KERNFORSCHUNGSZENTRUM

KARLSRUHE

Oktober 1972

KFK 1663
EUR 4845 e

Institut für Neutronenphysik und Reaktortechnik

European GCFR Program Plans

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by

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Abstract

In 1968 two specialist teams were set up by ENEA to evaluate the merits of steam and gas as alternative coolants to sodium for a fast breeder reactor. Following the conclusions of the ENEA Working Team, seven European countries, which were performing work in the field of gas-cooled fast reactors, joined together in the so-called "Zürich-Club" to coordinate their governmental efforts in this field and exchange information.

Subsequently, 14 European companies set up the Gas-cooled Breeder Reactor Association in Brussels. In the following two years the GBRA produced two assessment studies of a GCFR both with 1000 MWe. The first one based on steel clad, mixed oxides vented fuel pins, the second one on silicon carbide coated fuel particles.

In Germany a study on the feasibility and the economics of a GCFR was performed. The study came to the conclusion that the GCFR with steel clad vented fuel pins was the type with the minimum amount of required further development work. This reactor offered a performance comparable to that for the sodium breeder. The two German nuclear centers have agreed a four-year 6.5 million dollar program (1971-74) whose main items are:

- A joint study Karlsruhe-Siemens-Jülich of the safety aspects of 1000 MWe GCFR with steam turbine cycle, integrated primary helium circuit and vented steel clad fuel pins.
- A joint irradiation Jülich-Siemens-Karlsruhe of a 12 vented pin bundle in the Belgian reactor BR 2 with a surrounding driving fuel region capable to produce a relevant fast flux.

Kurzfassung

Die ENEA setzte im Jahre 1968 zwei Expertengruppen ein, die die Eigenschaften der Dampf- und Gaskühlung als Alternativen zur Natriumkühlung für einen schnellen Brutreaktor ermitteln sollten. Auf Grund der vom ENEA Working Team aufgestellten Schlußfolgerungen bildeten sieben europäische Länder, die Arbeiten auf dem Gebiet der gasgekühlten schnellen Reaktoren leisteten, den sogenannten "Zürich-Club", um die Bemühungen ihrer Regierungen in diesem Bereich zu koordinieren und Informationen auszutauschen.

Dann gründeten 14 Industriefirmen Europas in Brüssel die Gas-cooled Breeder Reactor Association. Die GBRA erstellte in den folgenden beiden Jahren zwei Bewertungsstudien für gasgekühlte schnelle Reaktoren (GCFR) mit je 1000 MWe. Die erste Studie betraf belüftete Brennstäbe aus Mischoxid mit Stahlhülle, die zweite siliziumkarbidbeschichtete Brennstoffteilchen.

In Deutschland wurde eine Durchführbarkeits- und Wirtschaftlichkeitsstudie für einen GCFR ausgearbeitet. Das Ergebnis dieser Studie war, daß der GCFR mit belüfteten Brennstäben in Stahlhülle der Reaktortyp ist, für den die geringsten zusätzlichen Entwicklungsarbeiten erforderlich wären. Die Eigenschaften dieses Reaktors wären mit denen des Natriumbrüters vergleichbar. Die beiden Kernforschungszentren Deutschlands vereinbarten ein Vierjahresprogramm (1971-74) mit einem Budget von 6,5 Millionen Dollar. Es umfaßt in erster Linie

- eine von Karlsruhe, Siemens und Jülich gemeinsam durchgeführte Untersuchung der Sicherheitsaspekte eines 1000 MWe GCFR mit Dampfturbinenkreislauf, integriertem Helium-Primärkreis und belüfteten Brennstäben in Stahlhülle;

- eine von Jülich, Siemens und Karlsruhe im BR 2 in Belgien gemeinsam durchgeführte Bestrahlung eines aus 12 Stäben bestehenden, belüfteten Brennstabbündels, das von einer Treiberzone umgeben ist, die den geeigneten schnellen Fluß herstellen kann.

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References

1. Early Studies

One of the first studies performed in the frame of the Karlsruhe Fast Breeder Project was concerned with helium-cooled fast breeders [1, 2]. One of the main results, which were reported briefly at the 1963 Argonne Conference [3], was that indeed high ratings of the order of 0.5 to 1 MWth/kg fissile material needed for fast breeders could be attained.

At the 1964 Geneva Conference Fortescue and coworkers from GGA published the results of their studies of a GCFR of 450 MWe. The reactor was helium-cooled at 68 Atms and the oxide fuel was contained in stainless steel clad pins with artificial roughness on the surface to improve the heat transfer between pin and helium coolant [4]. Later the same group showed that with carbide fuel and CO_2 cooling at 136 Atms a rating of 1.75 MWth/kg fissile material was feasible [6]. Contemporarily to the Gulf studies an Oak Ridge group performed a comparative study of helium, CO_2 and SO_2 as coolant of a 1000 MWe breeder [5].

In October 1965 Dalle Donne published a comparison between helium, CO_2 and superheated steam as coolants of a large fast reactor [7]. The main conclusions of this study were that although steam is a better heat transfer medium, helium- and CO_2-cooled reactors were better breeders and, with sufficiently high gas pressures ($\geq$ 70 Atms), reasonable performances could be obtained. Furthermore, while the coolant void coefficients of He and CO_2 were positive but always below one dollar for pressures below 100 Atms, the void coefficients with steam cooling were positive and considerably larger (between 5 and 9 dollars).

In 1967 various studies were performed on Gas Breeders in Europe. In Karlsruhe the interest in Gas-Cooled Fast Reactors was raised again by the introduction of new technical improvements such as the feasibility of large prestressed concrete pressure vessels for very high pressures (100 - 130 Atms), the use of partially roughened fuel element surfaces, the development of new vanadium alloys (we will discuss these later on in the paper) with good creep properties under fast flux irradiation at high temperatures and the possibility of using gas turbine cycles [8, 9]. The Belgian firm Belgonucléaire performed a study on a CO_2-cooled fast reactor with CO_2 gas turbines [10, 11]. A study was performed in Sweden as well with helium as coolant and steam turbines [12]. In the meantime, the Gulf group had continued its studies on the gas breeder [13-24, 26]. Some of these were performed in collaboration with the Swiss Federal Institute of Reactor Research [25]. The main results of these earlier activities are shown in Tab. I.

In 1967 the USAEC asked the Oak Ridge National Laboratory with the assistance of the Argonne, Los Alamos, and Pacific Northwest Laboratories and of the American firms Babcock + Wilcox, General Electric, Gulf General Atomic, and Westinghouse to perform a study on the alternate (to sodium) coolants for fast breeder reactors. The main results of these studies have been published in 1968 and 1969 [27, 28]. It is perhaps here worth-while to report in tableform the main advantages and disadvantages of helium as coolant of fast reactors as given in the foreword of WASH-1090 (Tab. II).

The main point of the conclusion was: "On the basis of the designs evaluated and the combined criteria of low power costs and good breeding capability, GCFR's have the highest potential of the concepts considered. Steam-cooled reactors, on the other hand, suffer either from higher power costs (85 and 180 Atms SCBR's) or low breeding ratio (250 Atms SCBR)".

Tab. I : Early Studies of GCFR's

Organization	Year	Results, Activities	Ref.
Karlsruhe	1961-1963	Rating in the range 0.5 - 1 MWth/kg fiss. mat. attainable	[1, 2, 3]
Gulf General Atomic	1964-1965	Design of 450 MWe plant, He cooling, 68 Atms, oxide fuel. With carbide and CO_2 at 136 Atms, rating = 1.75 MWth/kg fiss. mat.; S.S. cladding	[4, 6]
Oak Ridge	1964	Comparison of He, CO_2, SO_2 as coolant of 1000 MWe GCFR	[5]
Karlsruhe	1965	Comparison of He, CO_2, and steam for 1000 MWe GCFR; He and CO_2 better breeder, void coeff. less than 1 \$	[7]
Karlsruhe	1967	Possibility of using vanadium clad pins for direct gas turbine cycle	[8, 9]
Belgonucléaire	1967	300 MWe, CO_2 gas turbine	[10, 11]
Sweden	1968	Design of plant: He, 75 Atms, 1000 MWe	[12]
Gulf General Atomic	1965-1967	Safety considerations, design of test reactor, design of 1000 MWe plant	[13-24]
G.G.A., Würenlingen	1968	Study of test reactor facility	[25]
USAEC	1968-1969	SCBR is either more expensive or worse breeder than GCFR	[27, 28]

Tab. II (from WASH-1090) : Helium as Coolant of a Fast Reactor

Advantages	Disadvantages
No intermediate loop	High pressure (85 to 120 Atms)
Potential high breeding ratio	Lack of fast breeder reactor technology
Visible refueling maintenance	High pumping power
Minimal void coefficient	Emergency and postaccident cooling provisions not established
Most compatible with materials	Unproven high power density
Potential vented fuel	Gas leakage difficult to control
Utilization of thermal GCR technology	High cladding temperature
Fluidity at room temperature	Extensive component development required

2. The ENEA Winfrith Report and the "Zürich Club"

In 1968 two specialist teams were set up by the European Nuclear Energy Agency to evaluate the merits of steam and gas as alternative coolants to sodium for a fast breeder reactor. The results of these studies have been published [29, 30]. The ENEA Specialist Group, which met in Winfrith to assess gas cooling, examined the proposals of GCFR's, mainly those of the GGA, Sweden, Karlsruhe, and Belgonucléaire groups, which have been mentioned in the introduction, and in addition a gas-cooled fast reactor with coated particle fuel proposed by the UKAEA, which had not yet been reported in the literature up to that time and which was described in two papers later in 1968 [31, 32]. Tab. III shows the main data (after normalizing to the ground rules used during the study), which were chosen as representative for the main fuel concepts from the different gas-cooled fast breeder designs presented.

Tab. III : ENEA Winfrith Study. Main normalized data of Gas-cooled Fast Reactors

Net electrical output	MWe	1000	1000	1000
Coolant		He	He	He
Power conversion cycle		indirect	indirect	indirect
Fuel element		pin	pin	coated particle
Canning (coating)		SS 316	SS 316	(SiC C)
Fuel material		(U, Pu)O_2	(U, Pu) C	(U, Pu)O_2
Pin (particle) outer diameter	mm	7.6	7.7	(1.1)
Can thickness	mm	0.28	0.31	0.15
Surface roughening		yes	yes	---
Max. fuel rating	MW/t	139	257	310
Average burn-up	MWD/t	65 000	65 000	65 000
Max. hot spot canning temperature	°C	770	770	1200
Coolant temperature at reactor outlet	°C	640	587	700
Coolant pressure at reactor inlet	bar	70	120	52
Circulator power	MW	110	118	60
Thermal net efficiency		0.408	0.382	0.419
Breeding gain ("new" α-Pu)		0.41	0.50	0.29
Reactor fissile Pu-inventory	t	2.96	1.90	1.89
System fissile Pu-inventory	t	4.02	2.85	3.40
System linear doubling time at 80 % load factor	year	14.0	7.7	17.0

It was not possible to reach an agreement in the conclusions of the Working Team, which had to evaluate the two studies on gas and steam in comparison with sodium as coolant of large fast power reactors. One body of opinion held that the development of an alternative coolant was admissible only as a back-up solution in the event of difficulties with the large-scale application of sodium technology. An equally strong body of opinion held that gas cooling had ample scope for sharing the future fast reactor market with sodium and that there was merit in maintaining the principle of choice, which has evolved in the present-day thermal reactor market. This latter conclusion was confirmed by a subsequent Swedish study [43]. No further interest on steam cooling was shown at that time by any country participating at that study.

Following the conclusions of the ENEA Working Team, in July 1969 seven European countries, which were performing work in the field of gas-cooled fast reactors (Austria, Belgium, Germany, The Netherlands, Sweden, Switzerland, and the United Kingdom) joined together in the so-called "Zürich-Club" to coordinate their governmental efforts in this field and exchange information. Various "Zürich-Club" specialist meetings on fuel, heat transfer, physics, design, and safety have taken place since.

The Winfrith study and the "Zürich-Club" meetings stimulated the interest and the work in Europe on the GCFR, as it is shown by the many publications from Germany [33, 36, 37, 50, 56, 57, 58, 59, 61, 62, 66, 67, 68, 72, 73, 74, 78], Great Britain [31, 32], Switzerland [34, 39, 40, 42, 46, 49, 65], Sweden [43], and Belgium [45]. The work in Germany was centered on the evaluation of various fuels of GCFR's, on safety [33] and on improvement of the neutronphysics calculations with the objective to obtain more information on reactivity coefficients (void, steam inleakage, etc.) [37, 68, 73]. Originally the reference design was based on fuel pins clad in an especially developed vanadium alloy (V, 3Ti, 1Si), which allowed a maximum clad temperature of 850 °C and a helium temperature of 700 °C. The helium was flowing directly in gas turbines [50]. Design studies on the gas turbine circuit connected with a GCFR showed that this concept is feasible and the dimensions of the components reasonable (1000 MWe turbine: length 25 m, maximum outer diameter: 5.5 m, recuperative heat exchanger: 6 units, length: 18 m, outer diameter: 4.4 m) [66, 72]. Lately, however, experimental investigations have shown that the oxide fuel would, at high temperatures and in presence of temperature gradients in the fuel, oxidate the vanadium cladding unduly [67, 78]. Vanadium based cladding would therefore be compatible with oxide fuel only in presence of a suitable oxygen getter in the fuel or, perhaps, with carbide fuel. This is the direction, in which are going the present investigations in Karlsruhe.

The work in Great Britain is based on a GCFR with ceramic coated particles [31, 32]. These coated particles have been originally developed for High Temperature (thermal) Gas-cooled Reactors. For fast reactors the pyrolitic graphite cannot be used as fuel cladding material due to lack of dimensional stability in presence of large fast fluences and high temperatures. Silicon carbide has been proposed in its place. At present coated particles with pyrolitic SiC outer coating for GCFR application are developed and tested. The problems (pressure distribution in the fuel element, mechanical stresses, central ceramic porous tube) connected with the fuel element itself, are recognized, but not yet fully tackled.

The Swiss Federal Institute for Reactor Research since 1968 was mainly involved in the study of GCFR's with direct cycle helium turbine at relatively moderate gas temperatures (600 °C), obtainable possibly with steel clad pins [34, 39, 42, 49]. In Sweden a rather detailed comparison study between helium, steam, and sodium as coolants of a Fast Reactor was performed [43], while in Belgium the accent was on a GCFR with CO_2 cooling and direct cycle gas turbine [45].

3. The German Gas Breeder Memorandum

In August 1969 the German Federal Ministry for Education and Science requested the two nuclear centers at Karlsruhe and Jülich to prepare a study on the feasibility and the economics of a GCFR. This study (the so-called "Gas Breeder Memorandum") was carried out by the two centers with the collaboration of the German nuclear industry, which included the following companies: AEG, BBC, BBK, GHH, Krupp and Siemens. The Gas Breeder Memorandum has been published [56]. Summaries of it were presented at the Bonn Reaktortagung of 1971 [57, 58, 59]. The study was performed by five working groups (fuel elements, physical criteria, components, safety, economics). Three concepts were chosen as representative of the main possible options:

a) GCFR with steam turbine, oxide fuel in steel clad pins ("vented fuel"), primary system integrated in prestressed concrete pressure vessel (this concept is based on the GGA concept [16, 24, 44]).

b) GCFR with gas turbine, oxide fuel in vanadium pins ("strong clad") (this concept is based on the Karlsruhe concept [50, 66]).

c) GCFR with steam turbine, oxide fuel in coated particle form (this concept is based on the UKAEA concept [31, 32]).

These alternatives were calculated again in the context of the study based on consistent assumptions and methods. The heat transfer correlations used were the same, and so was the method to calculate the hot spots in the core. In all the cases the fuel density was assumed to be 83 % of theoretical and the mean discharge burn-up 75 000 MWD/t. The nuclear calculations were performed with the latest cross section set of Karlsruhe, the so-called MOXTOT set. The main results of these calculations are listed in Tab. IV together with the data of an advanced sodium breeder and a steam-cooled fast reactor, which have been calculated with similar assumptions.

The study came to the conclusion that the GCFR with steel clad vented fuel pins was the type with the minimum amount of required further development work, especially because the fuel element could be based on the current work for the sodium breeder and the reactor components on the development of the High Temperature Thermal Reactor. On the other hand, the reactor offered a performance comparable to that of a sodium-cooled reactor with probably smaller electricity generating costs. The calculated electricity generating costs of steam were also favourable, but the plutonium doubling time appeared to be too high.

Tab.IV : Main Parameters of Helium-cooled Breeder Reactors of 1000 MWe Compared to Advanced Sodium- and Steam-cooled Types

Concept No.	1	2	3	Advanced Na-Breeder	Steam Breeder
Cycle	Steam turbine	Gas turbine	Steam turbine	Steam turbine	Steam turbine
Fuel	Oxide	Oxide	Oxide	Oxide	Oxide
Fuel element	Fuel pin (vented)	Fuel pin (sealed can)	Coat. particle	Fuel pin (sealed can)	Fuel pin (vented)
Max. lin. power rating in pin W/cm	430	440	---	530	420
Mean discharge burn up MWd/t	75 000				
Inlet coolant pressure kg/cm^2	70	100	70	10	150
Mixed mean coolant temp. at reactor outlet ^{o}C	600	706	675	580	500
Max. hot spot temp. at clad midwall ^{o}C	755	850	950	700	720
Core fissile inventory kg Pu^{239} · Pu^{241}	3140	2770	1800	1630	2860
Breeding ratio	1.44	1.32	1.19	1.29	1.15
System lin. doubling time yrs^{+}	13.2	17.8	31.8	14.5	32.3
Specific investment $/kWe	162	145	162	170 - 240	152$^{*)}$
Fuel cycle cost mills/kWh	1.3	1.5	1.5	0.875	1.4$^{*)}$
Electricity cost mills/kWh^{+}	5.2	5.05	5.4	5.0 - 6.5	5.2$^{*)}$

$^{+}$ Load factor 0.7

All costs are for the spring 1970; *) estimated costs.

4. The Gas Breeder Reactor Association

In December 1969 14 European companies from Belgium, France, Germany, The Netherlands, Italy, Sweden, Switzerland, and the United Kingdom set up the Gas-cooled Breeder Reactor Association in Brussels. In the following two years the GBRA produced two complete design studies of a GCFR both with 1000 MWe, helium cooling, steam turbine cycle and primary circuit integrated in prestressed concrete pressure vessel; the first one based on steel clad, mixed oxides vented fuel pins, the second one on silicon carbide coated fuel particles. Furthermore, the possibility of using CO_2 cooling in connection with silicon carbide coated fuel particles was also investigated.

Tab. V from reference [75] gives the main data for the three reference designs. The main differences between the reactor number 1 of Tab. V and the number 1 of Tab. IV (Gas Breeder Memorandum) are the higher pressure (115 against 70 Atms), the standing core in place of hanging core and the system to drive the gas blowers (electrical motors in place of steam turbines). Fig. 1 from reference [71] gives some details of the primary helium circuit of the GBRA concept 1. The breeding gain and the plutonium doubling time of the coated particle designs are better than those of the Gas Breeder Memorandum (concept 3, Tab. IV), because the layer of the SiC coating on the particles in the GBRA designs was 50 μm thick, while in the Gas Breeder Memorandum it was 100 μm. Tab. VI shows the results of the cost calculations of the GBRA. The main conclusions of these are that a GCFR with fuel pins would have the same capital costs of a thermal High Temperature Reactor, while the helium and CO_2 reactors with coated particles would have 7 % and 9 % lower costs respectively. However, the fuel cycle costs with coated particles would be higher than with fuel pins due to the longer doubling time. If pin axial blankets are used in connection with the coated particle design, the greater fuel cycle costs would compensate almost completely the gains in capital costs.

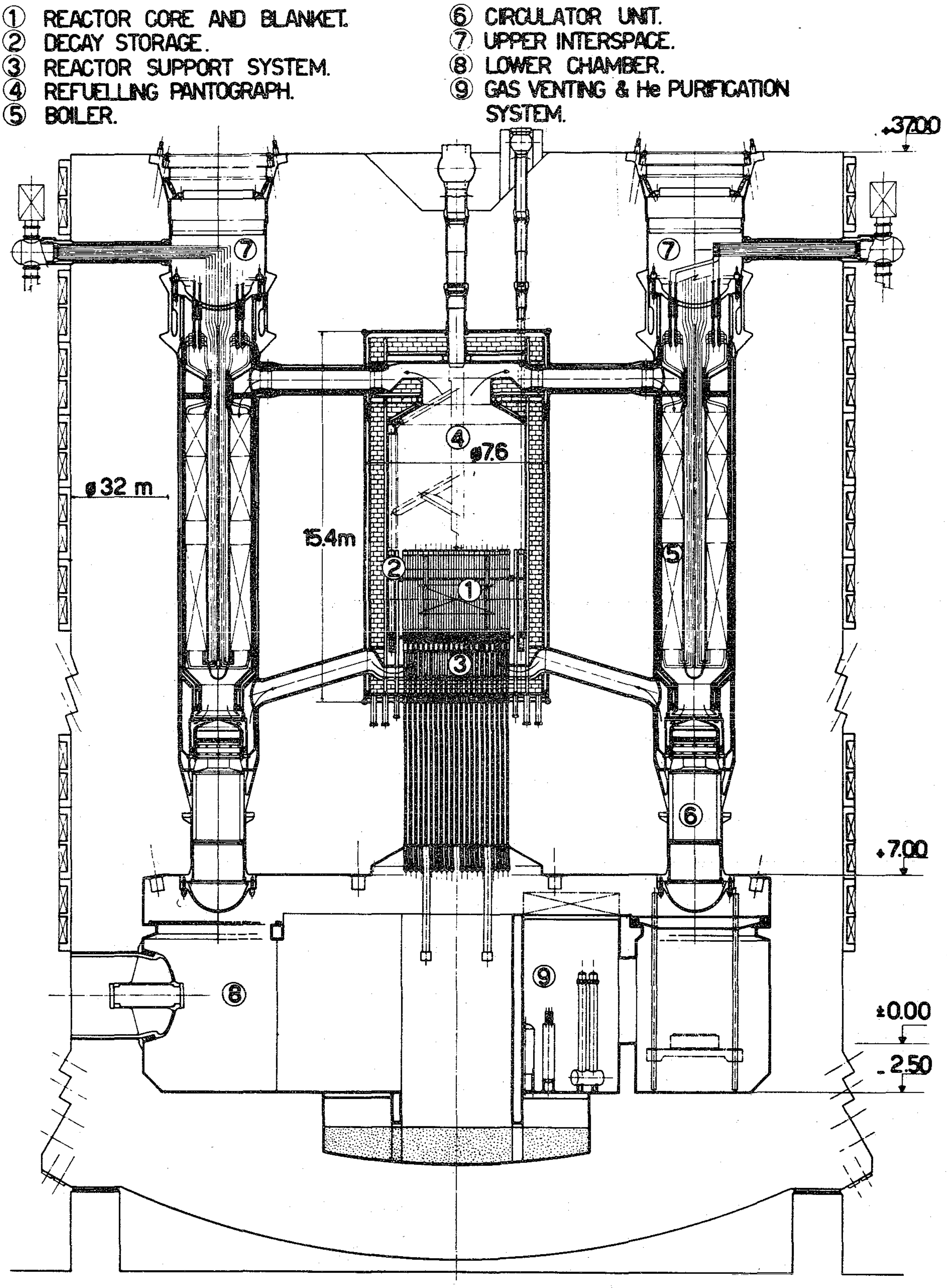

Fig. 1 (from ref. [71]) : Nuclear Steam Supply System.
Vertical Section.

Tab. V (from ref. /̅75̲/) : Parameters for three GBRA Reference Designs

System		1 He pin	2 He coated particle	3 CO_2 coated particle
Electrical output	MW	1028	1028	1028
Plant overall efficiency	%	35.4	36	35.9
Primary gas pressure	bar	120	120	60
Pumping power	MW	107	78	88
Inlet temperature (core)	°C	260	260	260
Mixed mean outlet temperature (core)	°C	587	700	650
Steam pressure (outlet)	bar	115	115	115
Steam temperature	°C	540	540	540
Total heat exchanger surface	m^2	20,600	12,360	23,520
Number of loops		8	6	8
Fissile inventory (core + blankets)	kg	4,310	2,800	3,070
Fissile inventory (system)	kg	5,250	4,650	5,100
Breeding gain		0.43	0.36	0.42
Doubling time	a	13	16	16

Tab. VI (from ref. /̅75̲/) : Comparative Capital Cost Estimates

Reference GBRA design based on fuel pin (GBRA 1)	1.0
High temperature reactor design (thermal reactor)	0.99 ± 0.04
Helium-cooled coated particle design (GBRA 2)	0.93 ± 0.02
Carbon-dioxide-cooled coated particle design (GBRA 3)	0.91 ± 0.02

5. Present Groups and Their Activities

5.1 Federal Republic of Germany

In 1971 the two German nuclear centers at Karlsruhe and Jülich agreed on a joint 6.5 million dollar program (1971-74) based on the conclusions of the German Gas Breeder Memorandum. 90 % of the funds are for the reference design concept (helium cooling, steel clad vented pins, oxide fuel, steam turbine cycle), 10 % for the research in the field of the advanced concepts (vanadium cladding, coated particles, gas turbine). Tab. VII shows the timescale and the organizations involved in this program, where main objectives are:

- A joint study Karlsruhe-Siemens-Jülich of the safety aspects of 1000 MWe GCFR with steam turbine cycle, integrated primary helium circuit and vented steel clad fuel pins.
- A joint irradiation test of Jülich-Siemens-Karlsruhe of a 12 vented pin bundle in the Belgian reactor BR 2 with a surrounding driving fuel region capable to produce a relevant fast flux (see in Fig. 2, the test fuel element).

Other work items are in Karlsruhe,

- Heat transfer: The Heat Transfer Laboratory of the Institute of Neutron Physics and Reactor Engineering of the Karlsruhe Nuclear Research Center is performing since 1963 research covering many aspects of the heat transfer with gas cooling; for a review of activities and results see ref. /79/.
- Development of a dynamic code for transient calculations in a GCFR.

and in Jülich,

- Study and development of fuel element concepts with coated particles.

The German firm Siemens, which collaborates with the two German nuclear centers in the GCFR program, has also signed an information exchange contract in the field of GCFR's with the U.S. firm Gulf General Atomic.

Table VII: German GCFR Research and Development Program

I Reference Design: helium cooling, steel clad vented pins, oxide fuel, steam turbine cycle

Activity	1971	1972	1973	1974	1975	1976	Organization
1. Fuel element development							
1.1 Heat transfer tests	———	———	———	———	- - -	- - -	Karlsruhe Nuclear Center
1.2 Out of pile mechanical tests of rod clusters			———	- - -			Karlsruhe Nuclear Center
1.3 Special material tests							
1.3.1 Mechanical tests on Sandvik 12R72HV tubes, cycle tests			———	- - -			Karlsruhe Nuclear Center
1.3.2 Cladding corrosion tests			———	———	- - -		Karlsruhe Nuclear Center
1.3.3 Erosion of rough surfaces				- - -	- - -		Karlsruhe Nuclear Center
1.4 Irradiations							
1.4.1 1 pin irr. in helium loop of FR2		———	———	———			Karlsruhe Nuclear Center
1.4.2 Trefoil irr. in fast reactor (DFR?)				———	———	———	Karlsruhe Nuclear Center
1.4.3 Irr. of 12 vented pin cluster in helium loop of BR2		———	———	———	———	———	Jülich + Siemens (Karlsruhe)
2. Safety and design studies	———	———	———	———	- - -	- - -	Karlsruhe + Siemens (Jülich)

II Advanced Concepts

Activity	1971	1972	1973	1974	1975	1976	Organization
1. Development of V-3Ti-1Si as cladding material	———	———	- - -	- - -	- - -	- - -	Karlsruhe
2. Development of coated particle fuel elements	———	———	———	- - -	- - -	- - -	Jülich
3. Study of gas turbine circuit (exp. dynamic studies)	———	———	- - -	- - -			Karlsruhe + Jülich

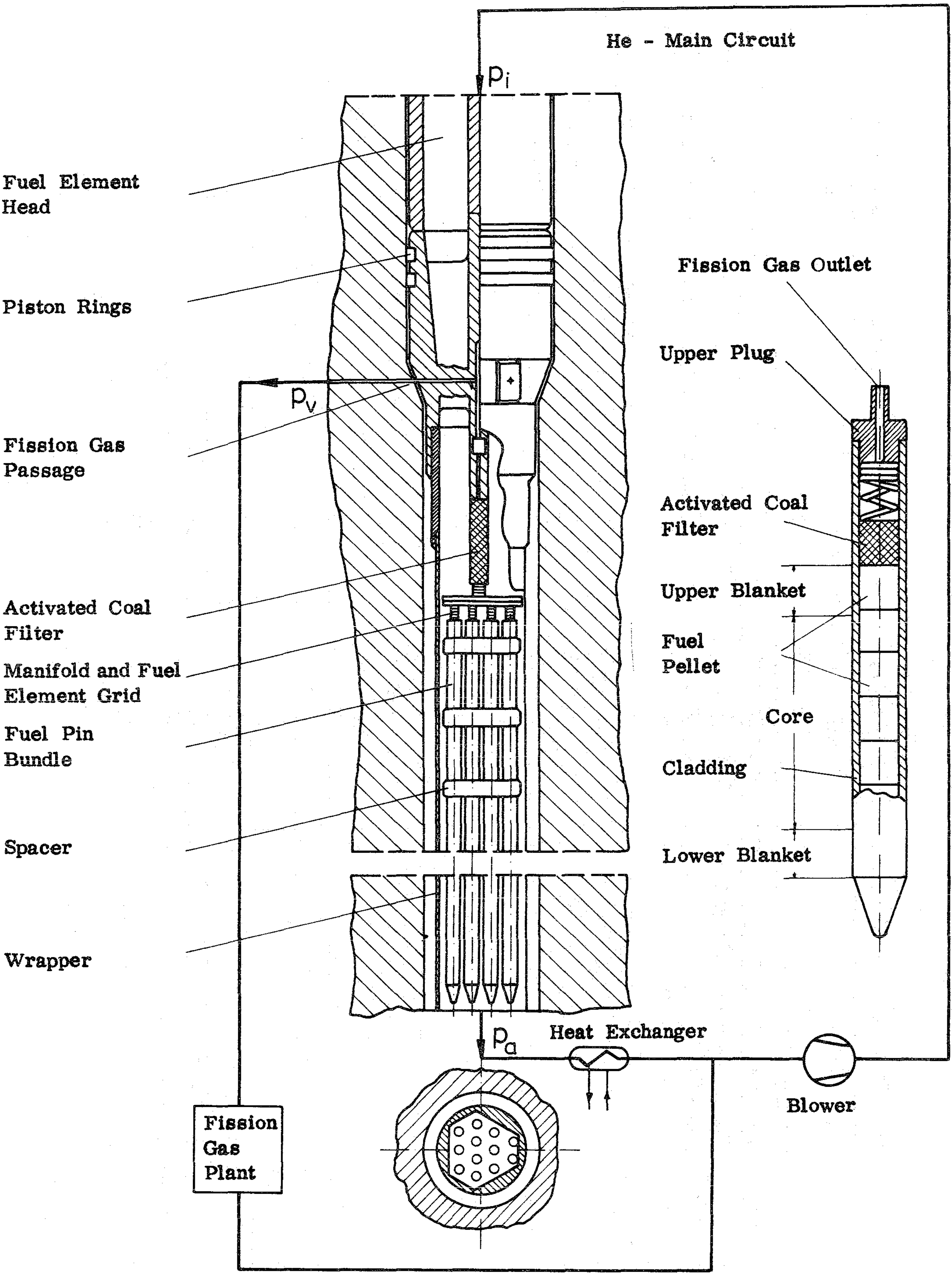

Fig. 2 : Test Fuel Element (Schematic)

5.2 ENEA Coordinating Group on Gas-cooled Fast Reactor Development

In September 1971 the ENEA created the Coordinating Group on Gas-cooled Fast Reactor Development which supersedes the "Zürich-Club". It has been agreed to have a joint program for two years, the main points of which are the above mentioned activities in Germany for the pin design and the development of ceramic coated particles for a GCFR in Great Britain and in France, which has recently joined the group of countries, which originally formed the "Zürich-Club". Tab.VIII shows the agreed and coordinated program of these eight European countries in schematic form.

The work will be performed in strict collaboration and coordination with the Gas Breeder Reactor Association, in which, as we explained in section 4, are represented the European private companies interested in GCFR's, while the ENEA Coordinating Group represents the European governmental organizations working in this field.

The total value of the ENEA program on GCFR's amounts to 14 million dollars for the years 1972 and 1973. About 57 % of these costs are related to work on the pin design, 28 % are devoted to the particle design and the rest to general R + D work beneficial for both concepts.

5.3 The Gas Breeder Reactor Association

Recently (March 1972) the decision to continue the Association for further two years has been taken. Eight European companies are represented in the Association (see Tab.IX).

Furthermore various European utilities have been invited as associated members.

In the next two years the GBRA will work in the following areas (as can be seen from Tab.VIII as well) :

- pin assembly development,
- coated particle assembly development,

Tab.VIII : ENEA Coordinating Group R + D Program

Activity	1972	1973	1974	1975	1976	Country
1. Pin fuel element technology						
1.1 Pin development	———	———	———	———	———	FG, NL, SL, SW, BE (US)
1.2 Pin assembly development	———	———	———	———	———	FG, GBRA, SL, BE (US)
2. Coated particle fuel element technology						
2.1 Particle development	———	———	———	———	———	AU, BE, FR, UK, NL, SW
2.2 Particle assembly development	———	———	- - -	- - -	- - -	FR, UK, GBRA, BE, FG
3. Safety work and overall assessment studies						
3.1 Safety assessment	———	———	———	———	- - -	FG, SL, UK, GBRA (US)
3.2 Development of prestressed concrete vessel for high pressures	———	———	- - -	- - -		AU, SW
3.3 Plant design and fuel cycle performance assessment	———	———	———	- - -	- - -	FG, SL, GBRA (US)
3.4 Final economic assessment of GCFR system compared to competing reactor systems	———	———	- - -	- - -	- - -	BE, FG, GBRA (US)

Abbreviations used: AU = Austria, BE = Belgium, FG = Federal Republic of Germany, FR = France, NL = The Netherlands, SL = Switzerland, SW = Sweden, UK = United Kingdom, US = United States, GBRA = Gas Breeder Reactor Association

- safety assessment,
- plant design and fuel cycle performance assessment,
- final economic assessment of GCFR system, compared to competing reactor systems.

Tab. IX : European Companies Members of the Gas Breeder Reactor Association

Company	Country
Hoch-Temperatur-Reaktorbau	Germany
Progettazioni Meccanico-Nucleari	Italy
Belgonucléaire	Belgium
CEN - Mol	Belgium
The Nuclear Power Group	United Kingdom
Neratoom	The Netherlands
Brown Boveri Sulzer Turbomaschine AG.	Switzerland
ASEA - Atom	Sweden

References

/‾1‾/ Proceedings of the IAEA Conference on Physics of Fast and Intermediate Reactors, Vienna, Aug. 1961, Vol. III, p. 544-546 and p. 601-602.

/‾2‾/ K. Benndorf et al., Technische Studie für einen gasgekühlten schnellen Brutreaktor, Karlsruhe Internal Report, 1962.

/‾3‾/ D. Smidt, Optimization and Safety of Helium-cooled Fast Breeders, ANL-6792, p. 515, 1963.

/‾4‾/ P. Fortescue, R. Shanstrom, L. Meier, W. Simon, P. Fischer, Gas Cooling for Fast Reactors, A/Conf.28/P/694, 1964.

/‾5‾/ The Gas-cooled Reactor Project Staff, Gas-cooled Fast Reactor Concepts, ORNL-3642, Sept. 1964.

/‾6‾/ P. Fortescue, R. Shanstrom, H. Fenech, Development of the Gas-cooled Fast Reactor Concept, ANS Topical Meeting on Fast Reactor Technology, Detroit, April 1965 and GA-6132; see also Evaluating Coolants for Fast Breeder Reactors, II. Development of the Gas-cooled Fast Reactor Concept, Nucleonics, May 1965.

/‾7‾/ M. Dalle Donne, Comparison of He, CO_2 and Steam as Coolants of a 1000 MWe Fast Reactor, Proc. Conf. on Safety, Fuels and Core Design in Large Fast Power Reactors, Argonne, October 1965, ANL-7120, p. 797-814 and KFK-447.

/‾8‾/ M. Dalle Donne, E. Eisemann, K. Wirtz, Some Considerations on Gas Cooling for Fast Breeders, KFK-595, May 1967; see also Discussions of 3rd FORATOM Congress, London, April 1967.

/‾9‾/ M. Dalle Donne, K. Wirtz, Gas Cooling for Fast Breeders, ANS Winter Meeting, Chicago, Nov. 1967 and KFK-689.

/‾10‾/ J. Chermanne et al., Les reacteurs a neutrons rapides refroidis au gaz, BN-6701, Jan. 1967.

/‾11‾/ J. Chermanne et al., Centrale nucléaire de 300 MWe avec réacteur à neutrons rapides refroidis au gaz et turbine à gaz en cycle direct, BN-6710, Oct. 1967.

/‾12‾/ Swedish Evaluation Studies of Full Scale Fast Reactors, Vol. IV. Fast Helium-cooled Breeder (FHcB) Studies, Aktiebolaget Atomenergi, p. 379, April 1968.

/‾13‾/ P. Fortescue et al., Safety Characteristics of Large Gas-cooled Fast Power Reactors, Proc. Conf. on Safety, Fuels and Core Design in Large Fast Power Reactors, Argonne, Oct. 1965, ANL-7120, p. 230-260.

[14] Project Staff, Conceptual Design Study of a Gas-cooled Fast Reactor Experiment, GA-6666, Dec. 1965.

[15] P. Fortescue, P. Fischer, R. Shanstrom, Fast Reactor Cooling - Projects of Alternate Systems, Proc. of the NUCLEX Conf., Basle, Switzerland, 1966.

[16] P. Fortescue, G.M. Schulz, A 1000 MWe Gas-cooled Fast Breeder Reactor, GA-7823, 1967.

[17] P. Fortescue, J. Broido, G. Schultz, R. Shanstrom, The Gas-cooled Fast Reactor Experiment, GA-7835, March 1967.

[18] Project Staff, Gas-cooled Fast Breeder Reactor, Annual Progress Report for the Period Ending July 31, 1965, GA-6667, Oct. 1965.

[19] Project Staff, Gas-cooled Fast Breeder Reactor, Annual Progress Report for the Period Ending July 31, 1966, GA-7645, May 1968.

[20] R.T. Shanstrom, Progress in Optimizing the Gas-cooled Fast Breeder Reactor, ASME Winter Meeting, 1967, 67-WA/NE-12.

[21] P. Fortescue, G. Melese d'Hospital, Thermodynamic Comparison of Gas Coolants for Nuclear Reactors, Symposium on High Pressure Gas as a Heat Transport Medium, Inst. Mech. Engineers, Vol.181, Part 3 I, March 1967.

[22] P. Fortescue, G. Melese d'Hospital, W. Thompson, Status of the Technology of Gas Cooling for Fast Reactors, ANS-101, p. 7.1-7.12, San Francisco, April 1967.

[23] G. Melese d'Hospital, Gas-cooled Fast Reactor Performance with Various Degrees of Surface Roughening, GA-8268, Oct. 1967.

[24] Gulf General Atomic Europe, Reference Design of a 1000 MWe Gas-cooled Fast Reactor Plant, GAE-37, March 1968.

[25] Swiss Federal Institute for Reactor Research, Status of Technology and Future Potential of Gas-cooled Fast Reactors, Study of a Gas-cooled Fast Reactor Experimental Facility, 51-EIR, March 1968.

[26] G. Melese d'Hospital, Factors Affecting the Design of Gas-cooled Fast Breeder Reactors, ANS Topical Meeting, Cincinnati, April 1968 and GA-8583.

[27] USAEC, An Evaluation of Gas-cooled Fast Reactors, WASH-1089, June 1968.

[28] USAEC, An Evaluation of Alternate Coolant Fast Breeder Reators, WASH-1090, April 1969.

[29] ENEA Working Team on Fast Reactor Evaluation, An Assessment Study of Gas-cooled Fast Reactors for Civil Power Generation, Winfrith, July 1968.

[30] ENEA Working Team on Fast Reactor Evaluation, An Assessment Study of Steam-cooled Fast Reactors for Civil Power Generation, Karlsruhe, September 1968.

[31] C.P. Gratton et al., A Gas-cooled Fast Reactor Using Coated Particle Fuel, J. Brit. Nucl. Energy Soc. 7, 233-242, July 1968.

[32] C.P. Gratton et al., A Gas-cooled Fast Reactor with Direct Cycle Potential, SM-111/67, IAEA Conf., Jülich, Oct. 1968.

[33] M. Dalle Donne, E. Eisemann, F. Thümmler, K. Wirtz, High Temperature Gas Cooling for Fast Reactors, SM-111/12, IAEA Conf., Jülich, Oct. 1968 and KFK-841, EUR-3978e.

[34] J. Broido, L.A. Lys, Principal Considerations in the Design of Gas-cooled Fast Reactors with Direct Cycle Gas Turbine, SM-111/69, IAEA Conf., Jülich, Oct. 1968.

[35] G. Melese d'Hospital, Advanced Fast Breeder Reactors with Gas Cooling, GA-8833, Sept. 1968.

[36] D. Smidt, Fast Reactor Heat Removal, Proc. Int. Conf., on the Constructive Uses of Atomic Energy, ANS, Washington, Nov. 1968 and KFK-883, EUR-4162e.

[37] E. Eisemann, Nukleare Eigenschaften heliumgekühlter schneller Brutreaktoren, KFK-864, März 1969.

[38] G. Melese d'Hospital, P. Fortescue, Fast Breeder Reactors with Direct Cycle Gas Turbines, GA-9346, May 1969.

[39] L.A. Lys, R. Brogli, W. Helbling, Parametric Studies of Gas-cooled Fast Reactors with Closed Cycle Gas Turbines, Atomkernenergie 2, 1969 and EIR-154.

[40] D.F. Streeton, L.A. Lys, Straight Steam Cycle for Gas-cooled Fast Breeder Reactors, Nucl. Engin. Internat. 14, and EIR-153, May 1969.

[41] G. Melese d'Hospital, The Gas-cooled Fast Breeder Reactor, GA-9390, June 1969, and Energie Nucleaire 11, 8, 1969.

[42] L.A. Lys, J.H. Broido, H. Frutschi, Gas Turbine Fast Reactor Design, J. Brit. Nucl. Energy Soc. 8, 3, and EIR-162, July 1969.

[43] Swedish Evaluation Studies of Full Scale Fast Reactors, Vol.I. Results and Discussion, Aktiebolaget Atomenergi, p.379, Sept. 1969.

/ 44 / P. Fortescue, G. Melese d'Hospital, J. Peak, L. Meyer, A Developmental Gas-cooled Fast Reactor Plant, GA-9413, NUCLEX 69, Basle, Switzerland, Oct. 1969.

/ 45 / J. Chermanne (Ed.), Preliminary Design Study of a 1000 MWe CO_2-cooled Direct Cycle Fast Breeder Reactor, BN-6912-06, Dec. 1969.

/ 46 / Eidg. Institut für Reaktorforschung, Würenlingen, Study of the Conversion of the Experimental Nuclear Power Plant of Lucens into a Gas-cooled Fast Reactor Experimental Facility, TM-IN-425, 1969.

/ 47 / M.L. Blumeyer, J.C. Peak, The Breeder Reactor of Your Future, The Gas-cooled Fast Breeder Reactor, GA-9960, March 1970.

/ 48 / P. Fortescue, W.I. Thompson, The GCFR Demonstration Plant Design, Proc. Gas-cooled Reactors Inform. Meeting, Oak Ridge, April 1970, CONF-700401.

/ 49 / L.A. Lys, G. Ciszewski, H. Frutschi, Gas Turbine Power Conversion Systems for Helium-cooled Breeder Reactors, Oak Ridge Conf., April 1970, Conf-700401 and EIR-181.

/ 50 / M. Dalle Donne, E. Eisemann, K. Wirtz, Latest Calculations for a GCFR with a Vanadium Clad Pin Core, Oak Ridge Conf., April 1970, CONF-700401, and KFK-1198, EUR-3726e.

/ 51 / R.B. Fitts, J.R. Lindgren, E.L. Long, D.R. Cuneo, Gas-cooled Fast Reactor Fuel Element Development, Oak Ridge Conf., April 1970, CONF-700401.

/ 52 / J.M. Waage, J.A. Larrimore, Safety Studies for the Gas-cooled Fast Reactor, Oak Ridge Conf., April 1970, CONF-700401, and GA-10049.

/ 53 / C.S. Walker, Safety and Afterheat Removal Studies of the Gas-cooled Fast Reactor, Oak Ridge Conf., April 1970, CONF-700401.

/ 54 / G. Melese d'Hospital, Status Report on Fast Breeder Reactors, GA-10171, June 1970.

/ 55 / R.H. Simon, J.R. Lindgren, J.N. Siltanen, R.B. Fitts, Gas-cooled Fast Reactor Fuel Element Development - Fuel Rod Irradiation Tests, Proc. Int. Meeting on Fast Reactor Fuel and Fuel Elements, ANS Local Section in Europe, Karlsruhe, September 1970.

/ 56 / Gesellschaft für Kernforschung Karlsruhe, Kernforschungsanlage Jülich unter Mitarbeit der deutschen Reaktorindustrie, Gasbrüter-Memorandum, KFK-1375, EUR-4575d, JÜL-744-RG, February 1971; see also M. Dalle Donne, K. Wirtz, H. Krämer, Assessment of Gas-cooled Fast Breeder, Nucl. News 14, 12, 42, 1971, and AED-CONF-71-100-10, Germany.

[57] K. Wirtz, Gaskühlung schneller Brutreaktoren, Reaktortagung Bonn, März 1971, S. 770, Kerntechnische Gesellschaft im Deutschen Atomforum e.V.

[58] M. Dalle Donne et al., Brennelement, Coreauslegung von gasgekühlten Schnellen Brütern, Reaktortagung Bonn, März 1971, S. 774.

[59] H.J. Preuß et al., Anlagekonzept, Sicherheit und Wirtschaftlichkeit des gasgekühlten Schnellen Brüters, Reaktortagung Bonn, März 1971, S. 778.

[60] C.P. Gratton, Gas-cooled Breeder Reactor Studies, Trans. ANS 14, 271, 1971.

[61] M. Dalle Donne, K. Wirtz, Problems of Gas-cooled Fast Breeder Reactors, Trans. ANS 14, 272, 1971.

[62] H.J. Preuß et al., Siemens Activities in the Field of Gas-cooled Fast Reactor Development, Trans. ANS 14, 273, 1971.

[63] P. Fortescue, J.B. Dee, Gas-cooled Fast Breeder Reactor Studies, Trans. ANS 14, 273, 1971.

[64] T.N. Washburn et al., Fuel Element Development for the Gas-cooled Breeder Reactor, Trans. ANS 14, 275, 1971.

[65] G. Markóczy, Core Heat Transfer and Fluid Flow in the GCFR, Trans. ANS 14, 275, 1971.

[66] C. Savatteri, Geschlossener Gasturbinenkreislauf für einen 1000 MWe gasgekühlten Schnellen Brutreaktor, KFK-1409, EUR-4578d, May 1971.

[67] S. Dorner, G. Schumacher, Compatibility between Vanadium Alloys and Oxides and Carbides under Irradiation, KFK-1410, May 1971; see also: Theoretische Betrachtungen über die Eignung von Vanadiumlegierungen als Hüllwerkstoff für oxidische (U, Pu)-Kernbrennstoffe, J. Nuclear Mat. 39, 69-76.

[68] E. Eisemann, Considerations on the Accident: Water Ingress in the Primary Loop of a Helium-cooled Fast Breeder Reactor with Secondary Steam Cycle, KFK-1487, Sept. 1971.

[69] A.K. Krasin et al., Physical and Technical Principles in the Design of Nuclear Power Stations Using Gas-cooled Reactors with Dissociating N_2O_4 Coolant, A/Conf.49/P/023.

[70] A.F. Fritzsche et al., The Gas-cooled Fast Breeder Reactor, A/Conf.49/P/116.

[71] C.P. Gratton, Some Design and Safety Aspects of Gas Breeder Reactors, A/Conf.49/P/023.

[72] C. Savatteri, Der rekuperative Wärmeaustauscher für einen schnellen heliumgekühlten Brutreaktor mit Heliumturbine, KFK-1566, EUR-4725d, Februar 1972.

[73] E. Eisemann, Anisotrope Diffusion bei gasgekühlten schnellen Brutreaktoren, KFK-1577, März 1972.

[74] C.A. Goetzmann et al., Erste Ergebnisse sicherheitstechnischer Untersuchungen für einen gasgekühlten schnellen Brüter, Reaktortagung Hamburg, April 1972, S.708, Kerntechnische Gesellschaft im Deutschen Atomforum e.V.

[75] C.P. Gratton, Gas-cooled Fast Reactor Studies by the GBR Association, Reaktortagung Hamburg, April 1972, S.712.

[76] P. Burgsmüller, J.R. Stanbridge, Plant Design and Safety of a Gas-cooled Breeder Reactor, Reaktortagung Hamburg, April 1972, S.716.

[77] A. Hubner, A. Krähe, Der gasgekühlte schnelle Brutreaktor mit Coated Particle Brennelement und dessen Coreoptimierung, Reaktortagung Hamburg, April 1972, S.720.

[78] M. Bober, S. Dorner, C. Sari, G. Schumacher, Oxidation of Vanadium Alloy Cladding Material in Contact with Mixed Oxide Fuel, Kerntechnik, August 1972.

[79] M. Dalle Donne, Heat Transfer Work on Gas Cooling for High Temperature and Fast Reactors, to be published as American Nuclear Society Critical Review in Reactor Technology.