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Beiträge zum Festkolloquium anläßlich des 60. Geburtstages von Professor Dr.-Ing. Günther Keßler

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Heads or Tails ? An all-winning game in KFK/CEA cooperation on fast reactor research

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former Chairman of the CABRI Comité Mixte

INTRODUCTION

In a near-term future, ten years from now, when thousands of students will crowd the German, and French, universities and engineering institutes specialized in fast breeders' physics and technology, to be instructed in the history of fast reactor research,

- since at that time even the greens and the other ecologists will have recognized that the desperate need for energy in highly populated developing countries can only be provided for if industrialized countries, truly worried about world conservation of fossil fuels and global warming, use nuclear fission for their own needs,

- and since at that time even an undergraduate student will have understood that the energetic content of uranium, and thorium, can only be efficiently utilized if some kind of breeding process is implemented in nuclear reactors,

then the history of fast breeder research will include a special sub-chapter dealing with the astonishing success of the CABRI PROJECT.

What was the CABRI PROJECT, why was it a success, and why was this success so astonishing ? But first, why is it appropriate today to talk about this project and what is the relation between the CABRI PROJECT, Prof. Dr.-Ing. Günther Kessler, and myself ?

THE SIGNATURE OF THE CABRI PROJECT

Let me go backwards in time, and tell you what happened in December 1973, slightly more than twenty years ago. I have always thought that if you can understand the lessons of events that have occurred twenty years ago, you are able to predict what will occur ten years ahead, or at least you will not be wrong more often that young people who were just born yesterday and pretend that they know better what will happen tomorrow.

In December 1973 I was here, in KFK, the world-famous Karlsruhe Nuclear Research Center. Günther Kessler was in the same room, with many other distinguished people, but since this colloquium is not held in their honour, I will not mention their names, and anyway since I do not keep my files in good order I would not be able to give the names without missing some important ones which will make them angry at me. So, here we were, Günther Kessler and myself, and some other fellows.

We signed an agreement between KFK and the French Atomic Energy Commission, the CEA, establishing a joint venture : to build and operate a research facility in the French nuclear center of Cadarache, aiming at a better understanding of the behaviour of a fast breeder reactor core, when exposed to the worst possible type of accident, a critical nuclear excursion with total loss of coolant in the fuel channels.

At that time Cadarache was not a well known place in your country, at least not so well known as it is now, when German tourists are cancelling a trip to the French riviera because some crazy Frenchmen are triggering a second Chernobyl catastrophe in one of their sloppy nuclear facilities, Phebus - a name copied from the sun, the seat of the most violent nuclear reactions you could imagine -. Well, these tourists are right on one point : Cadarache is located in the south-east of France, and not very far from the Mediterranean coast. Among the many aspects of this region they might not be aware of, is the very special accent, intonation, that the local populations include in their speaking. And, although he is quite good in the practice of the French language, maybe Günther Kessler did not realize at that time that the children of the German physicists who will stay in Cadarache for a few years in order to take part to the CABRI programme, would come back to Germany speaking a most fluent French with a delightful, but quite unmistakable for all French people, southern accent, "accent de Marseille", as we call it.

Going back to the time of the signature of the KFK/CEA CABRI agreement, what did we agree upon at that time ? It seems to me that we were in full agreement on the following topics :

- In the safety assessment of sodium cooled fast breeders, the critical issue was related to a very severe accident, with core melt, nuclear excursion and fuel coolant interaction, the so-called "core-disruptive accident", CDA. It was also called HCDA, "hypothetical core disruptive accident", because in order to melt down the fuel in a sodium cooled fast reactor, characterized by a very high thermal inertia coupled to a very fast acting control system for the neutron chain reaction, you must assume that all your redundant equipements fail at the same time. This concept was specific of fast breeders, at a time where LWRs' safety analysis was restricted to the DBA concept, "design basis accident". It is recognized today that fast reactors were precursors in this domain, since "severely degraded core accidents" are now a primary issue in LWR safety.

- Although there were several computer codes that, according to their promoters, were able to describe the CDA accidental sequence, such as SAS3D or SURDYN, although there have been before a few experiments, including in-pile simulations in the American TREAT facility, there was a clear need for new experimental results focused on the key events in the CDA sequence : high energy deposit in the fuel and sodium boiling in the channel. The key words were TOP, "transient over power" and LOF, "loss of flow".

- CEA had in operation in Cadarache two nuclear research facilities in the same building ; each one was equipped with a small swimming pool reactor. The first one was called CABRI. In French, a cabri means a kid, a young goat, jumping all around the place. It has been used for safety studies related to swimming pool reactors subjected to rapid nuclear excursions. At first sight, that was what we needed for the TOP phase. The second facility was running at steady power, giving the neutron source to feed an experimental loop in which a plutonium fuel element was cooled by sodium. The name of the facility was Scarabee, which means in French "beetle", but this time it has no relation at all with the insect, or with any musical group ; it is an acronym, where S stands for Sodium, but I have no idea of the meaning of the other letters. Anyway obviously Scarabee could fulfill objectives similar to those of the LOF phase. CEA and KFK therefore jointly decided that by combining the two facilities into a new one, called CABRI PROJECT, they could reach their common safety objectives.

FEASIBILITY AND IMPLEMENTATION OF THE CABRI PROJECT

The CABRI PROJECT was a fifty - fifty venture between the two organizations, with joint responsibility for all aspects, including finance. The only exception was related to the safety regulatory requirements : since the facility was on French soil, the CEA had to be the operating organization responsible for plant safety, in charge of getting from the French safety authorities all necessary authorizations (construction permit, operating licence, effluent releases, and so on).

The first step was to realize a feasibility study : the general idea looked reasonable, but it was certainly not obvious that the facilities could be modified in such a way that the tests could be performed safely and efficiently, that their results, which had to include the recording of many parameters during the tests, could deliver the information needed by the analysts of breeders' safety, and, last but not least, that all this could be obtained in a reasonable length of time and at a reasonable cost. Of course the key word here is "reasonable". In this context, reason should mean "common sense", but all of us who had the opportunity to work in radiological protection and use the ALARA concept, "as low as reasonably achievable", have to recognize that, unfortunately, common sense is not always shared by all. Therefore, the first challenge of the feasibility study would be to find whether the two parties would finally agree upon what was reasonable and what was not reasonable. And the first astonishing fact about the Cabri Project, is that they did agree on all issues, including the financial aspects.

I could give many examples of the problems which had to be solved during that feasibility phase. I will only mention the choice of fuel for the driver core. During a fast power transient, with a width at half peak of 5 milliseconds, we wanted to reach a peak to initial power ration of 5,000. What type of fuel could withstand such conditions without exceeding technological limits. For similar experiments, the American specialists had developed a quite sophisticated solution. For CABRI, the fuel experts from KFK and CEA decided that a uranium oxyde matrix and a zircaloy cladding, a design similar to the design of PWR fuels, could do the job, and they were right.

Both partners had to trust each other to make the decision process as effective as possible. I remember another example : the hodoscope. The idea was to collect and count neutrons emitted from the tested fuel during the power transient at short time intervals, in order to get at each time the equivalent of a neutronography of the fuel rod, and therefore be able to measure the kinetics of the fuel degradation. I must confess that I was not very enthusiastic myself when our German colleagues did propose to implement such complicated machine into the project. However I had to recognize that the benefit for the interpretation of the tests would be quite significant, and I did trust their ability to develop and operate such a complicated system. And they did it !

Finally, and it will be my last example, in such international ventures, where decisions can be taken only on a consensus basis, in a field where there are quite many unknowns, it may happen that the technical arguments are not strong enough to develop a consensus. It occurred once during the CABRI PROJECT, at a time when I was chairing the Comité Mixte, the franco-german steering committee for the project. I do not remember what was the issue at stake, but I remember how we did solve it, following my proposal : by the toss of a coin ! If it was "Heads", the decision would be "go", if it was "Tails", it would be "don't go". One of our German colleague, not Günther Kessler, did not like too much this unscientific approach to a project management problem, and sent me a special coin with "yes" on one side and "no" on the other side, and it was called "the chairman decision tool". But one of my French colleagues, who knew better, realized that a good chairman would need more. So he gave me three other coins, the first one with "yes" on both sides, the chairman knows best, the second one with "no" on both sides, of course, (which is very useful when someone is asking you to spend some more money for a new experiment or a new device), and the last one with "no" on one side and a question mark on the other. After all, we are living in a difficult world ...

THE CABRI PROJECT ACHIEVEMENTS

In my opinion, the first important achievement of the CABRI PROJECT lies in the experimental field. There has been quite a number of important developments, on instrumentation, on data collection and processing, on post-test examinations. I already mentioned the hodoscope ; there is no doubt that the quality of the results obtained from this equipment were most useful for the theoretical interpretation of the tests.

The tests performed in CABRI contributed to a better understanding of the accidental fuel behaviour, before and after the cladding rupture which would play an essential role in the development of a severe accident sequence.

Before the fuel cladding rupture, two phenomena are important for the reactivity aspects : fuel thermal evolution and sodium boiling. During the power transient, the fuel expands, and the time and location of the can rupture will depend upon the possible displacements of fuel pellets within the cladding and the variation of the gap between the pellet and the cladding. For new fuel, there is a gap which will accommodate fuel expansion ; for irradiated fuel, the cladding will be stuck to the matrix. Now the experts can use a good model validated on the CABRI results.

The can rupture is a key event in the accidental sequence, since it is the starting point for fuel ejection within the channel which can lead to energetic fuel-coolant interaction. Its time and location will vary according to the temperature distribution in the fuel in steady state condition, the mechanical fuel-clad interaction, the kinetics of gaseous fission products release, and the physical characteristics of the cladding. One of the important findings of the CABRI tests was to show that a can rupture occurring above the medium plane will help a transfer of the molten fuel towards the top of the core, in a low reactivity zone.

The phenomena following the can rupture are a mixture of sodium boiling, expansion of a "foam" made of fuel and gaseous fission products, thermal interaction between the foam ad the sodium, and channel plugging resulting for the solidification of the molten "corium" moving to cold regions. The CABRI tests have reproduced a few types of fuel behaviours representative of possible accident sequences in a power reactor. I will describe three sequences, well identified in CABRI :

- The power transient starts up in a channel voided from most of the sodium ; the cladding heats up, melts, and moves ; the fuel melts at the center of the pellet, and the melt zone moves radially ; the pellet swells under the fission gas pressure, and when the fuel geometry is lost, the dispersion starts with sodium ejection ; the dispersion stops when the fuel foam moves in contact with the solid cladding and transfers its energy.

- When the transient starts with the sodium in a boiling state, the can rupture takes place in the upper part of the channel ; a foam is produced and expands downwards ; it meets the liquid sodium ; the violent thermal interaction expels the sodium downwards, and the foam solidifies on the cold parts of the cladding.

- If the sodium is liquid at the beginning of the transient, the mechanical rupture of the cladding takes place around the mid-plane ; the foam gets into interaction with the sodium, and sodium boiling starts ; it slows down the dispersion mechanism, and the process is stabilized.

- In each case, the duration of the sequence is of the order of 200 milliseconds.

The quantitative results from CABRI have been used in the modeling of the various phenomena involved. Today, a code like the French Physura can realistically describe : the thermal and mechanical interactions between the fuel and the cladding, the sodium boiling, the release of gaseous fission products, the can rupture, the fuel-coolant interaction, the fuel movements and the plugging mechanisms. Of course, to evaluate the consequences of such phenomena for a postulated accident in a reactor, the code must be complemented by models dealing with a multi-channels geometry and coupling the neutronic behaviour of various reactor zones.

The destructive examinations performed on fuel pins pre-irradiated in Phenix and PFR before being tested in CABRI, has been used to modify the codes which were supposed to describe the fuel behaviour in steady-state conditions. This was not a part of the original objectives of the programme ; it has nevertheless been quite positive for the safety analysis of fast breeders.

As mentioned earlier in my presentation, one of the critical issue in the safety assessment of fast breeders was the analysis of the accidental sequences where a nuclear excursion would follow a complete loss of the sodium primary pumps without a reactor scram which would stop the chain reaction. Many of the questions raised during the licensing process of breeding nuclear power plants, in France Creys-Malville, have received satisfactory answers thanks to the CABRI results, even if, of course, other research programmes have also greatly contributed to the process. I will mention a few key points :

- the positive reactivity effect of sodium voiding due to the ejection of fission gases before the nuclear excursion ;

- the evaluation of the feedback effect of the axial fuel expansion ;

- the impact of fission gases on fuel displacements during the excursion ;

- the thermal interaction between molten fuel and sodium.

All these results helped verify that the value of 800 MJoules for the maximum mechanical energy release during a CDA, basis of the design of the Creys-Malville confinement structures, were highly conservative ; a more realistic value would be around 200 MJoules.

Finally, the code used for safety assessments of fast breeders have also been used in a recalculation of the Chernobyl accident, although it is not adequate to evaluate the thermodynamics of light water. It has nevertheless shown that the a strong fuel-water interaction is capable of leading to the rupture of the reactor pressure tubes.

CONCLUSION

I personally consider that the CABRI PROJECT is a successful story of an international cooperation built around a consensus between German and French experts on main breeders' safety issues, even before the European agreements which led later to the realization of Creys-Malville. Many actors have played a role in this success. Günther Kessler is certainly one among the most preeminent ones. I always enjoyed working with him. I have had several occasions of discussing with him critical safety issues a long time after our association with the CABRI PROJECT. His views have always been far-sighted, especially when he looked at the concept of confinement appropriate for severe accident mitigation in future PWR designs. However, what is at stake here might be much more important that what were our concerns at the time of the CABRI Comité Mixte. Therefore, I do not propose to use by magic coin. However, I cannot help thinking that if some of our politicians were using such decision tools, on the average the overall results could be greatly improved for the benefit of everybody.

APPENDIX

The CABRI PROJECT discussed in my paper, usually referred to as "Cabri I", lasted from 1974 to 1987. Its total cost has been around 900 millions French Francs (900 MF), evaluated in the economical conditions prevailing in France in 1987. The details are given below :

- plant modifications	140 MF
- operation and experiments	340 MF
- other expenses	270 MF
- interpretation & modeling	150 MF

The technical difficulties which were encountered during the first four years, both in the modification works, and in the operation, have led to a significant increase on both the length of the programme and its cost. It should be underlined that supplementary activities have always been endorsed jointly by the two partners.

Thirty-two tests have been performed, two more than foreseen in the original agreement, at an average rate of 4 to 5 tests per year from 1981 to 1987 :

- 12 tests with fresh fuel pins,

- 9 tests with moderately irradiated pins,

- 11 tests with highly irradiated pins (3 to 5% atoms fissioned)

The Role and Impact of Professor Günther Kessler in the Development of the German Ion Beam Driven Inertial Confinement Fusion Program

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I. Introduction

The role of Professor Kessler in the development of the German ion beam driven fusion program has been truly exemplary. While his leadership in the fission reactor field has been widely recognized for some time, the important role that he has played in fusion has been only apparent recently. The objective of this article is to provide documentation of his role, as well as to provide some perspective on the significance of his efforts in the ion beam driven fusion area.

II. Early Work in Fusion

Prior to 1975, Dr. Gunther Kessler had concentrated his research efforts on fission reactors. In early 1975, there was an exchange of technical letters on the subject of fusion between Professor W. Häfele, Director of the Energy project in the International Institute for Applied Systems Analysis (IIASA) and Professor J. Holdren of University of California-Berkeley [1-2]. The two scientists disagreed on the relative merits of DT fusion reactors and fast fission breeder reactors. It was decided that the only way to settle the apparent technical differences was to have the two proponents write a common article/book on the subject in which each could make their points subject to the examination by the other. In order to insure a breadth of technical input, it was agreed that each of the proponents could bring in an additional expert in their field. Professor Häfele chose Dr. Kessler of Karlsruhe Nuclear Center who had extensive experience in the area of fast fission reactors and Professor Holdren chose Professor G. Kulcinski of the University of Wisconsin who had experience in the design of fusion power plants. Work began on the common treatise in the summer of 1975 at IIASA in Laxenburg, Austria.

The ultimate product of the collaboration described above was a 500 page book entitled "Fusion and Fast Breeder Reactors" which was first published in November 1976 with a revised version appearing in July 1977 [3]. In the process of writing the book it is safe to say that all 4 authors gained an appreciation for the competing technology and this activity marks the formal beginning of Professor Kessler's entry into the field of fusion research. Several other related publications emerged from this study which summarize specific aspects of the work [4-5].

It is only natural that Dr. Kessler's first venture into independent research on fusion involved the fission-fusion hybrid reactors. In these systems, the 14 MeV neutrons are used to promote $(n, 2n)$, $(n, 3n)$, etc. reactions in a fertile material like ^{238}U. His early work in this field was a collaboration with Professor Abdel-Khalik of the University of Wisconsin [6-7]. The thrust of the work was to examine the impact that fission-fusion reactors would have on the extension of world nuclear energy resources in the U fuel cycle. It was concluded that the support ratio (the number of fission reactors supported by one fusion reactor of the same thermal power output) was between 4 and 5. It was also shown that the safety of these reactors was something that needed to be more carefully studied.

III. Kessler's Role in Ion Fusion Applications

A. HIBALL Project (1980)

The idea for the use of heavy ions to drive a fusion reactor had been proposed in the United States during the mid 1970's along with some preliminary work on the design of auxiliary power plant components [8-11]. However, it was not until the Fall of 1979 that Dr. Kessler proposed that Europe should enter this field of research and along with his colleagues from Darmstadt, set up what eventually became known as the HIBALL project. (Note that this decision was made in conjunction with a decision by Dr. Kessler to set up an experimental program on light ions at KfK; see Section IV.) His idea was to perform a self-consistent design of a power plant that utilizes high energy heavy ions to drive targets containing DT to ignition and burn. Once the physics of the thermonuclear microexplosions could be understood, then the rest of the power plant could be designed.

The team that was assembled included the following organizations:

Germany

- Kernforschungszentrum Karlsruhe
- Gesellschaft für Schwerionenforschung, Darmstadt
- Max-Planck-Institut für Quantenoptik, Garching
- Institute für Plasmaphysik, Garching
- University of Giessen
- Interatom

United States

- University of Wisconsin
- Lawrence Berkeley Laboratory
- McDonnell Douglas
- University of California-Los Angeles

The study began in January 1980 and the first report, "HIBALL-A Conceptual Heavy Ion Beam Driven Fusion Reactor Study", was published in June of 1981 [12]. There were 48 co-authors on the report. An overview of the reactor complex is shown in Figure 1 while a schematic of the reactor building is shown in Figure 2. A cross section of the reactor chamber is shown in Figure 3 and a list of the key parameters is given in Table 1.

There were several features of HIBALL-I which appeared for the first time in the open literature. These include:

- The first self-consistent design of a Heavy Ion Beam driven fusion power reactor outside the United States.
- The first use of porous, flexible woven tubes to act as a moderator and absorber of neutrons between the target and the first structural wall.

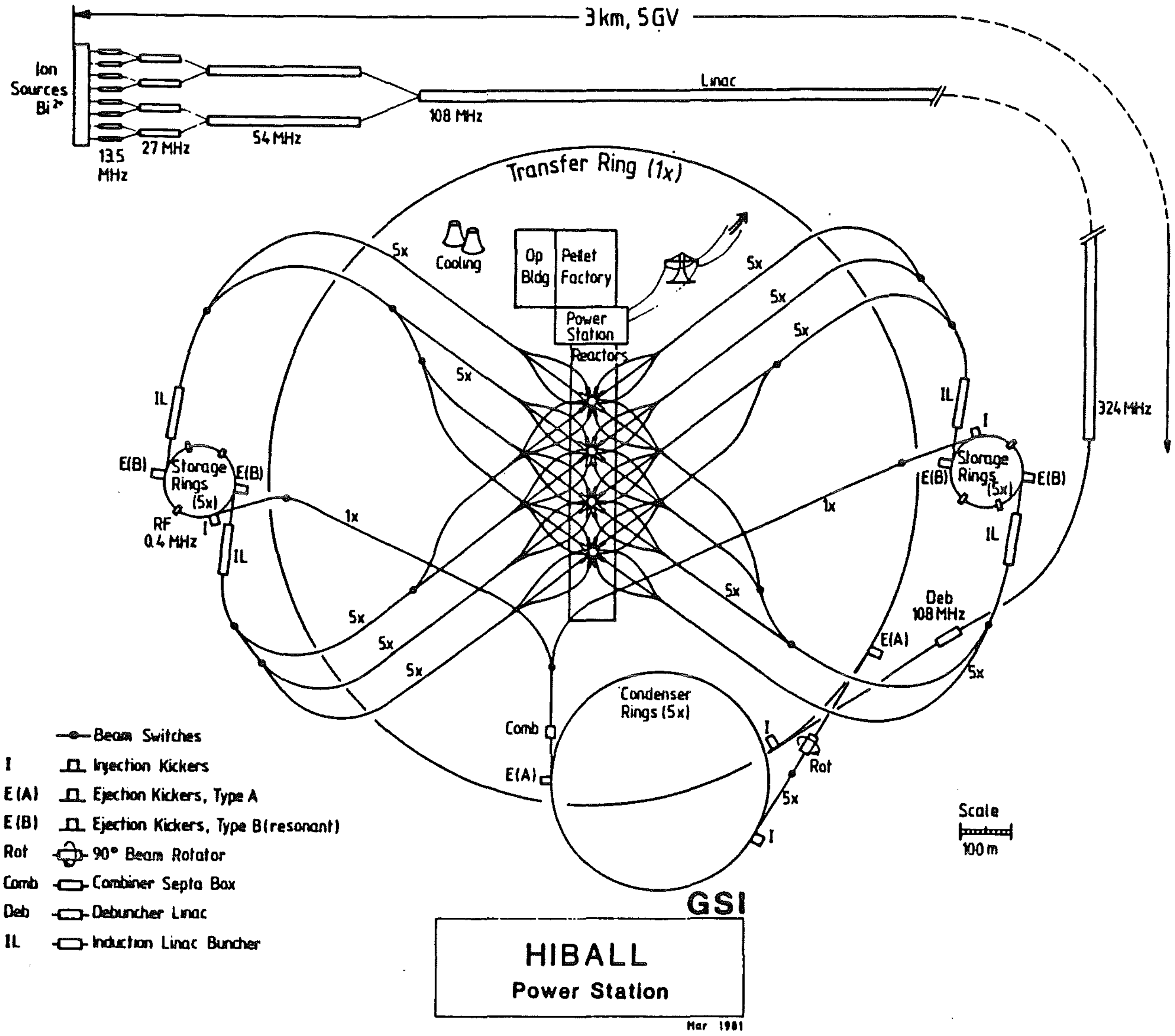
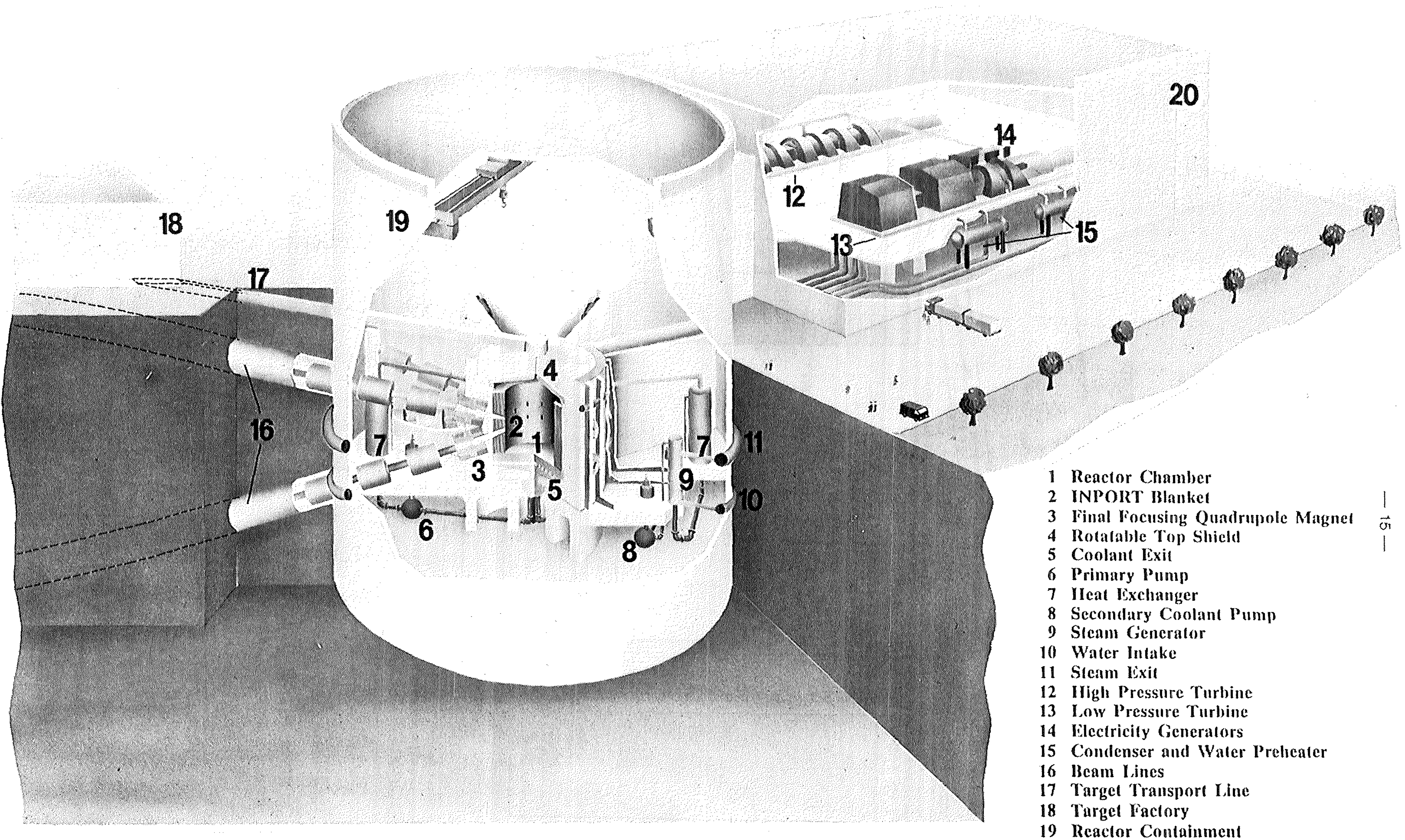


Figure 1. Schematic of the HIBALL reactor complex [12]. There are 4 reactor cavities driven by one induction linac.



1	Reactor Chamber
2	INPORT Blanket
3	Final Focusing Quadrupole Magnet
4	Rotatable Top Shield
5	Coolant Exit
6	Primary Pump
7	Heat Exchanger
8	Secondary Coolant Pump
9	Steam Generator
10	Water Intake
11	Steam Exit
12	High Pressure Turbine
13	Low Pressure Turbine
14	Electricity Generators
15	Condenser and Water Preheater
16	Beam Lines
17	Target Transport Line
18	Target Factory
19	Reactor Containment
20	Machine Building

Figure 2. Isometric of one of the HIBALL reactor buildings. The size of the building (which houses a $\approx 1,000$ MWe reactor chamber) is approximately the size of a fast breeder fission reactor of the same size [12].

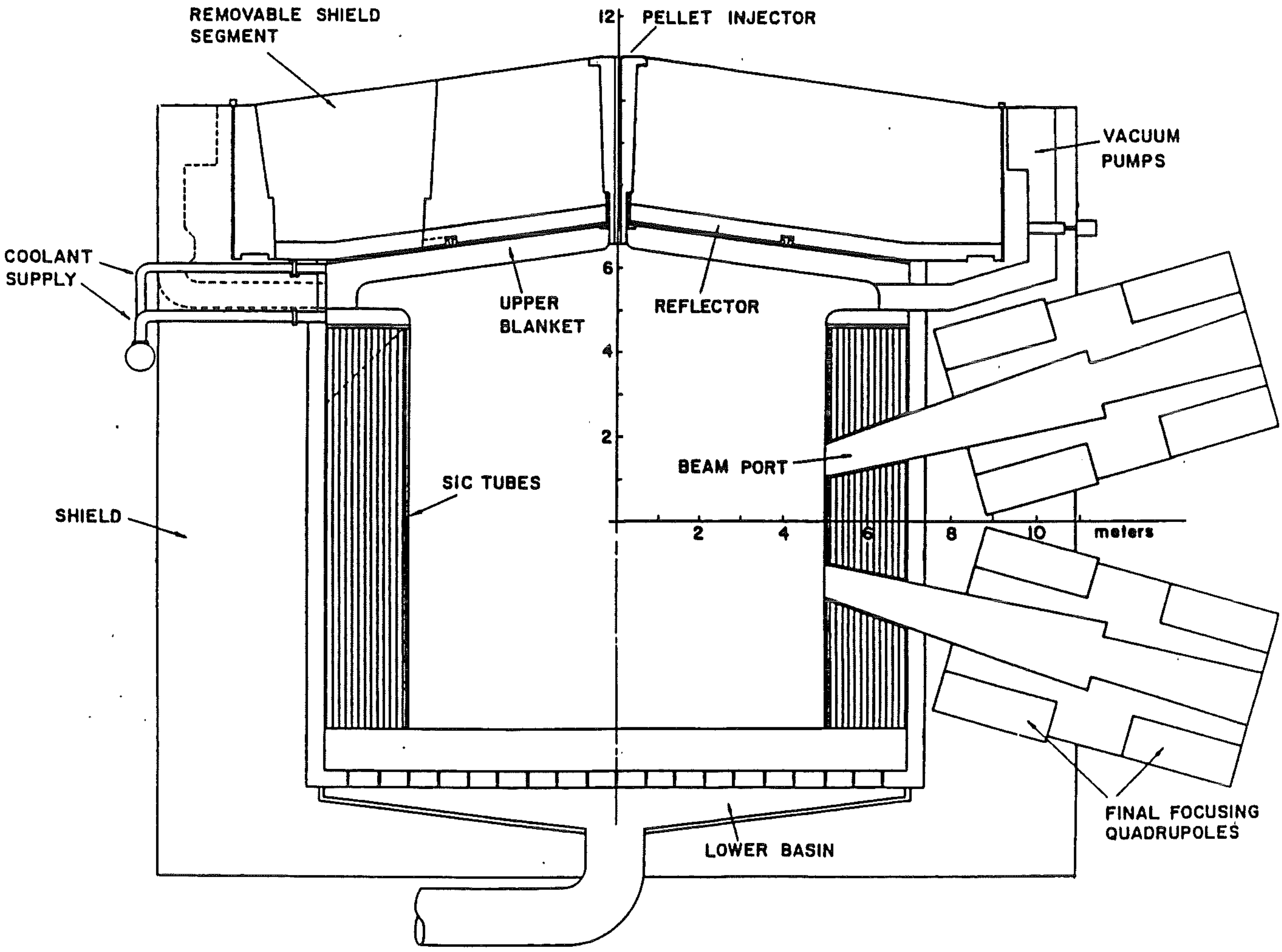


Figure 3. A cross-section of the HIBALL reactor chamber is shown including two of the final focusing magnets and the INPORT units[12].

Table 1

A List of Selected Parameters for the HIBALL Reactor

Parameter	Unit	HIBALL-I	HIBALL-II
Total DT fusion power	MWth	8,000	8,000
Total gross thermal power	MWth	10,272	10,272
Total gross electric power	MWe	4,278	4,314
Total net electric power	MWe	3,768	3,784
Number of chambers	–	4	4
Type of accelerator	–	RF Linac	RF Linac
Ion/Ion energy	-/GeV	Bi^{+2}/10	Bi^{+1}/10
Beam energy absorbed by target	MJ	4.8	4.56
Beam power on target	TW	240	240
Accelerator pulse rate	Hz	20	20
Number of ion beams per chamber	–	20	20
Current/beam	kA	2.5	1.25
Target yield/Gain	MJ/-	396/83	396/87
Target shot rate/cavity	Hz	5	5
Breeder and coolant	–	$Pb_{17}Li_{83}$	$Pb_{17}Li_{83}$
Tritium breeding ratio	–	1.25	1.25
Maximum coolant temperature	°C	500	500
First wall protection scheme	–	INPORT Units ($SiC/Pb_{17}Li_{83}$)	INPORT Units ($SiC/Pb_{17}Li_{83}$)

- The first use of an unclassified symmetric target from which meaningful reactor parameters could be calculated.

A more complete list of the papers of which Professor Kessler was an author is included in References [12-17].

After the initial reviews of the HIBALL-I RF linac driver, it was decided that a better and more reliable accelerator design could be devised with Bi^{+1} ions instead of the Bi^{+2} ions used in HIBALL-I. This improved driver (see Figure 4) was incorporated into the HIBALL-II study published in 1984 [8] and the final parameters of the power plant are also listed in Table 1 (see also references 19-23).

B. LIBRA Project (1985)

The LIBRA (Light Ion Beam ReActor) project began as a small, scoping study in 1982. The initial work involved KfK, Fusion Power Associates (FPA) in the U.S., and

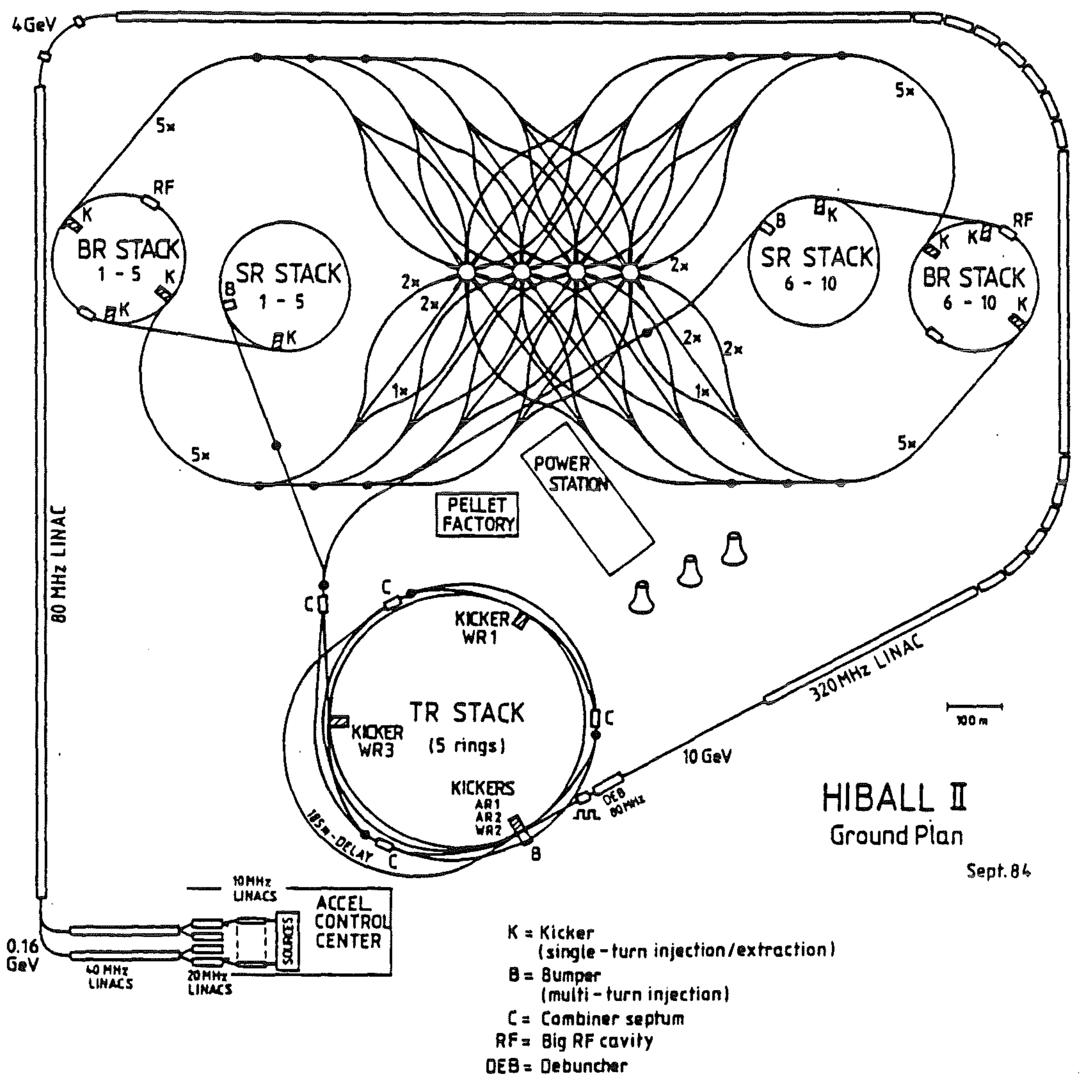


Figure 4. The improved HIBALL-II RF linac design was able to use Bi^{+1} and lower the current per beam by a factor of 2 [18].

Table 2

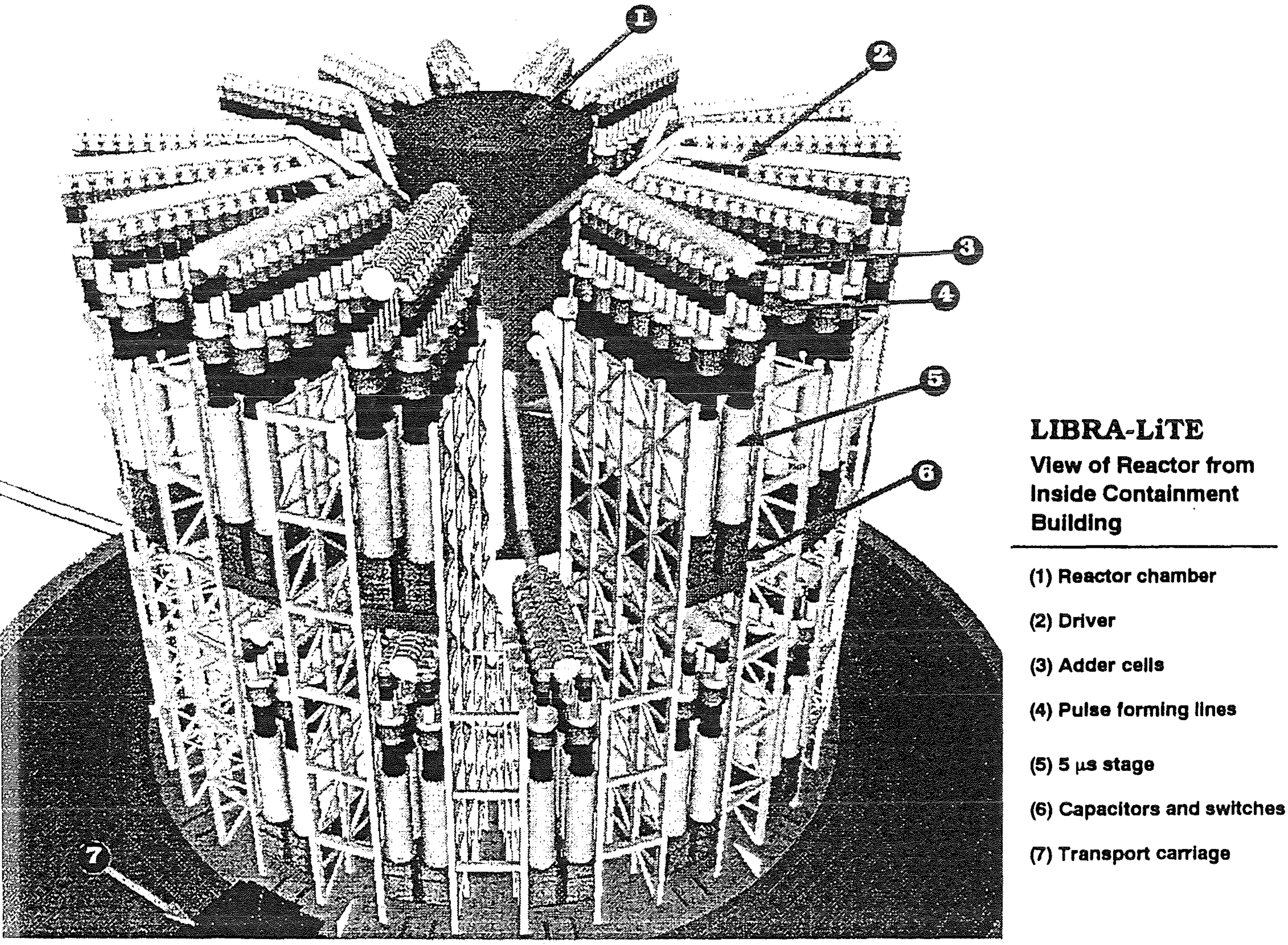
A List of Selected Parameters for the LIBRA Series of Light Ion Reactors

Parameter	Unit	LIBRA	LIBRA-LiTE
Total DT fusion power	MWth	960	2,400
Total gross thermal power	MWth	1,123	2,627
Total gross electric power	MWe	441	1,192
Total net electric power	MWe	331	1,000
Number of chambers	–	1	1
Type of accelerator	–	Helia	Helia
Ion/Ion energy	-/MeV	Li^{+1}/25-35	Li^{+1}/25-35
Beam energy absorbed by target	MJ	4	6
Beam power on target	TW	400	1603
Accelerator pulse rate	Hz	3	3.9
Number of ion beams per chamber	–	18	30
Current/beam and kA	1,100	3,690	
Target yield/Gain	MJ/-	320/80	600/100
Target shot rate/cavity	Hz	3	3.9
Breeder and coolant	–	$Pb_{17}Li_{83}$	Li
Tritium breeding ratio	–	1.36	1.41
Maximum coolant temperature	°C	500	525
First wall protection scheme	-	INPORT Units (SiC/$Pb_{17}Li_{83}$)	INPORT Units (HT-9/Li)

scientists at Pulse Sciences Inc. (PSI). In 1989, the scoping studies were elevated to a preconceptual design phase and scientists from Sandia National Laboratories (SNL) were added.

The object of the LIBRA project was to conduct the preconceptual study in enough detail that one could make a technical, environmental, as well as economic comparison of LIBRA to previous magnetic as well as inertial confinement fusion reactor designs. The first full report on LIBRA appeared in 1989 (later revised in 1990) [24] and was the result of 21 scientists working together under the guidance of Professor Kessler. This study was followed by yet another preconceptual design, LIBRA-LiTE, conducted from 1990 to 1991 [25]. A comparison of the two light ion reactor designs is shown in Table 2 and Figures 5-7 show some of the unique features of the LIBRA series.

The common features of the LIBRA series includes the same drivers (inductive energy technology), the same ion source (Li), and the same basic chamber design (INPORT units inside the cylindrical vessel).



LIBRA-LiTE

View of Reactor from Inside Containment Building

(1) Reactor chamber

(2) Driver

(3) Adder cells

(4) Pulse forming lines

(5) 5 μs stage

(6) Capacitors and switches

(7) Transport carriage

Figure 5. The isometric view of LIBRA-LiTE reveals the compactness of light ion beam fusion vs. the extensive land requirements of heavy ion fusion [25].

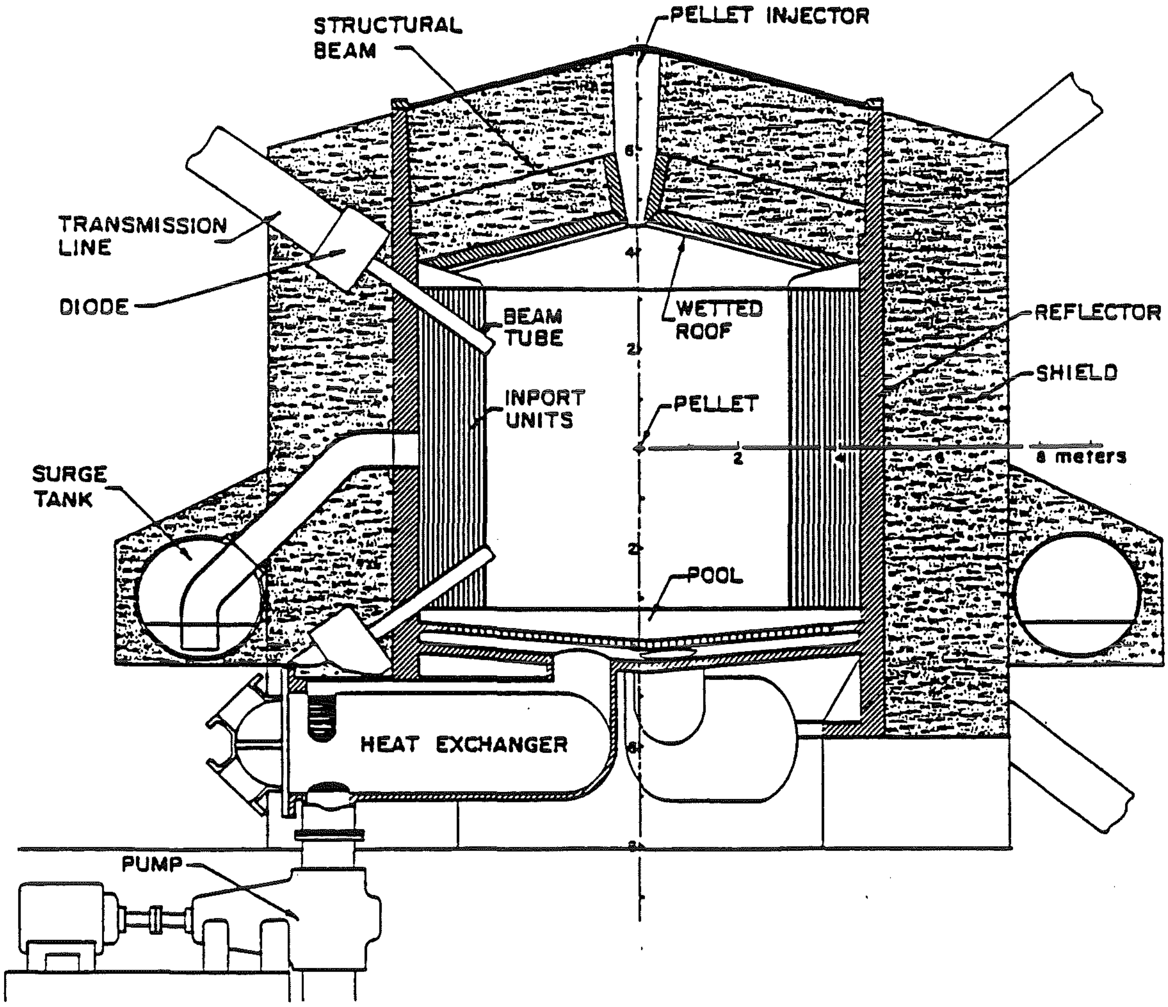


Figure 6. The cross section of the LIBRA reactor illustrates the channel transport mode of ion propagation [24].

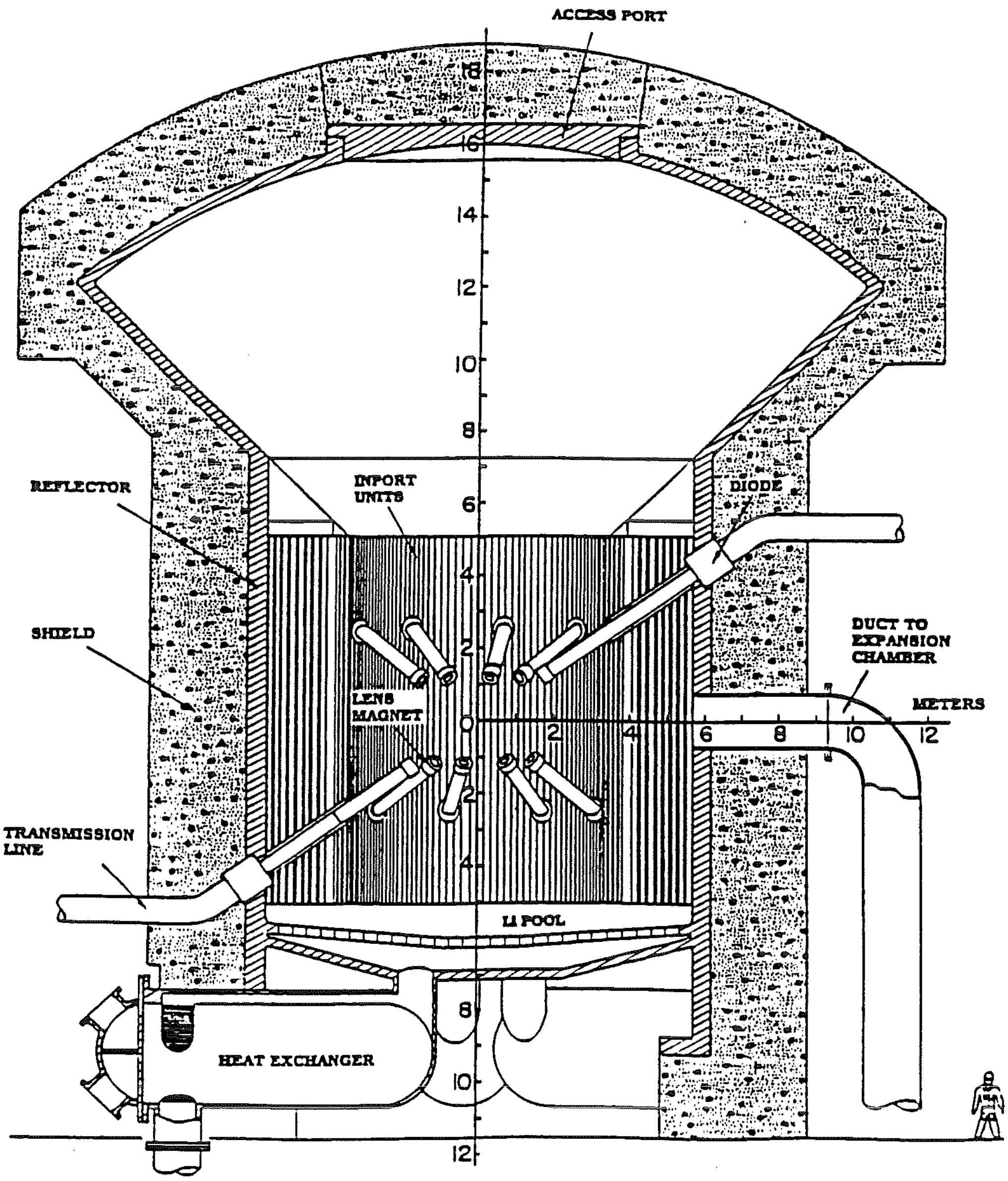


Figure 7. The cross section of the LIBRA-LiTE design illustrates the internal magnets required for the ballistic ion transport model [25].

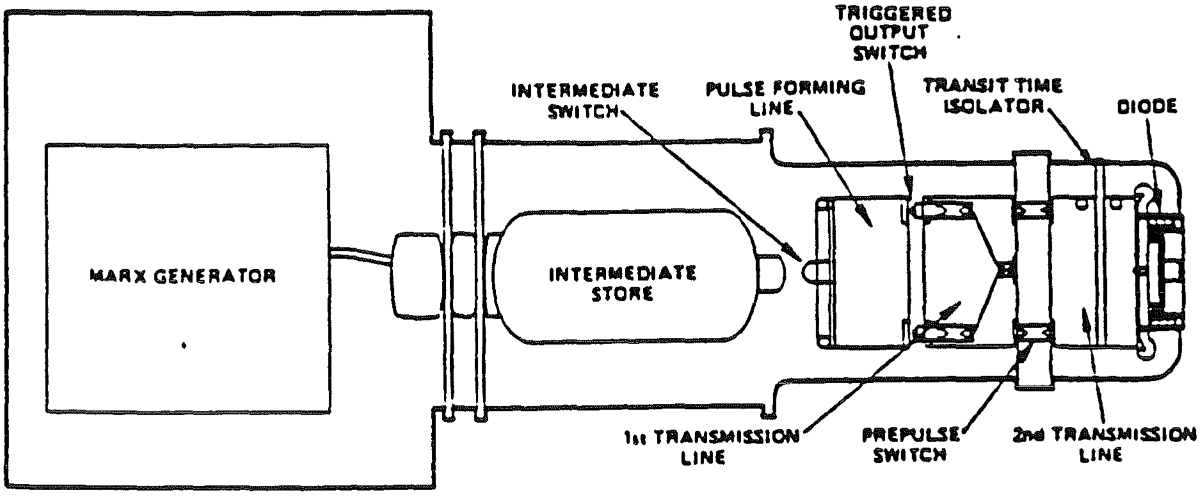


Figure 8. The KALIF was the first light ion pulsed power facility in Europe [26].

The unique features in each design include: ballistic focusing of the ion beam in LIBRA-LiTE vs. channel transport in LIBRA, the use of Li as a breeder/coolant in LIBRA-LiTE vs. $Pb_{83}Li_{17}$ in LIBRA, the use of woven metallic (HT-9) INPORT units in LIBRA-LiTE vs. SiC in LIBRA, and the larger power level of LIBRA-Lite (1,000 MWe) vs. 331 MWe in LIBRA.

IV. Kessler's Role in Light Ion Experiments

A. History of KALIF at KfK

The original decision, at KfK, to embark on an experimental program involving high density matter was made by Professor Kessler and his colleagues in late 1979. The intention was to pursue both the near term physics and the long term power plant applications in parallel. Professor Kessler was in the lead in both areas at KfK. Partly because of technical reasons and partly because the heavy ion beam (HIB) experimental program was already established at Darmstadt, Professor Kessler made the decision to pursue experiments involving the light ion beam (LIB) approach. His technical reasons to pursue light ions mainly related to the economic generation of electricity.

The experimental facility called KALIF (see Figure 8), was delivered in early 1983 and by late 1983 it was ready for experimentation. A schematic of the device is shown in Figure 8 and the main machine parameters are listed below:

- 20 kJ Marx Generator
- 1.7 MV
- 1.5 TW

The initial experimental program utilized two diodes for the source of protons accelerated to the targets; a Pinch Reflex Diode, and a B_θ diode. By 1988 his team, composed of (alphabetically);

W. Bauer,
H. Bluhm,
B. Goel,
P. Hoppe,
H. U. Karow,
C. D. Munz,
D. Rusch, and
W. Schimassek

reported [26] that they had been able to conduct target physics experiments with ≈ 0.2 TW/cm^2 of protons from the B_θ diode. At that time, only the Sandia National Laboratory in the U.S. had been able to conduct such high power density studies on a routine basis.

The KALIF experiments continued with the Applied B Extractor Diode and by 1992 they had achieved 1 TW/cm^2 [27]. The experimental group that achieved these impressive results was led by Dr. Kessler and included (alphabetically);

M. Althaus,
H. Bachamn,
W. Bauer,
K. Baumung,
H. Bluhm,
L. Buth,
P. Hoppe,
H. U. Karow,
H. Laqua,
D. Rasch,
E. Stein, and
O. Stoltz.

This experimental group has now been able to accelerate foils to > 12.5 km/s and to produce strain rates for experiments of $> 10^8$ s^{-1}.

B. History of Inductive Driver Technology at KfK

In the late 1980's it became apparent to Professor Kessler that a new driver would be needed to advance the state of the art in light ion beam fusion in Europe. A decision was made in 1990 to acquire inductive voltage adder technology from the U.S. in order to produce higher energy beams of protons and perhaps even Li ions. In this technology, magnetic induction is used to generate higher voltages than are possible in the original KALIF accelerator. This technology was demonstrated in the Helia accelerator at Sandia National Laboratories. In 1991, an order was placed for an advanced Helia type driver which was delivered in 1993. The entire facility will be operational in 1996. The specifics of the planned experimental facility are:

- 6 MV
- 2 TW
- p or Li source

With the inductive accelerator facility, KfK will be able to perform meaningful experiments with condensed matter that will substantially contribute to the world ICF effort.

V. Kessler's Role in Information Exchange on Fusion Energy

In addition to the technical input that Professor Kessler has made to the ICF community, he has also contributed to the exchange of information. Starting from his mid-1970's participation in the comparison of fission and fusion breeder reactors [3], he also co-authored an in-depth analysis of the fusion-fission hybrid concept in 1983 [8]. In the 1990's he authored a chapter on "Inertial Confinement Fusion Reactors-Conceptual Design Studies" in a comprehensive book on ICF edited by Velarde [28]. He was the technical program chairman of the Beams-88 Conference in Karlsruhe [29], and has been the chairman of the ICENES conference in Karlsruhe, 1986 [30]. Professor Kessler has also been responsible for bringing dozens of scientists from the former Soviet Union, Japan, the United States, and other European countries for extended periods to KfK. In this way he has substantially contributed to both the technical field and the mutual understanding between scientists that is so important for world progress.

VI. Summary

It is clear that Professor Günther Kessler has been responsible for major contributions to the worldwide quest for fusion energy. He has led the only effort in Europe investigating the use of light ion beam drivers to implode targets and he has been the major driving force behind commercial applications of ICF. He has been able to use his expertise in reactor safety to influence the direction of power plant design and he has been a strong advocate of environmental controls in fusion reactors. His clear and concise analysis of the issues to be faced in developing a new energy source will greatly influence future generations of scientists and engineers. These achievements, coupled with his illustrious career in the fission area, has made him one of the most important German European nuclear scientist of the last three decades.

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Beton unter extremer Beanspruchung – Schockbeanspruchung –

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Universität Karlsruhe

1. Problemstellung

Für die eindimensionale Wellenausbreitung in einem Feststoff gilt die nachfolgende Wellengleichung:

$$A\varrho \frac{\partial^2 u}{\partial t^2}\, dx - A\frac{\partial \sigma}{\partial x}\, dx = 0$$
$$\frac{\partial^2 u}{\partial t^2} - \frac{H}{\varrho}\cdot\frac{\partial^2 u}{\partial x^2} = 0 \qquad (1)$$

wobei $H(\sigma,\varepsilon) = d\sigma/d\varepsilon$ den Werkstoff charakterisiert und

$$\sqrt{\frac{H}{\varrho}}$$

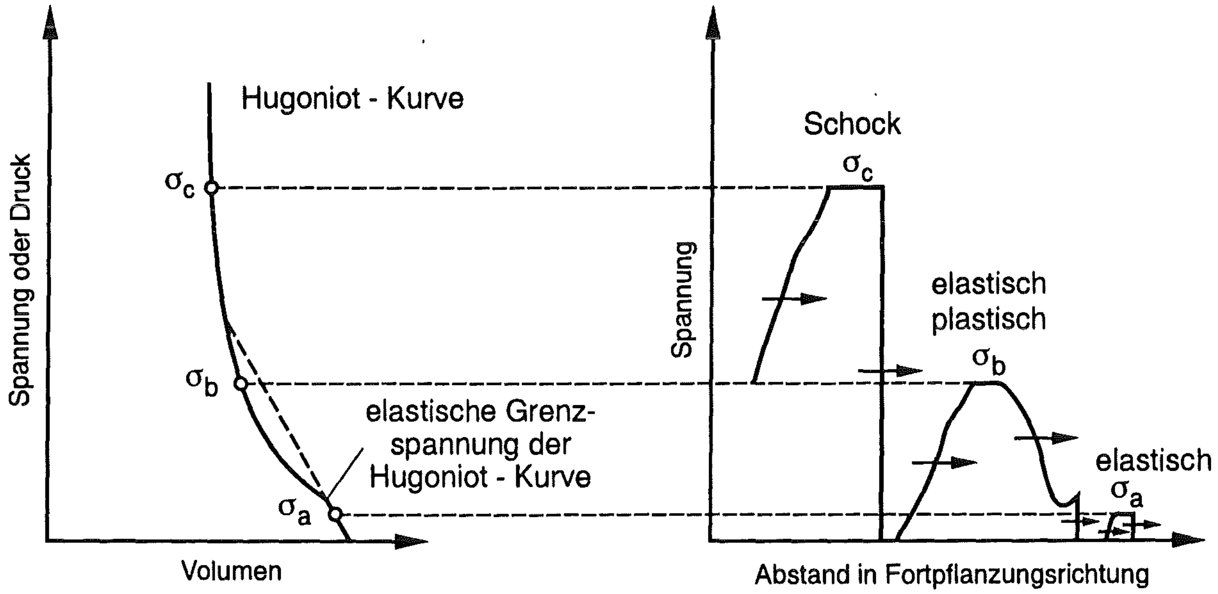

Abb. 1 Schockwellen in Feststoffen

die Wellengeschwindigkeit bezeichnet. Man sieht, daß sich Drücke mit kleinem $H = d\sigma/d\varepsilon$ langsamer ausbreiten als solche mit großem H. Dies gilt auch bei einer volumetrischen Beanspruchung, wo an die Stelle von H der Kompressionsmodul $K = dp/d\varepsilon_v$ tritt (vgl. Abb. 1).

Dies besagt, daß sich bei Wellenprofilen mit anfänglich niedrigen Beanspruchungen und nachfolgend hohen mit großem K die Wellenfronten " aufsteilen " (s. Abb. 1). Im Extremfall kommt es zu sehr steilen Druckfronten mit nahezu diskontinierlichem Anstieg, die sich extrem schnell ausbreiten, d.h. zu Schockwellen.

BOSLOUGH/ASAY [1] veranschaulichen diesen Vorgang wie folgt ".... Shock waves are the ubiquitous result of matter moving at velocities faster than the speed at which adjacent material can't move out of the way...."

In Betonstrukturen werden solche Schockwellen mit hohen lokalen Drücken z.B. induziert, wenn fliegende Metallteile als " missiles " mit Geschwindigkeiten von mehr als etwa 400 m/s auf Beton auftreffen oder Kontaktexplosionen an Betonoberflächen stattfinden. Derartige Phänomene sind für eine Reihe von Konstruktionen von großer praktischer Bedeutung. Weiter interessiert aber auch, wie bei anderen Werkstoffen, generell das stoffliche Verhalten von Beton bei sehr hohem Drücken unter statischer und dynamischer Beanspruchung, die im letzteren Fall speziell experimentell durch Schockwellen erzeugt werden.

Das Ziel eigener Forschungen ist derzeit deshalb ein zweifaches. Zum einen interessiert das Verhalten unter Schock-Beanspruchungen für die unmittelbare Anwendung, zum anderen soll aus Schock-Experimenten ein isothermes Stoffgesetz für statische Beanspruchung von Beton bei hoher Druckbeanspruchung zur Erweiterung der derzeit bekannten konstitutiven Beziehungen abgeleitet werden.

Wie in vergleichbaren Fällen von metallischen Werkstoffen wurde zunächst, der historischen Entwicklung folgend, die klassische Theorie der Schockwellenausbreitung in gasförmigen Medien resp. in Fluiden als Basis benutzt.

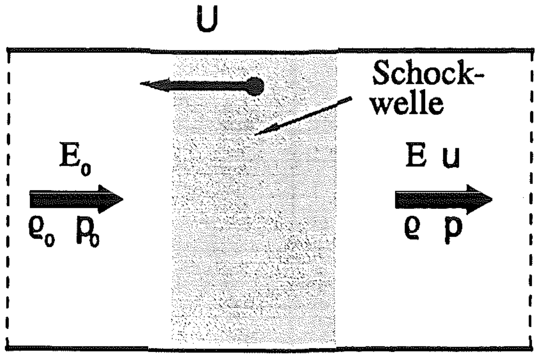

Abb. 2 Eindimensionale Strömung

Man geht vom eindimensionalen Fall einer diskontinuierlichen Schockfront nach Abb. 2 mit nachstehenden Erhaltungsgleichungen für Masse, Impuls und Energie aus:

$$\begin{aligned} \varrho_0 \cdot U &= \varrho \cdot (U - u) \\ \varrho_0 \cdot U^2 + p_0 &= \varrho \cdot (U - u)^2 + p \\ E_0 + \tfrac{1}{2} U^2 + \frac{p_0}{\varrho_0} &= E + \tfrac{1}{2}(U - u)^2 + \frac{p}{\varrho} \end{aligned} \tag{2}$$

wobei

U = Schockwellengeschwindigkeit
u = Partikelgeschwindigkeit
E = Innere Energie
p = Druck
ϱ = Dichte

Nimmt man eine Zustandsgleichung, z.B für ein ideales Gas hinzu

$$E(p,\varrho) = \frac{p}{\varrho\cdot(\gamma-1)} \tag{3}$$

wobei γ das Verhältnis der spezifischen Wärme bezeichnet, so stehen mit (2) und (3) vier Gleichungen für die fünf Unbekannten p, U, ϱ, u, (E- E_0) zur Verfügung. Damit läßt sich eine Hugoniot–Kurve p = f(ϱ) resp. p = g(V) ableiten.

Weiter kann man, ausgehend von den beiden ersten Gleichungen in (2), nach Elimination der Partikelgeschwindigkeit u folgende Gleichung:

$$\frac{p-p_0}{V_0-V} = \left(\frac{U}{V_0}\right)^2 \tag{4}$$

gewinnen. Diese wird verwendet, um bei Feststoffen in einem Schock-Experiment U und p zu messen, um sodann damit eine p-V Kurve – Hugoniot–Kurve – zu bestimmen, wenn die Zustandsgleichung unbekannt ist. Jeder Punkt auf dieser Kurve bezeichnet mit seinem Werte-Paar P, V ein Schock-Experiment bei unterschiedlichem E (Abb. 3).

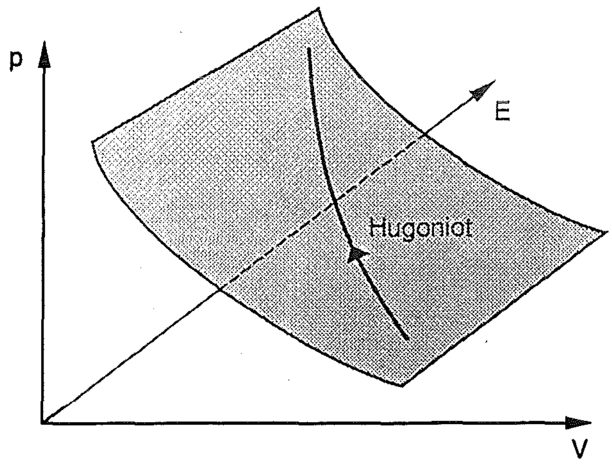

Abb. 3 Darstellung der Equation of State im p–V–E Raum

Macht man nun nach Mie-Grüneisen, ausgehend von

$$dE = \theta dS - p dV \tag{5}$$

für eine adiabatische Beanspruchung mit dE = 0 einen Ansatz für eine Zustandsgleichung

$$\Delta p = \gamma(V) \cdot \frac{\Delta E}{V} \tag{6}$$

mit Bezug auf die Referenzwerte $p_{0,K}$, $E_{0,K}$ bei 0° Kelvin, wobei $\gamma(v)$ nur von V abhängt, so kann bei gemessenen Hugoniot Werten p_H und V_H die durch den adiabatischen Belastungsvorgang erzeugte innere Energie E bestimmt werden und mit C_v die erzeugte Temperatur θ bei dieser extrem schnellen Belastung.

Für $\gamma(v)$ gibt es eine Reihe von Ansätzen (vgl. hierzu Anhang). Bei bekannten θ kann unter Zuhilfenahme des volumetrischen Ausdehnungskoeffizienten auf eine isotheme p-V Beziehung rückgerechnet werden.

Auf dieser Grundlage wurden in Analogie zu metallischen Werkstoffen eigene Experimente durchgeführt, wobei p und U gemessen wurden, wie im einzeln nachfolgend beschrieben wird.

2. Durchgeführte Experimente

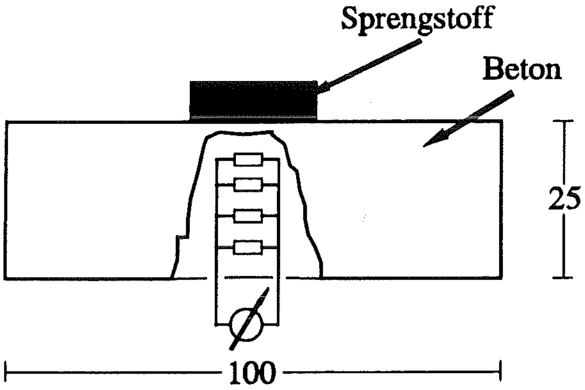

Abb. 4 Versuchsaufbau

Auf der Grundlage der oben angeführten Erkenntnisse wurden Schockwellenversuche zur Ermittlung des hydrostatischen Anteils des Stoffgesetzes durchgeführt. In den Versuchen wurden Platten mit Abmessungen quer zur Belastung zwischen 60 und 150 cm und Abmessungen in Belastungsrichtung zwischen 25 und 50 cm verwendet. Der prinzipielle Versuchsaufbau ist in Abb. 4 dargestellt. Die Sprengladung ist in der Mitte der Plattenoberfläche angebracht. Es handelt sich hierbei um einen sogenannten 'Plane Wave Generator' zur Erzeugung ebener Wellen im Probekörper. Dieser ist in Wirklichkeit, wie aus Abb. 5 ersichtlich, kegelstumpfförmig und besteht aus zwei Sprengstoffarten mit unterschiedlicher Detonationsgeschwindigkeit. Hier wurde Composition B und TNT verwendet, wobei TNT den überwiegenden Anteil der Gesamtmasse von 630 Gramm ausmacht.

Direkt unterhalb des Sprengstoffes sind mehrere Druckaufnehmer übereinander angeordnet. Als Meßaufnehmer wurden 470 Ohm Kohle–Masse Widerstände der Firma Allen-Bradley eingesetzt. Die Widerstandsänderung jedes Aufnehmers wird mittels der Messung der elektrischen Spannung durch schnelle Transientenrecorder bestimmt. Mit einer Kalibrierungskurve der Widerstände erhält man somit den Druckverlauf über der Zeit p(t). Zusätzlich kann noch die Schockwellengeschwindigkeit U_S aus der Ankunftszeit der Druckwelle an den Aufnehmern und ihrem Abstand untereinander ermittelt werden. Daraus resultiert dann, bei Kenntnis des Ausgangszustandes und mit Glg. 4, ein Punkt der Hugoniot–Kurve für jeden Aufnehmer.

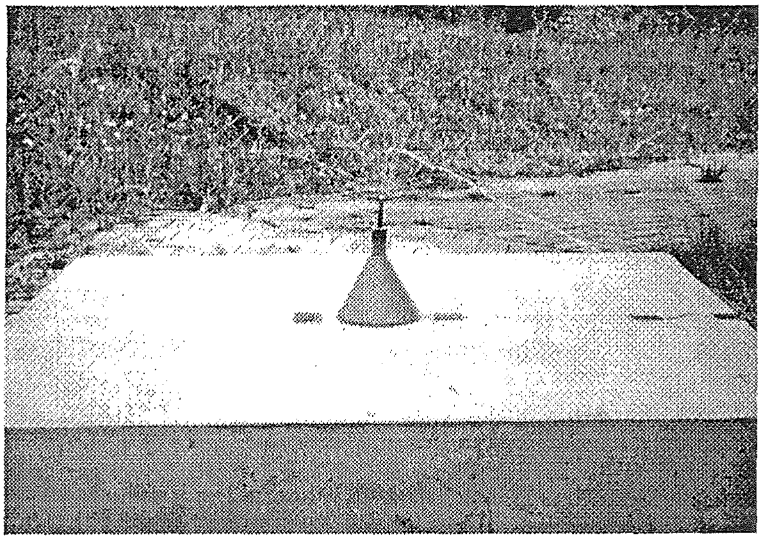

Abb. 5 Versuchsaufbau Platte P 1

Im Rahmen dieser Untersuchungen wurden bisher 8 Versuche durchgeführt. Druck–Zeit Verläufe der Versuche 4, 5 und 6 können Abb. 6 entnommen werden. Die größte gemessene Druckspannung in den Versuchen betrug 13,5 GPa. Solche Drücke fallen jedoch nur unmittelbar unterhalb der beaufschlagten Oberfläche an. So befanden sich die in Abb. 6 dargestellten beiden Widerstände der Platte 5 und 6 ca. 2 cm unterhalb dieser, während der Widerstand der Platte 4 ca. 10 cm von dieser entfernt war. Dieser starke Abfall in den Druckspannungen mit zunehmender Distanz von der Oberfläche konnte in allen Versuchen beobachtet werden.

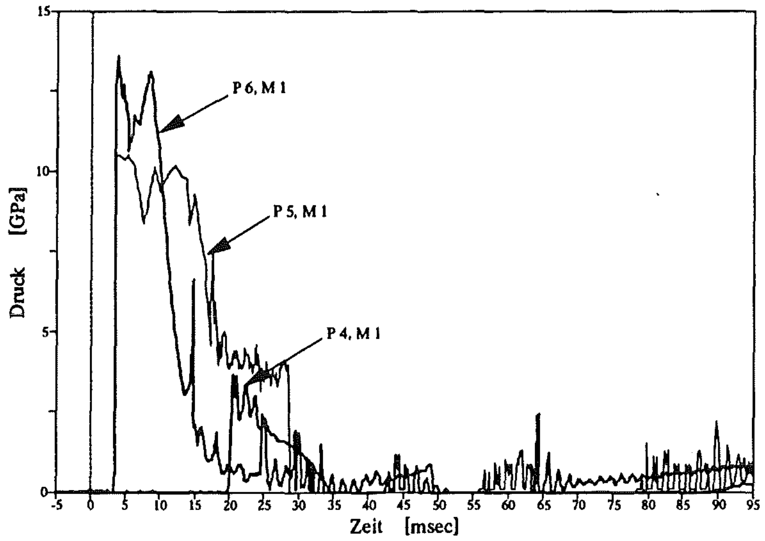

Abb. 6 Druck–Zeit Verläufe der Versuche P 4 – P 6

Die aus den Versuchen ermittelten Schockwellengeschwindigkeiten sind in Abb. 7 aufgeführt. Die maximal gemessene Geschwindigkeit betrug über 5000 m/s. Dies liegt deutlich über der Schallgeschwindigkeit des hier verwendeten Betons (≈ 3800 m/s). Weiter wurden auch Wellengeschwindigkeiten die unterhalb der Schallwellengeschwindigkeit lagen, registriert.

Abb. 8 zeigt die so gewonnene eigene Hugoniot–Kurve zusammen mit ersten amerikanischen

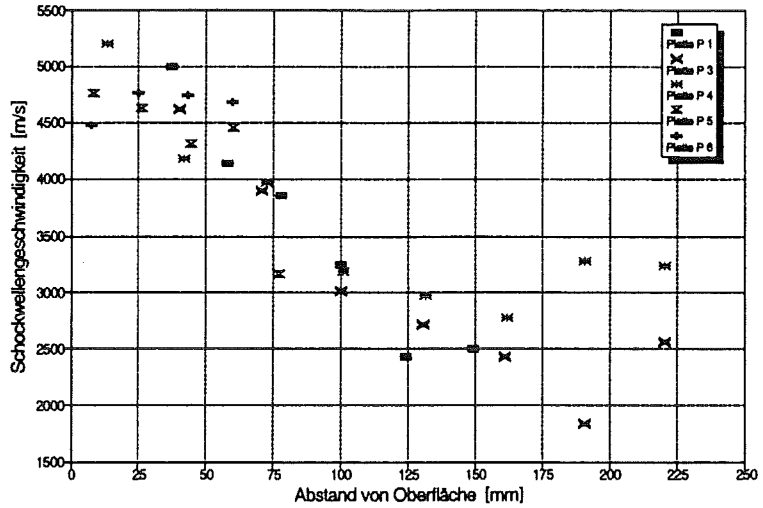

Abb. 7 Schockwellengeschwindigkeit

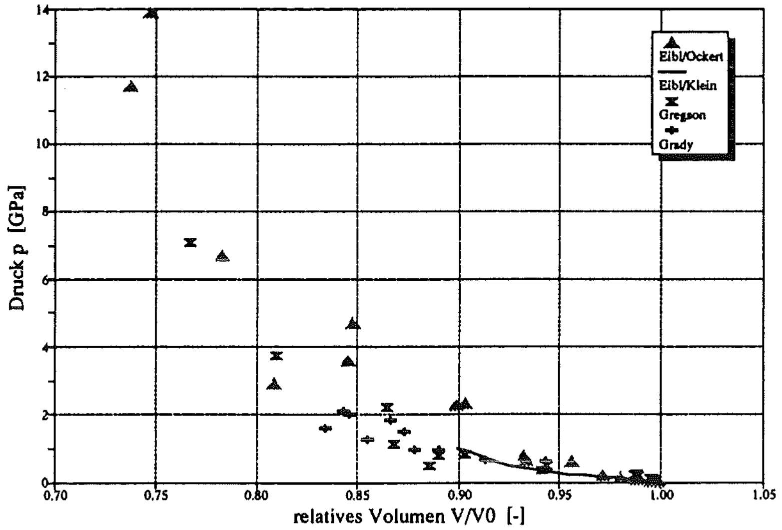

Abb. 8 Hugoniot–Kurve für Beton

Ergebnissen von Grady [5] und Gregson [6] mit Maximaldrücken von 52 resp. 2.5 GPa, die jedoch in Flyer-Plate Experimenten mit extrem kleinen Proben von 0,64 bzw. 1,5 cm in Belastungsrichtung, für Beton wegen seiner stark heterogenen Zusammensetzung zunächst eigentlich nicht akzeptabel, gewonnen wurden.

3. Erste rechnerische Studien

Mit den Ergebnissen nach Abschnitt 2 wurden erste rechnerische Studien zur Erfassung der Experimente mit Hilfe der Methode der Finiten Elemente (FEM) durchgeführt.

Zur wirklichkeitsnahen Durchführung der rechnerischen Untersuchungen wurde dabei auch der Sprengstoff mit Finiten Elementen abgebildet. Dadurch wird, im Gegensatz zu einer Abbildung der Belastung mittels einer Last-Zeit-Funktion, die Interaktion zwischen Sprengstoff und Beton voll berücksichtigt. Die jeweilige Belastung wird durch die Energiefreisetzung bestimmt. Der daraus resultierende Druck und die Volumenänderung erfolgt an Hand einer 'Equation of State' nach Jones, Wilkins und Lee [2], wobei A, B, R_1, R_2 und ω von der jeweiligen Sprengstoffart abhängige Konstanten sind.

$$p(V,E) = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \qquad (7)$$

Für die ersten rechnerischen Studien mit dem expliziten Finiten Element Programm DYNA [9] wurde ein relativ einfaches Stoffgesetz für Beton verwendet, das sich aus zwei Teilen aufbaut, dem hydrostatischen und dem deviatorischen Anteil. Hierbei wurde für den hydrostatischen Teil die oben angeführte, gemessene Hugoniot–Kurve angesetzt.

Der deviatorische Anteil des Stoffgesetzes ist nochmals unterteilt. Die Versagensoberfläche wird kreisförmig angenommen. Der Radius dieses Kreises ist proportional zu der zweiten Invarianten des deviatorischen Spannungstensors J_2, und dieser weist eine quadratische Abhängigkeit vom Druck p in der folgenden Form auf:

$$J_2 = a_0 + a_1 p + a_2 p^2 \qquad (8)$$

Die Konstanten a_0, a_1 und a_2 wurden anhand von Triaxialversuchen aus der Literatur bestimmt. Das Risseverhalten von Beton und die Begrenzung der Zugspannungen wird mit einem 'Tension Cutoff' abgeschätzt.

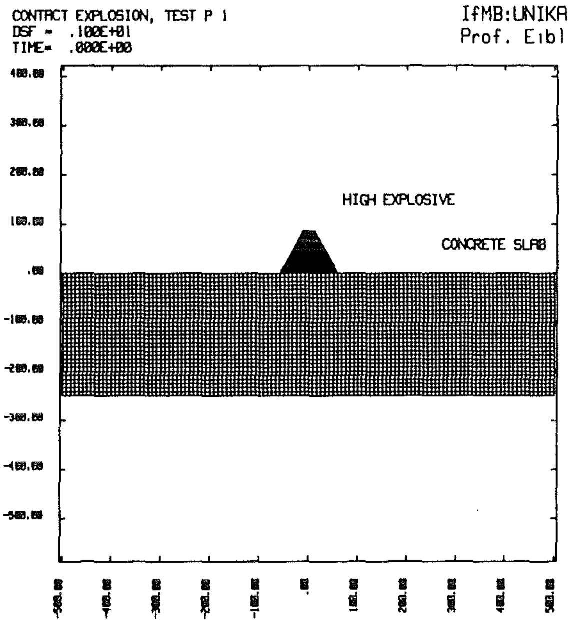

Abb. 9 Finites Element Netz

Für die Finiten Element Rechnungen wurde ein Elementnetz benutzt, das mehr als 2000 zweidimensionale rotationssymetrische Elemente enthielt (vgl. Abb. 9). Die Sprengstoffelemente sind sehr viel kleiner als die Betonelemente, da sie sich im Laufe der Rechnung infolge der großen Ausbreitungsgeschwindigkeit sehr stark ausdehnen.

Zwischen den Sprengstoffelementen und den Betonelementen wurde eine 'Slideline' zur Kraftübertragung angeordnet. Die Zündung erfolgt wie im Versuch am oberen Ende des Kegelstumpfes.

In einem Zeitraum von 16 µsec nach Zündung hat die Schockwelle den Sprengstoff komplett durchlaufen und ist ca. 2 cm in den Beton eingedrungen (vgl. Abb. 10). Jetzt wird im Beton die höchste Druckspannung von ca. 12 GPa erreicht. Nach 50 µsec ist die Druckwelle ca. 12 cm in den Beton hineingelaufen. Die Spannungswerte haben sich auf 0.95 GPa verringert

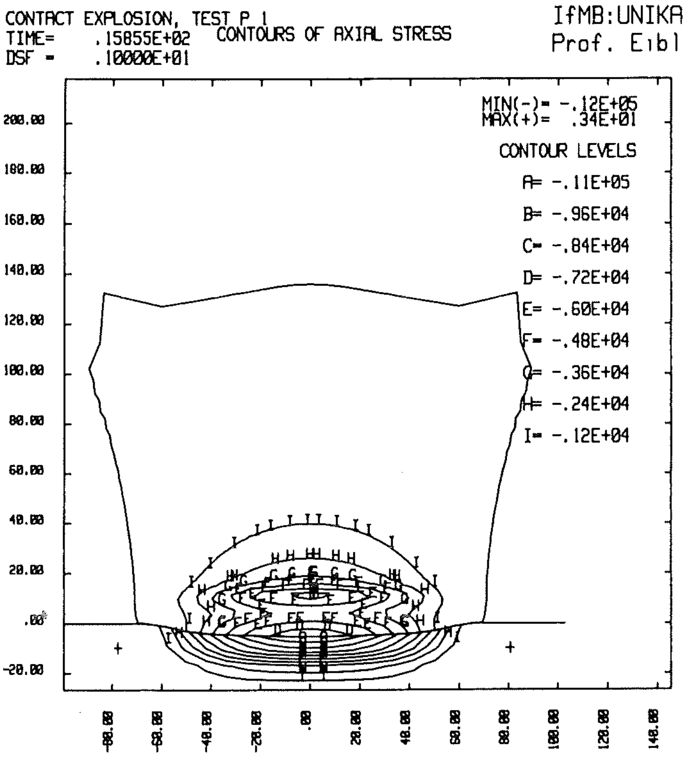

Abb. 10 Druckspannungen 16 µsec nach der Zündung

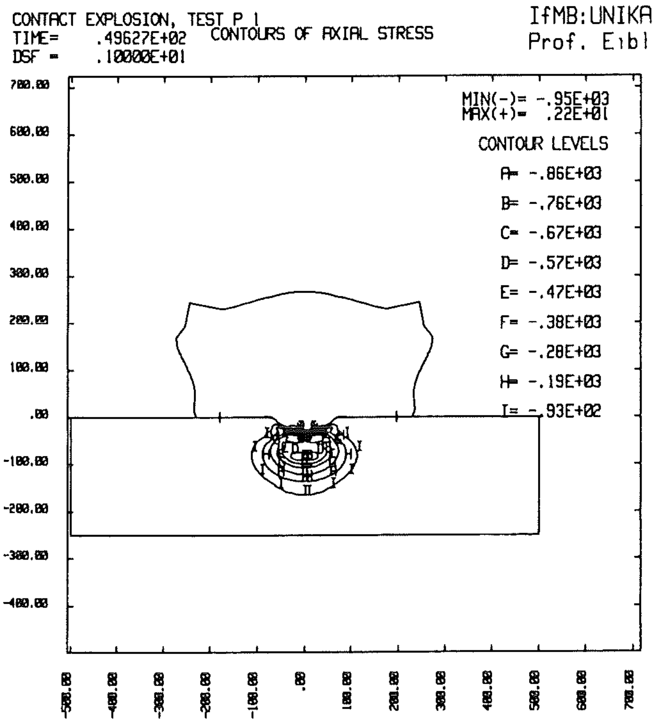

Abb. 11 Druckspannungen 50 µsec nach der Zündung

(siehe Abb. 11).

Dieser drastische Rückgang der Spannungen wurde, wie oben erwähnt, auch in den Versuchen festgestellt und resultiert aus der dreidimensionalen Ausbreitung und der verrichteten plastischen Arbeit der Druckwelle.

Bei 3100 µsec wurden einige Betonelemente so stark zerstört, daß die Rechnung nicht weiter fortgesetzt werden konnte, obwohl die Verformung zu diesem Zeitpunkt noch nicht abgeschlossen war. Die verformte Geometrie bei 3100 µsec ist in Abb. 12 dargestellt. Man erkennt deutlich den ausgebildeten Krater und die große Durchbiegung der Platte. Eine Perforation der Platte ist im Ansatz zu erkennen. Dieses Ergebnis stimmt mit dem Versuch überein, wo die Platte eine Perforation mit einem mittleren Durchmesser von 28 cm aufwies.

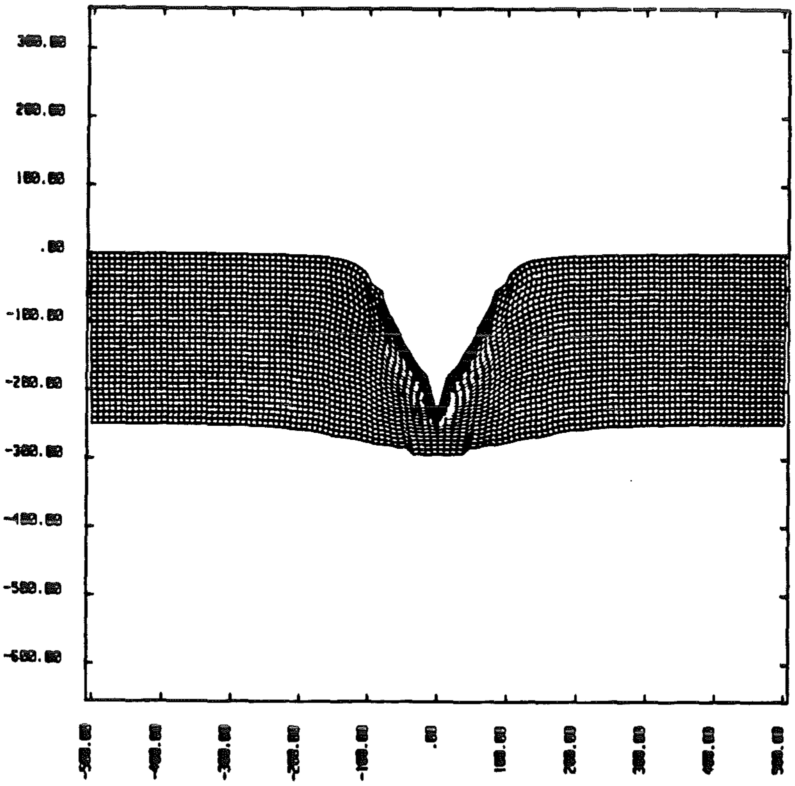

Abb. 12 Verformte Geometrie 3100 µsec nach der Zündung

4. Kritik und weiterführende Forschungsaufgaben

Die durchgeführten Versuche und ihre Auswertung decken sich weitgehend mit dem analogen Vorgehen anderer Wissenschaftler bei Festkörpern, sind aber doch wohl nur teilweise korrekt. Bei den meisten Experimenten zur Erzeugung von Hugoniot-Kurven, auch den eigenen, lag kein ausschließlich volumetrischer Spannungzustand vor.

Die den Rechencodes ausschließlich integrierten p-V Beziehungen geben, wie nachfolgend gezeigt wird, die tatsächlichen Spannungsverhältnisse nur bedingt richtig wieder.

Generell besteht nämlich in einem Festkörper bei einer Schockwellenbeanspruchung ein dreiaxialer allgemeiner Spannungszustand, der durch einen Spannungstensor beschrieben wird. Dieser kann prinzipiell in einen volumetrischen und einen deviatorischen Teil aufgespalten werden.

$$\begin{aligned} \bar{\sigma}_{ij} &= T_{ij} - \bar{p}_{ij} \\ \bar{p}_{ij} &= p \cdot \delta_{ij} \\ p &= \frac{1}{3} \cdot T_{ii} \end{aligned} \qquad (9)$$

wobei

T_{ij} = Spannungstensor
$\bar{p}_{ij}$ = hydrostatischer Kugeltensor
$\bar{\sigma}_{ij}$ = deviatorischer Spannungstensor
δ_{ij} = Kronecker Symbol

Nur in der Elastizitätstheorie lassen sich die Zusammenhänge zwischen diesen beiden Spannungsanteilen und ihren zugehörigen Dehnungen entkoppeln.

$$T_{ij} = \bar{p}_{ij} + \sigma_{ij} = K\varepsilon_{kk}\delta_{ij} + 2Ge_{ij} \qquad (10)$$

mit

ε_{ij} = Dehnungstensor
e_{ij} = deviatorischer Dehnungstensor

Im allgemeinen ist dies nicht der Fall.

Bei statischer Beanspruchung und volumetrischer Druck-Beanspruchung bis zum etwa 50 fachen Wert der einaxialen Druckfestigkeit liegen für Beton Formulierungen für eine dreidimensionale Versagensfläche [4] (vgl. Abb. 13) vor, sowie stoffgesetzliche Formulierungen, die ganz allgemein den kompletten Spannungstensor mit dem Dehnungstensor verbinden.

Abb. 13 zeigt prinzipiell eine solche Versagensfläche im Raum der Hauptspannungen. Entlang der hydrostatischen Achse ist der volumetrische Druck p – Spannungsinvariante I_1 – aufgetragen. Der Vektor ϱ gibt zusammen mit dem Winkel θ – Invarianten J_2, J_3 – die deviatorischen Spannungsanteile an.

Wenn nun üblicherweise nur eine Druckspannung σ_{11} in der Fortpflanzungsrichtung der Schockwelle gemessen wird und diese näherungsweise für den

$$\text{volumetrischen Druck } p = 1/3\ (\sigma_{11} + \sigma_{22} + \sigma_{33})$$

gesetzt wird, so ist dies nur richtig wenn $\sigma_{22} = \sigma_{33} = 0$ oder $\sigma_{22}, \sigma_{33} \ll \sigma_{11}$. Auch müßte Gleichung (5) durch:

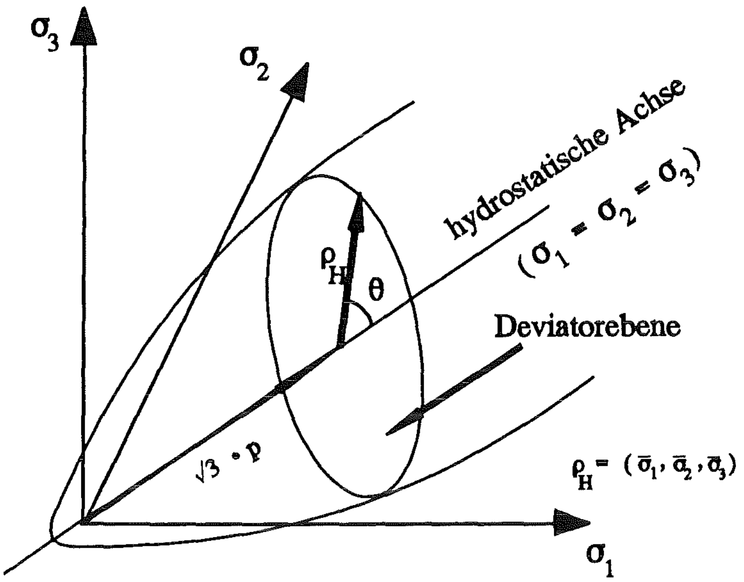

Abb. 13 Spannungsraum von Haigh–Westergaard mit Versagensfläche

$$dE = \theta dS - \underline{D} : \underline{T} \tag{11}$$

wobei

$\underline{D}$ = Tensor der Dehnungsrate
$\underline{T}$ = Spanungstensor (vgl. (9))

ersetzt werden. An die Stelle der Mie-Grüneisen Zustandsgleichung (6) müßte eine Gleichung:

$$\Delta \underline{T} = f(\Delta E, \underline{D}) \tag{12}$$

treten, es sei denn, man vernachlässigt den deviatorischen Anteil im Spannungstensor und im allgemeinen Fall der Koppelung auch den deviatorischen Anteil des Dehnungstensors.

Bei Metallen mag dies u.a. durch die mit starkem Temperaturanstieg bei schneller adiabatischer Belastung abfallende Schubsteifigkeit gerechtfertigt sein. Bei keramischen Werkstoffen ist dies wohl nur zu vertreten, wenn man davon ausgeht, daß zwar mit dem volumetrischen Druck auf Grund der ansteigenden inneren Reibung auch die ertragbaren deviatorischen Festigkeitsanteile langsam ansteigen, insgesamt aber sehr klein gegen den volumetrischen Anteil bleiben.

Ungeklärt ist weiter der Einfluß der Dehngeschwindigkeit – strain rate – , der wohl bei den deviatorischen Anteilen, falls solche vorhanden sind, von noch größerem Einfluß ist, als bei den volumetrischen. Was letztere betrifft, so darf vermutet werden, daß diese insbesondere im Bereich mittlerer Drücke – σ_a-σ_b in Abb. 1 – bei denen im Beton die inneren makroskopischen Hohlräume zerdrückt werden, nennenswert zum strain rate Effekt mit " viskosen " thermodynamisch irreversiblen Energieanteilen beitragen. Bei sehr viel höheren volumetrischen Drücken dürfte dieser Einfluß bei stark verdichtetem Material abnehmen.

Um hier weiter zur Klärung beim Werkstoff Beton beizutragen, sollen zukünftig in Experimenten, die die Voraussetzung:

$$\sigma_{11} \neq 0,\ \sigma_{22} = \sigma_{33}$$
$$\varepsilon_{11} \neq 0,\ \varepsilon_{22} = \varepsilon_{33} = 0$$

erfüllen, σ_{11} und σ_{22} unter Kontaktexplosionen gemessen werden, sodaß $p = 1/3(\sigma_{11} + 2\sigma_{22})$ korrekt bestimmt wird.

Über die Messung von σ_{11}, bevor der Meßaufnehmer als Folge der Betonzerstörung ausfällt, kann auch auf die Versagensfläche geschlossen werden, da diese dreifach symmetrisch durch den sogenannten Druckmeridian, mit $\sigma_{11} \neq 0$, $\sigma_{22} = \sigma_{33}$, wie gemessen wird, hinreichend charakterisisert wird.

Nach Annahme eines ersten Ansatzes in Anlehnung an (12) (vgl. auch Anhang) kann dann die Temperatur θ rechnerisch bestimmt werden. Diese soll im Experiment entweder über die Wärmestrahlung oder mit Hilfe von Bi-Metallstreifen gemessen werden, so daß dann gegebenfalls der Ansatz für ΔE korrigiert werden kann. Damit soll versucht werden, die Hugoniot-Kurve auf isotherme Verhältnisse rückzurechnen.

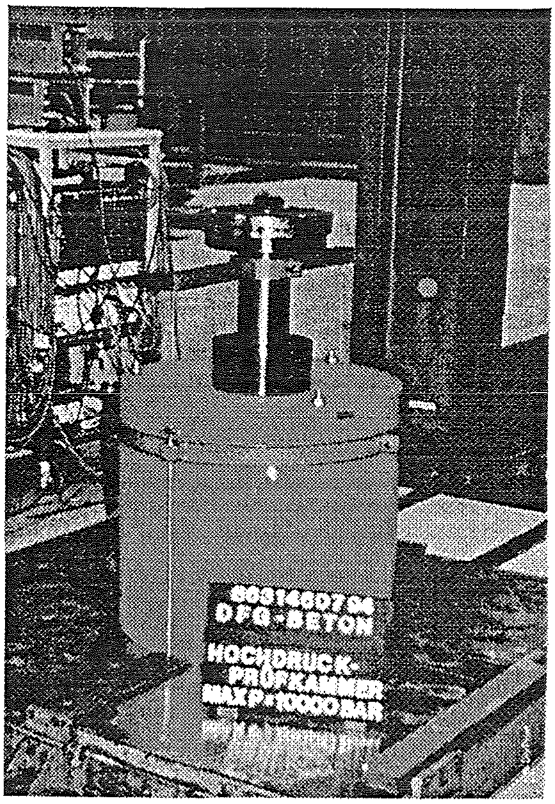

Abb. 14 Druckgefäß zum Aufbringen der hydrostatischen Belastung

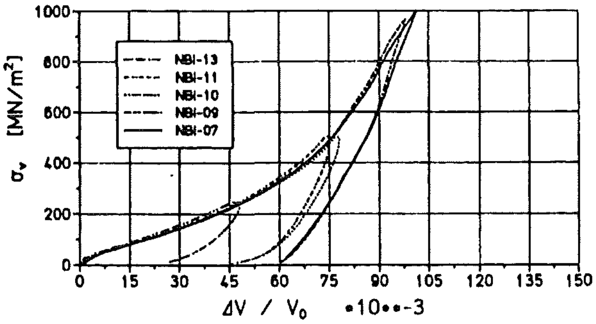

Abb. 15 statische p - V Beziehungen

Um dem Einfluß der Dehnrate in einer ersten Erkundung zu studieren, wurden eigene, relativ schwierige statische p-V Vergleichs-Versuche (vgl. Abb. 14 und Abb. 15), mit Drücken bis $p_{max} = 1$ GPa – der internationale Stand liegt derzeit bei etwa 0.5 GPa – durchgeführt [7]. Diese überschneiden sich bezüglich des Druckes mit den bereits durchgeführten eigenen Schockversuchen mit großer Dehngeschwindigkeit. Wenn letztere hinsichtlich der Temperatur θ, wie beschrieben, isotherm " bereinigt " sind, kann über einen Vergleich eine erste Abschätzung des rate-Einflusses erfolgen.

5. Zusammenfassung

Es wird über Experimente zur Bestimmung einer Hugoniot-Kurve für Beton berichtet, die an großen Betonplatten mittels Kontaktexplosion erfolgreich durchgeführt wurden und Nachrechnungen dieser Versuche mit der F.E. Methode.
Die üblichen Annahmen und Techniken vergleichbarer Art werden einer kritischen Sichtung unterworfen und erste Vorschläge für eine Verbesserung angegeben.

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7. Anhang

Nach Mie-Grüneisen gilt:

$$p(V,E) = p_{0°K}(V) + \frac{\gamma(V)}{V}[E - E_{0°K}(V)] \qquad \textbf{(A.1)}$$

mit den thermodynamischen Beziehungen:

$$\gamma(V,T) = V\left(\frac{\partial p}{\partial E}\right)_V = V\frac{\left(\frac{\partial p}{\partial T}\right)_V}{\left(\frac{\partial E}{\partial T}\right)_V} = \frac{V}{C_V}\left(\frac{\partial p}{\partial T}\right)_V = -\frac{V}{C_V}\left(\frac{\partial p}{\partial V}\right)_T\left(\frac{\partial V}{\partial T}\right)_p = -\frac{V}{C_p}\left(\frac{\partial p}{\partial V}\right)_S\left(\frac{\partial V}{\partial T}\right)_p \qquad \textbf{(A.2)}$$

Vereinfacht wird jedoch üblicherweise davon ausgegangen, daß γ nur vom Volumen abhängt. In der Vergangenheit wurden mehrere Modelle für $\gamma(V)$ vorgeschlagen. Das einfachste Modell ist die Annahme, daß $\gamma(V)$ linear vom Volumen abhängig ist.

$$\frac{\gamma(V)}{V} = const. \qquad \textbf{(A.3)}$$

Drei andere häufig benutzte Modelle, die Formulierung nach Slater, Dugdale/MacDonald und Zubarev/Vashchenko, die auf der Grundlage physikalischer Gesetzmäßigkeiten für Einkristalle bestehen, sind in der folgenden Formel zusammengefaßt. Für $\alpha = 0$ entspricht A.4 der Formulierung von Slater [8],wobei angenommen wird, daß die Querdehnzahl unabhängig vom Volumen ist. Die Fromulierung von Dugdale/MacDonald [3] entspricht $\alpha = 2/3$. Weiter ist damit auch die Theorie von Zubarev/Vashenko [10] mit $\alpha = 4/3$ eingeschlossen.

$$\gamma = \left(\frac{\alpha}{2} - \frac{2}{3}\right) - \frac{V}{2} \frac{\frac{d^2(p_{0°K} \cdot V^\alpha)}{dV^2}}{\frac{d(p_{0°K} \cdot V^\alpha)}{dV}} \tag{A.4}$$

Unter Verwendung der Erhaltungsgleichungen (A.1) und der folgenden Beziehung

$$p_{0°K} = -\frac{dE_{0°K}(V)}{dV} \tag{A.5}$$

für p und E bei 0° Kelvin erhält man aus Gl. (A.3) und Gl. (A.6) nach einigem Umformen die nachfolgend aufgeführte nichtlineare Differentialgleichung 3. Ordnung in $E_{0°K}$

$$\frac{d^3E_K}{V^3} + \left[\frac{\alpha + \frac{4}{3}}{V} + \frac{p_H + \frac{dE_K}{dV}}{p_H(V_{H0} - V) + 2E_{H0} - 2E_K}\right]\frac{d^2E_K}{dV^2} + \frac{\alpha}{3V^2}\frac{dE_K}{dV} + \frac{\alpha}{V}\frac{(p_H + \frac{dE_K}{dV})\frac{dE_K}{dV}}{p_H(V_{H0} - V) + 2E_{H0} - 2E_K} = 0 \tag{A.6}$$

Hierbei bezeichnet der Index K die Werte der 0°K Isothermen, der Index H die Werte auf der Hugoniot–Kurve und der Index H0 für den Ausgangszustand der Hugoniot–Kurve.

Zu dieser Differentialgleichung lassen sich zunächst die unten angeführten 2 Anfangsbedingungen angeben

$$\begin{aligned} E_{0°K}(V_{0°k}) &= 0 \\ p_{0°K}(V_{0°K}) &= -\frac{dE_{0°K}(V_{0°K})}{dV} = 0 \end{aligned} \tag{A.7}$$

Die noch benötigte dritte Anfangsbedingung kann, wie allgemein üblich, nur näherungsweise formuliert werden, indem man davon ausgeht, daß der Kompressionsmodul auf der 0°K Isothermen nährerungsweise dem elastischen Kompressionsmodul bei Raumtemperatur entspricht. Auf der 0°K Isothermen gilt, da sie gleichzeitig auch eine Isentrope darstellt

$$K_{0°K} = -V\left(\frac{\partial p}{\partial V}\right)_S = -V\frac{dp_{0°K}}{dV} \tag{A.8}$$

womit sich die dritte Anfangsbedingung zu

$$\frac{d^2E_{0°K}(V_{0°K})}{dV^2} = -\frac{dp_{0°K}(V_{0°K})}{dV} = \frac{K_{0°K}(V_{0°K})}{V_{0°K}} \approx \frac{K_{el}}{V_{0°K}} \qquad \textbf{(A.9)}$$

ergibt. Für die beiden noch unbekannten Größen in Gl. (A.8), die Energie bei Raumtemperatur auf der Hugoniot-Kurve E_{H0} sowie das relative Volumen bei 0°K $V_{0°K}$ können folgende Zusammenhänge angeben werden.

$$V_{0°K} = V_{H0}(1 - \int_0^{293} \alpha_V d\theta) = V_{H0}(1 - \int_0^{293} 3\alpha d\theta) \qquad \textbf{(A.10)}$$

$$E_{H0} = \int_0^{293} C_V(\theta) d\theta \qquad \textbf{(A.11)}$$

Mit diesen Beziehungen kann Gl. (A.8) numerisch integriert werden, so daß sich schließlich isotherme und isentrope bzw. adiabatische p-V Beziehungen mit der Mie-Grüneisen-Equation of State entwickeln lassen. Weiter kann die Temperatur entlang der Hugoniot-Kurve errechnet werden. Wurde im Schockwellenversuch zusätzlich die Temperatur gemessen, so kann der Ansatz für den Grüneisen-Koeffizient korrigiert, d.h. den spezifischen Bedingungen für Beton angepaßt werden.