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The History of the Construction and Operation of the German KNK II Fast Breeder Power Plant

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Abstract

The History of the Construction and Operation
of the German KNK II Fast Breeder Power Plant

This is a historical review of the German KNK fast breeder project, from its beginnings in 1957 up to permanent plant shutdown in 1991. The original design had been for a sodium cooled, albeit thermal, reactor. However, while KNK I was being commissioned on the premises of the Karlsruhe Nuclear Research Center, conversion into a fast nuclear power plant was decided, a process which had to overcome considerable licensing difficulties. KNK II attained high fuel element burnups, and the completion of the fuel cycle was achieved. Various technical problems encountered in specific components are described in detail. After the termination of the SNR 300 fast breeder project in Kalkar for political reasons, KNK II was shut down for good in August 1991.

Kurzfassung

Die Geschichte von Bau und Betrieb
des deutschen Schnellbrüter-Kernkraftwerks KNK II

Der Bericht beschreibt das deutsche Schnellbrüterprojekt KNK von seinen Anfängen 1957 bis zur endgültigen Abschaltung im Jahre 1991. Der ursprünglichen Planung lag ein natriumgekühlter, aber thermischer Reaktor zugrunde. Schon während der Inbetriebsetzung der KNK I im Kernforschungszentrum Karlsruhe wurde der Umbau auf ein schnelles Kernkraftwerk beschlossen, wobei beträchtliche Genehmigungsschwierigkeiten zu überwinden waren. KNK II erzielte hohe Brennelementabbrände, und es gelang die Schließung des Brennstoffkreislaufs. Verschiedene technische Probleme bei einzelnen Komponenten werden detailliert dargestellt. Nach der politisch verursachten Beendigung des Schnellbrüterprojekts SNR 300 Kalkar wurde die KNK II im August 1991 endgültig abgeschaltet.

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Preface

There is one fact which must not be forgotten in the politically motivated turmoil surrounding the fast breeder development in Germany: There was a fast breeder power plant designed and built in Germany which was operated successfully for more than ten years. The KNK II plant on the premises of the Karlsruhe Nuclear Research Center, planned and built by INTERATOM, operated by KBG, demonstrated that it was possible, even in this country and under the familiar difficult political conditions and licensing criteria, to make fast breeder technology succeed.

This report represents an attempt at retracing the history of that nuclear power plant which, including the KNK I preparatory project, extended over the long period between 1957 and 1991, i. e. more than 34 years. The project documentation covers a stretch of files more than 250 m long. The main problem confronting this historical survey was the need to condense the extraordinary wealth of material, work out the major development lines, and yet achieve an easy-to-read chronicle.

The achievements of individuals are emphasized in this report in the light of my subjective feelings. However, it should be stated, for the sake of fairness, that a project the size of KNK cannot be an achievement of a few, but only of all those who contributed to it. It is for this reason that I would like to **dedicate** this retrospective report to all my colleagues who cooperated in KNK, especially at

KfK, INTERATOM, and KBG,

but also with the

Ministries, Authorities and Expert Consultants.

It is only the sum total of all their efforts which made KNK succeed. Thanks are due to all of them, and this report is meant to record their achievements.

Dr. Willy MARTH

1 KNK - The Preparatory Stage to the Fast Breeder

1.1 The Beginnings

1.1.1 Early Atomic Power Programs

It all began in the pretty, small town of Eltville on the Rhine River.

Professor Karl Winnacker, Chief Executive Officer of Farbwerke Hoechst AG, had invited the leaders of German industry and nuclear research to attend a closed meeting at the guest mansion of his company in Eltville. Under the chairmanship of Professor Maier-Leibnitz, the "Nuclear Reactors" Working Group was to draft the outline of a German atomic power program on January 26 - 27, 1957.[1,2]

After World War II, the Allied Powers had prohibited the Federal Republic of Germany from ever venturing into nuclear technology again. However, as the country regained its political sovereignty in the Paris Treaties, this ban was lifted in 1955; at the same time, the young nation waived the production of atomic weapons. Participation in the first International Conference on the Peaceful Uses of Atomic Energy organized by the United Nations in Geneva in August 1955 had a "shock-like impact" on some of the German participants, among them Leo Brandt, then Undersecretary of State in the German Federal State of North Rhine-Westphalia:

> *"All participants suddenly realized that big things in the atomic sciences had developed in the world, completely independent of the problem of the atomic bomb... The German public was deeply concerned that all these profound changes might bypass Germany and make the country fall behind forever."*[3]

The Eltville circle suggested an approach to nuclear power by way of the design and construction of five technically different types of nuclear power plants of 100 MWe power each. The group was able to fall back on the advice by several renowned German electricity utilities and machine building companies, some of which had already established small reactor development groups. So, Siemens suggested a heavy water reactor of the pressure tube type, AEG proposed a light water reactor; the BBC/Krupp consortium, a high-temperature reactor; and the Deutsche Babcock & Wilcox, a natural uranium reactor of the British Calder Hall type.

At the final meeting in December 1957, Demag CEO Dr. Hans Reuter introduced yet another 100 MWe power plant, with an organic coolant and moderator, which was to be completed by an independent subsidiary, Interatom GmbH; the company was to be founded that same year. Professor Wirtz, finally, indicated the fundamental interest of the Karlsruhe Nuclear Research Center in the development of a sodium cooled fast breeder without, however, implying in his remark any direct intentions to build such a plant.

This "500 Megawatt Program," later called "Eltville Program," did govern the debate in the years to come, but did not develop into a resounding success. Of the five plants mentioned above, only one was ever built, namely the heavy water pressure tube reactor plant proposed by Siemens, which materialized at Niederaichbach. In retrospect, it would have been no disaster had it not been built. Newly founded Interatom had to be tided over into the spring of 1961 before, finally, receiving a DM 4 million project contract from the then Kernkraftwerk Baden-Württemberg company for the development of a reactor with organic cooling. This type of reactor was never built in the Federal Republic, although Euratom had temporarily offered its support.

The 500 Megawatt Program failed mainly because of the firm resistance put up by the electricity utilities, which had advised a cautious entry into nuclear power already at an earlier date.[4] The Eltville Program reflected the interests chiefly of vendors and of the Ministry for Atomic Affairs, and was not accepted by the electricity utilities. They considered nuclear power plants of 100 MWe, at the time a relatively large unit size, too much of an economic risk and, moreover, were miffed because they had hardly been consulted about the choice of reactor lines.

In order to overcome the stagnation, which lasted for approximately two years, the Ministry for Atomic Affairs in late 1959 suggested a "Program of Advanced Reactors." This included a number of small experimental reactors of approximately 20 MWe power. They were to be built mainly with government support; the program was not to be dependent on the electricity utilities.

Proposals for the project were filed in March 1960. AEG submitted a boiling water reactor with nuclear steam superheating; it was later built at Großwelzheim as the HDR with a power of 23 MWe, commissioned in 1969, and decommissioned only two years later because of technical fuel element problems. The Deutsche Babcock & Wilcox and BBC/Krupp each offered gas-cooled reactors which, however, were not built. Independent of the two programs mentioned above, Siemens (out of their own pocket) developed a heavy water pressurized reactor. This was the MZFR, later built on the premises of the Karlsruhe Nuclear Research Center, mainly with government funds, and operated very successfully.

Interatom, finally, had proposed an organically cooled reactor, but while still preparing for this program, switched to a sodium cooled reactor to be moderated with solid zirconium hydride. The reactor power was to be 10 MWe.[5]

The plant was to be called KNK.

1.1.2 Founding Interatom

Who was this newcomer, Interatom, elbowing its way into the line of renowned German companies, such as Siemens, AEG, or Krupp?

As we heard above, it owed its existence to a strategic concept hatched by Dr. Hans Reuter, the Chief Executive Officer of Demag AG. He had looked for ways to catch up with the lead the electrical companies mentioned above had meanwhile gained in nuclear technology thanks to their existing reactor development groups. Turning abroad, he established contacts with the U.S. Atomics International (AI) Division of North American Aviation Inc. (NAA) and its eloquent CEO, Chauncey Starr.

It was plain to see that the chemistry between these two gentlemen agreed phantastically, and also the know-how held by both firms was mutually supplementary: Demag was a machine building company of worldwide renown, and Atomics International had already scored some successes in the young field of nuclear technology. For instance, in one year, two reactor plants built by Atomics International had been commissioned, namely the graphite moderated and sodium cooled 7.5 MWe SRE in the Santa Susana mountains north of Los Angeles in the spring of 1957, and the organically moderated and cooled OMRE experimental facility in Idaho in the fall of the same year.[6,7]

Agreement was reached quickly, and the Internationale Atomreaktorbau GmbH, or INTERATOM for short, was established as a joint subsidiary of Demag and NAA on December 13, 1957.[8] The headquarters of the company initially was in Duisburg, but already one year later Interatom moved to Bensberg near Cologne, where offices were first set up in the old castle, but soon afterwards land was purchased in Moitzfeld for laboratories, shops, and administration buildings. The capital stock of the company initially was only DM 100,000, but was soon raised to DM 6 million. Interatom was to be a development company; it preserved that character although, for some time (1972), it had held the biggest contract ever for a plant construction in the Federal Republic of Germany - the SNR 300.[9]

The fathers of INTERATOM:
Dr. Hans Reuter (right), Demag AG, and
Dr. Chauncey Starr, Atomics International, USA.

Under the company agreements, the German partner also had been given the opportunity to have his personnel trained free of charge at NAA for a period of five years. Demag made ample use of that opportunity and sent its first staff members to Atomics International as early as in mid-1958, among them Dr. Hans Mausbeck and Dr. Rudolf Harde, who became Technical Managing Director of Interatom in 1966.

Of the two reactor lines pursued by Atomics International (AI) - organic cooling and sodium cooling -, only the latter line succeeded. The Piqua experimental power plant built by AI on behalf of the U.S. Atomic Energy Commission (USAEC) developed the same technical difficulties soon after commissioning which had already haunted the OMRE plant and had then been called "fouling." The radiation present in the reactor decomposed terphenyl, the organic coolant, and deposits developed on the hot fuel elements. The project therefore had to be abandoned. Interatom, which wanted to benefit from the experiences of its American parent company for projects of its own, as a consequence had to give up two reactor projects for which organic cooling had been envisaged. The know-how acquired in handling sodium ultimately was used in the KNK project, which is the topic of this report.

Ownership in Interatom changed repeatedly in subsequent years, also 1966 when the Deutsche Babcock became the third partner. In 1969, Siemens acquired a 60% interest in Interatom, when North American Aviation sold its shares and the other partners reduced their interests. At the same time, Siemens terminated its breeder development activities and moved those staff members from Erlangen to Bensberg who were prepared to go. Later on, also the other Interatom partners, Demag (1971) and Deutsche Babcock & Wilcox (1972), gave up their interests, leaving Siemens as the sole shareholder of Interatom. These shares were transferred to Kraftwerk-Union in 1974, when the nuclear interests of Siemens and AEG were incorporated. In 1987, KWU became a corporate division of Siemens AG; this made Interatom a member of the Siemens Group, but still as an independent private limited company, a "GmbH" under German law.[10]

The Managing Director for Commercial Affairs (later Chairman of the Managing Board) of Interatom between 1962 and 1991 was Dr. Claus Berke; in that period of time he witnessed the rise and fall of his company.

In memoriam: INTERATOM

As this report about KNK is being written, Interatom has ceased to exist:

In October 1991, after the politically motivated termination of the Kalkar project, Interatom GmbH became an integral part of KWU, the power generation division of SIEMENS AG. The name INTERATOM, under which the company had been known as a reactor vendor and famous breeder firm, ceased to exist. With its name, the company had also lost its identity. But, for the time being, Bergisch Gladbach, formerly called Bensberg, was to remain an independent location besides Erlangen and Offenbach.

This concept was given up in a decree by Siemens on March 30, 1993[11]. The Bergisch Gladbach location will be abandoned by 1994. Most of the breeder experts will be sent into (early) retirement, while the others will be scattered over other locations or will simply be fired. The sodium test facilities built at a tremendous expenditure, such as ILONA, or the 5 MW Facility, will be dismantled; the technical documents which still exist will disappear in a safe (after having been microfilmed).

Only memories will remain. This report is to preserve them.

1.2 The KNK Development Program

In 1960, the young Interatom company bravely had secured from the German Federal Ministry for Atomic Affairs a contract for designing a nuclear power plant, which it now had to fulfill. The technical specifications had been rather vague initially. There was talk of a 10 MWe nuclear power plant using thermal neutrons; later, the power level became 20 MWe; the plant was to be cooled by sodium. This liquid metal was supposed to offer at least two advantages: Sodium was a very efficient coolant allowing conventional steam temperatures of approx. 500 °C to be generated. It made for a very compact plant design which, at least at that time, was felt to cut costs.

The project drew its name from this latter fact: "Compact Sodium Cooled Nuclear Power Plant," or KNK for short. The letter K later was associated with Karlsruhe, the location of the plant. This association is incorrect because initially, for want of a utility customer, the Jülich Nuclear Research Establishment had still been envisaged as a location. Interest in moving to the Karlsruhe Nuclear Research Center was aroused only after the Fast Breeder Project had been established there.

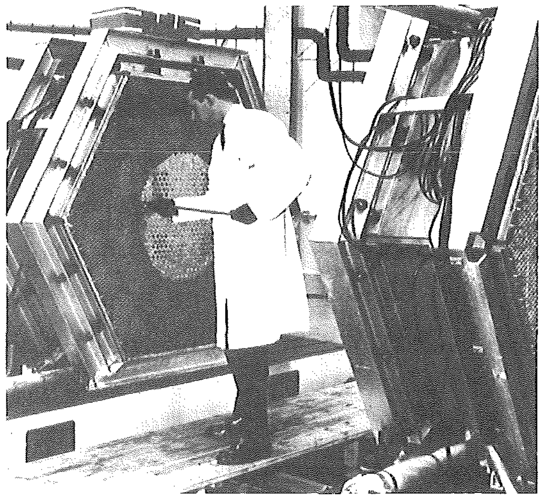
Interatom realized from the outset that the design of KNK would be viable only if backed by a parallel development program. Consequently, the technical key issues had to be identified early on and an R&D program had to be launched. The new fields in which the German parent, Demag, was unable to offer much support were nuclear physics, reactor safety, specific materials requirements and, above all, the sodium coolant. Only those few staff members who had been delegated to the U.S. parent, Atomics International, for a couple of months had ever seen the liquid sodium metal and had acquired some idea of its properties. That knowledge had to be put on a broader base, disseminated among the design engineers, which required the construction of experimental facilities.[12]

At the time, the money spent on this experimental program was not negligible, although it looks like peanuts to us now.[13] Between 1960 and 1966, DM 5 million was spent on reactor physics experiments, and approx. DM 2.5 million on materials studies. The irradiation experiments, mainly for zirconium hydride, cost DM 1.2 million, the technical safety experiments, DM 1.3 million. The most expensive item in the R&D program accompanying the planning phase were the test rigs (DM 11 million), especially the 5 MW Facility. However, compared with later expenditures for the SNR 300, those were indeed discount prices.

The young team at Interatom, mostly physicists, chemists, engineers, and metallurgists, enthusiastically tackled the technical problems which, because of their novel character, could not yet be found in textbooks. Almost all staff members were below thirty, firmly convinced of the need for nuclear power which, in turn, was supported by the positive attitude of politicians and the general public. Names, such as Harde, Stöhr, Brandstetter, Berke, Hennies, Hübel, Memmert, Knecht, Ruppert, Guthmann, Henssen, Mausbeck, Höchel, and Jansing, should be mentioned here vicariously for many others. They soon gained Interatom the respect of the reactor development groups in competing companies, such as Siemens or AEG.

1.2.1 Physics and Safety

Although KNK had been planned as a thermal reactor plant, its neutron physics differed greatly from that of the light water reactors emerging at that time. The hydrogen concentration of the zirconium hydride to be used as a moderator was comparable to that of water at 250 °C.



Split-table facility for critical experiments for KNK set up at GKSS in Geesthacht.

The volume ratio of moderator to fuel was lower than in LWRs, for KNK was bound to have a more heterogeneous materials arrangement because of the solid moderator. Another difference relative to water reactors stemmed from the different degrees of temperature dependence of the moderator density; with zirconium hydride moderation there was no highly negative temperature coefficient as in the pressurized water system.

So, experiments were necessary to back the neutron physics properties of the KNK reactor core. For this reason, numerous subcritical and critical experiments were run in a broad program, most of them employing pulsed neutron fields.[14,15] Among other factors, the reactivity worths of various shutdown configurations, their dependence on temperature, and the reflector action of a number of core materials were studied. In addition, the neutron spectrum in zirconium hydride was measured at temperatures of up to 550 °C.

Some of the critical experiments were run at the Geesthacht Reactor Center, later GKSS, in a split-table facility specially built for the purpose. The critical KNK configuration was made up of a matrix of aluminum tubes loaded with fuel, moderator and reflector rods. The facility which, incidentally, was built by the later Managing Director of Interatom, Amandus Brandstetter, was shut down by moving the two halves of the matrix apart, or by ejecting the fuel, or by inserting absorber rods. The experimental program mainly served to determine the critical reactor mass of various core arrangements, and the effect of shutdown rods. A pile oscillator, which periodically moved small specimens into the core and out, was used to measure reactivity worths and absorption cross sections. These experiments were conducted by Dr. Hans-Henning Hennies. For thirty years, he decisively contributed to many phases of the KNK I/KNK II project, first with Interatom, later at the Karlsruhe Nuclear Research Center.[16,17]

The safety analyses conducted for KNK revealed the reactor core to have a positive power coefficient at low power and high burnup. This was a characteristic KNK had in common with other reactors using solid moderators, i. e. the British and French facilities cooled by CO_2 and moderated by graphite. In all these cases, the positive effect is created by the neutron spectrum hardening as the moderator temperature rises, which results in a greater diffusion length and reduces parasitic absorption.[18]

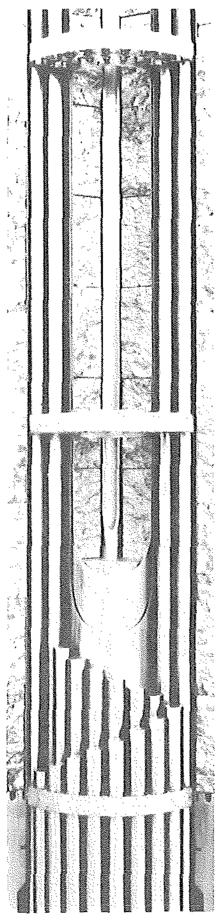
Naturally, this effect made the licensing authority frown. Detailed studies of the excursion characteristics, as well as extensive analyses of the safety system, were required. In the end, however, consensus was reached that the shutdown systems of KNK fully met the usual safety requirements of thermal reactors.[19,20]

1.2.2 Materials Problems

Efforts in materials development were focused on an inexpensive way of producing the zirconium hydride moderator and testing it under reactor conditions. Moreover, the suitability of ferritic steel grades for the components, instead of the more costly austenitic steel varieties, was determined successfully.

Zirconium hydride with hydrogen contents between 61 and 63 atom percent ($ZrH_{1.57}$ to $ZrH_{1.7}$), which make the substance attractive for nuclear purposes, is a ceramic-like material fully compatible with sodium and steel even at high temperatures. It is produced under carefully controlled conditions by pure hydrogen reacting with zirconium metal. After experiments extending over many years, Interatom succeeded in producing large solids economically and with little waste.[21,22]

The relatively mobile hydrogen atoms in the zirconium hydride lattice made the detection of hydrogen losses in reactor operation, and of potential relocations, one of the most important topics of study. Attention was also devoted to cracking of the moderator solids under thermal shock loads. Finally, resistance to radiation had to be demonstrated, which was achieved in preliminary tests up to a dose of $1.2x10^{21}$ neutrons/cm.[23]



Cutaway view of the fuel element of KNK I with the inner and the outer ZrH_2 moderators.

In choosing zirconium hydride as the moderator, the materials engineers of Interatom accepted a tremendous risk. Their experienced American parent, Atomics International, had urged them to use graphite moderators, as Atomics International had done in the SRE facility. Dr. Harde, then Head of Development at Interatom and the prime mover of the KNK project, worried about a potential chemical reaction between graphite and sodium, and also about the dimensional stability of the graphite solids in the reactor (neutron swelling!) and, therefore, decided to start developing a moderator of his own. This turned out to be the right step, for both in KNK and later in KNK II, the zirconium hydride solids never caused any problems.

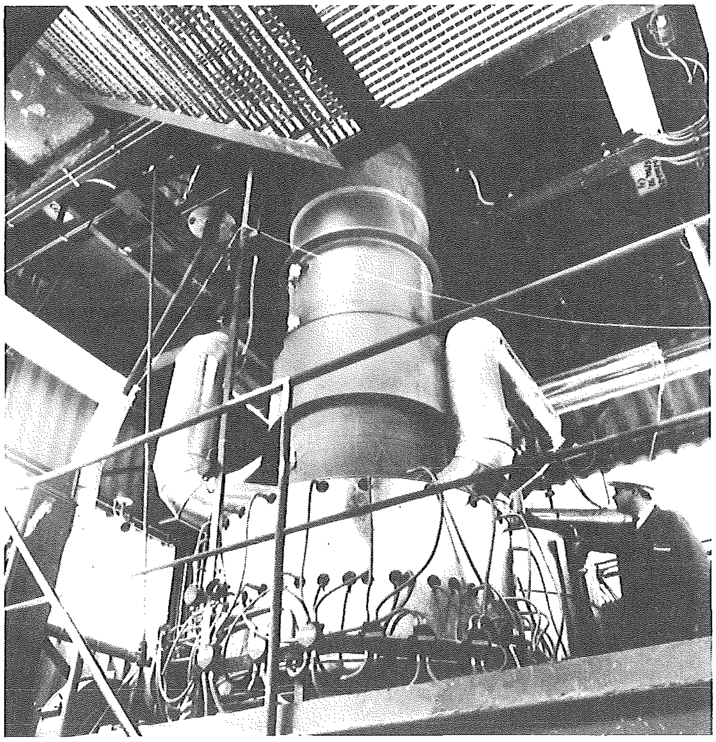
Interatom was also fortunate in choosing ferritic steel grades of high thermal stability for components, such as the reactor vessel and sodium pipes. Compared to heat resistant austenitic material, this not only meant major cost savings, but also offered considerable technical benefits. Thus, ferrites have better thermal conductivity, lower thermal expansion and, in addition, are less sensitive to stress corrosion cracking, a characteristic particularly important in the steam generator.[24]

Low-alloy heat resistant ferritic steel grades with approx. 2.25%Cr/1%Mo release sizable amounts of carbon into the ambient sodium at temperatures above 480 °C; this may cause austenitic reactor components, such as the fuel rod claddings, to embrittle. However, if a certain quantity of niobium is added to this steel alloy, the new material remains resistant to decarburization even at temperatures up to 600 °C. Specific additions of other alloying constituents helped to improve the ferritic material used in KNK so that it could be processed as easily as the conventional low-alloy ferritic materials. Thus, the 5 MW Test Facility described in the section below was made out of this carbon stabilized steel.

1.2.3 Experimental Facilities

In many cases, design basis data can be generated, or component behavior can be verified, only by means of experimental facilities. For this reason, Interatom early on built test rigs with gas, water, and sodium as the media. Thus, a water loop was designed in which the flow conditions simulated those in KNK fuel elements; an air test rig was used to observe fuel element cooling during handling phases.

The most important test facility, however, was the 5 MW Facility, which constituted the experimental base of KNK design. As the name implies, it had a heat transfer capacity of 5 MW. Except for reactor radiation, it simulated practically all conditions in KNK. Its reactor vessel, scaled down in length, was equipped with a rotating top shield and with flow orifice adjustment devices. Inside the vessel, control rod drives and reactor nozzles could be studied at fast temperature changes in the coolant.



Main sodium pump of KNK being tested at the 5 MW Facility in Bensberg.

The sodium was heated by oil and forced through the intermediate heat exchanger, steam generator and various valves and auxiliary systems by two mechanical pumps. All components were representative of sodium cooled nuclear reactors. The 5 MW Facility was commissioned in early 1965 and turned out to be a smashing success.[25,26]

The tendency of sodium to combine with oxygen contained in the air and in the water required protective measures to be taken in the steam generator. Studies of minor water leakages in the steam tubes (approx. 1-20 g/s) had indicated that nearby steel structures thus were made to corrode in a relatively short span of time. As a consequence, a hydrogen monitor was developed as a warning system indicating water leakages.[27]

A considerable amount of attention was devoted to studies of large steam pipe defects, i. e. pipe breaks. Especially the severity and duration of pressure shocks and their impacts on surrounding structures were investigated. These experiments were interpreted also theoretically and on the basis of models and constituted the basis for the design of the pressure relief system.[28]

Finally, the reaction mechanisms between hot sodium and air, and the mechanisms of sodium fires, were studied from the outset. Clear instructions for their control were elaborated for the subsequent operators.[29]

1.3 The Karlsruhe Nuclear Research Center Comes in

1.3.1 From a Nuclear Reactor to a Nuclear Research Center

After Germany had been permitted by the Allied governments to engage again in nuclear research, so-called reactor stations sprang up in many places in the Federal Republic of Germany, for instance in Berlin, Geesthacht, Jülich, and Garching. The Karlsruhe research institution was founded on the basis of an initiative by the Göttingen Max Planck Institute for Physics and its Director, Professor Werner Heisenberg. In Göttingen, a group headed by Professor Karl Wirtz designed research reactors based on natural uranium. Its studies of a heavy water cooled and moderated research reactor 2 (FR 2) aroused the interest of major industrial firms, such as Hoechst, GHH, Badenwerk, Siemens, and others which felt that they might accumulate experience in reactor construction in this way without having to acquire expensive licenses abroad.[30,31]

After lengthy debates, a site for the FR 2 was agreed upon at Leopoldshafen near Karlsruhe. The Kernreaktor Bau- und Betriebs-GmbH was founded there on July 19, 1956; the capital stock of the new company was DM 30 million, 50% of which was raised by 65 (later 92) industrial firms, 30% by the Federal Government, and 20% by the State of Baden-Württemberg.[32]

Signposts showing the way to the site of the Nuclear Research Center (1956).

Professor Wirtz was appointed Head of the Institute for Neutron Physics and Reactor Engineering (INR). A Technical Department was to advance construction of the FR 2; in addition, there was an Institute for Radiochemistry and an Institute for Radiobiology. The most important item under development clearly was the first German-built reactor, FR 2. For staff members living in the vicinity, the "Reactor" for many years was a beloved synonym describing a research objective and a job at the same time.

At that time, people were still proud of working at the "Reactor."

One of the most important technical modifications introduced later was the increase in reactor power of the FR 2 from an initial 6 MW to 12 and, later, to 44 MW; this measure served to raise the neutron flux by a corresponding margin. The extra cost this involved was borne by the industrial partners for some time only; the balance later was raised by another company, called K II, whose only shareholders were the Federal and State Governments. After the FR 2 had been completed, industry withdrew entirely, and in January 1964 the K II company was merged with the K I founding company into the Gesellschaft für Kernforschung. Because of the abbreviation, GfK, a dispute arose with the Gesellschaft für Konsumforschung in Nuremberg, which also used the GfK abbreviation. GfK Karlsruhe therefore decided in 1975 to adopt the name "Kernforschungszentrum Karlsruhe" (Karlsruhe Nuclear Research Center), or KfK for short, which had been used for a long time already as a geographic term.

Another change at Karlsruhe related to the *research program*. For the physicists, the design of the FR 2 had been completed by 1958/59, and new goals were sought. One of those, the fast breeder reactor, had already been an idea injected into the Eltville Program by INR Director Wirtz, as reported above. The influential Working Group III/1, "Nuclear Reactors," of the Atomic Industrial Forum in 1958 recommended that work on a breeder reactor be started, and the Federal Ministry for Atomic Affairs authorized the first funds. In April 1960, the Fast Breeder Project (PSB), then still called Project Group, was founded at the Center, and Dr. Wolf Häfele, Head of INR's Theoretical Department, was made its leader.

The project was to be developed in two phases: In Phase 1, mainly the coolant was to be chosen. Although sodium was about to be accepted internationally, the Project Leader stated:

"We intend to verify each and every decision made earlier."

This implied that also steam and helium were included as cooling options. Phase 1 was to take three years and require a budget of DM 25 million. In the ensuing Phase 2, a prototype power plant with a power of 200 to 300 MWe was to be designed and built. This was a strategy clearly different from those pursued in the competing breeder development countries, USSR, USA, France, and the UK, which ventured into the construction of large prototypes only by way of small experimental reactors (BOR-60, EBR II, Rapsodie, DRF) with powers between 10 and 20 MWe, and 50 to 70 MWth, respectively.

The timing of plans for Phases 1 and 2 later was changed several times. After the association with Euratom of the Karlsruhe project, the final choice of coolant was postponed until 1967. When a stronger commitment in the commercial breeder sector became evident in the United States (at General Electric), a decision was taken to advance to 1965/66 the beginning of Phase 2 - the development of two prototypes cooled with sodium and steam, respectively.[33]

The entry of Euratom greatly invigorated the project. On the one hand, the international base was broadened by agreements on cooperation with the research centers in Belgium (Mol) and the Netherlands (RCN Petten, TNO Apeldoorn), and with the American SEFOR Project. In addition, Euratom also brought to the project considerable sums of money, namely 40% of the DM 185 million appropriated by the German Federal Government between 1960 and 1967. A building construction boom arose at the Center in scientific institutes (such as IMF), utilities (liquid decontamination), and reactors (SNEAK). The number of personnel increased steadily; in October 1956, there were only 36 staff members who dared to move from Göttingen to Karlsruhe with the Wirtz Reactor Group, while the headcount in 1959 already amounted to 725, in September 1966 even to 3005 men and women. The average age of technical staff members was 34 years.[34]

The "Reactor" had grown up and become the Nuclear Research Center.

1.3.2 Interatom/GfK: a Delicate Balance of Interests

Around 1961/62, two power plant concepts were pursued independently in the Federal Republic of Germany which had one thing in common, despite all their technical differences: They were cooled with sodium. Interatom in Bensberg had a contract for the development, not yet construction, of a thermal 10 MWe nuclear power plant with a UO_2 core, ZrH_2 moderation, and Na cooling, which was to be built in Jülich. While talks about an association with Euratom were being started, GfK became interested in a 200 - 300 MWe fast breeder power plant with a UO_2-PuO_2 core and, also, sodium cooling. (The steam and helium variants pursued in parallel initially were only back-up solutions.)

The different nature of the two concepts implied considerable risks of their ever being implemented because, in each case, the Federal Government was to be the main source of funding. The Federal Ministry for Research had to be explained how - and whether - the two projects matched. This implied the need to seek a compromise, however, with neither Interatom nor GfK having any interest in abandoning "their project" in favor of the others.

GfK took the first step by emphasizing the complementary nature of the two projects. Although Karlsruhe had made internationally acknowledged progress in neutron physics, safety research and (theoretical) fuel element development, it still lagged behind in sodium technology and component development - for lack of experimental facilities. This opinion was expressed publicly, e. g., at a reactor conference at Argonne, USA, in 1963:

"The German program is oriented primarily around physics and safety considerations. The hardware aspects of the German program are totally lacking and it therefore will be quite difficult to meet an early 1970 schedule for a prototype fast reactor. It would appear to be advisable to have projects in Germany where experience in fabricating and testing vital sodium components and systems can begin."[35]

Breeder session at the Nuclear Research Center (from left to right): Prof. Wirtz, Dr. Beckurts, Prof. Seelmann-Eggebert, Dr. Häfele (standing), Dr. Smidt, Dr. Engelmann, Dr. Schnurr, Mr. Ritz.

Project Leader Häfele exploited this open criticism by pleading in Bonn for a move of the KNK site from Jülich to the Nuclear Research Center, especially emphasizing the usefulness of KNK in the field of sodium technology.[36] Interatom did not exactly oppose the argument, but demanded that the local electricity utility, Badenwerk, be included as a purchaser of the electricity to be produced and also as a source of funds for the turbo-generator; in this way, there would be no excessive dependence on GfK, and one would be able to demonstrate interest in the project by a utility.[37]

Another shortcoming of the Karlsruhe breeder development program was the absence of in-pile facilities for fuel element irradiation. True, the FR 2 was used, but its thermal spectrum provided no information about phenomena of cladding tube embrittlement and, subsequently, material swelling. Indeed, it would have made sense to equip KNK with an unmoderated core and use it primarily as a local irradiation reactor.[38]

However, this change of KNK from a thermal to a fast reactor did not materialize, because none of the partners were really interested. In 1963/64, Interatom had advanced the conceptual design phase of the thermal KNK power plant very far and wanted to start construction. Replanning for a fast core would have meant a considerable loss of time and even greater dependence on the (partly competing) Fast Breeder Project at the Nuclear Research Center.

GfK rather liked that approach, for it was realized that the priority plans for the 200 - 300 MWe prototypes would be shifted into a distant future if a KNK fast experimental reactor were interpolated. Wirtz, Chairman of the important Breeder A-Body, clearly expressed this in a memo:

> *"It is my view that the KNK reactor should not have a fast core... That would require very extensive preparatory activities."*[39]

The management of GfK finally concluded the internal debate by writing a letter to Interatom with the following conclusion:

> *"In the timetable of the Breeder Project, the KNK reactor is to help primarily in acquiring experience with sodium components... We therefore feel that all provisions should be made in the design to enable the future installation of several unmoderated subassemblies, but would like to reserve for a later point in time the decision as to when and whether this will be done."*[40]

This decision seemed to meet the interests of Interatom and GfK. The lack of in-pile facilities was to be taken care of by leasing half of the capacity of BR 2 in Mol, a reactor with a relatively higher fast neutron flux than the FR 2. For complete fuel element tests, the Enrico Fermi Reactor in Detroit had been envisaged, which was to go critical in 1966.

However, the future was to show that the idea of KNK with a fast core remained alive.

1.3.3 GfK/Experimental Facilities as a Contracting Party

Interatom's liaison at the Nuclear Research Center in matters of KNK as a rule was the Fast Breeder Project Management Staff, PSB (Dr. Häfele, Mr. Faude). Up until October 1964, it coordinated all questions about the site and the design, if necessary, with the Technical Department and the Building Department. When KNK seemed to be on the rails, a so-called KNK Head Office was set up in October 1964, which was managed by Dr. Diederichs, formerly with the FR 2.[41] Management intervened especially in contractual matters. This happened, e. g., in September 1963 when Interatom had submitted an estimated bid for KNK, and GfK had asked the Federal Ministry for Scientific Research (BMwF) to approve the conclusion of a corresponding R&D contract.[42] However, the Ministry for Research obviously had different ideas about project management, for it commissioned GfK/Experimental Facilities in early 1965 to negotiate the delivery contract with Interatom.

Who, or what, was this GfK/Experimental Facilities?

It was a separate management division of the Nuclear Research Center, whose official name had been Gesellschaft für Kernforschung mbH, or GfK for short, since 1964. GfK/Experimental Facilities, or GfK/VA or simply VA for short, had been established to manage the experimental facilities of the Federal Government laid down in Atomic Power Programs 1- 3. Those were the Multi-purpose Research Reactor, MZFR, in Karlsruhe; the Superheated Steam Reactor, HDR, in Kahl; the Niederaichbach Nuclear Power Station, KKN; the Karlsruhe Reprocessing Plant, WAK; and now, in addition, the Compact Sodium Cooled Reactor, KNK, in Karlsruhe.[43]

This development had begun with the MZFR, for which an appropriation decision had been sent to the administrative unit then still called Special Management Unit (under Dr. Brandl and Dr. Schöller) in 1961. Experience with that administrative setup must have been good, because the management scheme over time developed as follows:

(1) The Federal Government, represented by the Federal Ministry for Research, appropriated the funds for the experimental facility.

(2) GfK/VA acted as the organizer and owner, executed the projects as builder and owner, and managed them after completion.

(3) Industry designed and built the facilities either as a general contractor or as a general engineer (such as WAK).

(4) The electricity utilities agreed to purchase the electricity and founded subsidiaries for construction supervision and subsequent operation.

By 1973, the end of the 3rd Atomic Power Program, the VA unit had spent approximately DM 700 million in investments and DM 130 million in operating funds on the five experimental facilities listed above, plus their peripheral units. This is an impressive amount of money, and yet, it seems modest compared to the billions currently estimated for the demolition of those very plants.[44]

GfK management (from the left):
Dr. Schnurr (Technology, GfK), Dr. Greifeld (Administration, GfK), Dr. Eitz (GfK/VA).

GfK/VA was a small administrative unit with approx. 40 staff members, managed by a Managing Director (first Dr. Brandl, from 1968 on, Dr. August-Wilhelm Eitz), and an officer in charge of administrative and legal matters (Dr. Hubert Tebbert). The budget of GfK/VA was strictly separarate from the budget of the GfK/Research Section. The independence of the Experimental Facilities Unit was preserved also with respect to administration, spending of funds, and technical project management.

Each experimental facility had a project leader on the technical side, who was supported by a project engineer. For KNK, this was first Dr. Gerhard Brudermüller and, from 1969 on, the author of this report, together with Gregor Schnetgöke as engineer. Because of the small size of GfK/VA, also administrative distances were quite short; letters reaching the Mangaging Director, as a rule, landed on the desk of the person who had to process and, mostly, also finish the matter, on the very same day.

Working at VA was fun.

1.3.4 The Delivery Contract Awarded to Interatom

With its signatures dated March 1 and May 31, 1966, respectively, GfK/Experimental Facilities awarded the delivery contract for KNK to Interatom. In the almost three years of discussion among Interatom, GfK, and GfK/VA, the following purpose of KNK had been agreed upon:

(1) KNK was to be a preparatory stage of the sodium cooled 300 MWe prototype plant.

(2) It was to be used to train operating personnel, especially with a view to the large SNR 300 plant to follow.

(3) It was to allow the licensing conditions applying to sodium cooled reactors in the Federal Republic to be determined by way of example.

(4) Finally, it was to be an irradiation facility for tests of fast breeder fuel under representative operating conditions.

The delivery contract for KNK comprised the technical design and the delivery of the 20 MWe nuclear power plant plus engineering services for the building construction part and the fuel element inventory. GfK/VA as the builder and owner was responsible for the building shell, the fuel rods including the enriched uranium (made at AEG, Großwelzheim), the licensing procedure, and for operating the plant with inhouse personnel.

The total price of KNK amounted to DM 110.2 million; Interatom's share was DM 87 million, the balance consisted of the contributions by the builder and owner. It is remarkable to see that an absolute fixed price was negotiated which was not influenced by changes in materials prices and salaries and wages due to inflation and, consequently, contained none of the price escalation clauses which became customary later on. The period of delivery was estimated at 42 months, i. e. only 3 1/2 years.

The contract was 56 pages plus ten voluminous annexes long and contained a number of trickily worded clauses causing the project managements of the contracting parties to be on their toes all the time. One provision in the contract, the so-called completeness clause, implied that

> *"irrespective of the specifications, the deliveries and services provided by Interatom must be so complete as to allow proper operation."*[45]

This made for innumerable difficulties in detail; nearly every day, events had to be discussed which could be viewed controversially as to whether they contributed to the completeness of the plant or not. Other clauses referred to the state of the art at the time the contract was signed and to additions or reductions in performance due to technical modifications. Finally, there were the bulk of conditions imposed under the Atomic Energy Act, for which a party paying the expense involved had to be found in, mostly, lengthy discussions. At this point, special mention must be made of Gregor Schnetgöke, the Project Engineer, who executed the difficult job of defining the scope of deliveries in constant disputes with his colleagues on the side of Interatom (Gubo, Gilles) in such an excellent way that the subsequent audit of the KNK project by the Federal Auditing Court did not give rise to any criticism.

For commissioning after completion of the construction phase, a cost reimbursement price with an upper limit (DM 4.75 million) had been defined above which the extra cost had to be paid half each by the contracting parties. Finally, there were a number of warranty promises by the vendor, for instance, of the plant power, control rods, fuel element reactivity, materials specifications; in case of failure to meet these, either correction or substitute delivery was agreed upon. The construction period of 42 months was subject to a penalty; each additional month would have meant DM 60,000 as payment in default.

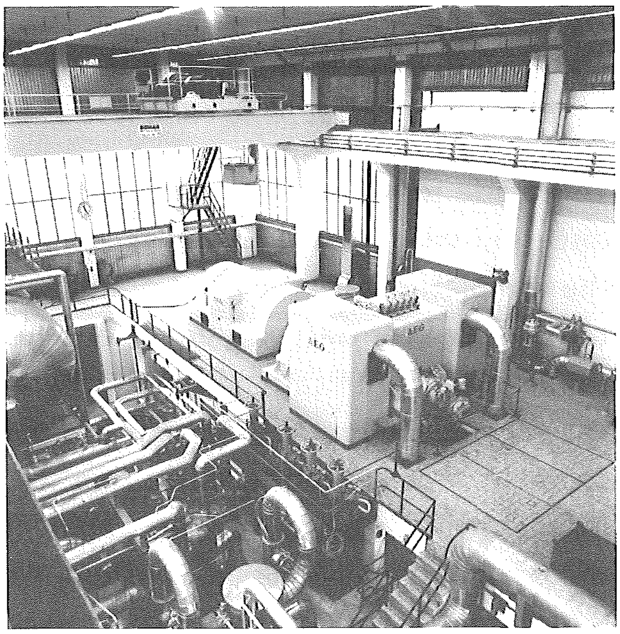
In retrospect it was seen that this type of contract, with its focus on the project goal and its definition of painful sanctions in case of failure to meet specific subgoals, constituted the most effective instrument of control in the hands of GfK/VA. KNK was built in the short time of 42 months at costs well within the contractual range of flexibility. Considering the general price escalation of nearly 10% in the construction phase between 1966 and 1969, it is evident that this must have implied a considerable indirect contribution of Interatom to the KNK project.

Because of the good experience in contract management for KNK, the Federal Ministry for Research in Bonn for some time considered building the large SNR 300 plant along the lines of the VA model. However, the idea was abandoned in the late sixties because the SNR 300 was to be organized "closer to industry."

1.3.5 KBG/Badenwerk as Operators

As early as in August 1963, the local electricity utility, Badenwerk, had responded to a query by KfK by expressing its willingness to make available for KNK a non-repayable grant of DM 4 - 5 million. This roughly met the expenditures for the turbine, generator, and switchyard. In addition, the Badenwerk was prepared to purchase the electricity produced in KNK, as it did already with the MZFR.[46]

While negotiations with Interatom about deliveries were still going on, a plant operations contract was signed in October 1966. The Badenwerk founded



View of the KNK turbo-generator in the turbine hall.

a subsidiary as the operating company, Kernkraftwerk-Betriebsgesellschaft mbH, or KBG for short, which was to be responsible for both KNK and MZFR. Dr. Helmut Armbruster was the committed, practical Managing Director of KBG between 1966 and 1973, after having accumulated more than four years of experience in leading positions with MZFR and GfK/VA. In the construction phase, KBG was to be responsible for technical building supervision, and after delivery, for operating the power plants. Project control on the spot by KBG helped the staff to become thoroughly familiar with the plant even prior to commissioning. To some extent, this compensated for the fact that the operator, and VA, had been commissioned to manage the KNK project only after the end of the planning phase.

KBG, an independent legal entity, was required to manage its business in accordance with the principles customary in the power industry. An annual financial plan and a program of work had to be negotiated with GfK/VA as the owner. Within this framework, KBG was refunded all expenditures less the income from electricity generation. KBG and VA were joint holders of the nuclear permit for KNK.[47]

In 1972, at a time when both MZFR and KNK were in full operation, KBG had a staff of 242.

1.4 Designing and Building KNK

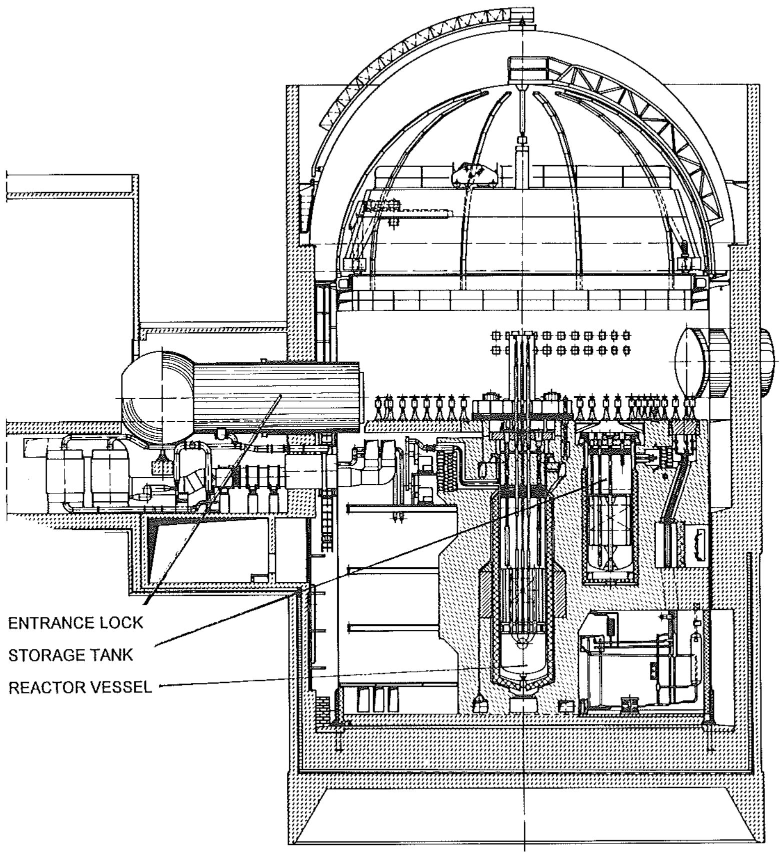
1.4.1 Plant Design

KNK was designed mainly between 1961 and 1964. The DM 30 million required were raised by the Federal Government; Interatom contributed DM 5 million out of its own resources. By 1964, the tendering documents and a preliminary safety report had been completed, on the basis of which Interatom was able to submit a bid. The main technical parameters of various power plant sections will be outlined below.[48,49]

Reactor Core

Among the most important components were the fuel and moderator elements. Their geometry was cylindrical, which simplified handling by obviating the need for azimuthal orientation of the elements. The elements were made up of a central cylindrical moderator section surrounded by 44 fuel rods arranged in two rings, and an outer moderator ring. The outside diameter (width across flats) of a fuel element was 126.1 mm; the fuel rods had an active length of approx. 1 m. The inner moderator section coupled to the fuel rods constituted the fuel element; during refueling, the outer moderator normally was to remain in the reactor. The fuel pellets made of UO_2 had an enrichment of 6.75%, a diameter of 8.7 mm, and were to ensure a mean burnup of 10,000 MWd/t of U.

In the normal design version, the reactor vessel contained 66 positions for fuel elements; in a freshly loaded core, there were additional absorber rods which could be withdrawn after they had reached a certain burnup. The fuel elements were kept down hydraulically. Their coolant flow in operation could be varied independently from the outside by control orifices. Actuation was by flexible cables carried in tubes like Bowden cables (orifice adjustment system).



Cutaway view through the KNK containment.

The core was contained in a reactor vessel 10 m high and 1.9 m in diameter. For safety reasons, it was surrounded by another steel vessel whose bottom centering pin could not be checked after installation and, for that reason, again and again caused speculations. Also the sodium inlet pipe as well as the two outlet pipes, including the reactor isolation valves, were double-walled. The reactor top shield consisted of two rotable parts fitted into each other eccentrically, which were filled with basalt granulate and very high density concrete for shielding. Tightness between the vessel and the top shield was achieved by two inflatable rubber seals similar in shape to the tubes of bicycle tires.[50]

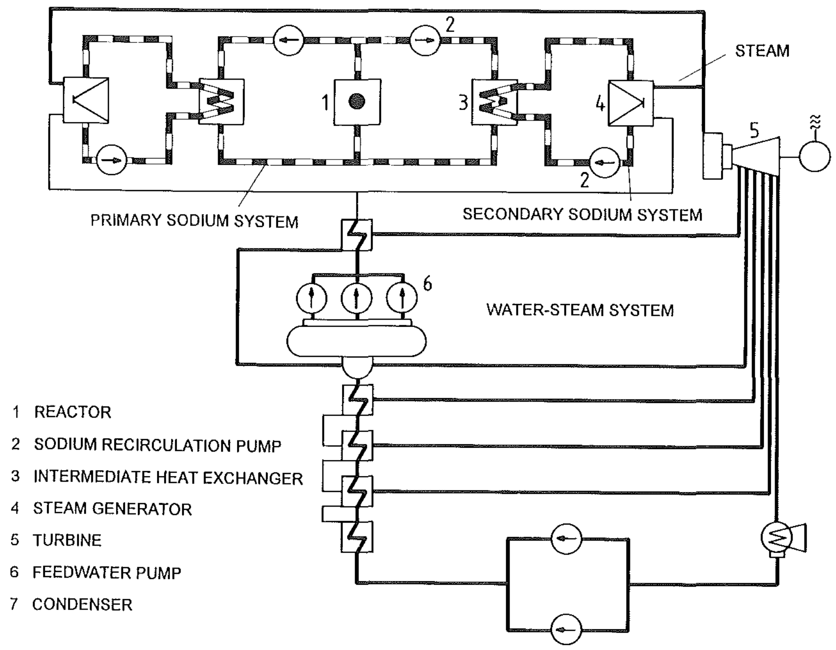
There were seven control rods for power control and shutdown, all of which could be operated as control rods, shim rods, or shutdown rods. They were made up of the drive at the top, the coupling linkage, and the absorber part running in a cladding tube inside the core. The drive used a recirculating ball spindle; in a scram, the electromagnetic coupling between the drive and the coupling linkage was disconnected. A cylindrical zirconium hydride moderator part was contained inside the absorber bundle to enhance the shutdown action.[51]

The fuel elements and activated reactor components were *handled* by means of a fuel handling machine which could be rotated as a semiportal system; a shuffling unit shuffled fuel elements within the reactor vessel. The fuel handling machine built by Demag had two separate gas circuits, which allowed a fuel element to be cooled with argon after withdrawal. The fuel handling machine was able to move to a sodium cooled fuel element storage pool and to an observation and disassembly station for fuel elements. The system was greatly simplified by the bottom of the carriage of the handling machine being designed as a semiportal system. The cooling gas was supplied through the base of the portal; in this way, all cooling and cover gas systems were installed below the reactor floor. Fuel element shuffling within the core was achieved by the shuffling system which could be put on top of the reactor top shield. As the fuel elements were only moved within the sodium pool in this handling step, no additional cooling was required.

In KNK, the fuel handling machine was a unit of special significance for technical safety. The "maximum credible accident" (thus the terminology used at that time) was defined to be the meltdown of a highly loaded fuel element because of cooling failure in the handling machine. This was the basis also for designing the containment to be gastight up to 200 °C and to an overpressure of 2.5 atm. Finding the fuel handling machine in good working order consequently was very important in in-service inspections. In most cases, it was the traction belts which needed maintenance.

Heat Transfer System

The heat transfer system consisted of two parallel circuits of 29 MWth each. The heat generated in the reactor core was carried by the two primary sodium circuits to one intermediate heat exchanger each and passed on there to the secondary circuits containing non-radioactive sodium. They were prepressurized to the pressure of the gas in order to prevent leakages of primary sodium into the secondary system. Except for a few austenitic parts, the heat transfer system was made entirely of the low-alloy ferritic steel mentioned above.



Basic circuit diagram of KNK.

The four sodium pumps in the two primary and secondary systems were mechanical, vertical, single-stage recirculation pumps with radial impellers, so-called open-surface pumps. The pumps were mechanically sealed at the top towards the driving motor and run in a hydrostatic sodium bearing at the bottom. Throughput was varied by changing the speed of the DC drive.

The intermediate heat exchangers had vertical, cylindrical plena along both sides of the tube bundle. The relatively thin-walled large shell surface areas of these plena allowed the helical tube coils to be connected with a minimum of thermal stress. The heat exchangers were arranged so that all flows followed the direction of natural convection. Moreover, they were displaced in height relative to the core in such a way that reliable afterheat removal was achieved by natural convection.

The steam generator consisted of parallel double tube coils, each of which transferred a thermal power of 1 MW. The inner tube carried water and steam, respectively, while the gap between the inner and the outer tubes carried sodium in a countercurrent flow. The diameters of 20 - 30 mm and wall thicknesses of 2 - 3 mm made for dimensions of the steam tubes which corresponded roughly to those of pipes in conventional boilers. The welds were inspected 100% for cracks, laminations, and slag inclusions. In a sodium-water interaction, automatic shutoff of the steam generator was ensured. Depressurization was achieved by means of a cyclone in which the sodium and the solid reaction products were deposited, while the rest was vented over the top.

The valves for stopping the sodium flow in the heat transfer system were conventional flat-body wedge gate valves. The spindle penetration was sealed by sodium freeze seals. Nozzle control valves were used for flow control in the afterheat mode of operation. Instead of the wedge gates, they had a permanently installed perforated plate whose openings were varied by a sliding plate.

The steam supply system of KNK corresponded to that of a conventional steam power plant of the same size. It was designed for a maximum generator terminal output of 25 MWe. The main steam pressure at the turbine inlet was 80 atm.abs., while the main steam temperature was 505 °C. The feedwater was preheated to 235 °C in a five-stage preheating system. The cooling water was cooled back in a three-tower fan-operated cooling tower system.

The whole plant was controlled in such a way that load changes left the temperatures in the systems as constant as possible in order to avoid thermal shock loads. This required all flows to be changed in proportion to the power. To keep the temperature level constant, the reactor outlet temperature was controlled by way of the neutron flux. The steam pressure was kept constant by way of the feedwater throughput. The steam temperature upstream of the turbine was controlled by changing the sodium inlet temperature of the steam generator. Also operation in the load following mode was to be possible For startup and shutdown, the rate of temperature change was limited to 2 degrees/minute in view of the thermal stress imposed. For non-steady state events, such as pump failure and scrams, which could not be influenced in operation, a limited number of cycles (approx. 200) beyond the yield point of the material were permitted under the strength analyses.

New Plant Features

A summary of the design parameters listed above shows that KNK featured a number of new characteristics in 1964 which made it clearly different from earlier sodium cooled reactors. Let me reiterate them briefly:

(1) The highest power per unit length in a fuel rod of the KNK fuel element was 510 W/cm, with the hot channel factor taken into account. At that time, this was the highest thermal load of a rector with oxide fuel.

(2) As a cladding tube for the fuel rods, austenitic steel with 16% chromium and 13% nickel was used for the first time. This steel grade was less susceptible to embrittlement by sigma phase formation than the steel grades with 18% Cr and 8 - 10% Ni normally used abroad.

(3) With a maximum sodium temperature at the reactor outlet of 560 °C, KNK was among the reactors with the highest coolant temperatures.

(4) The carbon-stabilized ferritic 10 CrMoNiNb 9 10-type steel was used for the thermal circuits. Compared to austenitic stainless steel grades, it was by far cheaper and, because of its higher thermal conductivity and lower expansion coefficient, was less susceptible to thermal shock, albeit at the expense of thicker walls.[52]

(5) The reactor contained an orifice adjustment system which allowed the flow through each cooling channel to be set and varied from the reactor operating level. Flexible cables were run through the reactor vessel inlet to actuate orifices in the fuel element bottom sections; at the same time, the fuel element outlet temperatures were monitored by thermocouples.

(6) Also the design of the intermediate heat exchanger and the steam generator was new. As explained above, the helical tubes of the intermediate heat exchanger entered the relatively thin-walled, large shell surface areas of the plena at a minimum of thermal stresses. The steam generators consisted of double tube coils connected in parallel; each of them terminated in four parallel plena for the inlet and outlet of secondary sodium and for the inlet of feedwater and the outlet of steam. One negative feature was their large space requirement, which practically excluded this type of steam generator from use in plants of more than 300 MWe.

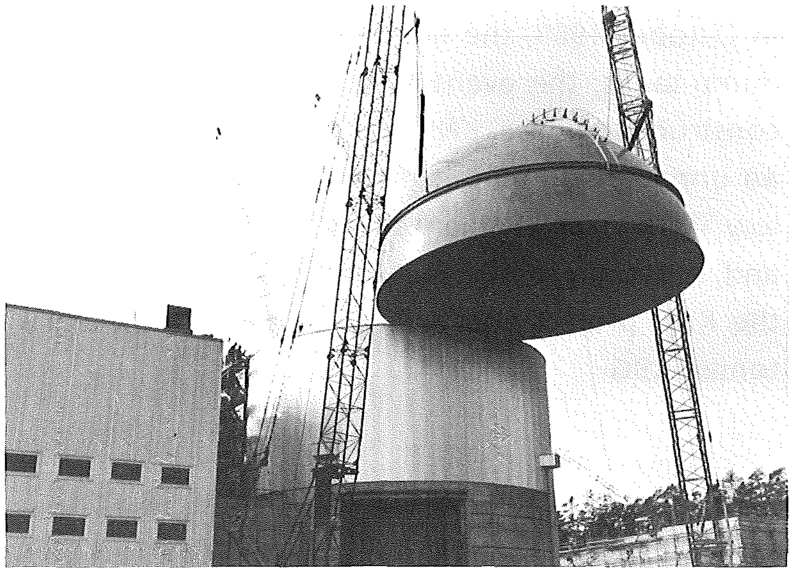
(7) Finally, KNK also confirmed the suitability of zirconium hydride as a moderator in thermal reactors. This indicated that ZrH_2, with its hydrogen density comparable with that of water, could become attractive also to shield against the high fast neutron flux in future fast breeders.

(8) The afterheat, with the reactor shut down, was removed by natural convection of the sodium coolant - an important safety criterion of the plant.

1.4.2 Speedy Construction

Construction of KNK began immediately after the delivery contract had been signed in May 1966. The first measure was the caisson foundation for the reactor building, which was necessary because of the relatively high ground water level on the premises of the Nuclear Research Center. The edge of the caisson was placed 13.6 m below ground level. After the caisson had been sunk, construction of the containment was started, and already in March of the following year the containment with its air locks was successfully subjected to leak tests and pressure tests. In June 1967, the administration building was delivered to the future operating crew. Chief Construction Supervisor Adam had ensured speedy progress of construction.

In the reactor building, the primary cells and the biological shield within the containment were completed next. After the cavities for the reactor vessel and the fuel element store had been lined, the double walled reactor vessel was put in place in September 1967. That same year, the cylindrical outer concrete shell around the containment was completed and covered with a second steel dome.


The dome of the KNK containment is swung into place (1967).

Erection of the building shells for the steam generator hall, turbine hall, control room building, cellular coolers, workshop, emergency Diesel power plant, and water treatment plant was begun in February 1967. Work was completed in late 1967, thus allowing the installation of mechanical equipment to be started as early as in January 1968 - what breathtaking speed, compared to the SNR 300 project which was to follow.

All major parts of the mechanical and electrical equipment had been ordered in the course of 1966. The 10 CrMoNiNb 9 10 special ferritic steel (materials No. 1.6770) for the heat transfer systems was purchased in accordance with a standardized program for semifinished products; in this way, optimum timing of the manufacturing process with various subcontractors was achieved. In October 1967, all major components, except for the steam generator, were in the final stages of completion.

Installation of the piping began in December 1967 and culminated five months later, when the primary sodium pumps were installed after first having been tested extensively in the 5 MW Facility at Interatom. Around mid-1968, most of the mechanical installations had been completed; next came the electrical equipment and the steam supply system. The structural components for the fuel elements, moderator elements, and for the control rods of the primary and secondary shutdown systems, which Interatom had built in-house, were shipped to Karlsruhe in the course of 1969. Occasionally, activities were five months ahead of schedule, but that lead was soon consumed by technical problems and delays, which will be described in the next section.

In October 1969, the operating volume of 89 tons of sodium was accepted in the dump tanks; this event, which had been contractually agreed upon, completed the construction phase. KNK had been built within the contractual time of 42 months in an unparalleled all-out effort, albeit at some risks, as described in Section 1.5 below.[53] This achievement is due to Interatom Managing Director Dr. Rudolf Harde and, especially, his Project Leader, Karl-Walter Stöhr, who devoted all his energies to the KNK project and willingly engaged in many a technical dispute with the customer, KBG.

1.4.3 Operation with Interruptions

The commissioning period of KNK was subdivided into four phases: commissioning without and with sodium (phases F1 and F2), zero power tests (F3), and power operation (F4).

Under the contract, the plant had to be accepted when

> *"operation, if possible without any interruptions, over a period of one week allowed a steam generation to be achieved which permitted the turbo-generator to be operated on the grid."*

This required a reactor power of approximately 30% of the rated power.[54]

Commissioning

While final assembly work was still going on, the F1 tests were started in the second half of 1969; they were completed approximately by the end of the same year. Between October 1969 and May 1970, the systems were filled with sodium and tested, and the sodium was purified. In the interim phase between May 1970 and May 1971, a large number of systems were modified as a result of experience accumulated in the commissioning phase (see Section 1.5).[55]

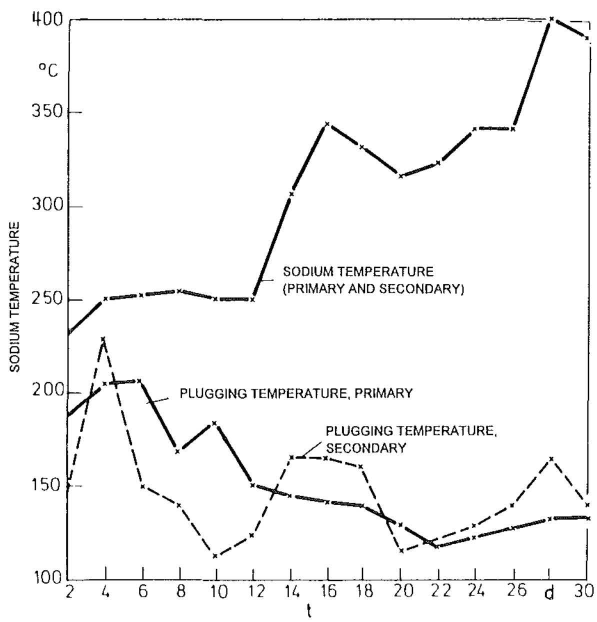
Loading the core, and the subsequent zero-power measurements, extended over the period between July and October 1971.

After a partial operating permit under the Atomic Energy Act had been received, the reactor was operated in the low power regime with the air coolers until May 1972. The power rise was interrupted for four months (September to December 1972) because of a steam generator defect. The plant was accepted on February 5, 1973. On February 21, 1974, KNK was raised to 100% power for the first time. Subsequently, the plant was operated at its rated power up until September 1974, when conversion activities for KNK II began.[56]

Sodium Purification

The 89 tons of sodium required for KNK were delivered in two tank cars and filled into the dump tanks at a temperature of 110 °C. This took one week. The oxygen content of the sodium corresponded to the saturation concentration at the filling temperature. The length of the ensuing sodium purification phase was caused by the high initial impurities in the ferritic system.

Purification was to achieve a plugging temperature of less than 150 °C, for which the systems temperature was raised in steps to 500 °C. It was typical of the purification campaigns that another plugging point developed above 400 °C. This was difficult to influence, but did not greatly impair plant operation. The plugging meters served as indicators showing sodium impurity; when the solubility limit was underrun, temperature-induced plugs were produced downstream of a throttle.



Typical curves of the systems and plugging temperatures during the cleanup phase.

Due to the initial impurities in the systems also the carbon content rose considerably above the level at delivery of the sodium (11.6 ppm). In the primary system, carbon levels of 50 ppm were measured, in the secondary system later, even 300 ppm, caused by an oil ingress from the pump bearings. After several purification runs, these levels were reduced to 12 and 18 ppm, respectively. One important experience gathered in this step was that the cold traps, originally designed to remove sodium oxides, could quite well be used also to reduce the carbon content.

Critical Experiment

Critical minimum loading was conducted with a concentric fuel element arrangement around the central position and with the control rods all the way out. Loading was completed in eight steps, and first criticality was reached with 38 fuel elements on August 20, 1971. Earlier theoretical estimates had resulted in 37± 1 elements, a very accurate prediction. For the first time, reactor physicists ran their extrapolations with one of those wonderful new pocket calculators equipped with microchips.[57]

The target core was loaded in nine additional steps. After the 13th loading step, the installation of two solid absorbers was planned to compensate for the excess reactivity. For the excess reactivity of the final configuration, a value of 709 cents was found; it was compensated to 419 cents by the introduction of the control rod bank. The reactivity gain achieved by heating the sodium from 207 to 472 °C amounted to 101 cents. In a sodium dumping test it was found that a reactivity gain of 120 cents resulted from a total sodium loss from the active core region.

Power Operation

After completion of the air cooler mode of operation, which permitted reactor powers below 8%, the steam generator was commissioned, and power was raised in steps up to 50% of the rated power. On August 9, 1972 the turboset was first synchronized with the grid system, and electricity was produced at a reactor power of 25 MWth. Along with the subsequent power increases up to 55% of the rated load, the coolant flows in the fuel elements were set by means of throttles. The criterion used for setting the flow orifices were the outlet temperatures at the fuel elements.

In the phase of power rise, also the natural circulation characteristics of the plant were verified. 4% reactor power simulated the maximum possible decay heat output with the core fully burned up. After the full enthalpy rise had built up, a reactor scram was simulated, and the sodium system was left alone with the coolant pumps shut off. The theoretical predictions of the reactor inlet and outlet temperatures were matched in the measurements.

In February and March 1973, the uninterrupted one-week test and acceptance operation was conducted, partly at a much higher power (59%) than was required under the contract. In the light of that performance, acceptance of the whole plant by GfK/VA was expressed on February 5, 1973. At the same time, KBG assumed responsibility for plant operation. On the side of Interatom, Gerhard Hendl played a particularly important role in the commissioning of KNK I; he was assisted by his successor, Wilfried Albat, who was responsible for setting up the programs.

After the permit for 100% power (5th Partial Operating Permit) had been received in February 1974, KNK reached its rated power two months later. The plant was in operation, mostly at 100% power, without any trouble until the autumn of 1974. At the same time, a small-scale experimental program was conducted in KNK with tests of plant instrumentation and sodium technology. The interested parties running the experiments were institutes at the Center, but also the Laboratory for Reactor Control and Plant Safety (LRA) at Garching (Prof. Birkhofer).

KNK ready and commissioned (1972).

On September 2, 1974, KNK was shut down permanently as scheduled to be prepared for the conversion into KNK II. This was followed, among other steps, by unloading the fuel elements and taking them to the Marcoule, France, reprocessing plant, disassembly of the fuel element store, and installation of the process computer.

1.5 Experience Accumulated in Construction and Operation

When a first-of-its-kind plant, such as KNK, is being built with thousands of components and switching elements, breakdowns and defects must be expected to occur. And occur they did. In an attempt to classify them, one could list them under the headings of lessons learnt in construction and commissioning, defects in quality and insufficient experimental experience, and problems in the licensing procedure.[58]

Especially the licensing procedure under the Atomic Energy Act reflected the fact that almost ten years had passed since the design of KNK had begun. In addition, a new breeder, the SNR 300, had been presented on December 31, 1969 which, of course, now had to be considered to reflect the state of the art. In the following three years, the basic technical concept of the SNR 300 was revised rather thoroughly by interventions made by expert consultants, licensing authorities, and the consortium of customers, which caused many conditions to be applied to KNK as well.[59,60]

New Findings

In the early project phase, the expense necessary to develop the right methods of calculation in some instances was underestimated quite considerably. Thus, for instance, complicated components combined with the good heat transfer properties of sodium gave rise to absolutely new design conditions. The classical computation approaches used in mechanical engineering often will no longer do in such cases. In project design work for the SNR 300, specific recalculations with newly developed codes therefore were conducted also for KNK. In some cases, this ultimately resulted in the installation of new, quite different components in a plant already completed. One case in point is the very sophisticated post-scram control system which, with the installation of additional compensators and mixing sections, caused some three months of delay in the commissioning phase.

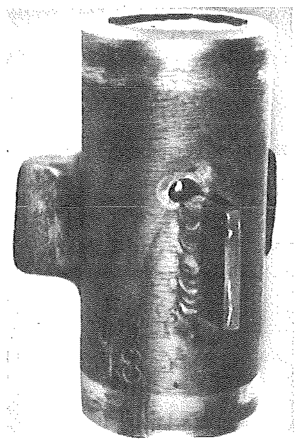
It also necessitated a modification in the pump rotors, if the given rate of temperature change of 0.7 °C/min was to be maintained. Moreover, the return feed pipe of the primary cleanup system had to be modified, and the secondary system had to be fitted new mixing sections to feed cold sodium into the hot leg. Also the neutronic shielding calculations were found to be insufficient in several cases. Consequently, after nuclear commissioning, the primary cells in various places had to be shielded additionally against the secondary system.

Also the compact design of the plant, originally chosen for cost reasons and, meanwhile, part of the name of KNK, more and more turned out to be a drawback. It was a hindrance in component assembly, and in many cases (such as in the primary sodium sampling case) also made access difficult for the plant personnel. Repair campaigns in the primary cells (which, contrary to the original design objective, were by no means maintenance-free) required complicated procedures to be developed, especially when work had to be conducted in radiation fields. Also in the ventilation system, separate closing of each individual ventilation duct, and stronger fire resistant barriers, would have been advantageous in case of sodium fires and the aerosol production associated with them.

Quality Problems

In the course of commissioning activities, occasional overheating was found in the sodium pipes. The cause were seen to be the circular-pipe heaters of the electric trace heating system, some of which occasionally developed ground faults. A tiny set screw, 1 mm long, but installed 9000 times in the connections of the heaters, had not been secured properly and then caused a delay of several months because the connecting heads had to be replaced completely.

In March 1971, sodium discharged from the purification system in the secondary circuit caused a fire. A startup heater installed temporarily for isothermal heating of the system to 500 °C contained a faulty end cap weld in one heating rod, which had produced leaks already twice before. The third leak caused a spill of approx. 500 kg of hot sodium, which then started a fire. Although the damage was localized, fire fighting was very difficult. Because of the ongoing aerosol generation, the center of the fire was hardly visible, and the sodium discharged had to be covered again and again for several hours.



Hole in the KNK steam generator pipe close to a spacer weld.

In September 1972, the first and only defect occurred in the otherwise very reliable steam generator of KNK. It later turned out that a leak had arisen at the fin of a spacer in the double-tube system where there had been a porous inclusion difficult to detect by inspection. Although depressurization under accident conditions worked, several kilograms of sodium penetrating into the tertiary system as far as a short distance upstream of the turbine caused modifications to be made in instrumentation and in the rupture disks.[61,62]

Other defects discovered in the course of commissioning were the break of a rupture disk in the tertiary system, which had been caused by a pump speeding up, and the simultaneous closure of two valves in the primary sodium system. When a solid absorber had to be reported floating, the angry supervisory authority responded by imposing a temporary shutdown.

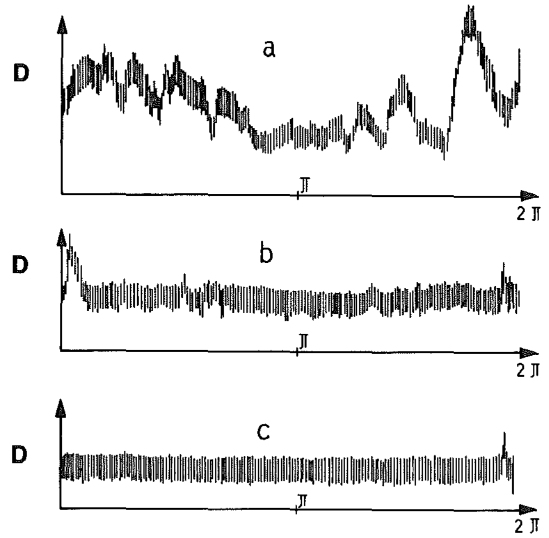
If human error is considered part of quality, also the false bores in the rotating top shield should be mentioned, which passed through all inspections and were discovered finally on the construction site. Also excessive lubrication of a pump bearing must be noted, which allowed some ten liters of oil to spill into the secondary sodium system, which then had to be distilled off.

Reference should also be made to the insufficient sealing of the primary cells against nitrogen leaks, which was due to a combination of faulty supervision on site and unsatisfactory sealing materials. Initially, operation under overpressure had been planned, but his led to unacceptable leakages on the order of 50 m^3/h and, therefore, had to be abandoned. Consequently, a mode of operation was chosen which included nitrogen feeding to lower the oxygen content in the primary cells to less than 2%, which was below the burning limit. This, too, resulted in major problems in maintaining the necessary amounts of nitrogen, and in safety risks associated with sodium leakages, because of the short escape times.

Lack of Experimental Experience

In some instances it became apparent that the preceding R&D program at Interatom in Bensberg only insufficiently met the subsequent risks found in implementation. The reason was either the experimental volume, which had been limited for financial reasons, or the fact that certain phenomena cannot be simulated completely outside the reactor.

Thus, it was found in KNK in the summer of 1970 that both rotating top shields sometimes were very difficult to move after the sodium in the system had heated up. The cause was found to be sodium aerosols plated out in the narrow gaps of the top shield system. As the geometry could not be modified, a mode of operation was developed which allowed the top shield to be thawed. For this purpose, the top shield cooling system had to be shut off briefly at a sodium temperature above 350 °C, which raised the temperature in the gaps to more than 100 °C and caused the aerosols to liquefy. Additional bores in the top shields also allowed mechanical removal of the sodium and its products. These procedures, though a bit cumbersome, proved to work well over the entire operating life of KNK.

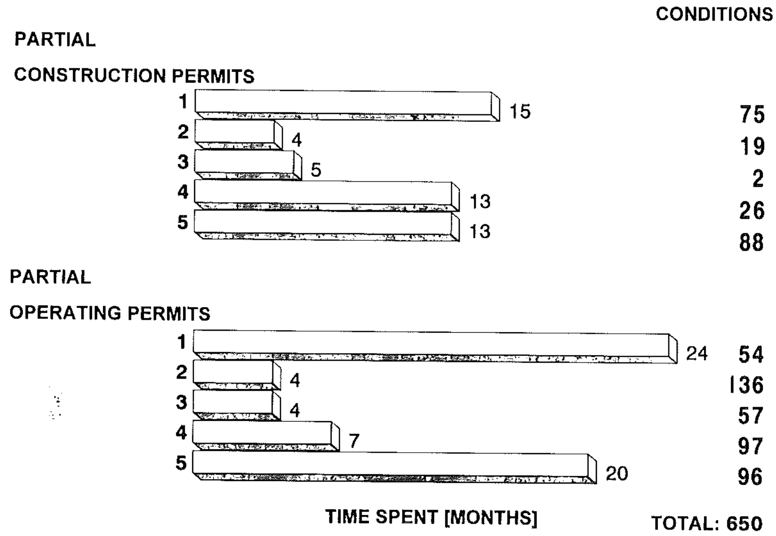


Curves showing the torque (D) over the whole circle of the rotating top shield
(a): with sodium deposits,
(b): after mechanical removal of the Na deposits,
(c): after meltdown of the sodium deposits.

Similar problems with aerosols plating out in the rotating top shield had occurred shortly before also in the French Rapsodie experimental reactor. Despite an official visit to Cadarache, it was not possible to acquire any information about that case; especially the repair measures, which obviously had been successful, remained a "trade secret" of the CEA engineers. The Breeder Agreement signed by Germany and France a couple of years later made an end to this blockage and initiated a very fruitful exchange of experience.

Lengthy Licensing Procedure

The timing of the KNK project was determined in a very special way by the licensing procedure under the Atomic Energy Act. In what may have been a spirit of exaggerated optimism, it was felt initially that one construction permit and one operating permit would do. In the end, this had become ten partial permits, five for construction, and five for operation of the plant. Half of these partial permits took more than one year, the first partial operating permit even a full 24 months, to come forth. All permits were issued by the Baden-Württemberg State Ministry of Economics; the State Ministry of Labor acted as the supervisory authority. Both ministries worked through the Baden Technical Inspectorate (TÜV) at Mannheim as the independent expert consultant.



Conditions imposed, and times required, for the partial permits for KNK I under the Atomic Energy Act.

The ten partial permits referred to above were accompanied by 650 conditions imposed. These conditions covered a wide range, from the relatively simple installation of additional locks up to the requirement of a second, redundant shutdown system at an expense of several million DM. That condition came unexpectedly, for never before had there been a sodium cooled reactor with such a component. The construction and testing of that shutdown system, with flexible modular absorbers, determined the critical path for quite some time. Other conditions referred to seismic calculations for buildings and installations, and to the installation of an emergency control center from which the reactor could be shut down, for instance, in case of a cable fire. Again and again, inactive periods occurred in project development for lack of a permit; ultimately, however, this was tolerable because one of the four reasons for building KNK as a first-of-its-kind plant was to establish the nuclear licensing procedure for a sodium reactor.

The future was to show that these licensing problems were only the beginning.

2 Converting KNK I into KNK II

While Karlsruhe spent the period between 1964 and 1970 negotiating the KNK project and building the plant, the nuclear scene in Germany changed profoundly. Nuclear power plants cooled with light water began to win the day, starting with KRB Grundremmingen (ordered in 1962) and soon followed by KWL Lingen (1964) and KWO Obrigheim (1965). Evidently, thermal sodium reactors, such as KNK, could have no economic chances in the near future. On the other hand, in the research sector, the Fast Breeder Project decided in favor of sodium as a coolant; after painful debates, the steam and helium coolant variants had been dropped. This made it an obvious choice to align KNK, and its future use, to the requirements of the Breeder Project and, consequently, equip the facility with a fast core. This is what was done, and the sections below will furnish a detailed account of this conversion of KNK with all its technical difficulties and licensing problems.[63]

The change in purpose of KNK was associated with a change in name. The original KNK facility with the thermal reactor core, from now on, was referred to as KNK I, while the facility with the unmoderated fast core was called KNK II.

2.1 A Difficult Decision in Favor of KNK II

2.1.1 A Reactor Is Needed for Irradiation

The main reason for employing KNK no longer primarily as an electricity generating plant, but as an experimental reactor and a neutron test bed, was the increasingly more evident bottleneck, even emergency, in fuel element irradiation facilities.

The importance of the fuel element as the most highly loaded breeder component had be recognized early on in the Fast Breeder Project. This is expressed in no uncertain terms, for instance, in the technical documents of the Association Agreement concluded with EURATOM in 1963:[64]

> *"The design of such a prototype offering promise for the future must be based on the fact that the fuel element is the dominating component. The reactor, in a way, must be designed and built around the fuel element."*

Testing the prototype fuel rods made by Alkem and GfK, respectively, with all their fuel and cladding materials variants, required experimental reactors with in-pile space for irradiation. Initially, the FR 2 reactor built at the Center had been equipped with so-called capsule test rigs as early as in 1965.[65,66] However, when the phenomenon of materials swelling was discovered, reactors with a fast neutron flux were in particular demand.[67] A makeshift solution was a lease of 50% of the capacity of the Belgian BR 2 reactor, which had a higher fraction of fast neutrons than the FR 2.[68]

At PSB, great hopes were pinned on the Enrico Fermi Fast Breeder Reactor (EFFBR) in the USA, which was to be used for irradiation of prototype bundles.[69] The accident caused in that reactor in October 1966 by a piece of sheet metal erroneously introduced during construction and now blocking a fuel element made an end to those plans and, at the same time, revealed a major bottleneck in the irradiation sector. After all, within the division of labor agreed upon in the Breeder Project, GfK was expected to irradiate at least 30 prototype fuel rods in sodium and in a fast flux - and that before the large SNR 300 plant would be tackled. Almost at the very last minute, a solution was found in the irradiation of small bundles in the Dounreay Fast Reactor. Agreement was reached with the United Kingdom Atomic Energy Agency (UKAEA) to irradiate 39 rods in the DFR (another 38 were made available by CEA); that irradiation was performed between January 1969 and April 1970 under the name of DFR 350.[70] Further irradiations in the amount of DM 43 million were to follow, but did not materialize because the underlying industrial agreements between Kraftwerk Union (KWU) and the Nuclear Power Group (TNPG) had not been signed.[71]

In view of all those problems with reactors abroad, the domestic KNK facility came back to peoples' minds. KNK was a sodium cooled plant, and the inlet and outlet temperatures of the fuel elements corresponded to those of modern breeder power plants; in addition, its core was compact in design and, thanks to the use of zirconium hydride instead of graphite as a moderator, also resembled that of a breeder. In a small-scale research study for GfK (costing DM 100,000 and 30 engineer-months) the fundamental usability of KNK as an irradiation reactor had been ascertained as far back as in 1964.

Following a request by the Fast Breeder Project, GfK/VA now commissioned another study with Interatom in which the suitability of KNK for accepting an unmoderated core of uranium oxide and plutonium oxide was to be examined in detail. This so-called feasibility study with an order volume of DM 2.5 million was conducted while KNK was still under construction, and was presented in 1968. It arrived at the summary conclusion that KNK's core center could be equipped with a fast core consisting of seven mixed oxide fuel elements. They would correspond to the elements of the

SNR 300 in their main specifications. In particular, the rod diameter, lattice pitch, U-Pu ratio, temperatures, power densities and, of course, fabrication specifications could be largely identical. As cladding materials, the steel varieties examined for the large breeder at that time, namely 1.4988 and 1.4981, were to be taken into account. Other important existing KNK components, such as the diagrid, the tank internals, and the rotating top shield, could be employed practically without any modification.

KNK also seemed to lend itself well to serving as a test bed for safety instrumentations. It had been instrumented lavishly from the outset, and its central position offered a possibility for testing, under in-pile conditions, a variety of detectors planned for use in the SNR 300 before installing them. Moreover, the installation of a sophisticated process computer had been envisaged which would have facilitated the evaluation of all these experimental objects.

The results of the KNK II feasibility study presented by Interatom were submitted for independent evaluation to the U.S. consultant, Nuclear Utility Service (NUS), by GfK/VA in 1969. NUS more or less confirmed the plans of Interatom and, in addition, made about two dozen suggestions, some of which will be mentioned here.[72] Thus, the spacers of the fuel rods were to be checked for homogenization of the sodium temperature, and the excess reactivity of the secondary shutdown system was to be raised from 2.3 to 3.3%. Because of the small core and the relatively large fuel element bundles, the reactivity increment produced by the introduction of fuel elements into the core was bound to be very large (around 7%); NUS therefore asked for additional technical safety measures in the fuel handling machine to avoid loading accidents. The time required to convert KNK I to KNK II was estimated by NUS to run up to ten months, which was similar to the figure quoted by Interatom (nine months). Unfortunately, both authors were far off the mark, as was to be seen later.

The Fast Breeder Project Management was highly pleased with the results of the KNK II feasibility study and expressed this feeling in a memorandum to the two managements of GfK and GfK/VA as follows:

> *"The use of a fast core in KNK (KNK II) is considered by the Fast Breeder Project a major constituent part of the development of fast breeder reactors. An aspect of major importance is the possibility to conduct in the central zone of KNK II instrumented in-pile experiments under real breeder conditions. The financial expenditures for the KNK II core seem to be adequate."*[73]

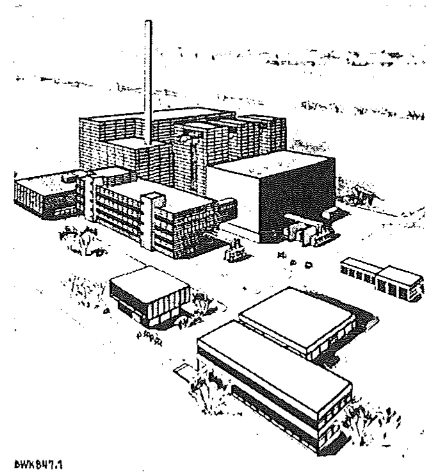
Now GfK/VA was faced with the problem of purchasing the plutonium plus enriched uranium needed for KNK II. This was no easy job, for in the late sixties there were only tentative beginnings of a plutonium market. In the United States, that market was controlled by the U.S. Atomic Energy Commission (USAEC), which also had fixed the price of plutonium within its domain to a level of $43 per gram. Thanks to fortunate coincidences, and thanks also to the assistance by Nukem, Hanau, some sublots of plutonium could be acquired cheaply from American electricity utilities (such as Yankee Atomics), which finally resulted in an average price of $23.75/g for the 100 kg of plutonium purchased. Alkem was commissioned immediately to convert the nitrate into an oxide, separate the americium, and manufacture the first trial rods.

KNK II was now well on its way, but this had not made KNK I any less important. Quite on the contrary, as will be shown in the next section.

2.1.2 Coming to Terms with Sodium Technology

On the last day of 1969, the planning consortium for the SNR 300 under the leadership of Interatom mailed the technical documents for that breeder power plant. In the bid submitted soon, April 1, 1971 was mentioned as the date construction of the SNR 300 was to be started.

The Fast Breeder Project Committee, an agency for steering breeder matters established by the Federal Ministry for Education and Science, then called a meeting. In March 1970, the Project Committee established an ad hoc committee assessing the technical maturity of the SNR 300, which was chaired by Dr. Eitz, Managing Director of GfK/Experimental Facilities. Other members were Dr. Däunert, BMBW; Dr. Keßler, GfK; Mr. Koop, RWE, and the author of this report. After six meetings, the Committee surprisingly found in June 1970 that the SNR 300 was not yet ready for construction, as a number of technical preconditions would not be met by the envis-



Artist's impression of the Kalkar Nuclear Power Station (state as of 1971, still without the cooling tower).

aged construction date. Those were conditions spelled out in the appropriation decision of 1966, five of which had to be handled by Interatom (A1 - A5), three by GfK (B1 - B3), before construction of the SNR 300 could be started.[74]

The so-called "Essential A3" was considered particularly important; it was associated with KNK and, in part, with the Hengelo component test facility. This is what it said:

> *"Management of sodium technology by making use of the experience accumulated by that date in the 5 MW Experimental Facility at Interatom and in KNK. This includes, in particular, the successful commissioning of KNK..."*[75]

In view of the technical problems in commissioning KNK as described in Section 1.5 above it was easy to see that essential A3 would not be met before the autumn of 1971. Although the planners tried to interpret this appropriation condition as a demonstration of the feasibility of KNK, thus weakening its impact, Dr. Schuster as Chairman of the Project Committee insisted that Interatom conduct a kind of "trial run" in the form of KNK before being awarded the SNR 300 contract.[76] Finally, agreement was reached on considering essential A3 to have been met as soon as KNK was operated at 50% of its rated power. Should that be unattainable by late 1971, another committee would be set up to look into the causes. All of a sudden, commissioning KNK had become very important. KNK I clearly enjoyed a higher priority than KNK II, as was underlined every day by the efforts made on site by the Interatom team.

Yet, the KNK essential was not fulfilled in time. Especially the aerosol problem associated with the rotating top shield was very time consuming. The timetable was strained also by the sodium fire in the secondary system in March 1971, because of the lengthy cleanup phase following the incident. As announced, the Project Committee therefore set up another committee that was to look into the "causes of the delays in the schedule of KNK," and assess their relevance to the SNR 300. The members of that subcommittee included Dr. Däunert, BMBW; Mr. Koop, RWE; Messrs. Stöhr, Guthmann, Dr. Herberg, all of Interatom; Dr. Brudermüller, KBG; and the author as chairman. The final report presented by that committee[77] listed some 25 minor and major events in KNK which had prevented the commissioning deadline from being met; in addition, a "list of risks" was presented with areas in which insufficient knowledge could be assumed to exist with respect to the SNR 300 breeder. In the opinion of the committee, operation of KNK at 50% of its rated power was not possible before 1972.[78]

That prediction turned out to be correct. On August 9, 1972 KNK, running at 55% power, for the first time supplied electricity into the Badenwerk utility grid. However, despite its commissioning problems, KNK had not delayed the SNR 300 project. Additional requirements imposed by the licensing authorities and by the customer consortium in the meantime had delayed the start of construction of the SNR 300 by two years, from April 1971 to April 1973. Moving the site from Weisweiler to Kalkar, and changing plans from a cylindrical to a rectangular containment, had been particularly time consuming in this respect.

2.1.3 A Bad Surprise

Let us return to KNK II.

After the positive outcome of the feasibility study and the evaluation by NUS, GfK/VA in June 1970 had filed with the Stuttgart licensing authority an application for conversion of KNK I and operation of KNK II with an unmoderated core. The application had been accompanied by a three-volume report with technical descriptions and documents containing the details of the modifications of KNK I to KNK II. The applicants expected a nuclear license based on the old KNK I facility, which had already been examined by expert consultants and licensed; expressed in the jargon of that time: a so-called modification permit was applied for.

At long last, in the autumn of 1971, the licensing authority responded to the application filed, creating a profound surprise: The conversion of KNK I to KNK II was considered a *material alteration* in the sense of Section 7 of the German Atomic Energy Act:

> *Any person who constructs... a stationary installation... or who materially alters such installation, or its operation, shall require a license."... "A license may be granted only if every necessary precaution has been taken in the light of the state of the art..."*

At the same time, the authority announced its intention to impose extensive conditions in the fields of emergency core cooling, earthquake protection, and power excursions. In addition, the entire plant, including the existing old KNK I plant, would have to be made the subject of new expert examination and new permits in which the advanced state of the art would have to be taken into account. Express mention was made of the need to reassess the site of the plant on the premises of the Karlsruhe Nuclear Research Center. No doubt, the intense SNR 300 debate between

1970 and 1972 had contributed to that official decision. This was true in particular of the site, as the rejection of Weisweiler was still very much in everybody's mind.

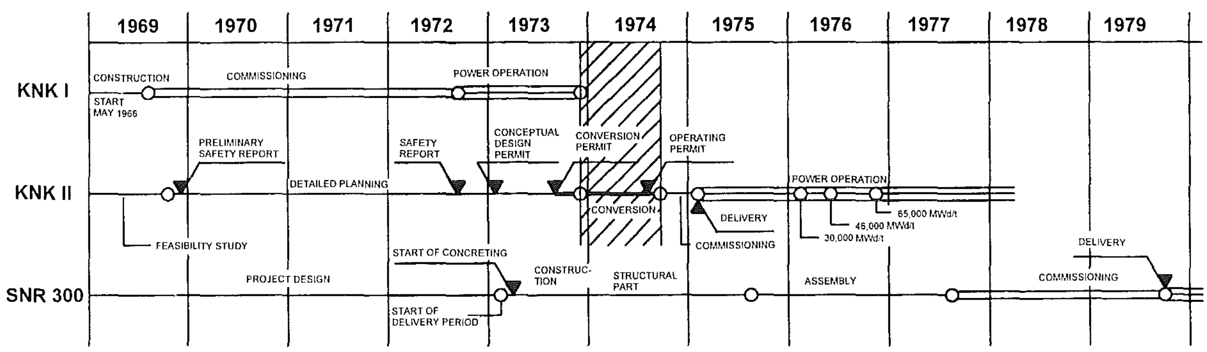
The author of this report will forever remember the moment when, on his trip back from the Stuttgart licensing authority in October 1971, he realized that KNK II had become incalculable because of the backfitting measures now to be expected and the unfathomable influences of the SNR. A project analysis conducted right away together with the VA Management at that time (Dr. Eitz, Dr. Tebbert) culminated in a nocturnal dispatch of a huge number of cables canceling and suspending, respectively, all contracts for KNK II.[79]

The fate of the KNK II project was wide open again.

2.1.4 Will the SNR 300 Outpace KNK II?

Concern was felt even in distant Bonn.

Expecting a speedy development of KNK II, the Federal Ministry for Research had appropriated funds amounting to DM 69.3 million already in 1971.[80] Of that amount, some DM 40 million had been spent on purchasing the fuel (approx. DM 30 million) and on preplanning activities and experiments at Interatom (approx. DM 10 million). Part of those funds would have been lost forever, had the KNK II project been terminated now.



Time schedule for KNK I, KNK II, and SNR 300 (state as of 1972).

There was another horror scenario haunting the persons responsible at the Federal Ministry for Education and Science even more: If both KNK II and the SNR 300 were built, it was no longer impossible for the SNR 300 to be commissioned *before* KNK II. For, at the 1971 Status Report of the Fast Breeder Project, it had been announced:

> *"The actual start of construction is to be in April 1972. Assuming a construction period of five years, this means that the SNR 300 could start its trial power operation in the first six months of 1977."*[81]

If the hit-and-miss mode experienced in commissioning KNK I continued, and if further time consuming conditions had to be fulfilled in converting and commissioning KNK II, there was hardly anybody who would guarantee regular KNK II operation before 1977.

As always when in need of good (inexpensive) advice, the Federal Ministry for Education and Science appointed a committee. It was the third committee within eighteen months discussing aspects of the KNK project. It was called "ad hoc Committee Verifying the KNK II Project." This time, a neutral member was appointed chairman, namely Mr. Kallenbach, Executive Board Member of the EVS electricity utility in Stuttgart, a company involved neither in KNK II nor in the SNR 300. The staffing of the committee was calibrated very nicely: Dr. Mausbeck (Interatom), Dr. Engelmann, Dr. Eitz, and the author (all KfK) probably were supposed to inject the expert knowledge about the project, but were considered proponents of KNK II; they were accompanied by the high temperature expert of the Jülich Nuclear Research Center (Dr. Bergmann), the officer at BMBW responsible for the German Advisory Committee on Reactor Safeguards (Dr. Schnurer), and the future head of SNR 300 operations (Mr. Koop).[82] The most intricate questions were asked by a non-member of the committee, BMBW unit head Dr. Lorenzen, and his assistant, Dr. Däunert. Probably anticipating the questions he would be asked by his superiors, he played the devil's advocate by asking for all the important information about the status and development of the project.

For four meetings, the committee delved into the technical risks of the modification of KNK II, its benefits to the irradiation program[83] and to breeder development[84], and the potential schedule of KNK II and the SNR 300. The committee jointly arrived at the conclusion that the benefit of KNK II continued to exist, and that it would help to reduce greatly the technical risks of the large SNR 300 facility.[85] For that reason it was recommended to continue to pursue the KNK II project. However, this was tied to two major conditions: The technical expert examination by the German Advisory Committee on Reactor Safeguards (RSK), which was about to be started, had to produce a positive finding, and the lead of KNK II over the SNR 300 - with respect to the commissioning dates of the two power plants - should not underrun three or four years.

At that point in time, nobody could have guessed that especially this last condition would be so easy to meet.

2.1.5 RSK Vote and KNK II Delivery Contract

The documents for the various technical subcommittees of the German Advisory Committee on Reactor Safeguards were prepared speedily throughout 1972. The RSK vote was expressed in January 1973, and quite positive it was:

> *"Within its discussions of a recommendation about the site and the safety concept, the RSK examined the major safety issues associated with the installation of a fast core in KNK... It recommends to BMBW to approve the granting of a permit for the site and for the safety concept."*[86]

The most important factor was the RSK approval of the Karlsruhe Nuclear Research Center as a site, for a change in location, the way Weisweiler had been replaced by Kalkar, would have been impossible in an existing plant, such as KNK. Yet, the expert consultants formulated some technical conditions with far reaching implications.

There was, for instance, the requirement of an emergency core cooling system to be designed as a third heat sink, in addition to the air cooler and the condenser. For this purpose, the gap between the vessel and the double tank could be used for gas cooling. Complete redundancy in plant supplies and electricity later was achieved by an emergency well specially drilled for this purpose, and an emergency Diesel power plant installed in a vault.

As with the SNR 300, increased attention was to be devoted to the Bethe-Tait accident, which could cause core meltdown. In addition to an analysis of the negative coolant coefficient, upgrading the instrumentation by installing reactimeters, etc., was demanded. Moreover, a weighty top shield clamping system was to be installed.

All predictive estimates were exceeded by far by the expense required to upgrade the old KNK I system against seismic impacts. The piping of a sodium system is restrained in soft suspensions because of the thermal expansion it undergoes and, as a consequence, by its very nature it is susceptible to the excitation of vibrations; attaching it with shock absorbers at precalculated points was a very time consuming and costly affair in the ensuing conversion phase to follow.

Also physical security, i. e. protection of the plant against sabotage and terrorism, was not easy to achieve. It is almost impossible to harmonize the requirements of traditional accident protection (as many open escape doors as possible) with those of physical security (only very few doors, and those should be locked, too).

Physical security at KNK.

The positive vote by RSK was the necessary prerequisite for concluding the KNK II delivery contract with Interatom. It was signed in June 1974 after three days of almost continuous negotiations among Dr. Traube, Mr. Brakelmann, Dr. Tebbert, and the author. All services and deliveries to be made by Interatom were laid down: complete detailed planning of KNK II; manufacturing the reactor components; assembling the fuel elements; installing the components in the plant, including the process computer. In addition, the engineering impact of those legal conditions which had already been imposed had to be covered.[87]

Among the most important components to be provided by Interatom were the fuel element store with its handling facilities, the reactor top shield clamping system, the structural parts of the core, and the primary and secondary shutdown systems. The fuel rods for the core were manufactured by Alkem and RBU, both at Hanau; for the central zone and the outer ring zone of the inner core section, nearly 2000 UO_2-PuO_2 fuel rods had to be manufactured.

The KNK II delivery contract was relatively complicated in structure, in principle, because it covered the conversion of an existing plant long since accepted under a previous contract. New components, such as the fuel elements or the shutdown systems, were intimately connected with existing components, which made for difficult definitions in liability, warranty and guarantees. Also when it came to personnel, Interatom had to use the assistance of the operator, KBG, without this being allowed to mix up responsibilities for each and every step. Moreover, the conditions which would be contained in the expert opinions in the partial permits to be issued at a later date were not yet known, or could be only "guessed at." As a price model for the delivery contract concluded between GfK/VA and Interatom, therefore, a cost price with an upper limit was agreed upon.

Project Management wanted to keep the total cost of KNK II for all these deliveries and services by Interatom, fuel purchase, fuel element fabrication, and experiments during the construction phase, below DM 100 million.[88] They ultimately succeeded in achieving this goal thanks to the provision, free of charge, of two MOX fuel elements by Belgonucléaire in compensation for the irradiation, also free of charge, of those elements in KNK II. The accounts on the entire KNK II project were settled four years later at a total of DM 140 million. The extra cost resulted from a much longer conversion phase and from many unexpected demands by the licensing authority in the wake of the conditions imposed upon the SNR 300. Considering that cost overruns of the SNR 300 and the THTR amounted to approximately 400%, the 40% overrun in KNK II appears quite tolerable.

2.2 KNK II Design

2.2.1 Reactor Core and Fuel Elements

Designing the reactor core of KNK II was a demanding task. Under the boundary conditions established by the KNK I plant, primarily these goals were to be achieved:

(1) Irradiation of a statistically sufficient number of breeder fuel rods in fuel elements of the type planned for use in the SNR 300.

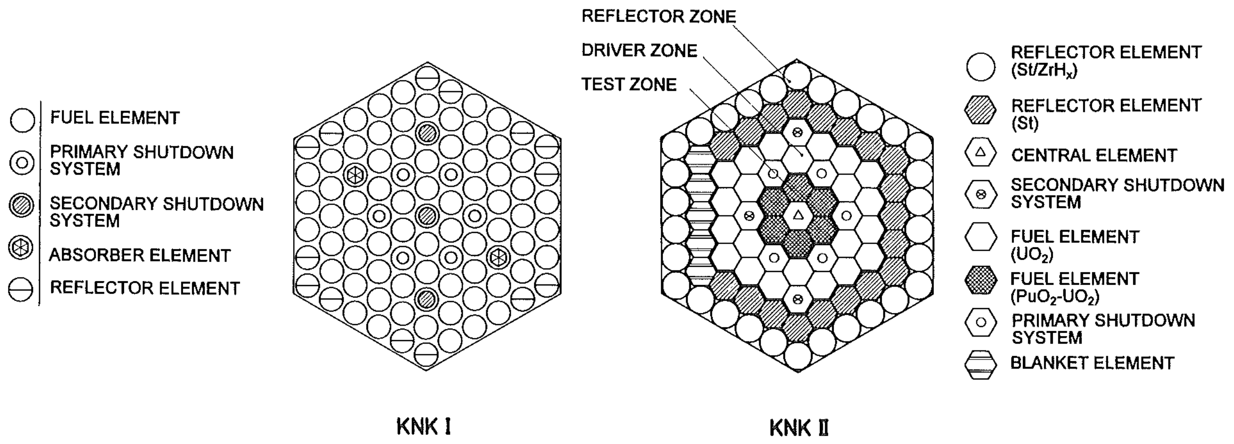
(2) Use of fuels typical of breeder reactors in the inner test elements, and establishment of a breeder-like neutron spectrum.

(3) Achieving representative powers per rod unit length of up to 435 W/cm.

(4) Achieving sufficient excess reactivity and in-pile times; for the first core, a burn-up of 80,000 MWd/t had been envisaged.[89,90]

The existing KNK I plant established narrow limits for KNK II in respect of its thermal power, coolant flow, and permissible pressure loss.[91] Also the fundamental lattice of the core elements and the positions of the absorbers were to be adopted from KNK I; merely the central secondary shutdown position was cleared for one test element.[92] Moreover, the neutron physics core design was to ensure a negative Doppler coefficient of sufficient magnitude.[93,94,95]

The result of all these considerations was a two-zone core with 29 fuel elements. The inner test zone with seven fuel elements was to ensure the test conditions, while the outer driver zone had to provide criticality. As the KNK II core was smaller than the thermal KNK I core, an additional five blanket elements could be accommodated on external lattice positions.[96,97]



Core cross sections of KNK I (left) and KNK II (right).

In contrast to conditions in KNK I, the power coefficient of the core was always negative. To ensure a sufficient Doppler coefficient, the spectrum in the U-238 resonance range was additionally raised by zirconium hydride rod moderators in the second row of driver elements. This made the neutron spectrum of the driver zone slightly softer, and that of the test zone slightly harder, than in the SNR 300. For energies above 0.1 MeV, the neutron flux in the KNK II core attained roughly half the level it had in the SNR 300. As precisely that energy range is responsible for radiation effects in the cladding tube, KNK II was excellently suited for in-pile tests.[98,99]

The fuel elements of the test zone were to incorporate 211 fuel rods each; merely the central element was equipped with 169 fuel rods. The diameter of the cylindrical fuel rods was 6 mm, which was identical to the design chosen for the first core of the SNR 300. For the cladding tube, three austenitic materials with numbers 1.4970, 1.4981, 1.4988 were planned in various metallurgical conditions. The fuel consisted of mixed PuO_2 and UO_2 in a mixing ratio of 30 : 70% sintered into pellets.[100]

The fuel smear density was 80% of the theoretical density, which offered sufficient porosity in the fuel to accommodate the fission products. The fuel density had been defined at 86.5% of the theoretical density, and the as-fabricated clearance between the pellet and cladding tube had been fixed at 155 µm. Specifying hypostoichiometric fuel was to achieve better chemical compatibility of the cladding tube with the fuel.

Above and below the fuel stack there was one stack each of pellets of fertile material integrated into the fuel rod. Below the active fuel rod region, the fission product gas plenum had been designed to 40 bar. Engineered safeguards design was made with the IAMBUS fuel rod computer program. The neutron physics methods and calculations were backed by a critical experiment which had been performed in SNEAK in Karlsruhe in 1968.[101]

The fuel rods were held in place by axially staggered grid-type spacers, which were said to offer thermohydraulic advantages over competing concepts. Most of them were spark eroded spacers; one innermost ring element of the test zone was equipped with a honeycomb spacer. A special mixing head was to facilitate temperature monitoring of the fuel elements.

The rods of the absorbers had a diameter of 10.3 mm and were filled with B_4C pellets and granulate, respectively. The helical fins ensuring the spacer function were integrated into the cladding tube. Below the absorber stack there was a gas plenum accommodating the helium gas generated in B 10 by neutron absorption. The absorber concept was backed experimentally by earlier in-pile experiments conducted in the Rapsodie reactor at Cadarache.

2.2.2 Safety and Instrumentation

In the design of KNK II much importance was attached to preventive safety. The concept implied, above all, the timely detection of losses of coolant flow in the fuel elements, and a reliable decay heat removal capacity with the reactor shut down. Unlike prototype-size fast breeders (such as Kalkar), KNK II was favored by its low fuel mass and by the void coefficient being negative throughout. In addition, the plant had a highly heterogeneous core structure ensuring incoherent accident development.[102]

There were three instrumented safety barriers for the detection of local losses of coolant flow in the core, namely the DND system for the detection of delayed neutrons, the thermocouples at the fuel element outlets, and the reactimeter. The DND system indicated the existence of emitters of delayed neutrons in the coolant and, in this way, the presence of free fuel surfaces in the core. The response time of the DND monitors was on the order of minutes; their sensitivity was deemed to be sufficient to detect blockages with a free fuel surface of approx. 5 cm^2, i. e., before the onset of local boiling.

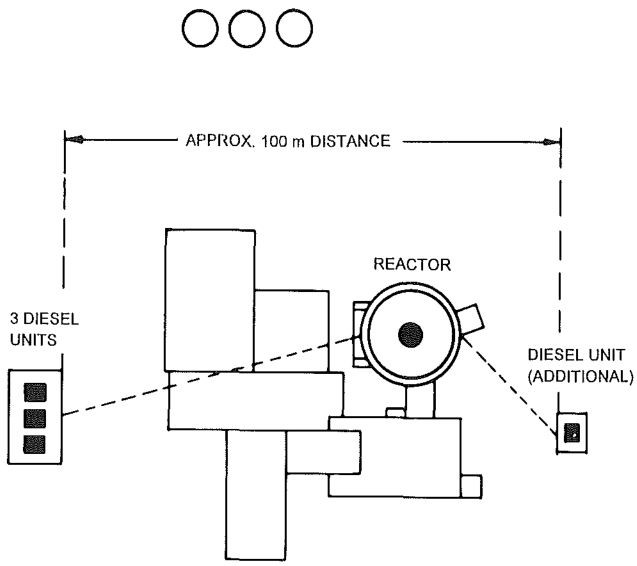
Integral flow reductions in elements of the test and the driver zones to less than 90% of the rated flow were to be detected by individual monitoring of the outlet temperatures of all test and driver elements. Impurities of various dimensions not removed by the plant cleanup system were to be retained at the sieve-like inlet structure of the fuel elements or at the lowest spacer level in the region of the fission product gas plenum.

Slowly growing blockages of this type were detected by the system long before the onset of integral boiling. Even the very unlikely case of fast, almost complete plugging of the flow area was detected in time before, or shortly after, the onset of integral boiling. Sudden total blockages were excluded by the special design of the coolant inlet zone.

The reactimeter was a boiling detection system able to monitor the decrease of reactivity in the course of boiling. The shutdown limit was at -8 cents. In the driver elements, stable boiling without interrupting rod cooling was most likely to occur because of the low bundle pressure loss, while unstable boiling followed by "burn-out" was more likely to occur in the test zone. The reactimeter was a device for reactivity measurement. It had a variable source term and nine variable measurement ranges between 2.5 cents and 10 dollars. The unit was able to indicate promptly both negative and positive reactivity changes.[103,104,105]

The RSK demanded that the installations for decay heat removal be supplemented by a diverse, physically separate emergency core cooling system in the conversion to KNK II. This was achieved by direct gas cooling of the wall of the reactor vessel. For this purpose, an existing nitrogen system was upgraded so that nitrogen coolant permeated the gap between the wall of the reactor vessel and the wall of the guard vessel from top to bottom as soon as redundant change-over valves had been actuated. The nitrogen circuit was recooled by the emergency cooling water supply system. The water was extracted from the fresh water system of the Nuclear Research Center or from an emergency well specially drilled for that purpose.

An additional Diesel power plant was installed to generate electricity for the emergency core cooling components. It was located in a separate building protected against seismic impacts and sabotage which contained also the necessary switching and monitoring installations. The emergency Diesel power plant building was designed so that an assumed airplane crash would not cause the plant electricity supply and the Diesel system to fail simultaneously.



Redundant emergency power supply by 3 + 1 Diesel units in KNK II.

The thermal design of the emergency core cooling system was based on an accident defined by the expert consultants in which, after a leakage in the unprotected section of a primary system, the isolation valves of both systems would close at the same time. A delay of thirty minutes was assumed for actuation of the emergency core cooling system. Thermal calculations performed by means of the NOTUNG computer code demonstrated that meltdown of the reactor core was avoided even in this hypothetical case.[106,107]

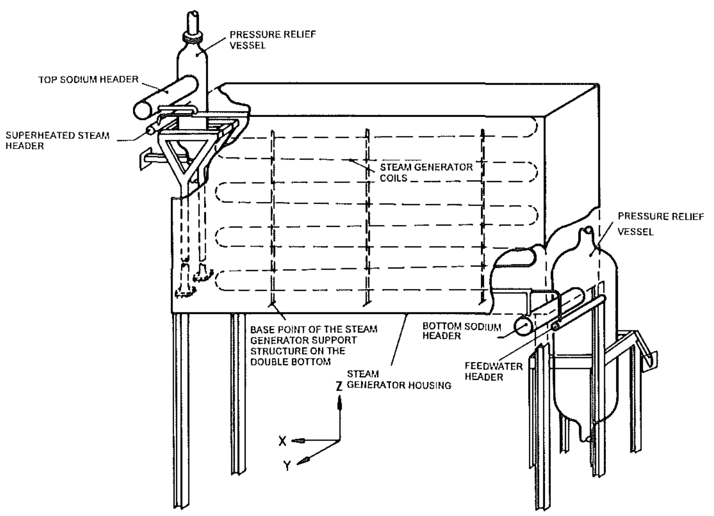
2.2.3 Protection against Seismic Events

In 1971, when the conceptual design of the conversion of KNK I to KNK II was being discussed, the design philosophy for seismic loads affecting nuclear power plants was tightened up considerably on the occasion of the 1st SMIRT conference in Germany. Instead of only steady state accelerations, dynamic effects now were to be taken into account as well. KTA Rule 2201 set forth the seismic design of nuclear power plants; accordingly, all those structural parts and plant components had to be designed earthquake-proof which were required to shut the reactor down, remove the decay heat, and prevent releases of radioactive substances.[108]

For KNK II, this requirement initially was to be met by the proper demonstrations and by upgrading the primary system as well as the newly added emergency core cooling system. However, anticipating the tighter criteria imposed by the German Federal Ministry of the Interior, the expert consultants demanded the same proof for the whole secondary system. This increased the amount of work by a factor of 5 over earlier concepts.[109]

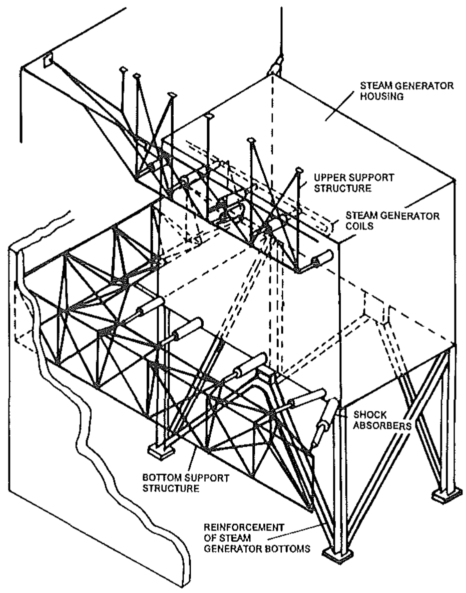
It had to be demonstrated that the components of the heat transfer system, such as pipes, sustained seismic loads; in case of doubt, they had to be upgraded. This was possible either by reinforcing structures or by increasing the vibrational mode of that component in order to achieve lower acceleration levels and, consequently, lower load forces. It primarily meant that the component under discussion had to be tied to parts of the building or to platforms which, of course, had to be stiff enough to sustain such loads.[110]

As no additional forces caused by seismic protection measures must act upon plant components during normal reactor operation, thermal movement of components had to be taken into account as well. For this reason, shock absorbers were used which followed changes in length during slow movements, but locked almost entirely in fast movements. In this way, "dynamic benchmarks" were obtained. The all-metal shock absorbers used in KNK II, which contained no fluid, were guaranteed to be resistant to radiation; various different sizes were provided in accordance with the loads encountered. However, because of the compact design of KNK it was frequently impossible to install as many seismic shock absorbers as would have been desirable.[111]



KNK steam generator before it was upgraded.

A group of approximately twenty people had to be recruited at short notice at Interatom to perform the dynamic calculations; for almost two years, they were occupied with vibration and stability calculations and the associated experiments.



KNK generator after being upgraded by reinforcement beams.

They also developed new methods of computation as well as computer codes which, later on, were used also for the Kalkar SNR 300 prototype. Dynamic benchmarks found suitable in systems analyses often turned out to be unfeasible technically. In most cases, therefore, numerous iterations in the computer analyses and design drafts were necessary to arrive at the final solution. Solving the finite element calculations of the pipe systems took roughly 350 hours on the CDC 6200 and CDC 172 host computers at that time. Other design problems arose because the usability of the American shock absorbers, which were supposed to be resistant to temperature and radiation, had to be demonstrated in lengthy functional tests and quality inspections which were run at the manufacturer's site in the United States in the presence of the expert consultant.

The large components of the heat transfer system, such as the reactor vessel, pumps, intermediate heat exchanger, air cooler, and steam generator, were the benchmarks with respect to thermal expansion for the piping. They had to be demonstrated to have sufficiently high vibrational modes, as a rule, above 10 Hz. Where they were too low, subsequent upgrading was required. For each of these components, observance of the permissible stress levels for the safe shutdown earthquake load case had to be demonstrated.

For the reactor vessel and the guard vessel, stresses were demonstrated to be within the permissible boundaries in an earthquake; no upgrading measures were therefore required. This also applied to the main sodium pumps.[112]

The sodium intermediate heat exchanger constituted the containment boundary, which meant that particular requirements had to be met in demonstrating its seismic stability. Because of mass distributions and the physical arrangement, no shock absorbers could be used in upgrading the sodium intermediate heat exchanger. Instead, the existing support structures and their couplings had to be improved. Because of cramped space conditions, the components had to be dismantled into small units for backfitting and assembly. These measures finally resulted in vibrational modes above 13 Hz in the sodium intermediate heat exchanger.

The seismic design of the steam generator was extremely difficult to achieve because of the special design features of this component. The meandering bent double tubes of the two steam generators were supported on the double bottom of the housing; the headers proper were elastically supported for thermal movement. The steam generator housing, in turn, rested on struts to ensure heat removal by natural circulation. The seismic qualities of the steam generator coils were demonstrated in the United States with the assistance of a specialist team from the Hanford Engineering Development Laboratory (HEDL). In principle, it boiled down to a clever attachment of the topmost pipes.

A sophisticated finite element model had to be established for dynamic analysis of the steam generator housing with the depressurization systems. The required rigid building structure necessitated extensive backfitting measures. Among other things, a rigid three-dimensional framework structure had to be installed to transmit forces only to the corners of the building. However, these measures, and others, finally raised the vibration mode of the building to a level above 9 Hz.

2.2.4 Fuel Handling and Spent Fuel Management

Handling the hexagonal fuel elements of KNK II required modifications to be made to the transport facilities of KNK I, as KNK I fuel elements had had round contours. The conveyor-type lifting systems used, in which flat steel conveyors had acted as lifting elements, did not reliably provide the necessary angular positioning capability for the elements. In addition, swelling of the wrapper tubes in KNK II required higher tensile and compression forces to be exerted in handling.[113]

In the light of these considerations, the conveyor-type lifting systems so far used were abandoned in favor of a new shuffling unit, a machine with a rod-actuated lifting system able to push and pull the fuel elements. It moved elements in the reactor vessel between a fixed orientating position and the core position to be approached.

Also storage of the fuel elements had to be modified. The so-called wet store, i. e. the fuel element store under sodium, was designed so as to accommodate a complete core load of fuel elements and absorber elements. This required a new storage drum to be designed, which had to be adapted to the dimensions of the fuel elements. Permanently installed absorbers ensured subcriticality under all loading conditions.

A dry store was planned for the fuel elements not yet irradiated, in which these elements could be stored under criticality-safe conditions. To make the fuel zone accessible for nuclear safeguards inspections, the sidewalls of the so-called fuel element wardrobes had to be designed as fold-down walkways.

In the area of disposal, the Atomic Energy Act as amended in 1976 included obligations for waste management provisions. An excerpt from Sec. 9a reads as follows:

> *"Any person who constructs, operates, otherwise holds, materially alters, closes or disposes of installations within which nuclear fuels are handled, ... shall ensure that resulting radioactive by-products... are used in a safe way... or, to the extent that this is not possible at the current state of the art, is not meaningful economically,... are properly disposed of as radioactive waste..."*

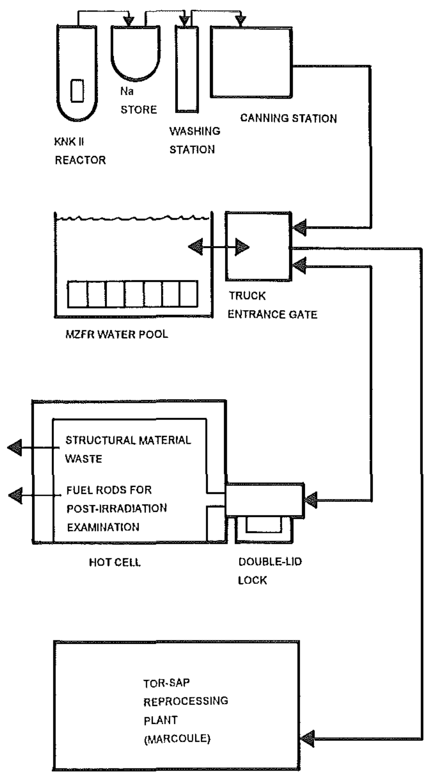
A number of aspects had to be taken into account in the disposal of KNK II in which KNK II fuel elements differed from typical light water reactor fuel elements:

(1) The elements contained highly enriched uranium, and those of the test zone in addition contained 30 per cent by weight of plutonium.

(2) The target burnup of the elements was between 30,000 and 80,000 MWd/t, which was considerably higher than the LWR burnups at that time (approx. 30 - 40,000 MWd/t).

(3) After the elements had been unloaded from the reactor, sodium adhered to them, and they had to be taken through special washing and drying steps.

(4) Before they were delivered to the reprocessing plant, fuel element bundles had to be dismantled, as the reprocessing companies accepted only fuel rods. This "singulization" could only be carried out in hot cells.[114]



Management and disposal of KNK II fuel elements (state as of 1975).

Under the spent fuel management plans, the fuel elements unloaded from the reactor were to be transferred into a sodium-cooled fuel element store inside the containment. After a cooling phase of several months, the length of which depended on burnup, they were to be stripped of any adherent sodium in a sodium washing plant. Then they were to be encapsulated and transported into the existing storage pool of the MZFR Multipurpose Research Reactor on the KfK premises and stored there for a period of 6 - 12 months. The final stage was to be the Hot Cells, where the elements were to be singulized and prepared for shipment to the French reprocessing plant at Marcoule.

The sodium washing plant for spent fuel elements was a new system on the spent fuel management pathway. The fuel element to be washed was to be inerted in a container and cleaned of any adherent sodium by means of slightly superheated steam. The hydrogen thus produced in the offgas had to be monitored carefully. Finally, the fuel element was to be dipped into fully demineralized water and dried with nitrogen.

2.3 The Licensing Procedure

2.3.1 The Public Inquiry under the Atomic Energy Act

As a consequence of the decision by the licensing authority in Stuttgart to treat the conversion of KNK I to KNK II like the construction of a new plant, a public inquiry had to be held. The licensing application together with the usual documents, such as the safety report and expert opinions, therefore was laid open for public inspection at the office of the mayor at Eggenstein-Leopoldshafen and with the licensing authority in Stuttgart in the summer of 1973. Within the official period for registering objections, 22 persons and three associations filed objections. Remarkably enough, all opponents - in some cases, several members of the same family - came from Karlsruhe and the immediate vicinity; the phenomenon of "long-distance opponents" or professional traveling "NPP opponents" did not exist at that time. The most prominent of the three associations was the so-called Rheintal-Aktion (Rhine Valley Campaign) led by Helmut Wüstenhagen, one of the earliest nuclear power opponents, who disappeared from the nuclear scene rather abruptly in the late seventies.

The hearing was organized at the Nuclear Engineering School of the Karlsruhe Nuclear Research Center on September 4, 1973. Very few of the opponents, and quite a large number of visitors and discussants, turned up. Contrary to later practice, almost all of them were admitted and allowed to ask questions *ad hoc*. Most of the questions were about the "hazardous nature" of sodium and the proximity of the nearest village, Leopoldshafen, to the site of the power plant. Fortunately, the Nuclear Engineering School had a scale model which allowed everybody to handle liquid sodium and, in this way, obtain a visual impression of this substance whose surface gleamed like water.

The written objections were dealt with separately and emphasized again in the permit issued later. They concentrated on four points: the hazards associated with plutonium; the accident in the U.S. Enrico Fermi reactor; the fire in the U.S. Rocky Flats plant; and the recent ruling on fast breeders by a U.S. court of appeals. Remarkably enough, all these objections were based on foreign critics; at that time, there were no German eco-institutes formulating objections of their own.

Also in the objection concentrating on the hazards inherent in plutonium, an external expert was quoted, the Frenchman, G. L. Verot, who had estimated in the "Energie Nucléaire" journal that an annual 20 - 100 kg of plutonium would escape into the environment annually by the turn of the millennium. However, his assessment had been based on outdated process techniques; it was easy to show that the improved methods of chemical precipitation, ion exchange, and evaporation available now and in the immediate future would achieve much higher decontamination factors.

The accident in the Enrico Fermi reactor on October 5, 1966 was caused by a zirconium baffle below the core coming off and subsequently blocking part of the coolant flow. This caused incipient melting in two fuel elements without giving rise to any major radioactive pollution of the environment. However, the plant was decommissioned later, mainly for economic reasons, and has since served as one of the pet examples quoted by nuclear opponents to prove their point against breeder technology.

At the Rocky Flats plant of the USAEC, self-ignition of plutonium waste occurred in May 1969; it contaminated various buildings by way of the ventilation system. The cause of the defect was never disclosed in any detail, as Rocky Flats was a classified nuclear weapon plant.

The decision by the U.S. court of appeals, finally, for the first time required that the USAEC present an environmental protection report on the American fast breeder program; this was a far cry from the rejection of breeder reactors by a court of law, which opponents had cited.

By and large, the public inquiry proceeded very smoothly. After arguments had been exchanged for a few hours, the Chairman, Mr. Blickle of the State Ministry of Economics in Stuttgart, was able to close the proceedings.

2.3.2 Expert Opinions and Permits

The feasibility study in 1968 and the subsequent positive recommendations expressed by the American NUS company and a few KfK institutes were the preconditions under which planning work on KNK II could be continued. All these efforts converged in a three-volume preliminary safety report submitted to the State Ministry of Economics in Stuttgart as the leading licensing authority in June 1970, together with the application for a permit under the Atomic Energy Act. Following the decision by that authority to the effect that the conversion of KNK I to KNK II constituted a major change, a second, revised, safety report was submitted in 1972. In November 1972, the Baden Technical Inspectorate submitted its expert opinion on the site and the plant concept; it contained the respectable number of 230 conditions imposed, comprising conditions in the expert opinion and the documents called for. After five subcommittee and three full-committee meetings, also the German Advisory Committee on Reactor Safeguards (RSK) in January 1973 expressed its positive vote on the conversion of KNK.

However, the first partial construction permit did not materialize for a long time yet. First, a considerable part of the conditions expressed in the expert opinions on the site and the design concept had to be worked on, the documents had to be disclosed for public inspection, the public inquiry had to be conducted and, above all, the expert opinion on construction had to be obtained from the Baden Technical Inspec-

Escalating licensing requirements under the Atomic Energy Act in the period 1960-75. Michael M., 3, holds the filing documents for the FR 2 under his right arm; the stack on the left are the corresponding documents for KNK I/II.

torate. It arrived in the spring of 1975, again containing more than 200 conditions, but otherwise was very positive. On May 2, 1975, the 1st Partial Construction Permit was issued.[115]

Conversion proper of KNK, i. e. installation of the new systems and components, proceeded on the basis of other partial permits. The entire KNK II conversion volume required two partial construction permits with seven amendments, which were obtained between May 1975 and June 1977. The 3rd Partial Construction Permit, under which the old KNK I plant was to be incorporated in KNK II and the combination of old and new plant components had to be licensed, created particularly difficult formal problems. This was due to the different documentation standards of the two plants as a consequence of the different times at which they had been built.

The 1st Partial Operating Permit for KNK II operation was filed for already in the spring of 1976; it covered the storage and handling concept. The permit was issued in May 1977 and included a number of very sophisticated physical protection measures for the Pu elements. The 2nd Partial Operating Permit, which related to zero-power operation, bore the date of September 30, 1977. On the basis of a third, revised, safety report, KNK II operation at the rated power was finally permitted under the Atomic Energy Act in March 1978.

The KNK II licensing procedure was quite expensive. The three applicants, KfK, KBG, and Interatom, remained in continuous contact with the State Ministry of Economics in Stuttgart as the licensing authority proper, and with the State Ministry for Labor, Health, and Social Order (supervisory authority), the State Ministry of the Interior, and the Federal Ministry of the Interior in matters pertaining to the Advisory Committee on Reactor Safeguards (RSK). The leading expert consultant was the Baden Technical Inspectorate assisted by its sister organizations, the Rhineland Technical Inspectorate, the Stuttgart and the Palatine Technical Inspectorates, and GRS for special matters. Occasionally, sixty specialists were involved in passing expert opinions on KNK II. In the line of "conventional" authorities and offices, the Karlsruhe Testing Agency for Structural Building Stability must be mentioned here as one of the institutions required to examine most of the seismic measures taken. The State Criminal Investigation Department in Stuttgart checked the measures of protection against sabotage and terrorism, thus introducing a slightly unusual touch into the project management activities.

A few statistical figures perhaps can convey an impression of the expenditures involved in the KNK II licensing procedure. The KNK II plant was described in three safety reports to different degrees of detail, each report consisting of three volumes. The three bulky expert opinions by the Technical Inpectorates based on those reports contained nearly 600 conditions, which had to be met by the commissioning date of 1977. For this purpose, the applicants submitted additional documents, which accumulated to a stack approximately 7 m high. The documentation of the whole plant ran into approximately 100 meters of file cases. Between 1972 and 1977, some 1500 safety-related meetings were held, roughly 200 of these at project management level.

2.3.3 Specification and Documentation

In the licensing procedure under the Atomic Energy Act, all components and systems must be described as planned and laid down in specifications. Subsequently, the documentation must prove how the plant was built in actual fact. Consequently, the specifications indicate what the plant is to be like, while the documentation records what it really is.[116]

Also in this area, the state of the art had progressed so much between 1965 and 1975 that it was impossible to simply transfer to KNK II the specifications and documentations of the old KNK I plant without modification. Instead, the licensing authority requested the expert consultant to examine in detail all KNK I specifications as to their usability for KNK II. In a time consuming, costly procedure running into several million DM, all specifications of the old plant were checked for consistency with the conditions imposed upon the new plant by the Technical Inspectorate and "upgraded" in a so-called "Index 10 Procedure." Changes of specifications in the middle of an ongoing, sometimes even completed, manufacturing process were particularly expensive and frequently resulted in delays. Many existing systems and components achieved a higher safety-related importance in KNK II; for this reason, the new "supplementary specification" category came into being.[117,118]

In order to find even a relatively clear classification of the large number of specifications, the "specification family" category was agreed upon with the supervisory authority. The term meant the summary of all detailed specifications drafted at various points in time (KNK I, KNK II) to describe the plans for the same plant component. For KNK II, there were 163 specification families for the mechanical sector, 50 for the electrical engineering sector, and some of these had ten family members.

A similar amount of red tape prevailed in documentation. In this sector, a distinction was made between old and new documentations, depending on whether documents referred to KNK I or KNK II. For all components in KNK II, there was a supplementary documentation which the respective part carried through all manufacturing stages. In principle, manufacturing a component was allowed to be started only after all documents examined by the Technical Inspectorate had become available. In the acceptance procedure, the manufacturer, operator, and the expert consultant had to indicate their clearance on the same sheet of paper. For valid reasons, Karlsruhe did not accept any component for storage on site which did not bear these three signatures.[119]

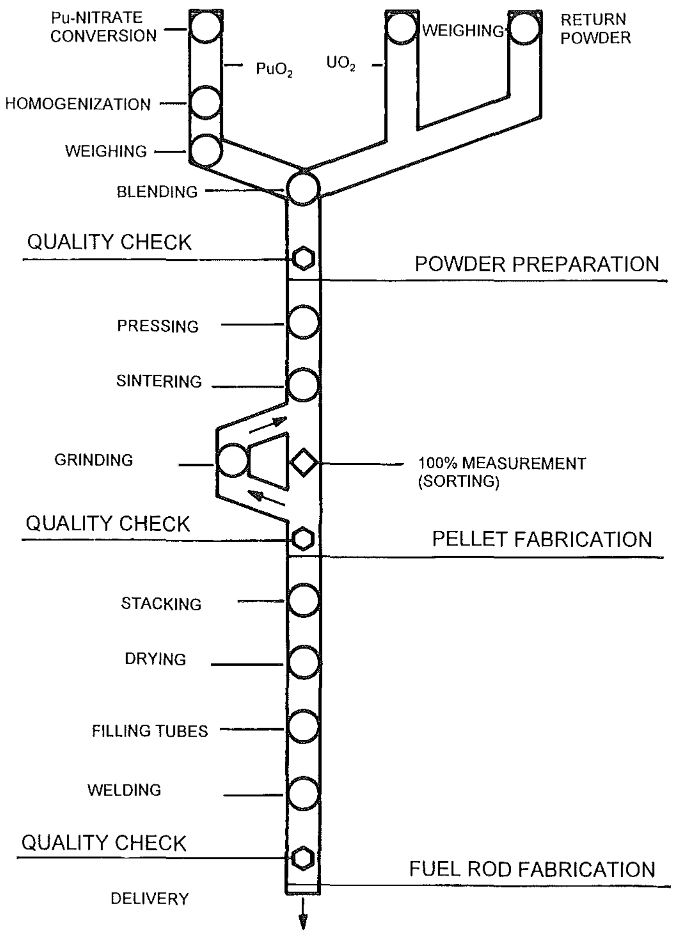
2.4 Experience in the Conversion of KNK I into KNK II

2.4.1 Problems in Sourcing and Manufacture

Purchasing the components and systems for KNK II frequently suffered from difficulties in finding suitable sources. This problem was caused by the extremely stringent quality and acceptance requirements under the Atomic Energy Act. As a consequence, prices often were several factors higher than those of comparable conventional components, merely because of the extreme requirements imposed by the Technical Inspectorates. However, as numerous companies which had been asked were unable, or unwilling, to meet the stringent quality requirements - also against the background of a booming economy - many of them simply submitted no tenders or quoted prices so high that it would have been impossible to award them a contract.[120]

In order to be able to buy some important KNK II components at all at reasonable prices and deadlines, collective orders occasionally were placed together with components for the larger SNR 300 reactor. But in the case of some components even this junctim - either deliveries for SNR *and* KNK II or no contract for SNR - failed, thus requiring top management level discussions to be initiated in order to motivate potential suppliers to quote at acceptable conditions.

In some instances, vendors overestimated their technical capability and then had to be supported by Interatom to such an extent that they were finally able to produce components ready for installation. The first contracts placed for KNK thus had a certain teaching function for subsequent contracts placed by the SNR 300 consortium. One example to be mentioned here is the complicated manufacture of the structural parts for the fuel elements. (No mention shall be made of those companies which initially had tried in vain to manufacture them.)



Flowsheet of KNK II fuel rod fabrication.

Problems in many areas were created also by the fabrication of the mixed oxide fuel rods for the test zone. The contract awarded to Alkem in Hanau comprised some 2000 PuO_2-UO_2 rods. Alkem so far had manufactured only 200 rods of that type for irradiation purposes. The mere step of scaling up to a much bigger lot seemed to invite difficulties. (Incidentally, 20,000 rods had to be produced for the SNR 300.)

The first bad surprise encountered was the susceptibility to cracks of the high-temperature austenitic cladding tubes, when the end caps were welded in place. Welding to specifications succeeded only after initiation and extinction of the arc had been moved into the solid material of the end plug. Developing the new welding technique took almost six months.[121,122]

Problems were created also by the plutonium delivered, which came from highly burnt-up light water reactor elements. As a consequence of the unexpectedly long manufacturing campaign it became highly enriched in americium 141, thus causing a radiation protection problem when handled in the gloveboxes. Additional shielding and more frequent switches of personnel had to be planned for. In addition, the relatively high plutonium content of 30% affected the strictly specified oxygen/metal ratio and hydrogen adsorption in such a negative way that a number of lots had to be discarded.[123]

This playing around with small fabrication lots led to a situation in early 1976 in which all the enriched uranium had been used up. Until that time, ordering uranium in the U.S. had been easy, something to be settled almost by postcard. This changed with the anti-proliferation policy adopted by the new U.S. President Jimmy Carter. It had an impact even on KNK II, for 8.8 kg of highly enriched uranium, which had been ordered and were needed urgently, were not cleared for export. Only after the German Ministry for Foreign Affairs had intervened, the competent U.S. Atomic Energy Commission was willing to organize a hearing. That hearing was held at the Argonne National Laboratory (ANL) in the summer of 1977; for several hours, the German customers were interrogated in great detail about the causes of the increased quantities in fuel rod manufacturing. More than one question touched upon trade secrets, but the German representatives (Dr. Tebbert, the author) could not afford to "skirt" such questions, for the consequence would have been non-delivery of the material. That experience with a monopoly holder makes the cliché of "self sufficiency" appear in a much more understandable light.[124]

The lack of source material for the fuel rods seriously jeopardized the KNK II project. After many futile attempts to purchase the material elsewhere, the number of standby elements had to be reduced in the end. In addition, Alkem, in intense efforts, successfully developed a technique of dry reprocessing and reuse of the uranium scrap which had arisen in the production process. After that process had become ready for use, the Americans granted clearance to export the uranium ordered. Whether this was just a coincidence, we will never know.

2.4.2 Assembly under Difficult Circumstances

The KNK I plant was shut down in September 1974 for preparation for conversion. Assembly work for conversion could not yet be started, as the required permit was expected to come forth not before the next year.

The main activities in the preparatory phase were concerned with the removal of the KNK I core. The fuel elements were taken to the French SAP facility at Marcoule for reprocessing.[125] Surprisingly, to the French experts, disassembling the bundles in the hot cells at Marcoule turned out to be more difficult than assumed. (The extra cost charged had to be refused nonetheless, as a fixed price had been agreed upon.) Also the other core internals, such as absorbers, moderators, and reflector elements, were washed to remove all traces of sodium, and passed to the KfK collection point for scrapping. Some of the major steps included the removal of the KNK I drum for the fuel element wet store under argon as a cover gas. It had become necessary because of the hexagonal contour of the KNK II fuel elements. Finally, mention should also be made of the replacement of the tops of the sodium main isolating valves; this step was carried out by the KBG operating crew, incidentally under extremely cramped space conditions in the primary cell.[126]

The 1st Partial Construction Permit for the conversion into KNK II arrived on May 2, 1975. As customarily happens with first permits, it was of the more conceptual type ("blank permit"). The actual conversion volume was determined in two amendments, which came in July and October of the same year. Now, conversion of the KNK plant could be started for good.

Under the permits referred to above, also the stores for fresh and spent fuel elements and the moderator store were installed. Moreover, the emergency cooling system with the component loop and the penetration through the containment had been licensed together with most of the instrumentation and reactor protection systems. Also the large area of handling, with the fuel handling machine and the shuffling device, could now be addressed.

These conversion activities going on side by side, and the continued operating steps, such as in-service inspections, handling, repair, and maintenance, necessitated close harmonization between the responsible KNK operator, KBG, and the responsible KNK II vendor, Interatom. In order to ensure the safety both of the plant and of the work conducted, some conditions specific to KNK had to be observed:

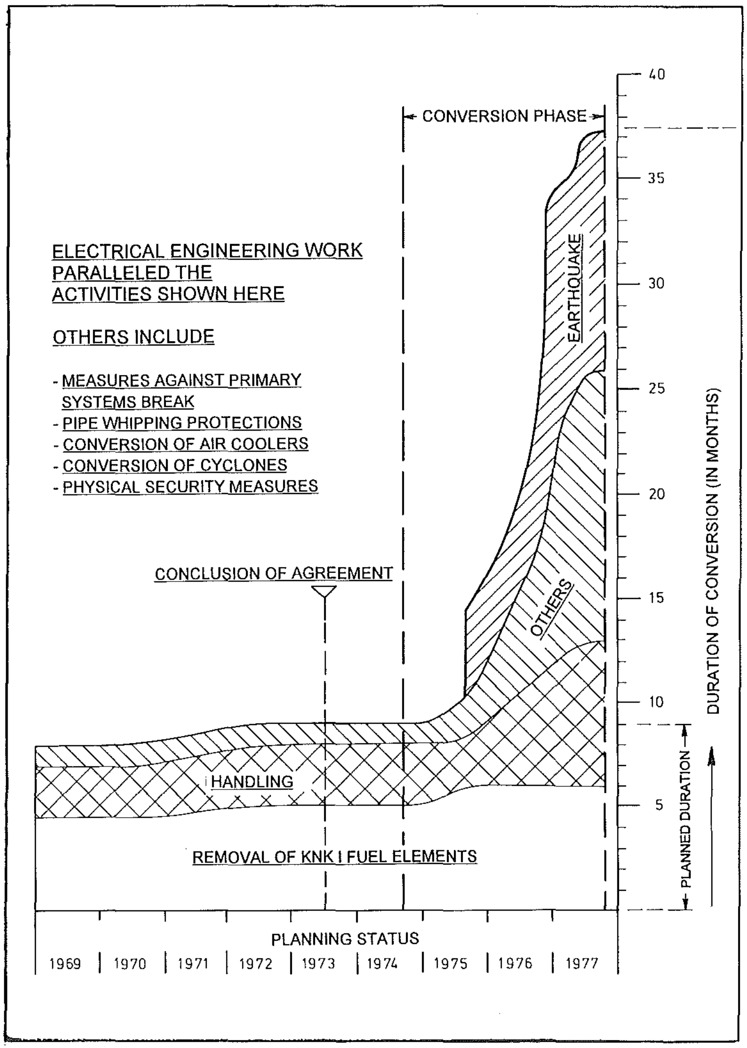
(1) A reactor plant which had been in operation and accumulated a correspondingly high activity inventory was to be converted; radiological monitoring of the personnel had to be ensured, and personnel exposure had to be minimized.

(2) Given the large number of simultaneous conversion and examination activities, there was a possibility of mutual interference; not all systems converted could be shut down at the same time.

(3) Many activities, especially those in the primary cells, had to be carried out under extreme conditions, both with respect to cramped space and the temperatures prevailing (40 - 50 °C).

Günter Finke, for many years KNK Plant Operations Manager, introduced a job clearance procedure which allowed the KNK II conversion to be conducted efficiently and without any accident. A draft directive for maintenance and backfitting activities in nuclear power plants later issued by the German Federal Ministry of the Interior (BMI) incorporated major parts of the KNK I job clearance procedure.[127]

However, the most difficult conversion measures had yet to be taken: upgrading the plant against seismic effects. These measures were not to be cleared until the 2nd Partial Construction Permit in February 1976 and one of its amendments of June 1976, respectively. The immense scope of this step could not have been foreseen. Merely detuning the frequency of the steam generator casing, together with the penetrations through the floor bottom troughs, the roof cover, and electrical assembly work, implied an expenditure of approx. 10 man-years and the use of 30,000 kg of steel. The heat transfer system required not only bracing of a large number of components, but also 34 seismic energy absorbers to be installed. In quite a number of places, the compact design of the plant did not allow these absorbers to be installed easily. Specific dynamic points derived in a theoretical systems analysis frequently were impossible to comply with in reality, or only after extensive dismantling of existing components.



Planning and execution of the conversion of KNK I to KNK II.

Solutions required numerous iterations to be made in analysis, design, and feasibility checks. This necessitated close cooperation among the designers at Bensberg and the crew on site in Karlsruhe. Even placing dowels for the installation of seismic energy absorbers and struts caused problems, for the official rules applied only to concrete with undamaged reinforcement. Very frequently, the drills hit reinforcing bars, which meant that the standardized distances between dowels could not be maintained; consequently, special permits had to be applied for on the basis of an approved change in specification, or a brand new design had to be developed.

Also installing the shutdown systems was permitted at a relatively late point in time, namely in the 5th amendment of May 1977. The functional reliability of these systems first had to be demonstrated in an extensive experimental program. A prototype had to undergo lengthy tests both in water and in sodium. The sodium tests had to be conducted under conditions very much like those prevailing in a reactor. The prototype of the primary shutdown system was to survive 2000 scrams, 2800 complete double strokes, and 1,400,000 standard strokes, which had to be demonstrated in subsequent wear studies.[128]

Because of the increasing demands made on specification and documentation, in upgrading against seismic effects, and the measures of physical security, which will not be discussed in this paper, both the timetable and personnel planning had to be revised thoroughly several times between 1975 and 1977. In all these areas, the number of personnel should have been increased as soon as possible, but this was not easy to achieve, as this requirement conflicted with the long-term personnel planning of the vendor, Interatom, for the SNR 300. This created special problems for the KNK II project management at Interatom; the responsible Chief Project Manager, Elmar Guthmann, and his committed Project Leaders, Hubert Andrae and Peter Romeike, finally produced a workable solution, also thanks to the competent work of Gerhard Hendl, who returned to KNK as Chief Construction Supervisor. Short-term delegations from the SNR sector allowed up to 200 persons to be engaged in conversion and operations jobs at KfK for brief periods of time. It frequently happened that the Interatom project managements for KNK and the Kalkar SNR 300 fought violently for the best breeder engineers within the company. As the success of these efforts mostly became visible first in KNK, a KNK team developed at Interatom which was characterized by its special team spirit and devotion to the Karlsruhe project, led by its mentor, Dr. Mausbeck.[129,130]

In retrospect, it is safe to say that the phase of converting KNK I to KNK II, which had been planned for only nine months, was absolutely too short. It finally extended over two years, from the autumn of 1975 to the autumn of 1977. Within that period of just two years, enormous achievements were made. Against the background of increasingly tighter criteria in the nuclear field, and in view of the standard put up by the large SNR 300 plant, an existing thermal plant no longer fully accessible in all its parts was converted into a fast experimental breeder.

The team who made it possible must be commended on their performance.

2.4.3 The Project Meetings

The three contracting partners, KfK (initially, GfK/VA), Interatom, and KBG, together worked on the KNK project for 26 years, between 1965 and 1991. Frequently, they were the joint holders of the permit under the Atomic Energy Act; they always had to play their roles as builders and owners, designers and vendors, and as operators of the plant. Frequent discussions were held over these many years, but none of them so influenced project management as the so-called project meetings. They constituted the common table around which KfK, Interatom, and KBG met every two or three weeks in order to analyze the project status and determine the next steps to be taken. As the author was chairman of that body for twenty years and, in those years, saw many participants come and go, he would like to address also some human aspects.

The project meeting was always held in the same room, the so-called OBL Hut, which was situated in the KNK area on the premises of the Nuclear Research Center. Preparations for the meeting could be sensed roughly one week in advance especially by a drastic increase in telephone calls, from which conclusions could be drawn about persons commissioned by KfK or KBG, preferably Interatom, who were deeply involved in this, that or the other "action items" of the previous meeting they had been assigned as their homework. At the same time, the agenda of the coming meeting was prepared, for which Interatom had to collect proposals. At this point, at the latest, the trend for the meeting to come was evident. In addition to the unavoidable project topics, it was always attempted to also put items on the agenda which allowed certain parties to make effective sales pitches, or which allowed the buck to be passed to some other party, not too obviously, of course. A tempestuous meeting was to be expected when one of the parties, often KBG, did not even try to word its agenda item in a neutral way. In such cases, the item did not read "problems with valve tops," but quite bluntly "maldesign of the valve tops by Interatom."

The project meetings began at 9 a.m.; participants from Interatom mostly arrived thirty minutes earlier in order to hear from their Chief Construction Supervisor delegated to KfK about the most recent events in the plant and, in particular, to sense the "mood." The seating arrangements in the meeting room were defined precisely; nobody would have dared to usurp somebody else's accustomed seat. On the left, as seen from the door, were the seats of KBG, on the right those of Interatom; at the top sat Dr. Brudermüller and the author. One always faced the same person (adversary). Invited experts had to move to the bottom end of the table in the relatively crammed space; in those years, smokers of any kind were not yet suppressed. Officers, such as heads of operation or project managers, were required to attend *ex officio*, otherwise, the three parties were free in selecting their participants. Those in the know about these events immediately concluded from vacancies or from new arrivals who had fallen in disgrace or who was about to rise. Especially for the plant crew of KBG it was an honor to be invited to a project meeting.

After the preliminary remarks at the beginning of the meeting, traditionally the Operations Manager of KBG, Mr. Finke, had to deliver the operations report. He often went into great detail, relying on memoranda by his staff whose handwriting he occasionally had reason to complain about. This was followed by the discussion of topical points for which a presenter, frequently a guest from Bensberg, mostly had been nominated in advance. The ensuing debate, as a rule, was held only by the "old campaigners," in the case of KBG, Dr. Brudermüller and Mr. Finke, in addition to the group leaders (Messrs. Reuter, Zimmermann, Dr. Richard); on the side of Interatom, it was the project leaders (Dr. Höchel, Messrs. Guthmann, Andrae, Romeike), and Dr. Mausbeck, who had an immense knowledge of sodium technology and was held in high esteem as "Mr. Interatom." On the side of KfK, it was particularly Mr. Schnetgöke, who was competent in many subjects of contract management, and, *ex officio*, it was the author as chairman of the discussion. Occasionally also Mr. Griesenbach, the commercial expert, asked for the floor from the side of the Interatom section. He must have memorized the complete list of all contractual deliveries and performances to be made by his company, for whenever he seemed to feel that some additional item or service was being asked for, he mentioned extra costs, just for the record and to be on the safe side. Also as a matter of principle, the customer immediately and expressly contradicted such claims, also for the record.

It is safe to say that every technical subject of any importance appeared on the agenda of the (300) KNK project meetings at least once, if not more often. Some of these topics stayed there for years, such as the problem items, gas bubbles and control rod actuating equipment. The participants fully well realized that they bore responsibility for the project, each in his area, and had to come to grips with the problems themselves. This probably caused a kind of group dynamics process to be initiated of full commitment and active participation, which also fostered active enthusiasm for the job.

Some entertainment value, especially for the silent participants in the project meetings, was provided by occasional disputes, even arguments. They followed a clear ranking order. Minor skirmishes with Interatom were nothing extraordinary; the representatives of industry were accustomed to being attacked a bit more forcefully; probably, it was all included in the price. The discussions within KBG were listened to with slightly more amusement. However, some participants seemed to reach the peak of enjoyment when the two top ranking representatives of the customer (Dr. Brudermüller and the author) got into arguments. True, it did not happen too frequently, but happen it did. For the rest, the healthy regional mix around the table, which included Berliners (Finke), people from the Rhine region and Franconia (Dr. Mausbeck), Swabians (Dr. Brudermüller), and Bavarians (author), ensured that no bad mood persisted for a very long time.

Expert and connoisseur alike:
Project Manager Gregor Schnetgöke, KfK.

In most cases, the participants in the project meeting had had their say by 1 p.m.; all criticism and frustration had been expressed, and homework for the next few weeks had been assigned. The unanimous decision then taken was to have lunch. As it was a bit late for the canteen of KfK, whose qualities were known and esteemed, the group mostly opted for the Kärcherhalle restaurant in Weingarten. A drink helped to release the tensions which had accumulated over the previous hours; the most important project agreements were reconfirmed over steak, and desserts smoothed the discussions of some easier topics, such as the best organization to be found for the Siemens group, or whom the Federal Chancellor should appoint the next Minister for Research. After characteristic follow-ups to dessert (Mausbeck: a Brazil cigar; Höchel: brandy; Romeike: an extra large helping of vanilla ice with cream) the group members went their respective ways.

They met again for the next project meeting three weeks later.

This procedure took place exactly three hundred times.[131]

3. Operation with the KNK II First Core

The conversion of KfK was a turbulent phase straining participants to the limits of their ability. The large number of conditions imposed in the licensing procedure could not have been foreseen, and it was sometimes very difficult, and took a lot of engineering skills, to implement them in an existing plant. Quite a number of these requirements were "duplicates" of conditions imposed on the SNR 300, whose construction at Kalkar had begun in the spring of 1973. Karlsruhe felt like being in a competition with the "big brother," for the Federal Ministry for Research had ordered that KNK II was to be commissioned at least three or four years prior to the SNR 300. As the contracts provided for a commissioning date of the SNR 300 in 1979, KNK II should have been started up by 1976 at the latest. However, that was beside the point, as seismic protection measures were still in full swing in that year, and commissioning the plant was absolutely out of the question before the end of 1977.

But soon things began to go wrong also in Kalkar. After a speedy start, the project began to slow down in 1975/76 because the demonstrations of the vessel support beams demanded by the licensing authority were not produced in time. The reason for the requirement was the famous, or rather infamous, Bethe-Tait accident, which was to make life difficult for the SNR 300 also in subsequent years. After 1978, the Kalkar project almost came to a complete standstill because it was the subject of investigation by a Committee of Inquiry of the German Federal Parliament for nearly four years, during which period the authorities no longer issued any substantial construction permits.[132]

Thanks to these massive project delays in Kalkar which, as is well known, were never recouped, KNK II never again ran the risk of being overtaken by the SNR 300 in terms of time.

Perhaps it should be added that this was a pity.

3.1 Operation up to Peak Burnup

3.1.1 Commissioning the Fast Core

As far as was possible under the conditions of conversion, the primary sodium systems in KNK II were continuously maintained in the recirculation mode to keep up the desired purity of the sodium. The secondary systems had largely been drained for the attachment of seismic energy absorbers, and were kept under the pressure of an inert gas. Despite the many activities in the reactor area, the radiation protection record for the plant crew was very positive. The average exposure dose per person in 1977 amounted only to 41 mrem, which was roughly 10% of the levels normally sustained in spas in the Black Forest and Fichtelgebirge mountains as a natural background.

Commissioning KNK II was begun with trial handling of fuel element dummies and extensive functional testing of the refueling machine and the reshuffling system. After these preparatory jobs had been completed, the external round and hexagonal reflector elements were loaded into the core. In May 1977, the authority issued the 1st Partial Operating Permit for putting the nuclear fuel into the interim store of KNK II.[133]

Zero Power Operation

The 2nd Partial Operating Permit, so eagerly waited for, was issued on September 30, 1977. It finally allowed nuclear commissioning of the plant at a very low power level, the so-called zero power operation. All necessary preparations had been made, and it came as no surprise that this measuring campaign, which comprised the buildup of the critical minimum loading, loading up to the target, calibration of the shutdown systems, and assessment of the reactivity coefficients, took only six weeks.[134]

To reach the critical minimum load, the blanket and the seven UO_2/PuO_2 fuel elements were loaded in the first step. In an additional four steps, unmoderated as well as moderated UO_2 elements were added. Extrapolation of the final loading step indicated a critical minimum load of 20.6 fuel elements. A compliment should be paid to the reactor physicists of Interatom, who had estimated 20 $\pm$ 1 elements in their advance calculations. KNK II went critical for the first time on October 10, 1977; one week later, also the target core with 29 fuel elements had been built up.

The following program of measurements for rod calibration served to demonstrate the availability of sufficient shutdown reactivity in the two shutdown systems. Different measuring techniques were employed to determine this reactivity, e.g., the compensation method and the fast rod insertion method. Of course, corrections had to be applied because of the flux deformations caused by movements of the absorber rods and their interactions. Again, the measured data were in good agreement with the nominal design levels.

Determining the reactivity coefficients completed the program of measurements for the zero power campaign. For the isothermal temperature coefficient, the sodium temperature was increased in steps, and the reactivity loss created in this way was measured by the reactimeter. For measurement of the negative void coefficients, the sodium had to be drained into the dump tank step by step from the operating level onward. The results for these coefficients also were in good agreement with precalculated values; only one flow coefficient initially was an outlier.[135]

Power Operation

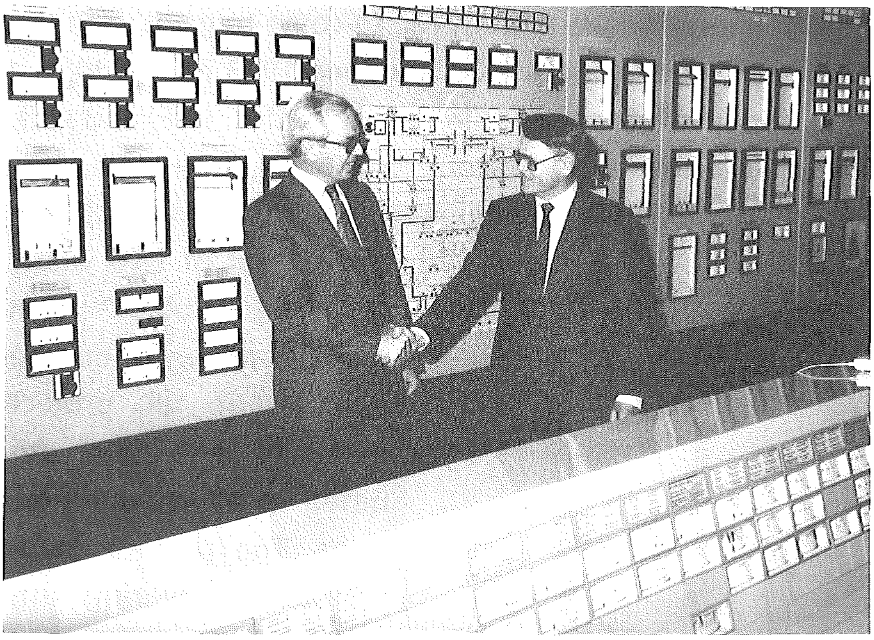
After several weeks of high-temperature cleanup at 400°C the plant was ready for power operation in early 1978. However, it took until late March for the permit covering operation at a maximum of 40% of the design power to come forth. The reactor power was increased in small preset steps, the full enthalpy rise of 160°C was built up across the reactor core, and only one month later KNK II generated electricity and was connected to the Badenwerk power grid for several weeks without any problem.[136,137]

In August 1978, the 3rd Partial Operating Permit was achieved, which covered operation up to 100% of the rated power. Increasing the power had become almost a routine event, but at 60% of the rated power an unforeseen event occurred: the plant was shut down automatically by an unscheduled scram activated by the "negative reactivity high" limit. That limit had been set to -7.3 cents and was monitored by three reactimeters each in the primary and secondary shutdown systems. In KNK II safety philosophy, the underlying idea was protection against losses of coolant flow and the detection of boiling events.

These scrams occurred repeatedly and caused extensive thinking and actions by the three contracting parties. A more detailed description will be given in the next section.

Very soon it was possible to exclude the occurrence of boiling processes with bubble formation in the core. Instead, the experts rightly thought of entrained bubbles of the argon cover gas, which caused negative step changes in reactivity when passing through the core. After a degassing line had been found to be the main cause, and corrections had been made, KNK II was restarted and kept in operation at more than 60% power. In this way, full power was reached for the first time on March 3, 1979; on November 6, 1980, after the gas bubble problem had been solved, the plant was delivered by Interatom to KfK, and KfK charged KBG with the responsibility for plant operation.

The first fast breeder reactor in the Federal Republic of Germany had been commissioned.



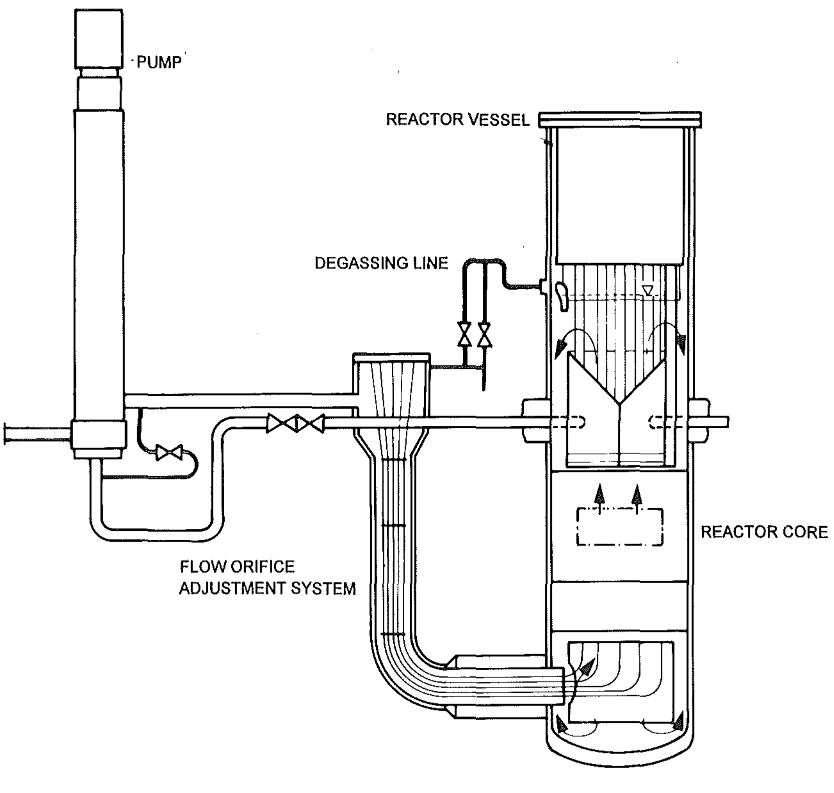
KNK is delivered in the control room (from left):
Dr. Mausbeck (Interatom), the author (KfK).

3.1.2 Problems with Gas Bubbles

The gas bubbles passing through KNK II created quite a stir in the media. The daily newscast on the first TV channel (ARD) on January 16, 1979 reported that KNK II "had failed temporarily in December." FDP Member of Parliament Hölscher even addressed a widely disseminated query to the Federal Government "about severe defects in the KNK experimental reactor and uncontrollable changes in criticality," and the untiring breeder critic Kurt Rudzinski, finally, devoted a long article to this event in the "Frankfurter Allgemeine Zeitung" under the headline, "The Accident at the Karlsruhe Experimental Breeder Reactor."[138]

The reason for the sudden interest of nuclear critics and the journalists associated with them was evident. In faraway Bonn, the Committee of Inquiry mentioned above was looking into the events initiating a potential core meltdown in a breeder reactor, and the gas bubbles in KNK II fitted this scenario very nicely. Extrapolated to the larger SNR 300, they would have caused positive reactivity step increases in that plant and, consequently, not initiated harmless scrams, as in KNK II, but power increases and, potentially, meltdown of the fuel elements. Although Dr. Helmut Hübel, the renowned safety expert of Interatom, called these conjectures absurd, also by referring to the relatively small amount of gas, and to the gas bubble separator installed in the SNR 300, among other things, "*semper aliquid haeret.*"[139]

There were ample reasons, both operational and political, to come to grips with the gas bubble problem. This was managed in the period between 1978 and 1980 in a very committed joint effort by the institutes of KfK (in particular INR, IMF, and IRE), the operator, KBG, and above all the vendor, Interatom. Dr. Höchel, in his company, coordinated all the studies, making the whole issue his very own problem child. Over this period of two years, the "gas bubbles" item was permanently on the agenda of all project meetings and was debated in all its ramifications. The project documentation covering this problem runs to several meters of files. In reality, the problem was so difficult to address because the events took place in the core of a reactor in operation, to which access was possible only to a limited extent because of radiation protection.[140]



Cross section through the KNK II primary system.

Very soon it was possible to exclude radial core oscillations, levitation of fuel elements, and absorber oscillations as potential causes of the reactivity changes.[141,142] Instead, it had become apparent that argon was transported from the cover gas plenum into the primary system through a degassing line for the old KNK I plant. When this pathway was blocked by a throttle, the amount of gas entering dropped to approx. 1% of the original volume. The remaining sources now were only the plena of the primary sodium pumps.[143]

It was also seen that the entrained gas accumulated in certain spots for some time. Potential locations could have been the valve tops, the flow orifice adjustment system and, possibly, the internal sodium plena. The gas then gushed through the core when this gas accumulator was discharged sporadically. This produced negative reactivity effects which, after registration by the very sensitive setting of the reactor protection system, initiated scrams. When many experiments with deliberate additions of gas to the primary sodium turned this assumption into a certainty, ways were considered to discharge these accumulators in a safe way. Spin separators located in the region of the so-called grid plate inserts underneath the core were considered a possibility. They were to pass the argon bubbles released in the accumulator in such a way that they had to flow not through the active core region, but through the reflector zone, which had no impact on reactivity.[144,145]

This turned out to be the correct solution. The mode of action of these gas separators was tested in sophisticated air and water test rigs at Interatom.[146,147] Their installation together with the second core of KNK II was a complete success. Together with certain modifications and the instrumentation of KNK II (reactimeter!) the gas bubble problem has been solved in a way compatible with plant operation, and the subject soon ceased to be of interest to the public.

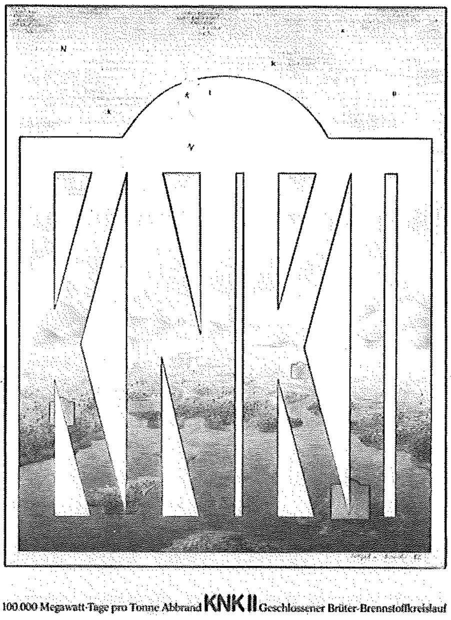
3.1.3 100,000 MWd/t Burnup Attained

Let us return to the operating history of the first core in KNK II.

After a solution had been found of the gas bubble problem which was tolerable from the operational point of view, irradiation of the test zone and the driver zone was continued. However, very soon after full power operation had been reached in April 1979, the xenon activity in the cover gas was observed to rise suddenly. Every indication pointed at a fuel element cladding defect, the first ever in KNK, as the old KNK I plant was known to have suffered from no such event. At that time, no experience existed in localizing failed fuel elements in the core structure. Therefore a decision was taken in favor of individual tests to be conducted in the fuel handling machine. After some three weeks, the failed fuel element had to be identified; it was a special test element which, for lack of standby elements of the same type, had to be replaced by an ordinary test zone element.[148]

When another fuel element failed approximately one year later, in May 1980 - both cases clearly being early defects -, a little more courage was demonstrated. The element was left in the core for some months as a so-called gas leaker until it was possible to detect the emissions of delayed neutrons by the DND system. Also the further development of the defect was observed for another eighteen days, in which KNK II was operated under part load and load tilting conditions. This mode of operation provided important findings for the localization of failed fuel elements, which are valuable especially for the second core of KNK II because of the much larger number of fuel cladding failures. In addition, experience was accumulated about the dispersion of fuel into sodium; these findings were of immense international interest, especially in the exchange with Japan.[149,150]

An important milestone was reached in August 1981: 5 UO_2/PuO_2 fuel elements of the test zone, with more than one thousand fuel rods, had reached the contractual target burnup of 60,000 MWd/t after 255 full-power days. This achievement was important also to colleagues working on the SNR 300 project, the design of the fuel elements in both reactors being very similar. Because of existing reactivity reserves, a permit for a so-called life extension was applied for with the licensing authority; this was a kind of extended operating permit, which was granted up to 355 full-power days. When 310 full-power days had been reached in late 1981, another application for 400 full-power days was filed and also approved by the authority.



Cover page of the KNK calendar.

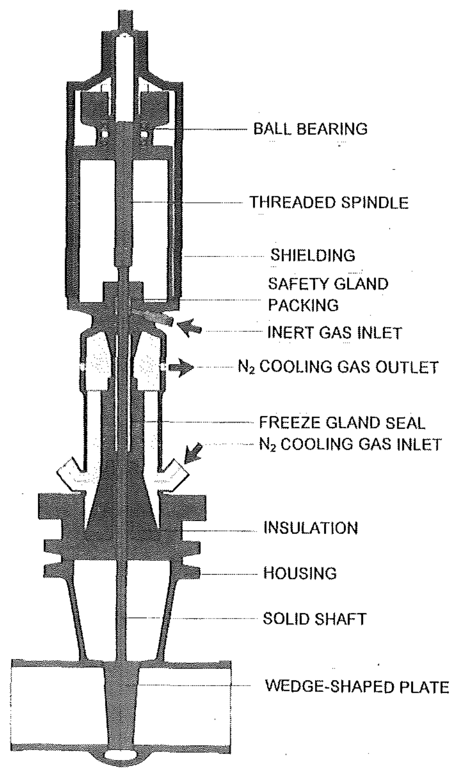
The deadline was reached on August 30, 1982: the 400 full-power days were attained without any further cladding tube defects. In the test zone, a local peak burnup of 100,000 MWd/t was attained, which corresponded to an average of 66,100 MWd/t. Reaching this impressive target level was an immense source of motivation for everybody involved in the KNK II project. It meant that the criteria set in-house had been exceeded by far, an achievement significant also by international standards. The French Phénix at that time had just reached 90,000, the Japanese JOYO only 50,000 MWd/t. The contractual target burnup of the SNR 300 had been exceeded by a full 20%. The press took notice of that record burnup achieved by KNK II, as was reflected in many articles and reports.[151,152]

Project Management used the event as a reason for having a calendar designed for the following year, 1983, with lithos drafted by an artist showing subjects related to KfK. The calendar was a hit; the circumstances surrounding its production will forever be cherished memories of all participants.

3.1.4 Reliable Components

In 1982, an aggregate operating experience of roughly ten years was available for KNK I plus KNK II. This applied in particular to the components of the sodium loops which, irrespective of any reactor outages, were in operation almost continuously. The main sodium pumps and intermediate heat exchangers, for instance, had attained 84,000 hours of operation, for they had been in operation almost continuously since the sodium had been loaded. No major defects or failures had occurred.

This also applied to the steam generators, which had been run for 19,000 hours. Only in 1972, as reported above, there had been one leak in a gas pore in the course of KNK I operation; the cause obviously had been a manufacturing defect. Afterwards, no further sodium-water interactions had occurred - incidentally, up to the end of the project in 1991. Also other important components, such as the cold traps for sodium purification, worked without any failure. On the other hand, the pump tubes of the electromagnetic pumps had had to be replaced several times because of minor leakages.[153]



Sodium shutoff valve with freeze gland seal.

One reason for this smooth functioning of the components certainly had been the regular preventive maintenance within the annual revision and repair phase. This was normally organized in the autumn and claimed four weeks, sometimes even more, of the time of the KBG crew headed by Erich Zimmermann.[154] At the same time, all maintenance and repair jobs were painstakingly recorded statistically with the assistance of the process computer.[155] In a joint effort with Interatom, these reliability data were entered also into risk analyses of important safety systems, e.g. in the SNR 300, or caused improvements in design whenever replacement parts had to be ordered. In this way, the mean values of faultfree periods of use, repair times, periods of unavailability, etc. were determined for several hundreds of components and taken into account in reliability analyses.[156]

All in-service inspections were listed in the inspection manual with respect to type, scope, deadline, etc.; in addition, the manual contained detailed instructions and step-by-step programs. Additional special inspections had already been conducted in the conversion phase, especially of the vessel and the primary piping. Most of these inspections comprised pressure tests and leak tests as well as internal and external inspections. The pressure test was run in the primary sodium system at 1.1 times the design level, i.e., at 13.1 bar over a holding time of 30 minutes. Internal inspections were conducted of the reactor vessel, among other components; also the gap between the vessel and the rotary top, which was known to be susceptible to blockage by sodium aerosols, was inspected by means of endoscopes.[157,158]

3.2. Closing the Nuclear Fuel Cycle

3.2.1 Fuel Reprocessing and Recycling

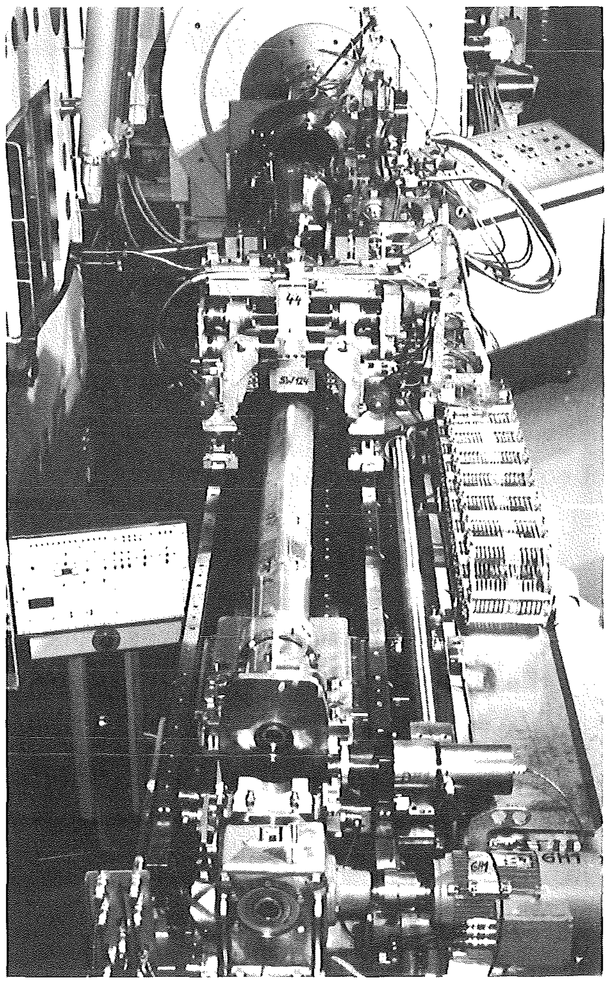
One man's food is another man's poison.

This dictum also applied to the operation of KNK II with the first core. The premature defect arising in a mixed oxide fuel element at the modest burnup of 17,500 MWd/t certainly was no source of joy to the operator, KBG, and even less so to the manufacturer, Belgonucléaire, which had made the element available free of charge to KfK for irradiation. At the same time, the event sparked off many practical and theoretical activities within the external fuel cycle, which will be described below.[159]

Disassembly into Fuel Rods

The failed fuel element with the number NY 208 BN - another element was added later with a burnup of 48,000 MWd/t - was taken out of the sodium store, after 17 months of cooling time, and blown with argon for some thirty minutes within the fuel handling machine. Further cleaning in the washing plant was omitted deliberately, as the defect was to be preserved in its original form, and fuel was to be prevented from escaping. The element was taken to the adjacent Hot Cells in the so-called fuel element transport flask. After fifteen years of experience in disassembling small bundles from the FR2, MZFR, and KNK I reactors, this was the first element reaching the Hot Cells which had more than 200 rods.[160,161]

The Hot Cells had facilities to cope even with this situation, a five meter long disassembly unit having been built as a matter of precaution which accommodated two of the three work stations in the entrance cell. First, the wrapper tube was removed from the element; this required the relatively high force of 7500 Newton because the adhering sodium residue acted like a strong adhesive. Next, the screw connections in the rod support plate were drilled out, which then allowed the individual rods to be disengaged without too much of an effort. The time required for disassembly of the KNK II fuel elements later decreased more and more; initially, several weeks were needed, but the disassembly time of the second failed element had already dropped to 110 hours, and for the third (intact) fuel element only 40 hours were required in 1983.[162,163]



Multi-purpose system for fuel element examination and disassembly in the Hot Cells of KfK.

Searching for Defects

After the fuel element bundle had been singulized, the suspected defect was to be detected by visual inspection of the fuel rods, but this attempt failed. Instead, a surprisingly large number of fretting marks were discovered at the level of the spacer pads. Metallographic examinations indicated materials wastage down to a maximum depth of 80 µm. As the wall thickness of the cladding tube was 350 µm, the fission gas leakage could not have been caused by these fretting marks. Later, oscillatory movements of the fuel rods were found to be the cause of the wastage, which was particularly pronounced at the level of the third spacer.

Even a leak test in a silicone oil bath did not help in finding the failed rod. Identification was produced finally by weight measurement: One rod was almost five grams heavier than the others, and this weight gain could have been due only to sodium entering through the defect site. In this way, a new method of detecting fuel element failures had been discovered. Now the precise location of the defect in the fuel rod had to be found. This was done by a so-called sipping test at a higher temperature, at which sodium leaked out. The fault had been localized: It was a hairline crack in the cladding tube extending over roughly one quarter of the circumference. In the other failed element, which had been left in the reactor for more than two weeks, the cause of defect did not have to be looked for expressly: The longitudinal crack some 30 mm long was openly visible over an area of approx. 20 mm^2 and could be seen with the naked eye.[164]

Fuel Dissolution

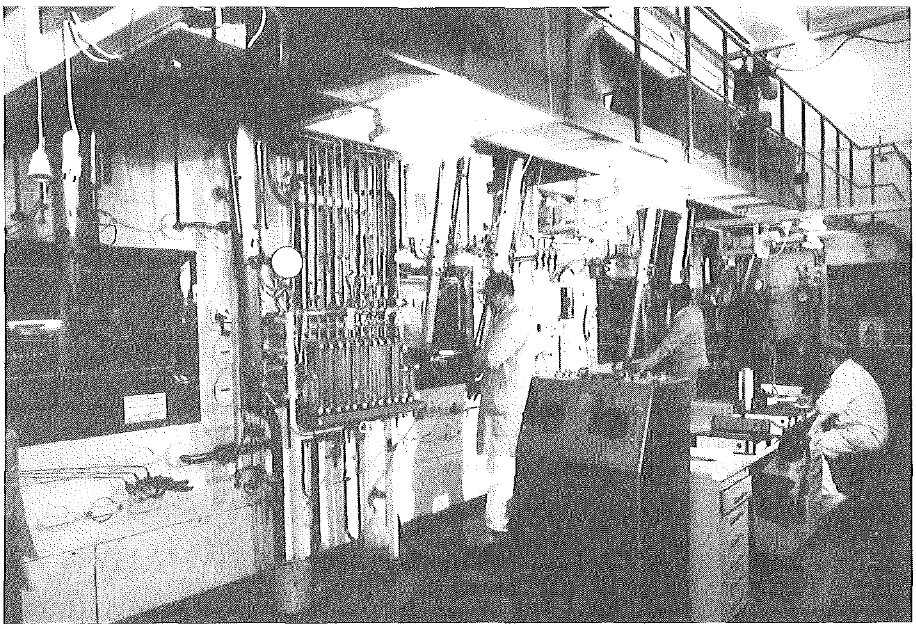
New, but adverse, experiences were associated with the dissolution tests of spent fuel in the Hot Cells of KfK. Prior to the planned reprocessing of fuel bundles, short fuel rod sections, from which the hulls had been removed, were put into nitric acid and dissolved for approx. six hours at boiling temperature. Surprisingly, the fuel was dissolved only in part; a solid residue of some 14%, relative to the mixed oxide, was left over. The situation was not changed very much by variation of the acid molarity or the length of exposure.[165,166]

Other dissolution tests resulted in the important finding that the method of manufacturing the fuel pellets was the reason for the large residues. In the standard procedure applied by Alkem at that time, UO_2 and PuO_2 were still blended mechanically; after pressing and sintering this obviously did not produce a satisfactory solid solution. On the other hand, the homogeneity of the fuel determined its dissolution capability, as was found out in a number of subsequent studies. It was influenced positively, e.g., by high rod powers, because they allowed more diffusion processes to take place. On the other hand, this was counteracted by radial U/Pu segregation of the fuel, especially at PuO_2 concentrations above 35%. As higher fuel losses in the breeder cycle had to be avoided under all conditions, the development of an improved way of manufacturing mixed oxide for breeders was imperative. This subject will be discussed in the section following the next section.

Fuel Reprocessing

The fuel elements made available by KNK II were reprocessed in the MILLI pilot plant of the Institute for Hot Chemistry (IHCh). MILLI used the so-called PUREX process based on liquid-liquid extraction and was designed to a throughput of approx. 1 kg of fuel a day. As a rule, uranium, plutonium and the fission products were separated in three extraction cycles, which will be briefly described below.[167]

Dissolution of the fuel, of course, produced fractions of insoluble residues as high as described above. However, as all parts and process phases of MILLI had been designed in the light of criticality safety, this created no safety problems. The first extraction cycle, also called co-decontamination cycle, was designed to separate the fission products from uranium and plutonium. At the end, the particularly notorious fission products, zirconium 95 and ruthenium 106, were contained in the U/Pu solution to the tune of only 0.4%, while all the other fission products contributed even lower shares. The plutonium concentration of approx. 1 mg/l at the discharge end of the aqueous solution implied a loss in the waste of less than 0.01%.



The MILLI II pilot reprocessing plant at KfK/IHCh.

In the second cycle, uranium and plutonium were separated and the fission products were further reduced.

The third extraction cycle served for the so-called purification of the uranium product. The Zr 95 and Ru 106 fission products meanwhile had dropped to 10^{-5}, and the decontamination factors of the other fission products were even better. In retrospect, it can be said that reprocessing the KNK II fuel elements in MILLI posed no problems. The Institute for Hot Chemistry later optimized the separation process still further; when electrochemical methods were applied, a single extraction cycle was sufficient. This result, which had an immense impact on the economics of reprocessing, was widely acclaimed internationally (Impurex process).[168]

Fuel Recycling and Refabrication

The uranyl nitrate and plutonium nitrate obtained in MILLI was subsequently shipped to Hanau for further processing into mixed oxide fuel rods by Alkem. Because of the unsatisfactory dissolution results, the decision was taken to abandon the current mechanical method of fuel manufacture. In order to produce a homogeneous solid solution, the uranyl nitrate and plutonium nitrate solutions were to be mixed (in a 75:2 ratio). A similar procedure, but for uranium only, had been used by the RBU sister company for many years already and had allowed reliable production of several tons of UO_2.

The fuel produced by co-precipitation as ammonium uranyl plutonyl carbonate and subsequent calcination was characterized by its excellent microscopic homogeneity and dissolution capability even prior to irradiation. It is referred to in the literature as the AUPuC process. Some of the fuel pellets were loaded into a so-called KNK II ring element for test purposes, while another part was used for making the third core.[169]

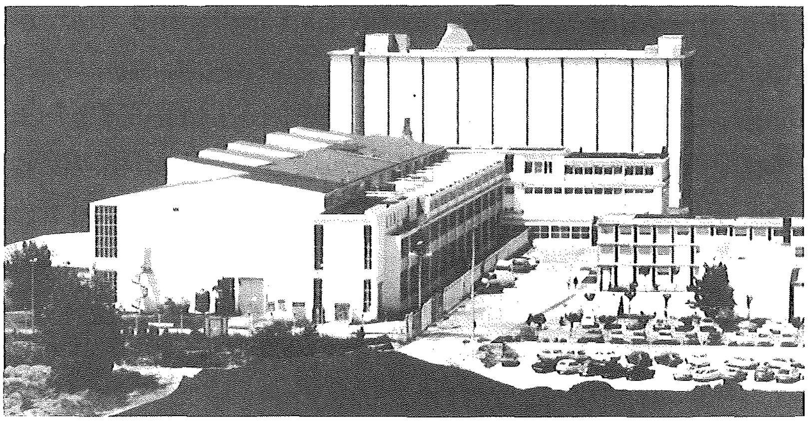
In this way, the cycle for fast breeder fuel on a kilogram scale had been closed in Germany for the first time.

Spent Fuel Management in KNK II

"Spent fuel management" - a phrase coined in the seventies - had to be ensured also for the spent cores of KNK II. The appropriate provision in Section 9a of the German Atomic Energy Act at that time was interpreted to imply that the core material had to be reprocessed and separated into uranium, plutonium, and waste. As the MILLI plant of KfK was not designed for the throughputs now required, only the MOX reprocessing plants of the French CEA at Marcoule and of UKAEA in Dounreay could be employed. Tenders were invited from both plants; at the end, CEA was commissioned to reprocess the fuel, which was quite in line with German-French cooperation in the fast breeder field, as laid down in a government agreement in 1976/77.[170]

The plant in Marcoule, situated close to the famous vineyards of Châteauneuf-du-Pape, mainly comprised the existing SAP extraction part and the TOR head end under construction. The plant was used preferably for reprocessing MOX fuel from the French Rapsodie and Phénix breeder plants and was designed for a total capacity of 47 t. KfK bought 2.44 t for three cores (KNK II/1-3), which is the reason why the contracts show the rather odd numbers of the respective shares, 2.44/47.[171]

The agreement with CEA Marcoule was signed in December 1980 and, as was customary at that time, included a provision for the return of all fuels and of the high-level vitrified waste. CEA also agreed to accept failed fuel elements contained in cans, and MOX elements of lower dissolvability. For these latter elements, a modified process flowsheet had to be designed, for which detailed experiments were run at the French research center of Fontenay-aux-Roses, albeit with little success.



French TOR - SAP reprocessing plant in Marcoule.

Initially, the French wanted to accept only fuel rods, no bundles; KfK therefore made extensive provisions for disassembling the fuel elements in the Hot Cells. Before disassembly, the elements had to be washed and canned in a station specially built for this purpose. However, it became increasingly more difficult in the following period of time to obtain the permit under the Atomic Energy Act for handling some 70 kg of plutonium in the Hot Cells; costly conditions were likely to be imposed for internal and external plant safety. For this reason, disassembly of the KNK II fuel elements at the Nuclear Research Center was soon abandoned, and another agreement was signed with CEA, under which complete bundles could be delivered.

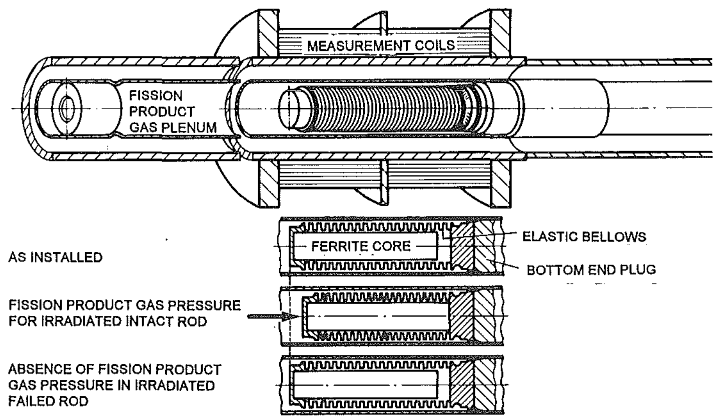
3.2.2 KNK II Studies of the External Fuel Cycle

KNK II operation gave rise to a number of ideas about the steps of the external fuel cycle. They were presented at a seminar held at the Nuclear Research Center in October 1981, and they demonstrated the close cooperation of KfK institutes with its industrial partners.[172,173] Thus, roughly half a dozen ways to remove sodium from fuel elements were identified and compared in their respective pros and cons.[174] Disassembling fuel elements was another topic of technical and economic optimization, especially with regard to the expected bowing of fuel elements due to burnup. The Central Engineering Department (IT) of KfK was busy designing economically viable shipping containers meeting the technical specifications of KNK II fuel elements.[175]

Some of these project studies were particularly remarkable for their scope and importance and will therefore be described briefly below.

Repairing Breeder Fuel Elements

The operation of KNK so far had indicated that, in most cases, only one fuel rod failed in a fuel element bundle. Consequently, it was economically attractive to localize and replace only this failed rod instead of changing the entire bundle. The IMF III Institute of KfK developed a number of ideas on this problem. In their opinion, future fuel elements were to be designed so that the rod bundle was accessible from below, could be dismantled in the installations of the Hot Cell and reassembled after the failed rod had been replaced.[176]



Detection of failed fuel rods (basic principle).

One problematic point undoubtedly was the reliable detection of the failed fuel rod. For this purpose, a small pressure cell was to be introduced into each fuel rod which was able to record the internal fission product gas pressure. A major component item of this measuring device was a ferritic core within a bellows; it was displaced by a certain amount if a cladding defect had caused the pressure in the fission product gas plenum to drop. The position of the ferritic measurement core was to be determined by inductive displacement measurement by means of chokes. For the third core of KNK II, one element was equipped with these measuring cells; unfortunately, it was never used, as KNK II was shut down prematurely.

Interim Storage of Fuel Elements

Extensive work was devoted also to the interim storage of breeder fuel elements on the premises of the Nuclear Research Center. Three storage variants, namely wet store, dry store, and cask store, were studied separately by three different groups and, finally compared. Each store was to be able to accommodate ten core loads of KNK II; specific criteria had been laid down, e.g., on technical design, the demonstration of licensability and, of course, the estimated cost.

The wet store was a conventional storage pool cooled by light water, but equipped with provisions against airplane crash and blast waves.[177] The fuel elements were to be stored under water in cans with inert cover gas. The dry store consisted of a vault-type building protected against external impacts, in which the fuel elements, also contained in cans, were to be suspended.[178] The decay heat was to be removed by free atmospheric air convection. The cooling system was described as being self-regulating and inherently safe. Another variant was dry storage in shipping-storage casks of the type also used for light water reactors. Casks with type-B approval and storage qualification were to be stored in a light hall only for protection against the weather and against radiation.[179]

The final comparison showed certain advantages in favor of the wet store, because it was based on a proven technology. In addition, it offered a possibility for decomposing the fuel elements under water.[180] The dry store was the most compact unit and, consequently, also the most inexpensive one. A certain risk was seen in remote handling systems in case of an accident. The cask store was the most flexible variant in terms of construction, expansion, and decommissioning. It was erected in a short period of time and offered the added advantage of the capital costs arising only step by step. Had any of these stores been built, the cask store probably would have been chosen on economic and licensing grounds.[181]

The MILLI II Reprocessing Plant

Another important piece of work was the study about the MILLI II pilot reprocessing plant. As the name implied, it was to be a follow-on project after the successful MILLI laboratory-scale reprocessing plant. MILLI II was designed for a throughput of 50 kg of heavy metal (U+Pu) a day. This would have served KNK II and SNR 300 and a certain capacity reserve for foreign customers would still have remained.[182]

The block diagram of the plant comprised the head end store with disassembly, chopping and leaching, the extraction section, and the product store. In addition, there were installations for offgas treatment and the usual utility systems. Reprocessing was to follow a three-stage PUREX process. The plant capacity listed above was determined on the basis of the minimum throughput of the pulsed columns used. In addition, especially the process steps of waste minimization developed at KfK were to be tested, such as the low-salt process and the Electro-Redox process. Also the centrifugal contactor was to be demonstrated. Remote exchange techniques were to be employed in maintenance and repair, as KfK had invested a great deal of development work in these fields.

The confusion engulfing the Kalkar and Wackersdorf projects unfortunately also has caused the MILLI II concept to be discontinued.

4. Operation with the KNK II Second Core

4.1 New Fuel Elements for Kalkar

The operating record of the fuel elements in the first core of KNK II was ample cause for satisfaction. The elements not only had reached the contractual target burnup of 60,000 MWd/t, but even had exceeded it considerably. Only two fuel rods out of more than one thousand had developed leaks; these defects, in turn, had triggered off extensive R&D activities in the fuel cycle area. Also the finding, new at that time, that exposed fuel does not enter into a violent exothermal reaction with sodium, and that a dispersion of fuel into the coolant must not be expected to occur under normal circumstances, was owed to these two failed fuel rods. Had KNK II been an "ordinary" nuclear power plant, the operator certainly would have ordered reload fuel elements of the same, or perhaps slightly modified, specifications.

But KNK II was not an ordinary power plant.

Let us recall that, in negotiations with the Federal Ministry for Research in the early seventies, especially one argument pro KNK II had swung opinion in favor of building the plant:

> *"The possibility to irradiate a statistically sufficient number of breeder fuel rods in fuel elements of the kind planned for use in the SNR 300."*

So, KNK II had to act as a kind of pathfinder for its bigger brother in Kalkar, with all the opportunities - and risks - this entailed.[183]

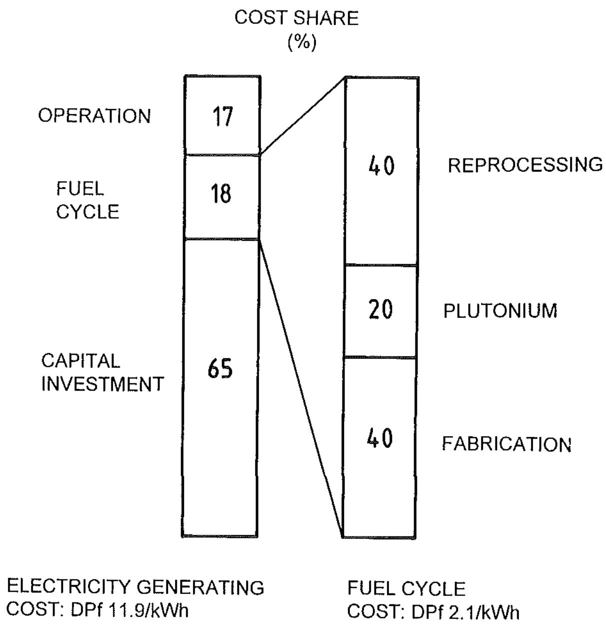
And lots of requirements came in from Kalkar. While KNK II was still being operated with its first core, SBK, the operators consortium of the SNR 300, was engrossed in economic thoughts about reloads. The prevailing opinion was that both the design specifications and the fabrication specifications for the second Kalkar core loading had to be changed fundamentally to allow the plant to be operated on the basis of economic principles. Some of the more important desiderata included thicker fuel rods and improved solubility of the fuel. However, these requirements entailed a host of other changes in specifications, and the new Mark II design thus finally differed drastically from the old, proven Mark Ia version.[184,185]

4.1.1 Design and Fabrication

Thinking was based initially on the fuel cycle costs for the SNR 300, which made up some 20% of the total electricity generating costs. These costs were composed of three fractions: the plutonium costs (20%), which were relatively difficult to influence; the costs of fuel element fabrication (40%), and the reprocessing costs (40%). The latter two cost items simply had to be reduced.[186]

The fuel rod fabrication costs for rods of 6 mm diameter were much higher than had been assumed in earlier strategic studies. More recent cost variation calculations indicated that thicker rods would have a significantly positive impact on the fuel cycle costs. For this reason, a fuel rod diameter of 7.6 mm was defined for the SNR 300 reload - and, hence, for the second load of KNK II. At the same time, this came close to the specifications for the French Phénix reactor. That modification also had an impact on the residence time of the fuel elements. While 255 full-power days had been planned for the first core, the target burnup of the second core was to be reached at 455 full-power days.[187]

A change was also made in the cladding material for the fuel rods. While the first KNK II core still combined number 1.4988, 1.4981, and 1.4970 austenitic materials of various degrees of treatment, sometimes even within one element, the reloads for KNK II and SNR 300 were to use only 1.4970 material. The reason for this change was the lower amount of swelling and creeping under fast neutron irradiation of this new material.[188]



Cost structure of the fast breeder (status of 1980).

Also the way in which fuel rods were bundled into fuel elements was different in the second core, the fuel elements of KNK II/2 being packed much more densely. The p/d ratio characterizing the rod pitch, i. e. the ratio of rod center to rod diameter, was 1.32 in the first core and had been reduced to 1.16 in the second core. As in the first core, the required spacers were manufactured from solid plates by electrochemical erosion to ensure satisfactory flow and cooling conditions. As was seen in the course of in-pile residence later, the dense packing of the fuel rods may have been taken one step too far.

In the first core, the spark eroded spacers were still held in place by six structural bars in the corners of the hexagonal bundle. In the second core, that design was abandoned and the spacers were spot welded to so-called flow aprons which, in turn, were welded to the wrapper tube.

Other major changes were made in the fuel. In KNK II/1, the fuel smear density had still been specified at 80%, which corresponded to a pellet density of 86.5%; the smear density in KNK II/2 was increased to 85% (corresponding to 92% pellet density). As a consequence, the fission products generated in reactor operation were assigned less space in the second core. Why this sudden courage? The reason was the finding made in the meantime that mixed oxide fuel showed good plastic strain behavior at temperatures above 1400°C, which made large porosities and other void spaces superfluous.

This latter concept was in good agreement with the wishes expressed by Alkem, the fuel manufacturer. The company had been asked to improve the solubility of the fuel in the second cores of KNK II and SNR 300. It was seen that pressing and sintering "naturally" produced fuel of higher density whenever the new OKOM and AUPuC manufacturing techniques were used. Moreover, this fuel had the specified higher solubility because it was a good solid solution from the outset.[189] It is interesting to note in this connection that also the Japanese had major problems manufacturing low-density MOX fuel for their MONJU prototype power plant, which resulted in a delay by more than one year.

Alkem had progressed greatly in the development of new manufacturing techniques for breeder fuel. Depending on the feed material, two alternative techniques were available. If the material came as plutonium oxide, the "optimized co-grinding process," called OKOM, was used. In that process, the MOX powder mix was ground to such a degree of fineness that the following sintering step achieved complete solid solution formation and, hence, full solubility. The alternative AUPuC process was used when liquid plutonium nitrate was the feed product. Together with uranyl nitrate, a homogeneous solid solution was precipitated (ammonium uranyl plutonyl carbonate), which produced a free-flowing, fully soluble mixed oxide powder in the subsequent calcination step; this powder could be directly processed into pellets. Most of the fuel rods for KNK II/2 were produced by the OKOM process; a small number of rods were also made by the AUPuC process. Those were the failed fuel elements from the first core, which had been reprocessed in MILLI.[190,191]

Let us summarize the major changes in specifications for KNK II/2 as compared to KNK II/1: The fuel rod diameter was increased; the fuel rod pitch was reduced; the spacer design was modified; the in-pile residence time was increased. Two new types of fuel fabrication were applied, and the pellet density, an important parameter, was changed.

Most of these modifications practically had no basis of experience. Only in the French Rapsodie experimental reactor, a small bundle with nineteen rods had been irradiated between 1976 and 1978. It had contained rods of 7.6 mm diameter, but both the density of the fuel and the fuel production process did not agree with the new specifications; only helical wires had been used for the spacers.[192]

These circumstances should not be forgotten when looking at the operating performance of the second core.

4.1.2 A Mixed Operating Record

Operation with the second core of KNK II covered the period between 1983 and 1991, the year of permanent shutdown. It was a period of time rich in experience, both positive and negative. The latter category included problems with the fuel elements and with the rod actuating equipment of the shutdown systems. They will be discussed in more detail in the next section. On the positive side, there are the large number of findings and activities of the experimental program. In the eighties, KNK II inspired many breeder scientists of the then Fast Breeder Project (PSB) to conduct experiments with the KNK reactor. A separate chapter is devoted to those activities.

However, let us first have a brief look at the operating experience with the KNK II/2 core arranged by calendar years.[193,194,195]

1983

This was a busy year. The fuel elements of the first core had to be removed from the sodium store, and some of them had to be transported to the Hot Cells for post-irradiation examination. The bearings of the turbo-generator set were overhauled after 18,000 hours of operation, and the inside of the vessel was inspected with a video camera. Finally, the discharge tubes of the gas separation unit, which had meanwhile been completed, had to be installed in the outer reflector row.

In June, at long last, the operating permit under the Atomic Energy Act was received. Within just ten days, the fuel elements of the second core had been loaded, and the reactor had achieved its first criticality on June 26, 1983. Everything proceeded according to schedule and without any problems; one test element of the first core was allowed to remain in the reactor by special permit of the authority. Especially the gas bubble separators worked extremely well; after they had been installed, no more disturbing reactivity changes were observed.

Finally, construction of a storage hall for spent fuel and waste management components was completed; a separate chapter will be devoted to the problems associated with that building.

1984

This was a year with many activities in the experimental program. Sixteen test rigs had been installed in seven reactor positions throughout the year, including one ring element with an inner carbide fuel rod bundle; a second ring element contained pressurized cladding tube specimens. An electrically heated boiling generator was operated in the central position for nearly two months in addition to several boiling detectors on surrounding positions.

In May, the rotor of a primary sodium main recirculation pump was replaced by a new unit for the first time. The pump had been in operation for fifteen years, accumulating more than 90,000 hours of operation without requiring any special maintenance. However, in recent years, it had become a bit noisy at high speeds and was replaced for that reason. The maximum individual personnel dose associated with the replacement amounted to 52 mrem.[196]

The test element from the first core, which had been left in the reactor, had reached a burnup of 130,000 MWd/t by the end of the year, which corresponds to 600 full-power days. The other test zone elements of the KNK II/2 core load were around 200 full-power days.

1985

In this year, the risks of the fresh fuel elements loaded became apparent for the first time: In April and in August, a rise in the activity of the cover gas indicated one failed fuel element each. Operation was continued for another 28 and 50 days, respectively, and the failed elements were subsequently localized by load tilting and individual detection in the fuel handling machine.

Nevertheless, performance throughout the year was reason for satisfaction. The reactor had achieved 45% availability in terms of time, and 360 full-power days had already been accumulated. As only a small margin of approx. 100 full-power days was left until the licensed level of 455 full-power days and, in addition, there were still reactivity reserves, KfK and KBG as the permit holders filed an application with the authority for an extension of the core life to 720 full-power days.[197]

An important personnel change took place: Managing Director Dr. Gerhard Brudermüller, who had supervised the fate of KBG with his extensive knowledge of detail and Swabian temperament since 1973, was appointed Managing Director of the Obrigheim Nuclear Power Station. He was replaced by Werner O. Steiger, former Operations Manager of FR 2 and experienced in plant decommissioning.

1986

This was an unsatisfactory year of operation with only 13% availability in terms of time and, again, two failed fuel elements. Surprisingly, in one case the plant was operated for another 51 days until the leaker turned into a real DND defect.

For the rest, all the difficulties became apparent in this year which the operating crew would have to grapple with also in the future. The failed elements removed the year before had been examined in the Hot Cells and had shown defects in the region of the spacers. The experts attributed these phenomena to oscillations, but were uncertain about the source of excitation. Moreover, the outlet temperatures of the fuel elements began to rise uncomfortably. This so-called temperature drift, which had become apparent already at an earlier point in time, was the reason for extensive studies of sodium purity. Finally, the most serious problem was encountered when a shim-shutdown rod in the primary shutdown unit was found to seize in December; an urgent report was sent to the authority immediately. However, no hazard to technical safety was implied, as another six boron carbide rods were available for shutdown of the reactor.

1987

Again, not a particularly satisfactory year of operation, but the licensed 455 full-power days were reached in November 1987. In the absence of a new permit for the extended core life, the plant had to be shut down. Yet, the operating period was long enough for two additional fuel element failures to develop. One was located in the fuel element from the first core, which had been left in place. At 832 full-power days (corresponding to a reactor burnup of 175,000 MWd/t) it had more than doubled its originally planned in-pile time of 400 full-power days, thus proving the relative ruggedness of the earlier Mark-I specification for the first core. In November, the tenth anniversary of KNK II operation was celebrated - an event reported in many papers.[198,199]

For the rest, broad-based research was conducted into the causes of the problems mentioned in the section above. For instance, the sodium of the primary system was examined for entrained particles, with the reactor shut down, which might have blocked the flow channels of the fuel elements. Experiments about the correlation of neutron flux and fuel element outlet temperature were run to determine the oscillation behavior of fuel elements in the core. And as far as seizing of a shim-shutdown rod was concerned, the conjecture turned into a fact that this was less a problem of operation than a problem of downtime and handling.

1988 and 1989

Anni horribiles. No operation for two years!

1988 passed with a multitude of maintenance activities, such as turbine revision, inspection of the vessel internals, installation of torque measuring shafts for the shutdown units, etc. When the primary sodium pump was removed, loose and broken screws from the flow baffles were found. The permit extending the core life arrived a few days before Christmas.

Yet, no operation was possible also the following year, 1989; the seizing control rods appeared to have turned worse. Alternately, torque measurements and attempts at high-temperature cleanup and gas sweep experiments were carried out. In November, finally, the Advisory Committee on Reactor Safeguards gave the green light, permitting "easy" continued operation of the plant.[200]

On October 1, 1989, the author (after twenty years with KNK and eleven years with PSB) changed to the EFR European Fast Reactor Project. The Executive Board appointed Gregor Schnetgöke his successor in KNK, who had been associated with the project since 1965 and was well versed in all its technical, financial, and contractual ramifications.

1 9 9 0

At long last, the reactor resumed operation.

In late January, approval from the supervisory authority to restart KNK II was received; the maximum reactor power was not to exceed 60% of the rated power. This "soft mode" had been discussed with the consultants in many expert rounds, had been proposed by the applicants and, finally, had been ordered by the supervisory authority. However, in order to set the so-called f_i-temperature limits, the plant had to be raised to 100% very briefly.

Despite this allegedly soft mode of operation, another fuel element developed a leak this year; the leaker was localized relatively soon by load tilting and by using the reshuffling system. For the rest, 1990 was a year with the relatively high availability in terms of time, for an experimental plant, of 48%.

1991

The last year of operation of KNK II.

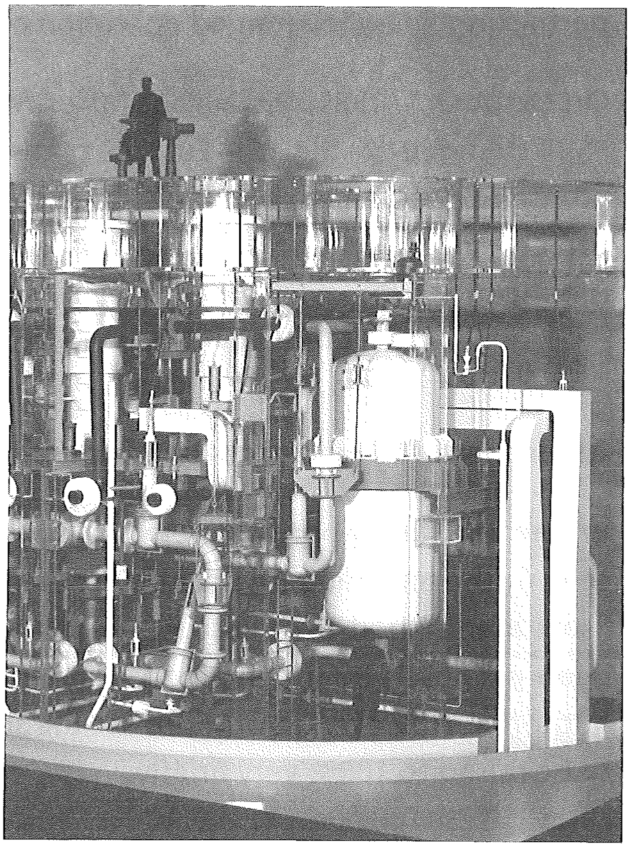
Because of the sticking control rod actuating equipment, reactor operation had to be stopped for almost six months after a brief phase of operation in January. After the control rods had been moved individually and the route of the sweeping gas in the reactor top shield had been changed, cleanup soon proved to be successful, and official approval to restart the plant was obtained in July.[201]

KNK II then ran for an uninterrupted period of almost six weeks and was shut down permanently by order of the KfK Executive Board on August 23, 1991. The reasons for that decision will be described in detail in the last chapter.

4.1.3 On the Availability of KNK II

As far as availability is concerned, KNK II certainly was not equivalent to a modern light water nuclear power plant, as its design and operation had served purposes other than those of electricity generation only.[202]

The need to serve as a test bed for the fuel elements of the SNR 300 has been mentioned above. The large number of fuel rod failures in the second core turned out to be a major burden on the operation of KNK II, for localizing a failed fuel element and obtaining the official permit for replacing it always took several weeks. On the other hand, these defects proved to be a valuable early warning system for the SNR 300. Had the Kalkar plant ever been in operation, it certainly would have had to be equipped with improved reload fuel. KNK II, in a way, was the technological scout for the SNR 300.



Compact arrangement of KNK components in the primary cells (scale model).

The extensive experimental program also reduced the theoretical level of electricity generation. For some periods of time, the plant was loaded with 25 - 30 experiments for scientists within KfK and outside. The requirements to be met in reactor operation ranged from the continuous mode at various power levels to cycling and even zero-power operation, the latter during eight weeks of "irradiation" of a boiling generator in the central core position. Also installing and removing the test rigs, sixteen of which were loaded in the core in 1984, was very time consuming, because the reactor top shield had to be dismantled in a very cumbersome procedure each time.

Especially the prototype character of KNK, the first-of-its-kind plant of a newly founded, though committed, vendor, entailed many technical risks. Many defects, even design errors, could not have been foreseen, such as the gas bubble problem or the sticking shutdown rod actuating equipment. Nearly all components, just consider the sodium pumps, were unique and first-of-their-kind designs, whose operating characteristics and life expectancy could not possibly be estimated.[203,204]

Also handling the sodium coolant had to be learnt. Certainly it is due also to the circumspection of the plant and maintenance crews that no major accidents occurred. Even the sodium fire and the steam generator accident in KNK I never put the personnel or the environment in any danger.

The permits under the Atomic Energy Act turned out to be no small obstacle. Solely for KNK II, a full 36 written permits had to be obtained from the authority in the period between 1975 and 1988. For all of them, detailed applications had to be filed whose technical contents had to be scrutinized by the Technical Inspectorate and the Advisory Committee on Reactor Safeguards, respectively, before the licensing documents were obtained in many discussions with the supervisory authorities and the licensing authorities. Not infrequently, KNK II had to be stopped for some time whenever a necessary operating permit had not been issued early enough. This happened, for instance, for a full year between 1987 and 1988, when the permit for the extension of core life took much longer to come forth, in the wake of the Chernobyl debate, than could possibly have been assumed.

The conditions imposed in the permits *inter alia* referred to the maintenance rules for the plant. Most of these duties and inspections were completed in the major annual revision outage which, because of the extent of the work at hand, sometimes took 6 - 8 weeks to complete. They also reduced the number of unplanned scrams by improving the electrical and mechanical components. In 1980, there were still twelve scrams while only one scram was recorded in 1987.[205]

Finally, also the consequences of political developments cannot be overlooked. Although KNK II was not an object of strong opposition the way the SNR 300 was, it nevertheless was under continuous observation. Whatever happened in the operation of KNK II was registered by the media and frequently exaggerated with respect to its potential impacts on the Kalkar project. One case in point is the gas bubble problem. Also for this reason, the operating crew untiringly sought to avoid incidents and the resultant headlines.

In Europe, KNK II for a long time was overshadowed by such breeder power plants as the British PFR and the French Phénix and Superphénix. However, since those plants also have become the subjects of examination by independent external authorities, require licensing and can no longer escape political influences, also their availability has declined drastically and is no longer better than that of KNK II. The technical problems encountered by the British and French plants were discussed in detail by the AGT 8 trilateral Working Group, among other agencies.

4.2 Phenomena and Problems

4.2.1 Experience with Failed Fuel Elements

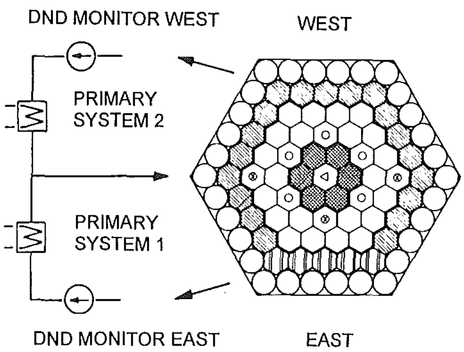
Let us return to the in-pile performance of the second core, and let us remember the statistics of failed fuel elements.[206]

The first two years of operation, 1983 and 1984, were without fuel element failures. Two failures each occurred in the three following years, 1985 - 1987, and two more failures were encountered in 1990 and 1991. If one subtracts the fuel element left over from the first core, which achieved a record in-pile time of 832 full-power days, a total of seven fuel elements of the second core load developed leaks at burnups between 27,000 and 47,000 MWd/t. Of these elements, three were in the test zone and four were in the driver zone.[207,208]

The standard procedure followed in case of a fuel element failure included leak detection, localization of the leaker and, finally, its replacement by an unirradiated fuel element. Detecting a cladding defect mostly turned out to be possible in the very early phase of a fission product gas leak. Continuous monitoring of radioactivity in the argon cover gas, for instance, allowed the xenon 133 added to be detected by the 81 keV line. Further clarification, especially in the distinction between test elements and driver elements, was achieved by mass spectroscopic determination of the ratio between the Xe 131 and Xe 134 gaseous xenon isotopes. As a rule, operation with a "leaker" was continued for a couple of days or even weeks until the so-called DND failure had developed. At that point in time, two neutron monitors applied to the primary sodium pipes were able to measure the concentration of emitters of delayed neutrons. Once a certain count rate had been reached, e. g. 2000 counts per second, preparations were made to replace the defective element in order not to contaminate the primary sodium unnecessarily.[209]

Localizing such a failed fuel element frequently developed into a fascinating competition between the operating crew of KNK II and the scientists of adjacent institutes, such as IRE and IHCh. All available measured data were analyzed, entered into computer programs, such as COCOSS, and a "hit list" of particularly suspicious fuel elements was compiled.[210] The "winner" who had betted on the right element, of course, was overjoyed. But occasionally all experts were far off the mark in their predictions.

Operation of the reactor with load tilting - which also required a license - allowed the number of potentially failed fuel elements to be limited. Final confirmation was obtained in the next, final step: The suspicious elements were pulled into the fuel handling machine and cleared of sodium by blowing. Subsequently, cooling was reduced, and the pressure in the flask was lowered. When there was a leakage, failed fuel elements then emitted fission product gas, which was collected and analyzed. This procedure took about four hours; examining the core required at least one week.



DND monitor arrangement in KNK II.

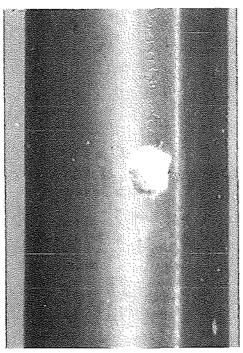
Only some of the experiences accumulated with failed fuel elements can be reported here. Thus, the period of time passing between the occurrence of a "leaker" and the DND signal was very much shorter in test elements than in driver elements. This was due to the fact that sodium reacts much more strongly with PuO_2/UO_2 than with UO_2 alone; the reaction product generated initiated a much larger volume increase in mixed oxide, which caused the point of failure to expand and a DND signal to be generated.[211,212]

Whenever the DND instruments supplied unequivocal readings, it was known from experience that the plant now had to be shut down speedily so that as little sodium as possible was sucked into the fuel rod through the defect. Prolonged operation with open failed rods was bound to cause a rise in the Cs 137 fission product in the primary system. As a sort of countermeasure, incidentally, the installation of a cesium trap was planned within the experimental program.[213,214]

Once a fuel element had been recognized as having failed and had been removed from the core, the next burning question was, what is the defect like, and what can have caused it. This will be outlined in the next section.

4.2.2 Fuel Rod Vibrations

Within two years, from 1986 on, three fuel elements were taken to the Hot Cells of KfK for post-irradiation examination. They all showed evident fret marks between the fuel rod claddings and the spacers, especially at the 6th and 7th levels, i. e. the upper rod end. The fuel elements in the driver zone showed more pronounced wear than those in the test zone; abrasion was minimal in the zero-power moderator rods.



Fret mark in KNK II fuel rod.

Wear at the spacer level obviously was a cause also of ensuing leaks in cladding tubes. Rod failures always occurred in the regions of maximum wear. In the test zone rods, they produced longitudinal cracks in the cladding tube; in the driver zone rods, circumferential cracks. These differences in the types of defect can be explained conclusively with the different reactions of uranium oxide and mixed oxide fuels with sodium, as described in Section 3.2.1 above.

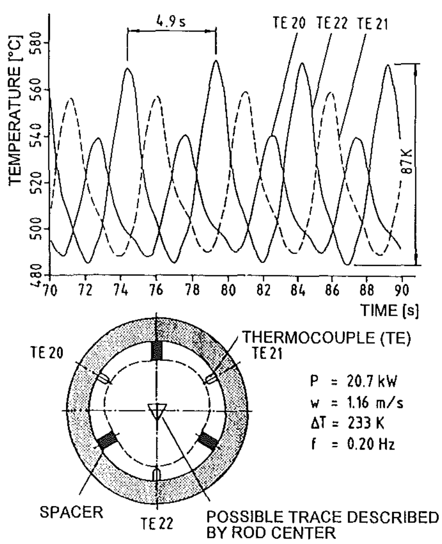
Investigating the causes of wear marks turned out to be an extremely complicated affair, which kept scientists occupied for a full ten years. Starting from the "chatter marks" in the first core, which simply appeared to be due in 1981 to the gas bubbles passing through KNK II/1, 1989 - 1991 saw the so-called THIBO experiments, in the course of which the phenomenon finally was verified as thermohydraulically induced rod vibrations. In between these two dates there were many futile attempts at explanations never supported by experimental data, and there was also an extended study of international experiences in this field.

Gas bubbles could not have excited the vibrations for two reasons: on the one hand, because bubbles deliberately injected into the coolant in an out-of-pile test were unable to excite vibrations in the dummy fuel elements; on the other hand, because the second core continued to show wear marks although (because of the separators installed) the gas bubble problem no longer existed. Consequently, different sources of excitation in the plant had to be found. Connecting rods were employed and complicated coherence analyses conducted to study, over many months, the vibrations of the grid plate, the reactor vessel, the primary pipes, and the main sodium pumps - all in vain.

In mid-1987, when no new explanations were believed to come forth any more, the situation changed when the post-irradiation examination findings of a Mark II element irradiated in the French Phénix reactor became known. That element was almost identical in design with the KNK II/2 element, and after the end of its in-pile time it showed the same defects. From now on, the explanation was based on the hypothesis that the cause for fuel element wear was to be found not in the reactor but in the design of that very element. "Far-field" excitation was abandoned in favor of "near-field" excitation.[215]

Further corroboration was found in international exchanges of experience. Scientists from the Japanese JOYO and the American EBR II plants reported about similar (albeit less pronounced) fret marks in their facilities. A piece of particularly interesting information came from the French CABRI reactor at Cadarache, where rod movements had been detected in some CABRI experiments and in heated Mark II bundles. From now on, "thermal wobbling" was the explanation of the vibration phenomenon. It was thought to happen like this: Differences in temperature around the rod circumference cause the rod to bow, which has repercussions on thermohydraulic conditions in the cooling channel and, ultimately, gives rise to periodic helical wobbling movements of the fuel rod.

These low-frequency fuel rod oscillations now had to be demonstrated also experimentally. This was achieved by the Institute for Materials Research, IMF, in the THIBO test beds in which an electrically heated, generously instrumented rod was operated in a sodium loop. Experimental results indicated that fuel rods may start moving already at relatively low enthalpy rises even if the rod clearance in the spacer was set at low levels.[216,217]



Reproduction of KNK II fuel rod movements in THIBO experiment.

These experiments, which were published in 1991, completed the range of experiments started a full decade ago: At the Institute for Neutron Physics and Reactor Engineering, INR, the reactivity signals of the KNK II in-plant instrumentation had been analyzed in 1981, and very sensitive correlation measurements had indicated nearly harmonic oscillations, which were explained as being due to fuel element vibrations.[218] The mechanism exciting those vibrations at that time had been felt to be either vortices or fluid jets.[219,220]

The failure analysis of the fuel elements of the second core, of course, had direct repercussions on the design of the elements of the third core to follow. As major parts, such as the fuel rods and structural components, had already been manufactured in 1989, not all design parameters could be chosen at random. Actually, the only parameters which could still be influenced were the reduction in the diameter of the cell and the radial displacement of the spacers. Nobody will ever know whether these modifications would have been sufficient to ensure later satisfactory reactor operation. When the operation of KNK II was discontinued in 1991, before the third core was loaded, this probably protected fuel element designers from further criticism, but it may just as well have prevented their achieving high distinctions.

4.2.3 Temperature Drifting at the Fuel Element Outlet

The fuel element vibrations described above were accompanied by another strange phenomenon throughout the whole period of operation of the second core, the so-called temperature drifting at the fuel element outlet, which made it very difficult to separate individual problems and understand their causes.[221]

Temperature drifting manifested itself in a rise in the outlet temperatures of the test elements, not the driver elements, by roughly 1/3°C per full-power day without any changes having been made in the coolant flow through the elements. This temperature rise, which was called temperature drifting, after roughly 100 full-power days caused a fuel element outlet temperature increase by 20-30°C, thus reaching the saturation level. When the reactor had been shut down, this phenomenon disappeared entirely or in part and, with increasing length of operation, returned approximately to its earlier, higher, level. The phenomenon in no way jeopardized the technical safety standard of the plant.[222]

Nobody was able to make head or tail of the situation for almost an entire year until a serendipitous result of an experimental program pointed the right way. In the irradiation of the boiling generator in the reactor core it was found in mid-1984 that the temperature drift previously accumulated had been reduced to zero. Obviously, the pressure impulses generated by the collapsing sodium vapor bubbles had been sufficient to return the outlet temperatures to normal levels. The same results were achieved later by means of an ultrasonic generator deliberately introduced into the core. This at least showed one way of undoing the temperature drift; however, now it was imperative to learn more about its causes.

There were some indications of deposits in the fuel elements partly blocking the cooling channels. Consequently, the IRE institute at KfK performed calculations with the BACCHUS code and arrived at particles in the diameter range of 0.3 to 0.7 mm assumed to have accumulated at the level of the spacers.[223]

However, filtering experiments in the in-plant sampling station did not confirm this assumption, probably because of the non-isokinetic sampling technique. For this reason, special screens were produced for a grid plate location and, in addition, a dummy bundle with 37 rods was operated in the reactor core for some 300 hours. Now, indeed, it was possible to extract particles from the primary sodium. However, their diameter of 0.1 mm and less made them much smaller than had been assumed. In addition, there were agglomerations of even smaller particles, a kind of sludge which, together with the particles, must have caused partial blocking of the cooling channels. The chemical composition mostly showed Fe, Cr, and Ni - elements which had been dissolved out of the surfaces on the hot side of the primary system.[224]

Final confirmation was produced by way of findings in the Hot Cells in 1986. These findings had indicated large areas of depositions structured like rough plaster on the fuel rods, especially at the level of the sixth spacer. These deposits changed the hydraulic drag and the pressure loss, which explains the temperature changes at the outlet of the fuel element. As the KNK II plant was operated in the 60% "soft mode" after 455 full-power days, the phenomenon of temperature drift no longer played any role in subsequent years.[225]

4.2.4 The Rod Actuating Equipment Problem

A difficult problem in operation, not a safety problem, was posed by sticking in the shutdown systems of KNK II. These phenomena were discovered in the actuating equipment of these components between 1986 and 1991 and each time were reported to the supervisory authority as "special events." The rod actuating equipment comprised components which, as the name implies, were located between the absorber effecting shutdown and the drive unit located above the reactor vessel. It incorporated a mechanical coupling, the scram magnets, and the rotating spindle and was located partly within the sodium of the reactor vessel, partly in the argon cover gas plenum, and partly even above the rotating top. This extension over various compartments handling different media finally gave rise to the problems of the component. The four events will be briefly described below; the numbers refer to the consecutive numbers in the reporting record of KNK to the supervisory authority in Stuttgart.[226,227]

(1) Event No. 64

In December 1986, a control rod of the primary shutdown unit for the first time was found to stick while the reactor was down. The cause was found to be sodium aerosols plated out during prior handling steps, when the rod actuating equipment had not been swept with gas.[228]

(2) Event No. 83

In December 1988, deposits were found on a rod of the secondary shutdown system; they impaired the mobility of the component, but not the shutdown function. Probably the fact that the primary system had been opened for maintenance purposes a number of times before had caused the quality of the cover gas to deteriorate and thus produced the deposits.[229]

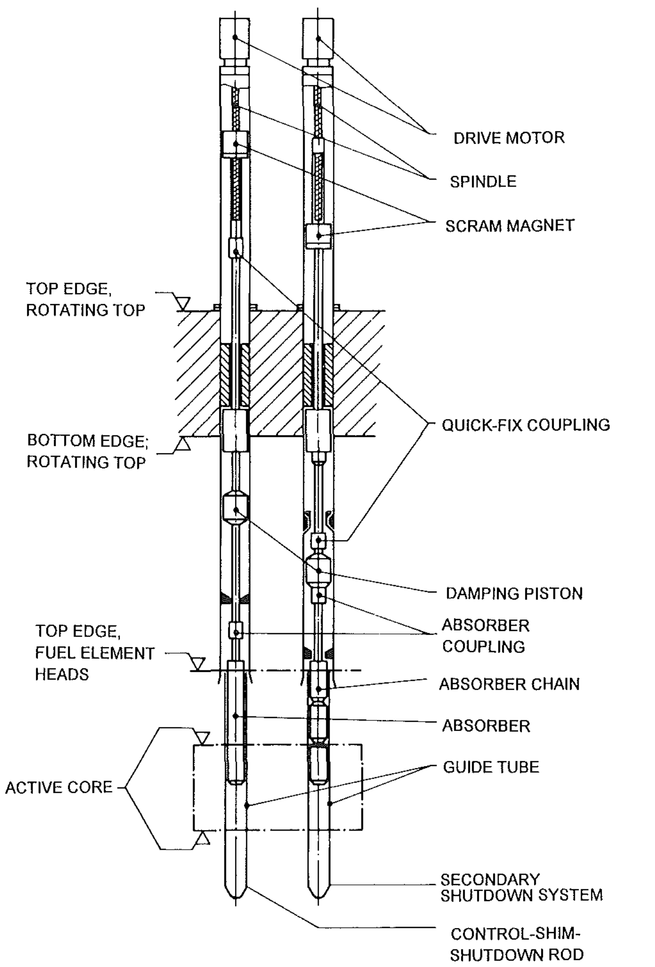
(3) Event No. 97

This occurred in the primary shutdown system in June 1990, when the reactor was operated with 17% load tilting. The sudden downward movement of the absorber initiated a reactor scram via the temperature change rate at the fuel element outlet. When the rod actuating equipment was inspected in the Hot Cells, no deposits were found, but a metal chip was detected and assumed to be the cause of the temporary obstruction of movement in the driving function.[230]

(4) Event No. 103

As in event No. 97, the scram (in January 1991) at 15% reactor operation was initiated by a sudden absorber movement after an obstruction in movement had been overcome. This blockage in the primary shutdown system again was caused by depositions in the rod actuating equipment in a phase in which the cover gas quality had been insufficient.[231]

All events, except for the unique event No. 97, had in common their having been caused by sticking in the rod actuating equipment. When the quality of the cover gas is insufficient, the sodium in the rod actuating equipment is oxidized to sodium oxide whose dough-like consistency impedes lifting movements of the equipment. This diagnosis already includes the therapy: Cover gas had to be free from oxygen and moisture, especially during revision and handling outages. For requalification, a method of flushing the rod actuating equipment in hot sodium was developed. The authority in addition demanded regular measurements of the torque at the drive end, and verifications of the dropping times of the absorbers which, ultimately, are responsible for safe shutdown of the reactor.[232,233]



Schematic representation of the shutdown rods in the primary and secondary KNK II shutdown systems.

The role played by the different chief construction supervisors delegated by Interatom, as listed in the Annex to this report, in helping solve plant problems together with the parent company at Bensberg, must be mentioned especially. In assessing and repairing the sticking control rods, close cooperation of Chief Construction Supervisor Klaus Brockmann with the KNK II Plant Operation Managers at that time (Messrs. Finke, Zimmermann, Pleesz) surely helped to get things done.

International exchanges of experience revealed similar problems at the British PFR and the French Phénix reactors. In those plants, successful remedies had included periodic single-rod operation ("rod exercising"), e.g. during outages. Also in the SNR 300 in Kalkar, depositions were found in some shutdown systems in 1986. They had been caused by outgassing of the granulate contained in the reactor closure head. In that process, moisture must have entered the shutdown rod actuating equipment, causing deposits up to 10 mm thick and very hard, and blocking the movement of six actuating rods.[234]

4.3 Spent Fuel and Waste Management and Core Life Extension

Between 1975 and 1988, a total of 36 permits of all kinds under the Atomic Energy Act had to be obtained for KNK II. No less than 529 conditions had to be met. With the exception of one permit for a storage hall, insignificant with respect to reactor operation, which was successfully delayed by court action, and the difficult permit required to extend core life after the Chernobyl accident, proceedings under the Atomic Energy Act required a tremendous effort, but ultimately went surprisingly well. The problems with the two licensing procedures mentioned above will be described in greater detail; however, first a few comments should be made on the way in which the applicants usually worked with expert consultants and supervisory and licensing authorities.

The applicants, i.e. KfK, KBG, and Interatom, followed the principle of openness and transparency in dealing with expert consultants and authorities. The principle was put into practice at the so-called Completeness Meetings at which, as a rule, KfK, KBG, and Interatom met with the Technical Inspectorate, the supervisory authority and the licensing authority. The special features of a licensing application which, in KNK II, normally included unique aspects, were presented in every technical and legal detail by and for all participants. Each participant at the meetings was allowed to join in the debates, irrespective of his rank or position. This procedure had the inestimable advantage of ensuring that everybody felt informed from here on and worked along the same lines. There were no political demonstrations at clerical or expert levels; an effort was made for the common cause. Practically, Section 1 of the German Atomic Energy Act, according to which these provisions serve to

> *"promote the research, development, and utilization of nuclear power for peaceful purposes,"*

was the general attitude prevailing in these discussions. Of course, this did not imply that matters pertaining to safety were taken lightly; however, the debates about such points covered only technical aspects, not ideologies. This became particularly evident in comparison with the licensing procedure of the SNR 300, which the author, as Project Leader at KfK, was required to go through at the same time.

The expert consultants of the Baden Technical Inspectorate (in particular Dr. Fendler, Dr. Eitner, and Mr. Jurgutat) had a rich background of professional experience; they concentrated on technical matters and never used bureaucratic formalisms as an excuse. Mr. Günther of the Stuttgart supervisory authority was a cautious person; he regularly obtained first-hand impressions of reality by visiting KNK II or, even more often, sending his staff members Dr. Heermann, Dr. Grözinger, Dr. Wörner, Dr. Zimmermann, and Mr. Schwarz on inspection tours of the plant. Mr. Blickle, the chief lawyer of the licensing authority, impressed especially by his grasp of technical conditions in a legal setting.

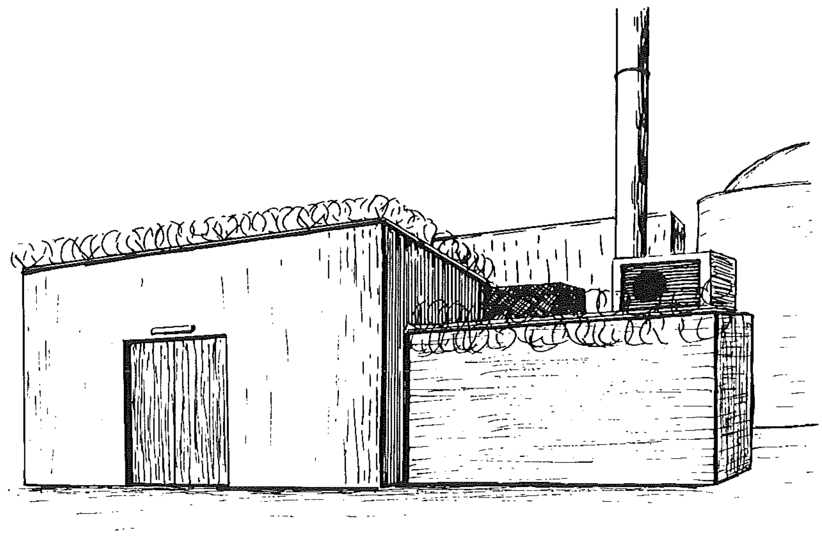
In order not to be accused of describing the licensing procedure of KNK II under the Atomic Energy Act as a smooth, undisturbed process, the author now would like to discuss the only two proceedings fraught with long delays and unforeseen problems.

4.3.1 The Dispute about the Storage Hall

The only legal dispute associated with the KNK I-KNK II double project arose from a rather unimportant building, the storage hall. Upon the urgent request of the KNK plant operations management, and after some hesitation by KfK, it had been included in the KNK II budget in the early eighties and approved for construction. The storage hall was to accommodate mainly large, bulky waste management components; in addition, some chemical hoods for cleaning small parts and a counting room had been planned. The storage hall expressly was not intended for handling spent fuel elements; the components to be introduced into the hall must not be contaminated more than slightly.

With the 4th Amendment to the 3rd Partial Construction Permit, KfK and KBG as the applicants in July 1982 received the permit for building the storage hall from the Stuttgart State Ministry of Economics in an amending decision. It was made the subject of litigation right away on the grounds of the absence of public participation, and in December 1982, Department IV of the Karlsruhe Administrative Court surprisingly accepted the case and decreed a halt of construction.[235] The plaintiff was Mr. Hans Blöchle, a student of mechanical engineering and active member of a

Karlsruhe action group against the Karlsruhe Nuclear Research Center. He was afraid the construction of the storage hall might result in "a concrete hazard to his health."



Arrangement of the storage hall (left), the emergency Diesel power plant building (right), and the reactor (in the rear).

Soon after, in January 1983, the same court, but under a different presiding judge (Dr. Jacob), in emergency proceedings reversed the preliminary injunction and canceled the halt of construction. The court had obtained information about the subject matter on the spot and explained in a uncommonly detailed writ of 31 pages why the unsettled complaint in the main cause "in all probability would remain ineffective."[236]

That assumption, however, was a mistake. The main proceedings took place in March 1984, and the very same administrative court now again canceled the permit for the storage hall, which building had already been completed. In the underlying reasons for that decision it was pointed out that the construction plans should have been laid open for public inspection. Especially in case of an earthquake, the building for the emergency Diesel power plant, which was very close to the hall, would have been endangered and could possibly have become inoperative.[237]

What was to be done? The storage hall had been completed, but could not be used. The State Ministry of Economics in Stuttgart, as the authority against which proceedings were directed, lodged an appeal with the Mannheim Administrative Court by way of the State of Baden-Württemberg, but nobody knew how long these proceedings might take, and nobody was able to guarantee whether "our side" would win in the end.

"At sea and in court you are in the hands of God." The validity of this statement had become apparent again .

At long last, the licensing authority and the applicant decided to remedy the "legal deficiency" the court of law had criticized, and to agree subsequently to a public hearing of the objections. In line with the rules of procedure under the Atomic Energy Act, the application, the safety report, and a brief description of the building project were laid open for inspection at the mayors' offices in the municipalities in the neighborhood in 1984.[238] One last delay was caused by the fact that, shortly before the end of the two-months period, the safety report was stolen from the Eggenstein townhall. For formal reasons, it had to be laid open once more for the period between September and November. The culprit, of course, was never found. *Cui bono?*

The public inquiry was held at the Leopoldshafen "Rheinhalle" on December 12, 1984. Roughly one dozen of the 600 objectors had appeared; they faced an equally large number of of KNK II experts. The sovereign director of the inquiry proceedings was Mr. Heitmann from the State Ministry for Economics. Of course, the debate focused on the alleged safety deficits of the storage hall. The main objector, Mr. Blöchle, again, and quite skillfully, recited the reasons for his opinion that seismic safety had not really been proven, in addition referred to the hazard of airplane crashes (in fact, one year before that date, an airplane had crashed 5 km south of KfK), and finally raised the point of a "drastically increased danger of war" caused by the recent stationing of Pershing II missiles. Other objectors referred to the "fire hazards associated with sodium" in the chemical compartments. Finally, Mr. Wilhelm Knobloch, the forester who wouldn't miss an inquiry, and who was later awarded the Federal Cross of Merit, criticized the defective description of the site within his beloved Hardtwald forest. After a few hours, all objections had been discussed thoroughly, and the parties separated peacefully, though not in agreement.[239]

Almost nineteen months later, in April 1986, the authority finally issued the permit to use the storage hall, now complete with all the legal trimmings.[240]

4.3.2 The Licensing Procedure on Core Life Extension

A few months after the beginning of operation with the second core it had become evident from the reactor physics data that it would be possible to operate the core beyond the 455 full-power days conservatively assumed. More precise calculations showed that utilization of the reactivity reserve of the core, and the addition of four moderated driver elements, would be able to raise the core life to 720 full-power days, corresponding to a maximum local burnup of 100,000 MWd/t. Accordingly, an application for the so-called extension of core life was filed in May 1984.[241]

The State Ministry of Economics, still licking the wounds it had suffered in the lawsuit about the storage hall which it had lost just two months before, immediately arranged for the public inquiry into the desired extension of core life plus a few other projects applied for. The application therefore ran as follows:

> *"Extension of the life of the second core from 455 to 720 full-power days and continuation of the experimental program, and canning of the fuel elements for transport purposes."*[242]

This was announced officially by the Ministry, and the required documents, such as the safety reports, were laid open for public inspection between January and March 1986 at the mayors' offices in the surrounding municipalities. This time, the documents were chained to the tables.[243] The inquiry was scheduled for May 26, 1986.

Between March and May, on April 28, 1986, the accident at Chernobyl occurred. This traumatic event for weeks and months confused the public, authorities, and also scientists, and reason seemed to stand very little chance. Holding a public inquiry into a fast breeder project in those turbulent times had to be considered well in advance; some people thought it was sheer madness.

It would have been possible to postpone the inquiry by a few months. At the end, however, KfK Executive Board member Professor Hennies decided to stick to the original date in May, using the logical argument that our valid reasons for prolonging the core life were independent of the events at Chernobyl and would not improve if we waited for a couple of months. At the same time, however, he asked for thorough preparation of the inquiry.

And thoroughly prepared it was. The objections received, which extended from breeder politics through nuclear and engineered safeguards problems to legal matters, were analyzed and subdivided into almost one hundred issues of detail.[244]

A team of roughly fifteen experts from KfK, KBG, and Interatom drafted written answers which were checked and doublechecked for correctness.

The public inquiry again was held at the Leopoldshafen "Rheinhalle" and was directed by Mr. Ostberg of the State Ministry of Economics. Right away he was challenged for bias on the grounds that he had been instrumental in the permit issued for the storage all, which the court then had rendered invalid. However, after a consultation with the Ministry over the telephone, the motion was denied, as was a motion brought against the operator, KBG, for alleged unreliability.

The student Hans Blöchle, still masterminding the Karlsruhe antinuclear scene, recognizably was the moving spirit behind the two dozen or so opponents present. He put things in a nutshell, followed up whenever he found the answers to be incomplete, and even went so far as to criticize what he called the "mess" on the Stuttgart desk of the chairman of the meeting. For the rest, the event proceeded in an orderly fashion; the questions were addressed to the author of this report, who mostly repeated them in order to gain time, added a few sentences of his own and then called upon one of his experts, who had been briefed before, to answer the question. The list of technical objections had been exhausted by the afternoon. The verbatim record of the event was 124 pages long and later was sent to each of the opponents who had attended.[245]

Although the inquiry took place in a calm atmosphere, it clearly differed from all those organized before. Chernobyl was mentioned in many contributions, and the chairman quite rightly did not suppress such references. People, who clearly were no professional opponents, again and again expressed their shock at the fact that such an accident could have happened. The complaint by a woman who introduced herself as a mother of six children will probably be remembered by everybody present. In her sober, non-technical way she made it clear to the nuclear experts attending what responsibility they had in handling this risky technology.

The licensing authority then took another two and a half years to actually issue the permit extending core life in December 1988.[246] The reasons for this long period of time in part were due to the fact that, after Chernobyl, any nuclear license automatically was something "to be handled by the boss" and checked and doublechecked even more painstakingly than before; in some way, also the problems associated with the operation of KNK II may have been a reason, such as the deposits on the rod actuating equipment in the shutdown systems.

Not unexpectedly, the permit became the subject of a court action just one month after it had been issued; that action was brought with the Mannheim Administrative Court in January 1989.[247] The grounds cited were all the defects and disturbances which the operator, KBG, used to publish in the annual reports printed in the ATOMWIRTSCHAFT and ATOM + STROM journals. They related primarily to fuel rod defects, temperature drifting, sticking shutdown rods, and the spent fuel problem. In February 1990, KfK and KBG drafted a comment, and in June 1990 the plaintiff withdrew his application (because of the cost risk), which made the permit legally valid for good.[248,249]

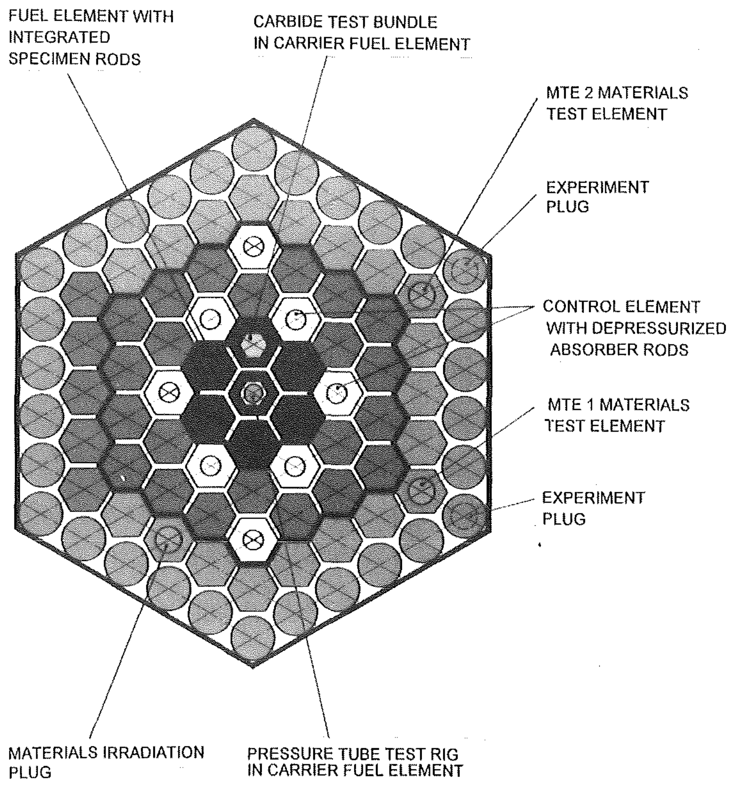
4.4 The KNK Experimental Program

An experimental program was run in KNK II which actually had been started back in 1971, still in KNK I, and had then become more and more extensive. These R&D activities were partly mixed with plant operation, for KNK II, by definition, was an experimental nuclear power plant in which electricity generation was not supposed to play the primary role. As a consequence, irradiation of the reactor cores, each of them a first-of-its-kind unit, could also have been assigned to the experimental program, as could have been the detection and localization of fuel rod failures.

The close connections between operation and research became particularly apparent whenever reactor disturbances occurred, such as the temperature drifting or the fuel rod vibrations described above. These occurrences, which gave little cause for joy to the operating crew, did present welcome opportunities to the scientists of KfK and Interatom to demonstrate their diagnostic capability, mostly with equipment developed in-house. It is worth recognizing that the teams of operators and research scientists assisted each other to the best of their capabilities, without especially being asked to do so, whenever an incident occurred.

A number of experiments conducted in KNK II also were very important for the SNR 300, especially when the Kalkar project had been resumed in late 1982, after the political obstacles had been overcome. One example to be mentioned are the hydrogen detectors for the steam generators of the SNR 300, which had to be tested first in KNK II; this also applied to the fuel element check device, whose sensitivity had to be examined in KNK II. Most important, however, was the test of the core outlet instrumentation for the SNR 300; its positive outcome even constituted a precondition for the permit for that reactor. As an "important interim finding," WZE 2.02, it kept the scientists busy for a couple of years.

In order not to exceed the framework of this description, only a few experiments selected from three subareas will be described below. The whole experimental program comprised 30 to 40 individual experiments, which were coordinated with circumspection by Werner Kathol, a member of the PSB Project Management Staff, and also managed with respect to the licensing procedure and international exchanges of experience (AGT 8).[250]

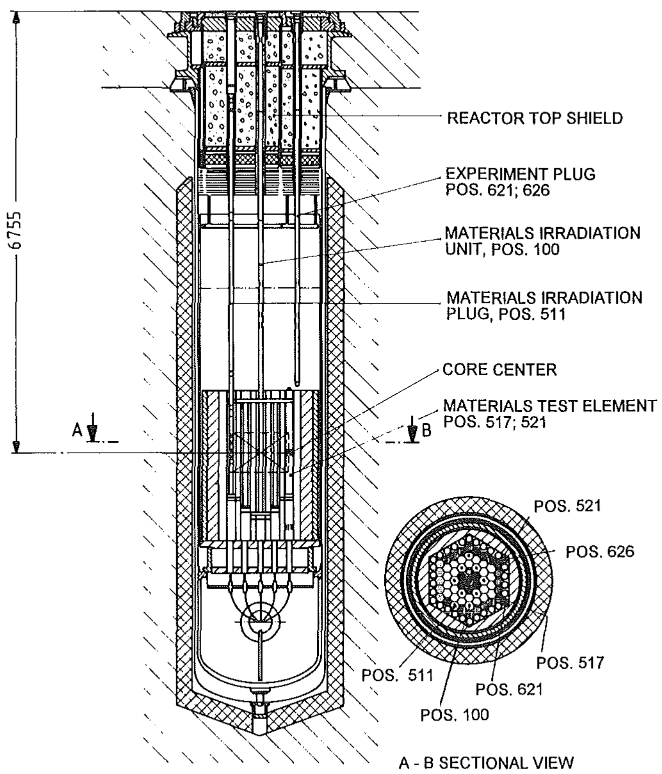


Positioning the in-pile experiments in KNK II/2.

4.4.1 Physics Experiments

An important physics experiment was the use of a boiling generator in the central position of KNK II. It was to demonstrate that sodium boiling, which could have arisen, for instance, in fuel element blockages, can be found out by suitable detectors.

To generate the boiling signals, a dummy element with 18 electrically heated rods was used in the position of the central fuel element. Specially designed microphones were installed in various positions of the core to detect and transmit the boiling noise. The experiments were run with the nuclear part of the plant shut down, but with the full sodium flow in operation, in order to obtain representative cooling and temperature conditions. The outcome of these safety experiments was extremely satisfactory: Boiling could be detected unequivocally by the sensors in all positions.[251]



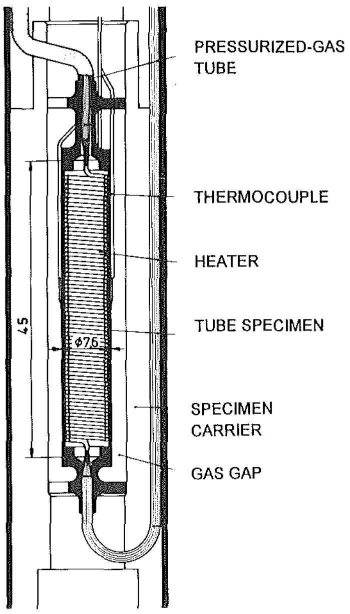
Cross section through the KNK II reactor vessel with the experiment plug.

The physics experiments in the reactor core were moved into place by experiment plugs 6 m long. These were very sophisticated special designs inserted into the reactor top shield, which transmitted signals from the core position to the experimentalist. A maximum of four plugs were moved in position simultaneously in KNK II. Detlef Artz was responsible for the design and sourcing of these important components as well as for the informative pamphlet describing the KNK II experimental program.[252,253]

As the plugs were costly objects, they were normally crammed with all kinds of measurement probes. In the test mentioned above of the core outlet instrumentation for the SNR 300, for instance, three different types of acoustic transducers, two different flowmeters, and various thermocouples were accommodated in one single plug. It was operated for nearly 7000 hours and supplied important findings about the long-term behavior of these detectors under high reactor radiation and sodium temperature. Incidentally, most of the defects encountered in the sensors were not caused by neutron radiation, but by the temperature shocks unavoidably associated with reactor shutdowns. In most cases, sodium entry caused the defects. Continuous improvement and quality insurance, however, was able to reduce successively the failure rate in these transducers.

Another important topic pursued in KNK II were noise analyses. These were evaluations of the signals of neutron flux, temperature, pressure, and acoustic signals which had originated either from the in-plant-instrumentation or obtained through special transducers.[254] The scientists, especially those of the INR, IRE and IRB institutes at KfK, checked by autocorrelation whether parts of the noise were periodically recurrent.[255,256] Often, the frequency revealed the cause of a repetitive noise fraction, for instance when it agreed with the eigenmodes of a reactor component. Cross correlations of various signals provided information about the propagation in space of an event. One example to be cited here are the harmonic oscillations of fuel elements described above, which were successfully demonstrated by this method.[257,258]

4.4.2 In-pile Experiments



Tube specimen subjected to internal pressure in the materials test element.

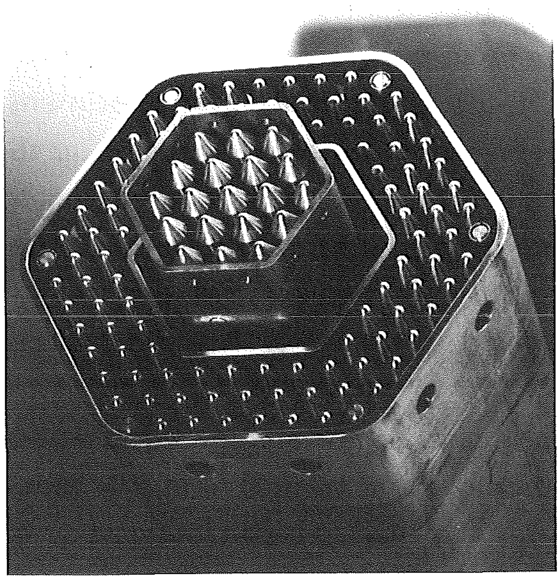
Irradiation experiments occupied most of the capacity and time of the KNK II experimental program. In most cases, cladding materials and structural materials, fuel rods, and absorber materials were irradiated. Technically sophisticated in-pile facilities were required for these activities; the IMF III institute of KfK deserves credit for providing them, mainly pressure tube test rigs, materials test elements with and without instrumentation, and a variety of carrier elements and small bundles.[259]

The pressure tube test rig allowed eight tubular specimens to be irradiated in the central position at the same time. The specimens were subjected to internal pressures of up to 500 bar; their temperatures could be controlled with high precision up to 800 °C. The pressure and the temperature could be set individually for each specimen. The eight specimens were arranged in the bottom part of an experimental plug, which accommodated also the measurement and control lines. For reactivity reasons, they had to be surrounded by a ring-shaped carrier element in the central position. The phenomena studied included creeping and the creep-rupture strength of the tubular specimens as a function of radiation, temperature, and stress.

The reloadable materials test elements had the contour of an ordinary fuel element and were able to accommodate either open or encapsulated specimens. In the former case, they assumed the temperature of the sodium flow around them while, in the latter case, they reached higher temperatures because of the absorption of gamma radiation. In the capsule specimens, the specimen temperature was set by means either of a gas gap or a heating tube. This heating tube kept the temperature at the desired level even when the reactor power was changed.[260, 261]

The Fast Breeder Project, for some time, also looked into carbide fuels in addition to the mixed oxide irradiated in many variants in the KNK II core. Carbide fuels have a rather high melting point, better thermal conductivity and, consequently, allow much higher powers per rod unit length to be achieved than oxide fuels. In conclusion of the KfK activities in this field, therefore, a small carbide bundle was irradiated in KNK II. It consisted of 19 rods integrated in a carrier fuel element with 102 test zone rods. Irradiation was conducted between 1984 and 1988 and attained a burnup of 80,000 MWd/t. The fuel is to be reprocessed in Dounreay.[262,263]

Two very interesting in-pile experiments had been prepared for the third core load of KNK II: TOAST and TETRA, which were never put to any practical use because the reactor was shut down permanently in 1991. The tolerance expansion study, TOAST, was to examine the specifications for unnecessary complications;[264] the TETRA temperature transient experiment was to study fuel rod behavior under temperature cycling and overload conditions.



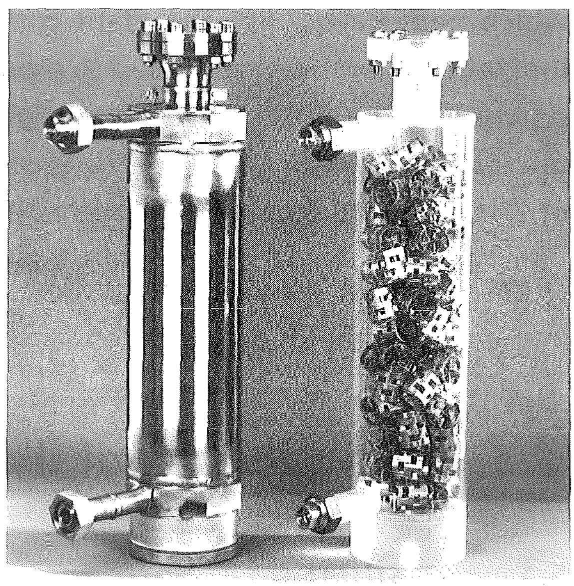
Small bundle element with
19 carbide rods (inside).

Mention should also be made of the absorber irradiations, which were conducted in connection with the absorber elements of the primary shutdown system. On the basis of boron carbide granulate, open and closed pressurized absorber rods with B_4C pellets and europium oxide compounds, which had the benefit of not releasing any helium, were irradiated in the second core.

In coordinating all these in-pile experiments, the Core Components Working Group (AKK) headed by the late Professor Karl Kummerer played an outstanding role. The objectives of the different irradiation experiments were defined, the design and construction of facilities was started, and the in-pile results were analyzed at 113 sessions between 1973 and 1991. Over that long period of time, the cooperation between AKK and the PSB Project Management Staff was characterized by absolute mutual confidence.[265]

4.4.3 Sodium Chemistry and Operations

Considerable effort was devoted to studies of the sodium and the cover gas. This was an area in which the activities of plant engineers and those of scientists frequently overlapped. The experimental program on sodium chemistry, among other topics, looked into the development of methods of analyzing the coolant and the cover gas, the difficult area of sodium sampling, and tests of oxygen and carbon probes.[266,267] In addition, corrosion and the development of protective coatings as a function of various operating conditions were studied in the steam generator.[268,269]



Cesium traps (plexiglass models).

KNK II was the only breeder power plant in which seven parallel specimens could be extracted from the primary coolant flow at the same time. An extensive program was conducted to analyze a large number of radionuclides in sodium, also as a function of the coolant temperature and the crucible material. Extensive experiments run especially with nickel supplied valuable information about the selective sorption of nuclides.[269] On the basis of further studies it was possible, in the summer of 1988, to install in KNK II a so-called cesium trap and run it successfully for several campaigns. It removed from the primary coolant the longlived cesium nuclides, which contributed greatly to the exposure doses in plant compartments. Sorbents, such as RVC and Sigratex, turned out to be most effective in these traps;

they resulted in small volumes, albeit at the expense of certain problems associated with the removal of these concentrated radiation sources.[270]

The tritium content of the tertiary steam system was determined for many years. Tritium is produced in the nuclear fuel by ternary fission, also in the B_4C of the absorber rods and, because of its high diffusivity, migrates from the primary to the tertiary systems. The influence of the secondary cold trap on the concentration of tritium found in the steam generator region was of particular interest.[271]

Plant engineering experiments concentrated on observations of the dose rates in the primary cells, studies of aerosol behavior, and inspection of the sodium valves.[272] Other activities were devoted to plant safety and plant dynamics, especially to the verification of theoretical models.[273] Also the natural convection of sodium after shutdown of the KNK II plant was the subject of extensive studies. In one test, the outlet temperature of the reactor was used as a set point value in temperature control. To check the shielding calculations, finally, an experiment plug was equipped with activation probes to determine the radiation fields actually existing between the core and the reactor top shield.

For measurements of the dose rate in the primary cell, an immersion tube was built which penetrated into the plant compartments in a vertical direction. Calibrated ionization chambers were used to measure the dose rate as a function of the reactor power and the duration of an outage, respectively, in positions planned for maintenance. Of course, Na 22 contributed most of the activity, but also sizable amounts of Zn 65, Ag 110m, and Mn 54 were detected.

These were just a few examples meant to give an impression of the variety of items in the experimental program conducted in KNK II.

5 Termination of the Project

5.1 Situation Report

The two-year outage of KNK II in 1988/89 because of technical problems with the rod actuating equipment and the lack of a permit to extend core life was ample reason to consider the fate of the plant. Added to this was the *de facto* standstill of the SNR 300 in Kalkar, which had become the subject of a political and legal tussle.[274]

Irrespective of future events, KNK II by that time had fulfilled all the objectives for which the project had once been launched. In particular, its very existence had demonstrated that it was possible to build and operate safely a sodium cooled fast breeder in Germany, and do so in accordance with the severe licensing criteria applicable in this country. The first core attained a peak burnup of 100,000 MWd/t, and one element was even operated up to 175,000 MWd/t. The second core developed not more than a dozen of rod failures with clearly defined causes, which surely would have been avoided by future design modifications. The breeder fuel cycle was closed for the first time in Germany, albeit only on a kilogram scale.

The achievements of the past had to be weighed against the risks posed by the future, however.

5.1.1 The Situation of KNK II

In evaluating the situation of KNK II, especially technical, licensing and manpower aspects had to be considered.

The technical situation was linked to the fact that the plant, which had been commissioned as KNK I in 1971, was almost twenty years old by now. Comparable sodium reactors in other European countries had been decommissioned after only sixteen years: the British DFR (run between 1961 and 1977) and the French Rapsodie (1967 - 1983). Certain problems in major components could not be overlooked, for instance in the fuel elements (wear, sodium deposits), the absorber rod actuating equipment (aerosol plate-out), and the primary pump (vibrations). Though they did not jeopardize plant safety, they did impede operation and reduce availability. Any future failure of major large components, such as the intermediate heat exchanger, the fuel handling machine, or the impulse turbine, could have caused a bottleneck in spare parts supply. Investigations of embrittlement of the vessel by IMF II were still under way.

Also the licensing situation was fraught with risks. The permit under the Atomic Energy Act for extending the life of the 2nd core had been applied for in 1984, issued as late as in December 1988, and then immediately become a subject of litigation. For the 3rd core, most of whose fuel rods had been fabricated by Alkem (now Siemens), the safety report was being compiled. The authority had already announced its intention to hold an inquiry with a public disclosure of the documents and a hearing of the opponents. In the light of the experience accumulated with the second core, this meant that the operating permit would not come forth before the end of 1992. The risks which could arise from the "check of the technical safety aspects of the whole plant" already ordered by the authority were hardly calculable. Certain conditions relating to fire protection, airplane crash, and core meltdown, which had already been put into effect in the SNR 300, probably would have gone beyond the backfitting possibilities of the old KNK II plant. Finally, also the licensing problems associated with the Hot Cells had to be borne in mind. Although a permit to increase the plutonium inventory had been applied for as early as in 1977, it was only issued in 1989 and carried rather extensive measures of physical security.

Also the future manpower situation of KNK II had to be considered. Had the third core been loaded, reactor operation would have had to be organized approximately up until 1998 and, if unloading the fuel elements had been considered, even up until the year 2000. This would have meant recruiting young technical personnel. Whether this would have been possible with the required level of quality, in view of the negative public breeder debate, is a mute point.

The situation in KNK II was covered in exchanges of information between decisionmakers and other responsible parties in 1988/89.[275,276] In addition to the Executive Board of KfK and the Project Management Staff, especially Interatom, KBG, and Alkem joined in those discussions.[277,278] It should not be overlooked that Alkem in particular was a strong advocate of the continued operation of KNK II, naturally also out of a certain vendor's interest. Especially Dr. Höchel conducted very profound analyses of the situation of the plant and made remarkable technical and administrative suggestions.[279,280]

The Supervisory Board was informed at the semiannual meetings and, in addition, by detailed letters.[281] These deliberations were brought to an end, for the time being, by a letter of Executive Board member Prof. Hennies to the Chairman of the Supervisory Board of KfK in October 1989. In view of the fact that KNK II had been down for almost two years, the following decisions were announced:

> *"The 2nd core will be operated to the end of its life so as to make full use of the present permit... Should no satisfactory long-term operation be achieved, decommissioning will be reconsidered in the spring of 1991 at the latest.*
>
> *The question of loading the 3rd core will also be discussed finally in the spring of 1991..."*[282]

Let us now briefly look at the SNR 300 master project and its political environment.

5.1.2 The SNR 300 and Its Political Environment

Construction of the SNR 300 was begun in Kalkar on the Lower Rhine River in March 1973. After speedy initial progress, the project ran into trouble in the following years. Numerous modifications demanded by the licensing authority in the field of intermediate heat exchangers and the emergency core cooling systems required time consuming and costly changes in planning. In addition, there were the conditions imposed to manage core meltdown, the so-called Bethe-Tait event. By 1976, the extra cost had already added up to DM 750 million, and the delay had grown to 20 months. The year after, the former responsible project officer, Dr. Klaus Traube, left Interatom and changed into the camp of the nuclear opposition.[283,284]

Between 1979 and 1982, a Committee of Inquiry established by the German Federal Parliament spent almost four years scanning the Kalkar project and finally voted in favor of continuing construction of the breeder power plant with a majority of more than two thirds.[285]

When the Christian Democrat-Liberal Federal Government took office in October 1982, after the so-called "Wende," the previous stagnation came to an end. Construction work now led by Wulf Bürkle progressed speedily, and when the primary systems had been filled with sodium in May 1985, plant construction as defined in the delivery contracts was completed. After some reworking (recovery of a vibration measurement lance, drying the closure head granulate) the plant could have been commissioned in 1986.[286]

That step, however, did not take place, for the political wind had changed in the meantime. The Social Democratic Party (SPD), which ruled the State of North Rhine-Westphalia with an absolute majority, now propagated the so-called coal-first policy under Minister President Johannes Rau, and Minister Farthmann, who had been responsible for the Kalkar permits so far, expressed himself against commissioning the SNR 300.

In April 1988, Federal Minister for the Environment Töpfer decided to issue instructions to the State of North Rhine-Westphalia in the further execution of the licensing procedure. The State responded by suing the Federal Government before the Federal Constitutional Court in Karlsruhe. The court decision was not expected until one or two years' time; in the interim period, the Kalkar project was kept dormant.[287]

In the meantime, in April 1989, an important decision was taken in a different field of nuclear power: Mr. Bennigsen-Foerder, the CEO of Veba AG and one of the main partners in DWK, decided rather abruptly (at least to outsiders) to withdraw his company from reprocessing in Germany, thus terminating the Wackersdorf project. The breeder reactor, which absolutely required reprocessing, thus had been robbed of an important (national) component. It meant a sudden end to the Reprocessing and Waste Management Project (PWA) of the Karlsruhe Nuclear Research Center.[288,289]

KfK, which had been neither a party to, nor had been informed of, this far-reaching decision by the VEBA CEO, from now on had to represent its interests more vigorously, for instance with respect to the breeder reactor and KNK II. The Chief Executive Officer of the Nuclear Research Center, Professor Horst Böhm, expressed this need in his address at the 1989 annual reception.

> *"The Wackersdorf decision once more has shown the limits to, and the reliability of, long-term planning in many areas of applied research. At the same time, it has made it clear that, next to the quality of research, also* ***flexibility*** *is a parameter just as important in evaluating a research institution as the detailed long-term R&D planning requested again and again."*[290]

In October 1989, the Fast Breeder Project (PSB), which had been existing since 1960, was terminated by agreement between the Executive Board and the Project Management Staff. The greatly reduced residual activities were combined with some R&D topics in the light water reactor sector to make up the Nuclear Safety Research Project (PSF). KNK II was separated from that area and came under the responsibility of G. Schnetgöke, as mentioned above.

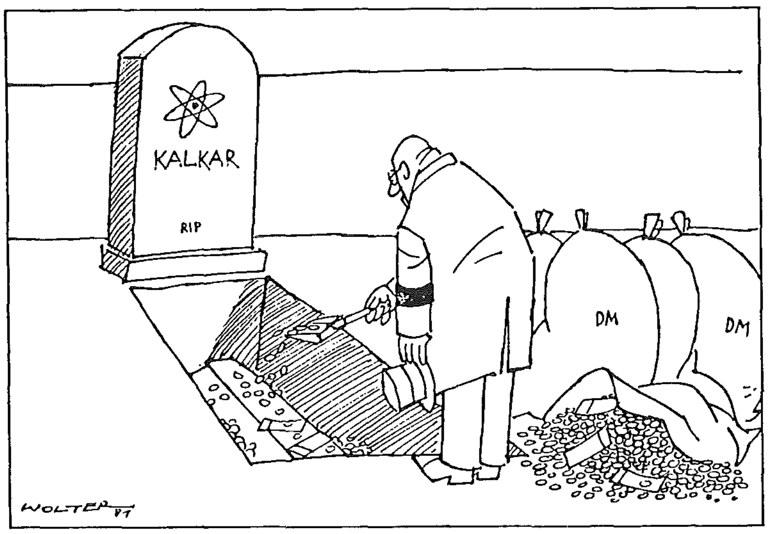
5.2 The Termination of German Breeder Projects

5.2.1 Discontinuing the Kalkar Nuclear Power Station

The ruling by the Federal Constitutional Court in May 1990 came as a pleasant surprise. The action brought by the State of North Rhine-Westphalia was dismissed on all points; consequently, the Federal Government had been right in exercising its competency to issue instructions. In the reasons underlying their ruling, the judges found that the Federal Government has the so-called technical competency in proceedings under the Atomic Energy Act, i. e. the responsibility for assessing the technical aspects; the federal state is required to obey the instructions issued by the Federal Government.[291]

Yet, the Kalkar project did not progress even after that court decision. The end of the SNR 300 was decided at a meeting on March 20, 1991, for which Federal Minister for Research Dr. Heinz Riesenhuber had invited the representatives of the three electricity utilities, RWE, PreußenElektra, and Bayernwerk, and Siemens. In reviewing the situation, the participants agreed that the attitude taken by the State of North Rhine-Westphalia made it unlikely that an operating permit would be issued. To avoid further expenses, it was therefore decided to discontinue the project. The press release issued the next day read:

> *"The responsibility for the discontinuation of Kalkar, in the opinion of the participating electricity utilities, the vendors, and the Federal Ministry for Research and Technology, clearly rests with the State of North Rhine-Westphalia."*[292]



Paying a final tribute.

The participants also agreed that the breeder option and the expertise accumulated by the experts were to be preserved by continuing the European breeder association within the framework of the European Fast Reactor, EFR - a promise which became null and void already one year later as a result of the stop of funding decreed by the Ministry vis-à-vis Siemens/Interatom and KfK.[293]

5.2.2 KNK II Is Shut down

The discontinuation of the SNR 300 changed the breeder scene in Germany and had direct consequences, above all, for KNK II. As no R&D activities were required anymore for the Kalkar master project, the experimental program run in KNK II clearly had to be reduced.[294] This was true in particular of reactor-related research activities. A new trend had been initiated at Interatom, but also at KfK. The nuclear programs had been scaled down more and more in recent years in favor of new research activities in nuclear fusion, the environment, and microstructure engineering. KNK II had become more or less superfluous as an experimental reactor.

When the Kalkar project had been given up, this also removed the need to test new reactor core variants in KNK II.[295,296] Consequently, there was no need either to irradiate the almost complete third core, for it should have been the precursor of the reload for the SNR 300.[297] There was an added new legal risk. Immediate execution under Section 80 of the Administrative Court Rules certainly would have been more difficult to attain in future permits under the Atomic Energy Act, because the SNR 300 could no longer have been used as a reason. The benefit of a permit without the possibility of simultaneous immediate execution would have been very limited; a lawsuit, which had to be expected practically all the time, would have made it impossible to use the permit.

In summer 1991, roughly three months after the discontinuation of the Kalkar project, all technical and political aspects pertaining to KNK II had been discussed with the partners and the Supervisory Board. It was up to the Executive Board of KfK to take a decision, more specifically to Professor Hans-Henning Hennies, who had been closely associated with the plant from the beginning. As a young scientist, he had worked for the neutron physics experiments on KNK I at Interatom; in the early seventies, he had been technically responsible for the core design of KNK II and, from 1975 on, as an Executive Board member of KfK, argued with the partners in favor of converting KNK I to KNK II, and subsequently had been responsible for the operation of KNK II. Now it was up to him to determine the fate of the plant.

In the light of all the conditions listed above, Professor Hennies decided that KNK II was to be shut down on Friday, August 21, 1991 after completion of the ongoing experiments about control rod oscillation.[298] He handed a written instruction to this effect to the Managing Director of KBG, Mr. Steiger, who had returned from his vacation, at 10.30 on the same day. Mr. Steiger, in turn, commissioned his Operations

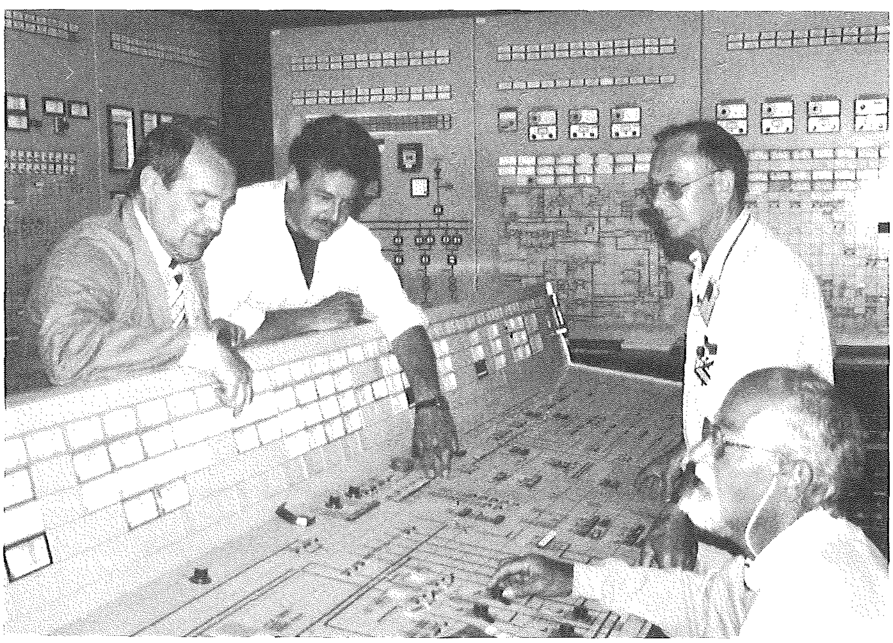
Manager (Mr. Pleesz) to carry out the instruction. The plant was to be shut down around lunchtime by the early shift.

What followed was routine.[299]

At 12.00 noon, Shift Supervisor Bernhard Kunle ordered his deputy Roland Lang to reduce the feedwater flow by operating valve RD3R1. The automatic reactor control system reacted by reducing the coolant flows in the secondary and primary areas and, subsequently, by inserting the control rods. At 1.36 p.m. the plant power had dropped to approx. 2 MWe, and then the turbine was tripped and shut down.

The late shift led by Günter Theil took over at 2 p.m. They supervised the further decrease of the differential temperature between the reactor inlet and the reactor outlet, and Günter Theil instructed his operator Rolf Zimmermann at 9.56 p.m. to activate the primary and secondary shutdown systems. When Mr. Zimmermann, at 10 p.m., had unlocked the SS 63 "solenoid current off" key operated switch, the shutdown process was completed.

KNK II was down for good.[300]



KNK II is shut down for good.
From left:
Kunle, Lang,
Zimmermann,
Theil.

Literature

1 W. D. Müller:
"Geschichte der Kernenergie in der Bundesrepublik Deutschland; Anfänge und Weichenstellungen."
Schäffer Verlag für Wirtschaft und Steuern GmbH, Stuttgart, 1990, pp. 366-85 and 425-28.

2 K. Winnacker und K. Wirtz:
"Das unverstandene Wunder."
Verlag Econ, Düsseldorf, 1975.

3 O. Keck:
"Der Schnelle Brüter; Eine Fallstudie über Entscheidungsprozesse in der Großtechnik."
Campus Verlag, Frankfurt/New York, 1984, ISBN 3-593-33339-2.

4 H. Schöller:
"Kernenergie für die Elektrizitätswirtschaft - aber wann?"
atomwirtschaft 1, 1956, pp. 331-32.

5 W. Cartellieri et.al:
"Taschenbuch für Atomfragen."
Festland-Verlag, Bonn, 1969.

6 "SRE kritisch."
atomwirtschaft, June 1957, p. 206.

7 "OMRE in Betrieb."
atomwirtschaft, October 1957, p. 343.

8 "Demag und NAA gründen Interatom."
atomwirtschaft 3, 1958, p. 37.

9 "Interatom zieht um."
atomwirtschaft, January 1959, p. 42.

10 "INTERATOM aktuell."
Sonderausgabe - 30 Jahre Interatom,
Informationen für Mitarbeiter.
Interatom, No. 30, January 1988.

11 "Siemens muß Standort Bergisch Gladbach schließen."
Siemens Presseinformation für die Wirtschaftspresse, Erlangen,
KWU 0393.062 d, March 30, 1993.

12 "Demag-Angehörige werden bei Atomics International ausgebildet."
atomwirtschaft, June 1958, p. 251.

13 R. Harde, K.W. Stöhr:
"Die Kompakte Natriumgekühlte Kernreaktoranlage Karlsruhe (KNK)".
Pt. 1: atomwirtschaft, July 1966, pp. 354-60 and
Pt. 2: atomwirtschaft, August/September 1966, pp. 448-53.

14 K. Einfeld, E. Ruppert:
"Experimentelle Bestimmung der Neutronenspektren und der Abklingzeitkonstanten in Zirkoniumhydrid als Funktion der Temperatur."
Nukleonik, 7, 1965, pp. 452 ff.

15 K. Einfeld, G. Memmert, W. Ullrich, P. Wiesner:
"Theoretical and Experimental Investigations of Slightly Enriched Zirconium-Hydride Moderated Lattices."
Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, August 31 - September 9, 1964.
Proc. of the conference, volume 3, Reactor Studies and Performance, United Nations, New York, 1965, P/645, pp. 291-99.

16 A. Brandstetter, H.-H. Hennies:
"Die Kritische Anordnung KNK."
Atomkernenergie, vol. 9, 7/8, 1964, pp. 259-62.

17 H. H. Hennies:
"Cross-Sections and Resonance Parameters for ^{235}U, ^{233}U, ^{239}Pu and ^{241}Pu between Cadmium Cutoff and 10 keV."
Proc. of a Conference on Nuclear Data - Microscopic Cross-Sections and other Data Basic for Reactors held by the International Atomic Energy Agency in Paris, October 17-21, 1966. Two volumes. IAEA, Vienna, 1967, vol. II, pp. 333-58.

18 H. Reichel, E. Ruppert:
"Messung des totalen und schnellen Neutronenflusses in der 'Kompakten natriumgekühlten Kernreaktoranlage,' KNK-I".
Atomkernenergie (AKTE) vol. 31, 3, 1978, pp. 137-43.

19 H. Hübel, D. Knecht, H. Mausbeck:
"Safety Aspects of the Experimental Power Station KNK."
Nuclear Engineering, 10, 1965, pp. 335 ff.

20 H. Hübel, O. Knecht, H. Mausbeck:
"Reaktorsicherheit bei positiven Leistungskoeffizienten der Reaktivität am Beispiel des KNK." Pt. 1: atomwirtschaft, 10, 1966, pp. 506-10.
"Reaktorsicherheit bei positivem Leistungskoeffizienten der Reaktivität am Beispiel des KNK (II)." Pt. 2: atomwirtschaft, 11, 1966, pp. 566-68.

21 J. Motz:
"Über das System Zirkon-Wasserstoff."
Zeitschrift f. Metallkunde, 53, 1965, pp. 770 ff.

22 P.Paetz:
"Über die Wasserstoffaufnahme von Zirkonhydrid, über seine Gitterparameter und über sein Verhalten bei der Bestrahlung mit schnellen Neutronen."
Fakultät für Bergbau und Hüttenwesen der RWTH Aachen, Ph. D. thesis, 1970.

23 P. Paetz, K. Lücke:
"Über die Dichteänderung von Zirkonhydrid bei der Bestrahlung mit schnellen Neutronen."
Journ. Nucl. Materials, vol. 43, 13, 1972, pp. 13-27.

24 J. Motz:
"Untersuchung einiger warmfester ferritischer Stähle auf ihre Verwendbarkeit in Natriumanlagen bis zu Temperaturen von 600 °C."
Zeitschr. f. Metallkunde, 55, 1964, pp. 485 ff.

25 R. Harde:
"Activities in the Field of Sodium Technology."
Proceedings of Sodium Component Developing Program.
TID - 4500, 1965, pp. 156 ff.

26 H. Mausbeck:
"Entwicklungsstand und Probleme der Natriumtechnologie in der Bundesrepublik."
Paper presented at Reaktortagung 1969, Frankfurt/Main, April 15 - 18, 1969. Deutsches Atomforum e.V., Bonn. Published in: Atomkernenergie (AKTE), vol. 15, 1, 1970, pp. 1-13.

27 E. Büscher, W. Jansing, H. Knuth, H. Mausbeck:
"Tests of a Tube-in-Tube Sodium-heated Steam Generator."
Proc. of the International Conference on Sodium Technology and Large Fast Reactor Design, November 7-9, 1968. ANL-7520 (Part I), 1968, pp. 335-44.

28 K. Dumm, H. Mausbeck, W. Schnitker:
"Status of Sodium-Water Reaction Test Work at INTERATOM."
Proc. of the International Conference on Sodium Technology and Large Fast Reactor Design, November 7-9, 1968. ANL-7520 (Part I), 1968, pp. 374-83.

29 H. Münster:
"Untersuchungen über Natrium-Luft-Reaktionen."
Nukleonik, 7, 1965, pp. 477 ff.

30 R. Greifeld, O. Haxel, G. Ritter:
"Der Aufbau der Kernreaktor Bau- und Betriebs-Gesellschaft."
atomwirtschaft 2, 1957, pp. 394-98.

31 R. J. Gleitsmann, Universität Stuttgart:
"Im Widerstreit der Meinungen: Zur Kontroverse um die Standortfindung für eine deutsche Reaktorstation (1950 - 1955)."
Ein Beitrag zur Gründungsgeschichte des Kernforschungszentrums Karlsruhe und zu einem Kapitel deutscher Kernenergiegeschichte.
KfK-Bericht 4186, March 1988.

32 E. Neck:
"25 Jahre Finanz- und Rechnungswesen im Kernforschungszentrum Karlsruhe."
KfK-Bericht 3071 B, November 1980.

33 W. Häfele:
"Das Projekt Schneller Brüter."
atomwirtschaft 8, 1963, pp. 206-09.

34 "10 Jahre Kernforschungszentrum Karlsruhe."
Gesellschaft für Kernforschung mbH, Karlsruhe, 1966.

35 J. H. Wright:
Conference on Breeding, Economics and Safety in Large Fast Power Reactors.
October 7-10, 1963.
Quoted in: Letter from Dr. Häfele, KfK, to Bundesministerium für wissenschaftliche Forschung (BMwF), Bonn, Nov. 27, 1963.

36 Memo Dr. Häfele,
"Die Bedeutung der KNK und ihr Zusammenhang mit dem Karlsruher Projekt Schneller Brüter." June 15, 1963.

37 Letter from KfK (Dr. Greifeld, Dr. Schnurr)
to Vorstand Badenwerk AG, July 31, 1963.

38 H. Oehme, W. Marth:
"Die Ausnutzung des Reaktors FR 2 als Forschungseinrichtung."
Kerntechnik, vol. 8 , 6, June 1966, pp. 253-56.

39 Memo Prof. Wirtz, INR, to DI Vomhof, PtA.
June 30, 1964.

40 Letter from KfK (Dr. Schnurr, Dr. Greifeld)
to Interatom,
"Zusatzstudien zum KNK-Reaktor."
July 21, 1964.

41 Letter from KfK (Dr. Schnurr, Dr. Greifeld)
to Interatom,
Oct. 5, 1964.

42 Letter from KfK (Dr. Schnurr, Dr. Greifeld)
to Bundesministerium für wissenschaftliche Forschung (BMwF), Bonn,
Sept. 12, 1963.

43 G. Brudermüller, J. Gallenberger, H.-J. Kraus, W. Müller, H. Ramdohr:
"Die Rolle der GfK-Versuchsanlagen im Projekt Schneller Brüter."
atomwirtschaft, vol. 12, April 1967, pp. 191-94.

44 A. W. Eitz, H. Tebbert:
"Gesellschaft für Kernforschung mbH, Karlsruhe - Versuchsanlagen."
Description, Sept. 1, 1972.

45 Delivery Contract, KNK
GfK/VA, Karlsruhe - Interatom, Bensberg.
Signed Dr. Armbruster, Dr. Tebbert - Dr. Harde, Stöhr .
March 1, 1966 - May 31, 1966.

46 Kromer, Krück:
Letter from Badenwerk, Karlsruhe, to KBG dated Aug. 8, 1963.

47 KNK plant management contract.
GfK/VA, Karlsruhe - KBG, Karlsruhe.
Signed Dr. Brandl, Dr. Tebbert - Dr. Armbruster, Kullmann.
Nov. 3, 1966 - Nov. 30, 1966.

48 H. Tebbert, G. Brudermüller, R. Harde, K. W. Stöhr:
"Die Kompakte Natriumgekühlte Kernreaktoranlage Karlsruhe (KNK) - Die Vorstufe zum natriumgekühlten Brutreaktor."
Atom und Strom, vol. 13, Sep./Oct. 1967, pp. 117-29.

49 H. Armbruster, A. W. Eitz, R. Harde:
"Bedeutung der Kompakten Natriumgekühlten Kernreaktoranlage (KNK). Die Vorstufe für das SNR 300-Projekt."
atomwirtschaft, vol. 18, 2, 1973, pp. 84-85.

50 H. Rothfuss, F. Vogt:
"Reactor Vessel System."
Nuclear Technology, vol. 78, Sep. 1987, pp. 245-54.

51 F.H. Morgenstern, H. Buchholz, H. Krüger, H. Röhrs:
"Diverse Shutdown Systems for the KNK-1, KNK-2 and SNR-300 Reactors."
Fast Reactor Safety Meeting, Beverly Hills, California, U.S.A., April 2-4, 1974.
Proc. ANS Technical Group for Nuclear Reactor Safety, CONF-740401-P3, pp. 1349-69.

52 H. Zeibig, E. Fortmann:
"Fracture Behaviour Investigations of 10 Cr Mo Ni Nb 910 Steel Pipes."
First International Conference on Structural Mechanics in Reactor Technology, Berlin, September 20 - 24, 1971.
Proceedings, Commission of the European Communities, Brussels. Bundesanstalt für Materialprüfung (BAM), Berlin, vol. 6 Structural Analysis and Design, Part L, Thermal and Mechanical Analysis, L 6/7, pp. 605-14.

53 G. Brudermüller, W. Marth, H. Tebbert:
"Erfahrungen bei der Durchführung des Projekts KNK."
atomwirtschaft, vol. 18, 2, 1973, pp. 85-87.

54 J. Gilles, G. Hendl, G. Herberg, H. Mausbeck, G. Brudermüller, G. Finke:
"Bau- und Inbetriebnahme-Erfahrungen bei KNK."
atomwirtschaft, vol. 18, 2, 1973, pp. 88-93.

55 G. Hendl, G. Herberg, L. Jegeroff, W. Marth:
"Erfahrungen während des Natrium-Probebetriebes an der KNK."
Reaktortagung 1972, Hamburg, April 11 - 14, 1972. Deutsches Atomforum e.V., Bonn, 1972, pp. 602-5.

56 G. Kirchner, U. Schäfer, S. Herberg, G. Hendl, W. Albat:
"Erfahrungen mit Na-Versuchsanlagen und bei der K N K - Inbetriebnahme im Hinblick auf schnelle Na-gekühlte Reaktoren."
"Experience in Sodium Test Facilities and Commissioning of KNK with a View to Fast Sodium-Cooled Reactors."
Int. Conference on Engineering of Fast Reactors for Safe and Reliable Operation, Kernforschungszentrum Karlsruhe, October 9-13, 1972.
Proceedings, ed. D. Faude. Gesellschaft für Kernforschung mbH, Karlsruhe, 1973, vol. II, pp. 522-36.

57 H. Henssen, A. Stojadinovic:
"Die Auswertung der Nulleistungsversuche bei KNK."
Reaktortagung 1972, Hamburg, April 11 - 14, 1972. Deutsches Atomforum e.V., Bonn, 1972, pp. 94-97.

58 D. Althaus, W. Jansing, R. Kesseler, G. Kirchner, J. Menck:
"Experience with Handling Core Subassemblies in Sodium-Cooled Reactor KNK and Test Rigs." International Conference organized by the British Nuclear Energy Society held at the Institution of Civil Engineers, London, March 11 - 14, 1974.
Proceedings BNES, vol. 2, Specialist Session 6: Fuel Handling and other Mechanisms, London, 1974, pp. 545-54.

59 W. Marth:
"Erfahrungen bei der Inbetriebnahme der KNK I und Umbau-Vorbereitungen für KNK II."
Statusbericht 1974, Projekt Schneller Brüter, Karlsruhe, March 26, 1974.
KfK-Bericht 2003, March 1974, pp. 35-46.

60 G. Brudermüller, G. Finke, E. Guthmann, G. Hendl, W. Marth:
"Operating Experience with the KNK Reactor and Preparations for a Fast Mixed Oxide Core (KNK II)."
International Conference organized by the British Nuclear Energy Society held at the Institution of Civil Engineers, London, March 11 - 14, 1974.
Proceedings BNES, vol. 2, Plenary Session 3: Planned Power Plants, London, 1974, pp. 111-18.

61 H. Lorenz, G. Herberg:
"Dampferzeugerschaden an der KNK-Anlage."
2. Internationales Kolloquium "Schweißen in der Kerntechnik," Düsseldorf, Oct. 23 - 24, 1974, pp. 299-302.

62 W. Marth, K. Dumm:
"Problems with Sodium Steam Generators: Example of a Leakage in a Steam Generator of the Sodium-Cooled KNK Nuclear Power Station."
Symposium on Experience from Operating and Fuelling Nuclear Power Plants, Vienna, Oct. 8 - 12, 1973.
Proc., International Atomic Energy Agency, IAEA-SM-178/17, Vienna, 1974, pp. 343-52.

63 W. Marth:
"Das Projekt KNK - Vorstufe zum natriumgekühlten Brutreaktor."
KfK-Nachrichten, vol. 13, 1-2/81, pp. 17-22.

64 GfK - EURATOM Association Agreement (Technical Annex), 1963.

65 H.E. Häfner:
"Bestrahlung an Brennstäben in instrumentierten Blei-Wismut-Kapseln."
Kerntechnik, 3, 1968, pp. 136-41.

66 H. Oehme, W. Marth:
"Die Ausnützung des FR 2 als Forschungseinrichtung."
Kerntechnik, vol. 8, 5, 1966, pp. 253-56.

67 C. Cawthorne, E.J. Fulton:
"Voids in irradiated stainless steel."
Nature, vol. 216, November 11, 1967, pp.575-76.

68 G. Karsten:
"Die Arbeiten zur Brennelemententwicklung."
atomwirtschaft, vol. 16, 1971, pp. 256-59.

69 "Euratom bestrahlt Brennelemente für Schnelle Brüter in den USA."
Deutscher Forschungsdienst,
Sonderbericht Kernenergie (Jan. 13, 1966), 10.

70 D. Geithoff, K. Kummerer:
"Auslegung, Bestrahlung und zerstörungsfreie Nachuntersuchung des UO_2-PuO_2-Brennstabbündels DFR 350."
KfK-Bericht 1377 (1972).

71 P. Engelmann:
Memo to Projektrat PSB,
Oct. 23, 1971.

72 W. Marth:
File memo,
Discussion with BMwF on Sep. 3, 1969.

73 W. Häfele:
Memo to Geschäftsführung Versuchsanlagen through Geschäftsführung/F, May 12, 1969.

74 A.W. Eitz:
"Ad hoc Ausschuß des Projektkomitee Schneller Brüter - Stellungnahme zur technischen Baureife des SNR 300." July 21, 1970.

75 Anlage B zum Bewilligungsbescheid (Annex B to the Appropriation Document).
III B1 - 5532 - 11 - 56/66.

76 Summary record.
15th meeting of the Fast Breeder Project Committee, March 18, 1971.

77 W. Marth:
"Zusammenfassung des Ausschußberichts über Essentials KNK."
Oct. 25, 1971.

78 H. Mausbeck:
"Materials Experience with Large Sodium Loops and Components."
International Conference on Liquid Metal Technology in Energy Production, Champion, Pennsylvania, U.S.A., May 3-6, 1976.
Proceedings, American Nuclear Society, Hinsdale Ill, U.S.A.. CONF-760503-P1, November 1976, pp. 67-74.

79 Cable to
Alkem, RBU, Interatom,
Oct. 29, 1971.

80 G. Schnetgöke:
KNK II Financial Plan,
Dec. 31, 1971.

81 W. Häfele:
Statusbericht 1971.
Schweizerische Vereinigung für Atomenergie, Encl., Bulletin No. 7, April 1971, and atomwirtschaft, May 1971, pp. 247-50.

82 "Ad hoc Ausschuß Überprüfung des Projekts KNK II."
July 19, 1972.

83 J. Höchel:
"BE-Bündelbestrahlungen im KNK II"
(Letter to GfK/VA).
Jan. 18, 1972.

84 K.W. Stöhr, H. Andrae:
"Bedeutung und Nutzen der KNK II für die Entwicklung des Schnellen Natriumgekühlten Reaktors SNR 300." (Memo).
Jan. 10, 1972.

85 Summary record, 4th meeting:
"Ad hoc-Ausschuß Überprüfung des Projekts KNK II."
March 8, 1972.

86 Minutes,
80th RSK meeting.
Jan. 24, 1973.

87 Agreement on Converting KNK into a Fast Core Facility (KNK II).
GfK/VA, Karlsruhe - Interatom, Bensberg
(signed: Dr. Marth, Dr. Tebbert - Dr. Traube, Brakelmann)
June 19, 1973 - June 12, 1973.

88 W. Marth:
KNK II file memo.
March 30, 1973.

89 H.H. Hennies, H. Mausbeck:
"Die Bedeutung der KNK II für das Kernforschungszentrum Karlsruhe und die Entwicklungsgemeinschaft Schneller Brüter."
KfK-Nachrichten, vol. 9, 3/4, 1977, p. 3.

90 A. G. Plessa:
"Fuel Element Irradiation in the KNK for the Development of the German Fast Breeder."
Proceedings of the International Conference held at Thurso, Caithness, Scotland,
April 14 - 17, 1969. UKAEA Reactor Group, Risley, U.K., 1970, paper 2/3, pp. 175-83.

91 H. Schäfer, W. Klassmann:
"Application of Hot Channel Analysis to KNK-II."
Principles of Hot-Channel Factor Calculations for Fast Reactors.
Summary Report of a Panel Meeting on Principles of Hot-Channel Factor Calculations for LMFBR's held in Karlsruhe, November 22 - 24, 1973, IWGFR, International Atomic Energy Agency, Vienna, IAEA-166, 1974, pp. 161-88.

92 U. von Möllendorff:
"SNEAK 11: Kritische und unterkritische Experimente zu Nachladekernen für KNK II."
KfK-Bericht 3464, August 1983.

93 W. Marth, K. W. Stöhr, H. Andrae:
"KNK II Auslegung und Stand des Projekts."
Reaktortagung '71, Bonn, March 30 - April 2, 1971. Deutsches Atomforum e.V., Bonn, 1971, pp. 754-57.

94 H. Andrae, H. Mayer, K. H. Wenk:
"Entwicklung und Auslegung der KNK-Brennelemente."
Reaktortagung '71,Bonn, March 30 - April 2, 1971. Deutsches Atomforum e.V., Bonn, 1971, pp. 594-97.

95 D. Eitner, P. Engelmann, E. Ruppert:
"Physics Considerations in the Design of, and Mock-up Experiments in SNEAK for, KNK-II."
International Conference on the Physics of Fast Reactor Operation and Design, London, June 24-26, 1969. The British Nuclear Energy Society.
Proc. of an International Conf. at the Institution of Civil Engineers, London SW1.
Paper 2.1, June 1969, pp. 201-12.

96 H. Henssen, W. Feltes, J. Heinecke, E. Ricken, H. Wilhelm:
"Die Auslegung des Reaktorkerns."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 10-11.

97 J. Höchel:
"Die SNR-Kerne - KNK-II, SNR-300 bis SNR-2."
Das Brennelement des Natrium-Brüters. Fachtag der Fachgruppe der Kerntechnischen Gesellschaft zum Thema Brennelemente und Brennstoffkreislauf, Karlsruhe, October 28 - 29, 1976. KfK-Bericht 2416, October 1976, pp. 12-18.

98 W. Marth, K.W. Stöhr:
"Das KNK-Projekt als Vorstufe des Schnellen Brüters."
Reaktortagung '72, Hamburg, April 11 - 14, 1972. Deutsches Atomforum e.V., Bonn, 1972, pp. 696-99.

99 H. Andrae, W. Marth:
"Das Projekt KNK II."
atomwirtschaft, vol. XVIII, 2, 1973, pp. 93-95.

100 P. Voj, A. Benemann, K. Brockmann, D. Markfort:
"Untersuchung der Druckprofile in Brennelement-Stabbündeln."
Reaktortagung 1973, Karlsruhe, April 10 - 13, 1973. Deutsches Atomforum e.V., Bonn, 1973, pp. 178-81.

101 W. Dietz, P. Dünner, H. Mayer, B. Steinmetz, H. Többe:
"Die Auslegung der Kernelemente."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp.12-13.

102 H. W. Glinsky, F. Mehren, P. Voj, H. Hoffmann, K. Marten:
"The Shutdown Systems of KNK and SNR 300."
International Symposium on Design, Construction and Operating Experience of Demonstration LMFBRs held in Bologna, Italy, April 10-14, 1978. IAEA-SM-225/28. Proc. IAEA, Vienna, 1978, pp. 191-203.

103 W. Bergmann, S. Janson, R. Meyer:
"Die Sicherheits- und Prozeßinstrumentierung - Das Konzept."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 20-21.

104 H. Hans, J. Barzantny, A. Schönsiegel, H. Jäger, H. Richard, E. Zimmermann, W. Zirlewagen:
"Die Sicherheits- und Prozeßinstrumentierung - Die Ausführung."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 22-23.

105 D. Klein, K. Gielen, H. Niebel, H. Kappauf:
"Das Verhalten der Anlage bei betrieblichen Transienten."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 16-17.

106 H. Vossebrecker, F.J. Bange, S. Dreyer, G. Grönefeld, P. Meyer, K. Schwarzin:
"Das Notkühlsystem."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 26-27.

107 H. Hübel, P. Cerutti, G. Friedel:
"Zentrale Fragen der Sicherheitsauslegung."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 30-31.

108 K.A. Busch, D. Schmitz, H. Zeibig:
"Kriterien und Methoden zur Erdbebenertüchtigung."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 32-33.

109 A. Angerbauer, H. Kappauf:
"Beurteilung der KNK-Primärrohrleitungen nach neuen Spannungs- und Dehnungskriterien."
Reaktortagung 1974, Berlin, April 2 - 5, 1974. Deutsches Atomforum e.V., Bonn, 1974, pp. 199-202.

110 K.A. Busch, H. Hillekum, G. Radermacher, D. Schmitz, K. Vinzens:
"Die Erdbebenertüchtigung der Rohrleitungen des Wärmeübertragungssystems."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 36-37.

111 W. Marth, H. Andrae, K.A. Busch, E. Guthmann, G. Hendl:
"KNK II - Construction and Aseismic Design."
International Symposium on Design, Construction and Operating Experience of Demonstration LMFBRs held in Bologna, Italy, April 10 - 14, 1978. IAEA-SM-225/30. Proc. IAEA, Vienna, 1978, pp. 205-16. ISBN 92-0-050278-4.

112 K.A. Busch, H. Kappauf, H.W. Klein, J. Schmitter, K. Vinzens:
"Die Erdbebenertüchtigung der Komponenten des Wärmeübertragungssystems."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 34-35.

113 F. Vogt, W. Erdmann, H. Katzmann, J. Menck, H. Breitländer, B. Reuter:
"Das Handhabungssystem."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 28-29.

114 W.Marth, G. Schnetgöke, W. Kathol, H. Richard:
"Die Entsorgung der KNK II."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 58-59.

115 1st Partial Construction Permit, KNK II.
IV 8722. 412/57. May 2, 1975.

116 R.Gürtler, W. Perabo, B. Reuter, Katemann, J. Ristow:
"Betriebshandbuch und Sicherheitsspezifikation."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 52-53.

117 H.-G. Fendler, F. Bosten, H. Jurgutat, E. Morgner:
"Die Begutachtung der Anlage."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 38-39.

118 H.Andrae, D. Forst, E. Guthmann, G. Schnetgöke:
"Das Genehmigungsverfahren."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 40-41.

119 K. Stickel, H. Eversberg, P. Romeike, E. Zimmermann:
"Die Dokumentation der Anlage."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 42-43.

120 W. Marth:
"Erfahrungen bei Bau und Betrieb der KNK II."
KfK-Nachrichten, vol.15, 3, 1983, pp. 191-97.

121 O. Grözinger, H. Jurgutat, E. Morgner:
"Praktizierte Qualitätssicherung bei der KNK II."
Reaktortagung, Mannheim, March 29 - April 1, 1977, Kerntechnische Gesellschaft Deutsches Atomforum e.V., Bonn, S. 852-856.

122 H. Beisswenger, F. Brodt:
"Beurteilung der Auslegung von oxidischen Brennstoffen und Abnahmekriterien für Brennelemente."
Konferenz Charakterisierung und Qualitätskontrolle von Kernbrennstoffen, Karlsruhe, June 13 -15, 1978. Journal of Nuclear Materials, volume 81 (1979) 283-86.

123 K. Ennerst, K. Gruber, G. Bestenreiner, W. Feldmann, K.-H. Wenk:
"Die Brennelement-Fertigung und -Qualitätssicherung."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 14-15.

124 W. Marth:
"Die Errichtung der KNK II aus der Sicht des Bauherrn."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 4-5.

125 H. Richard, G. Finke, K. Ch. Stade:
"Entladen und Abtransport des KNK I - Cores."
Reaktortagung 1976, Düsseldorf, March 30 - April 2, 1976. Deutsches Atomforum e.V., Bonn, 1976, pp. 762-65.

126 D. Forst, E. Guthmann, H. Andrae, P. Romeike:
"Einflüsse des Backfittings im Genehmigungsverfahren KNK II."
Reaktortagung 1978, Hanover, April 4 - 7, 1978, Kerntechnische Gesellschaft, Deutsches Atomforum e.V., Bonn, 1978, pp. 406-9.

127 G. Brudermüller, G. Finke:
"Die Betriebsführung und Bauüberwachung aus der Sicht des Betreibers."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 8-9.

128 R. Kimpel, F. Nowitzki:
"Untersuchung zur Funktionstüchtigkeit und Lebensdauer der 1. und 2. Abschalteinrichtung KNK II."
Reaktortagung 1977, Mannheim, March 29 - April 1, 1977. Deutsches Atomforum e.V., Bonn, 1977, pp. 710-13.

129 E. Guthmann, H. Andrae, D. Forst, P. Romeike:
"Die Abwicklung des Projektes KNK II aus der Sicht des Herstellers."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 6-7.

130 G. Hendl, W. Albat, H. Katemann, O. Kuck:
"Die Montagearbeiten auf der Baustelle."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 44-45.

131 300th Project Discussion.
Interatom, Ident-No. 75.19855.1
Sep. 23, 1991.

132 H. Overbeck:
"Der Schnelle Brüter in Kalkar."
VDI-Verlag, Düsseldorf, 1992.

133 M. Schmidt-Hönow, N. Mörig, R.-D. Eisele, H. Richard:
"Das Inbetriebnahmeprogramm."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 46-47.

134 W. Albat, M. Schmidt-Hönow, G. Finke, H. Richard:
"Nukleare Inbetriebnahme der KNK II-Anlage."
atomwirtschaft, March 1978, pp. 122-24.

135 H. Richard, M. Schmidt-Hönow, H. Wilhelm, W. Feltes, A. Strömich:
"Die Nukleare Inbetriebnahme KNK-II."
Reaktortagung 1978, Hanover, April 4 - 7, 1978. Deutsches Atomforum e.V., Bonn, 1978, pp. 82-85 and pp. 935-38.

136 G. Brudermüller, G. Finke, W. Marth, H. Mausbeck:
"Power Startup of the First German Fast Sodium-Cooled Reactor, KNK II."
European Nuclear Conference, Hamburg, May 6 - 11, 1979.
Trans. Am. Nucl. Soc. (1979), vol. 31, pp. 112-14.

137 A. Stanculescu, U. Wehmann, H. Wilhelm, F. Sperber, W. Feltes:
"Nuclear Design of the Fast Test Reactor KNK II and some Aspects of its Operational Behaviour."
International Symposium on Fast Reactor Physics, Aix-en-Provence, France, Sep. 24 - 28, 1979. IAEA-SM-244/51. Proceedings Fast Reactor Physics 1979 (in two volumes). IAEA, Vienna, 1980, vol. I, pp. 481-94.

138 K. Rudzinski:
"Der Störfall am Brüter-Versuchsreaktor in Karlsruhe."
Frankfurter Allgemeine Zeitung, 17.1.1979.

139 H. Hübel:
"Gasblasen im Reaktorkern."
Frankfurter Allgemeine Zeitung, Feb. 22, 1979, No. 45.

140 P. Hoppé, H. Massier, F. Mitzel, W. Väth:
"Untersuchungen zum Gaseintrag an KNK II."
KfK-Bericht 2867, November 1979.

141 H. U. Borgstedt:
"Zur Frage eines Beitrags der Löslichkeit von Argon zum Gastransport in der KNK II."
atomwirtschaft, June 1980, pp. 303-4.

142 M. Edelmann, P. Hoppé, F. Mitzel, W. Vaeth:
"Two-Phase Flow Effects Observed in a Sodium-Cooled Reactor."
American Nuclear Society Annual Meeting, Las Vegas, Nevada, June 8-12, 1980.
Trans. Am. Nucl. Soc. (1980), vol. 34, pp. 798-99. ISSN: 0003-018X.

143 J. Höchel, H. Schott:
"Untersuchungen zu den Gasdurchläufen durch den Reaktorkern der KNK-II."
Summary report outlining the findings made up until December 1979.
Interatom, Bergisch Gladbach 1, INTAT 75012841, April 1980.

144 J. Höchel, W. Marth, G. Brudermüller:
"Operational Safety Experience gained with KNK II."
International Topical Meeting on Liquid Metal Fast Breeder Reactor Safety and Related Design and Operational Aspects. July 19-23, 1982, Lyon, Ecully, France.
Proc. of the L.M.F.B.R. Safety Topical Meeting. Vol. I, Actes de la Conference de Lyon, Vol. I, Societé Française d'Energie Nucléaire (SFEN), Paris, 1982, pp. I.257-I.267.

145 K. Brockmann, P. Voj, G. Bestenreiner:
"Entwicklung eines integrierten Zyklonabscheiders für das KNK II - Reflektorelement."
Jahrestagung Kerntechnik '82, Mannheim, May 4 - 6, 1982. Tagungsbericht Kerntechnische Gesellschaft e.V., Deutsches Atomforum, Bonn, ISSN 0720-9207, pp. 141-44.

146 H.-J. Schade, H. Püschel, J. Heinecke, D. Klein:
"Berechnung von Brennelementaustrittstemperaturen zur Interpretation der Reaktivitätsänderungen aufgrund von Gasdurchläufen durch den Kern der KNK-II."
Jahrestagung Kerntechnik '80, Berlin, March 25 - 27, 1980. Tagungsbericht Kerntechnische Gesellschaft e.V., Deutsches Atomforum, Bonn, ISSN 0173-0924, pp. 811-14.

147 K. Bär, K. Brockmann, P. Voj:
"Versuche zu Gasblasentransport und -speicherung an der KNK - Anlage."
Jahrestagung Kerntechnik '81, Düsseldorf, March 24 - 26, 1981. Tagungsbericht Kerntechnische Gesellschaft e.V., Deutsches Atomforum, Bonn, ISSN 0173-0924, pp. 97-100.

148 H. Richard, K. Ch. Stade, S. Jacobi, L. Stieglitz, R. Becker, J. Dauk:
"Experience of Failed Fuel Detection and Localization at KNK II."
Specialists' Meeting Fuel Failure Detection and Location in LMFBRs, Karlsruhe, May 11 - 14, 1981. Editor: S. Jacobi. KfK-report 3203/IWGFR 38, June 1982, pp. 93-111.

149 J. Dauk, M. Relic, G. Finke, H. Richard, S. Jacobi, L. Stieglitz:
"Detektion und Lokalisierung des 2. Brennelementschadens in der KNK II."
Jahrestagung Kerntechnik '81, Düsseldorf, March 24 - 26, 1981. Tagungsbericht Kerntechnische Gesellschaft e.V., Deutsches Atomforum, Bonn, ISSN 0173-0924, pp. 537-40 and short contribution, atomwirtschaft, August/September 1981, pp. 481-82.

150 G. Brudermüller, G. Finke, H. Richard, K. Ch. Stade:
"18 Days KNK II Operation with a Failed Fuel Element Based on In-Pile Loop Experiments."
ANS Topical Meeting on Reactor Safety Aspects of Fuel Behavior, Sun Valley, Idaho, U.S.A., August 2-6, 1981. Proceedings American Nuclear Society, LaGrange Park, Ill., U.S.A., 1981, pp. 1.232-1.242.

151 "Versuchsbrüter erzielt Spitzenwerte:"
Frankfurter Rundschau, Dec. 18, 1982.

152 "Brüter-Brennelemente mit hohem Abbrand."
Frankfurter Allgemeine Zeitung, Jan. 19, 1983, No. 15.

153 E. te Heesen, W. Ohly:
"Werkstofftechnische Überwachung von Reaktortank und Einbauten bei KNK und SNR 300."
Jahrestagung Kerntechnik '83, Berlin, June 14 - 16, 1883. Deutsches Atomforum, Bonn, 1983, pp. 635-38. ISSN 0720-9207.

154 H. Jung, E. Zimmermann:
"Das Wiederholungsprüfprogramm."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 54-55.

155 H. Schöller, H. Richard, H. Lindhorst, D. Schlottmann, D. Schneeloch:
"Der Prozeßrechner und seine betriebliche Nutzung."
KfK-Nachrichten, vol. 9, 3/4, 1977, pp. 50-51.

156 W. Marth:
"KNK II Back-Fitting Requirements and Operational Experience."
Second International Conference on Liquid Metal Technology in Energy Production. Richland, Washington, U.S.A., April 20-24, 1980. Proceedings, Editor: J. M. Dahlke, Washington D.C., American Nuclear Society, CONF-800401-P1, 1980, pp. 6.10-6.16.

157 G. Finke, E. Zimmermann, H. Breitländer:
"Inspection and Maintenance at KNK II."
International Topical Meeting on Liquid Metal Fast Breeder Reactor Safety and Related Design and Operational Aspects. July 19-23, 1982, Lyon, Ecully, France.
Proc. of the L.M.F.B.R. Safety Topical Meeting. Vol. II, Actes de la Conférence de Lyon, Vol. II, Société Française d'Energie Nucléaire (SFEN), Paris, 1982, pp. II.709-II.716.

158 W. Schmidt:
"Zuverlässigkeit von natriumspezifischen Komponenten."
atomwirtschaft, February 1981, vol. 26, 2, pp. 77-79.

159 W. Marth:
"Das Brüter-Versuchskernkraftwerk KNK II und seine Nutzung für den Brennstoffkreislauf."
Atom + Strom, vol. 28, 3, May - June 1982, pp. 77-84.

160 H. Enderlein:
"The Hot Cells of the Kernforschungszentrum Karlsruhe."
Proceedings, 35th Conference on Remote Systems Technology, ANS, 1987, pp. 70-75.

161 H. Enderlein, H. Ziegler:
"Remotely Handled Disassembly of the KNK II Fast Breeder Fuel Elements."
Proceedings, 37th Conference on Remote Systems Technology, ANS, 1989, pp. 69-74.

162 H. Enderlein, W. Kathol:
"Die Zerlegung und Nachuntersuchung des ersten und zweiten defekten KNK II-Brennelements."
Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB. KfK-Bericht 3278, March 1982, pp. 56-82.

163 G. Bestenreiner:
"Die Zerlegung von Schnellbrüter-Brennelementen mit Gitterabstandshaltern."
Jahrestagung Kerntechnik, Fachsitzung, March 24 - 26, 1981. Deutsches Atomforum e.V., Bonn, 1981, pp. 55-72.

164 W. Köhler, J. Vagner, H. Enderlein, H. Lahr, H. Deckers, H. Reiser:
"Forschungs- und Entwicklungsarbeiten zum mechanischen Teil des Brüterbrennstoff-Kreislaufs." KfK-Nachrichten, vol. 15, 3/83, pp. 180-89.

165 H. Kleykamp, R. Pejsa:
"Untersuchungen zur Homogenität des Mischoxids in verschiedenen Stadien des Brennstoffkreislaufs."
Schnellbrüter-Brennelemententwicklung - Beiträge zum Seminar am 15./16. November 1982 im Kernforschungszentrum Karlsruhe.
Hrsg.: W. Marth, G. Mühling, PSB. KfK-Bericht 3505, August 1983, pp. 70-80.

166 H. Kleykamp:
"Zusammensetzung des Rückstands von KNK II/1-Brennstoff nach Auflösung in HNO_3."
atomwirtschaft, May 1987, vol. 32(5), pp. 235-36.

167 H.-J. Bleyl:
"Die Wiederaufarbeitung von Brennstoff aus dem ersten defekten KNK II-Brennelement in der MILLI." Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB. KfK-Bericht 3278, March 1982, pp. 93-99.

168 K. Ebert, E. Henrich, H. Schmieder:
"Concept of an Advanced FBR Purex Process."
International Conference on Fast Breeder Systems: Experience Gained and Path to Economic Power Generation, Pasco-Richland, U.S.A., September 13-17, 1987. Proc. American Nuclear Society (ANS), La Grange Park, Ill., U.S.A., 1987, pp. 7.3-1 to 7.3-8.

169 V. Schneider, W.G. Druckenbrodt:
"Erfahrungen zur Brennstoff-Rezyklierung."
Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB. KfK-Bericht 3278, March 1982, pp. 121-24.

170 G. Schnetgöke:
"Das Referenzkonzept zur Entsorgung der KNK II."
Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB. KfK-Bericht 3278, March 1982, pp. 14-28.

171 "Service Agreement for the Reprocessing of KNK II Irradiated Fuel."
Commissariat à l'Energie Atomique and Kernforschungszentrum Karlsruhe GmbH. December 1980.

172 W. Marth:
"KNK II Operating Experience and Fuel Cycle Activities."
International Conference on Nuclear Power Experience, Vienna, Austria, Sep. 13 - 17, 1982. IAEA-CN-42/379. Proceedings "Advanced Systems and International Co-operation." Vienna: IAEA, 1983, vol. 5, pp. 167-77. ISBN 92-0-050483-3.

173 W. Marth, G. Bestenreiner, H.-J. Bleyl, H. Enderlein, K. Knecht, W. Köhler, H. Lahr, W. Ochsenfeld:
"Fuel Cycle Activities at the German Experimental Fast Breeder Plant KNK II."
International ENS/ANS Conference, New Directions in Nuclear Energy with Emphasis on Fuel Cycle, Bruxelles, B, April 26-30, 1982.

174 K. Ch. Stade, H. Breitländer, H.H. Stamm:
"Die Entfernung des Natriums von Brennelementen."
Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB. KfK-Bericht 3278, March 1982, pp. 29-45.

175 G. Bestenreiner, W. Köhler:
"The Mechanical Headend for KNK II and SNR 300 Subassemblies."
International Conference on Fast Reactor Fuel Cycles, London, U.K., Nov. 9-12, 1981. BNES, London , Thomas Telford Ltd., 1982, pp. 381-84. ISBN 0 7277 0157 6.

176 H. Alfke, H.-J. Bleyl, R. Grimm, W. Ochsenfeld, H. Enderlein, H. Kleykamp, H. Wertenbach:
"Die Schließung des Brüterbrennstoffkreislaufs der KNK II."
KfK-Nachrichten, vol. 15, 3/83, pp. 171-79.

177 K. Wasinger:
"Konzeptstudie zur Zwischenlagerung von KNK II-Brennelementen unter Wasser."
Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB. KfK-Bericht 3278, March 1982, pp.157-64.

178 P. Arntzen, A. Gasch:
"Konzeptstudie zur Zwischenlagerung von KNK II-Brennelementen in einem Blocklager."
Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB.
KfK-Bericht 3278, March 1982, pp. 165-72.

179 W. Bergmann, G. Dries, R. Laug:
"Konzept zur Zwischenlagerung bestrahlter KNK II-Brennelemente in Transport-/Lagerbehältern."
Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB.
KfK-Bericht 3278, March 1982, pp. 173-83.

180 K. Knecht:
"Unterwassertechnik zur Reparatur von LWR-Brennelementen unter deren Anwendung für die Zerlegung von KNK-BE."
Technologische Fragen des Brüterbrennstoffkreislaufs - Beiträge zum Seminar am 15. Okt. 1981 im Kernforschungszentrum Karlsruhe, Hrsg.: W. Marth, H. Lahr, PSB.
KfK-Bericht 3278, March 1982, pp.142-50.

181 H. Lahr, W. Marth:
"Interim Storage of Spent KNK II Breeder Fuel Elements."
International Conference on Fast Reactor Fuel Cycles, London, U.K., Nov. 9 - 12 , 1981.
BNES, London , Thomas Telford Ltd., 1982, pp. 273-81. ISBN 0 7277 0157 6.

182 G. Koch, H. Goldacker, H. Haug, E. Henrich, W. Ochsenfeld, H. Schmieder, G. Böhme, W. Köhler, L. Grimm:
"MILLI II: Konzeptstudie einer Pilotanlage zur Wiederaufarbeitung von Schnellbrüter-Brennelementen."
KfK-Nachrichten, vol. 15, 3/83, pp. 158-70.

183 H. Mayer, H. Andrae:
"The Role of the KNK-II Facility for the Development of SNR Fuel Subassemblies."
Topical Meeting Irradiation Experimentation in Fast Reactors, Jackson Lake Lodge, Wyoming, September 10-12, 1973.
Proc. American Nuclear Society, Hinsdale, Illinois, U.S.A., 1973, pp. 166-85.

184 H. Mayer:
"Begründung für die ursprüngliche Wahl der Brennstoffdichte; internationaler Stand der zeitlichen Entwicklung der Dichteauswahl."
Interatom Memo 54.3376.7 of April 6, 1979.

185 H. Morelle, H. Hübel, W. Roßbach:
"Umstellung des Brennstoffs auf bessere Löslichkeit (höhere Dichte): techn. und genehmigungstechn. Daten, Bewertung und Empfehlung der INB an SBK."
INB Memo 401.1898.5 of July 28, 1980.

186 J. Höchel:
"Abbrand von Schnell-Brüter-Brennelementen."
KTG-Fachtag 1982, Geesthacht, 1982.

187 J. Höchel, H. Mayer:
"Entwicklung und Betrieb von Brennelementen für natriumgekühlte Brutreaktoren in Deutschland."
Atomkernenergie, Kerntechnik, vol. 36, 4, 1980, pp. 264-70.

188 K. Ehrlich, L. Schmidt:
"Stand und Tendenzen bei der Hüll- und Kernstrukturmaterialentwicklung."
KfK-Nachrichten, vol. 15, 2, 1983, pp. 132-42.

189 H. H. Hennies, J. Höchel, W. Marth, H. Mausbeck, W. Stoll
-Entwicklungsgemeinschaft Schneller Brüter-:
"Die deutsche Brüterentwicklung - Stand und Perspektiven."
atomwirtschaft, March 1981, pp. 151-56.

190 U. Neumann, K. Ennerst, K. Gruber, J. Krellmann:
"Erfahrungen bei der Herstellung der Plutonium-Brennstäbe für die erste Kernladung des KNK II und die weitere Entwicklung für die Folgekerne."
Letter to Dr. W. Marth from H. Roepenack, Alkem, Hanau, dated Oct. 15, 1982.

191 "Löslichkeit von Brüterbrennstoffen verbessert."
FAZ - Blick durch die Wirtschaft, No. 210, Oct. 31, 1983.

192 W. K. Biermann, K. Ehrlich, G. Mühling:
"Operational Behavior of FBR Mixed Oxide Fuel Pins."
Effects of Radiation on Materials: 14th International Symposium (Volume II), ASTM STP 1046, N. H. Packan, R. E. Stoller, and A. S. Kumar, eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 769-81.

193 "Betriebserfahrungen mit Kernkraftanlagen in der Bundesrepublik Deutschland."
Betriebs-/Jahresberichte von 1972-1987 des ABE-Ausschusses im Arbeitskreis I "Technik und Industrie" des Deutschen Atomforums e.V., Bonn, published in "Atom und Strom."

194 "Jahresberichte der Kompakten Natriumgekühlten Kernreaktoranlage (KNK II) Karlsruhe." 1988 to 1991. Annual Reports, ed. by Kernkraftwerk-Betriebsgesellschaft mbH, Egg.-Leopoldshafen.

195 "Legende und Betriebsdaten der KNK."
Ed. by Kernkraftwerk-Betriebsgesellschaft m.b.H., Egg.-Leopoldshafen, 1982 - 1991.

196 E. Zimmermann:
"Induced Vibrations in the Pumps: Experience with Sodium Pumps in the KNK."
IAEA Specialists' Meeting on 'Flow Induced Vibrations in Fast Breeder Reactors', Paris, France, October 22-24, 1986, Proceedings. Editor: M. A. Perez, International Atomic Energy Agency, Vienna, IWGFR-62,
October 1986, pp. 277-83.

197 J. Heinecke, A. Stanculescu, W. Kathol, H. Richard:
"Operating Experience with KNK-II as an Experimental Reactor."
Proceedings of a Symposium. Fast Breeder Reactors: Experience and Trends, Lyon, 22-26 July, 1985, vol. 1. International Atomic Energy Agency, Vienna, IAEA-SM-284/7, 1986, pp. 95-102.

198 "Erfolgreicher Schnellbrüter."
Badisches Tagblatt, Oct. 21, 1987.

199 "Zehn Jahre Versuchsreaktor."
Ludwigsburger Kreis-Zeitung, Oct. 21, 1987.

200 G. Finke, K.-Ph. Streib:
"KNK II/2, Anlagenbetrieb während der Standzeitverlängerung zur schonenden Fahrweise der Brennelemente."
KBG-KNK-Bericht: BL 88/05, Oct. 27, 1988.

201 K.-Ph. Streib, R. Pleesz:
"KNK II/2, Anlagenbetrieb während der Standzeitverlängerung zur schonenden Fahrweise der Brennelemente."
KBG-KNK-Bericht: BL 91/30, Aug. 5, 1991.

202 G. Brudermüller:
"Betriebserfahrungen mit KNK II."
KTG Fachtag 1980, Deutsches Atomforum e.V., Bonn, 1980, pp. 8-16.

203 H. Zeibig, W. Marth, G. Brudermüller, W. Schmidt:
"Collection of Reliability Data for Sodium Components in KNK."
International Symposium on Reliability of Nuclear Power Plants, Innsbruck, April 14 - 18, 1975. Proc. of a Symposium organized by International Atomic Energy Agency, Vienna, IAEA-SM-195/31, 1975, pp. 83-89.

204 H. Zeibig, O. Knecht:
"Bestimmung der Ausfallwahrscheinlichkeit mechanisch und thermisch beanspruchter Reaktorbauteile."
Reaktortagung 1969, Frankfurt/Main, April 15 - 18, 1969. Deutsches Atomforum e.V., Bonn, 1969, pp. 111-12.

205 W. O. Steiger:
"The KNK II Instrumentation for Global and Local Supervision of the Reactor Core."
IAEA/IWGFR Specialists' Meeting on Instrumentation for Supervision of Core-Cooling in Fast Breeder Reactors, Kalpakkam, India, Dec. 12 - 15, 1989. Proc. International Atomic Energy Agency, Vienna, Austria, International Working Group on Fast Reactors, IWGFR-72, March 1991, pp. 109-42.

206 B. Heß:
"Bestrahlungserfahrungen mit KNK II-Schnellbrüter-Brennelementen."
Siemens KWU-Bericht No. KWU BGL N22/1993/E001, Bergisch Gladbach 1, February 1993.

207 W. O. Steiger:
"Erfahrungsaustausch über den Betrieb von KNK II- und BOR 60/BR 10-Anlagen."German-Soviet Cooperation in the Peaceful Uses of Nuclear Energy,"
Dimitrovgrad, USSR, Sep. 5 - 8, 1988.

208 H. Richard, K. Ch. Stade, K. Brockmann:
"10 Years Experience with Failed Fuel at KNK II: Operation, Detection and Localization."
International Conference on Fast Breeder Systems, Experience Gained and Path to Economical Power Generation, Pasco-Richland, U.S.A., September 13-17, 1987.
Proc. American Nuclear Society (ANS), La Grange Park, Ill., U.S.A., 1987, pp. 8.20-1 to 8.20-9.

209 G. Hoffmann, S. Jacobi, K. Schleisiek, G. Schmitz, L. Stieglitz, M. Becker:
"KNK II Experience with Local Flux Tilting to Locate Defective Fuel Subassemblies."
International Conference on Fast Breeder Systems, Experience Gained and Path to Economical Power Generation, Pasco-Richland, U.S.A., September 13-17, 1987.
Proc. American Nuclear Society (ANS), La Grange Park, Ill., U.S.A., 1987, pp. 8.21-1 to 8.21-9.

210 G. Hoffmann:
"Consulting Core Surveillance System COCOSS I at KNK II."
KfK-Bericht 4139, October 1986.

211 W. O. Steiger:
"Operating Experience with Failed Fuel Elements in the Compact Sodium Cooled Fast Research Reactor KNK II."
International Symposium on Research Reactor Safety, Operations and Modifications, Chalk River, Ontario, Canada, Oct. 23 - 27, 1989. Proc. International Atomic Energy Agency, Vienna, AECL-9926(v.1); IAEA-SM-310/42P, March 1990, pp. 214-23.

212 S. Jacobi, G. Hoffmann, G. Schmitz:
"Brennstoffverlust aus defekten Brennstäben in natriumgekühlten Reaktoren und Konsequenzen."
KfK-IRE/5/330/91, July 1991.

213 M. Becker, K.Ch. Stade, H. Richard, H. H. Stamm, H. D. Hanke, H. Clauss, S. Jacobi, G. Schmitz, G. Hoffmann:
"Radionuclide Behaviour in the KNK II Primary Cover Gas during Operation with Open Fuel." 3rd International Conference on Liquid Metal Engineering and Technology, Oxford, U.K., April 9 - 13, 1984. British Nuclear Energy Society, London, 1984, Vol. 1, pp. 509-13. ISBN: 0 7277 0209 2.

214 G. Schmitz, G. Hoffmann, S. Jacobi, D. Klein:
"Monitoring of Fuel Failure Development at KNK II by Measurement and Analysis of Fission Products in the Sodium and Cover Gas."
International Fast Reactor Safety Meeting, Snowbird, Utah, August 12-16, 1990.
Proc. of the 1990 International Fast Reactor Safety Meeting. American Nuclear Society Meeting, Session 3, Volume IV, pp. 243-52.

215 K. Schleisiek:
"Thermisch induzierte oszillatorische Stabbewegungen in Mark II-Stabbündeln."
KfK-IRE Memo: IRE/5/261/87 dated March 4, 1987.

216 E. Bojarsky, H. Deckers, H. Lehning, D. Piel, H. Reiser, L. Schmidt:
"Experimente zu thermohydraulisch induzierten Brennstaboszillationen (THIBO) in natriumgekühlten Reaktoren."
Jahrestagung Kerntechnik '89, Düsseldorf, May 9 - 11, 1989. Deutsches Atomforum e.V., Bonn, INFORUM Verlag, May 1989, pp. 433-36.

217 E. Bojarsky, H. Deckers, H. Lehning, D. Piel, H. Reiser, L. Schmidt:
"THIBO Experiments - Experiments on Thermohydraulically Induced Fuel Rod Oscillations in a Sodium Flow."
KfK-Report 4798, May 1991.

218 F. Mitzel, W. Väth, S. Ansari:
"Nachweis von Brennelementschwingungen in KNK II."
KfK-Bericht 3379, November 1982.

219 W. Väth, F. Mitzel, S. Ansari:
"Identification of Vibrational Effects in KNK II Fuel Elements."
KfK-Bericht 3157, July 1981.

220 W. Väth, H. Massier:
"BE-Schwingungen und Schonbetrieb."
KfK-INR Memo dated Aug. 26, 1991.

221 J. Heinecke, B. Heß:
"Zusammenfassende Darstellung zum Verhalten der Brennelementaustrittstemperaturen der KNK II/2."
Siemens KWU Bericht No.: KWU BT71/92/0055, Bergisch Gladbach 1, December 1992.

222 G. Finke, H. Richard, K. Ch. Stade:
"Drift Phenomenon of the Sodium Outlet Temperatures of KNK II Fuel Subassemblies Caused by Insoluble Corrosion Products."
International Conference on Fast Breeder Systems, Experience Gained and Path to Economical Power Generation, Pasco-Richland, U.S.A., September 13-17, 1987.
Proc. American Nuclear Society (ANS), La Grange Park, Ill., U.S.A., 1987, pp. 8.19-1 to 8.19-5.

223 H. Mausbeck, W. Marth:
"Safety-Oriented Operating Experience with KNK II."
ANS/ENS International Topical Meeting on Fast Reactor Safety, Knoxville, Tennessee, U.S.A., April 21-25, 1985. Proc. of the International Topical Meeting. Vol. I. Oak Ridge National Lab., Tennessee, U.S.A., July 1985, pp. 373-80.

224 H. Clauss, H. D. Hanke, H. H. Stamm, H. Wild:
"Partikeln im Primärnatrium der Kompakten Natriumgekühlten Kernreaktoranlage in Karlsruhe (KNK)."
Jahrestagung Kerntechnik '87, Karlsruhe, June 2 - 4 , 1987. Deutsches Atomforum e.V., Bonn, 1987, pp. 711-14.

225 K. Brockmann, H. Richard:
"Temperature Drift at the Outlet Temperature of the KNK II Subassemblies."
International Fast Reactor Safety Meeting, Snowbird, Utah, August 12-16, 1990.
Proc. of the 1990 International Fast Reactor Safety Meeting. American Nuclear Society Meeting, Session 2, Volume III, pp. 259-68.

226 B. Heß:
"Schwergängigkeiten an den KNK II-Abschalteinrichtungen, Untersuchung der Ursachen und Bewertung im Vergleich mit Erfahrungen anderer Anlagen."
Siemens KWU, Bericht Nr.: KWU BGL N22/92/007 dated Dec. 3, 1992.

227 B. Heß, K. Brockmann, R. Pleesz:
"Experience with the Control and Shut-down Rods of the Reactor KNK II."
Kerntechnik 57, No. 2, 1992, pp. 123-25.

228 Bericht über Untersuchungen an der 1. Abschalteinrichtung der KNK II und Schlußfolgerungen für den weiteren Betrieb.
KBG-Bericht BL 1/87, January 1987.

229 Meldepflichtiges Vorkommnis Nr. 83. Klemmen des Zwischengestänges YC 230 der 2. AE auf Pos. YG 304.
TÜV Baden, Az.: 116-522-2.1 B, Nov. 29, 1989.

230 Schwergängigkeit einer Steuer- und Abschalteinheit der 1. AE. Besonderes Vorkommnis Nr. 97 Zwischengestänge YC 215 mit Antriebseinheit YA 21.
TÜV Baden, Az.: WBB2(M)-101/90, Oct. 10, 1990.

231 Gutachtliche Stellungnahme zum Besonderen Vorkommnis Nr. 103 der KNK.
TÜV Baden, Az.: KS(M) - 126/91, Mannheim, June 1991.

232 Analyse von Belagsproben an Zwischengestängen der Abschalteinrichtungen KNK II.
Interatom Memo 55.09778.5 A, Bensberg, Sep. 13, 1989.

233 W. Steiger, J. Schreibmaier:
"Some Experiences with Sodium Exposed Components in KNK."
FR'91 International Conference on Fast Reactors and Related Fuel Cycles.
Kyoto, Japan, October 28-November 1, 1991, vol. I, pp. 5.2-1 to 5.2-10.

234 Natriumchemische Abläufe im Zusammenhang mit Schwergängigkeit bei den Zwischengestängen.
Interatom Memo 55.10313.3, Bensberg, May 3, 1991.

235 "Bau für KfK-Lagerhalle eingestellt."
Badische Neueste Nachrichten, No. 284, Dec. 10, 1982.

236 "Baustopp aufgehoben."
Stuttgarter Zeitung, No. 10, Jan. 14, 1983.

237 "Student stoppt Kernforschungsanlage."
Handelsblatt, No. 59, March 22, 1984.

238 Land Baden-Württemberg "Bekanntmachung"
Amtsblatt der Gemeinde Eggenstein-Leopoldshafen, Nr. 25, Friday, June 22, 1984.

239 H. Blöchle:
"Erstmals Erörterungstermin seit fast 10 Jahren für KNK II."
Umweltschutz, 1, February 1985, p. 16.

240 Genehmigung Lagerhalle, Chemieraum I und II.
Ministerium für Wirtschaft, Mittelstand und Technologie Baden-Württemberg, Stuttgart.
AZ: IV 8760 - KNK II/350.
April 9, 1986.

241 Atomrechtliches Genehmigungsverfahren KNK II.
Standzeitverlängerung für KNK II/2.
Letter from KBG to Ministerium für Wirtschaft, Mittelstand und Verkehr Baden-Württemberg, Stuttgart, May 23, 1984.

242 KNK II: Kompakte Natriumgekühlte Kernreaktoranlage mit schnellem Kern.
"Standzeitverlängerung 2. Kern auf 720 Vollasttage." Sicherheitsbericht.
KfK, KBG, Interatom, Ident-Nr.: 75.15917, January 1986.

243 Land Baden-Württemberg. Bekanntmachung.
Badische Neueste Nachrichten, No. 11, Wed., January 15, 1986.

244 Sammeleinwendung gegen die Standzeitverlängerung des 2. Kerns KNK II.
KFZ-AK, Karlsruhe.

245 "Standzeitverlängerung KNK II."
Transcript of the public inquiry held in Eggenstein-Leopoldshafen on May 26, 1986.
Ministerium für Wirtschaft, Mittelstand und Technologie Baden-Württemberg, Stuttgart.
Az.: III 8760.1-KNK II/9.

246 "KNK II Genehmigung zur Standzeitverlängerung."
Ministerium für Wirtschaft, Mittelstand und Technologie Baden-Württemberg, Stuttgart.
GV-003377 - 0.135, Az.: IV 8760 - KNK II/377 dated Dec. 20, 1988.

247 Verwaltungsrechtssache Junker ./. Land Baden-Württemberg.
Verwaltungsgerichtshof Baden-Württemberg, Mannheim, Feb. 7, 1989.
Az.: 10 S 291/89.

248 Verwaltungsstreitsache Klaus Junker ./. Land Baden-Württemberg
KBG application, Feb. 13, 1990 to Verwaltungsgerichtshof Baden-Württemberg, Mannheim.

249 Az.: 10 S 291/89 und 10 S 292/89 Verwaltungsrechtssache Klaus Junker ./. Land Baden-Württemberg.
Letter from Rechtsanwalt M. P. Schulze to Verwaltungsgerichtshof Baden-Württemberg, Mannheim, June 13, 1990 .

250 W. Kathol, H. Richard, H. Schott:
"Ergebnisse des KNK II-Versuchsprogramms."
KfK-Nachrichten, vol. 14, 4, 1982, pp. 216-24.

251 J. Aberle:
"Akustische Messungen zur Siededetektion in der KNK II."
KfK-Bericht 4580, June 1989.

252 W. Kathol, D. Artz, J. Schindewolf:
"Das Versuchsprogramm am Brüterkraftwerk KNK II."
Booklet publ. by Kernforschungszentrum Karlsruhe GmbH, Karlsruhe, December 1986.

253 D. Artz, H. G. Leiste, B. Konstandin:
"Experimentierstopfen, bewährte Versuchseinrichtung der KNK II."
Jahrestagung Kerntechnik '88, Travemünde, May 17 - 19, 1988, Deutsches Atomfourm e.V., Bonn, 1988, pp. 547-50.

254 St. Müller, G. Thun:
"Performance of Permanent Magnet Flowmeter Probes for Instrumentation of LMFBR's."
Second International Conference on Liquid Metal Technology in Energy Production. Richland, Washington, U.S.A., April 20-24, 1980. Proceedings, Editor: J. M. Dahlke, Washington D.C., American Nuclear Society, CONF-800401-P1, 1980, p. 4.44-4.51.

255 V. Bauernfeind, B.J. Olma:
"Experimental and Theoretical Vibration Analysis by Noise Measurements of a Sodium Cooled Reactor."
3rd International Conference on Structural Mechanics in Reactor Technology. London, U.K., Sep. 1 - 5, 1975.
Proc. Compiler: T.A. Jäger, International Association for Structural Mechanics in Reactor Technology; Commission of the European Communities, Brussels, British Nuclear Energy Society, London Amsterdam, The Netherlands: North-Holland, 1975, Vol. 2, Part F, Paper F1/3, pp. 1-13.

256 L. Caldarola, P. Ferranti, F. Mitzel:
"Fast Reactor Transfer Functions with Special Reference to the Nonlinearities and to the Spatial Dependence of the Heat Transfer Process."
KfK-Bericht 2027/EUR 4978e, October 1974.

257 G. Weinkötz, L. Krebs, H. Martin:
"The Cooling Disturbances Indication and Analysis System CODINAS - an On-Line Temperature Noise Surveillance of KNK II Subassemblies."
International Conference on Fast Breeder Systems: Experience Gained and Path to Economic Power Generation, Pasco-Richland, U.S.A., September 13-17, 1987.
Proc. American Nuclear Society (ANS), La Grange Park, Ill., U.S.A., 1987, pp. 8.22-1 to 8.22-8.

258 H. Eggert, K. P. Scherer, K. Schleisiek, P. Stiller, H. Schöller, P. Rohnacher:
"An Intelligent Diagnostic System for the Experimental Fast Reactor KNK II."
FR'91 International Conference on Fast Reactors and Related Fuel Cycles.
Kyoto, Japan, October 28-November 1, 1991, vol. I, pp. 4.1-1 to 4.1-11.

259 K. Anderko, W. Dietz and K. Ehrlich:
"Developments in Fast Breeder Core Materials."
Feature Articles in Nuclear Europe, vol. VI, No. 2, February 1986, pp. 22-26

260 L. Schmidt, H. Lehning, K. Müller, G. Reimann:
"Regelbare Bestrahlungseinrichtungen für den KNK II-Reaktor."
KfK-Bericht 4149, December 1986.

261 K. Müller, E. Bojarsky, P. Norajitra, L. Schmidt:
"Bestrahlungskapsel mit Wärmerohr für KNK II und SNR 300."
KfK-Bericht 4151, November 1986.

262 H. E. Häfner, H.-J. Ritzhaupt-Kleissl, H. Steiner:
"Erfolgreicher Karbid-Brennelementtest im KNK II-Reaktor."
Kerntechnik, 52, No. 3, June 1988, pp. 164-68.

263 K. Richter, U. Benedict, J.F. Gueugnon, H. Kutter, C. Sari, G. Mühling:
"Specification, Fabrication and Characterization of (U, Pu)C Fuel."
Journal of Nuclear Materials, 153, North-Holland, Amsterdam, 1988, pp. 205-10.

264 H.-J. Ritzhaupt-Kleissl, H.-J. Heuvel:
"Das Bestrahlungsexperiment TOAST im 3. Kern der KNK II - Zielsetzung und Umfang -."
Jahrestagung Kerntechnik '86, Aachen, April 8 - 10, 1986. Deutsches Atomforum e.V., Bonn, 1986, pp. 333-36.

265 Arbeitskreis Kernkomponenten.
Minutes, 113th meeting, Dec. 6, 1991.
Author: W. Kathol.

266 G. Finke, H. Richard, K. H. Menges:
"System Contamination and Radiological Aspects after 12 Years' Operation of KNK I/II."
3rd International Conference on Liquid Metal Engineering and Technology, Oxford U.K., April 9 - 13, 1984. British Nuclear Energy Society, London, 1984, vol. 1, pp. 505-8.
ISBN: 0 7277 0209 2.

267 K. Ch. Stade, H. Richard, G. Hoffmann, S. Jacobi, G. Schmitz:
"Radionuclides in the Cover Gas of KNK II."
Second International Conference on Liquid Metal Technology in Energy Production. Richland, Washington, U.S.A., April 20-24, 1980. Proceedings, Editor: J. M. Dahlke, Washington D.C. American Nuclear Society, CONF-800401-P2, 1980, p. 14.38-14.45.

268 K. Ch. Stade, J. Zschetke:
"Betriebserfahrungen mit alkalischer und kombinierter Fahrweise am Versuchs-Kernkraftwerk KNK."
VGB Kraftwerkstechnik 65, 9, September 1985, pp. 844-49.

269 K. Ch. Stade, H. H. Stamm, H. D. Hanke, H. Clauss, N. Hanebeck, R. Tusche:
"Status of Cesium Removal from Primary Sodium in the German LMFBR Program."
ANS/ENS International Topical Meeting on Fast Reactor Safety, Knoxville, Tennessee, U.S.A., April 21 - 25, 1985. Proc. of the International Topical Meeting. vol. I. Oak Ridge National Lab., Tennessee, U.S.A., July 1985, pp. 197-204.

270 W. Haubold, K. Ch. Stade, H. H. Stamm:
"Chemie in natriumgekühlten Kernkraftwerken - Erfahrungen in der Kompakten Natriumgekühlten Kernreaktoranlage (KNK)."
VGB Kraftwerkstechnik 55, 2, February 1975, pp. 94-104.

271 H. D. Hanke, H. E. Noppel, H. Wild:
"Tritium im Tertiärkreis der Kompakten Natriumgekühlten Kernreaktoranlage Karlsruhe (KNK II)."
KfK-Bericht 4972, November 1991.

272 W. Salowsky, J. Blombach:
"Zuverlässigkeitsdaten von Natriumkomponenten, ermittelt aus dem Betrieb der KNK."
Jahrestagung Kerntechnik '88, Travemünde, May 17 - 19, 1988.
Deutsches Atomforum e.V., Bonn, 1988, pp. 219-22.

273 B. Schubert:
"Untersuchungen zur Anlagendynamik von natriumgekühlten Schnellen Brutreaktoren - Verifikation eines Anlagenmodells."
GKSS-Forschungszentrum Geesthacht GmbH, Geesthacht-Tesperhude.
GKSS 88/E/18.

274 R. Hüper, W. Kathol, M. Kempken:
"Status of Fast Breeder Reactor Development in Germany."
Twenty-Fourth Annual Meeting. Tsuruga, Japan, April 15 - 18, 1991.
Proc. International Atomic Energy Agency, Vienna, IWGFR/83, 1991, pp. 13-16.

275 Memo Dr. Marth, Dec. 12, 1988.

276 KNK II
File memo, G. Schnetgöke, June 12, 1989.

277 "Stellungnahme des Arbeitsausschusses F + E-Programme Schnelle Natriumgekühlte Reaktoren zur aktuellen Diskussion über KNK II"
Memo, Aug. 15, 1989.

278 Minutes, 40. Geschäftsführersitzung der Entwicklungsgemeinschaft Schneller Brüter, Karlsruhe, June 13, 1989.

279 J. Höchel:
"Memorandum zur Situation der KNK II."
IA-Notiz, Ident-Nr. 65.08038.1,
March 1989.

280 J. Höchel:
Letter to Dr. H.-H. Hennies,
May 12, 1989.

281 "Weiterbetrieb der KNK II-Reaktoranlage."
Letter from Prof. Hennies, KfK to Dr. Borst, BMFT, Bonn.
July 14, 1989.

282 "Weiterbetrieb der KNK II-Reaktoranlage."
Letter from Dr. Wagner, Prof. Hennies, KfK to Dr. Borst, BMFT, Bonn.
Oct. 23, 1989.

283 A. H. de Haas van Dorsser, A. R. Braun, H. Mausbeck:
"Fortschritt in Forschung und Entwicklung der Natriumtechnologie."
Statusbericht 1976, Projekt Schneller Brüter.
Atoomenergie en haar toepassingen 18 (1976).

284 K. Traube:
"Müssen wir umschalten? Von den Grenzen der Technik."
Rowohlt, April 1978.

285 W. Marth:
"Der Schnelle Brüter SNR 300 im Auf und Ab seiner Geschichte."
"The SNR 300 Fast Breeder in the Ups and Downs of its History."
KfK-Bericht 4666, March 1992 (in German), KfK 5455, December 1994 (in English).

286 W. Bürkle:
"Brüter vor dem Start."
Energiewirtschaftliche Tagesfragen, 3, 1986.

287 Die Weisung.
atomwirtschaft, July 1988, p. 334.

288 Kohl:
"Neue Situation für Wackersdorf."
Badische Neueste Nachrichten, 86, April 14, 1989.

289 "Endlich: Letzter Spatenstich in Wackersdorf."
Die Tageszeitung, Berlin, June 1, 1989.

290 Address by the Chief Executive Officer of the Nuclear Research Center,
Prof. Dr. Horst Böhm, at the 1989 Annual Reception.
Press release, KfK, 42/89, Dec. 7, 1989.

291 U. F. Nobbe:
"SNR 300: Das Urteil des Bundesverfassungsgerichts."
atomwirtschaft, July 1990, pp. 339-42.

292 Bundesminister für Forschung und Technologie.
"Brüterprojekt SNR 300 wird nicht weitergeführt."
Press release 14/91, March 21, 1991.

293 W. Marth
"The Story of the European Fast Reactor Cooperation."
KfK 5255, December 1993 (in English).

294 "Betrieb der KNK II."
Memo from W. Kathol to Dr. Marth.
June 15, 1989.

295 "Arbeiten an KNK II/3."
Letter from Dr. Marth, G. Schnetgöke, KfK to Interatom.
July 14, 1989.

296 "Herstellung und Lieferung von Brennelementen für die 3. Kernladung KNK II (KNK II/3)."
Letter from Dr. Tebbert to Siemens AG, Brennelementewerk Hanau.
July 25, 1989.

297 "Weiterbetrieb der KNK II-Reaktoranlage."
Letter from Prof. Böhm, Prof. Hennies, KfK to Dr. Borst, BMFT, Bonn.
Feb. 22, 1991.

298 "KNK II-Reaktoranlage."
Letter from Prof. Hennies, KfK to Geschäftsführung KBG.
Aug. 22, 1991.

299 B. Kunle, KBG:
Personal Communication to Dr. Marth, KfK.
April 1, 1993.

300 "KNK endgültig abgeschaltet."
Press release, KfK, No. 27/91, Aug. 23, 1991.

Timetable

1955	
August	The First United Nations Conference on the Peaceful Uses of Atomic Energy is held in Geneva.
October	A German Federal Ministry for Atomic Affairs is installed; F.J. Strauß (CSU) is appointed Minister.
1956	
July	The Karlsruhe Reactor Center is established; Kernreaktor Bau- und Betriebs GmbH is founded.
October	S. Balke (CDU) succeeds F.J. Strauß as Minister for Atomic Affairs.
December	The North Rhine-Westphalian State Parliament decides to establish a research center, whose location later is decided to be Jülich.
1957	
March	The treaties establishing the European Atomic Energy Community are signed.
August	Construction of the FR 2 reactor is begun at the Karlsruhe Nuclear Research Center.
December	Breeder topics begin to be covered in the Federal Republic of Germany at a seminar held by the Institute for Neutron Physics and Reactor Engineering (INR) of the Karlsruhe Nuclear Research Center.
December 13	Interatom GmbH is founded; the head office of the company is in Duisburg.
1958	
January	The European Atomic Energy Community, EURATOM, is founded.
December 15	Interatom moves to Bensberg (Old Castle).

1959

June	The Gesellschaft für Kernforschung (GfK) is founded by the German Federal Government and the State of Baden-Württemberg.
July	The Soviet BR-5 experimental reactor attains full power.

1960

April 1	The Fast Breeder Project (PSB) is established at the Karlsruhe Nuclear Research Center.
April	The German Advisory Committee on Atomic Energy adopts the Advanced Reactor Program.

1961

May	The Supervisory Board of KfK decides to step up activities in the Fast Breeder Project.
October	The EBR II (25 MWe) in Idaho, USA, goes critical.

1962

December	The German Federal Ministry for Atomic Energy is renamed Ministry for Scientific Research (BMwF).
December	H. Lenz (FDP) succeeds S. Balke as Federal Minister for Research.
December	The FR 2 reactor at the Karlsruhe Nuclear Research Center begins full-power operation (12 MWth).

1963

March	Construction of the 5 MWth Facility is begun at Interatom (sodium is filled in late 1964).
August	The Badenwerk AG utility declares is willingness to finance the turbo-generator for KNK I.
August	The Enrico Fermi fast breeder reactor (60 MWe) goes critical in the United States.
December	General Electric (USA) is awarded the contract for the Oyster Creek Nuclear Power Station; this is the first commercial order for a light water nuclear power plant.

1964

January	The Gesellschaft für Kernforschung and the Kernreaktor Bau- und Betriebs-GmbH are merged.
May	The contracts for construction of the SEFOR reactor are signed (reactor transient experiment).

1965

May	The EBR II experimental breeder reactor is commissioned in Idaho, USA.
October	G. Stoltenberg (CDU) succeeds H. Lenz as Federal Minister for Research (BMwF).

1966

March 7	The KNK I construction site is opened, the fence is built.
March 29	First regular Project Meeting.
May 1	Start of construction of KNK I at the Nuclear Research Center.
May 23	The 1st Partial Construction Permit is received.
May 31	The contract for construction of KNK I is signed.
July 19	Sinking the caisson is completed.
October	Accident at the Enrico Fermi fast breeder reactor (fuel meltdown).
December	The SNEAK facility at the Nuclear Research Center goes critical.

1967

February 16	The steel dome of the KNK I containment is put in place.
October	The Na-2 Study by KfK (with contributions by industry) is published.
October	Memoranda of Understanding are signed with Belgium and the Netherlands.

1968

July	The steam generator is subjected to a pressure test.
September	Assembly of the sodium systems is completed.
September 12	Assembly of the turbo-generator.
December	The Nuclear Reactors III/1 Working Group proposes to discontinue work on the steam cooled breeder.

1969

February 5	Industrial activities for the steam cooled fast breeder reactor are discontinued by order of Federal Minister for Research Stoltenberg.
March	Acceptance of building construction at KNK I; start of F1 tests.
April	AEG and Siemens merge their power plant activities in a joint subsidiary, Kraftwerk Union (KWU).
October	6th German Parliament, SPD/FDP coalition (Chancellor: W. Brandt).
October	H. Leussink (independent) succeeds G. Stoltenberg as Federal Minister for Research.
October 28	First delivery of sodium to KNK I.
November	Start of F2 functional tests with sodium.
December	The Soviet BOR-60 experimental breeder goes critical.
December 31	Presentation of the SNR 300 Safety Report by the SNR Consortium.

1970

March	Delivery of the fuel elements; precleaning of the QP1/2 primary system.
May	Successful irradiation of 39 fuel rods typical of SNR completed in the DFR.
July - October	Installation of new steam traps; revamping the trace heating system; measures taken on the reactor top shield; cleaning and modification as well as commissioning of the cold trap.
September	The R&D Programs Working Group is founded.
October	The Projektgesellschaft Schneller Brüter announces new site of Kalkar.
October/ November	Secondary systems are filled with sodium.
December	Primary systems are filled with sodium.

1971

February 15	Fast Breeder Status Report held at Karlsruhe; public debate about reasons for abandoning the steam cooled breeder line.
March 20	Sodium leakage in the QU1H1 heater (sodium fire).
April	The HDR reactor is decommissioned because of fuel element failure.
May	First Agreement on Breeder Cooperation concluded with Japan.
July	Inspection of top shield gap because of seizing.
August 20	KNK I goes critical for the first time with 38 fuel elements.
September	Start of F3 tests (zero power tests with 66 fuel elements, 2 solid absorbers, 14 dummy elements, complete core).

1972

January	K. v. Dohnanyi (SPD) succeeds H. Leussink as Federal Minister for Research.
January 2	Termination of experimental operation with air cooler.
February 8	Floating of solid absorbers.
May 20	Delivery of the nuclear plant section of KNK I.
July 6	First water and sodium flows through the KNK I steam generator.
August 9	KNK I generator first connected to the grid at 45% plant power.
August 10	Essential A3 for SNR 300 met at 55% rated power of KNK I.
August	KNK reactor produces first electricity.
Sepember 11	Vibrations detected in turbine shaft.
September 18	Both reactor isolation valves close.
September 23	Steam generator defect (QS2E1) in KNK I.
November	7th German Federal Parliament, SPD/FDP coalition (Chancellor: H. Schmidt).
November	Positive opinion on KNK II by Technical Inspectorate.
December	H. Ehmke (SPD) succeeds K. v. Dohnanyi as Federal Minister for Research.

1973

January	Positive RSK vote on conversion to KNK II.
February 5	Delivery of KNK I to GfK/VA and KBG following acceptance operation at approx. 55% power.
April 1	Start of SNR 300 construction at Kalkar.
April	The Nuclear Reactor Divisions of AEG and Siemens are merged with Kraftwerk Union.
May 25	Prolonged drop time of secondary KNK shutdown system (signal No. 1).
July 24	Increased enthalpy rise found in fuel element.
August 20	QS1A14 rupture disk actuated.
September 4	Public discussion about KNK II at KfK Nuclear Engineering School.

1974

February 18	Permit obtained for 100% rated power.
April 29	Faulty turbo-generator synchronization.
May	First operation of all five turbine extractions.
May 14	100% rated power attained
May	H. Matthöfer (SPD) succeeds H. Ehmke as Federal Minister for Research.
June	KNK II contracts negotiated and signed.
July 14	The French 280 MWe PHENIX prototype breeder starts commercial operation.
September	Experimental program: completion of run II plug experimental program.
September 2	Shutdown of KNK I; preparation for conversion to KNK II.
December	Start of replacement of fuel element storage drum.
December 13	Beginning of KNK I core unloading.

1975

February	Core unloading completed; 42 fuel elements shipped to Marcoule, 24 to the MZFR storage pool.
March	All fuel elements shipped to Marcoule.
May 2	1st Partial Construction Permit issued for conversion to KNK II (basic permit).
May	Beginning of replacement of valve tops.
June	Installation of additional emergency Diesel power unit completed.
July	Beginning of conversion to KNK II.

1976

February	German-French Government Agreement on Breeder Cooperation signed.
March	Leak rate test of KNK containment performed by Technical Inspectorate.
March	Soviet BN-350 breeder attains full power.
October 25	QP2 primary system again filled with sodium.

1977

January	Siemens takes over AEG holdings in Kraftwerk Union (KWU).
January 11	Permit obtained for process computer system.
February	Neutron shielding installed for dry fuel element store; final acceptance of building.
February	British 250 MWe PFR prototype breeder attains full power.
April	Assembly of DND system in KNK II completed; F3 commissioning programs completed.
April	U.S. President Carter announces new atomic energy program (no reprocessing, breeder activities scaled down).
May	Completion of seismic protections of primary piping and intermediate heat exchangers.

July — Acceptance and storage of 23 driver elements, 2 blanket elements, 6 test zone elements for KNK II first core.

August — Seismic protection activities in primary system completed.

September 30 — 3rd Partial Construction Permit issued for old specifications.

September 30 — 2nd Partial Operating Permit issued for zero power tests.

October 10 — KNK II goes critical for the first time.

December — Commissioning measurements and setting of reactivity meters.

1978

January — High temperature cleanup operation of KNK II sodium systems.

February — V. Hauff (SPD) succeeds H. Matthöfer as Federal Minister for Research.

April 18 — First scram via "negative reactivity high" reactivity meter limit (report No. 4 of April 21, 1978).

April 26 — First electricity generation in KNK II.

July — Vibrations of bearings and shaft found in KNK turbine.

July — Japanese JOYO experimental breeder reaches full power.

September — State Minister Riemer, North Rhine-Westphalia, recommends operation of SNR 300 as a plutonium annihilation plant.

November 15 — 50% reactor power attained in KNK II.

December 8 — German Federal Constitutional Court finds licensing provisions in the Atomic Energy Act constitutional ("Kalkar Ruling").

1979

March — 8th German Federal Parliament establishes Inquiry Committee 1, "Future Nuclear Power Policy," (Chairman: R. Ueberhorst).

March 3 — KNK II attains first full power.

March — Experimental programs begun: investigation of scrams via negative reactivity effect; noise analyses; neutron flux and acoustic measurements.

April 1 — First failed fuel element found in KNK II/1.

1980

February	American 400 MWth FFTF experimental breeder goes critical.
March	German Federal Ministry for the Interior promulgates Principles of Waste and Spent Fuel Management.
April	Soviet BN-600 (600 MWe) breeder delivers first electricity.
May 20	Second failed fuel element in KNK II/1.
October 5	9th German Federal Parliament, SPD/FDP coalition (Chancellor: H. Schmidt).
November	A. v. Bülow (SPD) succeeds V. Hauff as Federal Minister for Research.
November 6	Contractual acceptance of KNK II by KfK and KBG.

1981

April	German Federal Parliament establishes Inquiry Committee 2, "Future Energy Policy" (Chairman: H.B. Schäfer).
July - August	Experimental studies of the gas bubble problem.
August	Contractual target burnup of KNK II/1 (255 full-power days) reached.
December	310 full-power days reached.

1982

February	Storage hall annex building: excavation and concrete construction.
May 3	"Startup chamber for Superphenix" experiment plug installed in core position 100.
August 30	Target burnup of extended core (400 full-power days) reached.
September	Positive vote by "Future Nuclear Power Policy" Inquiry Committee.
October	Change of government in Bonn ("Wende"); Chancellor: H. Kohl. H. Riesenhuber (CDU) succeeds A. v. Bülow as Federal Minister for Research.
December 3	Reservation about commissioning SNR 300 rescinded by Federal Parliament.

1983

April	Installation of bubble tubes licensed.
May	Removal of NY 203-IA fuel element to Hot Cells.
June 20	Beginning of KNK II/2 core loading.
June 26	First criticality of KNK II/2.
July 10	Cesium trap started up for the first time.
August 22	First full power attained with KNK II/2.

1984

May	Replacement of main sodium pump rotor.
June 6	Government Agreement about Cooperation on Sodium Cooled Breeder Reactors among Germany, France, and the United Kingdom.
Dec. 4 -6	Public inquiry in Wesel on Mk. Ia core modification of SNR 300.

1985

April 6	First failed fuel element found in KNK II/2.
May	Construction of Kalkar Nuclear Power Station completed; sodium filled into main system.
August 20	Second failed fuel element found in KNK II/2.
September 7	1st criticality of Superphénix at Creys-Malville.
October	SNEAK at Karlsruhe decommissioned and converted into tritium laboratory.

1986

January	Experiments on sodium deposits in rotating top shield.
March	400 full-power days of burnup attained in KNK II/2.
March 17	Third failed fuel element detected in KNK II/2.
April 26	Chernobyl accident.
June	W. Wallmann (CDU) appointed Federal Minister for the Environment (BMU).

August 10	SPD party rally at Nuremberg demands opting out of nuclear power within ten years (proposal by Hauff Committee).
August 10	Fourth failed fuel element found in KNK II/2.
December	Shim shutdown rod found to stick.

1987

March	K. Töpfer (CDU) succeeds W. Wallmann as Federal Minister for the Environment.
March 31	Third failed fuel element detected in KNK II/1 (at 175,000 MWd/t).
May	KNK II/1 fuel element unloaded after 832 full-power days.
June	THTR 300 delivered to operator.
October 10	10th anniversary of first criticality of KNK II.
October 20	Fifth failed fuel element detected in KNK II/2.
November	Licensed core life of 455 full-power days for KNK II/2 attained.

1988

January	Major turbine and generator revision.
March	Primary shutdown system equipped with torque meter.
April	Loose screws discovered in primary pump.
May	Requalification of dismantled pump rotor.
October	Cesium trap commissioned.
December 19	Urgent report to authority because of problems with rod actuating equipment.

1989

February 16	Agreements among Germany, the United Kingdom, and France signed in Bonn about breeder cooperation on the European Fast Reactor (EFR).
April	Materials test elements installed in KNK II.
August	Cleaning campaigns for shutdown rod actuating equipment.
October	THTR 300 decommissioned.

October 31	Fast Breeder Project (PSB) terminated at Karlsruhe; LWR and Breeder Safety Programs merged in Nuclear Safety Research (PSF) Project.
November 1	Management Group for Research and Development (MGRD) founded for the European Fast Reactor (EFR).
December 20	Permit issued to extend core life of KNK II/2 to 720 full-power days.

1990

January 29	KNK II/2 restarted after two-year outage.
May 22	German Federal Constitutional Court dismisses as unfounded all points of the action brought by the State of North Rhine-Westphalia: "SNR 300 Ruling."
June 9	Sixth failed fuel element detected in KNK II/2.
August	Chip discovered in absorber rod actuating equipment during investigations in Hot Cell.
October 3	Unification of Germany.

1991

January	New term of CDU/CSU-FDP government coalition (Chancellor: H. Kohl); H. Riesenhuber confirmed as Federal Minister for Research and Technology.
March 20	The contracting parties and BMFT decide to discontinue the SNR 300/Kalkar Nuclear Power Station project.
March 21	Press release by the Federal Minister for Research and Technology accusing the State of North Rhine-Westphalia of bearing responsibility.
April 10	Delivery contracts for SNR 300 terminated by SBK.
May	Single-rod exercising in primary shutdown system (because of event No. 103); various cleanup steps.
July 15	KNK II/2 recommissioned.
August 10	Seventh failed fuel element found in KNK II/2.
August 23	Permanent shutdown of KNK II.

Persons *

1. Nuclear Research Center

Dr. Rudolf Greifeld	1956-74	(Managing Director, K I and GfK)
Dr. Walther Schnurr	1960-70	(Managing Director, K I and GfK)
Dr. Josef Brandl	1961-68	(Managing Director, GfK/VA and K II)
Dr. Helmut Armbruster	1961-65	("Prokurist," MZFR and GfK/VA)
Heinrich Schöller	1961-63	(Managing Director, K II)
Dr. Hubert Tebbert	1963-	("Prokurist," GfK/VA, EKM)
Dr. Gerhard Brudermüller	1964-68	(Project Leader, KNK)
Gregor Schnetgöke	1965-91	(Project Leader, KNK)
Dr. August-Wilhelm Eitz	1968-73	(Managing Director, GfK/VA)
Dr. Willy Marth	1969-89	(Project Leader, KNK and PSB)
Prof. Dr. Otto Haxel	1970-73	(Managing Director, K I and GfK)
Werner Kathol	1972-91	(Project Engineer, KNK)
Detlef Artz	1974-91	(Project Engineer, KNK)
Prof. Dr. Hans-Henning Hennies	1975-	(Executive Board member, GfK/KfK)
Prof. Dr. Rudolf Harde	1976-83	(Chief Executive Officer, GfK/KfK)

* Holders of management and project management functions, respectively, for KNK or the preparatory project; in each case, the top ranking position is listed; names are arranged by year of entry.

2. Kernkraftwerk-Betriebsgesellschaft

Dr. Helmut Armbruster	1966-73	(Managing Director, KBG)
Burkhard Reuter	1966-	(Deputy Plant Manager, KNK)
Erich Zimmermann	1966-91	(Plant Manager, KNK)
Günter Finke	1966-88	(Plant Manager, KNK)
Max Werner	1967-70	(Deputy Plant Manager, KNK)
Dr. Gerhard Brudermüller	1969-85	(Managing Director, KBG)
Dr. Hermann Richard	1969-	(Deputy Plant Manager, KNK)
Heinrich Semke	1970-76	(Deputy Plant Manager, KNK)
Werner-O. Steiger	1986-	(Managing Director, KBG)
Robert Pleesz	1987-93	(Plant Manager, KNK)
Karl Korn	1989-	(Plant Manager, KNK)

3. INTERATOM (Bergisch Gladbach)

Dr. Rudolf Harde	1960-75	(Managing Director)
Dr. Klaus Berke	1960-91	(Managing Director)
Karl-Walter Stöhr	1960-72	(Project Leader, KNK)
Dr. Hans Mausbeck	1963-85	(Group Executive)
Joachim Gilles	1965-72	(Project Leader)
Dr. Horst Brakelmann	1965-73	(Division General Manager)
Bernd Gubo	1965-73	(Project Administrator)
Peter Sieveking	1969-84	(Managing Director)
Hubert Andrae	1970-78	(Project Leader)
Dieter Forst	1970-78	(Project Engineer)
Peter Romeike	1971-91	(Project Leader)
Dr. Klaus Traube	1972-76	(Managing Director)
Elmar Guthmann	1973-77	(Senior Project Manager)
Dr. Lutz Mentrup	1974-91	(Division General Manager)
Alfred Griesenbach	1974-91	(Project Administrator)
Dr. Jochen Höchel	1976-91	(Division General Manager)
Horst Schott	1976-92	(Project Leader)
Isidor Weissbrod	1983-85	(Division General Manager)

4. INTERATOM (Chief Construction Supervision Staff, KNK)

Gottfried Adam	1965-68
Paul Jürgen	1969-70
Karl-Walter Stöhr	1970-71
Dr. Götz Herberg	1971-72
Gerhard Hendl	1972-77
Wilfried Albat	1977-79
Dr. Martin Schmidt-Hönow	1979-82
Dr. Bernhard Heß	1982-85
Dr. Bernhard Klemme	1985-86
Klaus Brockmann	1986-91

5. Ministries, Authorities, Expert Consultants

Dr. Günther Schuster	Federal Ministry for Research, Bonn
Dr. Hans-Peter Lorenzen	Federal Ministry for Research, Bonn
Manfred Kempken	Federal Ministry for Research, Bonn
Dr. Ulrich Däunert	Federal Ministry for Research, Bonn
Dieter Kutschke	Federal Ministry for Research, Bonn
Dr. Klaus Schroeter	Federal Ministry for Research, Bonn
Dr. Herbert Diehl	Federal Ministry for Research, Bonn
Alfred Kleinmann	Licensing Authority, Stuttgart
Dieter Blickle	Licensing Authority, Stuttgart
Ludwig Ostberg	Licensing Authority, Stuttgart
Gerd Heitmann	Licensing Authority, Stuttgart
Karl Geiger	Supervisory Authority, Stuttgart
Joseph Günther	Supervisory Authority, Stuttgart
Manfred Heermann	Supervisory Authority, Stuttgart
Dr. Oskar Grözinger	Supervisory Authority, Stuttgart
Achim Krohn	Supervisory Authority, Stuttgart
Dr. Dieter Wörner	Supervisory Authority, Stuttgart
Dr. Volker Zimmermann	Supervisory Authority, Stuttgart
Anton Schwarz	Supervisory Authority, Stuttgart
Dr. Dietmar Keil	Supervisory Authority, Stuttgart
Theodor Himmel	Federal Ministry for the Environment, Bonn
Dr. Heinz Vetter	Baden Technical Inspectorate, Mannheim
Dr. Hans-Gerhard Fendler	Baden Technical Inspectorate, Mannheim
Herbert Jurgutat	Baden Technical Inspectorate, Mannheim
Ekkehard Morgner	Baden Technical Inspectorate, Mannheim
Friedhelm Bosten	Baden Technical Inspectorate, Mannheim
Dr. Dieter Eitner	Baden Technical Inspectorate, Mannheim
Hans-Jürgen Hetmank	Baden Technical Inspectorate, Mannheim
Friedrich Brodt	Baden Technical Inspectorate, Mannheim
Ludger Dierkes	Baden Technical Inspectorate, Mannheim
Franz-Albert Meyer	Baden Technical Inspectorate, Mannheim
Dieter Wildberg	Baden Technical Inspectorate, Mannheim