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**SOME BR2 IRRADIATION DEVICES
FOR FAST REACTOR FUEL
AND FUEL ELEMENTS**

by

P. von der HARDT

1971



Report prepared at the CEN
Centre d'Etude de l'Energie Nucléaire, Mol - Belgium
Association No. 006-60-5 BRAB

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The "FASOLD" concept covers a new type of BR2 irradiation device for high power, long term testing of carbide (nitride) fuel elements in an epicalcium neutron flux ("Fuel Assembly Specification Test Of Long Duration"). The rig consists of a single-walled niobium carrier with NaK filling, containing fuel pin and thermocouples, and of an external removable cadmium screen with stainless steel cladding. The screen assembly can be removed from the rig and is replaced regularly to compensate the cadmium burn-up. Hence, no life-time limitation is caused by the screen.

The 650°C sodium-filled non-fissile rig has been developed for the irradiation of flat and tubular specimens of candidate alloys for fast reactor fuel pin cladding.

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ABSTRACT

The present report deals particularly with three types of irradiation devices for fast reactor components which have been developed in the scope of the Fast Breeder Reactor programme :

The " FAFNIR " concept has first been presented in April, 1969 (International Conference on Fast Reactor Irradiation Testing, Thurso, Caithness, U.K.). It features the irradiation of \varnothing 6 mm oxide fuel pins, 500 to 1000 mm long, inside a cadmium-containing thimble. Recent work included fabrication and operation of fission gas pressure measurement rigs, and investigations to overcome the problem of thermocouple failure.

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The 650°C sodium-filled non-fissile rig has been developed for the irradiation of flat and tubular specimens of candidate alloys for fast reactor fuel pin cladding.

KEYWORDS

BR-2
CAPSULES
IRRADIATION
MATERIALS TESTING
FUELS
FUEL CANS
FUEL ELEMENTS
FAST REACTORS
BREEDER REACTORS

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*) Manuscript received on October 2 , 1970

Summary.

The Belgian Materials Testing Reactor BR2 (MOL, Belgium) has currently been used as a test irradiation facility for fast reactor fuel elements (Ref. 15).

The present report deals particularly with three types of irradiation devices for fast reactor components which have been developed in the scope of the Fast Breeder Reactor programme :

- the oxide fuel pin rigs "FAFNIR",
- the design of a carbide fuel pin rig "FASOLD",
- the 650°C Na-filled cladding specimens rigs.

The "FAFNIR" concept has first been presented in April, 1969 (International Conference on Fast Reactor Irradiation Testing, Thurso, Caithness, U.K.). It features the irradiation of \varnothing 6 mm oxide fuel pins, 500 to 1000 mm long, inside a cadmium-containing thimble. Recent work included fabrication and operation of fission gas pressure measurement rigs, and investigations to overcome the problem of thermocouple failure.

Irradiation parameters currently reached are (hot plane values) :

- 450 to 550 W/cm linear fission power rating,
- 600°C fuel pin cladding surface temperature,
- 50.000 MWd/t burn-up.

The "FASOLD" concept covers a new type of BR2 irradiation device for high power, long term testing of carbide (nitride) fuel elements in an epicadmium neutron flux ("Fuel Assembly Specification Test Of Long Duration"). The rig consists of a single-walled niobium carrier with NaK filling, containing fuel pin and thermocouples, and of an external (removable) cadmium screen with stainless steel cladding. The screen assembly can be removed from the rig and is replaced regularly to compensate the cadmium burn-up. Hence, no life-time limitation is caused by the screen. The design and development include power density and thermal calculations for different rig concepts, particular reactor safety studies, corrosion tests and niobium technology work. One prototype rig is scheduled for irradiation in 1970, about 10 more are to follow from 1971, including fission gas pressure measurement devices. The irradiation parameters aimed at are :

- 1200 to 1500 W/cm linear fission power rating,
- 500 to 600°C fuel pin cladding surface temperature,
- up to 100.000 MWd/t burn-up.

The 650°C sodium-filled non-fissile rig has been developed for the irradiation of flat and tubular specimens of candidate alloys for fast reactor fuel pin cladding. One rig has been irradiated in 1969, and three are under irradiation in 1970. Specimens and thermocouples are housed inside a stainless steel carrier which is filled with sodium. The carrier is mounted into the outer rig tube (thimble) of stainless steel. The only heat source is the absorption of reactor radiation in the rig components (gamma heating), and the desired specimen temperature is reached by a thermal barrier (gas gap) between inner and outer tube. Helium-neon mixture creates the required temperature control. Two particular design features provide adequate temperature stability in space and time :

- the outside of the inner tube (specimen carrier) is tapered towards both ends, in order to compensate roughly the sinusoidal reactor gamma heating distribution,
- the rig head is fitted with a manually operated axial displacement mechanism which enables correct positioning of the specimen column with regard to the maximum gamma heating under irradiation.

Development work included thermal calculations, sodium technology, high-temperature thermocouples brazing and precision tube machining.

I. General.

The Belgian Materials Testing Reactor BR2 is operated on the basis of a contract associating the Centre d'Etude de l'Energie Nucléaire (C.E.N.) and the European Atomic Energy Community (EURATOM).

BR2 is designed as a high-flux engineering reactor using highly enriched MTR-type fuel, light water as coolant and moderator, and beryllium as moderator and reflector (Ref. 6, pp. 10-20).

The reactor has been working since the beginning of 1963, with an average of about 220 full power days per annum (Ref. 2), and a large number of irradiation experiments have been carried out (Ref. 1 and 2).

Three main groups cover the major part of the BR2 experiments :

1. irradiations for high temperature gas-cooled reactor programmes,
2. irradiations for liquid metal cooled fast breeder reactor programmes,
3. radioisotope production.

A summary of the fast reactor fuel and fuel element irradiation facilities in BR2 is given on table 1.

The increasing demand for cadmium-screened facilities with their high load on reactor core reactivity on one hand, and the need for longer reactor cycles i.e. extended per annum utilization on the other hand lead to the development of cermet reactor fuel elements (Ref. 4) with higher initial contents of U 235 and burnable poison (boron and samarium) for initial reactivity balancing. UAl_3 was selected for technological reasons (Ref. 3), although a further increase of the fissile nuclei inventory appears possible through the use of UAl_2 (Ref. 5). The new fuel elements of which several prototypes have been irradiated in BR2 in 1970, will be fully available in early 1971, together with an increased reactor thermal capacity (100 MW) created by the replacement of the primary heat exchangers.

T A B L E 1

Fast Reactor Fuel and Fuel Element Irradiation Programme
for the Belgian Materials Testing Reactor BR2.

Type of irradiation device.	Neutron Spectrum	Target(s)	Hot Spot Irradiation Cond.		Irradiation Period	Remarks.
			Linear Power	Surface Temperature		
			W/cm	°C		
200 kW Na Loop	Epicadmium	3 to 7 oxide or carbide (nitride) fuel pins	600 to 3300	650	from 1965	from 1965 to 1970 : 6 in-pile sections
500 kW Na Loop	Epicadmium	19 oxide fuel pins or 7 carbide fuel pins	600 1500	650 700	from 1972	
"FAFNIR" oxide rigs	Epicadmium	1 oxide fuel pin per rig	600	700	1968-1971	1968 through 1970 : 8 rigs irradiated 4 rigs under irradiation
"FASOLD" carbide rigs	Epicadmium	1 carbide fuel pin per rig	1500	550	1971-1975	
Fuel creep rig	Thermal	short fissile specimens	500	700	1970-1972	C.E.A. development
Hollow fuel pellet rig	Thermal	1 oxide fuel pin per rig	1000	500	1970-1972	
Several rig types	Thermal (fission spectrum)	Transuranium isotope pellets			from 1964	
Boiling water capsule	Thermal	1 oxide fuel pin per rig	700	600	from 1965	
Several rig types, incl. creep facil.	(fission spectrum)	cladding material specimens			from 1965	Development by GfK Karlsruhe, C.E.A. etc..
650°C Na filled rig	(fission spectrum)	cladding material specimens		650	1969-1971	4 rigs in 1969-1970

Another problem caused by the increasing number of instrumented irradiation devices is the recording and reduction of instrument signals (thermocouple readings, pressure transducer output, etc.). It will be solved by the installation of automatic data acquisition and treatment systems the first of which are scheduled to operate from early 1971. The intention is to replace during a 3 to 5 years' transition period, the "conventional" control panels (with strip chart recorders and electromechanical warning and regulation devices) by computerized systems.

II. Specific Rigs.

1. Mixed Oxide Fuel Irradiation "FAFNIR".

1.1. Scope of the Experiment.

Fuel pins representative for fast reactor oxide fuel are to be irradiated in a neutron spectrum above the cadmium cut-off. The device developed enables the irradiation of one pin per rig, under an incorporated cadmium filter (Fuel Array Fast Neutron Irradiation Rig = FAFNIR).

Four rigs have been irradiated in 1968-1970, four rigs are under irradiation (August, 1970), and five new rigs are under construction.

1.2. Description.

The rig (Ref. 8) is made essentially of a NaK filled specimen carrier and the outer tube assembly comprising the cadmium screen.

The specimen carrier consists of a \varnothing 11,8/13,3 mm stainless steel tube with welded end covers. The upper cover contains the high-temperature brazed penetration of 10 to 12 thermocouples and, in the case of the pressure transducer version, of the fission gas capillary tube (see figure 1).

40 to 60 cm³ of eutectic sodium-potassium alloy serve as a thermal bond between the carrier tube and the fuel pin. It is filled into the specimen carrier by means of its lower cover which is crimped and seal-welded after the operation. Filling and sealing take place in a glove box under controlled argon atmosphere.

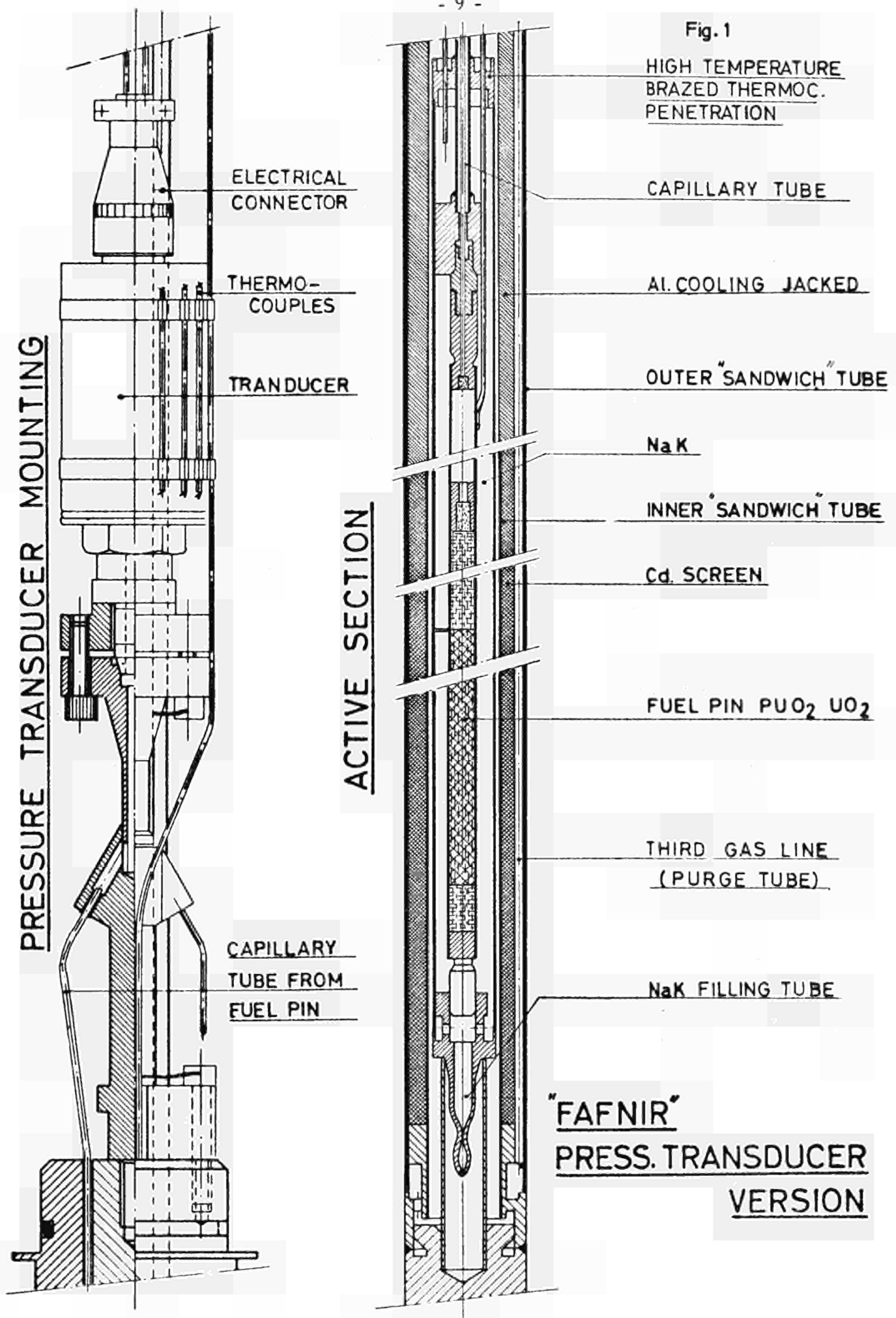


Fig. 1

HIGH TEMPERATURE
BRAZED THERMOC.
PENETRATION

CAPILLARY TUBE

Al. COOLING JACKED

OUTER "SANDWICH" TUBE

NaK

INNER "SANDWICH" TUBE

Cd. SCREEN

FUEL PIN PUO₂ UO₂

THIRD GAS LINE
(PURGE TUBE)

NaK FILLING TUBE

"FAFNIR"
PRESS. TRANSDUCER
VERSION

PRESSURE TRANSDUCER MOUNTING

ACTIVE SECTION

ELECTRICAL
CONNECTOR

THERMO-
COUPLES

TRANSDUCER

CAPILLARY
TUBE FROM
FUEL PIN

Fuel pins of the following specifications can be incorporated :

- fuel diameter	mm	5,1
- cladding diameters	mm	5,24/6,0
- fuel nature	-	UO ₂ -PuO ₂
- Pu contents	%	20
- U 235 enrichment	%	90 to 95
- fissile length	mm	290 to 510
- total fuel pin length	mm	500 to 1000.

The fissile column is usually located in the lower part of the pin, and separated from the fission gas plenum by a U_{nat}O₂ axial blanket (100 to 200 mm long).

Thermocouples are AISI 304 or 316 clad chromel-alumel couples with 1,0 mm O.D. About 50% of all couples used are swaged down to 0,5 mm over 300 to 500 mm from the hot junction (see paragraph 1.3. of this report).

The outer rig tube is made of a "sandwich" structure of two concentric stainless steel tubes with an intermediate Cd-4% Ag screen which is manufactured by coextrusion. The assembly is finished by grinding of the outer clad tube O.D. and honing of the inner clad tube I.D.

The gas filled gap between specimen carrier and inner Cd screen clad tube is used, within certain limits, for the adjustment of the thermal characteristics of the rig (see paragraph 1.5. below).

The active rig portion is connected to the rig head by a stainless steel suspension tube. In the case of the pressure transducer version, the suspension tube comprises a special chamber for the transducer (see figure 1).

The rig head follows standard BR2 design practice, it contains the connections for thermocouples (+ pressure transducer) and gas lines.

Each rig features two gas pressurizing systems :

- rig(thimble), with access to the gas gap,
- rig head.

These systems are controlled by means of gas supply consoles of which two types are used :

- the two-rig console with two gas lines per rig,
- the eight-rig console with three gas lines per rig.

Figure 2 shows the flow diagram of a two-rig console. The symbols used are :

V	manual shut-off valve	
MV	solenoid valve	
SV	relief valve	
PI	pressure gauge	} with indication of maximum working pressure.
PA	pressure switch	

The gas filling of the rig (thimble) can be swept into a glove box where gas samples are taken for supervision on fission products.

Initial and periodic cleaning, as well as overall routine leak testing, are carried out by means of a built-in vacuum pump.

The electrical control console which accompanies the equipment comprises single and multi-point recorders for thermocouples (+ pressure transducer), and alarm circuits for low and high pressure, and low and high temperature warnings.

1.3. Thermocouples.

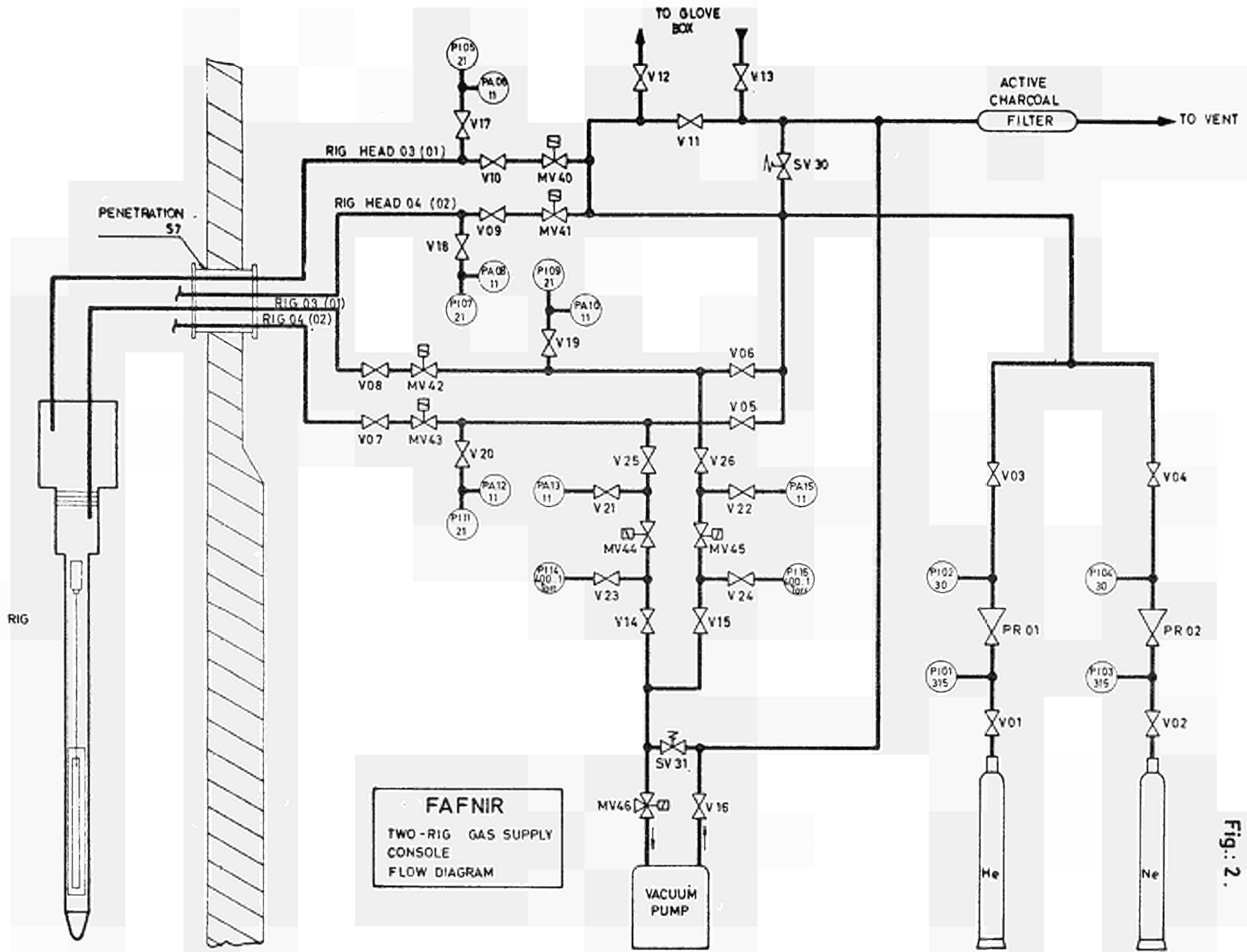
As reported in Ref. 8, most of the thermocouples used in the early rigs failed (65% within 40 days) by open circuit or earth contact. All of them had 0,5 mm O.D. "hot" ends, AISI 304 sheaths and MgO insulation. They had been tested by the standard procedure, i.e. :

- 2 X-ray photographs of the hot junction,
 - visual examination of the sheath under a microscope,
 - loop and insulation resistance measurement
- a. as supplied,
 - b. after immersion of the "hot" end into boiling demineralized water containing a commercial detergent.

About 30% of the thermocouples from the batch concerned had been eliminated as a result of the tests.

Post-irradiation micrography of sheaths from the first rigs did not reveal evidence of an overall corrosive attack by the NaK. The metallographic structure was essentially unchanged as compared to sections taken on unirradiated thermocouples of the same batch. This structure, however, presents gross grains, and carbide precipitations along the grain boundaries.

A further investigation is carried through in a long-term out-of-pile test.



FAFNIR
 TWO-RIG GAS SUPPLY
 CONSOLE
 FLOW DIAGRAM

Fig. 2.

The test capsule corresponds to the initial "FAFNIR" specification, with exception of

- a dummy (stainless steel) fuel pin
- a \varnothing 11,6/13,3 mm carrier tube made of the special stainless steel alloy X 8 Cr Ni Mo V Nb 1613 (to German Standard WN 4988)
- a pressure transducer connected to the test capsule internal volume by means of a long capillary tube.

The capsule is placed into a vacuum autoclave with incorporated furnace. Furnace and capsule thermocouples are recorded as well as the capsule pressure and the pressure (vacuum) inside the autoclave, on strip chart recorders. Furnace trips are wired on high temperature, low and high capsule pressure, and autoclave high pressure (unsufficient vacuum).

Figure 4 shows the head of the test autoclave, with the electrical connections towards the control panel.

The test was started in February, 1970, with temperatures between 460 and 500°C on the capsule thermocouples, and pressures between 80 and 100 kg/cm² inside the capsule. The autoclave vacuum is usually kept between 10⁻² and 10⁻³ Torr, and applied to limit both the test capsule oxidation and the required heater power. The first test campaign ended beginning of July, 1970, and was interrupted by two intermediate "cold" inspections of the test capsule. The second campaign, with capsule temperatures between 550 and 590°C, started end of July, 1970. One thermocouple failure was observed during the first campaign.

Although the investigations on thermocouple failure under irradiation in NaK are not closed at present, the purely statistical elaboration of the observations allow the following hypothesis : Out of each coherent batch of thermocouples, three groups can be recognized :

1. 10 to 15% with faults which have not been detected during pre-assembly testing, or induced during assembly. These will fail during the first irradiation cycle,
2. 10 to 15% of the "tough" type which will stand through 200 and more days of irradiation above 650°C,
3. the major part, or roughly 3/4 of a given bath will follow a more or less "exponential" curve of temperature vs. life expectancy which tends against very long times (i.e. above 250 days net irradiation time) near the 500°C line.

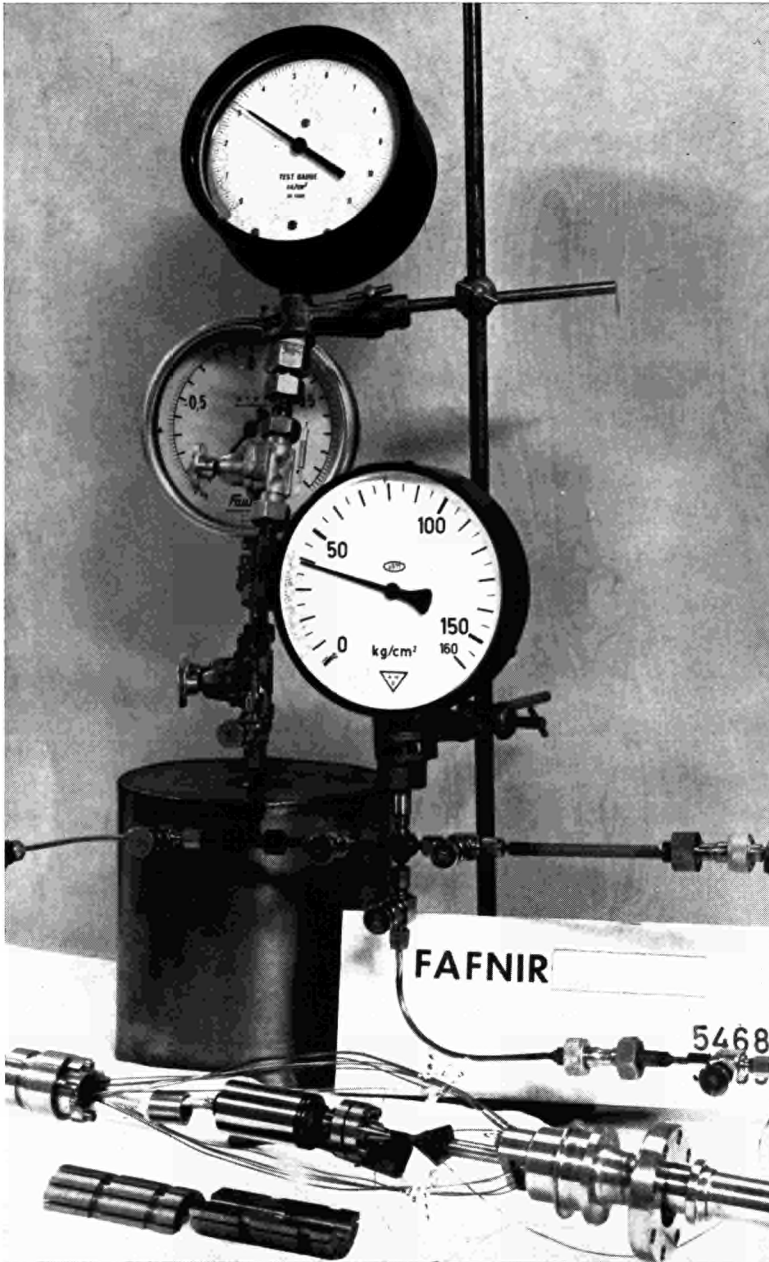
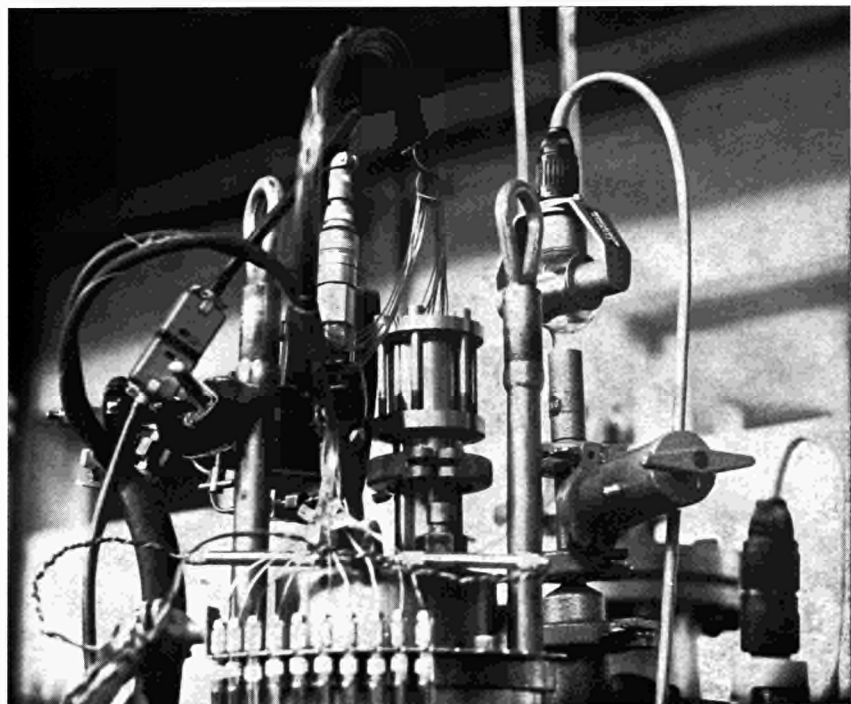


Fig. 3 :
FAFNIR Pressure Transducer
Version
Test set-up for the
transducer gas system

Fig. 4 :
FAFNIR
Long-term out-of-pile test.
Head of the test autoclave



The batch parameters are :

- Material, dimensions and metallographic structure of the sheath,
- Material and density (Ref. 13) of the insulation,
- Dimensions and positioning of the thermoelectric wires and quality of the hot junction.

As expected, thermocouples with a continuous 1,0 mm O.D. sheath perform much better : On "FAFNIR" nr. 07 and 08, only 2 out of 16 couples have failed after over 160 days net irradiation time (situation in August, 1970).

Purchase requirements on thermocouples for liquid metal rigs now include :

- AISI 316 (321, 347) stainless steel sheaths,
- sheath helium leak tests.

On FAFNIR nr. 05 and 06 which are fitted with a mixed set of 0,5 and 1,0 mm thermocouples, no 0,5 mm couple failures have been reported after 66 and 78 days of operation, respectively (August, 1970).

The thermocouples eight of which have 0,5 mm O.D. in the "hot" section comply with the above-mentioned revised specification.

1.4. Special Aspects of the Pressure Transducer Version.

The utilization of zero-balance membrane or bellow type transducers for in-pile fission gas pressure measurement has been reported (Ref. 13, 14, 24).

For the "FAFNIR" experiments, however, a strain-gauge transducer was selected. It compares as follows with the zero-balance type :

Advantages :

- No additional gas line and out-pile balance pressure system required,
- High resolution and capability of picking up fast transients,
- Convenient output signal.

Disadvantage :

- Unknown performance in long-term high gamma exposure service.

A mineral-insulated, radiation-resistant transducer has been chosen, and incorporated into the rig suspension tube about 1,5 m below the rig head. Shield plugs are placed both below and above the transducer. This solution keeps it sufficiently outside the reactor core radiation field, and not too near to the rig head which has to remain accessible for reactor shut-down period manipulation.

Calculations were carried out both for normal operation and accident condition dose rates created by fission gas activities in the rig. The results are reproduced in table 2 below. The active charcoal filters have been incorporated into the rig gas lines for halogene retention and decay of the short-lived fission products.

T A B L E 2.

Maximum Dose Rates at Different Points and Moments.

Point - Moment Indication.	Dose Rate.
1. <u>Normal Operation</u> :	
- pressure transducer : during reactor operation	17.500 R/h
- above reactor cover : during reactor operation	0,5 R/h **)
8 hours after shut-down	0,2 R/h
- on the "chariot vertical"	0,3 R/h
2. <u>FP Leak into thimble</u> :	
- stuffing box : during operation	2×10^4 R/h
- above reactor cover : during operation	90 R/h *
8 hours after shut-down	40 R/h *
- gas line : during operation (at 30 cm from pool wall penetration)	10 R/h
3. <u>FP Leak into thimble and Rig Head</u> :	
- rig head : during operation	1.850 R/h
8 hours after shut-down (supposing that no activity has been swept out)	880 R/h

*) supposing that the active charcoal filter fills up with F.P.

***) dose rate only from rig F.P.

Measurements are being carried out during each reactor shut-down period of the gamma dose rates at contact of the pressure transducer casing of the first two transducer rigs ("FAFNIR" nr 05 and 06). At present (situation in August, 1970) they have been oscillating between 2 and 10 R/h, measured below the transducer level. Hence, the normal operation dose rates have been largely overestimated, probably by assuming too short fission gas diffusion times from the fuel into the transducer in order to be "on the safe side".

The standard "FAFNIR" quality assurance programme has been completed by a set of particular operations for the testing of the fuel pin - capillary tube - pressure transducer system :

- A pressure test to 80 kg/cm² helium, using the auxiliary pressure tube, An evacuated container is used to collect the gas after the test in order to avoid any contamination by Pu dust. Figure 3 shows part of the test set-up with the mounted transducer and its split Pb shield plug.
- The system is closed with 4 kg/cm² confined helium pressure and the output signal from the transducer is measured. Thus, the leak tightness of the system can be followed up until the irradiation starts.
- Correct connection, both pneumatic and electrical, of the transducer is checked by warming up of the lower (active) rig portion.

Future pressure transducer rigs are fitted with a third gas line (see figure 1) for purging of the rig thimble in the event of a fission product leak from the transducer system.

1.5. Thermal Characteristics.

A computer programme has been written (Ref. 11), and calculations carried out (Ref. 12) on the correlation between fuel pin power rating and cladding temperatures (thermocouple readings) under irradiation. Figure 5 represents typical results, for different "effective" gas gaps and for He and Ne filling in the thimble. Thermal expansion of the rig components, variable thermal conductivities, radiative heat transfer and NaK convection are taken into account.

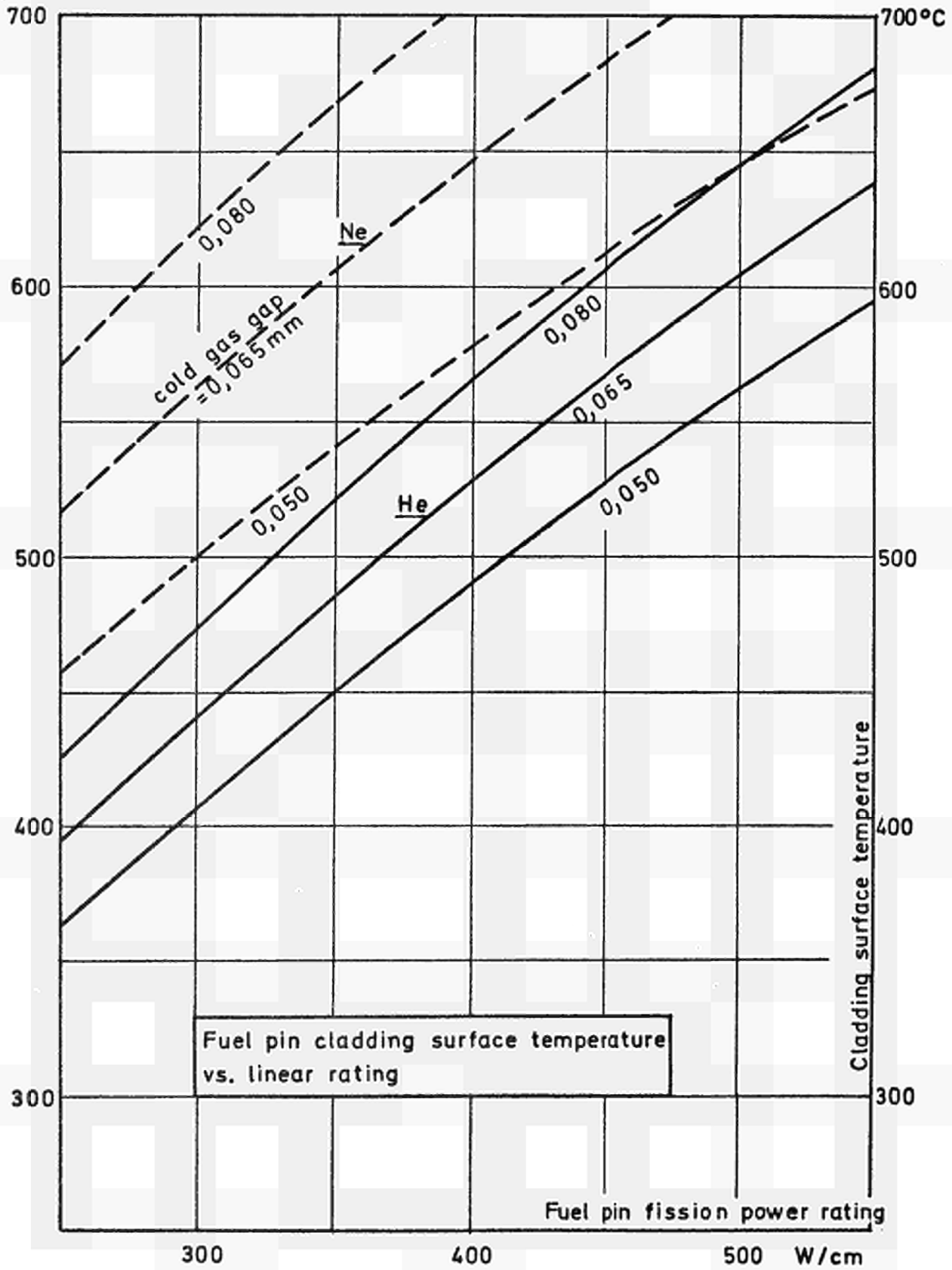
The diagram permits an approximate thermal calibration of each rig by replacing the initial thimble helium filling with neon during irradiation at deliberately low power (300 W/cm, e.g.), by comparing the predicted temperature increase with the measured one.
Example :

A maximum "helium" thermocouple reading of 430°C (corresponding to about 440°C cladding surface temperature) corresponds to

- 338 W/cm with an effective cold gas gap of 0,050 mm and would lead to about 545°C "neon" temperature,
 - 300 W/cm - 575°C
 - 264 W/cm - 595°C,
- for 0,065 and 0,080 mm gas gap , respectively.

Fig. 5

Epicadmium Oxide Fuel Pin Irradiation "FAFNIR"



The real figure can then be interpolated after reading the thermocouples at Ne filling. Assuming that the heat transfer conditions do not change by mechanisms other than those included into the code (thermal expansion, variable conductivities,...), the fuel pin power rating can be determined at any level by thermocouple readings.

Typical readings during one reactor cycle, and deduced cladding surface temperatures are plotted on diagram figure 6.

1.6. Power Rating Calculations.

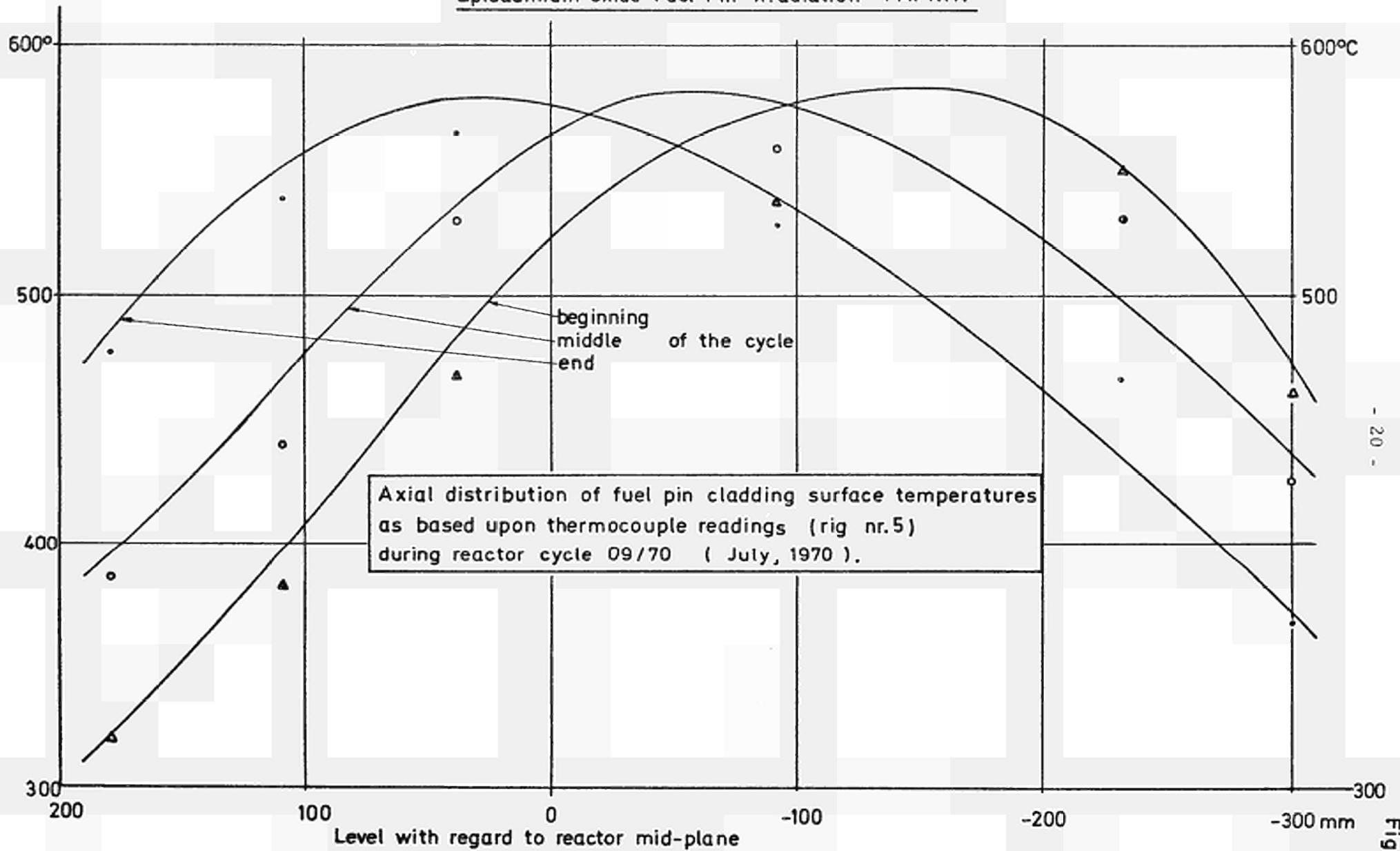
Spectral and geometrical distribution of neutron flux and fission power density inside the fuel pin have been calculated (Ref. 7). They result in a correlation between the unperturbed thermal neutron flux in a BR2 irradiation position (i.e. without rig), and the fission density by "epicadmium" neutrons created in the rig after it has been loaded into the position considered. Measurements in the zero power facility BRO2 are being carried out in order to verify the predicted figures. In general, the temperatures read under irradiation are higher than the figures calculated through the flux-power rating, and power rating-cladding (thermocouple) temperature correlations, by 0 to 60°C approximately. The reasons for this systematic deviation are being investigated.

1.7. Cd Screen Life.

Since the neutron spectrum inside the rig starts shifting towards lower energies with decreasing effective thickness (Ref. 9 and 10), a minimum admissible remaining layer of 0,5 mm "unburnt" cadmium has been adopted. The calculated screen life is then about 270 days for 510 W/cm rating.

Cadmium turnings from the first FAFNIR rig are being examined at present in order to determine the remaining effective layer by gamma scanning in different depths of the screen. This procedure is largely impeded by Ag 110 activity originating from epithermal resonances of the 4% silver compound in the original Cd screen.

Epicadmium Oxide Fuel Pin Irradiation "FAFNIR"



Axial distribution of fuel pin cladding surface temperatures as based upon thermocouple readings (rig nr.5) during reactor cycle 09/70 (July, 1970).

2. Design of a High-Power Carbide Fuel Rig.

2.1. Scope.

As potential advanced fuel for fast breeder reactors (Ref. 16), uranium carbide and mixed uranium-plutonium carbide (nitride) fuel pins are to be irradiated in an episcadmium spectrum up to a high burn-up of the fissile material loading.

The device developed (Fuel Assembly Specification Test Of Long Duration = FASOLD) is a single-walled niobium capsule with removable Cd screen (see fig. 7), a prototype of which is now under construction for irradiation towards November, 1970.

2.2. Design Stages.

Several tentative solutions have been examined from the point of view of design, technological aspects, reactor physics and thermal characteristics (see fig. 8).

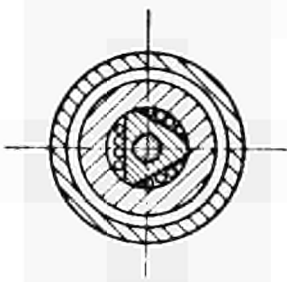
The Mk.I design proposed the utilization of a cadmium containing liquid metal bath for both heat transfer and thermal neutron shielding. The alloy (54% Bi, 26% Sn, 20% Cd) has a melting point of 102°C (Ref. 25) and requires the use of auxiliary electrical heaters for the melting of the bath prior to each reactor start. Heater windings and thermocouples were to be carried by an intermediate \varnothing 15,0/16,0 mm stainless steel tube. Theoretical calculations (Ref. 27) showed that the irradiation is, in principle, feasible in BR2, but information on the thermal conductivity of the proposed alloy and on its compatibility with structural materials was missing.

The corrosive attack of Bi-Sn-Cd on stainless steel has been investigated by a series of out-of-pile tests. An all-stainless-steel filling apparatus was built, and six test capsules were filled under helium cover gas. The alloy was found to be easily handled. The test capsules were made up of an external \varnothing 25/28 mm stainless steel tube of 140 mm length with welded end covers. They contained a dummy "fuel pin" of \varnothing 6,7/7,7 mm stainless steel tube with electron-beam welded end plugs and two \varnothing 1,0 mm stainless steel clad chromel-alumel thermocouples (see fig. 12). The test was carried out in a helium filled autoclave, with strip chart recording of furnace and capsule thermocouples. After about 57 days of operation with temperatures between 560 and 580°C, all thermocouples of the six capsules were found to have zero insulation resistance. One capsule was cut open (fig. 12), and metallographic examination carried out on capsule wall, "fuel pin" and thermocouple sheaths.

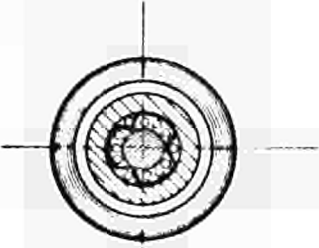
Fig. 7

Mk. III b Design

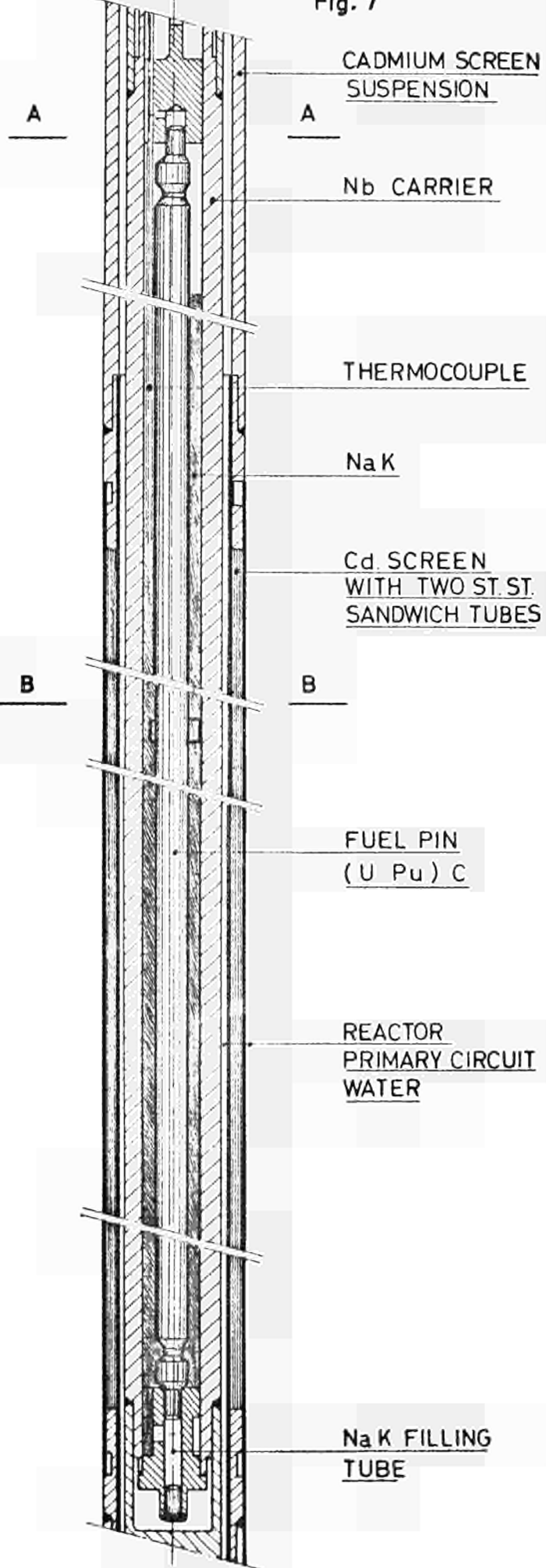
SECTION A-A



SECTION B-B



ACTIVE SECTION



CADMIUM SCREEN
SUSPENSION

Nb CARRIER

THERMOCOUPLE

Na K

Cd SCREEN
WITH TWO ST. ST.
SANDWICH TUBES

FUEL PIN
(U Pu) C

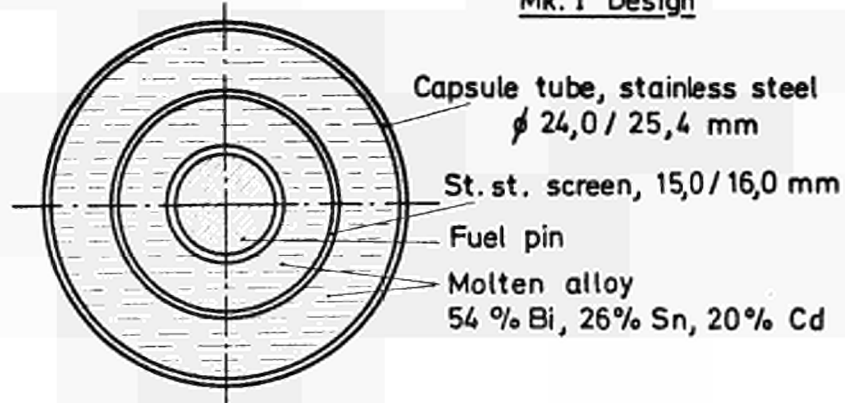
REACTOR
PRIMARY CIRCUIT
WATER

Na K FILLING
TUBE

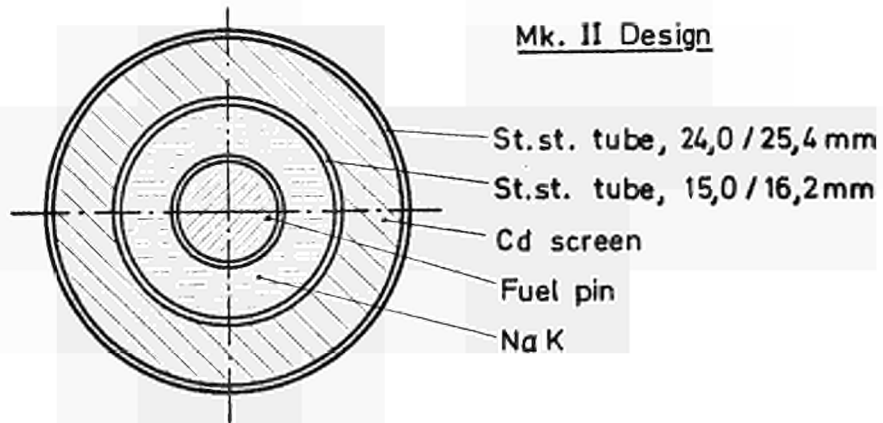
"FASOLD"
EPICADMIUM
CARBIDE RIG

"FASOLD"

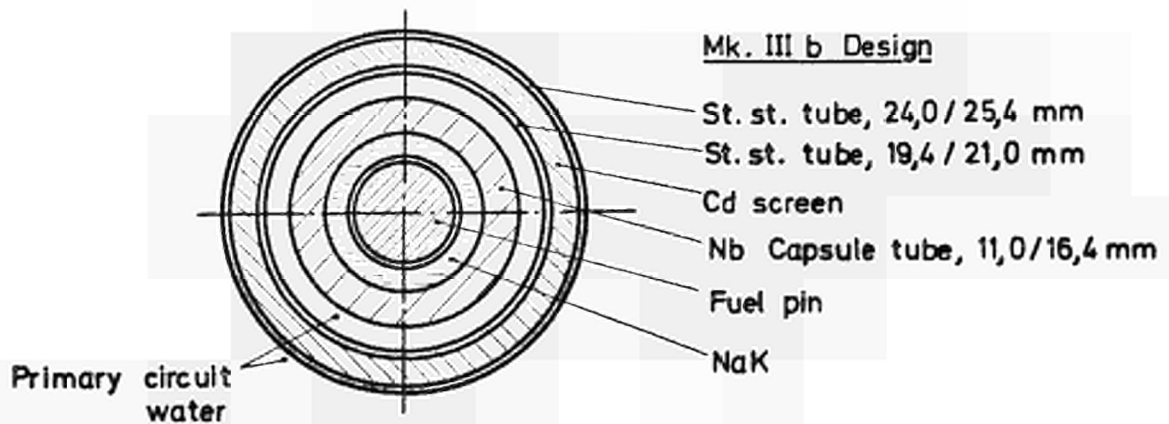
Mk. I Design



Mk. II Design



Mk. III b Design



Design and Development Stages

As a result, most severe attack was stated on all components. Figure 13 shows an enlarged metallographic section of test "fuel pin" nr. P5, with a reaction zone depth of 40% of the wall thickness. It was then decided to discontinue the corrosion test, and to abandon the Mk.I design.

The Mk.II layout is a direct extrapolation of the FAFNIR concept, obtained by the elimination of the specimen carrier tube and the rig gas gap. Again, feasibility in BR2 could be proved by neutron physics calculations. Thermal behaviour analysis showed, however, that cadmium melting would be reached at about 1400 W/cm fission rating, inspite of reducing the screen thickness to 3,9 mm. Since no cadmium melting would be tolerated for safety reasons, a design limit to 1200 W/cm nominal rating was given. Moreover, the reduced cadmium thickness represented a severe rig life-time, i.e. fuel burn-up limit. For these two reasons, the Mk.II design was not followed up, although it represents a simple and proven solution.

The limits on both Cd temperature and service life are eliminated by the removable screen concept (Mk. III design) : The heat flow from the fuel pin does no longer cross the cadmium, but is carried away by a 1,5 mm thick stream of reactor primary water separating the rig from the screen assembly. The screen assembly can be replaced in regular intervals (after about 70 full power days) by a "fresh" one.

The Mk.III a design featured two concentric stainless steel tubes with two intermediate layers of NaK (not shown on fig.8). It was discarded because of too high temperatures at the fuel pin cladding for the power rating range above 1200 W/cm, and replaced by the single-walled Nb design.

2.3. Mk.III b Design.

The rig is designed for the following irradiation parameters.

a. fuel pin		
Fuel nature	-	Uranium or uranium-plutonium carbide, nitride or carbonitride
Pu contents (for mixed fuel)	%	15 ... 25
U 235 enrichment	%	90 ... 95
Fuel diameter	mm	7,0
cladding diameter	mm	7,1 / 8,0
Fissile length	mm	300 ... 510
Total pin length	mm	600 ... 1100

b. Irradiation (hot spot figures).

Fission rating	W/cm	1200 (1500)
Cladding surface temperature	°C	520 (645)

Thermal calculations have been carried out for the steady-state heat transfer, and the results are shown on figures 9 and 10. Reactor gamma heating (on top of the fission heat), thermal expansion, variable conductivity, radiative heat transfer and convection are taken into account. Pollution of the fuel pin gas gap by fission gases has not been considered, but the thermal conductivity in the fuel has been assumed to be as high as 0,23 W/cm°C, after a couple of hours of irradiation (Ref. 26).

2.4. Loss-of-Coolant Analysis.

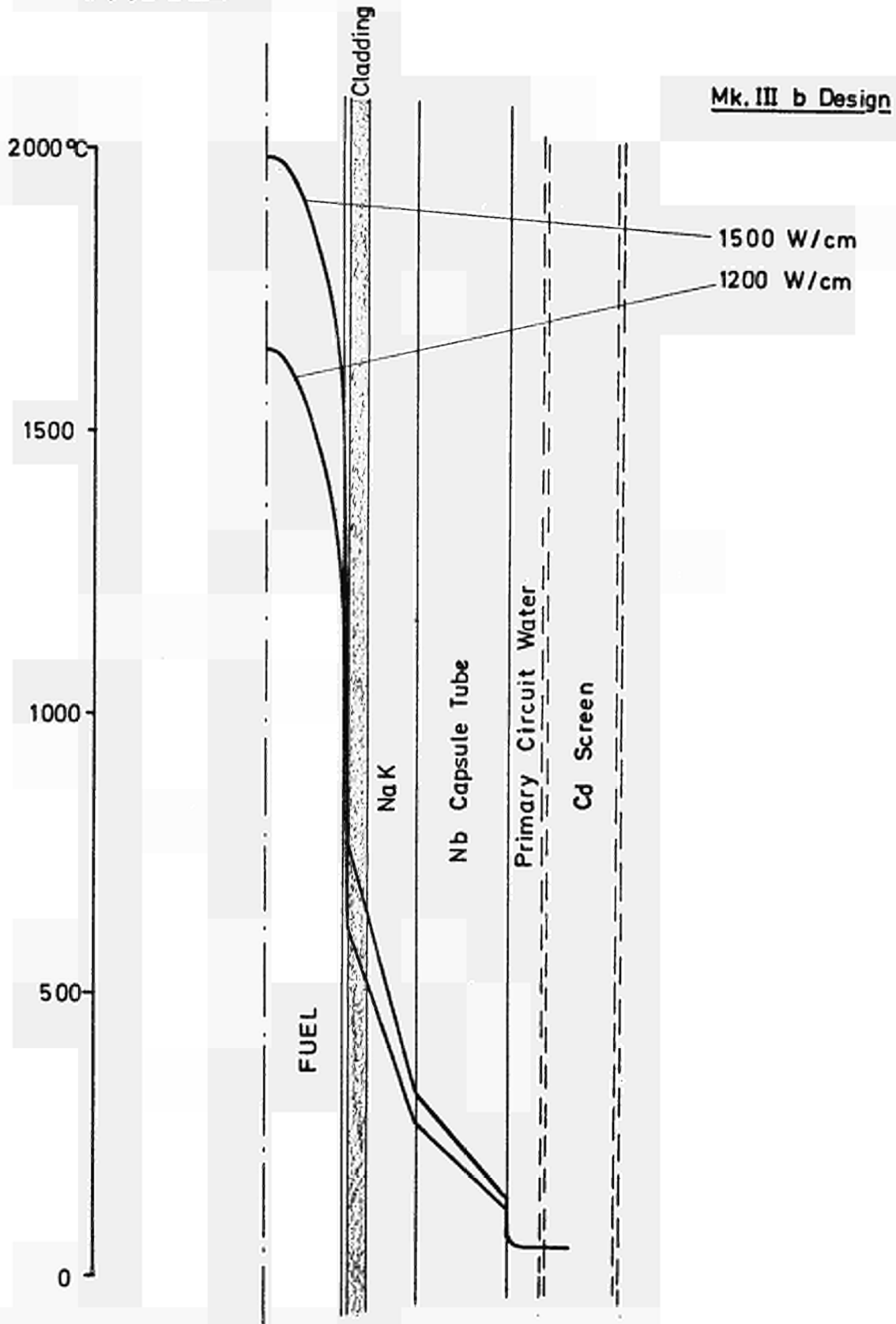
Safety considerations related to carbide fuel irradiations in single-walled alkali-metal filled rigs had been carried out for earlier BR2 experiments, and for similar projects in other reactors (Ref. 17).

A particular analysis was considered necessary for the event of a major failure of the reactor primary cooling system. The accident which may be caused by a failure of the primary pumps and/or a large burst in the pipework brings about a reactor trip through low flow, low pressure and/or low differential pressure signals. The downward water flow in the reactor pressure vessel will slow down and eventually turn over to upward natural convection. Two aspects are to be considered :

1. the remaining heat flow from an irradiation device towards the common cooling channel, in case of a rig loaded inside a fuel element without support tube during the critical flow inversion period, must not exceed a predetermined value in order to avoid critical heat flux problems on the adjacent fuel plate. (This is a standard practice BR2 requirement).
2. Overheating of the rig during and after flow inversion has to be avoided.

In the case considered (separate Cd screen), it can be seen that condition 1. is easily fulfilled since only a small fraction of the heat flow appears at the screen assembly O.D.

"FASOLD"

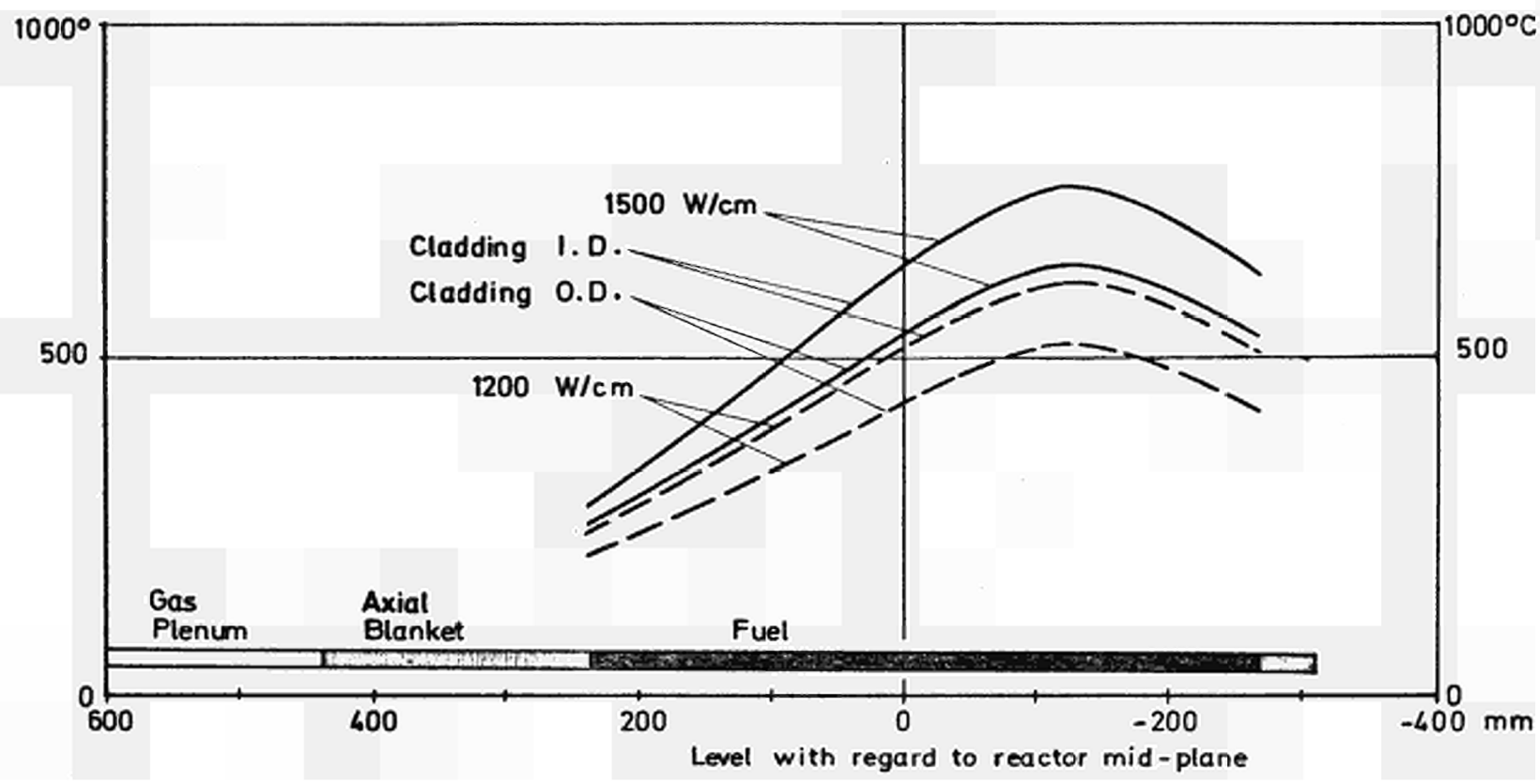


Mk. III b Design

Estimated initial temperature distribution in the hot plane

"FASOLD"

Mk. III b Design



Estimated initial axial distribution of fuel pin cladding temperatures in the fissile region

For the rig itself, however, calculations (Ref. 18) yielded the following results :

- During the flow inversion period, local water boiling will probably occur, at 8 kg/cm² primary pressure : above 1200 W/cm fission rating, at 12 kg/cm² primary pressure : above 1500 W/cm fission rating.
It will certainly occur for all power figures considered, if the water pressure drops to 1 kg/cm² (case of a tube burst in the primary circuit of the reactor).
- If boiling has occurred during flow inversion, critical heat flux (burn-out) will not be reached at 1200 W/cm maximum rating, but will most probably be reached at 1500 W/cm, resulting in niobium tube temperatures as high as 1550 to 1750°C.

Hence, the Mk.III b design can be considered as safe under the loss-of-coolant point of view only up to a maximum rating of 1200 W/cm (fission).

A summary of the design stages discussed is given in table 3.

2.4. Mk.III c Design.

A further and final approach was made in order to overcome the safety limit of 1200 W/cm fission rating which appeared during the loss-of-coolant accident analysis. The main objective was to improve the rig O.D. cooling both for the steady-state and the emergency heat transfer conditions. It has been reached by

- increasing the upper and lower Cd screen extension pieces which contributed about 40% of the total pressure drop, and shaping the Nb capsule lower extension piece,
- profiling the Nb capsule O.D. between the + 670 and - 340 mm levels (with regard to reactor core mid-plane).

Figure 11 represents a section through the Mk.III c design capsule.

T A B L E 3.

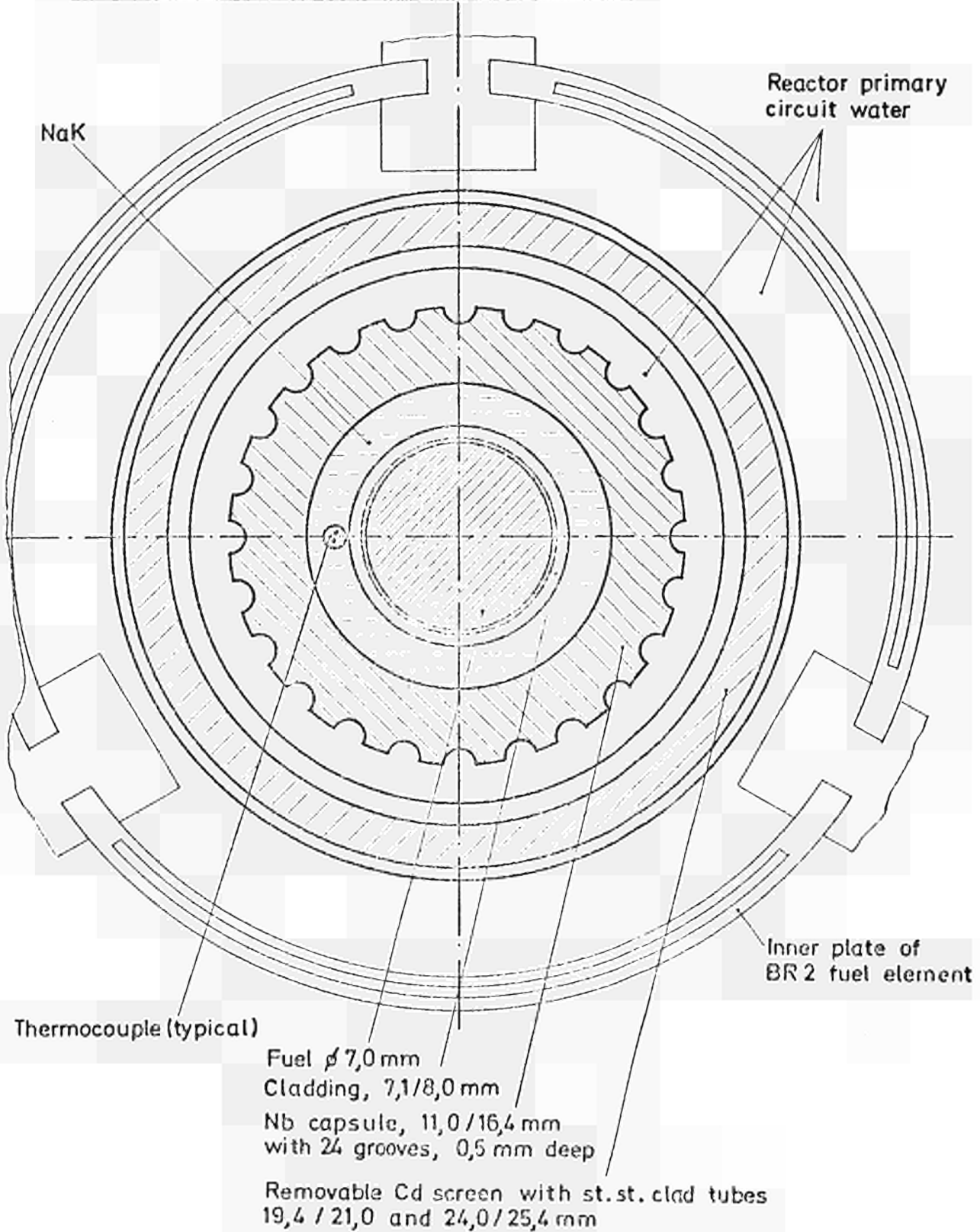
Design Stage	Characteristics	Required unperturbed thermal neutron flux for 1200 W/cm fission rating (10^{14} n/cm ² s) *)	Fuel pin cladding O.D. temperature for 1200 W/cm fission rating (°C)	Remarks.
Mk.I	Molten Cd screen	3,1	about 700	Discarded for severe corrosion problem
Mk.II	Integrated Cd screen	3,7	650	Limits on fission rating (Cd melting) and fuel pin burn-up (Cd life). Too high cladding temperatures.
Mk.III a	Removable Cd screen St. st. capsule	3,0	660	Too high cladding temperatures.
b	Nb capsule	3,0	520	Safety limit at 1200 W/cm fission rating for loss-of-coolant accident.
c	Profiled Nb capsule	2,9	480	Safe at 1500 W/cm

*) Conventional thermal neutron flux, for 20 w/o Pu and fully enriched U.
Figures taken from (Ref. 27).

Fig. 11

"FASOLD"

Mk.III c Design: The profiled Nb capsule concept



5: 1

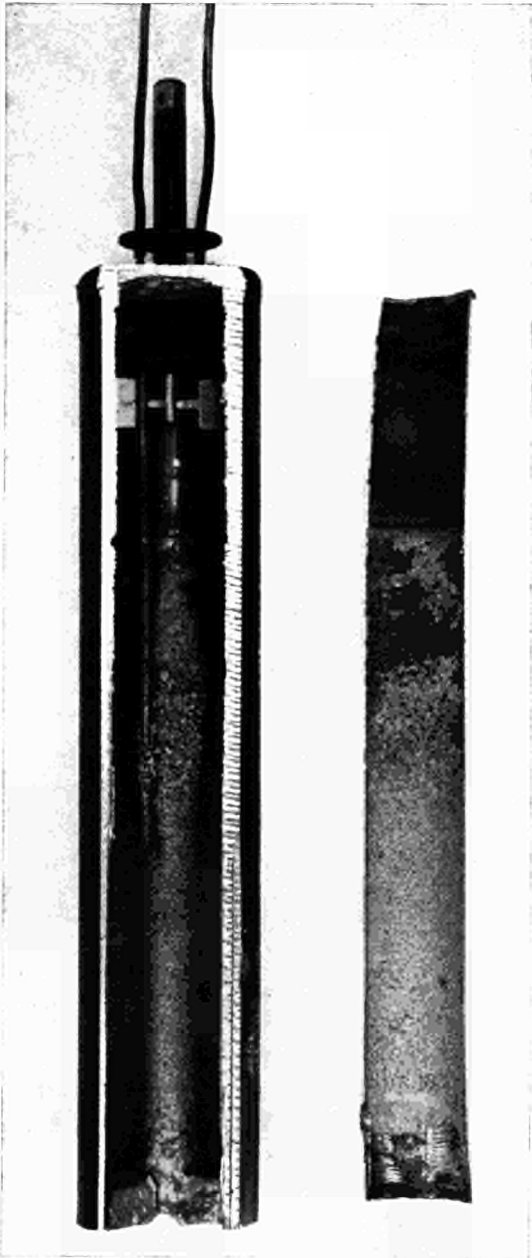
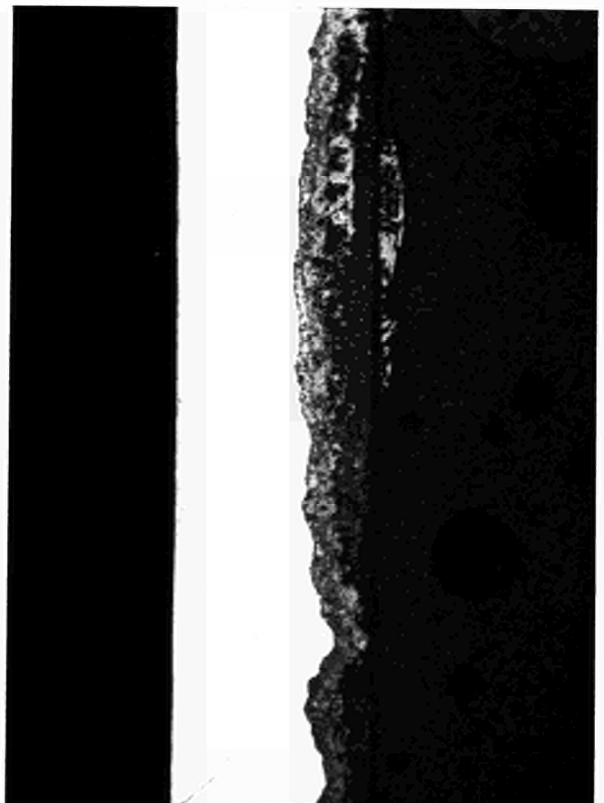


Fig. 12 :

FASOLD Mk. I Design Corrosion Test
Test Capsule
Sectioned after the Test

Fig. 13 :

FASOLD Mk. I Design Corrosion Test
Test « Fuel Pin » No. P 5
Cladding Micrograph after
57 days at 560 to 580°C
50 x



The results of the revised loss-of-coolant accident calculations are as follows :

For 1500 W/cm, local water boiling during the flow inversion period will occur at about 7 Kg/cm². During the subsequent natural convection phase there will be no more boiling even after a pressure drop of the primary circuit to 1 Kg/cm², and the Nb tube temperature remains at about 110°C.

The increased water volume between Cd screen and Nb capsule (+ 11%) results in further shifting of the neutron spectrum inside the rig towards lower energies.

Since the initial Cd thickness is only 1,5 mm the "softening" of the spectrum with cadmium burn-up will be stronger than for the Mk.II design (3,9 mm) or the FAFNIR series (4,5 mm) (Ref. 9, 10 and 27).

2.5. Niobium Technology.

A testing programme is being carried out in order to settle parameters for high temperature brazing, electron beam welding and glove box "argon-arc" welding of the capsule components.

Figure 14 shows the micrograph of a Nb test weld (electron beam).

Extension chambers and supports for the electron beam welding machine have been designed and built in order to cope with the outstanding overall length of the final Nb assembly (2,6 m).

2.6. Conclusion.

The design study resulted in the choice of the niobium capsule concept with removable cadmium screen for 1200 W/cm (Mk.III b) and 1500 W/cm (Mk.III c) maximum fission power rating. The high initial fuel inventory and the possibility of periodic Cd screen renewal render high burn-up of the test fuel possible (100.000 MWd/t and beyond). The fission power density depression inside the test fuel pin is stronger than for integrated screen concepts, due to reduced screen thickness and the presence of water between screen and capsule, but still much more realistic than for comparable thermal irradiations :

Case.	Axial to Surface Power Ratio.
Thermal Irradiation of a 20 w/o Pu, U _{nat} fuel pin	0,2
Mk. II Design	0,85
Mk.III b Design	0,6

Moreover, the high thermal conductivity of carbide fuel results in a more "realistic" temperature distribution inside the test fuel than for oxide fuel pins with comparable power depression.

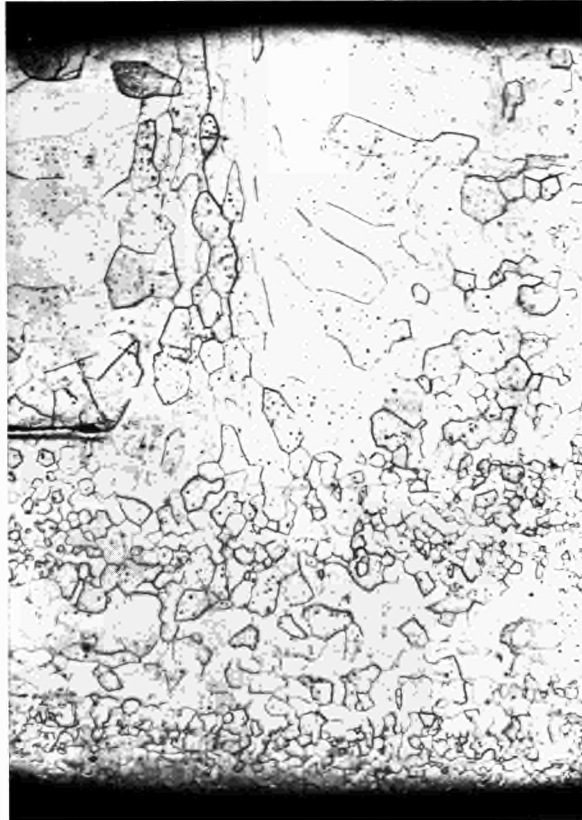


Fig. 14 :
FASOLD
Micrograph of a Niobium Test Weld
50 x

3. 650°C Sodium-Filled Cladding Material Specimens Rig.

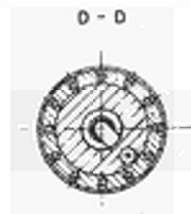
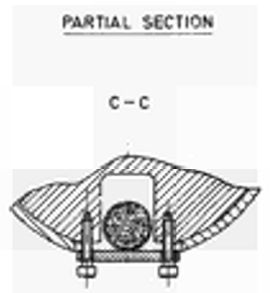
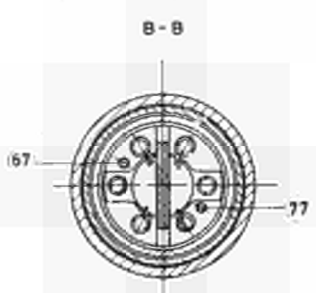
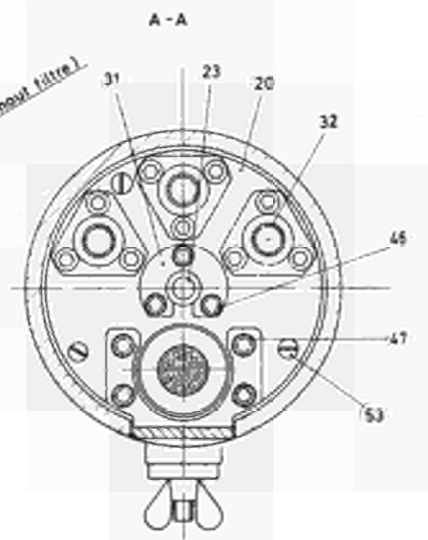
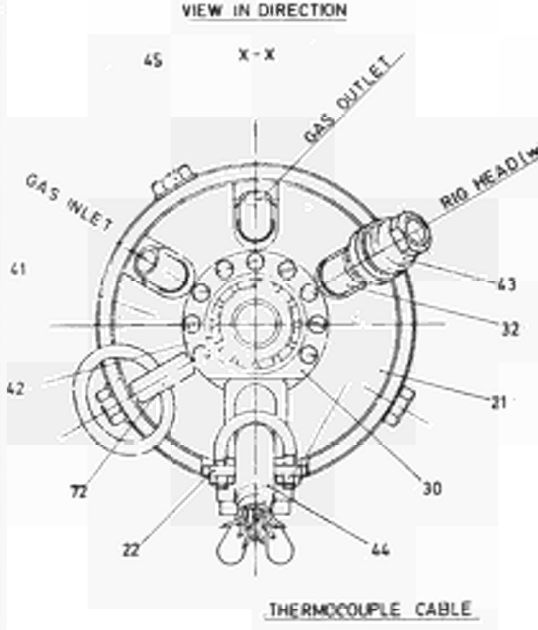
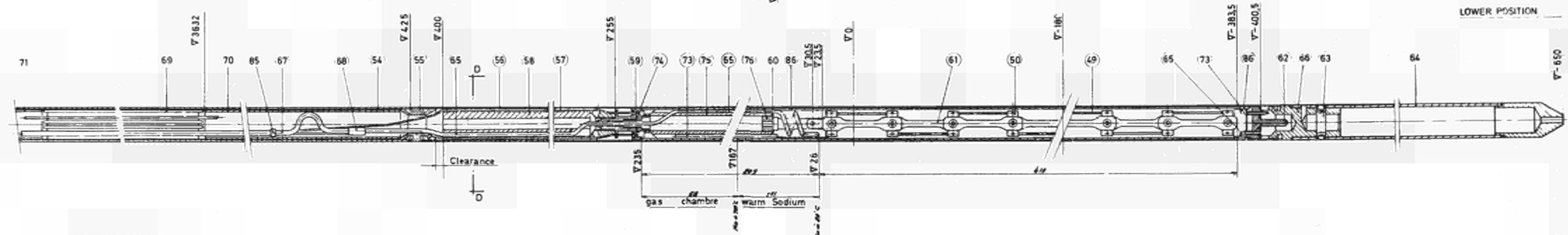
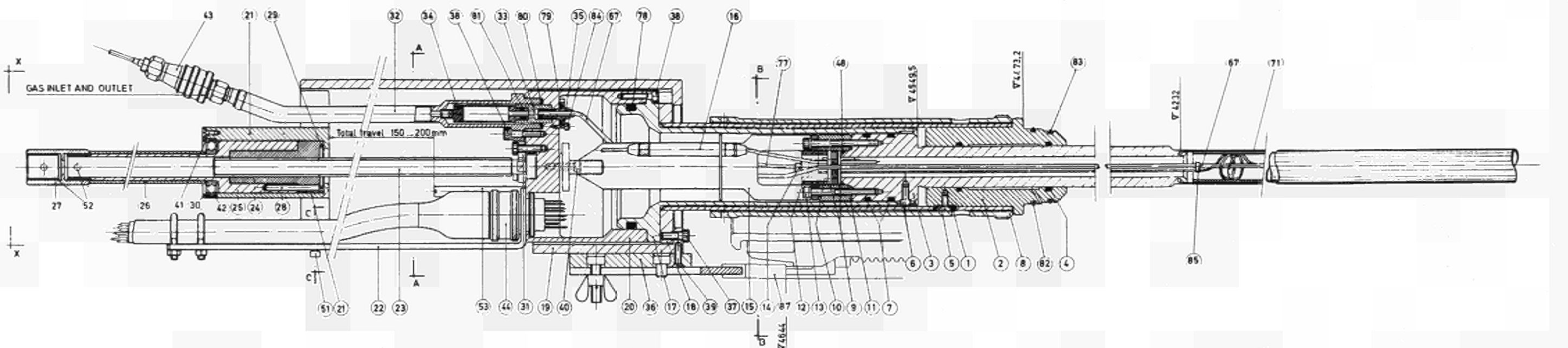
3.1. Scope.

Irradiation experiments on potential fast reactor fuel cladding specimens have been carried out in BR2 since 1964 (Ref. 15, VIII and X.). The fast neutron dose which can be reached is in the order of 10^{22} nvt (above 0,1 MeV) in one year gross irradiation time, i.e. low as compared to the predicted 10^{23} ... 10^{24} nvt which will be integrated by fast reactor fuel claddings. Phenomena like void formation and dislocations cannot be investigated in BR2. It is believed, on the other hand, that the predominant mechanism for stress rupture strength reduction is high temperature embrittlement (Ref. 19), which has been observed from neutron doses as low as 10^{18} nvt.

The device developed features a utilizable specimen space of 21,0 mm diameter and 400 to 600 mm length, filled with sodium and fitted with thermocouples in which flat, tubular or other specimens can be irradiated in BR2 high flux positions at 650°C.

3.2. Description.

The general assembly of a flat specimens rig is shown on figure 15. The specimens are riveted to a column of 9 (or 11) packs containing eight and nine specimens, alternatively. The specimen carrier tube comprises a central cylindrical section, and its O.D. decreases in tapered portions towards both ends. The increasing gas gap compensates to a certain extent the nearly sinusoidal gamma heating distribution in the reactor. The carrier contains 12 thermocouples (chromel-alumel, 1,0 mm O.D. st.st.sheath) of which one is used to measure the sodium temperature above the specimen column whereas the remaining couples are fixed to the specimens by wire bindings (\emptyset 0,02 mm stainless steel). Two capillary tubes penetrate into the specimen carrier : one running through both top and bottom cover is used as a gas lead for He-Ne mixture inlet to the rig, the other penetrating through the bottom cover and ending in the gas chamber above the Na bath serves as an auxiliary lead during the liquid metal filling operation and is seal-welded below the bottom cover.



RIG TO BE USED IN A S V^{235} FUEL ELEMENT

FIG: 15

DATE	BY	CHECKED	APPROVED
IN PILE SECTION ASSEMBLY 650°C STEEL IRRADIATION IN Na.			

The specimen carrier is mounted inside a precision-bore tube (thimble) which extends through a lower appendix ("nose cone") and the upper suspension tube leading towards the rig head. The rig head comprises a standard design connection chamber for gas lead and thermocouple joining and a jack screw gear for axial positioning of the rig under irradiation: a trapezoidal thread spindle is moved by rotation of a bush containing a synthetic material nut. A manually operated tool of about 7 m length transmits the rotation through the reactor pool to the rig in its irradiation position. The thrust created by the pressure inside the reactor vessel is taken up by a stainless steel ball bearing. Sintered stainless steel filters in both gas inlet and outlet lines protect against the migration of activated particles towards the out-of-pile equipment.

Temperature control is achieved either by gas mixture regulation (closed circuit, manual adjustment, or open circuit, automatic adjustment) or by an automatic rarefied gas regulation system (Ref. 22 and 23).

3.3. Development Work.

Temperature distributions have been computed including axial heat losses at both ends of the specimen column. These were found to be rather important on top of the specimens where an "unheated" quantity of sodium would be present upon expansion under irradiation. For this reason, an auxiliary thick-walled stainless steel lining has been added which acts as a gamma heating "furnace". Figure 16 shows the axial distribution of gas gap width and calculated temperatures as well as typical readings of the first rig's thermocouples. The "cold spot" of TE 09 is unexplained, but generally the readings were within $\pm 20^\circ\text{C}$ over one reactor cycle and between the different thermocouples.

Sodium filling of the specimen carrier asked for particular attention since low oxygen contents are requested, mainly for vanadium or vanadium-alloy specimens (Ref. 19 and 20). The filling apparatus now used is represented schematically on fig. 17. The specimen carrier or capsule to be filled is welded to the main filling line on top of the sodium vessel, and its auxiliary gas tube (if any) connected to the valve panel. Previous cleaning of the internal metal surfaces is carried out by degreasing (acetone) and pickling (HCl-HNO_3 - Inhibitor) before assembly, and rinsing with hot demineralized water containing a commercial detergent after assembly.

650 °C STEEL IRRADIATION IN SODIUM

Cold gas gap and axial temperature distribution

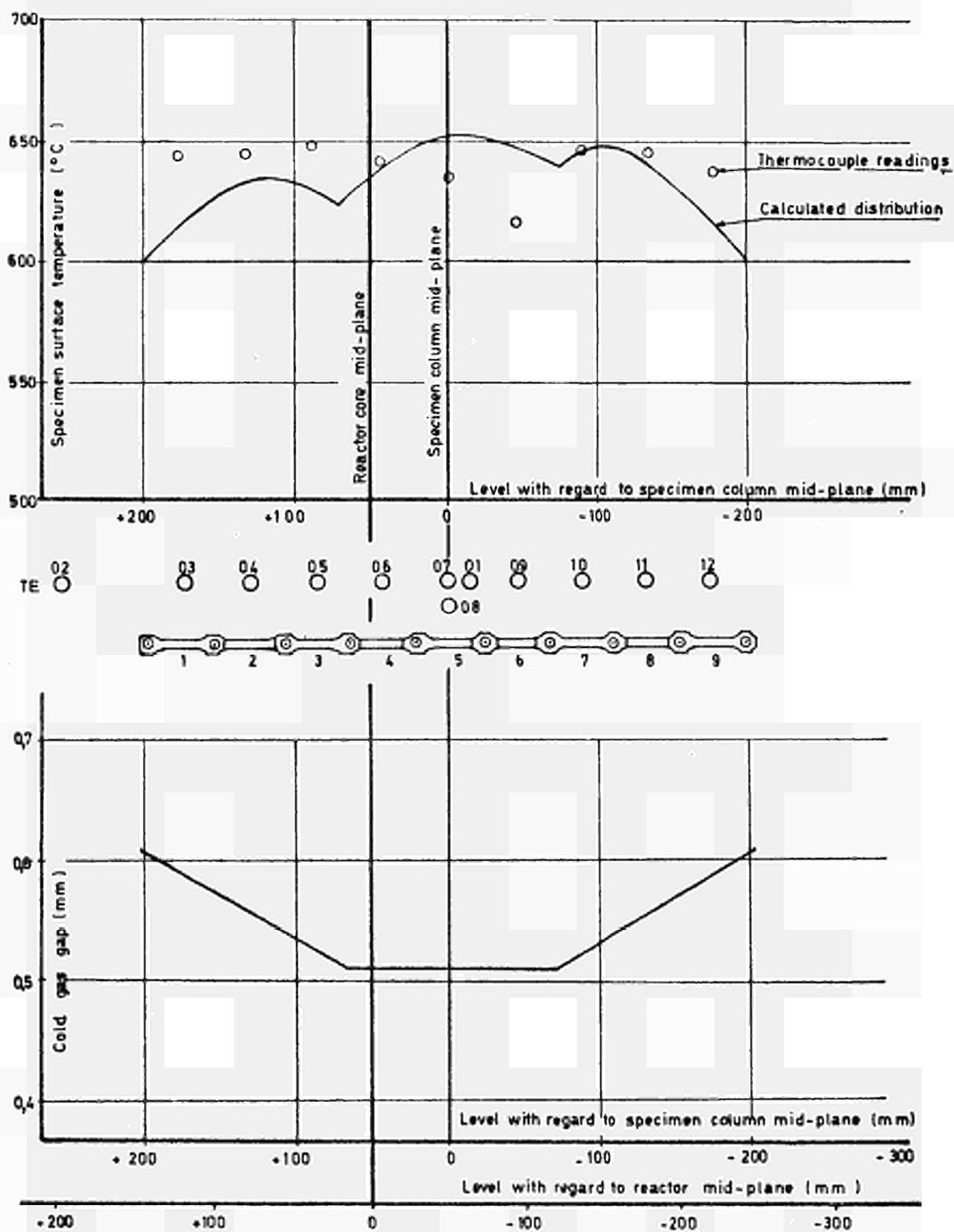
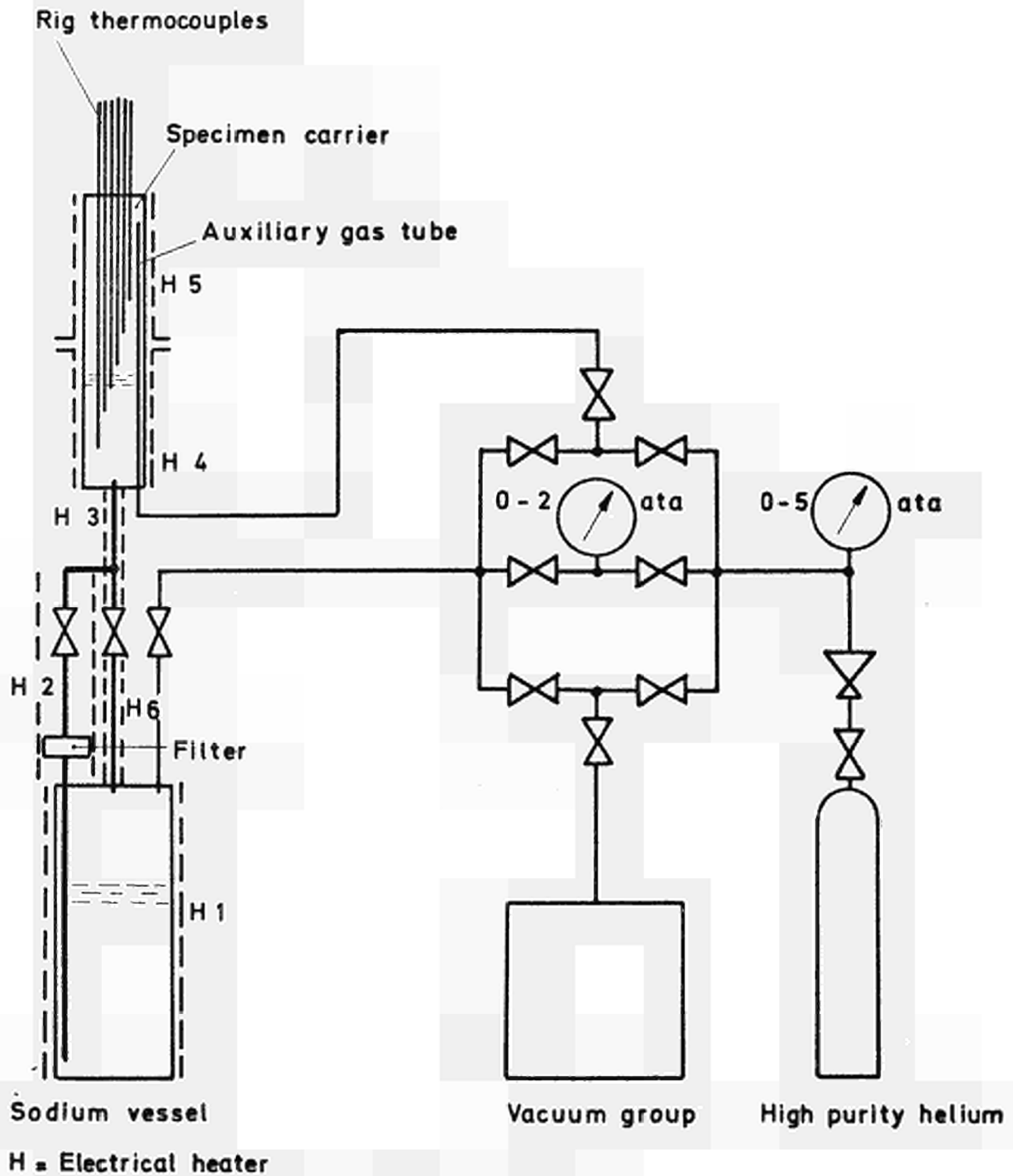


Fig. 17



Sodium Filling Installation

650°C Steel Irradiation in Na

After rinsing with pure demineralized water, the specimen carrier or capsule is vacuum dried. The final cleaning takes place when the carrier or capsule has been connected to the filling apparatus, and uses the principle that the best cleaning agent for volumes to contain sodium, is sodium (Ref. 21). After thorough leak testing and evacuating of the installation, using the different heaters for better surface degassing, pressure is applied onto the sodium in the main vessel. The liquid metal is pushed upwards into the capsule, passing through a sintered filter. The capsule (rig) thermocouples control the rising of the Na level.

When the required level is reached, all valves are closed and the capsule heaters adjusted to reach about 500°C for "wetting" of the metal surfaces and picking up impurities. The hot sodium is then pushed back into the main vessel using the filter by-pass line, by inversion of the pressure gradient.

The described procedure is repeated two to five times, the cleaning being achieved through the cold-trapping effect of sending hot sodium (500°C) into the cool vessel (120°C), and through impurity retention in the filter. After final filling, auxiliary gas tube and sodium filling tube of the specimen carrier (capsule) are crimped and seal welded.

After a couple of filling tests on short capsules (see fig. 19), two fully equipped dummy specimen carriers have been built, and filled with sodium according to the procedure outlined above. The first dummy carrier was used mainly for thermal cycling tests between melting and solidification of the sodium, in order to find out any damage caused to specimen or thermocouple fixtures by the expansion and contraction during the liquid-solid transition (reported e.g. in Ref. 28). No evidence of damage could be found. The second dummy carrier which had been assembled and Na-filled according to procedures identical to those applied to irradiation carriers, was intended to undergo a long-term high temperature test with internal pressure recording. The test had to be cancelled after a few days when sodium was blown out into the test autoclave through a leaking weld in the pressure sensing line, and was not continued.

Difficulties are encountered with the precision machining of the double-tapered specimen carrier tube and of the rig tube (thimble) where tolerances of 0,05 mm (bore) and 0,01 mm (O.D.) are required over 800 mm with 0,70 and 0,85 mm wall thickness. Several subcontractors had to be contacted, and the rejects percentage is still about 50%.

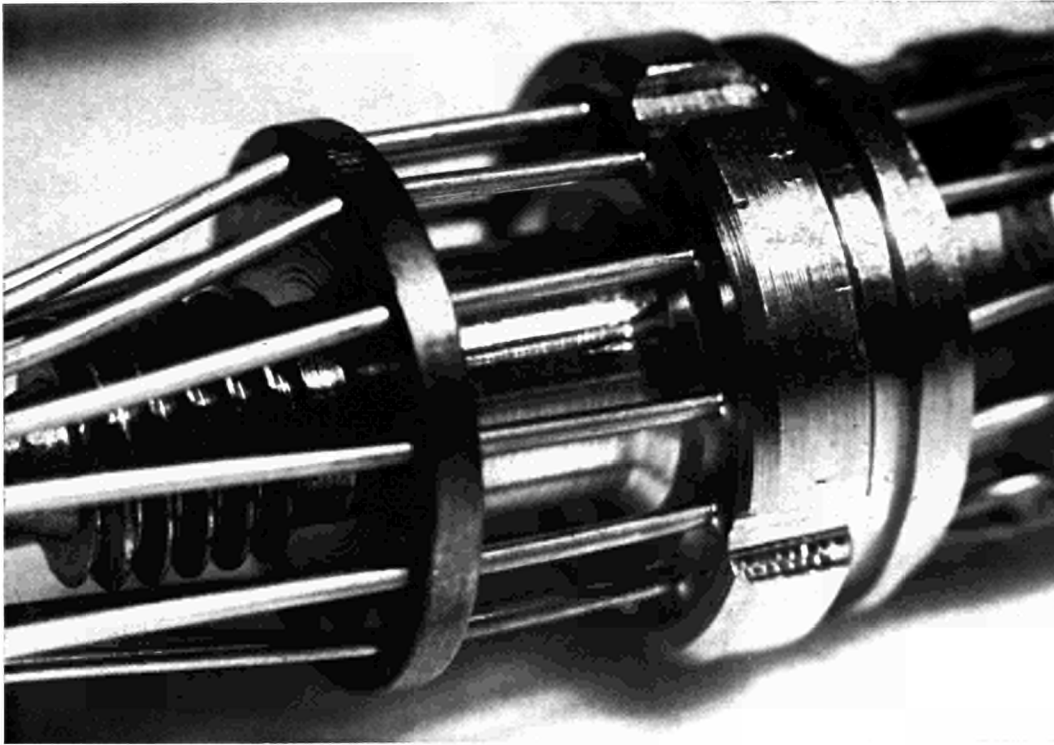


Fig. 18 :
650°C Sodium-Filled Steel Rig
Upper Specimen Carrier End Plug with High-Temperature Brazed Thermocouple Penetration
4 x

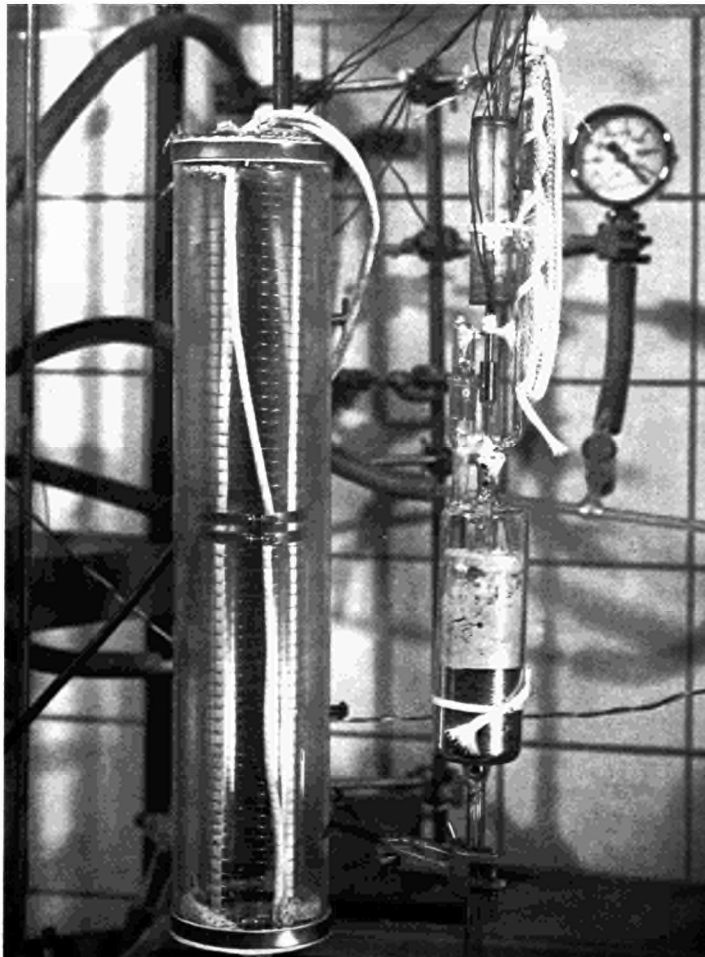


Fig. 19 :
650°C Sodium-Filled Steel Rig
Main Furnace of the Na Filling Apparatus
with Test Capsule in Filling Position

High-temperature brazing of the specimen carrier thermocouples, on the other hand, followed standard practice and did not bring about any particular problem. The alloy used is a Ni-Cr-Si compound, the brazing takes place under vacuum ($< 10^{-4}$ Torr) in an induction furnace at about 1150°C. An enlarged photograph of the upper end plug assembly after brazing is shown on fig. 18. Earlier tests had proven that the alloy is perfectly compatible with alkali metals, and that embrittlement of the thermocouple sheaths can be checked by limiting the brazing time (i.e. the time above 1000°C) to a few seconds.

III. Conclusion.

Capsule-type irradiation devices have been and are being irradiated in BR2, and new designs are developed, in support of the research on fast reactor fuel and fuel elements and as a complement to the sodium loop experiments.

Most of the work described has been performed and/or coordinated by the CEN Technology Department. The author wishes to acknowledge the valuable contributions given by CEN and EURATOM staff in MOL to the work described in this report.

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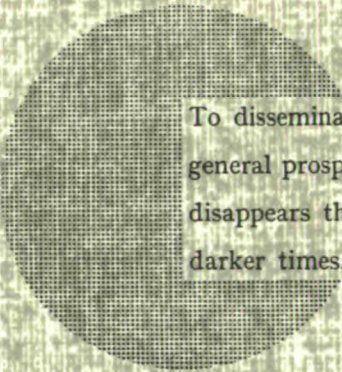
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