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The German Fast Breeder Program

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Paper to be presented at the Symposium on Fast Reactor Physics and Related Safety Problems held at Karlsruhe, Germany, Oct. 30. - Nov. 3., 1967

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1. THE GENERAL PROGRAM

The German fast breeder program started in 196o, when the reactor physics group finished the design work for the Karlsruhe research reactor FR 2. The original approach was characterized by the idea to have not only a fast breeder but also a commercially competitive nuclear power station. This led us immediately into the more detailed examination of the fuel cycle, and our point of departure was then to study the oxide fuel fast breeder concept. The physics of such a reactor is notably different from that of a metal fueled breeder. It was in particular the determination of power coefficients and in this connection, the investigation of the safety features of such a reactor which was of prime importance. And reflecting on the title of this meeting, we feel that it is still of prime importance. It was quite natural therefore, that the first thing in Karlsruhe was the lay-out of a fairly large physics program. From this the constantly increasing engineering studies evolved. Here it was the choice of coolant which was the overriding problem. Attached to this was an experimental engineering program. Parallel to that, we started a fuel element development program which included the construction and operation of the necessary facilities, that is besides the FR 2, a number of hot cells and Pu fabrication facilities and others. At a somewhat later state we emphasized even more strongly R+D work on facilities related to the fuel cycle. Euratom has been associated to this work since 1963. The present association lasts until the end of this year. In the course of the work it was possible to determine more specifically the target of the project: Germany wants to have 1ooo MWe fast breeder power stations by 198o. These fast breeder power stations shall be competitive with the light water reactors, then available. The target for the fuel cycle costs is 1 mill/kWh or less, and for the capital cost the target is 1oo $/kW.

In order to arrive at this goal it is necessary to have fast breeder prototype reactors. This class of reactors has to go into construction by 197o and go into operation by 1974. This gives enough time then for one or even two parallel 1ooo MWe demonstration plants. The successful operation of these plants will be the basis for the commercial phase of fast breeder reactors.

Detailed studies of Karlsruhe concluded that sodium and steam have the same industrial potential. The quality of the potential is different though. Na has a potential of a high gain breeder with the associated fuel cost benefit, and high gain breeding is ultimately, say beyond the year 2ooo, an absolute necessity. We still feel, that capital cost is a problem, the industrial and commercial solution of which can be demonstrated only fairly late in the game. Steam cooled breeder technology on the other hand will directly evolve from present-day light water technology with all the greatly increasing operating experience to come. Please recall that two 6oo MWe light water reactor stations have been ordered in Germany a couple of months ago on a clean and competitive basis without any subsidies whatsoever. Associated with steam cooling is a somewhat lower breeding ratio which partly compensates the capital cost advantage with respect to Na plants.

In 1965/66 the important decision has been taken to prepare the early construction of one sodium and one steam cooled fast breeder 3oo MWe prototype in Germany. And at the same time it has been decided that, instead of the national laboratory, industry has to take the lead and the responsibility for these prototypes, because it is industry and not government which shall handle the expected fast breeder market after 1980. Therefore, the Konsortium Siemens-Interatom will bring up the sodium prototype and the group AEG/MAN/GHH will bring up the steam cooled prototype. The Kernforschungszentrum Karlsruhe as a National Laboratory will have a double function: On the one hand it will actively support the industrial work and accept certain tasks in the framework of the direct prototype work. On the other hand Karlsruhe will pursue a basic program under its own responsibility which broadens and strengthens the project work more generally. Therefore the Fast Breeder Project is no longer a Karlsruhe affair, it became a national effort to arrive independently at the competitive stage of reactors of the second generation, that is the fast breeders.

Looking ahead, one realizes that the market for fast breeder reactors will be tremendous and simultaneously it becomes clear that the German national basis is somewhat narrow. Since the last couple of years there has been an intensive contact to both Belgium and the Netherlands, and as a result there will be a three or ultimately even four level joint fast breeder venture. Belgian and Netherlands industrial groups, that is Belgonucleaire and Neratoom, join the Siemens Interatom Group, the national laboratories of these countries, that is Mol and Petten join Karlsruhe, and the three governments have a corresponding agreement which also provides the funds. There is hope that also the electrical utilities of these countries will come to a parallel understanding at a later stage. There is a good chance that Luxemburg will join the group too. A similar arrangement with other partners is under way for the steam cooled breeder.

The Fast Breeder Project which originated at Karlsruhe is therefore a joint venture of a fairly large size. The involved partners agreed in a fair partition of work. In so doing, the larger physics efforts remain at Karlsruhe, in cooperation with Mol and Petten. Keeping also in mind that this meeting here is concentrating more specifically on physics and safety I will do the same and narrow my report down to these topics.

2. EXPERIMENTAL PHYSICS

As it has been mentioned before, it was the investigation of the physics of an oxide fueled fast breeder with its low energy neutron tail that attracted the attention from the very beginning. In 1961 a four step experimental program was envisaged. It is the following:

2.1. SUAK

The pulsed subcritical assembly SUAK makes use of the accumulated experience with 14 MeV pulsed neutrons here at Karlsruhe. The fast assembly allows for decay measurements and spectrum determinations by the time of flight technique. For easier interpretation of measurements only bare assemblies are constructed which also contain as few materials as possible.

So far three assemblies have been investigated. The first assembly consisted of pure uranium (2o $^{o}/o$ enrichment) only. In the other assemblies different amounts of hydrogen containing material were added to shift the neutrons to lower energies and to study the anisotropic scattering effect of hydrogen in greater detail. The present stage of physics effort at Karlsruhe is concentrating among other things on the effect of the interface between core and blanket. The spectrum in the core is fairly constant with respect to the radius, but in the blanket there are rapid changes of the spectrum with the radius (or z axis). The large mean free path lets this effect penetrate also into the core. The clean geometry of SUAK and the easiness of experimental access enables us to investigate these interface effects at SUAK in the near future. Right now we have a joint French-German venture at SUAK, to compare exponential and pulsed experiments, also by the use of SUAK. This is the program HEUREKA of the Cadarache project. It should be kept in mind that SUAK is not designed for the use of plutonium.

2.2. STARK

The fast-thermal Argonaut reactor was the first critical assembly with fast neutrons on the European continent. The graphite column of the original Argonaut has been replaced by a fast core. Again, only enriched uranium but not plutonium can be used. STARK was of very great help to develop the fast neutron experimental techniques at an early stage, in particular spectrum measurement techniques have been developed. But also a pile oscillator for heated samples and a heated foil furnace for studies of the Doppler effect have been installed. Further, investigation on pulsed sources and with particularly large emphasis on noise analysis techniques came up. This noise analysis is of great help in order to determine the neutron life time and the reactivity features during shut down including the approach to criticality. Parallel to that, the analysis of coupled systems has been carried on. STARK will be persistently of importance to prepare experiments of the larger and more complicated SNEAK machine.

2.3. SNEAK

The fast zero power assembly is a full scale critical facility designed to perform in particular large scale Pu fuel experiments. It went critical on the 15th of December 1966, in the same night when the Cadarache facility MASURCA became critical. SNEAK is comparable not only to MASURCA but to the British zero power reactor ZEBRA and the US ZPPR in Idaho. Physics-oriented experiments are being conducted in the present phase with great emphasis on steam and the involved reactivity coefficients, and the mock up of the two German prototypes will come afterwards. The measurements in SNEAK will ultimately give the physics reference points for the whole German-Belgian-Dutch fast reactor project. You will have a fair amount of detailed information on SNEAK in the course of this meeting.

2.4. SEFOR

The South-West Experimental Fast Oxide Reactor is a joint venture of General Electric and Karlsruhe together with Euratom, the South West Atomic Energy Associates, and the USAEC. As it is well known, it is a 2o Mwth experimental dynamic test reactor, the construction of which is fairly advanced. First criticality is expected for the early summer of next year. The objective of this reactor experiment is to obtain information on the dynamic behaviour of oxide fueled fast breeders, particularly the Doppler coefficient, under operating conditions. At the same time one acquires engineering experience on a significant scale. The experimental program provides for four distinct steps

a) static tests
b) oscillator and balanced oscillator tests
c) sub prompt critical excursions
d) prompt critical excursions.

At the recent Cadarache meeting there has been a fairly large paper on SEFOR reporting the latest stage of the work.

2.5. KRITO

KRITO is at present a thermal critical facility at the Netherlands nuclear research center of Petten. In the framework of the joint Karlsruhe-Mol-Petten program Petten will transfer this facility into a coupled facility in order to investigate the reactivity influence of the fission products. More on this subject will be presented directly by the Petten group.

The reactor physics of fission products has been neglected for quite some time. This stems from the early days of a very hard spectrum and comparatively low burn ups. But fast ceramic reactors of a high burn-up do have a considerable fission product poisoning which decreases not only reactivity but also breeding with the consequence that fuel costs are increasing again beyond a certain amount of burn-up as it is the case with thermal reactors. Thermal reactors have their optimum around 3o ooo MWd/to, large fast oxide reactors seem to have their optimum somewhere near 1oo ooo MWd/to. More precise information on fission product cross sections is necessary to give more accurate evaluations.

2.6. Van de Graaff Accelerator

In Karlsruhe a 3 MeV Van de Graaff accelerator with a bunching facility is used for cross section measurements in the fast breeder project. The experimental program is concerned with the measurement of capture cross sections of structural material and fission products in the energy range of 1o - 2oo keV. Also fission cross sections of the plutonium isotopes 239, 24o, and 241 are measured. Further effort is under way for absolute measurements of cross sections and neutron fluxes as well as for self-shielding factors and resonances in the keV energy region. It may be mentioned in this connection that cross sections of shielding materials are studied in the MeV-range by the use of the Karlsruhe cyclotron.

3. REACTOR THEORY

Reactor theory has always been a field of special interest at Karlsruhe. As a matter of fact, reactor theory was the door to enter the fast reactor field here at Karlsruhe. Looking backward one can recognize a number of phases in the development of fast reactor theory. Originally, one-dimensional diffusion theory with 11 or 13 groups was applied for calculating critical masses or enrichments, the spectra in core and blanket, and breeding ratios. Very soon the emphasis on the lower end of the spectrum led into a larger number of groups and the evaluation of energy self shielding effects. One should recall that there are only about 1o °/o of all fissions below 1o keV where most of the power coefficients originate. S_N versions and other transport techniques were introduced in the multigroup procedures somewhat later.

The next round was concentrating on the calculation of the Doppler and coolant void effects. More extended perturbation codes had to be developed for this, and a detailed examination of the resonances of the neutron cross sections was necessary. The more realistic evaluation of the Na void coefficient necessitated two-dimensional calculations. In addition to the diffusion and S_N codes in two dimensions, group collapsing procedures had to be developed for this two-dimensional procedure. Multizone arrangements in core and blanket also required two-dimensional procedures. The preparation of self-shielded cross-sections, including heterogenity-effects, one-dimensional calculations with very many groups (say 26, 6o or more), group condensation in different regions of the reactor, two-dimensional calculations with a few groups (6 or so) perturbation theory, the calculation of reaction rates, the calculation of power coefficients and neutron lifetime, and the one-dimensional burn-up code have been put together into one super-code, the Karlsruhe NUSYS system. This code has been the basis for all design work at Karlsruhe and the German industrial groups during the last two years. Emphasis is now being put on the transport effects in the region of scattering resonances. Besides applying the well-known ELMOE code, a new technique using about 2oo groups is being developed.

In a third round of effort attention is concentrating on the non-idealized actual power reactor. The influence of fission products is being studied in detail, also the influence and burn-up of control rods, two-dimensional power distributions with control rods, the proper distribution of control rods, the influence of burn-up on the reactor behaviour, the change of the Na void coefficient and breeding ratio with control rod insertion and fuel burn-up, the change of power distribution with plutonium build-up in the blanket, the calculation of the different temperature coefficients in different regions of the reactor, and more engineering details are being studied. We also envisage the large-scale application of Monte Carlo techniques, for example in order to calculate streaming effects. These more elaborate and partially cumbersome procedures are mandatory for a responsible prototype design and describe to some extent the present state of the art at Karlsruhe. Fast reactor theory and calculation may arrive at its asymptotic stage if all these steps are combined into an even larger code, and ultimately we have to look for three-dimensional calculations, when power stretching is required to reach full competitivity. As of today, explicit three-dimensional calculations will not be available at Karlsruhe for more direct design of the prototype reactors, but they will be there in time to calculate best core-blanket management schemes and control rod operation programs. We are aware of the fact that a computer of the IBM 36o/91 size will be necessary for this, whereas for the prototype calculations as described above a computer of the IBM 36o/65 size can handle the supercodes exceeding NUSYS. Such machines will be installed at Karlsruhe next year.

4. REACTOR SAFETY

Reactor safety is as old a concern as reactor theory and it is intimately related to it. Fast reactor safety is particularly challenging, because the configuration of an actual fast reactor is not the one with the highest reactivity, contrary to the situation with thermal reactors. In the old days it was the melt-down accident which attracted the greatest attention. Loss of sodium reduced the reactivity of the original core configuration, and it was the slow core melt-down without additional neutrons which destroyed the core and could have led to a second configuration of much higher reactivity and therefore to an extreme power excursion with subsequent production of large amounts of mechanical energy.

Large fast ceramic power reactors have a region with a positive coolant void coefficient in the inner part of the core. If the coolant is lost the production of neutrons is enhanced, and the destruction of the core is combined with the power excursion and the subsequent production of mechanical energy. Parallel to that one has to consider now the large inventories of plutonium of these fast breeders, together with the formerly unusual sizes of 1ooo MWe. This leads into new orders of radiological concern. It is our conclusion that these hypothetical disasters produce mechanical energies of not much more than 1ooo MWsec, even if extreme measures to obtain a small Na void reactivity effect like pancaking are not taken. 1ooo MWsec is a limited figure and this is so because of the Doppler coefficient. As a matter of fact, this seems to be the most important benefit from having the Doppler coefficient. Rather sophisticated versions of the Bethe-Tait technique are now available at Karlsruhe, taking into account the cylindrical geometry and the axial structure of subassemblies, also a fair amount of work is going on to determine the equation of state for the mixed oxide fuel.

It seems to be possible to contain 1ooo MWsec in a reactor building. Enjoying also the experience from SEFOR safety and licensing procedures we arrived at the two-containment concept, having an inner concrete containment around the reactor and the primary circuit which is nitrogen filled and designed to withstand the 1ooo MWsec event but having only a 1o $^{o}/o$ tightness. Therefore a second containment which is of high tightness and houses the rest of the reactor installation is being planned.

The 1ooo MWsec event can happen more or less only if the safety system fails completely. Measures of diversity and redundancy can avoid such a malfunction practically completely. There are a limited number of events like sodium voiding after a break in the primary circuit and subsequent melt-down which cannot be affected by a functioning safety system. Therefore a safe and reliable design of the primary circuit comes out to be equally important as the design of the safety system itself. But we do hope to arrive ultimately at a situation of engineered safeguards including that of the primary circuit. In such a case no reactor containment but an ordinary building is necessary. We are not confident enough to design such all-out engineered safeguards already for the Na and steam cooled prototypes. Much more work on engineering components testing is required for that. In order to prepare this we started some time ago an effort on the mathematics and statistics of reliability and availability which is quite an exciting new area. In so doing we hope to identify the schemes and fields of excessive engineering testing thus ultimately arriving at the concept of engineered safeguards eventually to be applied to our 1ooo MWe demonstration plants of about 1975/6.

Besides we will pursue a number of more obvious tasks in the field of reactor safety like aerosol research, the radiochemistry of primary circuit contamination in the case of steam cooled breeders, iodine filtering, and others.

Fast reactor physics and safety is becoming more and more a mature business which requires large-scale ventures with all features of being a field of big science.

But this will enable us to have a responsible prototype design by 197o.

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