed earlier in the book it was stated that the comparatively common variety of uranium known as 238 greedily gobbled up neutrons of some lower energies in a reaction that produced plutonium but endangered the fission process. Fast neutrons, instead, would cause uranium 238 to undergo fission itself.

Now, the deuteride bomb reaction outlined above would produce a vast number of fast neutrons. The economics of bomb manufacture might be completely changed if a way could be found to utilise these neutrons to bring about fission of the more plentiful 238 uranium used in an outer shell, nor could any better substance be found to "tamp" the bomb and prevent it from flying apart too soon, in much the same way as miners tamp the hole and increase the effect of conventional explosives when they are blasting.

The suggestion has in fact been made that it might have been the unforeseen detonation of such a "tamper", an outer shell of uranium 238, which led to the unexpected violence of the test hydrogen bomb explosion in the Pacific on March 1, 1954, and the unusually widespread contamination that resulted in many casualties. Responsible physicists outside the Atomic Energy Authority tell me that the effect, impossible to obtain from a simple hydrogen, or fusion, bomb, could have been achieved by the use of a shell of natural uranium one inch thick.

So now we have a new sort of super bomb that any country with a substantial atomic energy programme could manufacture relatively easily and which combines tremendous explosive power with the power to contaminate anything from 5,000 to 100,000 square miles of territory.

From a military point of view it puts the so-called "cobalt bomb" in the shade. The cobalt bomb, which has never been and is never likely to be exploded, would be an "ordinary" hydrogen bomb surrounded by a shell of the metal cobalt. When such a bomb went off many of the neutrons produced by the fusion of the hydrogen atoms would be absorbed by the cobalt to form a new and highly radioactive form of the metal known as cobalt 60.

Now cobalt 60 is far more deadly than radium. Exploded anywhere in the world it would produce results too horrible to contemplate. There is a very good reason why such a bomb is never likely to be used. The cobalt 60 "decays", that is loses its radioactivity, at the rate of half every 5·3 years. Since it takes an average of 1,700 hours for particles of bomb debris to fall to earth from the stratosphere, they might have been carried several times round the world, without having lost any appreciable percentage of their original activity, before falling to earth on the territory alike of friend and foe.

The position with the fission-fusion-fission bomb, that using a shell of uranium 238, is very different instead. The products when this shell undergoes fission will be very similar to those of an ordinary atomic bomb of uranium 235 or plutonium. The majority of them will be intensely radioactive for a comparatively short time and those that are not deposited within some hundreds of miles of the explosion within a few hours will have lost much of their virulence before they reach the earth.

The explosion of a single such bomb might lay waste and contaminate thousands of square miles of enemy territory without constituting any greater risk to the user than did, say, the Bikini explosion of March 1945.

[19]

Isotopes—Friends of Man

THERE are ninety-two different naturally-occurring elements in the world, to which man has, since the inception of the atomic era, added nine more of his own making. The lightest of all these elements, we have seen, is the gas hydrogen; the heaviest, element number 101, was recently discovered by scientists of the University of California and given the name mendeleevium in recognition of the nineteenth-century scientist Dmitri Ivanovitch Mendeleev, who is generally given credit for being the first to arrange the elements satisfactorily in systematic fashion.

As far back as 1829 scientists had been trying to establish a relationship between the weights of the known elements and their behaviour. At first these attempts were severely handicapped by the lack of any precise knowledge of what those different weights were. Then the Italian chemist Cannizzaro made a great step forward in 1858 and very soon it was possible to arrange the elements in something very like their correct order. But it was Mendeleev who provided the first clear-cut picture of a general and simple law that ordered the elements in what he called the Periodic Table.

In his table Mendeleev arranged all the elements according to their weights and showed that there was a regular recurrence of certain chemical and physical properties that in many cases ran right through the table. It was just as if someone had dealt out the elements like a pack of cards, starting with the lightest of them and finishing with the heaviest. All cards in the same "hand" showed this special relationship to each other.

The scientific explanation of this fact is quite outside the scope of the present discussion. The only point that interests us is that each element has its own *place* in the table. Its behaviour can be forecast from knowledge of the place that it occupies, with such certainty in some cases that in the early days when many elements that we know now remained undiscovered, it was already possible to see that these blanks existed and to prophesy that elements would later be found to occupy them and to say how those elements would behave. Mendeleev himself made three such predictions that were borne out by later discoveries.

His table, it will be remembered, had been based on an arrangement of the elements in the order of their weights. There was only one element in each place. The weight of the element, by determining its position in the table determined also its chemical and sometimes its physical behaviour. The key to the theory was "one element, one place", and conversely, "one place, one element".

By 1910, scientists in many countries were baffled by the discovery that in some cases the theory did not hold good. Soddy, the English physicist, reviewing the position in that year, pointed out that ionium, thorium and radio-thorium, all different by weight, still behaved chemically as if they were identical. There were a number of others that showed similar exceptions to the rule.

In 1913 Soddy proposed the word "isotope", derived from the Greek *isos*, equal, and *topos*, place, to describe elements which had different weights but which, as far as chemical behaviour was concerned, appeared to occupy the same "place".

Aston, one of Cockcroft's early colleagues, quickly showed that the gas neon had two isotopic forms, weighing 20 and 22 units respectively and both behaving exactly like each other. There was always about ten times as much of the lighter isotope present as there was of the heavier one.

This provided an immediate explanation of why the weight of neon, in its normal, naturally-occurring form had been found to be 20·2 units instead of a whole number of units. Aston went on to show that the gas chlorine, which was known to weigh 35·457 units, consisted of at least two different isotopes which weighed 35 and 37 units respectively.

It had, of course, been known since the turn of the century that while some elements were "stable" and remained always the same, there were others like radium, that were "unstable" and emitted radiation of one sort or another, changing their identity in the process and becoming different elements.

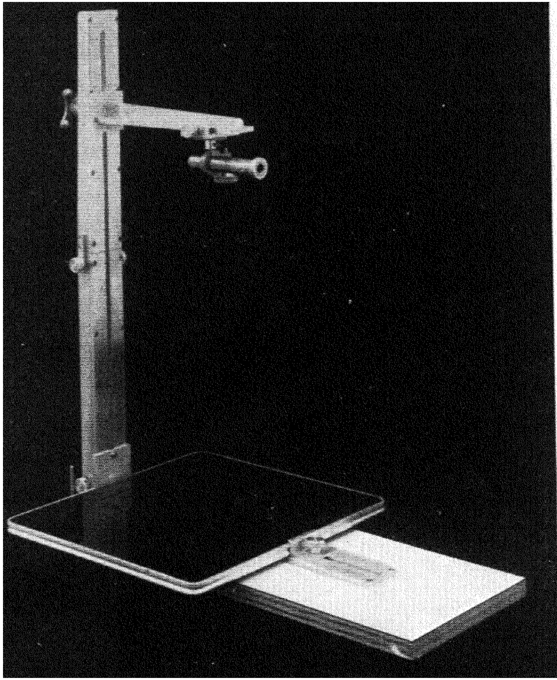
The quest for knowledge became far more exciting when Rutherford showed in 1919 that it was possible to use the rays emitted by one substance to bombard another and change its identity, and when Cockcroft and Walton, in 1932, achieved similar transmutations with the electrical machines that scientists called accelerators but which rapidly became known to most as "atom smashers".

The earliest elements to be produced in this way were stable, but soon it was shown that radioactive elements could be made as well. By the time the Second World War broke out many such forms were known and, ten years later, what with the incentive supplied by atomic energy research and the new facilities that were available such as atomic reactors and ever more powerful atom-smashing machines, something like 1,000 different isotopic forms of the elements had been discovered in nature or manufactured by man. Of these, many were radioactive and there had been found at least one radioactive form, or "radio-isotope", of every stable element.

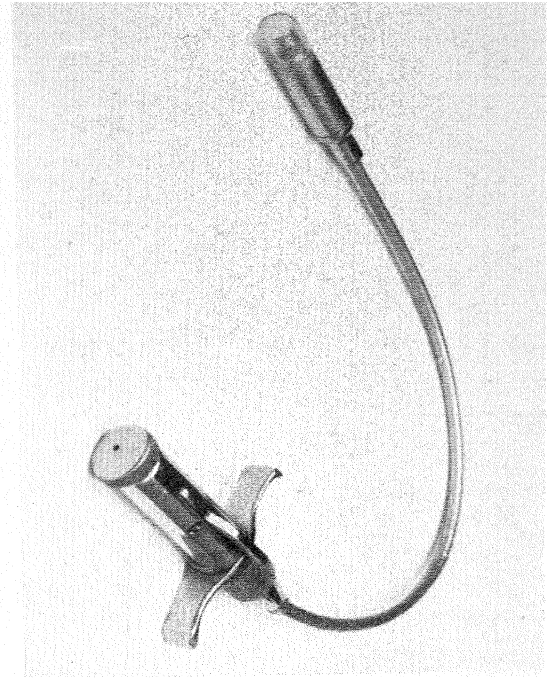
The "rays" emitted by the active forms are of many different sorts, some of very high powers of penetration and others with hardly any power of penetration at all, so that they can be stopped even by a small amount of air or a piece of paper. It soon became apparent they had tremendous potentialities.

It has been said of these radio-isotopes that they represent in fact the happiest chapter in the atom story. On many occasions it has been predicted that when present atomic energy programmes are reviewed in the light of history, it will not be the gigantic power-producing reactors or nuclear weapons that will claim pride of place, but the contribution to humanity of the many ray-emitting substances that first came into abundant supply when men began building atomic piles for other purposes.

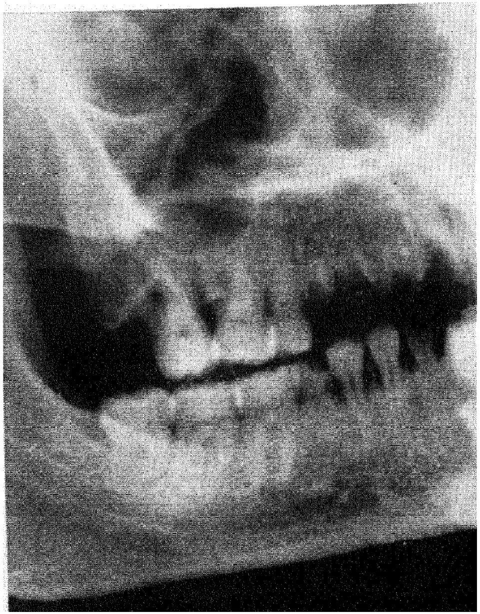
16. Mr. Christopher Hinton, F.R.S., and senior members of the United Kingdom Atomic Energy Industrial Group. *Seated* (*left to right*): Mr. R. E. France, O.B.E., former assistant secretary, Department of Atomic Energy; Mr. R. W. Preston, first general manager of the ore-processing factory at Springfields; Mr. W. L. Owen, C.B.E., deputy director; Sir Christopher Hinton; Mr. D. A. Shirlaw, C.B.E., director of administration; Mr. D. W. Cole, asst. controller, production; Mr. L. Rotherham, in charge of research and development. *Standing:* Mr. H. H. Bannister, O.B.E.; Mr. S. F. Hines, O.B.E., general manager, Capenhurst uranium enrichment factory; Mr. H. V. Disney, designer and builder of Capenhurst; Mr. J. W. Kendall, designer and builder of the Windscale piles; Mr. H. G. Davey, Windscale general manager; Mr. C. S. Turner, designer and builder of the Windscale chemical plant.



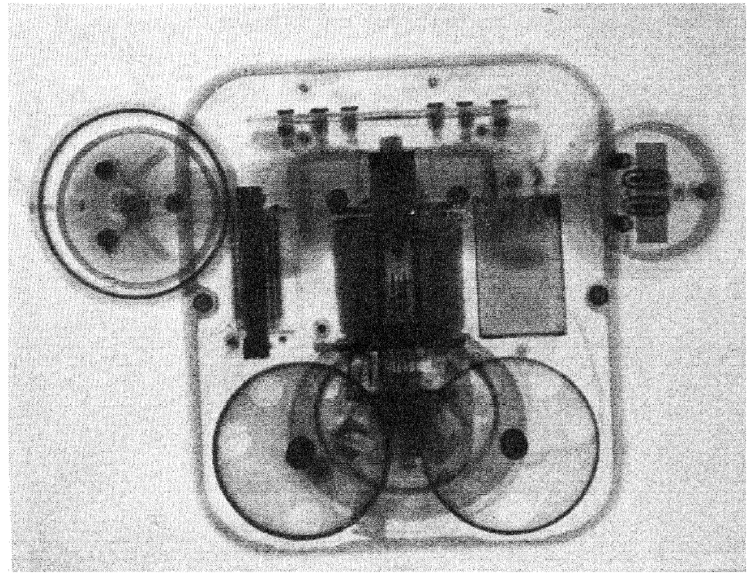
17. A very light source of X-rays capable of taking photographs such as that of a telephone set on the opposite page, or of a human limb. Both this and the device shown in plate 18 were developed by Prof. W. V. Mayneord at the Royal Cancer Hospital.



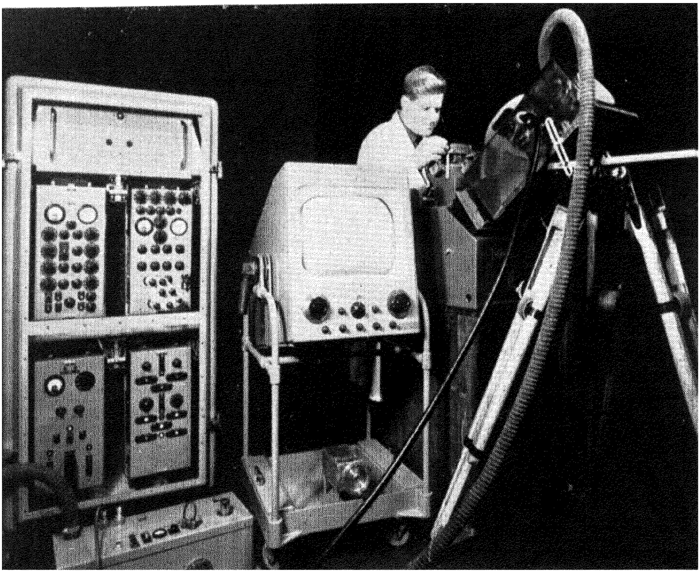
18. A "vest pocket" source of X-rays capable of being introduced through the mouth or through surgical incisions. The source, no bigger than a cigarette end, is only exposed when the plunger at the other end of the cable is depressed.



19. Use of internal sources of X-rays enable extremely clear photographs to be taken of large areas.

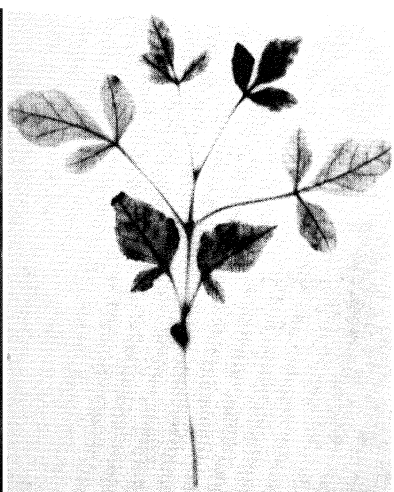


20. An X-ray photograph of a telephone set, obtained with the aid of a radio-isotope. The microphone (*top left*) and the two bells (*bottom centre*) can be clearly distinguished.



21. A television set being used at the Atomic Energy Research Establishment, Harwell, for microscopic examination of a specimen that is far too radioactive to be examined by direct methods.

22. A radioactive crystal of the metal zirconium, photographed through a microscope by means of television to see what damage it has suffered by a period of irradiation in an atomic reactor.



23. An "autoradiograph" of a young ash plant, made by allowing it to remain in contact with a photographic emulsion after it has taken up water containing radio-phosphorus. Cells in the process of growth have taken up most. *Reproduced by courtesy of Kodak Ltd.*

They are, as we have seen, atoms with a difference. The difference lies in the fact that they can be traced wherever they go and identified for what they are, however few of them there may be. Using the right instruments it is as easy to trace the presence of a minute quantity of some radio-isotope amongst a great mass of other material as it is to see the blazing torch of a skier on a mountainside or rockets fired from a nearby ship.

Chemically, however, these radioactive isotopes behave in exactly the same fashion as ordinary, stable isotopes of the same element. Thus, if food containing a quantity of radio phosphorus is fed to an animal, a plant or a human being, it would be absorbed in a perfectly normal fashion. The radio phosphorus would later on be found dispersed in all the usual places where phosphorus from food accumulates, such as in the bones of an animal or leaves of a plant.

Its presence there and elsewhere would be detectable through the use of Geiger counters placed nearby, and if one of the leaves were subsequently put on a plate of photographic emulsion suitably shielded from the light and the plate afterwards developed, there would afterwards be found an "autoradiograph", that is to say a photograph taken by the plant itself (*Plate 23*).

Little black spots would have been produced on the film wherever a ray from the leaf had hit the emulsion. There would naturally be most spots in areas where there had been most phosphorus and this would prove to be in the stem and along the many branching channels which form a lace-like pattern over the leaf. The result would provide an accurate outline of the whole of the structure of the leaf if left there long enough.

While it may be convenient to lay a leaf or other small object on a photographic plate and allow it to photograph itself, the same is obviously not possible with an object as large and unwieldly as the human body, nor would it remain in the same position long enough, probably, to secure the desired effect. In the workshops of the Royal Marsden Hospital I recently saw an ingenious answer to this problem in the form of a fully automatic "robot" which could draw a "map" of the whole body in fifteen minutes, showing exactly how a radioactive substance had dispersed itself in various organs.

This "scanner", a piece of delicate machinery about one yard square and one foot high, contains a "counter", about the size of a pint milk-bottle, which travels backwards and forwards across the body in much the same way that a paper-hanger eventually covers the whole of a wall. As it travels across each part the counter measures the amount of radiation, if any, that is being emitted. The electric pulses that result are magnified many times and used to operate a stylo travelling in exactly the same way across a sheet of paper bearing an outline of the body. Whenever the counter passes a radioactive area of the body the stylo shades the picture on the paper.

Like many other devices for the detection and cure of disease that have been conceived in the same hospital and are now being copied with its ready approval in institutions all over the world, the scanner was designed and its construction directed by Prof. W. V. Mayneord, one of the leading authorities on the biological effects of radiation and a pioneer in the use of radio-isotopes in medicine.

Mayneord is a red-bearded genius with a rare ability for translating thoughts into nuts and bolts. The scanner, in addition to fulfilling the function for which it was designed, has already shown important possibilities in a further direction. This came about when it revealed localised "pockets" of radioactivity in unexpected parts of the body. On their being further investigated, medical men found that they came from unsuspected metastases, that is, secondary growths of an earlier cancer that were not detected by normal methods. There is other evidence that these secondary growths may take up iodine to a greater extent than normal cells, and in some cases the amount taken up is enough to destroy the new growth. In this way the unsuspecting cancer cells have taken in the radio-isotope for their own destruction.

All living cells are liable to suffer damage from radioactive radiation passing through them, but this sensitivity enormously increases while the cell concerned is in a process of "division", that is to say, while it is in the act of reproducing itself. Thus, the reproductive organ of the human body and also the cells in bone marrow responsible for producing new blood are all particularly sensitive to such radiation.

For the very same reason, cells of a malignant growth, or cancer, which sometimes reproduce at a phenomenal rate, are also easily damaged, and it is for this reason, of course, that sources of radiation, whether they be naturally-occurring radio-isotopes like radium or artificially-produced ones such as cobalt 60, or even the great electronic machines, are used in the treatment of malignant disease.

The hope is always that the rays will kill the rapidly reproducing cells of the cancer without doing too much damage to the surrounding healthy tissue. This treatment can be very effective, especially when the tumour is on the surface, but there are many cases where it will not work. Thus, the discovery of ray-emitting substances that could be introduced easily with food into the body and that could be relied upon to concentrate in certain organs immediately suggested to scientists and doctors a new chance to attack many deep-seated tumours in the body if only the suitable radio elements could be found that would accumulate there and nowhere else.

The thyroid gland seemed to offer such an opportunity, for this important organ which controls the growth of the body is situated in a part of the neck where surgery is often hazardous. The thyroid gland is greedy of iodine so that it attracts to itself the greater part of any quantity of iodine that enters the body. It is also an organ that is attacked by cancer. Here, however, as in many other cases, early hopes were not borne out. For one thing, the power of the thyroid to concentrate iodine depends on its remaining healthy. When a tumour occurs in the gland the cells lose their power to function in a normal manner and then they cease to concentrate the iodine.

Radio iodine first became available in 1938. Since then it has been of outstanding value in the study of thyroid function in diseases other than cancer, and it has been possible to use quantities which, although easily detectable, were far too small to do harm. The radiations emitted by radio iodine are in fact so penetrating that even minute quantities may be followed as they make their way through various organs of the body. The very short half-lives of some varieties make them suitable for short-term diagnostic tests where total body radiation can be kept down to an almost negligible level.

The most obvious application of radioactive material in medicine is the use of substances like cobalt 60 or caesium 137 as substitutes for the far more expensive radium. The difficulty in the case of cobalt lies in its manufacture, but caesium is becoming available in increasing quantities as a by-product of normal atomic reactions.

It will be remembered that one of the factors governing the manufacture of radio-isotopes in a pile is the probability that any particular neutron will be absorbed by the target nucleus and able to convert it to the new form. This, in the case of cobalt, is a very low probability indeed, and it could only be made economically in reactors like the heavy water reactor at Chalk River and the new E443 reactor under construction at Harwell, where the flux of neutrons, that is to say, the number crossing a given area in a given time, is high and the probability of collisions is large in consequence.

The development of atomic reactors like these, where the number of neutrons crossing a given square inch of surface in one second may be more than a hundred million million, has made possible the manufacture of sources of cobalt 60 so powerful that a source less than one inch in diameter and one-tenth of one inch thick can deliver a dose rate of thirty to forty röntgen units per minute at a distance of two and a half feet. The X-rays so produced are in every way comparable with a beam of X-rays produced by a super-voltage machine. The mountings are often very much more flexible.

Some of them permit the "bomb" containing the cobalt to make a complete circle round the point within the patient on which the beam is to be concentrated. The advantage of such a procedure is that while the growth itself will be under constant bombardment any given part of the surface and intervening tissue will be exposed only for a small fraction of this period.

Units of this sort may contain cobalt giving radiation equivalent to as much as two pounds of radium. Far smaller ones, containing one hundredth or one two-hundredth of this amount, are also used, with the added advantage in certain cases that the beam may be controlled within stricter limits.

Apart from the fact, however, that cobalt is not a natural fission product and can only be satisfactorily manufactured in atomic reactors of great power, it has the further disadvantage that the half-life of cobalt 60, once it has been made, is only 5·3 years.

In a well-planned hospital, however, a great deal of work can be done in the period before its strength has fallen off. The source can always, too, be put back into a pile for further "hotting up" by new periods of neutron bombardment. Its comparatively short half-life, however, has been one of the reasons why interest has recently swung to other elements like caesium, which has a half-life of thirty-three years and is a natural product of the normal fission reaction and is readily separated by chemical means from the other fission products.

Plans are going ahead to use radio-caesium units in a number of hospitals. This substance has the good point that shielding of workers from the rays that it emits is far simpler than in the case of cobalt. Against this must be weighed the fact that the dose delivered in a given time is much smaller and units need therefore to be larger.

In the same way that man-made radio-isotopes have replaced naturally-occurring substances like radium and radon in "telecurie" units, that is to say, devices used to bombard malignant growths from a distance, they also offer many advantages over substances like radon gas in the close treatment of disease. Radon is a highly radioactive gas emitted by radium when it decays. The old practice, still maintained in most countries, is to collect this gas and to seal it into hair-like tubes of gold known as "needles" or "seeds".

Radon seeds suffer from many disadvantages. For a start, the radiation they emit is of short life and is not all of one kind. Some of it being far too energetic for convenience. Seeds cannot be delivered in Britain in less than a week from time of order, and seeds in a batch vary greatly in activity. Variations in length and diameter are such that most devices designed to permit introduction of a number of shots in succession around a tumour are rendered unreliable due to jamming. It is just as if an attempt were made to fire cartridges of slightly varying shape from a repeating rifle.

The recent possibility of activating gold in atomic piles has led the Royal Marsden Hospital in London to devise a new "gun" which uses seeds of radio gold contained in thin tubes of platinum and which has proved very reliable. Unlike guns with which most of us have been associated this one can be, and is, boiled before use!

The variety of radio elements now available has led to a number of other ingenious methods of application in this field, Wires of radio tantalum in platinum tubes have been introduced into internal organs, and radio cobalt, in the form of a powder or small spheres incorporated in a malleable plastic medium, has been used to fit closely to a particular part of the body.

One of the most ingenious uses of radioactive material for irradiation purposes has been in the form of a solution or fluid suspension introduced into body cavities infiltrated into the tumour itself. Fine particles of known size have been injected also into arteries and veins in such a way that they would be trapped in fine blood vessels like the lung and remain there near the seat of the growth that needs to be destroyed.

Many of the methods described are already being used in hospitals while others are still in the experimental stage and may never be widely used. Experience gained is constantly leading to improvements and variations.

It is of interest to note that while nearly one thousand radioactive forms of different elements have been manufactured, only a relatively small number of them at present appear to have any application in the medical field. Among those produced by "cooking" or irradiation in atomic reactors are various isotopes of bromine, cobalt, gold, iridium, phosphorus, sodium and tantalum. Fission products used include different forms of the elements caesium, strontium, barium and lanthanum. Of these only phosphorus and iodine have shown any tendency to select any organs or tumour tissue to an extent that permits them to be used safely for curative purposes.

It was widely hoped at first that the possibilities of introducing some ray-emitting substance into the blood might prove an effective answer to some of the insidious malignant diseases of the blood that have successfully evaded all other methods of treatment. Most of these diseases are due to the uncontrolled multiplication of one sort of blood cell or another. With one exception, attempts in this direction have up till now been disappointing.

Some of the most significant and potentially useful advances in the medical and biological field have been made in the gaining of fundamental knowledge of natural processes where radio-isotopes have been used as "tracers".

The idea here is to "label" one or more atoms in each molecule of a particular compound, use it in food, and see where it ends up and in what form. One of the most interesting applications here is in the study of the "metabolic" functions of the body, in the many processes of construction and destruction that go on within the cells of the body.

The nuclear physicists and chemists have now succeeded in producing suitable radioactive forms of most of the biologically important elements, with the notable and important exceptions of oxygen and nitrogen.

The term "suitable" here needs some explaining. The type of radiation produced is obviously of importance, but the flexibility of the various counting devices and techniques now used enables research workers to adapt their methods to suit a wide range of radiation energies. Of far more basic significance is the half-life of the isotope concerned. These vary from small fractions of one second to millions of years. When used on human subjects radio-isotopes must not belong to either of these extremes. They would obviously be of no use if they decayed before the experiment was completed, and too long a life would prevent repetition of the experiment and might result in danger to the patient's health. It might also cause difficulties in eventual disposal of wastes.

[20]

The Atomic Egg

THE diversity of the uses to which radio-isotopes may be put in medicine is as nothing compared to the possibilities in scientific research and industry and it may safely be said that up till now the surface of this immense subject has barely been scratched. It really seems that no suggested application can be too fantastic.

The high penetrating power of rays emitted by cobalt 60 enable steel plates six inches thick to be photographed in search of defects more simply than the body is photographed for broken bones, and the insides of coal retorts in gas works can even be examined while coking is in progress to see the state of the reaction.

Sources of less penetration may be used with equal effect to examine thin sheets of aluminium. A variation of the same application is one in which the beam of rays passing through a continuous strip of metal in a rolling mill is allowed to impinge on a measuring device which automatically stops the mill if the thickness of the newly rolled plate is greater or less than it should be.

The same use of interrupted beams can be applied to an unlimited degree in the factory production line, as, for example, when bottles are checked to see that they are sufficiently full or match-boxes are scanned to make sure that approximately the right number are going into each box.

In the oilfields the injection of a small amount of ray-emitting material into a pipeline at the same moment that a new grade of oil is about to be delivered has proved to be a simple and effective way of telling those several hundreds or thousands of miles away when the moment has come to switch over the feed into a new tank.

Another pipeline application has been used, as it were, on our very doorsteps. The isotope radiosodium has demonstrated on many occasions in Britain the ease with which leaks may be detected in long stretches of buried water-piper or sewer. There are several ways of doing this, but the description of one of them will suffice here. It relies on the fact that, if water containing radioactive sodium is passed through the pipe under pressure, it will accumulate in the ground around any leak. After a short time the pipe is well flushed out. The position of a faulty portion of pipe will then be readily detected by virtue of the activity that has been left behind in the soil.

Radioactive gold found an unusual and money-saving use in the detection of faulty filters in the brewing industry. The filters in question are of finely packed asbestos wool and their object is to keep out of the beer microscopic material that might later make the beer turn cloudy.

Filters are normally tested daily by a process that takes from two to four days to complete by conventional methods and much beer is wasted before the defective filter is discovered. Using radio-isotopes, however, the test takes only half an hour.

What the scientists did was to take granules of carbon of about the same size as the microscopic organism which normally causes the cloudiness. The carbon was then coated with radio gold and a watch kept for this ray-emitting material in the filtered beer. If any got through, the beer would be rejected and the filter changed, but so long as the filters remained in good condition the gold would be held back and the finished beer would remain uncontaminated.

A completely different use of a radio-isotope and one that will undoubtedly find wide application is in testing the efficiency of a mixing process where it is essential to make sure that a small quantity of one substance is evenly distributed over a much larger amount of another.

Animal foodstuffs provide an excellent example in the case of manganese, a most important dietary additive of which, nevertheless, only about half of one dessertspoonful is required in every ton of feed.

A big manufacturer wanted to know how efficient the various mixing equipment was that he was using and applied to Harwell for help. The answer was provided in a very short time by putting some of the manganese compound into an atomic reactor for a period to render it radioactive. Sensitive counting apparatus was then used to measure the activity in the different bags.

The pigs did not need to worry, for within two days the activity, never very great, would have decayed to one millionth of its original strength.

The lethal effects of more powerful sources of radiation have been used in certain circumstances to kill germs and may one day provide a new and simple method of preparing dead vaccines to protect human beings from disease. Work is going on, too, in several countries to discover whether food could be sterilised in this fashion after canning to avoid the present system of cooking, which in many cases destroys the vitamin content of the food.

In the plastics industry a number of most novel phenomena have recently been brought to light which demonstrate the far-reaching effect that radiation can have on the structure and linkage of aggregates of atoms. A block of perspex, for example, may look completely unchanged after a short period of irradiation within a pile, but the moment it is heated it will disintegrate into a mass of foam-like sponge. In just the same way that this demonstrates a breaking down of links between atoms, another case demonstrates exactly the opposite effect.

Say, for example, that a rod of polythene has been irradiated for a period in an atomic reactor and is then bent into a curve by the use of pressure and a little heat. On being further heated the polythene will demonstrate a "memory" for its original shape and the curved rod will tend to straighten itself out again.

There are some scientists who believe that this ability of radiation to disturb the normal linkage between atoms may be of tremendous importance to the chemical industry and that many substances may one day be made to react together, under the influence of atomic rays, that would normally show no inclination to do so. New substances of complicated structure and of great potential use to man may thus be formed from the simplest of raw materials.

There is nothing revolutionary in this conception when it is remembered that heat radiation is commonly used to bring about or to speed up chemical changes, while some of the most complicated substances that we know, the proteins of living things, are synthesised in nature from extremely simple things like carbon dioxide with the aid of light-rays from the sun that are closely related to some types of atomic radiation.

The cases so far described have been fairly straightforward ones in which activised substances have been relatively simple ones, often composed of a single element like radio gold or radio cobalt. Demands for such materials, manufactured simply by irradiating suitable raw materials for periods in atomic piles or bombarding them in atom-smashing machines, are usually met by the Isotope Division of Dr. H. Seligman at Harwell.

In many instances, however, a far more complex and delicate substance needs to be labelled or "tagged" in such a way that only one of its atoms, the same one in each case, needs to be radioactivised. Often in such a case a period of treatment in a pile would lead to destruction of the specimen or promiscuous labelling of many different atoms. In such instances the only way to achieve the desired result may be by a lengthy, step-by-step chemical synthesis.

For this sort of work, and also for the handling of radium and radon, a separate establishment, known as the Radiochemical Centre, exists at Amersham, Bucks. Under its director, Dr. W. P. Grove, substances are prepared which, by virtue of the painstaking and skilled work that has gone into their making, may cost many hundreds of pounds for no more of the material than would cover a sixpenny-piece.

Using only BEPO, the larger of the two graphite reactors at the Harwell establishment, the departments of Dr. Seligman and Dr. Grove have between them increased the number of yearly consignments from 135 in 1947 and 7,443 in 1950 to nearly 20,000 a year in 1954. Of these latter, 7,252 consignments were sent overseas in 1954 alone, making Britain the largest exporter of radioactive materials in the world.

Up till now forty-seven different countries, including such widely scattered places as the United States, New Zealand, Zanzibar and Russia, have bought radio-isotopes from Britain for research purposes or for the investigation or treatment of disease.

It goes without saying that the delivery of such consignments is a special problem on its own. Some of them are relatively long-lived, but the majority lose much of their activity in a matter of weeks. All are ray-emitting, and while the penetrating nature of the rays varies tremendously all must be conveyed under conditions of extra special care and surveillance. For this purpose the wing-tips of planes are often used and all new aircraft of British Overseas Airways Corporation have special compartments in their wings for this purpose, where packages may be carried in safety.

Of all the varied uses that these many deliveries of radioactive material from Britain's atomic energy establishments have been put to, none, I think, can be more fantastic in a way than that of a consignment of radioactive green pondweed that left Amersham a year or so ago for the National Institute of Medical Research at Mill Hill. Few, either, could have followed so devious a path from the atomic reactor to their eventual destination.

The institute is one of the many departments of the Medical Research Council which advises the Government on all questions of medical science. Its members usually have set tasks that occupy a proportion of their time but they are encouraged to spend the rest of their time in tackling fundamental problems.

One of these workers, Dr. John Humphrey, wanted to study the body's protective mechanisms against disease. What usually happens when a virus or germ gains access to the body is that vast numbers of "antibodies" are formed to fight it. No-one knows just how or why these are formed, and very little is known, either, of the way in which they combat disease. The ability to provoke the production of antibodies is not limited, either, to active carriers of disease. Dead or weakened forms of bacteria and viruses can do so too and are used, of course, to step up the body's resistance to specific diseases like smallpox or poliomyelitis. Many harmless chemicals also have the effect of creating antibodies when they enter the bloodstream, and any substance, live or dead, which has this property is known as an "antigen".

Dr. Humphrey, who read biochemistry at Cambridge and then gained a medical doctorate at University College Hospital, London, joined the National Institute after some years at the Lister Institute and as a pathologist. His routine task is to look after the international standards of antibiotic drugs. While at Mill Hill he decided to study protective mechanisms of the body using albumen or egg-white as an antigen. In order to see what happened to the albumen molecules after they had been "attacked" by the antibodies, he planned to label each molecule of albumen by making its contained carbon atoms radioactive.

This was not easy, however, for radioactive carbon is made by irradiating, not carbon itself, but another element, nitrogen. Thus, even if albumen would have survived a period of irradiation in an atomic reactor the desired result would still not have been achieved.

With Dr. J. R. Catch of the Radiochemical Centre, Amersham, Humphrey found an ingenious way out. First, they would make radio carbon by irradiating a nitrogenous substance in a reactor. The carbon would then be burned to form carbon dioxide, which could be bubbled into a basin of the green pond-weed known as chlorella.

The chlorella would, just like any other plant, "breathe" in the carbon dioxide and use it to synthesise normal protein tissue. This protein, which would thus contain radioactive carbon, could then be fed to a chicken, which would in due course, it was hoped, lay an egg containing radioactive albumen. This very long way round was necessary because man has not yet succeeded in synthesising albumen himself.

While Dr. Catch was arranging for the supply of radioactive chlorella, Dr. Humphrey carried out pilot experiments to see how long it took chlorella to turn up in the egg after being fed to a hen. Six birds were studied, and Henrietta, a particularly handsome White Leghorn, was selected for the experiment because of the large eggs that she laid and her apparent absolute reliability. A lot was at stake for the chlorella had cost £300.

At first, Dr. Humphrey tells me, everything went according to plan and Henrietta laid an egg which contained one-twentieth of an ounce of moderately active albumen. The really valuable egg should have been the next one. At that moment, however, Henrietta apparently began to suspect that she was being made a fool of. Perhaps too much attention was showered on her. At any rate she stopped laying.

"We began to get really worried", Humphrey confesses. When no more eggs came Henrietta had to be killed and the egg extracted from the oviduct. It contained 1·8 gramme, about one-fifteenth of an ounce, of very highly radioactive albumen, worth more than £200, which was later crystallised and purified. Other organs of the bird also contained radioactive material and were equally valuable for future research and these and all but one-quarter of the albumen were sent back to Amersham to remain in stock against the day when more workers ask for these substances.

[21]

The Genetic Price

INCREASING use of atomic energy processes both in the weapons field and also in hospitals, research institutions and in industry has emphasised the urgent need to find out more about their effect on the human body, and discussions in and outside parliament have emphasised the sketchy nature of man's knowledge in this vital field.

The problem is basically one of human genetics, a subject about which scientists still know very little, and all computations yet made of the damage to be expected from atomic radiation have been made in the absence of the one piece of information on which all such computations need to be based, that is to say, the spontaneous rate at which "mutations" or permanent genetic changes occur in the absence of any abnormal incentive.

And yet all present assessments of the harm that may be done to posterity by careless exploitation of atomic processes, both peaceful and warlike, are based on assessments of the "dose" that would double this still unknown basic rate.

Radiation damage strikes, in fact, at the very basis of the hereditary processes, and it is therefore worth while to see how these operate.

In the broadest terms it can be said that our inherited characteristics—the blue eye of the father, that special ability of the grandparent, every little variation that distinguishes us from our fellows—are passed from generation to generation in the male and female germ cells. The same process works in other animals and in plants. The various characteristics are recorded as stripe-like "genes" on a number of tape-like "chromosomes" that vary in number from species to species. Every cell of the body contains such chromosomes. In human beings there are forty-eight of them, except in the germ cells, where there are twenty-four. The full number of forty-eight is regained, however, when male and female germ cells unite. Parents hand on not only their own characteristics but those of their forebears.

Many of these will obviously be conflicting. The mother may have had blue eyes and the father brown. Some characteristics are known to be "dominant" or self-assertive and others "recessive". Thus in a battle between blue eyes and brown eyes, the brown, being dominant, will tend to win. But the matter is not quite so simple as that. The effects of earlier generations must be taken into consideration and there will still be a chance for blue eyes to show themselves, even in the children of brown-eyed parents. All this may seem a long call from atom bombs and X-ray machines, but it is not, for the chromosomes carrying the genes, or units of inheritance, are very subject to outside interference, especially by any form of atomic radiation. In such cases the radiation, in its passage through the cell, either directly or indirectly does physical damage. It may be irreparable and destroy the cell or its ability to reproduce, or it may just damage one of the many stripe-like genes. From then on, the cell, if it is able to reproduce at all, will do so in the modified form. Any new characteristic it has gained will be passed on to posterity and the newly acquired character is known to scientists as a mutation.

The process is not a new one introduced by the atomic age. Nature is continually producing its own mutations, so that, to take one example of a dominant mutation, there are produced in Britain alone every year sixty-three large-headed dwarfs from parents who show no sign of dwarfism.

Some of these normal mutations are caused by atomic radiation from natural sources. One-quarter of this radiation comes from cosmic rays that rain down on the earth from outer space; another quarter comes from minerals like radium in the ground; but one-half comes from within the body itself from naturally radioactive substances like potassium. It would appear, however, that radiation accounts for only one-tenth of all the mutations that are known to occur. Just why the rest happen it is the scientist's task to find out. Some are almost certainly the result of chemical reaction within the cell, a process that has been repeated in the laboratory with substances like mustard-gas and formaldehyde.

It would be a curious thing if some of them were not simply the result of nature's failure to duplicate exactly countless millions of times the cells involved in the normal process. Compared with the many genetic hazards to which nature has herself exposed us, it would seem that the increased dangers due to nuclear weapons up till now tested are insignificant. Mr. Macleod, Minister of Health, told the House of Commons of one eminent scientist who had informed him that he was "a good deal more worried about crossing the road than he was about the present levels of radiation".

We are faced, nevertheless, with the fact that most of the mutations so caused are harmful and that in a welfare state we no longer enjoy nature's own safeguard, the law of survival of only the fittest. It is generally assumed that artificial increase in the natural mutation rate would be damaging to the race and that to double it would be a very bad thing. The difficulty is in assessing either of these amounts.

Mr. Macleod, in addressing the House of Commons on this subject in March 1955, said that "estimates of the dose of radiation over a generation that is likely to double the spontaneous mutation rate varied from 3 röntgen units to 300". A figure of 50 r over twenty-five years, he said, was "as good a guess as we could make".

The figure of twenty-five years is taken here because it is the average age at which we reproduce. The fact that the dose figure should be a global one emphasises one thing that has been ascertained about radiation damage, which is that it is cumulative.

It appears that there is no "tolerance" dose for genetics. Any exposure at all will result in the production of mutations. There seems to be no recovery from such damage, as there is when other cells of the body are subjected to moderate doses of radiation. It thus becomes imperative to discover the "rate" at which such mutations are produced, that is to say, the relationship between the amount of radiation received and the damage done. Much effort has already been devoted to the objective. A great deal of work has been done in their field in the United States and also in Sweden.

It has been hampered by a number of factors. First of these is the impossibility of conducting any experiments on man himself. As Professor Kenneth Mather of Birmingham University, a well-known geneticist, has pointed out, many of the changes are "recessive" and may not show themselves for twenty generations or more, so that, apart from any ethical consideration, an experiment started at the time of William the Conqueror might only now begin to show results, and none that we started ourselves would ever be of use to us.

Another good reason is a purely statistical one. To be of value any such experiment must take in vast numbers of subjects, all of which must be reared in strictly controlled circumstances.

When we start looking for a subject that will meet these conditions of ready availability, rapid reproduction and economic size, we find ourselves being driven to experiment with mice, with insects as far removed from man as the fruit-fly, *Drosophila*, and with runner-beans. Such derived data can only be applied to man conditionally, but it is fairly argued that in many respects, since the general mechanisms of reproduction are the same, that if a certain behaviour is found to operate over widely different species of the animal kingdom it may equally well apply to man too.

The need for research into the biological effects of atomic radiation became obvious soon after the discovery of X-rays and of natural radioactivity at the end of the last century. Although the question of long-term genetic effect had not then arisen, it was soon realised that these rays could cause serious damage to human beings, and there were many reports of ill effects among those who used these phenomena for diagnosis or treatment of disease and in industry. Hospital workers and scientists suffered skin burns and other more serious injuries in the form of tumours. The painters of luminous watch-dials who had the habit of "sharpening" their brushes, contaminated with radium, on the tips of their tongues paid heavily for man's ignorance.

Obvious lessons were soon learned from this experience and precautions were introduced wherever possible to protect the bodies of operators. Great care was taken to avoid ingestion into the body through the mouth or nose of any contaminated material. It was only when war-time research brought atomic physics to the point where it could be exploited on a large scale that the problem of protection assumed one of major importance.

One reason was that it became obvious that any risks would no longer be restricted to a small fraction of the population, and, the larger the fraction of population involved, the larger would be the probability of recessive or hidden damage showing itself through marriages between couples who had suffered similar damage.

The most important source of man-made radioactive contamination in the world at present is the hydrogen bomb, which is capable of producing and spreading anything up to at least 1,000 times more radioactive material than an ordinary atomic bomb. It is important, however, to distinguish between its indiscriminate use in war over populated areas, which would be disastrous, and the occasional testing of a weapon in the national interest over some unpopulated corner of the Pacific or over what may possibly prove to be the best testing ground of all, the Antarctic.

Contamination of the atmosphere over Britain due to weapons tests elsewhere is monitored by aeroplanes which make regular flights at high altitudes, carrying filters which concentrate airborne dust. Measurements of rainwater with sensitive counters enable calculations to be made of radioactivity reaching the ground. These measurements all indicate that in the case of hydrogen bomb explosions the level of intensity in the stratosphere 40,000 to 50,000 feet up is far greater than that at ground-level. They suggest that the dose which will ultimately have been received in this country by unprotected people from fall-out that has already occurred is about 0·01 röntgen units, and that they may expect to receive a further 0·02 röntgen units from debris that is still airborne but will ultimately settle. This total of 0·03 röntgen is one-third of that which the average American, who is closer to the testing ground, may expect.

This figure is obviously an exaggerated one because it assumes first of all that none of the activity, having once fallen with rain, will be washed away and become diffused in the ground. Secondly, it applies only to a person spending the whole of his life, night and day, out of doors. Were he instead to spend it all in a normal brick house the dose would be reduced to one-twentieth.

Acting on the fairer assumption that a person spends about half his time out of doors, but again ignoring the fact that much of the activity would inevitably be washed away by subsequent rain, one arrives at an average figure of 0·003 röntgen units over a generation. This would be something like 1,000 times less than one might expect to receive from natural sources and nearly 2,000 times less than the dose that a Tibetan, living in an area where cosmic ray bombardment is more intense, might expect to receive without suffering any obvious ill effects.

Other harmful effects of hydrogen bomb test explosions have been alleged. M. Charles Noel-Martin, for example, in a communication to the French Academy of Sciences, made under the sponsorship of Prince Louis de Broglie, one of France's leading physicists, suggested that a hydrogen bomb 1,000 times as powerful as the atomic bomb which exploded over Hiroshima would result in the formation of 500,000 tons of nitrous-oxide gas, leading to the production of nitric acid and a harmful increase in the acidity of rainwater.

Enough radioactive carbon 14, he said, might be produced by interaction of neutrons with atmospheric nitrogen to increase the natural radio-carbon content of the air by from 10 to 30 per cent. He further stated that a ground explosion of the same magnitude could lift up into the atmosphere 1,000 million tons of matter and that this would appreciably diminish the transmission of solar radiation.

These suggestions, which received a great deal of publicity at the time, have been answered by Sir John Cockcroft. Unites States figures for the production of nitric acid, he points out, suggest that M. Noel-Martin's figure is about ten times too high and that the real amount, about 50,000 tons, is unlikely to be important since it is about the same as that produced each day by thunderstorms.

Calculations made at Harwell of the radio-carbon situation suggest that an unduly pessimistic view has been taken here too. It is true that the amount produced might be equal in activity at first to 670 lb of pure radium, but that this would rise rapidly into the atmosphere and only diffuse slowly downwards. It would then represent one-thousandth of the amount naturally present in the atmosphere due to cosmic rays. Since carbon 14 contributes only 1 per cent of all the radiation received by the human body from natural sources, the effect is likely to be negligible.

On M. Noel-Martin's third point, the masking effect that explosion debris might have on the sun's rays, Sir John points out that the explosion of the Krakatoa volcano in 1883 caused a diminution of 10 per cent in the intensity of sunlight reaching the earth's surface. The amount of dust thrown up into the air on that occasion was variously estimated at between 100 million tons and a figure 200 times higher. Records show that this great amount of dust had no apparent effect upon the weather. If British figures are correct, then the amount of matter thrown up by a hydrogen bomb would in any case be only about one-thirtieth of that suggested by M. Noel-Martin. Its effect would be negligible.

The large-scale development of nuclear power obviously creates its own problems. The reactors themselves are intense sources of radiation and must be properly shielded. The resultant "ashes", the product of uranium fission, are identical with those produced by ordinary atomic explosions. There was a time when even "experts" considered that the accumulation of these products might present an almost insuperable problem. The position has now changed to one in which these "wastes" have found so many applications in hospitals, research and industry, that the demand for them has outstripped the supply.

The wastes from Harwell are small in quantity compared with those of a production factory like Windscale but the problem of handling them is typical. The man responsible for this task, Mr. R. H. Burns, the son of a chartered accountant, was born at St. Bees, within a stone's throw of the Cumberland plant. He graduated from university with first class honours in chemistry in 1926, and after a period of five years with a firm of consulting metallurgists, joined the chemical branch of the L.C.C., dealing with water-pollution, sewerage and the like. He had a wide experience of the problem by the time he joined the Harwell establishment in 1948.

"There are two distinct problems as far as atomic energy establishments are concerned", he told me. "The first and easiest is that presented by factories like Windscale, situated near the sea. The second is that of the inland sites such as Harwell, Aldermaston and, to a lesser extent, Springfields, where the restrictions are much worse and more difficult than those of sea sites." Every major action, he told me, had to receive prior authority from the Ministry of Housing and Local Government and the Ministry of Agriculture and Fisheries. "They must authorise all effluent disposal in principle. They are empowered to and do set limits on the amounts of activity that we discharge during any given period. Both may appoint Radiochemical Inspectors, and the Ministry of Housing and Local Government have the right to enter any establishment of the Authority to see that authorisations are not exceeded.

"The law requires the Authority to take such samples, to keep such records, as the Minister requires, and when requested to keep duplicates for them to check on. We keep a sample of every local discharge we make into the Thames. We use the batch basis. This gives us better control and we can sample and check everything before we let it go, so that there is not the slightest chance of undue activity reaching the river."

A Ministry of Housing and Local Government Inspector actually has his own office in the effluent laboratory at Harwell. He has the legal right to go into the establishment whenever he wishes to see that the regulations are being complied with. The restrictions are readily accepted by Harwell scientists. "After all," Burns points out, "the Thames is the drinking-water supply of London."

The Harwell establishment discharges between 300,000 and 400,000 gallons of effluent into the Thames each day. The activity is extremely low, however, and based on the assumption that reservoir inlets are nearby, whereas they are in fact some thirty miles further down the river. Burns told me it cost about five shillings per 1,000 gallons to handle effluent. "I was staggered the other day", he said, "to learn that one well-known chemical firm spends four times that amount on treating some of its more difficult wastes. They did not seem to regard their figures as excessive." The proof of their effectiveness would seem to lie in the fact that the Metropolitan Water Board have never yet detected any unusual activity in their reservoir intakes.

The present view of the Authority is that the disposal of effluent in the future will not be nearly as difficult as had previously been anticipated. Apart from radioactive gases like radiokrypton and radioxenon, which are at present allowed to escape but may later be bottled and put to useful purpose, radioactive wastes fall into three main groups, only one of which presents any serious problem.

The first of these contains substances that are only slightly radioactive. They are comparable to naturally radioactive elements of the earth's crust. These present no problem. The second group are those fission products which have half-lives of one year or less. If nothing else can be done with them storage for a period of about ten years is feasible and would reduce their activity to a level where dispersal would be practicable and completely safe.

The third group is one which, on the face of it, presents most difficulty. It consists essentially of two elements, strontium 90, with a half-life of twenty years, and caesium 137, with a half-life of thirty-three years. The chemical separation of these elements is, however, a relatively easy task and they are finding an increasing use in industry and medicine. It is expected that for a considerable future period these two substances will be a valuable by-product of atomic energy processes that will be saleable at a profit. Dr. Seligman of Harwell believes, in fact, that it would be possible to sell at once all the radioactive wastes of this sort that are likely to be available from British atomic power stations over the next 10 years.

If at any time the supply should begin to exceed consumer demands the normal method of storage applied to short-lived elements would obviously be uneconomical since the time required would be from 200 to 300 years. There is, however, a further possibility which has emerged from recent research and which demonstrates the lively and effective way in which science is dealing with some of its problems.

Experiments have shown that these two potentially troublesome elements are readily absorbed by natural clays and that when these are later baked a glasslike substance is produced in which the radioactive particles of strontium and caesium are permanently attached to the particles of clay in a manner so effective that not even powerful chemicals like nitric acid with a strong affinity for strontium will remove them.

Hospitals, of course, are a source of radioactive waste that must not be forgotten, and there are the most stringent regulations governing the amounts that they release. At the present stage, however, when the total amounts used are still relatively small, one of the easiest general ways of supervision is the purely administrative method of totting up the total amount of radioactive material received from places like Harwell by all the hospitals in a given area. The water board official need not worry too much so long as he knows that even if all the isotopes in the area were discharged into the drains at once they could cause no damage. In essence the problem of the hospital is a simple one of disposing of liquid wastes, including excreta and laboratory and laundry water, and the solid-waste problem, including that of all kinds of paper, swabs, dressings, instruments, glassware and contaminated linoleum and woodwork, and sometimes even bed-linen and clothing.

It is obviously a good thing if as much of this waste as possible can be disposed of without pretreatment by normal utilities or if the amount of treatment and storage can be kept to a minimum. As far as the public is concerned, the chief dangers are those of contamination of sewers and, through them, of public water-supplies, which might in certain circumstances suffer if sewage that had become radioactive were incorporated in a chemical fertiliser. There is also the problem of sewerage workers and of workers in garbage dumps. The problem of handling contaminated laundry is obviously a very difficult one. If costs are to be kept down in hospitals then every effort must be made to deal with them in the normal fashion. But very active clothing or bed-linen will need to be given a preliminary wash under controlled conditions.

It is worth remembering too that atomic bombs and reactors are not the only man-made sources of radiation to which we are subjected. In America, for example, where the dosage due to atomic explosions is higher than elsewhere, the average amount of radiation likely to be received per head from all atomic and hydrogen bomb explosions to date is 0·1 röntgen unit, or only one-tenth of that which a person might receive from a single mass-radiography chest examination.

There are many doctors who are concerned about the widespread use of shoe X-rays. "It is not the single examination of a pair of shoes that matters so much", one of them told me, "as the fact that many mothers may take their children into two or three shops and have them try on a number of shoes in each and repeat this procedure several times a year. I would be very unhappy to think that any child of mine were subjected to it."

[22]

Bombs and the Weather

MANY queer letters reach the desk of the science correspondent of a national newspaper. Some of them are from obvious cranks, but the majority of them are from perfectly normal, seriously-minded members of the public who cannot help being perturbed by the bewildering succession of events in the world of science. Many of them concern flying saucers and unusual phenomena seen in the sky, more worldly matters like atmospheric pollution, the shortage of scientific manpower or the use of preservatives in food, but a large proportion of all letters concern atomic energy in one way or another.

They contain such questions as "Can H-bombs set fire to the sea?", or about the effect of these major explosions on the weather. Some writers, echoing the statements of Prof. Soddy, express preoccupation at the amount of radioactive gas discharged into the atmosphere by atomic factories, while others are worried about plans to dump such material in the sea or in disused mine-shafts.

On the matter of H-bombs and their effect on the weather, I have found that there are few scientists who will give an outright "No". The best one can get them to say is that "We know of no way in which it could do so".

They usually base this answer chiefly on a factor that is constantly in the back of the mind of every physicist, the question of energy. Like everything else in this world the behaviour of the weather depends on the expenditure of energy. Everything connected with our life on earth, we might say, depends on energy, and that energy is all derived in one way or another from the sun. It does not matter whether we are thinking of something obvious, like sunshine itself, or something more remotely connected with the sun, like the coal we burn in our fires, or the petrol we use in motor-cars, which has been derived indirectly from the sun through the process of photosynthesis, or chemical combination brought about by the action of light.

Even the rain which waters our crops and provides reserves of hydro-electric power has been evaporated from the sea or the face of the earth by heat from the sun. We may release some of it by what is known as "trigger action" by providing tiny particles of dust, crystals or even droplets of water on which cloud-borne moisture can form larger droplets heavy enough to fall to earth. This is, in fact, achieved by makers of "artificial rain" when they drop seeding particles from high-flying aeroplanes, spray water underneath clouds where it will be caught in the up-draught, or send up rockets full of tiny crystals or discharge similar chemical substances by burning smoke candles on the ground. It is also achieved by atomic bombs on a purely local scale when they scatter soil or explosion debris or lift water. The effect here, however, will be purely local and temporary. To have a lasting effect the bombs would need to lift enough water to replace the rain that fell or provide small particles in quantities vastly in excess of anything they actually achieve.

The forces released by an atomic bomb are puny compared with those of nature. The energy provided by the explosion of a single uranium or plutonium bomb amounts to less than that provided by the sun each day over each square mile of the earth's surface. An average thunderstorm would involve energies equivalent to those of several hundred such bombs, while a hurricane would equal many thousands.

In the same way the trigger action can only be achieved where there is an adequate supply of particles to bring about condensation. In many parts of the globe there is in any case a superabundance of them already, due to particles of salt and the like.

The whole matter was summed up by Sir Graham Sutton, the director of the Meteorological Office, in the scientific journal *Nature* on February 19, 1955. After summarising the available data he concluded that the testing of hydrogen bombs in the Pacific the previous year "cannot be held responsible for any world-wide extremes of weather".

There were two possible ways, he wrote, in which a thermonuclear explosion might affect the weather—a direct disturbance of pressure distribution and air-currents caused by the shock of the explosion, or by the distribution of large quantities of dust.

"The energy released in what is thought to have been the most violent explosion to date is equivalent to the addition of one rather small depression to the atmosphere . . . so that those who seek support for the theory that the effects of the explosion were felt all over the world in increased cyclonic activity, lasting for many months, are faced with a difficult task."

The question of dust, said Sir Graham, was more complex because the amount thrown up into the atmosphere by the explosions was not known—nor was it known for certain whether an increase of dust in the air would affect rainfall or temperature. The explosive eruption of Mt. Krakatoa, he recalls, probably threw up very much more dust than the Pacific bomb explosion, but "there is no evidence of abnormal weather in England following this eruption, although the optical effects of the dust were evident all over the world".

The suggestion that an atomic bomb or an H-bomb might get "out-of-control" and set the world on fire has been adequately dealt with by Prof. Frisch in a broadcast made in 1954 at a period of great public alarm after the President of the United States had reported that the explosion of the hydrogen bomb at Bikini on March 1 that year had been "much more powerful than was expected". Radioactive ashes had fallen on people and caused radiation injuries at distances of 100 miles or so, a distance that until then had been considered safe.

He recalled uncertainties among the scientists themselves when he and others nine years before awaited the explosion of the world's very first atomic bomb at Alamagordo in the deserts of New Mexico. Some, says Prof. Frisch, thought they might get hurt in their observation post twenty miles away. Others did not believe it would work at all. In the end it all happened just as the theoretical physicists had predicted. They achieved this although the atomic bomb, at the moment of explosion, was "many thousand times hotter than the hottest furnace". They had to calculate the behaviour of that exceedingly hot mass of gas by stretching their scientific imagination far beyond the range of any previous experiments.

In the case of the hydrogen bomb, explained Prof. Frisch, the rate at which the explosion develops depends very much on temperature, so that any slight error in predicting the temperature could mean a big error in predicting explosive effect. A slight variation in the efficiency of the detonator might cause the violence of the whole explosion to vary a great deal. "But there is one thing no bomb can do: it cannot produce more energy than is contained in the explosive."

Reports that scientists were startled by the violence of the explosion could only mean that the previous test had produced only a fraction of the available energy and that the more recent one had unexpectedly produced a larger fraction. Scientists might not be able to predict that sort of variation but they can predict the maximum explosive effect with complete confidence. "If an eye-witness said it looked 'as if the explosion had got out of control', that was purely a figure of speech. The explosion cannot get out of control", said Frisch. "There is no possibility that the earth, the sea or the atmosphere could catch fire as it were. The explosion cannot spread to common materials."

One of the most vexed questions of atomic energy has been concerned with the disposal of certain solid waste matter that could not be dealt with by normal methods of storage and eventual dispersion. Within this category come a variety of laboratory instruments that have become contaminated with radioactive materials of long half-life.

The normal procedure here, a very expensive one, is that of sea-dumping. Several times a year one of the Royal Fleet Auxiliaries makes a journey several hundred miles out to sea to dump a number of concrete-covered metal canisters into the deep water beyond what is known as the "Continental Shelf" where the canisters are undoubtedly safe for as long a time as their contents will remain active.

Much of this waste matter comes from the Atomic Energy Research Establishment at Harwell, Berks, and the suggestion was made some years ago that it would be quite safe and much more in the taxpayer's interest to dump these canisters in one of the many disused mine-shafts of the Forest of Dean, not many miles from the establishment.

The suggestion, a perfectly sound one, was opposed by a group, known as the Free Miners, with ancient rights in the forest. There could be no sound scientific basis for their attitude. The mines were disused and, even if mining were for any reason restarted in nearby parts of the forest, there could be no risk of a spread of contamination to nearby workings.

No-one expects the Free Miners of the Forest of Dean to be scientists, nor was it incumbent on them, who had nothing to gain, to seek scientific advice at their own expense. There are, however, fully qualified scientists outside the Atomic Energy Authority who are employed by the Ministry of Housing and Local Government and who are specifically charged by law with the protection of the public against harmful practices of this sort.

A far more enlightened attitude was adopted by the people of the little town of Thurso on the north-east tip of Scotland when they were consulted about the establishment of an atomic reactor of a new and revolutionary type, the Dounreay breeder reactor, several miles from the town. Led by their Provost, a senior official in the Salvation Army, they welcomed the project and the small element of risk which they had been told went with it. Their action will undoubtedly lead to Thurso becoming one of the leading centres of the North.

[23]

The Way Ahead

IN TEN years atomic energy has grown to be one of Britain's largest and most important industries. The United Kingdom Atomic Energy Authority has ten different establishments and a payroll of 20,000, compared with a modest 6,000 employed by its transatlantic counterpart, the United States Atomic Energy Commission.

The comparison, of course, is not a fair one and the American project is many times bigger than our own. The difference lies in the way the U.S.A.E.C. has enlisted private industry and the universities to do its work, both in the research and development fields and also in the operation of plant. If contractors were counted in, the labour force would be nearer to 120,000.

In Britain, instead, until quite recently, very little development work has been done by private industry and all factories are still operated by what was, until December 31, 1953, the Atomic Energy Division of the Ministry of Supply and which is now the U.K.A.E.A.

The situation is now rapidly changing. The U.K.A.E.A. is retaining its role of a pioneering organisation feeding firms with the data they need, and also remaining responsible for the manufacture of atomic explosive and weapons, but the designing and building of civil power stations is being left to the Central Electricity Authority and to private firms. The responsibility for running these stations will be C.E.A.'s.

The various groups of the Atomic Energy Authority work closely together. In much the same way that a private firm might operate, the directors of the various groups meet every alternate Thursday under Sir Edwin Plowden for a "board meeting", Sir John Cockcroft representing research activities, Sir Christopher Hinton from the Production and Industrial side, Sir William Penney from the Weapons Group, and Sir Donald Perrott in charge of administration and finance.

One of the main tasks of the Authority since it took over from the Ministry of Supply has been to try and get private industry interested. They have had signal success. There are now nearly two hundred firms engaged in the manufacture of atomic energy equipment and the number is likely to increase rapidly as other companies realise the tremendous opportunities that the future holds in store.

The building of a nuclear power station, of course, is a big job. It may cost anything from £10 million to £20 million and involves many different trades and professions. There is nuclear and electronic equipment, the trickiest of all, of course, and heat-exchange plant required for steam-raising, turbines and dynamos, and the structural work itself, which involves many problems not met with in a conventional power station. It is not the sort of job that any small company could tackle and no big one of the pre-atomic era could hope to do it on its own. In Britain, as in the United States, the right answer has been achieved by the formation of groups of companies, each made up of firms specialising in the different component fields.

There are in Britain already four such groups of companies, each trained and equipped to design and construct, and, if necessary, to operate, nuclear power stations in any part of the world. Many of these member companies have already gained experience in building one or other of the existing U.K.A.E.A. facilities and all of them are currently engaged on much larger contracts in connection with the new programme of nuclear power.

All this work will provide them with ample experience to take on export orders. Apart from the various research reactors and the adventurous experimental power project of advanced design now under way at Dounreay in the North of Scotland, there are no less than fifteen large-scale industrial nuclear power stations scheduled for construction at present that will derive their power from twenty-two atomic reactors. The know-how they gain in this work is going to pay dividends in the future.

The speed with which things are happening in the atomic energy industry has surprised even the men most intimately connected with it. The "Programme of Nuclear Power" announced by the Government in February 1955, which involved the building of twelve atomic power stations costing £300 million over an initial ten-year period, represented, we were told at the time, the most that industry could possibly hope to cope with, having regard to the country's resources and other calls that had to be met. Yet only four months later the U.K.A.E.A. announced its decision to go ahead with the construction of a further three power stations of its own, involving six more reactors of the Calder Hall type. The production of more military explosive is their main object. The substantial contribution they will make to the country's electricity supplies is secondary but important. They will incorporate few new ideas, it is true, but the fact that they are likely to be finished by 1961, thus almost doubling construction over that period, shows how industry is bending to the new tasks.

Sir Edwin Plowden, who heads the Authority, is a curiously undramatic man, shy and modest but with a tremendous sense of purpose and a sure knowledge of the importance of the task. Born in Argyll in 1907, he is well and away the youngest member of the Atomic Energy Board, and, having come from outside, is still a little diffident at first when he talks on the subject. His father was a Scottish "country gentleman". His mother is an American, the daughter of W. S. Haseltine, the painter. He went to schools in Switzerland and in England, saw a bit of America, and then came back to take an economics degree at Cambridge. Unlike so many of the men he now has under him, Plowden took things pretty easily, describing himself as an "average idle undergraduate".

After a short spell on the sales side of a firm manufacturing telephone equipment, Plowden joined C. Tennant and Sons, a London chemical firm, in 1931. It was a time when business everywhere was bad and competition was sharp. Still on the sales side, he was up against old and experienced competitors, but his shy frankness made up for other people's self-confidence and glib sales talk. Within seven years, and still only thirty-one, he was made a director of the firm.

When war broke out, Plowden went first to the Ministry of Economic Warfare and then to the Ministry of Aircraft Production, where he shot straight to the top and finished up as chief executive. The war ended, he returned to Tennant's, but he had only been there a year when he was asked to join the Treasury and help to plan the country out of the welter of post-war economic difficulties. He was called Chief Planning Officer and worked in close contact with Sir Stafford Cripps, first in getting the country onto a peace-time footing and then in the equally difficult task of rearming again on a major scale without provoking a new crisis. Always he worked with tactful efficiency and showed a knack of getting his own way with a minimum of fuss.

Plowden is not a man for the limelight, and when his chairmanship of the Atomic Energy Authority was announced he managed to avoid a public appearance for a whole year on the excuse that it was "people like Cockcroft, Hinton and Penney that matter most".

Plowden has his office on the eighth floor in St. Giles Court, an imposing new block of offices built for the Ministry of Supply just off Holborn. The whole of the floor has been loaned to the A.E.A. until their own headquarters is ready on the site of the old Junior Carlton Club in Great Charles Street. Workers in the building and members of the Ministry of Supply employed in London can enter by showing a pass to a uniformed War Department policeman at the door, but most other visitors, even if they are Atomic Energy men from Harwell or Risley, are motioned to a long reception desk where they have to fill in a pass with their name, nationality, and office and home addresses. They must wait while the letters A/E, for Atomic Energy, are impressed across the pass with a rubber stamp and a messenger is called to take them up in the lift.

For those unused to Atomic Energy procedure the wire cage that meets them as the lift doors open at the eighth floor is a bit of a surprise. It is designed to make all file past the guard-post singly as they enter or leave the floor.

I had gone to St. Giles Court to see the Chairman and, after a further stamp on my pass upstairs to indicate that I had been checked into the precincts, I was shown along to the "Press Office". Here Stanley White, a cheery, round-faced and much over-worked ex-R.A.F. officer who has had the difficult task of keeping newspapers happy almost since the war, was busy taking in turn a continuous stream of incoming calls on two telephones. As he put one down to answer a waiting caller on the other, the first one rang again. And so it would go on for the rest of the day.

White took me along to the Chairman's office and discreetly retired. Plowden, a dapper, clean-shaven man with inquiring, friendly eyes, got up and shook hands and motioned me to a seat. He looked a very prim and proper business man, tidy and precise and obviously a little shy.

When I asked him to talk about his job he took refuge at first in published statements and reports, quoting from official papers. "I believe what was said in the White Paper", he told me, referring to the Programme of Nuclear Power and avoiding any expression of personal views. Then, slowly at first, he began to warm to his subject. "Atomic energy already affects, and will affect more and more, every phase of our national life", he said. "It matters to this country enormously, both in defence and in the economic field.

"It has come first in Britain, not because we are cleverer than anyone else, but because it is an industrial country with the most immediate need. It is economic here quicker than it would be in any other place." Because Britain could, with its lower capital costs, build atomic reactors more cheaply than they could be built, for example, in America, they were bound to be economic here more quickly.

"There is another thing", he went on. "It is a very obvious one. The whole of our existence in Britain is based on the assumption that we are at the centre of a political and economic nexus. In the past our influence has been based on political and military power. More and more, now, it has got to be based on a strong economy and on what people think is going on here and whether we seem a live lot with new ideas. If we demonstrate that we are, then people are going to want to come and work with us and that is going to bring all sorts of advantages.

They will say we are pretty good people to collaborate with. 'Let us remain close to them and trade with them'."

The results of progress in the atomic energy field were already being felt, he told me. A great number of approaches to Britain had already been made. "People want to work with us and we feel that we can help them."

Sir Edwin is not sure at this stage just how an export business could work. "The Authority itself will not be in the market", he told me. "That side of it is going to be up to industry. We shall feed them with the data they need. It looks at present as though British companies will then design and build complete units where needed for other countries and the Authority will supply the fuel elements and be responsible for processing them again afterwards."

Plowden told me that as far as British firms are concerned the interest they were now showing in atomic energy matters was tremendous and quite embarrassing. The difficulty was that so many people were all at once waking up to the fact that there was something in it and wanting to know about it. After a long period in which very little interest had been shown they were now all saying: "This is a new thing. We are all entitled to know about it. You must put us in a position where we can take part." The difficulty was to organise the passing on of information to those who needed it.

"They come to us and tell us they want someone from the firm to 'know about atomic energy' and ask us if so-and-so could work as a member of our staff. Many of them have been given these facilities, but there are far more requests of this sort than we can possibly cope with. There is first the security problem and then the physical task of how to get the information over. It was to simplify matters that we asked industry to form four groups of companies which would then work in close collaboration with us, and we have had to stick resolutely to this arrangement, except in cases where we have firms working with us on individual projects."

I asked Plowden about other applications, such as ships, and he told me they were doing something there both for the Admiralty and for shipbuilders, but there were many problems connected with this application of nuclear power apart from the shielding. "The main point here", he told me, "is that, whereas with ships the time is still some way off before nuclear propulsion can become a commercial proposition, the use of it in large industrial central stations is commercial already."

Plowden is essentially an economist and an administrator and he prefers not to be drawn into discussion on scientific matters. That field is the realm of Sir John Cockcroft, and the simple, concise and friendly way in which he can discuss these matters with anyone from the Prime Minister down to a schoolboy has had much to do with the speed with which the atomic energy project was able to gain funds and grow in the difficult post-war years when there were many great hopes to offer but few firm promises.

Like so many of the really great scientists, Cockcroft had the knack of saying what he wanted to say in the simplest possible language, and, being an engineer as well as a mathematician and physicist, he knew how to win over the men who were really going to count more than anybody, the Hintons, Owens and Kendalls, when it came to putting scientific theories into bricks and mortar, graphite and steel.

John Cockcroft was born in 1897, one of five sons of a Todmorden cotton manufacturer. Three brothers went into the family business, but John won a scholarship to Manchester University from the local secondary school and did engineering. When the First World War broke out before his studies were completed he was still too young to join a combatant unit and worked with the Young Men's Christian Association until he was old enough to be accepted by the Royal Field Artillery. In the improvident way in which Britain in those days squandered its best brains on the field of battle, she went near to losing, unknown, the man who was destined to build the world's first atom-splitting machine, play a leading part in the development of radar in the Second World War and, afterwards, became chief scientific adviser on defence to the Cabinet.

As it was, Cockcroft was able to return to Manchester and complete his engineering studies before taking a job with Metropolitan-Vickers. In 1923 he left Manchester for St. John's College, Cambridge, and soon gained the highest honours in the Mathematics Tripos. All that time he was working as a research student under Lord Rutherford in the Cavendish Laboratory and in 1928 he was elected a fellow of his college. His big day came in 1932 when, with his fellow worker, E. T. S. Walton, he used a home-made device of ingenious but rude construction to split the atom for the first time by purely artificial means.

Rutherford, it will be remembered, had already shown that the source of atomic energy lay in the minute, positively-charged core of the atom, the nucleus. Using rays emitted by certain unstable nuclei, he had succeeded in disrupting others, but it was a slow business and very limited in its applications. The engine of Cockcroft and Walton, which was to set a new fashion, speeded up this process enormously and opened up new fields. It paved the way to the giant atom-smashing machines of the mid-century, which have jumped in size from the table-top variety to something weighing thousands of tons and costing millions of pounds.

John Cockcroft was as excited at the time as any schoolboy on catching his first pike. He didn't know how to contain his emotions (and probably did not want to). He went rushing out into King's Parade, the busy, college-lined street that forms the focal point of the university, dancing along and stopping anyone he knew to tell them: "We've split the atom and the Americans have been spending *millions* to try and do the same thing."

Cockcroft was thirty-five at the time and has now grown more sedate, but he still preserves much of the same youthful spirit of adventure of the young research student. Reporters have learned, too, that the many speeches and lectures that he makes up and down the country to learned societies and professional institutions almost invariably contain something new in them, which is quite a difficult thing to achieve when anyone has to make as many speeches as Sir John does.

A man of wide interests, he has been a keen hockey player, is a good bat, and still likes to lead a cricket team at Harwell on special occasions and public holidays. He has the rare ability, too, of being able to cut himself off completely from his work when he is at home, he tells me, and places his five children foremost among his interests. He is keen on music, although he does not play himself, and loves to read, with a preference for history, archaeology and "all sorts of politics". He likes to work in his garden, too, but concentrates on things like strawberries and asparagus, leaving the rest to Roger, a retired agricultural labourer who puts in two days a week.

Cockcroft is a man of medium build with sparse, flat hair. His wise-looking, half-closed eyes never miss anything. His eyebrows are bushy, sharply angled and gnome-like. Although quick on the sports-field, he normally walks in a slow and purposeful way and his favourite attitude is to stand with hands in his jacket pockets and thumbs resting on the tops, a habit that inevitably ruins the shape of his suits. His conversational manner would be perfectly in keeping with a cup of afternoon tea in a Victorian drawing-room, and he can flit from atomic piles or nuclear accelerators to the Test score with the same facility that a society hostess dismisses the servant problem to chat about a wedding that she has attended.

Dr. B. F. J. Schonland, the brilliant South African physicist who left a professorial chair in the University of Witwatersrand to become Cockcroft's deputy at Harwell, tells a homely story about him. They were dining in Cape Town with friends who had the usual irrepressible small son, who had been warned carefully beforehand by his mother to keep silent during the meal. Towards the end this ten-year-old suddenly electrified the company, which had kept well away from delicate subjects.

"Sir John, may I ask you a question?" he burst out.

"Yes, certainly you may", replied Sir John.

"Well, it's about the atom bomb", said the boy, to everybody's horror, "I don't want to know how it's made. We know that, and we know what to put in it. What I wanted to ask is how big it is and what you put it *into*."

"Well, I haven't seen one and I really don't know how big it is", Cockcroft told him.

"Anyway, it must be small enough to be carried in an aeroplane", said the boy, thoughtfully.

"Yes, I think it is quite small really."

"But what we want to know is, what is it packed in?"

"Well, I really don't know," replied Sir John carefully, "but I shouldn't think it is very important."

"The metal wouldn't make any difference?" pursued the boy.

"No, I don't think it would."

"Oh, well," replied the boy with relief, "then do you think that something like a jam tin would do?"

"Yes," said Sir John, "I think it would do very well."

"Thank you very much indeed", said the irrepressible one. "That is just what I wanted to know. You see, we're making one."

* * *

It has been said of Hinton that he runs the Industrial Group as an autocracy. That would never have worked at Harwell, and Cockcroft would have been the last man in the world to have wanted it so. Engineers like a target all the time, an end in view. At Harwell there are no firm targets. There is no such thing as perfection. The horizon is always running on ahead. The solution of each problem merely opens up new fields to conquer. There can be no defining those new fields until they come into view. The result is that Harwell has become a glorified university of atomic energy where individual initiative is at a premium.

While workers in the research establishments of the Industrial Group in the North are concentrating on the immediate problems of raising the temperature of fuel elements, preventing corrosion and finding more efficient ways to extract heat from reactors now being designed, such problems only provide one facet of the work at Harwell and many lines of fundamental work are being pursued that have no apparent bearing at all on problems of the next ten or fifteen years.

With better fuel elements now being developed, Cockcroft reckons that it will be possible to produce in the first British commercial power stations heat equivalent to 10,000 tons of coal for every ton of uranium fuel. By the time stage two is reached in the early sixties that figure should already have been multiplied by a factor of 10. "In the long run, if nuclear power is to become a major source of power in the world, we should like to see this figure multiplied ten times more again," he told me, "so that we would be extracting from each ton of uranium heat equivalent to something like a million tons of coal, thus approaching the theoretical limit of three million if all the uranium undergoes fission."

Breeder reactors, using a small core of almost pure fissile material, and preferably plutonium, offered the best chance of achieving this. The core would be surrounded with a fertile blanket of uranium 238 or thorium 232 which would take up surplus neutrons from the central core. Many of the neutrons absorbed in this way would be transmuted into the new fuels, plutonium or uranium 233, but, because escaping neutrons would be travelling fast, a fair proportion of them would be able to cause the normally inactive uranium 238 to undergo fission and thus make an important contribution to the total amount of heat produced.

Cockcroft reckons that when such processes are available there should be no shortage of atomic fuel for the next millennium or two.

I asked him what he thought of the chances of using the hydrogen bomb reaction, the fusion of hydrogen atoms to form helium as they do in the sun, as a source of useful energy on earth. Sir John, whose work in the early thirties under Rutherford was in this very sphere of fundamental research, told me with quiet confidence: " I think everyone feels that this is going to come off. It is something for the future, though, which we are intensely interested in."

Cockcroft was far more confident than I had expected him to be about the chances of producing really small "packaged power" units. The tendency of many scientists, especially those outside the atomic field, is to ridicule any small-scale application. Packaged power units of the sort that the Americans were planning to make for military purposes were certainly feasible, he told me, as lorg as you did not mind paying between threepence and sixpence for a unit of electricity. "In places like Broken Hill, in Southern Australia, where they are already paying threepence a unit, and in other parts of the world, where it is costing sixpence, a small unit might be well worth while."

"What about atomic locomotives?" I queried him. They might be possible in the future when plutonium becomes really cheap, he reckoned, but although the size presented no difficulty it had to be remembered that diesel traction cost only about 0·4 penny per shaft horsepower/hour.

I asked Sir John with some diffidence about reports from the United States of plans to build small, self-contained units, with control rods pre-set in the factory, that could be used in any house to run the normal central-heating and water installations. To my surprise he did not rule them out as a long-term project. It all depended on the availability of cheap fuel, he told me. Small reactors using concentrated fuels without a moderator tended to be self-adjusting. When they got too hot they tended to switch themselves off and the reaction started again when they began to cool down. An equilibrium was thus set up which should make control fairly simple.

"And aeroplanes?" I queried. The Americans, he reminded me, were developing atom-powered aircraft only for military use. He did not think they had any civil applications, at least in the foreseeable future. With plutonium or uranium contaminated with fission products, and also liquid metal coolants around, there would be too much damage done if one of them crashed.

Aircraft applications brought me to gas-turbines. Since it was almost impossible to stop water from turning to steam at temperatures of more than 370 degrees Centigrade, whatever the pressure applied, I asked him what he thought of the chances of using gas-turbines, which have no such temperature limitation, to improve the operating efficiency of electric generating stations.

Sir John believes that there is a great future for gas-turbines in the atomic energy industry. "It is purely a question of time and we have preferred to take the easy things first." This line was taken up again by Mr. Leonard Rotherham, head of the Industrial Group's research and development division, when I saw him at Culcheth, near the Risley headquarters, some weeks later.

Culcheth is one of five laboratories devoted to solving immediate problems and surmounting the obstacles that crop up in the day-to-day building and operation of plant and in the design and execution of sanctioned new projects. Unlike

Harwell, where so much of the effort is fundamental and academic, work at these Northern laboratories is very much of an applied nature. The emphasis is all the time on "knowing how" at a particular date.

"You do a lot of broad planning in atomic energy work," explained Rotherham, "but you then proceed by a series of short steps. The great thing is to design a reactor that you can sell and that produces enough money to pay for the development of the next stage so that you can always keep ahead of your competitors."

I was amazed at Culcheth to note the frank and open way in which members of the staff explained their work and discussed their problems. They were getting ready for an "open day" on which each member of the staff would be able to invite a friend along to see work at the establishment. Harwell has similar functions periodically. The Authority finds that they are invaluable in demonstrating to the general public that there is really nothing very terrifying about atomic energy.

It was surprising, nevertheless, to see how much previously secret work was on show and how ready senior staff were to answer questions that would have been considered very indiscreet only six months ago. The explanation, I was told by Rotherham, was that a very genuine change had taken place in the field. "We have entered the commercial era", he told me frankly. "We are expanding rapidly and we want to attract new blood. We can do that best by showing people that ours is a fascinating but otherwise very normal job."

The shortage of scientific and engineering staff is a serious problem. It is not preventing the execution of the present programme, but it is certainly preventing the planners from expanding in the way they would like to. Culcheth, for example, has only 10 per cent of the middle-grade scientists that it needs and there are ninety jobs going to the right sort of people at salaries ranging from £300 to £3,000 a year. Most of them are for young graduates with first or good second class degrees, who at twenty-two years of age will get £500 or £600 and have a good chance of earning £1,500 or more by the time they are in their middle thirties.

Now that the main bogey of atomic energy work, the idea that it is dangerous, has been exploded, there is still one more thing that worries many who would otherwise be keen to enter the new field. It is the bogey of security. The Authority offers its employees marvellous prospects and often a house, but there are many people in Britain who still believe that they will be marked men once they join an atomic energy project, that their telephone lines will be tapped, and that if they want to go abroad they will either be prevented from doing so or followed by secret service men wherever they go.

It would be a physical impossibility, of course, for any such procedure to be implemented and it would require a security force far larger than all the scientists, engineers, and industrial staff put together. The real answer is that the great majority of the work is now non-secret anyway and much of it is published eventually with due credit to the workers responsible. But every commercial organisation has its own trade secrets, and the atomic energy business has got its own trade secrets just like any other. The police at the gates and the security officers inside are carrying out the same function that their counterparts have to carry out in a chemical works, or a factory making some highly competitive form of electronic equipment.

The safety position could not be described more succinctly than it was when Sir Christopher Hinton addressed the people of Thurso about the new reactor that was to be built at Dounreay, just outside the town. "I am not going to claim that there is no risk", he told them. "Every human activity involves a certain amount of risk and we can only evaluate one by comparing it with another to which we are also subjected. By far the greatest risk we run is that of dying from natural causes." He then gave some interesting figures.

In the age groups 10 to 45, about 150 in every 100,000 die every year. Of these, some forty die deaths of violence; they are electrocuted in their own homes, are victims of road accidents, fall down stairs or, possibly, commit suicide. The rest of them, about 110, die from illness or from diseases like tuberculosis, pneumonia, malignant disease, and so on.

If a man works in one of the dangerous industries such as quarrying or coalmining, his risk of dying prematurely is increased by about 50 per cent. In "safe" industries like engineering, chemicals and electricity, the chances are only increased by 7 per cent.

In the atomic energy industry, by contrast, in spite of the fact that it is in its infancy and has been dealing with completely new problems in a relatively unknown field, the corresponding rate is only 2 per cent higher than the normal. It is therefore three times safer than the chemical and engineering industries, which are rightly proud of their safety records.

It is worth adding that not a single one of the deaths up to date has been due to radioactivity, and, in fact, not a single case of damage due to radiation has ever been recorded in Britain since the project started.

Index