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The Race for Norwegian Heavy Water, 1940-1945

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Introduction

By Olav Njølstad

The sabotage action against Norsk Hydro's heavy water factory at Vemork, Rjukan, in February 1943 was undoubtedly one of the most astonishing and heroic Norwegian-Allied operations in Norway during the Second World War. Its blend of high politics, scientific adventure, military drama and individual courage has intrigued people for more than fifty years. Numerous accounts of the event have been made, including two commercial films, and in Norsk Industriarbeidermuseum (the Norwegian Industrial Workers Museum) at Rjukan there is now a permanent exhibition of related sabotage memorabilia. On each anniversary hundreds of people still gather at Vemork to participate in the «Saboteur March», which basically takes the same route down the mountains to the Norsk Hydro plant as the saboteurs did in 1943.

However, the fact that the memory of this remarkable sabotage action is so well preserved and observed does not mean that there is nothing left to say about it - or, for that matter, about the other Allied military operations against Vemork and the stocks of heavy water which the Germans kept there. This can be seen from the three papers presented in this study which, each in its own way, add substantially to our understanding of the wartime race for the Norwegian heavy water.

In the first paper, Professor Ole Kristian Grimnes explains why heavy water was produced in such exceptional quantities at Rjukan in the first place, and also sheds illuminating light on the fundamental question of how significant the sabotage operations at Vemork were for the German nuclear weapons programme and the Allied war effort. His balanced conclusion is that whereas the German effort was not critically influenced by the events in Norway, the operations were nevertheless of crucial importance to the Western powers because they helped eliminate whatever uncertainty there still was about German ambitions in the nuclear field and they thus relieved for good the Anglo-American fears of a German atomic bomb. Finally, Grimnes points out that the Norwegian-Allied heavy water operations "may be considered the first attempt to secure the non-proliferation of nuclear weapons by military action", and he discusses what kind of legacy they represent in that respect.

In the second paper, Joachim Rønneberg, who at the age of 22 led the sabotage action in February 1943, shares with us his memories of that dramatic event. In addition to the many fascinating details about how the sabotage was planned and executed, the reader will find some very valuable reflections on why that particular operation became such a huge success. Here, Rønneberg - who has always been very modest about his own role in the affair - plays down the individual qualities of the saboteurs, stressing instead how the Gunnerside group benefitted from exceptionally good intelligence and strong Allied support. The reader, however, cannot fail to see that the operation must also have been helped tremendously by the personal courage, physical fitness and superior tactical dispositions of Rønneberg and his men. To be sure, this was fully acknowledged at the time: the members of the Gunnerside Operation became the most decorated sabotage group in Norwegian history, and even the leader of the German forces in Norway, General von Falkenhorst, described their action as "the most remarkable coup I have ever seen in this war".

While the story of the German-Allied struggle for the Norwegian heavy water is well known to most Norwegians, they are less familiar with the *intra*-Allied aspects of the race. In the third paper, some of these are exposed by Dr Bertrand Goldschmidt, the former General-Director of the French Atomic Energy Commission (Commissariat à l'Energie Atomique). A prominent physicist himself, Goldschmidt gives a wonderfully concise account of the scientific developments that led to the U.S. decision in October 1941 to launch a crash programme to build, if possible, a military weapon based on nuclear fission. But the main purpose of his paper is to show that without their privileged access to Norwegian heavy water, which was obtained by France through secret negotiations with Norsk Hydro in March 1940 and with the Norwegian government in exile in March 1945, Goldschmidt and his colleagues in the CEA would have had great difficulty in fulfilling the goals of the French atomic energy programme.

In Goldschmidt's judgement, the prewar supplies of 185 kilos Norwegian heavy water to France served as «the entrance ticket» to the Allied nuclear enterprise, which eventually provided French scientists with invaluable know-how about the plutonium extraction process in a heavy water reactor. Then, in the late 1940s, the delivery of 7 tons Norwegian heavy water was "indispensable" for the increasingly successful French effort to build a plutonium-producing nuclear reactor. According to Goldschmidt, *without* these early achievements it is doubtful whether the advocates of a national French nuclear weapons programme could have defeated their opponents in time to obtain their ultimate goal.

The Norwegian willingness in the 1940s and 1950s to assist France in her military-related nuclear effort shows that nuclear non-proliferation had still to become the guiding principle for Norway's export of heavy water. (Instead, Norwegian policy appears to have been restricted primarily by a secret export control agreement with the USA, which ensured that items used in the production of nuclear energy were not to be exported to the Communist bloc countries.) Because of the extreme secretiveness that still surrounds some of the large-quantity sales of Norwegian heavy water, historians are left in the dark about when, and for what reason, the initial export policy was changed, and how strictly the new rules were adhered to afterwards. Hopefully, the day is approaching when scholars will be allowed to address these questions with the same unrestricted access to primary sources as they now enjoy in their research on the time period covered by the present study. Only then will it be possible to make a fair and comprehensive historical assessment of the Norwegian heavy water's impact on the nuclear energy programmes of nations other than Nazi Germany and France.

The Allied heavy water operations at Rjukan*

By Ole Kristian Grimnes

The Allied heavy water operations at Rjukan during World War II are certainly worth a study in themselves. The sources for such a study are abundant. Here I am not concerned with a detailed examination of these operations, however. Rather, my interest is how to put them in a broader perspective. They certainly ought to be viewed within a wider framework, too.

Let us address questions like these: Was heavy water so important? If it was, why in the whole wide world was it produced only at Vemork near the town of Rjukan in any appreciable quantity? And even more to the point, in what way did the Allied heavy water operations affect the German nuclear programme during the war? Surely, these are essential questions which could receive only a very partial answer during the war. Today we know most of the relevant facts and are in a better position to evaluate them objectively.

But first let us very briefly review the heavy water operations at Rjukan during the war. There were four of them, and they were carried out within a period of little more than a year, from autumn 1942 to the beginning of February 1944.

The first action was a glider operation. On 19 November 1942 two Halifax aircraft left Scotland, each towing a glider. The gliders carried 34 British soldiers and were supposed to land on some marshes about 15 miles west of Rjukan. There they would be received by a Norwegian advance party that had parachuted into Norway a month before. They would guide the British to the heavy water plant at Vemork which they were to blow up, if possible also the power plant. The operation proved a complete disaster. Only one of the Halifax aircraft returned safely to Scotland. Due to bad weather the other crashed as did both the gliders. 41 soldiers and airmen were either killed in the crash or by the Germans after they had been taken prisoner.

The second operation was a sabotage action on 28 February 1943, carried out against the heavy water plant at Vemork by a party of nine Norwegian soldiers. They descended from the mountains, crossed the valley, and reached the high concentration plant for heavy water which they blew up before returning to the mountain plateau of Hardangervidda. They destroyed the plant for a period of one and a half to two months, and stopped production of heavy water for five months.

The third operation was an American bombing attack on 16 November 1943. 173 B-17 and B-24 bombing machines swept over the Rjukan valley and dropped their bombs at Vemork and also further down the valley at Rjukan. The bombs inflicted severe damage on the factory, the power station and the pipelines but the high concentration plant for heavy water in the cellar of the factory was hardly touched. Still, after this operation the Germans decided to halt the production at Vemork completely and send their stocks of diluted heavy water to Germany to have it concentrated there.The attack took its toll in human lives. 21 Norwegians were killed during the attack.

The fourth and last operation was again a sabotage action, carried out by three Norwegian saboteurs on 20 February 1944. It was an action against different concentrations of heavy water under transportation from Rjukan, destination Germany. The ferry which carried the precious cargo on lake Tinnsjø east of Rjukan was blown up and most of the heavy water went to the bottom of the lake. Again there were losses in human lives. 14 Norwegians and four German soldiers were killed as a result of this action. Later in the year the Germans dismantled the heavy water apparatus and dispatched it to Germany.

Let us then address the questions related to an overall assessment of the heavy water operations. First, was heavy water really so important and if so why? It was. I am no scientist and shall certainly not attempt to act as one. But this much seems

* *A paper presented at the International Conference on Nuclear Technology and Politics, Rjukan, 16 - 18 June 1993.*

clear even to a layman in these matters. Nuclear research during the war was largely a question of fissioning uranium and of turning a first fission into a self-sustaining chain reaction. Such a chain reaction requires a moderator to be effective. A moderator is a substance which slows up the extreme speed of the neutrons which are liberated in a chain reaction and which are needed to maintain it. Only if the neutrons are thus moderated will they operate effectively in the process.

Heavy water was considered the best moderator. True, the Americans did not use it in their atomic bomb project, they used pure graphite. But that was because they had no heavy water at the outset and only started a modest production of it at a later date. The Germans, however, did have access to heavy water since it was produced in occupied Norway so they settled for heavy water as their moderator. Through this decision heavy water became indispensable to German nuclear research.

Another question is why heavy water was manufactured in any significant quantity only at Vemork/Rjukan of all places, in this wild ravine in the very heart of mountainous southern Norway. There is a basic answer to that question and one which provides a clue to another question at the same time: Why is there any industry at all in this inaccessible part of Norway which used to be a godforsaken valley in its time, before the turn of the century? Even the sun disappears for several months during the winter at the bottom of this grim gorge, the high mountains blocking its rays from entering.

Cheap hydroelectric power is the basic answer, cheaper than in any other part of Europe. Cheap not so much because there are high falls and rapid streams in Norway - the European Alps also boast those - but cheap because the Norwegian mountains in addition hold huge lakes and water reservoirs which can be regulated to guarantee a steady water supply. Vast regions are largely uninhabited and so the construction of dams, the flooding of fields, and the channelling of streams and waterfalls into tunnels and pipelines until recently did not draw much political opposition from those affected by such works. Nor did hydroelectric development projects run up soaring bills of indemnification because the proprietors must be compensated at a high cost.

A new industry, founded on electricity-consuming technology and inexpensive hydroelectric energy was therefore developed here and in other parts of Norway from around the turn of the century. It was a development which added a distinct feature to the Norwegian industrial landscape. In fact, it constituted a very characteristic second industrial revolution in this country which like many other European countries outside England had started its industrial revolution around the middle of the 19th century.

One particular company initiated this development at Rjukan and has dominated it ever since, Norsk Hydro - or Hydro for short. Hydro was founded on a Norwegian invention, the fixation of the atmosphere's nitrogen through the use of an electric arch. In the late 1920s the company had to give up that technology and switch to the German Haber-Bosch method for the same purpose, the fixation of nitrogen. This method required hydrogen which in Germany was obtained from coal or coke of which Germany has ample supplies. Norway had and has very little coal. In this country it was better to extract hydrogen from water by means of electrolysis - that is by sending an electric current through water so that the hydrogen and the oxygen in the water were separated. By 1929 Hydro had built the world's largest plant for the electrolytic separation of water at Vemork.

At that time heavy water was still unknown. But in 1934 the American chemist Harold Urey was awarded the Nobel prize for his recent discovery of heavy water. This kind of water is very much like ordinary water and ordinary water contains a tiny bit of heavy water. So tiny in fact that one ton of ordinary water contains no more than 150 grams of heavy water. In other words, you have to have a lot of ordinary water if you want to extract significant amounts of heavy water from it. Such extraction is possible through electrolysis. In fact, heavy water could be separated from ordinary water as a byproduct of the electrolysis of water which Hydro was already engaged in.

In 1934, therefore, Hydro started a modest commercial production of heavy water. A small plant for the high concentration of heavy water was placed in the cellar of the large electrolytic factory. At that time scientists still did not know how to fission uranium atoms so that heavy water had not yet acquired its sinister significance. It was used for scientific purposes and was believed to have its greatest potential in biochemistry.

To sum up, Hydro and only Hydro produced heavy water at Vemork in industrial quantities before the war *because* there is only a small amount of heavy water in each ton of ordinary water, *because* this small amount could be obtained as a byproduct of electrolysis, *because* only a huge electrolytic plant could produce a significant amount of heavy water, and *because* Hydro and only Hydro had such a plant, the world's largest, owing to the company's access to Europe's cheapest hydroelectric power. The plant was situated very close to the power station at Vemork. That station is still standing and is today a museum. The old electrolytic plant, however, with its high concentration installation in the cellar has been pulled down.

Heavy water was crucial to German nuclear research. One would think, then, that the Allied heavy water operations - to the extent that they were successful - would be just as crucial in their detrimental effect on German nuclear research. But things were not that simple. Paradoxically, the Allied heavy water operations had only a modest effect on the German nuclear programme even though heavy water was indispensable to it. The Germans were never able to produce an atomic bomb. But that fact can in no way be attributed to the Allied heavy water operations. These operations did, however, affect the German non-bomb nuclear research.

This was not because the Allied heavy water operations did not enjoy considerable success. They did. True, the Germans did obtain heavy water from Vemork. They got it before the Allied operations started and they still got some after the first operations had been carried out until the production was completely halted in late 1943. Jomar Brun, who is certainly more qualified than I am to handle the technical aspects of the matter, has calculated that the Germans received only 2.5 tons of heavy water from Vemork instead of twice that amount, which they might have received had there been no Allied operations.[1] But that is not the main point. The German nuclear programme was only moderately influenced by the availability or non-availability of heavy water. Quite other and more important factors were at work.

The story of German nuclear research during the war is by now well known and I can only touch upon it here in the briefest of outlines. It was only about or just before the beginning of the Second World War that scientists in several countries had come to the conclusion that uranium could be fissioned and that a chain reaction might be initiated on the basis of such a fission. Experiments with a chain reaction could, however, aim in two rather different directions. They might generate energy which could be utilized for different purposes, including civilian ones. But the experiments might also produce a big explosion, an atomic bomb. Thus, in principle, the scientific groundwork for the development of a bomb was laid about the beginning of the war. This was known by scientists on both the German and Allied sides. And on both sides the scientific premises for a nuclear project were elaborated over the next two years. In this work the Germans were most probably ahead of the Allies.

But in the course of 1942 their ways parted. The Americans made a tremendous technical and industrial effort to put the purely scientific principles into operation and produce a bomb. As we all know, they succeeded only at the end of the war, in the summer of 1945. The Germans, on the other hand, gave up trying to make a bomb and confined themselves to the development of a uranium burner which might be installed in German submarines and provide energy for their operation.

There has been much debate on why the Germans accorded such a low priority to their nuclear research and why they, by the autumn of 1942, had discarded any thought of making a bomb. The main reason seems to be that the German scientists did not believe they could develop any bomb before the end of the war. It would therefore be a waste of valuable resources, much needed elsewhere for the German war effort, to give top priority to a bomb project. This pessimism implanted itself in 1942 to German political and military authorities who consequently did not feel any impulsion to push an atomic bomb project. In his memoirs Albert Speer, the Minister of Armaments, writes: "On the suggestion of the nuclear physicists we scuttled the project to develop an atomic bomb by the autumn of 1942, after I had again queried them about deadlines and been told that we could not count on anything for three or four years. The war would certainly have been decided long before then."[2]

Even if the Germans had given first priority to the bomb and concentrated all their resources on it, it is very doubtful whether they would have been able to manufacture a bomb before the end of the war. Even the Americans with their enormous resources and the top priority which they accorded to developing a bomb had no bomb ready until July 1945.

Against this background it becomes clear that the presence or absence of Norwegian heavy water played no role for the German decision to refrain from trying to make a bomb. By the autumn of 1942, prior to any Allied operation against Vemork, the Germans had already given up the bomb. On the other hand, the Allied heavy water operations most likely did play a role in the more modest German project which aimed at developing an energy-producing uranium machine. There was even a danger that the Germans might use a successful uranium reactor to manufacture radioactive material and employ it as poison gas in their warfare. But the Germans never reached the point where they were able to produce a self-sustaining chain reaction. Plausibly, shortage of heavy water was one cause for this failure. Others were the generally low priority that the Germans gave to their nuclear research and the Allied bombing of Germany where the nuclear experiments were carried out.

I remember vividly a young interviewer's worried face when he questioned me on a TV programme earlier this year and I stressed - as I have done here - that, on the one hand, the Allied heavy water operations were a considerable success and that, on the other, they nonetheless had only a limited significance for the German nuclear programme during the war. Possibly, the young man was troubled by the question whether all the lives lost in the Allied operations were really worth the effort when they had such a limited effect. But I really think that the strained look he gave me revealed something else. He probably felt unconsciously that a national myth was being threatened, that the heroic heavy water sabotage about which all Norwegians have heard so much and on which they pride themselves, was in danger of being exposed.

I do not think it is. The saga of the heavy water sabotage loses none of its thrill, the saboteurs none of their valour, the action none of its audacity of design even if hindsight puts the actions in a different perspective from that which prevailed during the war. War is a hidden game, which only a postwar period lays bare. The struggle for heavy water was fought on the assumptions of the war and becomes no less successful and no less gallant on those premises even if we today know more about all those other factors that were at work but which were hidden from the Allies at the time.

But this certainly calls for another question. How much did the Allies know about German nuclear research during the war? What were the assumptions on which they acted when they decided to take the risks and disregard the possible losses which the struggle for heavy water might entail?

The Allies knew very little about German nuclear research in the beginning. What they did know was that the Germans shared the common knowledge among physicists that a nuclear bomb was feasible in principle though still far ahead in terms of technical and industrial execution. Indeed, the German scientists themselves had made important contributions to that knowledge. But Allied intelligence knew next to nothing about how far the Germans had advanced in their nuclear research and how hard they pushed it.

The Allies were, however, increasingly worried, not because they knew anything specific about the Germans but because they knew how their own nuclear research was advancing, aiming precisely at a bomb. Might not the Germans do the same thing, was there not a nuclear race going on? From the beginning of 1942 special efforts were made to improve the supply of intelligence on German nuclear research. It was a difficult task. By May 1942 Secret Intelligence Service (SIS) and Special Operations Executive (SOE) - the organisation responsible for carrying out subversive action in occupied countries - had succeeded only in confirming in general terms that the Germans remained active.

One factor which contributed to the Allied anxiety was their knowledge that the Germans were taking steps to increase production of heavy water at Vemork. The Secret Intelligence Service might not know much about the actual nuclear research going on in Germany. But it was well informed about the developments at Vemork. One of those who knew most about the heavy water installation, Professor Leif Tronstad, had participated in the resistance but had to escape and came to England in the autumn of 1941. He cooperated intimately with British intelligence and operative organs. Contact was also established clandestinely with key persons in Hydro and at Vemork. Signs of increased German interest in heavy water certainly worried the Allies. Such interest could hardly be explained by anything but German concern with nuclear research even though it could not reveal the more specific nature of that research.

It was on these general grounds that the British, still lacking firm intelligence about the German programme, decided in April/May 1942 that they would attempt to halt the production of heavy water at Vemork. In other words, the first heavy water operations were carried out because the Allies wanted to eliminate a vital link in German nuclear research about which they knew very little in more specific terms. Certainly, the Allies did not know whether they were trying to deny the heavy water to a bomb project or some more modest nuclear endeavour.

From spring 1943 on the basis of intelligence from different sources, including Norwegian and German ones, the Allies became more assured regarding German nuclear research. The British were coming to believe that the Germans now thought they could not produce an atomic weapon in time for use in the war and that the Germans did not give priority to their nuclear research programme. Still, other reports made it clear to the Allies that the Germans continued to carry out nuclear research. As late as November 1944 an analysis of these reports said that "it is extremely difficult to form a definite opinion as to the urgency and purpose of this work".[3]

It seems then that the later heavy water operations were carried out at a time when the Allies - or the British at least - were less worried about the German nuclear research than before. But they were still determined to put a stop to the German heavy water production in Norway. Evidently, they did not want to take any risks. The Germans might possibly be more ambitious in their research than the intelligence reports indicated or they might make a sudden leap forward in their nuclear experiments. Better then to deny the Germans any access to heavy water.

The four Allied or Allied/Norwegian heavy water operations, taken together, may be considered the first attempt to secure the non-proliferation of nuclear weapons by military action. Such action is certainly not what one would wish for regarding non-proliferation which should rather be promoted through negotiations and agreements freely entered into. But should military action be deemed essential I wish it could be inspired by the first "counter-proliferation" action which took place at Vemork. It is my favourite, I must admit, of the four heavy water operations. A handful of men slipping down from the mountains, then vanishing into their blizzards and fog again, executed what could only be called a surgical operation. An attack which hit precisely at its target, destroying heavy water equipment whereas no human lives were lost neither, on the Norwegian or Allied side, nor on the German. Let us hope there will be no need for military non-proliferation actions. But should they be necessary let them be as surgical and with as little loss of human life as the Vemork heavy water sabotage of 28 February 1943.

Notes

[1] *Jomar Brun, Brennpunkt Vemork 1940-1945, Oslo 1985, p. 97.*

[2] *Albert Speer, Inside the Third Reich, p. 318.*

[3] *F.H. Hinsley, British Intelligence in the Second World War, vol II, p. 128.*

Operation "Gunnerside": Reminiscences of a heavy water saboteur*

By Joachim Rønneberg

At the end of November 1942, I was in Aviemore in Scotland responsible for instruction and sabotage and the use of explosives in our unit, when I was called up to our commanding officer. He said he had a signal from London asking if I would lead an expedition to Norway. Of course I was very glad to be offered this opportunity. He told me that I had to select five men for the job.

I asked him, "Are we going in by boat, or are we going in by plane? Do we need to be good at skiing? Is there any advice you can give me in my choice of men?"

He said he did not know, I would have to go down to London. When I got there, I met Major Leif Tronstad, who was our commanding officer at the time. Tronstad, who was a chemistry professor, had advised Norsk Hydro on building the heavy water factory at Vemork. He told me that it was our task to destroy it. He also informed me that a Norwegian soldier had been sent there early in the spring of 1942 to provide information for London. Moreover, four men from our unit had already been sent to Hardangervidda in October to prepare for landing 34 British commandos. They had landing equipment for the gliders that were to carry them. I suppose it was the first time the Eureka radio system was used on the continent for landing a sabotage group. Unfortunately, the chaps down on the ground heard the aeroplane and had it on the Eureka, but the plane turned back. It received no signal from the ground. That was a tremendous blow to the chaps who stayed there, as they had suffered quite a lot since they arrived in Norway. They got orders to stay on because London was planning another operation. My party was going to be sent in and we were to join forces with the Swallow group so there would be nine or ten of us carrying out the attack.

**Based on an oral presentation at the International Conference on Nuclear Technology and Politics, Rjukan, 16 - 18 June 1993.*

Tronstad told me that we should be ready by the December moon. That gave us just over a fortnight to plan our equipment, plan our trip to Sweden, and get acquainted with the target and the explosives. And we were very short of time. It was not like the present time, when you can go into any shop and say that you want to buy a sleeping bag to withstand 30 degrees C of frost, or any other items for a winter expedition. Sleeping bags were one of the difficult problems to solve. I ended up in a bedding equipment store in London. Down in the factory by the docks, I met a very good man who was willing to try to sew the first sleeping bag on my instructions. We made a few alterations, and he then made six sleeping bags. He made more bags for other operations later in the war.

We decided to take weapons that would give us the strongest possible hit on the spot. Hence we chose the tommy gun and the Colt 45. Both weapons used the same type of ammunition. We also went to the Norwegian Intelligence Office, saying that we wanted a map of southern Norway, marking the places where German soldiers were stationed. We ended up by planning our route from Vemork - Dagali - Svenkerud - Nord-Aurdal - Svatsum - Losna - Rena - Flisa and ordered detailed maps (1:100,000) to cover the retreat route to Sweden, altogether some 600 kilometres.

Major Tronstad showed me a photo of our target. I had never been to Vemork before, and it was an impressive target, I must say. The photo showed the gorge and the suspension bridge, and the road leading up to the factory area. The plant itself was a huge building - 25 x 100 metres - seven stories high (35 metres) concrete. Our target, the heavy water factory, was down in the cellar.

The assault had to be done in wintertime. The original plan was to strike on Christmas Eve, but there was no chance of flying at the time of the full moon in December. We flew over in January, but were unable to make contact with the reception committee. So we returned to England, a great setback for us and for them.

The radio station they had opened up in October was sending information to London about everything the Germans did in this area. It was one of the longest-serving radio stations in Norway.

The group got maps covering the whole route to Sweden. In case we got separated, each of us had a map of southern Norway and a compass so that we could take our bearings between the valleys for a possible retreat.

We were dropped on 17 February 1943. At first we thought that we had been dropped on the right spot, and we made our depots and put down poles for finding the depots when we returned. However, we soon discovered that we were 25 kilometres away from where we should have landed, and things looked very difficult. Then we were delayed five nights because of heavy snow storms.

When we finally met the Swallow group, we started planning the operation. I must say I do not think that any group sent into Europe was supplied with such good intelligence. I could sit there with a blank piece of paper and draw a map of the area, including the roads and buildings and tell them that according to the latest reports which they had brought up from the valley, from our local contacts at Norsk Hydro, there was a German barracks at the plant containing some 20 soldiers. Moreover, the Germans had a double guard down on the bridge. There were also a gate in the middle of the bridge and a sentry box with a button to set off the alarm to the guards at the factory. Everything was fenced in, there were mines all along the water pipeline, except for the entrance to the railway which was on the southern side of the valley.

We were planning to go down the slopes from the mountains between Vemork and Rjukan. But the local guides said that there was too much snow and the slope was too steep. We said that we planned to cross the gorge, and they told us that that was not possible. Their solution was to mingle with the shiftworkers when they came up at 10 p.m. and get rid of the sentries down on the suspension bridge.

We said "Well, we will have to try the gorge, because if we have 20 Norwegians as onlookers when we kill the Germans down here, they will be shot the next morning".

The reason we were in uniform was to prevent reprisals.

When we were in our advance position for the attack, we sent one of the chaps down to reconnoitre a possible crossing a bit further down the river. We knew from a photo that the terrain looked a bit easier to traverse at one spot, and a couple of hundred yards further up the river it looked even better, and then we could climb up on the railway line. When he came back four hours later, we knew that it was quite possible to cross the river. In the beginning we felt that we had an 80 per cent chance of success. We did not think very much about retreat then. But when we saw that we could cross the river without crossing at the bridge, we immediately increased our odds to 90-95 per cent.

We came down through the woods - our route was very, very steep, with lots of snow - and onto the road. To avoid some workers' buildings, we decided to go straight out into the valley, which meant a lot of climbing. I remember at one point, the bus with the shiftworkers passed by. Two of my men who were hiding above the road, waiting for the bus to pass, nearly fell down onto the roof of the bus. But it turned out all right.

We left our equipment near the road leading down to Rjukan, and had only the explosives and the weapons with us when we crossed the river. At about 11.30 p.m. we were sitting just outside the fence, watching the changing of the guard down on the bridge. We saw them pass by, and waited until they entered the barracks, and then we thought, as it was just over midnight, 'This is it'. We cut the barbed wire, and the fence - or the padlock - and went inside. The covering party went into position in a half-circle around the barracks and once they were in position the Germans could not do anything, no matter what happened. We who were in the demolition party climbed down and opened another gate and went into the building over the cellar. At first we had difficulties, but in the end we found a cable tunnel, up underneath the roof, which was five metres high.

As mentioned, the main building was 25 by 100 metres in seven stories. The production started in the top storey and continued in circles until it ended as heavy water down in the bottom. And that was our target: a battery of 18 cells, the last stage in the production. Two of us managed to get in and we started laying the charges. The order was that if anything happened that could endanger the result, you had to act on your own. The three other chaps in the demolition party, one of them carrying a set of charges, decided to break the window to get inside because they did not know that we were busy inside. When the window broke, both goups were equally surprised.

I helped one of my friends to get in, and we finished laying the charges. They were not big charges. They weighed about 4.5 kilos, and had been chained up by the British before we left. Two-minute fuses, four of them. There was a Norwegian workman inside the factory reading the instruments and filling out the logbook. He heard us talking Norwegian, discussing whether we should put on a 30-second fuse just to be sure that we heard the bang as soon as possible. That was when he asked for his glasses. It was difficult to get glasses in Norway, so he wanted to have them before we lit the charges. I remember I threw away what I was doing and searched for the glasses and found the case and handed it to him. He was very pleased and I started getting the ignition sets ready when he suddenly said that the glasses were not in the case.

I said "Where the hell are they then?"

And he said "Well, they were there when you came in." In the end I found them being used as a bookmark in his logbook, and gave them to him. Then we ordered him to give us the key for the cellar door so that we could go out through the door like other human beings. We opened the door and I remember Major Tronstad saying that in case we needed to lock up the guard, the key for the lavatory was on the left-hand side of the door. I remember just after we had lit these 30-second fuses, I saw the key, but we did not need it.

We said to the man, "You just run around the corner, up the staircase, lie down and keep your mouth open, until you hear the bang. There will be only one bang, so when it is over you can go down and watch the result". I do not know if he did. But I know that he kept his mouth open, because he could hear when I met him two years later. Otherwise, if he had had his mouth closed he would have blown out his eardrums.

We had planned to meet the covering party down by the river. They expected to be there a while after they heard the bang, not knowing that we had used only 30-second fuses, so we met them just outside the gate. What astonished us was that the Germans did not understand what had happened at all. The covering party told us that one man came out of the doorway of the guard house with a torch, and made a sort of search around the house and went in again. When we got back across the river, we took a parallel road to the main road leading down to Rjukan centre. At the place where the funicular starts down in the valley, we began climbing a zigzag road leading up to the top. It was a rise of about six or seven hundred metres, and it took us, I would say, three hours from the explosion until we could put on our skis up on the mountainside. The alarm went off when we were down by the river, and immediately, as we got up on the road, the first car came up from Rjukan. Later on we saw lots of cars driving towards Vemork, because it was only 50 to 100 yards down to the main road, so that we could see all the traffic going up. Since the guards down on the bridge reported that nobody had passed, the Germans apparently believed that we had to be on the southern side of the valley. Therefore they did not do anything on the northern side at all. Remember that only three of us had been seen. The Germans did not know that there had been nine of us. Later on I heard that their main theory was that we had come to Vemork as civilians, had put on uniform for the operation, dressed in civilian clothes afterwards and tried to go by ordinary communication lines towards Oslo. So that was where they started to search.

Now we know that the Germans never had the faintest idea what had really happened, where we came from and how we escaped. Luckily we had left no tracks because the ground was frozen and there was no snow at all. I remember sitting up on the mountainside that morning seeing the sunrise on the other side with the Gaustadtoppen mountain peak lit in the red morning light - it was a marvellous sight. Of the nine of us, nobody was shot in the valley, not even a gun was loaded. It was a marvellous situation for the one who had had the responsibility of leading the operation. I remember we were sitting there eating biscuits and chocolate, and nobody said anything at all. I think everybody had quite enough with his own thoughts.

We then continued down to Langsjå, where we had stayed on our way towards Vemork, and here we rested. While resting, a storm blew up, so we went to bed and slept for 12 hours, and when we woke up the next morning it was still blowing, so we just turned our heads to the wall and slept for another ten hours. And in this way we managed to make a sort of recovery. At midnight the wind eased, and we were able to get a bit closer to where we had landed. There the Swallow group had its headquarters, and again we were pressed to stay for another night because of the weather. At Skryken, where we had landed, we found our equipment, and the five of us who had orders to go to Sweden in uniform started out. The maps we had were of a scale of 1:100,000 - 1 centimetre to the kilometre - and I think we worked out our way all right. It was 40 years before satellite navigation, but I do not think we strayed from our route more than a couple of hundred yards the whole way. Eighteen days after we had been pushed away from the building by the blast, we crossed the Swedish border, and had a good night's sleep in Sweden in sleeping bags and uniform.

The next morning we more or less undressed, and reported to the Swedish guards in white snow suits, underwear and a jersey. Our rucksacks were empty, because the escape had taken ten days more than we had calculated, and we had no food left. We said we were refugees. They treated us as such, and we were sent to a refugee camp. There we applied for three days leave to Stockholm. I remember going to the Opera with a friend of mine, sitting in one of the best seats listening to La Traviata, and digging each other in the ribs to be quite certain that we were alive and awake. And so we reported to the British Embassy and got all the help we needed. We started buying equipment for the next operation, and we got permission to go by the civil post plane to London. When we landed in Scotland at the end of March, it was like coming home again. We were in a very special situation; when we were in Great Britain, we always talked about getting back to Norway, getting home, but having landed on Norwegian soil, we immediately started talking about how long will it be until we get home again - and then we were thinking of England. And that feeling lasted all the time. It, could only be strengthened, of course, by the fact that our operation was also a very, very great Allied operation: We were trained by the British, we were flown by British airplanes, we were taken care of by the British the whole way. Moreover, 40 young British chaps gave their lives on Norwegian soil in the battle against the atom bomb.

Later on there was the bombing in November 1943, because the production of heavy water was started up again, a bit quicker than the British and Americans had expected. Finally, there was also the sinking of the ferry in February 1944, which put an end to Vemork producing heavy water for the Germans. Both the bombing and the sinking of the ferry caused loss of civilian lives - unfortunately. As far as our operation is concerned, I am quite certain that no other sabotage operation carried out in Europe during the war had the benefit of such wonderful intelligence. Nevertheless, we were extremely lucky we succeeded. Everybody engaged on our side - eleven men altogether - and also the chaps who were our contacts down in the valley, survived the war. And of the soldiers taking part, each one spent at least twelve months on operation in Norway after they had been to Vemork; some of them spent the whole time, more or less, between then and 1945 on operation, and lived to tell the tale.

And that is the reason why some of us go out and tell the younger generation of our experiences, hoping that this is one way of preventing it ever happening again.

The supplies of Norwegian heavy water to France and the early development of atomic energy*

By Bertrand Goldschmidt

The fundamental discoveries

One of the extraordinary aspects of the history of the making of the atomic bomb, from the brilliant basic scientific discoveries of the 1930s to the surprising achievements of the Manhattan project, is the fact that the weapon was ready exactly on time to abbreviate the most devastating conflict the world has ever faced.

If some of the major events of this history had not taken place at the proper moment, the final issue could have been delayed, if not drastically altered. One of these lesser-known events is the loan of the worldwide stock of heavy water by Norsk Hydro to France in 1940.

It all started in February 1932 by the discovery of the neutron by James Chadwick at the Cavendish Laboratory in Cambridge. By a strange coincidence, during the same week Harold Urey at Columbia University, New York announced the discovery of the isotope of mass 2 of hydrogen, known as Heavy Hydrogen. In addition to the single proton of the nucleus of ordinary hydrogen (mass 1), which is six thousand times more abundant in nature, its nucleus contains a neutron.

Then, in early 1934, Irene Curie and Frederic Joliot in Paris discovered artificial radioactivity. Soon afterwards Enrico Fermi in Rome found that the neutron was the ideal particle to penetrate inside the nucleus and create new isotopes; more easily when it is slowed down by passing through materials containing light elements. Soon afterwards Fermi's team was faced with an enigma: the nature of the surprisingly numerous radioisotopes formed by bombarding uranium, the heaviest element in nature, with neutrons. It took more than four years to solve this problem, by a kind of scientific ping-pong which took place between the leading radio elements in Rome, Berlin and Paris and which culminated in the revolutionary discovery of fission at the end of of 1938. The solution was arrived at by Otto Hahn, Fritz Strassmann and Lise Meitner of the Kayser Wilhelm Institute in Berlin as well as by Otto Frisch of the Niels Bohr Institute in Copenhagen, after they had been put on the right track by Irene Curie and Pavel Savitch in Paris.

A few weeks later Bohr rightly predicted that it is the rare isotope of uranium, uranium 235, which is fissile by neutrons of all energies, while the hundred and thirty-nine times more abundant uranium 238 captures neutrons of a given range of energy and is transmuted into isotopes of transuranium elements.

The secondary neutrons

The race towards the chain reaction started in earnest in March 1939, when Joliot at the College de France in Paris and his assistants Hans Halban and Lew Kowarski, of Austrian and Russian origin respectively, were the first to publish the fact that, in addition to the formation of radioactive fission products and a considerable release of energy, the splitting of each uranium atom by a neutron is accompanied by the ejection at high speed of new neutrons. A week later at Columbia University, the Italian Nobel prize winner Enrico Fermi and Leo Szilard, a Hungarian physicist, arrived at the same conclusion. Szilard had lived many years in Germany where he had worked with Einstein.

Early in April 1939, the French team published their estimation that the number of these secondary neutrons was about 3.5 per fission, while the Italian group found 2 (the exact value is 2.5). Any figure superior to 1 meant that in favourable conditions a chain reaction should be obtainable. From thereon the Frenchmen's work was shrouded

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in secrecy. They had reached the conclusion that to obtain a chain reaction with natural uranium, it should be mixed with a 'moderator'. This is a substance made of light elements capable of slowing down the secondary neutrons under the energy threshold where these particles are captured by the uranium 238 atoms, thus increasing their chances of creating new fission in uranium 235.

In the beginning of May, Joliot and his colleagues registered three secret patents in the name of the "Caisse Nationale de la Recherche Scientifique" (KRAUTS) which had substantially subsidised their research. The first two patents cover all the essentials of today's nuclear power plants, as they mention the moderator, the cooling fluid, the control rods, and the shielding for radiation protection. The third patent dealt with explosive charges, but here the inventors' foresight was not so brilliant.

The Belgian uranium

Once the patents had been registered, Joliot got in touch with the Belgian firm Union Miniere du Haut-Katanga. Since the 1920s this firm had possessed a near monopoly for the production of radium from exceptionally rich Congolese uranium ore and it owned in Belgium a stockpile of more than 1,000 tons of uranium oxide, unused 'wastes' of the past radium extraction. On 13 May, 1939 the CNRS and Union Miniere initiated a draft agreement, the first international nuclear contract, aiming at a joint and exclusive exploitation of the first two French basic patents. The outbreak of the war prevented this agreement's final ratification, but it began with the loan of 8 tons of uranium oxide to Joliot's team by the Belgian firm for a first experiment. So by the summer of 1939, the French scientists had access to uranium by the ton which none of their competitors had yet obtained.

At the same time, in July 1939, in New York, Szilard and two other Hungarian refugee physicists Eugene Wigner and Edward Teller became worried about the possibility, that, in case of war, the Germans could get hold of the Belgian uranium stockpile. Wanting to warn the Belgian government, they asked Einstein to sign a letter to the Queen Mother Elizabeth of Belgium, a patron of musicians, artists and scientists, with whom he was well acquainted, to obtain her help in this matter. Reluctant to mix his personal relations with politics, Einstein agreed instead, on 2 August 1939, to sign a letter to President Franklin Roosevelt. This letter was only handed to the President on ll October, with a report from Szilard depicting the terrible effects of a future atomic bomb smuggled in by ship and exploded in a port. Roosevelt took immediate action and set up a secret committee on uranium, which at its first meeting, ten days later, allocated 6,000 dollars to Szilard for his experiments.

Szilard was right to worry about the Germans as they had also entered the race after the French had published their estimation of 3.5 for the number of secondary neutrons by fission. Both their Ministry of National Education and the War Ministry had been alerted by nuclear physicists at the end of April 1939, and when the war started in September, Germany was the first and only country to have a secret military unit exclusively devoted to the military applications of uranium fission. It was located at Gottow near Berlin in a rocket projectiles and explosives establishment. It was directed by an able nuclear physicist Kurt Diebner, while the theoretical physicist Werner Heisenberg was going to assume the *de facto* leadership of the project.

The best moderator

By the end of 1939 the scientists involved in the race towards the chain reaction in natural uranium, in Germany, France and the United States, had all arrived practically at the same stage and had reached identical conclusions: the intervention of a moderator is indispensable; ordinary water absorbs too many neutrons to be usable (one could produce uranium enriched in uranium 235); carbon in its purest form could, maybe, just work out while heavy water offers the best chances of success, heavy hydrogen absorbing fewer neutrons than ordinary hydrogen or carbon. Heisenberg sent a report to the War Ministry on these lines, while Joliot wrote a memorandum to the Minister of Armament Raoul Dautry, who was responsible for scientific military research. This memorandum specified that "an appropriately constituted mixture of heavy hydrogen and uranium presents at the current state of knowledge all the conditions favourable for the development of a chain reaction and consequently for a massive release of energy".

Suddenly Norsk Hydro, at that time the only world producer of heavy water by the kilo, with its stockpile of 200 kilos, worth then about 120,000 dollars and its 10 kilos per month production, became a major focus of interest for the German and French chain reaction competitors. In contrast the Columbia University team of Fermi and Szilard, still awaiting its first grant of 6,000 dollars for the purchase of a few tons of pure graphite, was obliged by sheer lack of funds to disregard the more promising heavy water line.

In January 1940, the Germans, through the I.G. Farben cartel, which held shares in Norsk Hydro, were the first to contact the Norwegian firm; they ordered 25 kilos of heavy water, offered to buy all the existing stock and inquired about the feasibility and the cost of increasing production tenfold. This offer was refused by the Norwegian firm after I.G. Farben themselves had avoided answering Norsk Hydro's query about the exact nature of the future use of these large quantities.

The Allier mission

Having learned about the German move, Joliot convinced Dautry, his minister, who in turn got the agreement of Edouard Daladier, the Prime Minister, to dispatch rapidly to Oslo a secret mission to try to obtain as much as possible of the precious substance. Fortunately, a French bank, the "Banque de Paris et des Pays-Bas", controlled a majority interest in Norsk Hydro. Jacques Allier, the executive at the bank who dealt with the Norwegian firm, was chosen by Dautry to lead this mission with the help of three French secret agents due to join him in Stockholm on his way to Oslo. His mission order specified in the purest spy novel style without mentioning either Norway or heavy water that "Monsieur Jacques Allier is empowered by the Prime Minister to negotiate with the party holding the material that is the object of his mission to assure for France the availability of the largest quantities thereof ".

A surprise awaited Allier on his arrival in Oslo: the general manager of Norsk Hydro Axel Aubert, unjustly suspected of pro-German sympathies by the French Embassy, was in fact entirely devoted to the Allied cause; when told by Allier that the heavy water was needed for defence purposes, he decided to lend free of charge the entire stock of 185.5 kilos to the French government; after the end of the war, it would have the choice of either purchasing or returning it. He agreed also, if the first planned experiments were successful, to reserve for France the entire future production which could probably be increased, if necessary, fivefold or tenfold.

Allier reacted to this generous offer by describing openly the secret objectives of Joliot's work to Aubert who replied, "Please tell Prime Minister Daladier on my behalf that my company does not wish to receive one centime for the product you are bringing back to him until France is victorious. As far as I am concerned, I know that if the experiments of which you have told me succeed and if later France has the misfortune of losing the war, I will be shot by the Germans for what I am doing today. But it is a matter of pride for me to run such a risk". Fortunately Aubert did not suffer personally at the hands of the Germans when they occupied Norway and his plant, but he was obliged to deliver to them the total increased production of his plant.

The negotiation was concluded on March 9 in Oslo by a gentlemen's agreement. It granted the Norwegian firm 15 per cent of the profits from any technical developments derived primarily from the loan of heavy water to France. In Allier's somewhat optimistic opinion, these technical developments might have led to the production of electricity at a cost even lower than the already very low price of the Norwegian hydroelectricity and therefore could be prejudicial to the economical interests of Norsk Hydro; hence the contemplated compensation of 15 per cent. (Today there are indeed nuclear power stations in the world operating with heavy water, in particular the Canadian ones, whose origin, as we will see, is directly linked to the 185 kilo loan to France, but the price of their electricity production, although economically acceptable, is still well above the price Norway can get from water power!)

After making reservations several days running on the flights from Oslo to Holland and from Oslo to Scotland, and pretending to load the heavy water containers on the Amsterdam flight (which was forced by German fighters to land in Hamburg and searched in vain), Allier and one of the secret agents left for Scotland with ten of the 26 cans which had been hastily fabricated in Oslo and filled in Rjukan. The 16 other cans followed by the same route two days later accompanied by the other two agents.

When the mission had been organized in February 1940, the French secret service were uneasy over the fact that Joliot's principal assistants Hans von Halban and Lew Kowarski, recently naturalised French, both came from countries now hostile or unfriendly to France. To assure that they would not be suspected in case of a breach of secrecy, Joliot asked them to agree to stay in a guarded residence during Allier's mission. They consented and chose respectively, the islands of Porquerolles in the Mediterranean and Belle-Ile in the Atlantic. On March 18, three weeks before the invasion of Norway by the Germans, the heavy water arrived safely at the College de France, while Halban and Kowarski returned to their laboratory. After having been "security risks" they were again indispensable scientists.

The crucial experiment

The following two months were devoted to setting up the decisive experiment, but it was still not ready when the German army started to invade France. When all hope was lost, Dautry decided to send the stock of 8 tons of borrowed Belgian uranium oxide to Morocco where it stayed hidden in an unused gallery of a phosphate mine until the end of the war. He also ordered Joliot, Halban and Kowarski to leave for England with the heavy water.

Joliot, however, decided not to abandon his laboratory where the first cyclotron in Western Europe was under construction. Meanwhile in June 1940, Halban, Kowarski and the 26 cans of heavy water boarded a ship with a cargo of coal, commandeered by Lord Suffolk, the British scientific representative to the French Ministry of Armament, who had decided to bring out of France any person, equipment or material capable of helping Britain in the pursuit of the war. Their mission order specified "They are required to continue in England, in absolute secrecy, the research begun at the College de France". So after being under a sort of house arrest for a few months, Halban and Kowarski found themselves assigned the grave responsibility of trying to keep France in the atomic race, and for this purpose their 185 kilos of heavy water was their best and most invaluable asset.

Halban and Kowarski were very well received in England by their scientific colleagues responsible for defence research. The British were all the more interested because they had so far concentrated their attention on the chain reaction by fast neutrons in pure uranium 235, on the methods of separating this isotope, and on an uranium 235 bomb, but had given little thought to the controlled chain reaction by slow neutrons in natural uranium.

The coordinating British committee on uranium research, code-named the Maud Committee, therefore invited the two French scientists to stay in Britain and pursue their research at the Cavendish Laboratory. In mid-December 1940 they successfully performed the crucial experiment planned in Paris, demonstrating for the first time that it would be possible to produce atomic energy with natural uranium.

The report of the Maud Committee

The conclusions of the Maud Committee were finalised in an official report in July 1941. One part dealt with the uranium 235 bomb and the other with the production of energy and was almost entirely devoted to the consequences of the work of the two French scientists. It stated: "Their results showed a definite indication of a divergent process; for each initial neutron 1.06 $\pm$ 0.02 were produced in one set of experiments, 1.05 + 0.015 in another. The system used was very small owing to the fact that the amount of heavy water at their disposal was only 180 kilos and a large loss of neutrons from the surface prevented a divergent chain from developing. They estimated that the critical size of the system which would liberate large amounts of energy would require 3 to 6 tons of water".

It was only in May 1942, nearly a year and a half after their French competitors, that Heisenberg and Dopel made a similar experiment in Leipzig with 140 kilos of Norwegian heavy water and arrived at the same conclusion that a diverging chain reaction would be feasible, estimating also that about 5 tons of moderator would be needed for criticality. During that same spring of 1942 Fermi and Szilard, now working at Chicago University where all the chain reaction work was to be coordinated, were at last practically certain that with pure enough graphite and uranium oxide or metal, the chain reaction would be achieved.

A year before at the University of California at Berkeley, a young American chemist Glenn Seaborg, utilizing the large cyclotron, had found in May 1941 that uranium 238 was transmuted by neutron capture to form a long-lived isotope of element 94 that he isolated and named plutonium; he also found that this plutonium 239 had better fissile properties than uranium 235 and could therefore be used for a fast neutron bomb.

The Maud Committee, informed of this discovery, underlined that this isotope of element 94 would be produced in a "machine of Halban Type" which could thus be used for military purposes. The report concluded that "Drs Halban and Kowarski have done all they can with the supplies which they brought into this country" and suggested that "they should be allowed to work in the USA" where steps were being taken to produce heavy water on a large scale.

It is an undisputed fact that the conclusions of the Maud report which were known in the appropriate high spheres in Washington at the end of the summer of 1941 were an important factor in the decision of President Roosevelt in October 1941 to give the highest priority to the pursuit of the research work on uranium, a decision which can be considered as the starting point of the American enterprise. Therefore it can be construed that the loan of the 185 kilos Norwegian heavy water to France had a definite influence on such a development, even though none of the plutonium for military purposes produced during the war originated from heavy water piles, as all of this nuclear explosive came from graphite moderated units. But in October 1941 heavy water was the only proven moderator for the obtention of the chain reaction with natural uranium, while the use of graphite for such a purpose was still in doubt.

Paradoxically while these 185 kilos had contributed to influence the major decision taken in Washington through the result of the Cambridge experiment, this result had considerably reduced their own value as an asset in the hands of Halban's team as it was now clear that they only represented a twenty-fifth of the amount needed to start up a chain reaction. Hence, the heavy water asset was passing now to the Americans who would produce it by the ton from the end of 1943 on.

The Anglo-Canadian project

Halban's weak position became clear when, in the beginning of 1942, he was sent on a mission to the States as the head of the chain reaction branch of Tube Alloys (the code name of the British project). All the doors were open to him, in particular at Chicago where, under the code name of the Metallurgical Laboratory, all the graphite-uranium and plutonium work had been concentrated. But the suggestion that Halban and his team of ten scientists of French, British and German nationalities should settle in Chicago as an independent British unit met an absolute veto from Washington, in particular because of the opposition of the FBI regarding the employment of foreigners on American defence projects.

Finally Churchill agreed during the summer of 1942, with the approval of Washington, that Halban's team should be transferred to Canada as the initial nucleus of a much larger Anglo-Canadian group devoted to the development up to the industrial stage of the natural uranium-heavy water system. It was also tacitly understood that this enterprise, the first scientific multinational project ever created, would profit from the proximity of Chicago Metallurgical Laboratory, and be the beneficiary of the first tons of heavy water produced in North America.

This was not to be. In late December 1942, three weeks after the successful start on 2 December of the Fermi zero-power graphite pile in Chicago, Roosevelt decided to limit any exchange of nuclear information with the British and Canadian partners to basic science only. The President had been briefed by his scientific advisers both on the considerable lead which the Americans had taken during the past year over the British, whose help was much less needed now, as well as on the power his country would gain by being the sole holder of the new weapon.

The presidential decision was the first manifestation of the non-proliferation policy which today plays such an important role on the world scene, and was the start of a nine months' breakdown of exchanges. This was a terrible blow for the Anglo-Canadian team, which was ready to start work in an adequately equipped laboratory in Montreal and instead was condemned to demoralising inaction during the whole year 1943.

Naturally Churchill reacted vigorously and insisted at each of his three summit meetings with Roosevelt in 1943 that such an unfair decision was totally contrary to the spirit of the Alliance. Finally, at the Quebec Conference in August 1943, the President gave in and accepted a resumption of the nuclear collaboration though strictly limited to the pursuit of the war. The "Quebec Agreement" sealed the reconciliation by which the three partners adopted a joint policy of secrecy and decided to purchase and share all the uranium available in the world. It was, however, too late for the first objective of the Montreal laboratory and the fulfilment of Halban's hopes, as the Americans had alloted their initial tons of heavy water to Fermi's team for the building of the first heavy water pile in the world. It was built at Argonne near Chicago where it went critical in May 1944 and ran later at low power.

Fortunately, in March 1944, the Americans, who felt that the postwar applications of the heavy water piles could be important, decided to make use of the Anglo-Canadian group and embarked on a joint tripartite project of a 10,000 kilowatts heavy water pile, to be built in Canada with American-supplied uranium metal rods and heavy water.

This pile was achieved in 1947 at Chalk River, Ontario. A smaller unit of zero power was planned as a first step and its construction was entrusted to Kowarski's leadership. Justice had been done: one of the members of the French nuclear tandem who had brought the Norwegian heavy water to England in 1940 was responsible for the building of the first atomic pile outside the USA. It diverged at Chalk River, in September 1945. This was the start of Canada's postwar atomic effort as well as of its present world leadership in the field of heavy water natural uranium power reactors following a chain of events which began with the Norsk Hydro loan to France in 1940.

Informing de Gaulle

Because of the special secret nature of their missions, Halban and Kowarski had not revealed their participation in the Allied atomic effort to the Free French organisation. Furthermore, neither General de Gaulle nor any leader of the United Nations had ever been informed of the development of the new weapon by the signatories of the Quebec Agreement who had committed themselves to a joint policy of secrecy towards any third party.

However, the Montreal project had among its leaders three other Frenchmen Pierre Auger, Bertrand Goldschmidt and Jules Gueron, who had double allegiance as all three had been seconded to the British by the Free French Forces. Conscious of the tremendous potentialities of the future bomb, and worried by the monopolistic tendencies of the

Americans from which they had suffered in 1943, they felt de Gaulle should be informed even if it meant breaching their British pledge of secrecy. Taking advantage of a short visit of the French president in Ottawa in July 1944 during the early days of the liberation of his country, they informed him briefly and in utmost secrecy of this new element of world politics; this element was expected, hopefully, to end the war one year later and would considerably influence the postwar equilibrium. They also insisted on the necessity of relaunching atomic research in France as soon as possible.

At the end of 1944, Joliot and Dautry, the two leaders of the early French enterprise of 1940, also alerted the President of the provisional government of the urgency of renewing atomic research. After the Liberation, they were again put in a position of authority, Joliot as director of the CNRS and Dautry as Minister of Reconstruction and Urban Affairs. So when, in March 1945, Dautry suggested to de Gaulle to reopen the negotiations on the supply of Norwegian heavy water, he received approval immediately and decided to send the indispensable "Monsieur Allier" on a mission to London to meet officials of the provisional Norwegian government in exile.

Reactivation of the 1940 agreement with Norsk Hydro

Allier had kept hidden during the occupation a photo of the agreement he had signed with Aubert in March 1940 as the French original copy (as well as the Norwegian one) had been purposely destroyed before the arrival of the Germans. It stated that Norsk Hydro would reserve for France its total heavy water production for a period to be fixed by the French side.

Allier first verified that neither Norsk Hydro, nor the Norwegian government in London, had committed any of its postwar production to any one of the United Nations, not even the USA and the UK whose governments had been adamant about the vital necessity for the Alliance to prevent heavy water getting into the hands of the Germans. Allier then told the Norwegian officials that France was about to resume its atomic research and so would be in a position to help Norway in future negotiations with third parties, in particular Great Britain. He also told them that, in the application of the 1940 agreement with Norsk Hydro, his government had decided to fix the period of its exclusive purchasing rights to ten years after the war, as it considered that this agreement mentioned "the duration of the hostilities" only as an example.

The Prime Minister Johan Nygaardsvold was naturally reluctant to commit either Norsk Hydro or the first Norwegian government after the liberation. He, however, accepted an exchange of letters between Allier and himself in which he took notice of the French request without objecting to it and in which he looked forward to the resumption and development of the collaboration initiated in 1940. This exchange of letters in April 1945 somewhat reactivated and officialised the March 1940 agreement at a time when the French were in no position to specify with precision the amount of heavy water they might need.

Because of the new situation created by the use of the bomb against Japan on 6 August 1945 and the French government's desire to finalise the negotiations as soon as possible, Allier was once again sent on a mission. He met Bjarne Eriksen, the general manager of Norsk Hydro, and Foreign Minister Trygve Lie in Oslo at the end of August. The latter also found the ten years' exclusivism requested by the French in April much too ambitious, but agreed in September, as a compromise, to the sale to France of 5 tons, the minimum quantity requested by French authorities and probably enough for a first pile. It was further understood that this sale should not contravene any future international law on the control of atomic energy.

Two months later, in November 1945, the three atomic war partners, the USA, the UK, and Canada, held a summit meeting in Washington devoted entirely to atomic matters. Until an effective international control regime was established, they decided to pursue the policy which they had adopted in Quebec in 1943. This was the policy of secrecy and of jointly purchasing all the uranium available in the Western world. Following this the Americans and the British had concluded an agreement with the Belgian government in exile in 1944 giving them a first option on all uranium coming out of Belgian Congo for ten years.

In the years following the war this agreement deprived many countries of the two indispensable ingredients for any atomic programme: know-how and uranium, and therefore it can be considered as the first comprehensive policy of non-proliferation. Fortunately the three partners did not extend it to heavy water (of which they now had a sufficient production in North America) by trying to purchase in advance the Norwegian output, the only other source in the Western world.

Thus France, Norway jointly with Holland, and Sweden were able to put to use the few tons of uranium they possessed or could produce, and start up respectively in 1948, 1951, and 1954, their first low power heavy water piles thanks to their access to Norsk Hydro's production. Should that access have been barred to France and Sweden, these two countries would have lost a few years in their nuclear development corresponding to the time required to obtain from their own uranium deposits the nearly ten times greater amount of uranium needed for a Fermi type of graphite pile.

The French postwar purchases from Norsk Hydro

In March 1946 the French paid back Norsk Hydro the amount of 280,000 Norwegian Crowns (NOK), the cost at a price of 1.5 NOK per gram of the precious initial 1940 loan of 185.5 kilos. Then the following week, as agreed six months earlier between Lie and Allier, a first contract for 5 tons of heavy water was concluded between Norsk Hydro and the French Commissariat á l'Energie Atomique (CEA), established in October 1945 under the joint leadership of Joliot and Dautry. The quantity involved in this contract was later extended to 7 tons following the agreement of the Norwegian government. The price was 1.35 NOK per gram and the delivery was completed by September 1948, on time for the start of the first French pile three months later. It was to be a zero power uranium oxide unit fuelled with about one half of the 8 tons loaned by the Belgians in 1939 and hidden in Morocco during the occupation of France. Its design was based on the know-how brought back from Canada by the French members of the Montreal project.

The next two contracts between the CEA and Norsk Hydro were concluded in 1950 and 1954 for respectively 4 and 10 tons. These two contracts as well as the following ones had to have the agreement of the head of the Norwegian Institute for Atomic Energy, Gunnar Randers, with whom the CEA had maintained close personal relations from the outset. In 1950, this dynamic physicist had initiated the Dutch-Norwegian nuclear alliance. As thanks he had received from Holland, from a hidden stock purchased by a Professor of the University of Leyden before the war, the totality of the uranium needed for the nearly completed Kjeller pile.

The 1950 contract with the CEA was contingent upon the delivery by priority of 4 tons of French nuclear pure graphite for the reflector of this pile. It also specified that Norway should be informed of the location and the use of its heavy water. In this case it was intended for the second French pile, a 2,000 kilowatt thermal unit which diverged in 1952. This pile was metal fuelled and carbon dioxide cooled (the cooling system used later in all the natural uranium-graphite first French power stations). The 1954 contract had an additional clause indexing the price of the heavy water to the rate of the Norwegian crown versus the American dollar and it corresponded to a price of 95 dollars per pound of heavy water.

The following year, in the application of the Eisenhower «Atoms for Peace» programme, the USA decided to sell heavy water for research reactors to friendly countries at a price of 28 dollars per pound, one third of the 1954 Norwegian price. Paradoxically the first American sale, of 10 tons, went to India for the Canadian-built reactor which was later to produce the plutonium for the 1974 Indian atomic explosion.

The CEA was also among the first countries to profit by the American offer by purchasing 30 tons in mid-1955 for delivery between 1956 and 1958. It was intended for the third French pile, a high flux material testing unit which diverged in 1957. Similarly the second Norwegian reactor built at Halden and started up in 1959 was moderated by cheap American heavy water, the expensive Norsk Hydro production being reserved for exportation.

Indeed, in 1955, France had decided to embark on the project of a nuclear submarine propelled by a natural uranium heavy water engine for which the Norwegian high-priced material was the only source. Thus the CEA concluded in June 1956 a fourth contract, this time at the price of 1 NOK per gram which corresponded to 64 dollars per pound, still nearly two and a half times the American price. Norsk Hydro could not have lacked clients at this high price as the delivery of these last 10 tons could not be promised before the end of 1958, even though its yearly production had reached the level of 25 tons.

This contract specified that the heavy water was to be used by the CEA which was not allowed to sell it to a non-French purchaser without the agreement of Norsk Hydro. The Norwegian firm, on the other hand, could not refuse such re-export without valid reasons, and would also have to buy the heavy water back at an agreed price.

When the natural uranium submarine engine project turned out to be a white elephant in March 1958 the CEA asked Norsk Hydro to cancel this last contract for which no delivery had yet taken place. Norsk Hydro refused but had to accept the fact that the CEA could resell the 10 tons of heavy water to any country except those covered by the COCOM and CHINCOM regulations.

Finally in 1962, Norsk Hydro, which had probably amortised its heavy water installations, decided to adopt the same price as the USA for its sales: i.e. 28 dollars per pound.

At that time the CEA was involved in building four large heavy water moderated reactors due to diverge in the second half of the decade and needing a total amount of the order of 250 tons: the only heavy water nuclear power plant ever built in France, an 80 MWe unit to be erected in Britanny, a high neutron flux reactor for a joint Franco-German Research Institute in Grenoble and two tritium producing units for thermonuclear weapons located in the south of the country. Simultaneously the first national heavy water producing plant was being constructed. It was based on the water-ammonia exchange process and planned for a production of the same order of magnitude as the Rjukan plant. These important requirements were then fulfilled by purchases from France, the USA and Norway, following, in this last case, a final large contract of 75 tons which Norsk Hydro delivered from 1962 to 1970.

Thus the total deliveries from Norsk Hydro to France since the war amounted to about 100 tons. During those years the French exports in the heavy water related nuclear field were limited to the 1956 decision to build in Israel at Dimona a large heavy water natural uranium reactor, similar to the one Canada had offered the year before to India for construction near Bombay. It was only in 1971 that India ordered two heavy water production facilities from French industry.

Out of the 100 tons of Norwegian heavy water delivered from 1940 to 1970 to France, the first two amounts of respectively 185 kilos and 7 tons were of vital importance for French atomic development. This holds true even though the later nuclear industrialisation of the country, decided by a first five year plan adopted in 1952 by the Parliament, followed the graphite moderated line and not the heavy water moderated one.

The 185 kilos were the entrance ticket to the the Allied nuclear enterprise and the obtention of the heavy water reactor and plutonium extraction know-how, while the 7 tons of the late 1940s were indispensable for the French access to the then prestigious and limited club of the nations owning nuclear reactors.

It is impossible to rewrite history and in this case to describe what French nuclear development would have been without these early deliveries. The CEA would have taken at least three more years to construct its first pile, which would have been a graphite unit fuelled from metropolitan uranium ore discovered only in late 1948, and therefore the first five year nuclear industrialisation plan would have been delayed by as many years.

Who knows whether, in the mid-fifties, a less advanced and weaker CEA would still have gained its battle for a nuclear weapons programme that it won against the partisans of the European integration, who were opposed to such a programme because it was discriminatory to West Germany? In any case one can conclude that these Norwegian sales to France had a considerable influence on its nuclear destiny.