2. Symposium on space nuclear power systems
Albuquerque, NM (USA) 14-16 Jan 1985
CEA-CONF--7803

FR8501857

LIQUID METAL VERSUS GAS COOLED REACTOR CONCEPTS FOR A TURBO ELECTRIC POWERED SPACE VEHICLE

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Recent CNES/CEA prospective studies of an orbit transfer vehicle to be launched by ARIANE V, emphasize the advantage of the Brayton cycle over the thermionics and thermoelectricity, in minimizing the total mass of 100 to 300 kW_e power systems under the constraint specific to ARIANE of a radiator area limited to 95 m^2. The review of candidate reactor concepts for this application, finally recommends both liquid metal and gas cooled reactors, for their satisfactory adaptation to a reference Brayton cycle and for the available experience from the terrestrial operation of comparable systems.

The development of conceptual designs for both reactor concepts provides the input data to identify the critical technological problems and design features associated with the choice of either coolant. Both considered designs assume a filling factor in fully enriched UO_2 of 40% in the form of 0.6 cm in diameter fuel pins canned in 0.1 cm thick Molybdenum/Rhenium tubes and arranged in a tight triangular lattice with a pitch of 0.9 cm. The aimed reactivity margin of 5% at the beginning of life assigns the core height and diameter to 45 cm, with 15 cm thick axial reflectors made of BeO pellets stacked at both ends of the fuel rods and with a 8 cm thick radial reflector made of Be or BeO. Meeting the beryllium temperature and fluence technological limitations restricts the reactor thermal power to 1 MW ; in return, a reactor power in excess of 2 MW implies the use of BeO for all reflectors. Auxiliary control devices in the form of either exchangeable $^{10}B_4C$ and BeO central plugs or distributed core poisoning by specific thermal absorbers such as Gd_2O_3, are compared with respect to providing a - 5% subcriticality margin in case of immersion and minimizing the penalty in normal operation.

The impetus for a gas cooled reactor lies in its immediate readiness for the start up and in its capability to drive a direct Brayton cycle, provided the temperature rise required by the reference cycle (1000 to 1400 °K in the core) be compatible with adequate heat transfer capability. Both fuel in and out of tube concepts are compared with respect to their capability to meet a temperature limitation of 1550 °K on the structure. The former is finally recommended in the form of a tight lattice of fuel pins cooled in double passes by helium pressurized at 25 bars, successively entering the cold core outer region and the hot inner zones. The alternative core concept cooled by axial pressure tubes exhibits the potential for an improved fuel filling factor and for an easy adaptation of a fuel venting system, able to relieve the pressure load on the walls of the cooling channels, when calibrated at the coolant pressure ; however thermohydraulic considerations prove that, even if the heat transfer enhancement brought by the use of annular cooling channels, equiped with individually calibrated diaphragms enables to meet the temperature limitation criterion over the entire core characterized by power fluctuations of 20% about the average, this solution finally appears not to be realistic, given the reduced size of the requested gap between the walls of the annular section (0.1 cm) and the extreme sensitivity of the wall temperature to any change in the gap width or the power distribution. Both gas cooled reactor concepts adopt a coolant routing scheme, specially designed to keep the pressure supporting structures below 1250 °K and to restrict the pumping power to less than 2% of the removed heat.

Contrary to the gas cooled reactors, liquid metal systems are featured by a significant thermal inertia, a low pumping power and a quasi isothermal heat transfer ($\Delta T \leq 50$ °C) to any type of separate conversion loop. The potential for a low pressure operation at 1400 °K increases with the metal melting temperature and depends on the ability to efficiently purge the coolant from the helium produced by (n,α) reactions ; however, the desirability of a low pressurized system comes in conflict with the search for a low melting temperature, necessary to keep the preheating manageable before the start up. The respective capability of lithium, sodium and NaK to realize an acceptable trade-off in this respect is evaluated as well as the realism of various preheating scenarios based on ohmic heating or on the use of Pu238 loaded fuel or heating devices. Preliminary investigations indicate, that a total auxiliary power of 4 to 6 kW would be adequate to preheat the core of the considered lithium cooled reactor (2 to 3 kW) and to bring the coolant of the primary loops from 270 to 500 °K in 4 hours.

This work performed in the frame of a joint CNES/CEA programme may be considered as a first attempt to evaluate the presently considered reactor concepts for space applications, with respect to their adaptability to the specific ARIANE launching conditions of a european orbit transfer vehicle.

INTRODUCTION TO FRENCH CNES-CEA SPACE GENERATORS STUDIES

- THE FRENCH NATIONAL SPACE AGENCY (CNES) INITIATED IN 1982 A COLLABORATION WITH THE FRENCH ENERGY COMMISSION (CEA) ON NUCLEAR SPACE POWER SYSTEMS FOR CIVILIAN APPLICATIONS
- PRELIMINARY SCREENING STUDIES IN PROGRESS
  DECISION YEAR 1986 TO LAUNCH R&D PROGRAMS
- PRESENT REFERENCE POWER SYSTEM SPECIFICATIONS

  ERATO - STUDY OF AN ATOMIC ORBIT TRANSFER VEHICLE

  - ELECTRIC PROPULSION FOR AN OTV TO EXTEND THE ARIANE 5 PERFORMANCE TO 9 TONS IN GEO (2000/2005)
  - ELECTRIC POWER : 100 TO 400 KWE
  - LAUNCH CONDITIONS SPECIFIC TO ARIANE 5 ALLOW THE RADIATOR AREA TO EXCEED 100 M^2 AND THE SYSTEM MASS TO EXCEED 3 TONS
- PRELIMINARY PROSPECTIVE STUDIES OF CANDIDATE CONVERSION SYSTEMS EMPHASIZE THE ADVANTAGE OF A BRAYTON CYCLE OVER THE THERMIONICS AND THERMOELECTRICITY IN MINIMIZING THE TOTAL MASS OF 100 TO 300 KWE POWER SYSTEMS UNDER THE CONSTRAINTS SPECIFIC TO ARIANE
- THE REVIEW OF CANDIDATE REACTOR CONCEPTS FOR THIS APPLICATION FINALLY RECOMMENDS BOTH LIQUID METAL AND GAS COOLED REACTORS, FOR THEIR SATISFACTORY ADAPTATION TO A REFERENCE BRAYTON CYCLE AND FOR THE AVAILABLE EXPERIENCE FROM THE TERRESTRIAL OPERATION OF COMPARABLE SYSTEMS

LIQUID METAL VERSUS GAS COOLED REACTOR CONCEPTS FOR A TURBOELECTRIC POWERED SPACE VEHICLE

- INTRODUCTION TO FRENCH CNES-CEA SPACE GENERATORS STUDIES
- REFERENCE ENERGY CONVERSION SYSTEM
- ADAPTABILITY OF VARIOUS REACTOR CONCEPTS AND TENTATIVE EVALUATION OF THE ASSOCIATED TECHNOLOGICAL OPTIONS

GAS COOLED REACTOR

- IMPETUS FOR A GAS COOLED REACTOR TO DRIVE A DIRECT BRAYTON CYCLE
- REVIEW OF SPECIFIC PROBLEMS
- HEAT TRANSFER ENHANCEMENT AND CONTROL OF THE STRUCTURE PEAK TEMPERATURE
- COMPARATIVE STUDY OF VARIOUS COOLING CHANNELS FOR A FUEL OUT OF TUBES REACTOR CONCEPT
- FUEL IN VERSUS OUT OF TUBES
- DESIGN OPTIONS FOR A GAS COOLED REACTOR DRIVING A DIRECT BRAYTON CYCLE

LIQUID METAL COOLED REACTOR

- IMPETUS FOR A LIQUID METAL COOLED REACTOR AS A HEAT SOURCE FOR ANY TYPE OF SEPARATE CONVERSION LOOP
- REVIEW OF SPECIFIC PROBLEMS
- GAS PRODUCTION AND PREHEATING BEFORE START UP
- DESIGN OPTIONS FOR A LITHIUM COOLED REACTOR

CRUCIAL ISSUES COMMON TO BOTH REACTOR CONCEPTS

FUTURE STUDIES

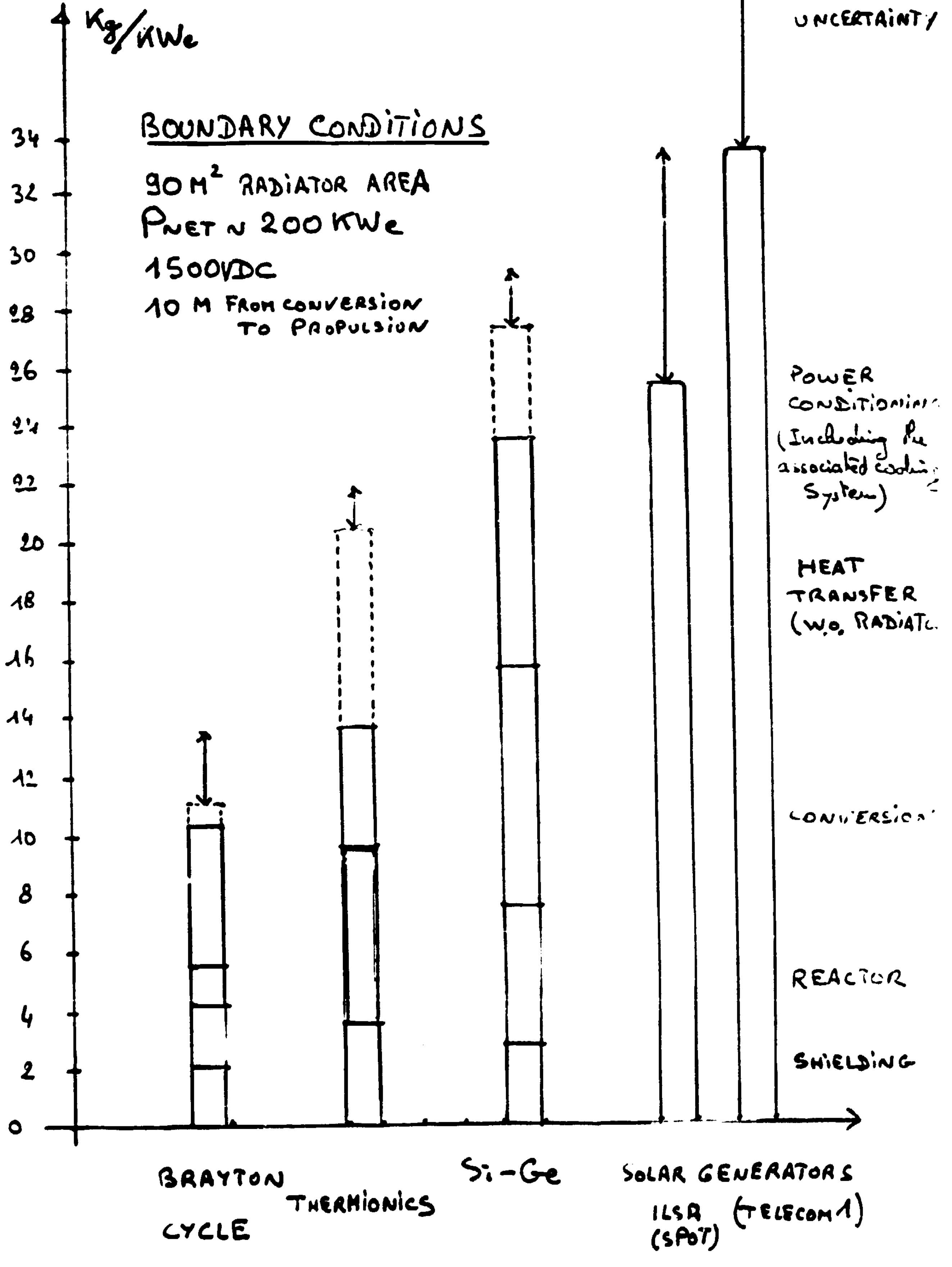
COMPARATIVE EVALUATION OF VARIOUS SPACE REACTOR CONCEPTS ACCORDING TO THEIR TECHNOLOGICAL OPTIONS

	LM COOLED REACTOR	GAS COOLED REACTOR		HEATPIPE REACTOR	IN CORE THERMIONICS
TODAY AVAILABLE EXPERIENCE IMPORTANCE AND TIMESCALE OF THE TECHNOLOGY DEVELOPMENTS REQUIRED BY THE CRITICAL ISSUES	!	!		?⃝	?⃝
START UP	?⃝	!		!	-
ADAPTABILITY TO VARIOUS CONVERSION CYCLES	!	?⃝		!	-
OPERATION WITH A FAILED FUEL OR COOLING ELEMENT	-	-		?⃝	-
FUEL ELEMENT	PINS	PINS	TABS	TABS AND FINS	TFE
COMPLEXITY	!	!	-	?	?
ΔT, PRESSURE LOADS	!	?	?	!	-
CORROSION	?	!	!	?	-
VENTING	?	?	!	!	-
BEHAVIOUR UNDER IRRADIATION	-	-	?	?	?
STRUCTURE OPERATING TEMPERATURE	?	-		?	?
ISOTHERMAL HEAT TRANSFER	!	?		!	!
THERMAL INERTIA	!	-		-	!
REDUNDANCY/RELIABILITY	-	-		!	!
POTENTIAL FOR EXTRAPOLATION	!	?		-	-
SUBCRITICALITY IN CASE OF IMMERSION	-	?		-	?
VESSEL THICKNESS/ DISPERSION IN CASE OF REENTRY/ CONTROL WORTH	-	?		!	-
TRANSIENT RESPONSE	!	-		TO BE STUDIED	!
MAJOR CRITICAL ISSUES	. PREHEATING . SEPARATION AND PURGE OF HE . ALL STRUCTURES OPERATING BEYOND 1 200°C	. BRAYTON/STIRLING CYCLES ONLY . CONTROL OF THE PEAK TEMPERATURE . AXIAL TEMPERATURE GRADIENTS (∿ 200°C)		. SIGNIFICANT TECHNOLOGY DEVELOPMENTS	
				FUEL ELEMENT ? . ACCOMMODATION TO HEATPIPE FAILURE ?	TFE ? . THERMIONIC CONVERSION ONLY . SIZE/WEIGHT . START UP ?

[3] MISSION AND SYSTEMS

French Activity on Space Nuclear Power Systems (C. Pohn)

CNES - SCREENING STUDY OF CANDIDATE CONVERSION SYSTEMS



BOUNDARY CONDITIONS

$90\ M^2$ RADIATOR AREA

$P_{NET} \sim 200$ KWe

1500VDC

10 M FROM CONVERSION TO PROPULSION

IMPETUS FOR A GAS COOLED REACTOR TO DRIVE A DIRECT BRAYTON CYCLE

<table>
<tr><th>ADVANTAGES</th><th colspan="2">GAS COOLED REACTOR</th><th>DRAWBACKS</th></tr>
<tr><td colspan="2">. AVAILABLE EXPERIENCE FROM TERRESTRIAL PLANTS (EXTRAPOLABLE ?)
. IMMEDIATE READINESS FOR START UP
. PRIVILEGED ADAPTATION TO BRAYTON AND STIRLING CONVERSION SYSTEMS IN THE FORM OF A DIRECT CYCLE
. WEIGHT SAVING ASSOCIATED WITH THE SUPPRESSION OF THE PRIMARY HEAT EXCHANGER (∿ 200 KG/200 KWE)
. THE PROPORTION OF STRUCTURES WORKING ABOVE 1 200°C DOES NOT EXCEED 30 % IN RETURN, THE FUEL ELEMENTS EXPERIENCE SEVERE AXIAL TEMPERATURE GRADIENTS (ΔT ∿ 200°C WITH DOUBLE PASSES)
. LIMITED CONSEQUENCES OF THE FUEL/COOLANT INTERFACE FAILURE</td><td colspan="2">. NO INCENTIVE TO ASSOCIATE A GAS COOLED REACTOR WITH ANY OTHER CONVERSION SYSTEM BUT GAS CYCLES (DIRECT COUPLING)
. DRIVING A DIRECT BRAYTOR CYCLE IMPLIES A LARGE COOLANT TEMPERATURE RISE (TYPICALLY 400°C) AND CONSEQUENTLY LARGE AXIAL TEMPERATURE GRADIENTS IN THE FUEL ELEMENTS
  . LOW COOLANT FLOW RATE
    —> LAMINAR REGIME
    —> TRADE OFF BETWEEN ACCEPTABLE HEAT TRANSFER PROPERTIES AND PUMPING POWER. INCENTIVE TO CONSIDER A DOUBLE PASSES COOLING
  . DIFFICULT CONTROL OF THE STRUCTURE PEAK TEMPERATURE AT THE EXIT OF THE HOT CHANNEL
  . LIMITED POTENTIAL FOR AN INCREASED SPECIFIC POWER BEYOND 10 W/GU
. QUESTIONNABLE COMPATIBILITY OF A 2-3 MPA PRESSURIZED VESSEL WITH :
  . THE ALLOWABLE CREEP RATE
  . THE VESSEL THICKNESS LIMITATION FOR :
    . AN EFFICIENT REACTIVITY CONTROL BY REFLECTOR/ABSORBER ROTATING DRUMS
    . THE SATISFACTORY DISPERSION OF THE CORE CONTENT IN CASE OF REENTRY
. ACTIVE REMOVAL OF THE AFTER HEAT
. EXTRAPOLABILITY TO MULTIMEGAWATT THERMAL POWER ?</td></tr>
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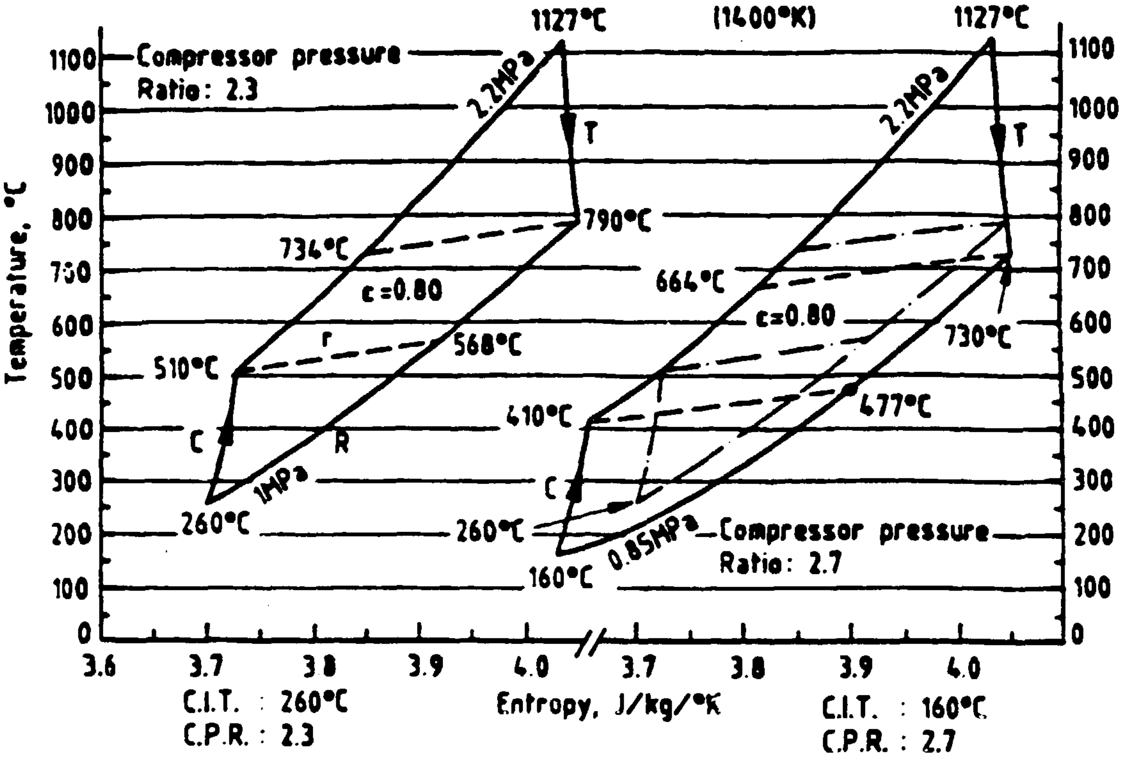
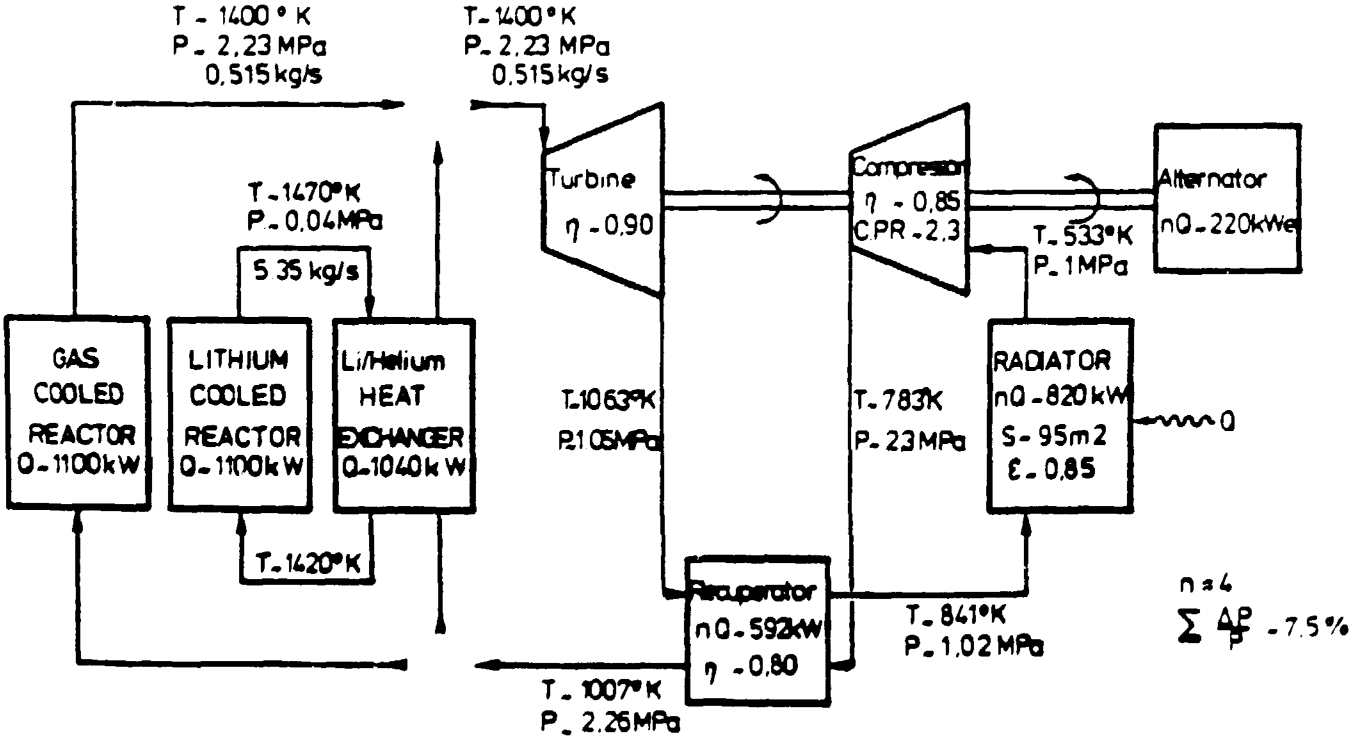
REFERENCE BRAYTON CYCLE



ADAPTATION OF BOTH CANDIDATE HEAT SOURCES TO THE REFERENCE CONVERSION CYCLE



COMPARATIVE STUDY OF VARIOUS COOLING CHANNELS FOR A FUEL OUT OF TUBES REACTOR CONCEPT

PRELIMINARY GAS COOLED REACTOR CONCEPT

$P \sim 1$ MWTH, $D \sim 31.6$ CM, $H \sim 37.1$ CM, 40 % UO_2

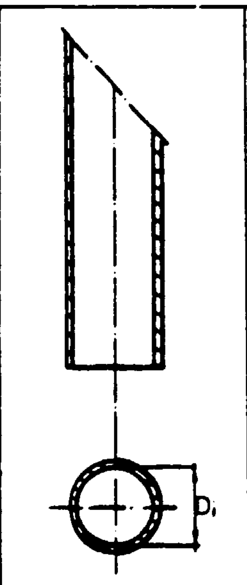
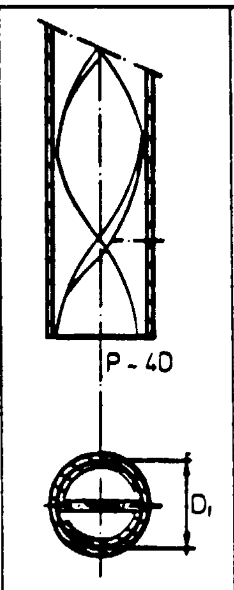
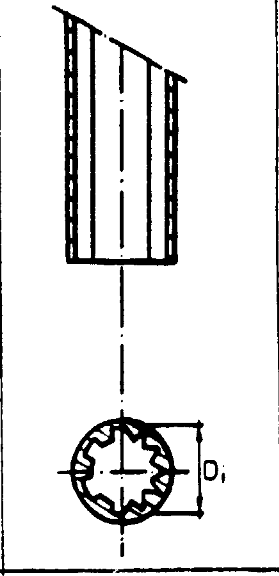
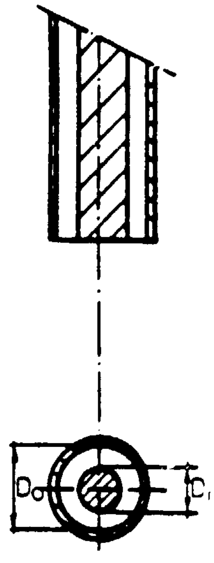
$P_S \sim 10$ W/GU, $P_V \sim 95$ W/CM^3

$P_{GAS} \sim 2{,}5$ MPA, $[1006\ ,\ 1400]$°K, $\rho VS \sim 0.515$ KG/S.

TECHNOLOGICAL LIMITATIONS

GAS AVERAGE EXIT TEMPERATURE 1127°C STRUCTURE PEAK TEMPERATURE $\leqslant$ 1300°C	NEED TO CONSIDER COOLING CHANNELS CAPABLE OF EXCELLENT HEAT TRANSFER IN SPITE OF THE LOW COOLANT FLOW RATE ASSOCIATED WITH THE DESIRED 400°K TEMPERATURE RISE IN THE CORE.

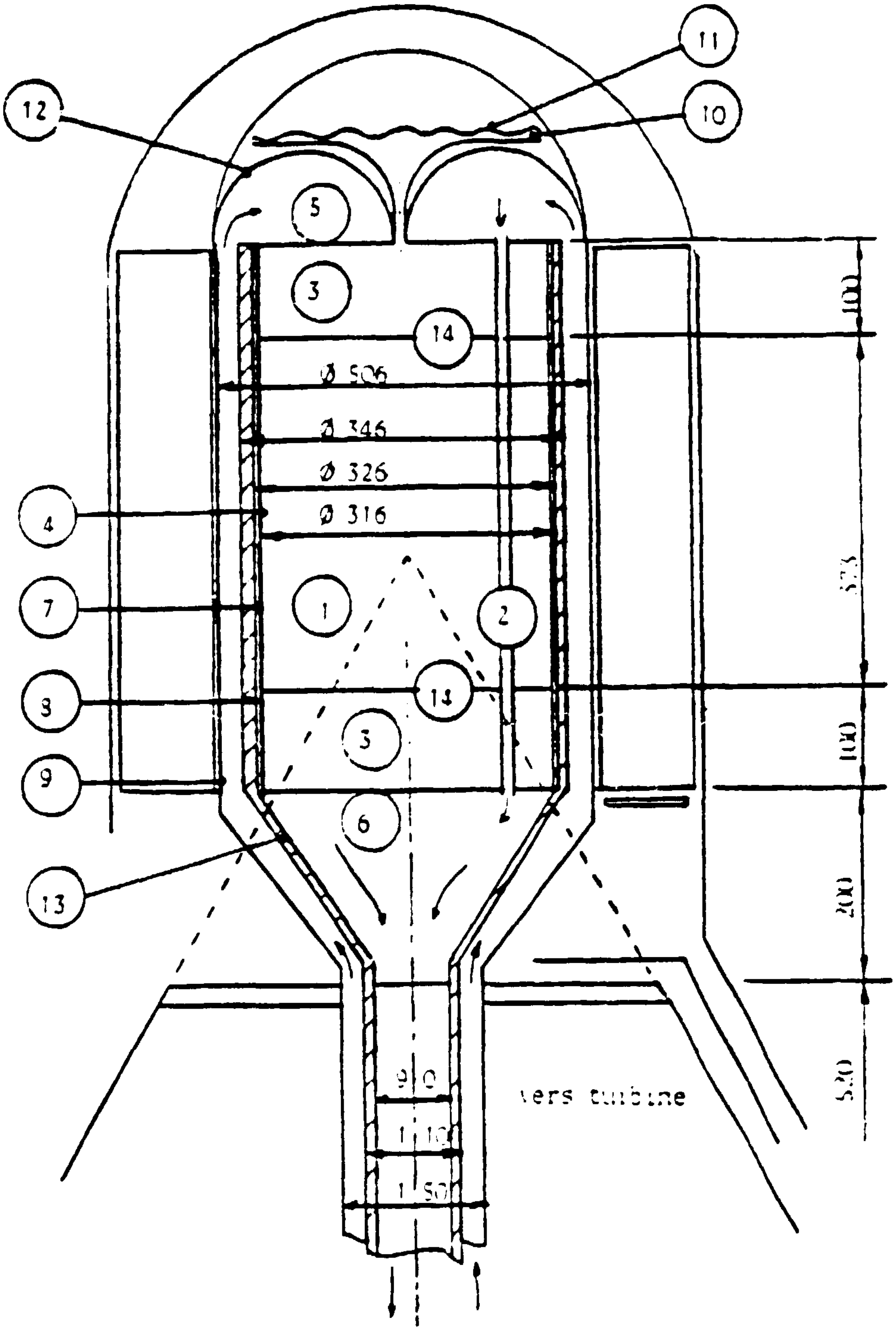
COMPARISON OF FOUR CANDIDATE CHANNELS HEAT TRANSFER PERFORMANCES

PLAIN TUBE TUBE WITH HELICAL PLATE FINNED TUBE ANNULAR TUBE				
40 % UO_2 $T_{STRUCTURE} \leqslant 1300$°C $F_{\Delta H} \sim 1$				
EXCHANGED FLUX (W/CM^2)	9.2	17.6	7.8	17.6
EXIT HX COEFFICIENT (W/CM^2/°C)	0.040	0.07	0.034	0.0765
PRESSURE DROP (PA) $L \sim 0.55$ M	700	1000	1000	6000
STRUCTURE AND COOLANT PROPORTIONS % MO	26	29	29	18 ÷ 23
STRUCTURE AND COOLANT PROPORTIONS % HE	34	31	31	42 - 20
NUMBER OF CHANNELS IN THE CORE	2100 $D_I \sim 0.4$ CM	540 $D_I \sim 0.95$ CM	540 $D_I \sim 0.95$ CM 8 x 0.26 CM FINS	540 $D_I \sim 0.65$ CM $D_O \sim 0.95$ CM

THE USE OF SPECIALIZED TUBULAR CHANNELS MAKES IT POSSIBLE TO EFFICIENTLY ENHANCE THE HEAT TRANSFER AND HENCE TO DIVIDE BY 3 OR 4 THE NUMBER OF COOLING ELEMENTS.

MANUFACTURING CONSIDERATIONS LEADS TO PREFER ANNULAR CHANNELS TO COOLING TUBES EQUIPPE WITH HELICAL PLATES OR FINS.

THE VOID FRACTION RANGING FROM 30 TO 35 % FOR ALL SOLUTIONS APPEAR COMPARABLE TO THAT FUEL PIN ASSEMBLIES OF SIMILAR FUEL CONTENT (~ 40 % UO_2).



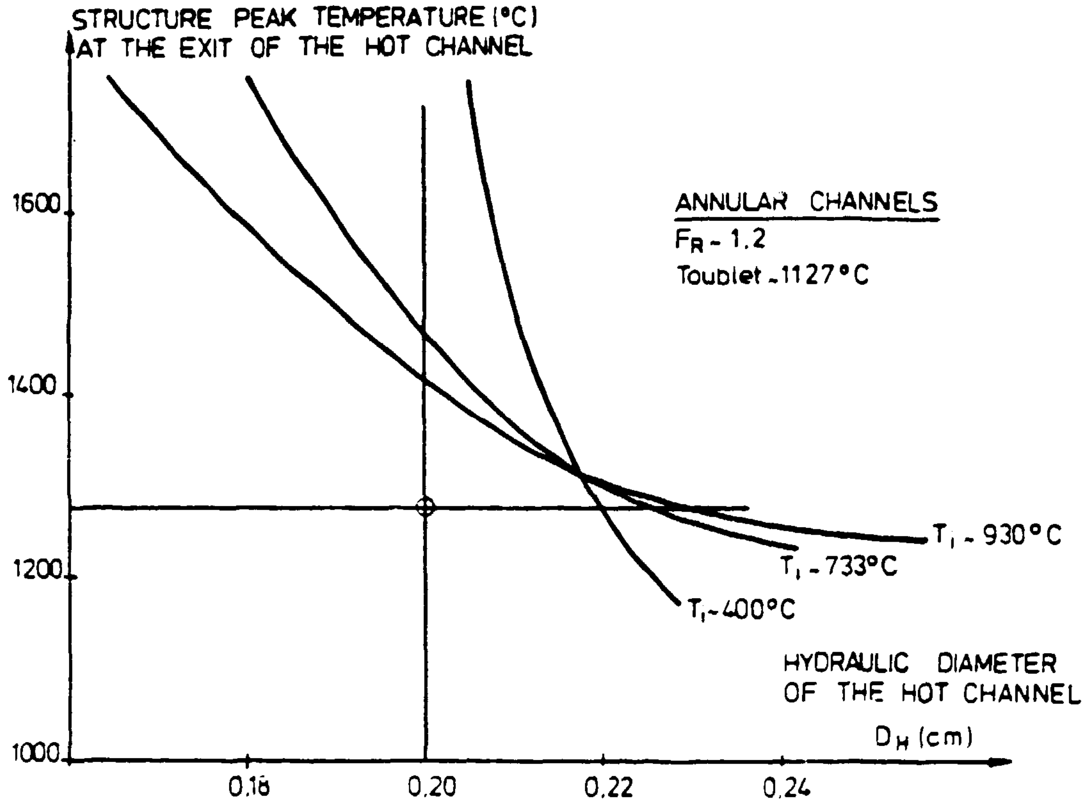
1 - COEUR
2 - Canal de refroidissement en alliage de Mo
3 - Réflecteur en BeO
4 - Cuve cylindrique en alliage de Mo
5 - Plaque support des canaux
6 - Plaque encaissant les dilatations
7 - Structure métallique fine et isolante
8 - Ecran en zircone massive
9 - Caisson tenant la pression
10 - Réservoir de gaz de fission
11 - Membrane déformable
12 - Déflecteur
13 - Isolant en mousse de ZrO_2
14 - Séparateurs en alliage de Zr

REACTEUR SPATIAL GEOMETRIE

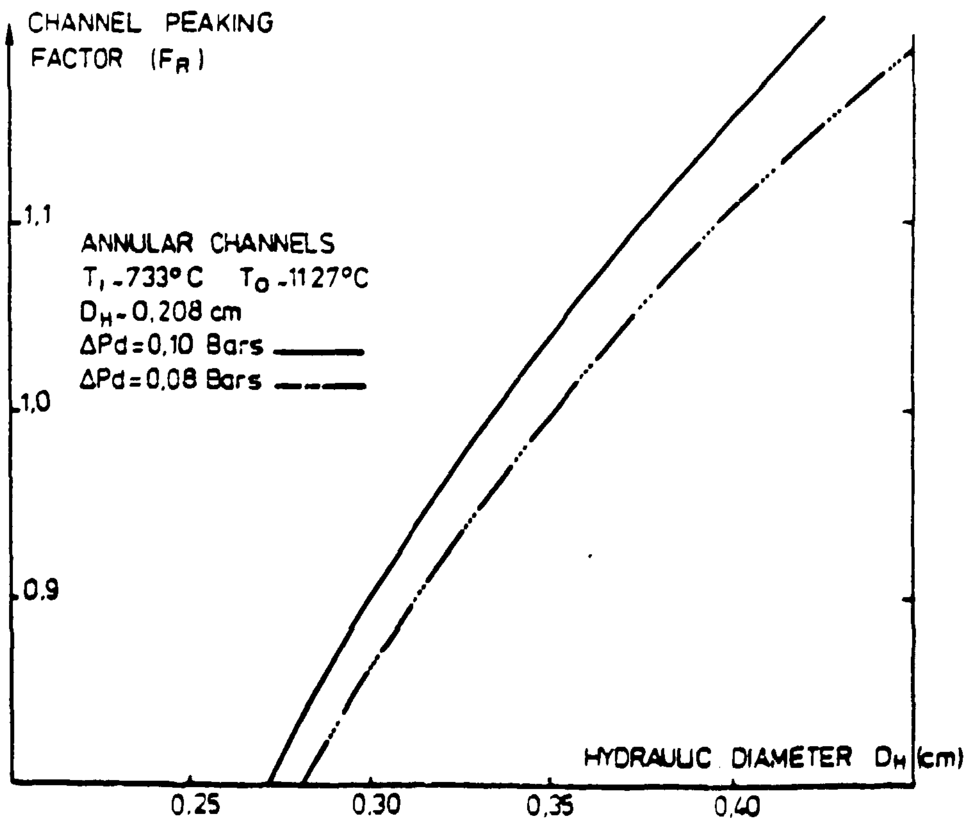
CEA DEMT
LECS

COOLANT FLOW RATE REGULATION AND HEAT TRANSFER CONTROL IN ANNULAR COOLING CHANNELS

STRUCTURE PEAK TEMPERATURE AS A FUNCTION OF THE HOT CHANNEL HYDRAULIC DIAMATER D_H



REQUISITE DIAPHRAGM EFFICIENCY AS A FUNCTION OF THE LOCAL POWER LOADING TO MAKE THE GAS OUTLET TEMPERATURE UNIFORM.



COOLANT FLOW RATE REGULATION AND HEAT TRANSFER CONTROL IN ANNULAR COOLING CHANNELS

PRESSURE DROP

ΔP NEGLIGIBLE IN COMPARISON WITH THE COOLANT PRESSURE.

ΔP VERY SENSITIVE TO THE CHANNEL GEOMETRY AND GAS TEMPERATURE.

—> DIFFICULT CONTROL OF THE STRUCTURE PEAK TEMPERATURE WITH A NON UNIFORM POWER DISTRIBUTION ($F_R \sim 1,2$).

—> LOW AVAILABLE MARGIN TO COMPENSATE POSSIBLE DEFORMATIONS OF THE NOMINAL ANNULAR CHANNEL.

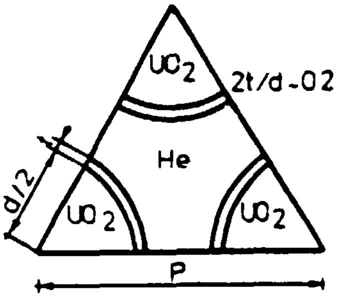
POSSIBLE ADJUSTEMENT OF THE COOLANT FLOW RATE TO THE LOCAL THERMAL LOAD

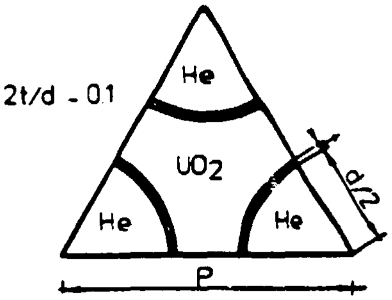
STANDARDIZATION OF THE GAS OUTLET TEMPERATURE ($T \sim 1127$°C) TO MAINTAIN THE STRUCTURE PEAK TEMPERATURE BELOW 1300°C.

1 - THROUGH THE SPECIAL ADAPTATION OF D_H FOR EACH INDIVIDUAL CHANNEL.

2 - THROUGH THE SPECIAL SETTING UP OF INDIVIDUALLY CALIBRATED DIAPHRAGMS AT THE INLET OF EACH COOLING CHANNEL.

FUEL IN VERSUS OUT OF TUBES





COMPARATIVE THERMOHYDRAULIC CHARACTERISTICS
OF BOTH FUEL IN AND OUT OF TUBES LATTICES

LATTICE	CANNED FUEL PINS		FUEL OUT OF TUBES	
FUEL PROPORTION (% UO_2)	40	50	40	50
D/P	0.664	0.743	0.739	0.675
(D + 2T)/P	0.797	0.891	0.813	0.743
HEATING PERIMETER P_H/P	1.252	1.400	1.162	1.060
HYDRAULIC DIAMETER D_H/P	0.587	0.347	0.739	0.675

HEAT EXCHANGE THROUGH THE TUBES OUTER VERSUS INNER SURFACE

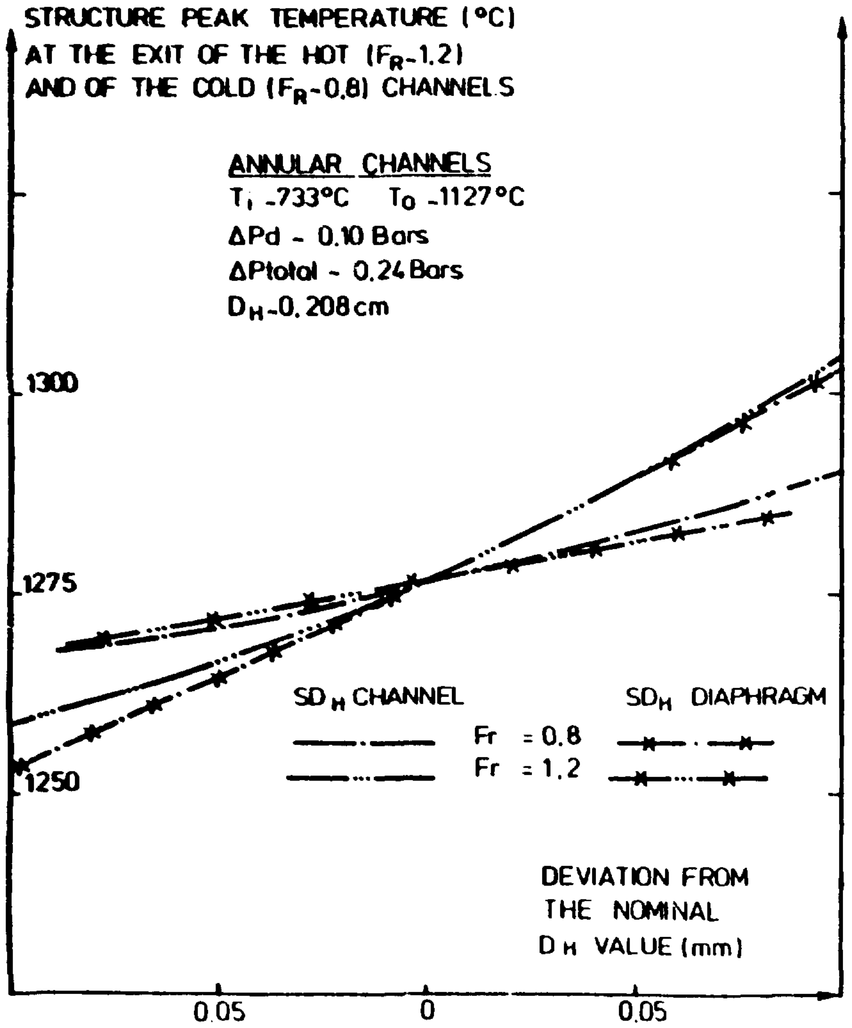
P_H PINS > TUBES (45 % UO_2, (2T/D) ~ 20 %)

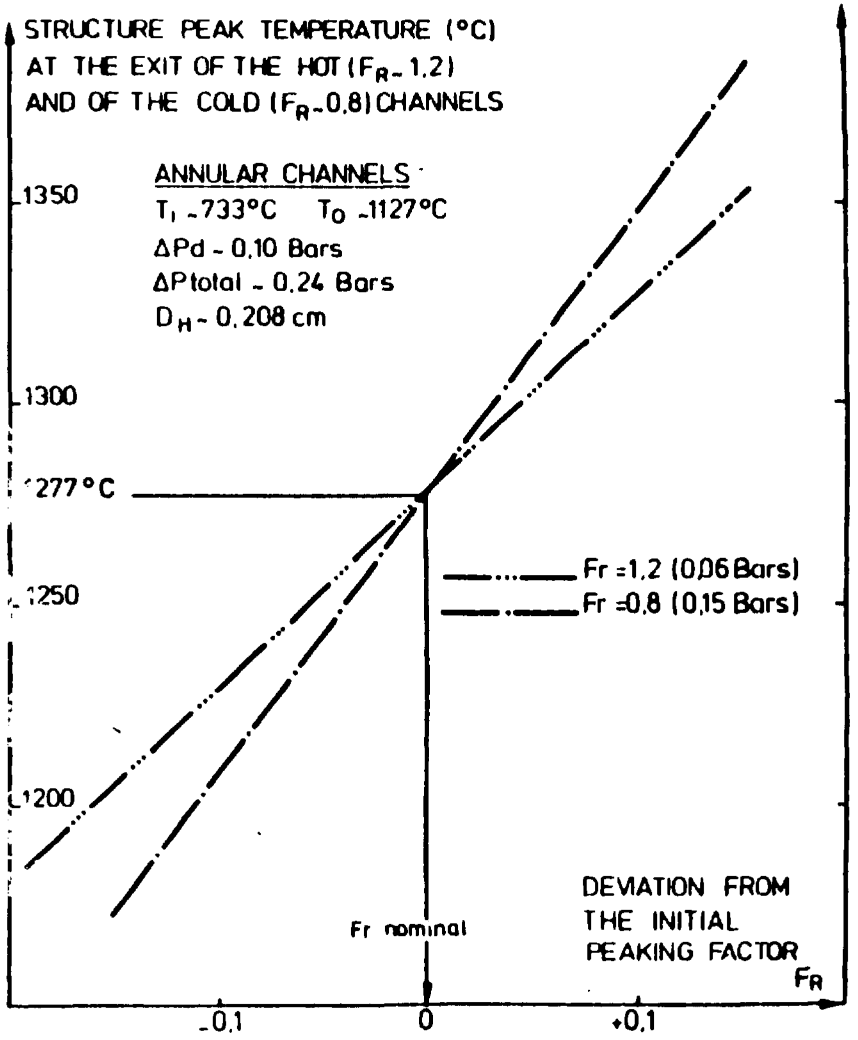
D_H PINS < TUBES (45 % UO_2, $h \sim \frac{Nu.\lambda}{D_H}$ IMPROVED BY 35 %)

DIFFERENCES IN P_H AND D_H ARE EMPHASIZED BY AN INCREASING FUEL PROPORTION AS THE TUBE DIAMETERS VARY IN OPPOSITE DIRECTIONS FOR BOTH LATTICES.

$$\Delta T^{GAS}_{WALL} \text{ (PIN/TUBES) } \begin{cases} -\,25\ \%\ \text{FOR } 40\ \%\ UO_2 \\ -\,60\ \%\ \text{FOR } 60\ \%\ UO_2 \end{cases}$$

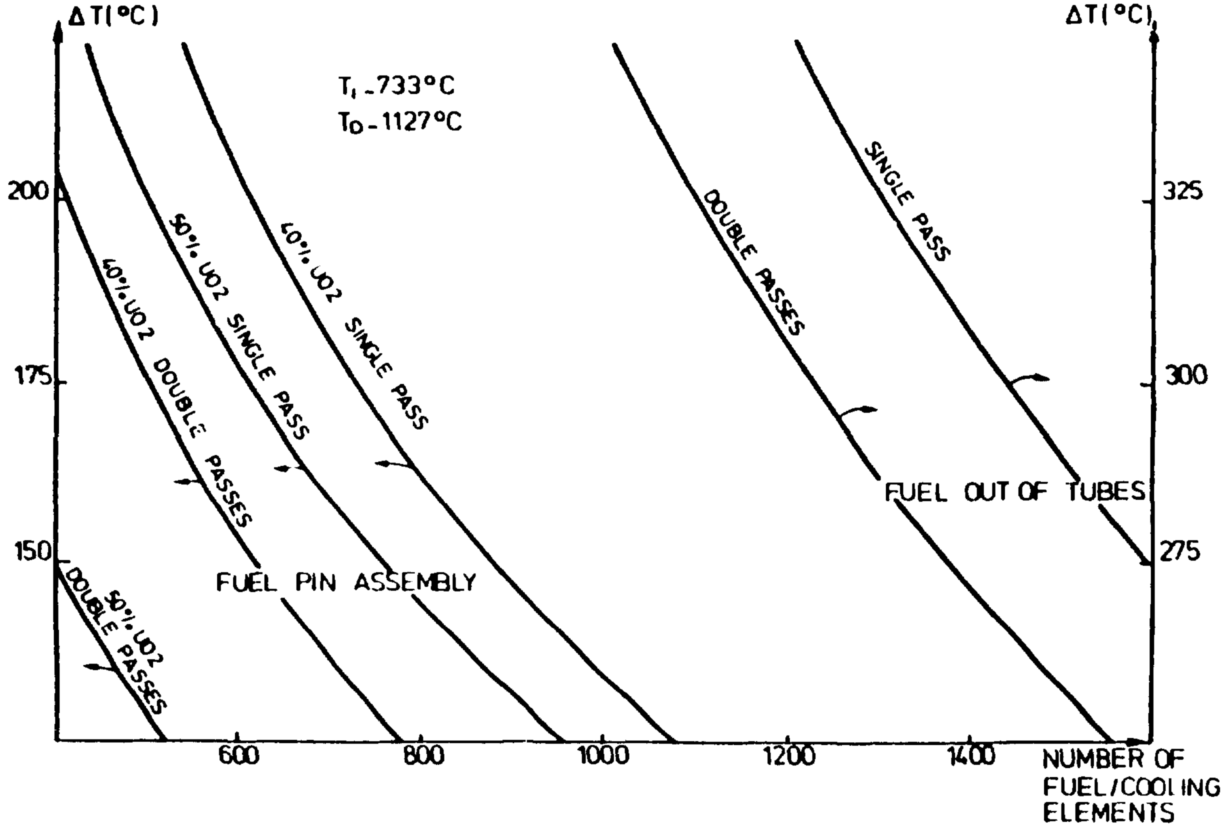
BENEFICIAL EFFECT OF AN ADDITIONAL PRESSURE DROP TO DAMP THE SENSITIVITY OF THE STRUCTURE PEAK TEMPERATURE TO ANY CHANGE IN THE CHANNEL GEOMETRY OR IN THE RADIAL POWER DISTRIBUTION





COMPARISON OF FUEL IN AND OUT OF TUBES LATTICES

REQUISITE NUMBER OF FUEL OR COOLING ELEMENTS WITHIN A 1MW REACTOR TO RESTRICT THE WALL/COOLANT TEMPERATURE DIFFERENCE TO A DESIRED VALUE ΔT



FUEL IN OR OUT OF TUBES

<table>
<tr><th>FUEL IN TUBE</th><th colspan="2">VERSUS</th><th>FUEL OUT OF TUBE</th></tr>
<tr><td colspan="2">. CONCEPT OF FUEL ASSEMBLY ADOPTED BY MOST TERRESTRIAL REACTORS
. COMPATIBLE WITH A HIGH FUEL PROPORTION ($\leqslant$ 60 %) IN THE FORM OF A TIGHT HEXAGONAL LATTICE
. EXTENSIVE EXPERIENCE IN MANUFACTURING AND TESTING
. SATISFACTORY HEAT TRANSFER CAPABILITY
. FUEL PELLETS CANNED IN A PROTECTIVE CLADDING</td><td colspan="2">. POSSIBLE ADAPTATION OF A FUEL VENTING SYSTEM ABLE TO RELIEVE THE PRESSURE LOAD ON THE WALLS OF THE COOLING CHANNELS, WHEN CALIBRATED AT THE COOLANT PRESSURE (GAS COOLED REACTORS)
. POTENTIAL FOR AN IMPROVED FUEL FILLING FACTOR</td></tr>
<tr><td colspan="2">. ACCOMMODATION TO FISSION GASES RELEASE ?
. PELLET/CLADDING INTERACTION
. CONSEQUENCE OF A CLADDING FAILURE ?
(UO_2/LI INTERACTION)
(. ACCOMMODATION TO THE PRESSURE DIFFERENCE ON BOTH SIDES OF THE CLADDING)</td><td colspan="2">. BEHAVIOUR OF NON-CANNED FUEL TABS UNDER IRRADIATION ?
. LESS ATTRACTIVE HEAT TRANSFER PERFORMANCES THAN THOSE OF THE PIN BUNDLE CONCEPT WITH COMPARABLE FUEL PROPORTION :
- THERMAL FLUX EXCHANGED ACROSS THE TUBE INNER VERSUS OUTER SURFACE
- HEAT EXCHANGE COEFFICIENT REDUCED BY A FACTOR OF 3
. AMPLIFICATION OF THE DIFFERENCE IN HEAT TRANSFER CAPABILITY WHEN THE FUEL PROPORTION INCREASES
. THE FUEL OUT OF TUBE OPTION APPEARS MAINLY TRACTABLE WITH EFFICIENT COOLING DEVICES SUCH AS HEAT PIPES OR LIQUID METAL</td></tr>
</table>

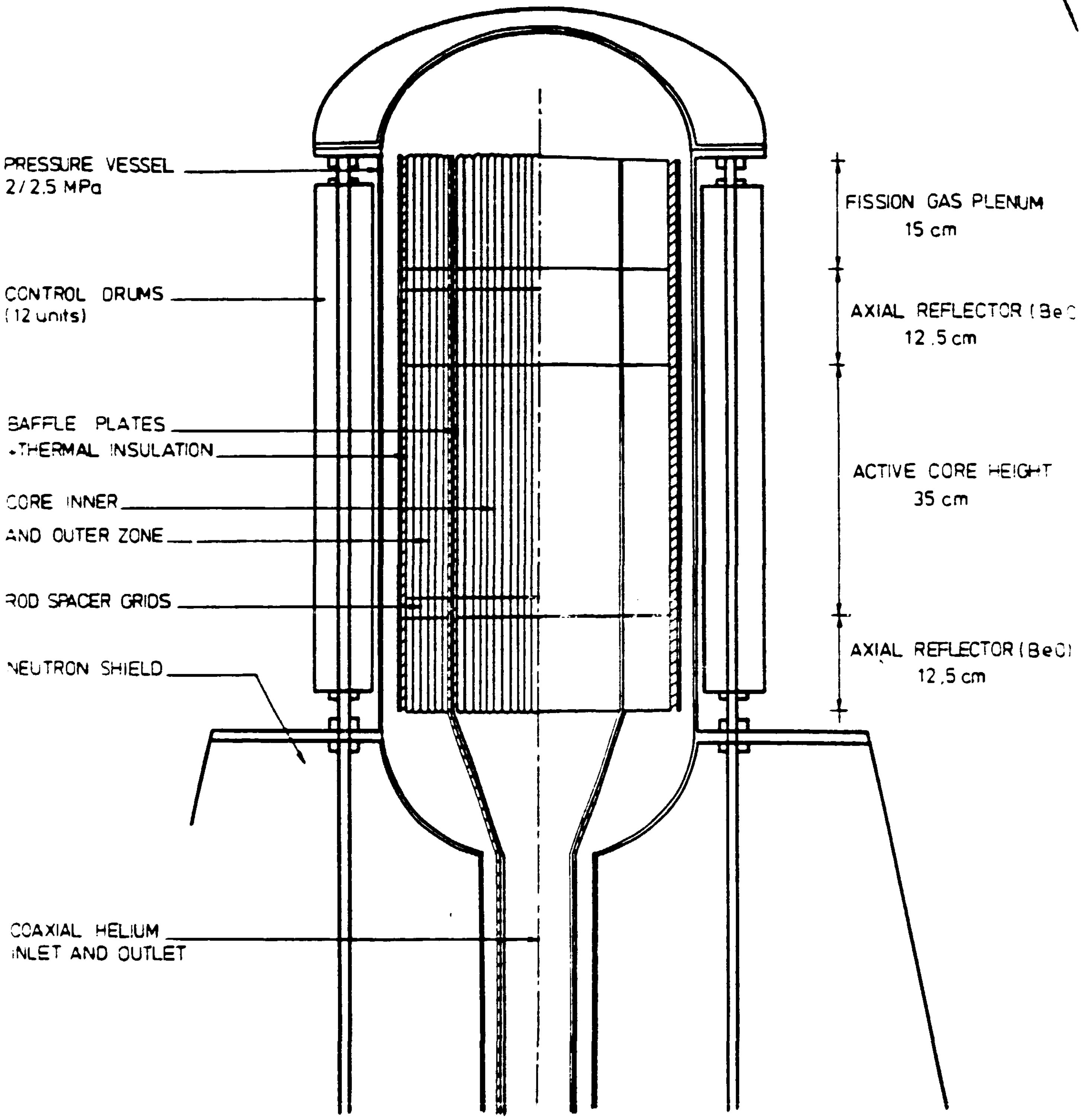
DESIGN OPTIONS FOR A GAS COOLED REACTOR TO DRIVE A DIRECT BRAYTON CYCLE

THE FOLLOWING OPTIONS IMPROVE THE CONTROL OF THE PEAK TEMPERATURE AT THE EXIT OF THE HOT CHANNEL :

- REDUCTION OF THE AXIAL TEMPERATURE GRADIENT BY THE USE OF :
  - A RECUPERATOR
    (DECREASE OF THE TOTAL CORE ΔT FROM 700°C TO 400°C)
  - A DOUBLE PASSES COOLING SCHEME
    (TOTAL 400°C SPLIT INTO TWO 200°C SINGLE PASS ΔT)
- USE OF CANNED FUEL PINS RATHER THAN FUEL OUT OF TUBE CORE CONCEPT
  - IMPROVEMENT OF THE HEAT TRANSFER PERFORMANCES FOR A GIVEN FUEL PROPORTION
  - LESSER SENSITIVITY OF THE STRUCTURE TEMPERATURE TO ANY VARIATION IN POWER DISTRIBUTION OR IN THERMOHYDRAULIC CHARACTERISTICS OF THE COOLING CHANNELS

AN APPROPRIATE COOLANT ROUTING SCHEME AIMS AT MAINTAINING THE OPERATING TEMPERATURE OF THE PRESSURE SUPPORTING STRUCTURES BELOW 1 000°C AND HENCE AT MINIMIZING THE ANTICIPATED CREEP RATE

- PRESSURE VESSEL SWEPT BY A BYPASS STREAM OF COOLANT AT THE INLET TEMPERATURE (∿ 750°C)
- COAXIAL INLET AND OUTLET COOLANT DUCTS.

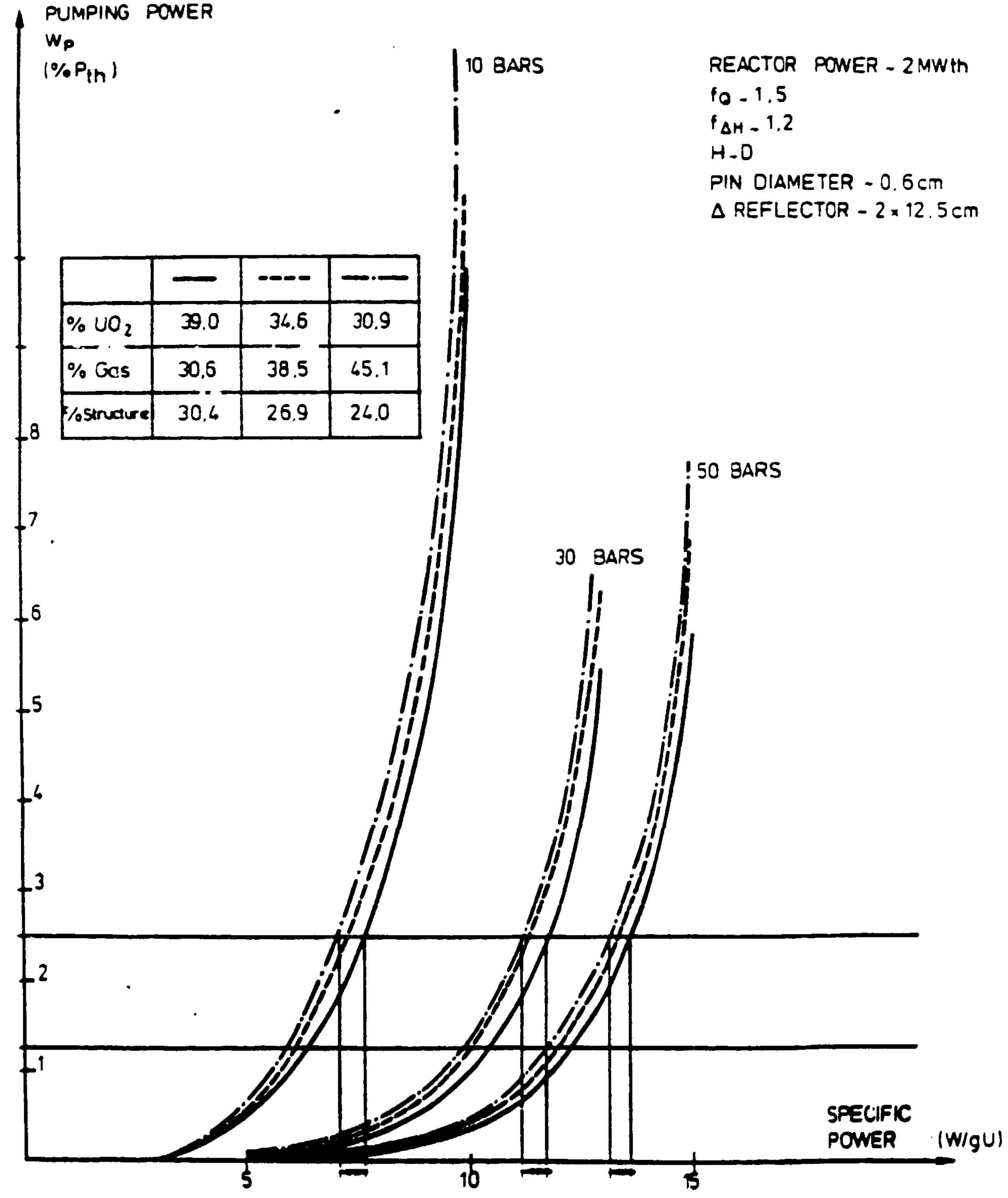


HELIUM COOLED ERATO REACTOR CONCEPT
(double passes helium cooling)

HELIUM COOLED PIN BUNDLE CORE ASSEMBLY

REQUISITE PUMPING POWER AS A FUNCTION OF THE SPECIFIC POWER

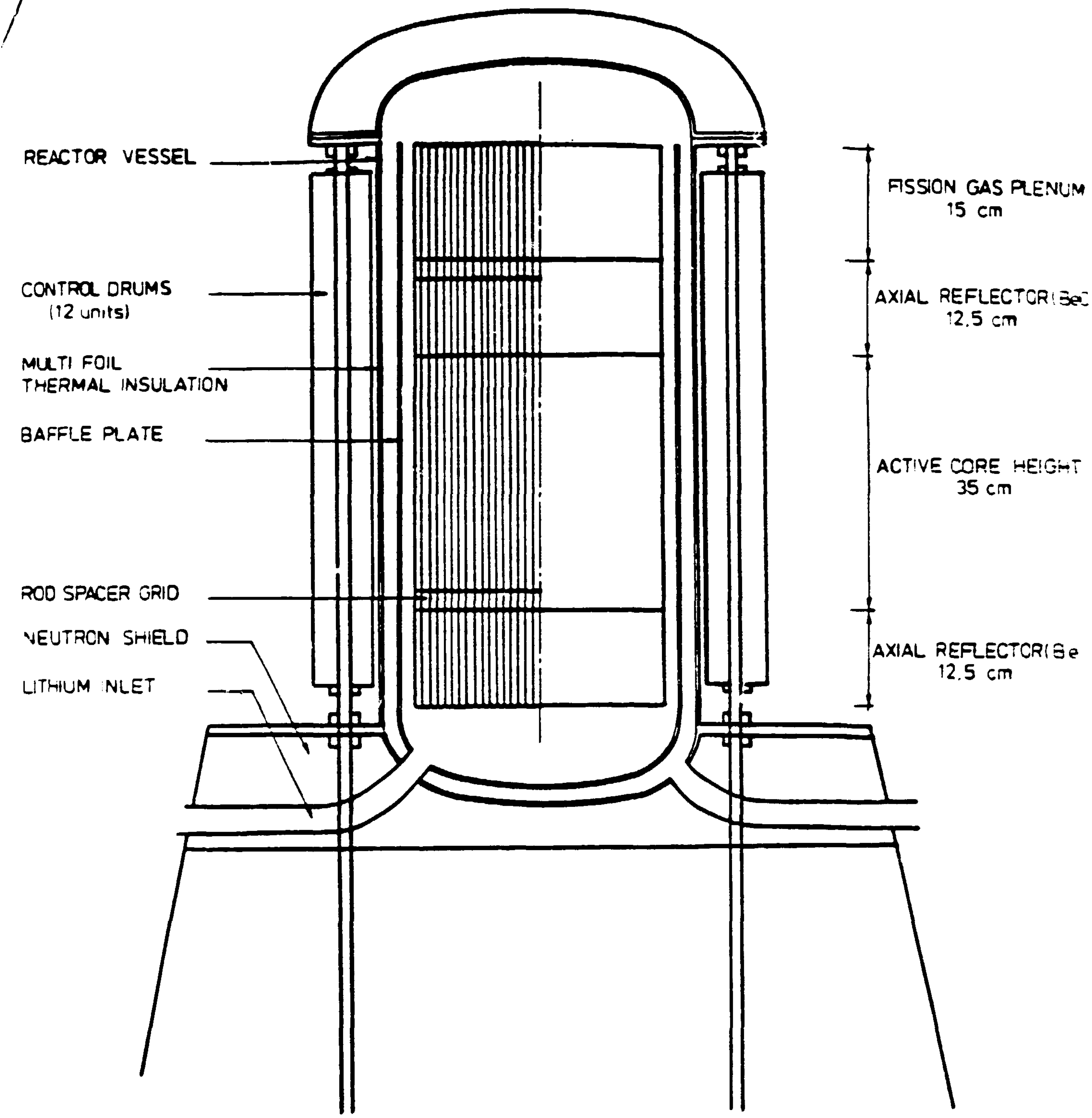
TO MAINTAIN THE MAXIMUM FUEL / COOLANT TEMPERATURE DIFFERENCE BELOW 270°C



	——	----	-·-·
% UO_2	39.0	34.6	30.9
% Gas	30.6	38.5	45.1
% Structure	30.4	26.9	24.0

DESIGN OPTIONS FOR GAS AND LITHIUM COOLED REACTORS TO DRIVE A DIRECT BRAYTON CYCLE

PRESENTLY ASSUMED (1984) DESIGN OPTIONS	GAS COOLED REACTOR	LITHIUM COOLED REACTOR
NET SYSTEM ELECTRIC OUTPUT	200 KWE	200 KWE
REACTOR THERMAL POWER	1 100 KWE	1 100 KWE
COOLANT	HELIUM-XENON (A $\sim$ 40)	LITHIUM 7
PRESSURE	2.25 MPA	0.05 → 0.1 MPA
COOLANT WORKING TEMPERATURES	[1006 ; 1400]°K	[1420 ; 1470]°K
FLOW RATE	0.515 KG/S	5.35 KG/S
COOLANT ROUTING	DOUBLE PASSES	SINGLE PASS
FUEL SPECIFIC POWER	9.5 W/GU	11 W/GU
ACTIVE CORE DIMENSIONS **HEIGHT $\sim$ DIAMETER**	$\sim$ 35 CM	$\sim$ 34 CM
REACTOR WEIGHT	500 KG	450 KG
FUEL ELEMENT		
FUEL	UO_2(95 % x 98 % T_D) OR UN (30 % CENTRAL VOID)	
PELLET DIAMETER	0.7 CM	
CLADDING THICKNESS	0.05 CM	
TRIANGULAR PITCH	1.0 CM	
NUMBER OF FUEL PINS	900/1 000	
% FUEL/STRUCTURE/COOLANT	45 % + 20 % + 35 %	
AXIAL REFLECTOR	BEO PELLETS ($\sim$ 12.5 CM) STACKED AT BOTH ENDS OF THE FUEL PINS	
RADIAL REFLECTOR	8 CM THICK BE REFLECTOR	
REACTIVITY CONTROL	12 ROTATING CONTROL DRUMS (BE, 10 CM I.D.) WITH $^{10}B_4C$ ABSORBER SEGMENTS ($2\pi/3$ x 2 CM)	
FISSION GAS PLENUM	15 CM AT THE END OF UO_2 PINS OR 30 % VOID WITHIN UN RODS	
SUBCRITICALITY IN CASE OF IMMERSION	Gd_2O_3-$^{10}B_4C$ POISONS MIXED WITH THE FUEL ? REMOVABLE $^{10}B_4C$ CONTROL DEVICES (SAFETY PLUG, RODS) ?	



LITHIUM COOLED ERATO REACTOR CONCEPT (1,1 MWth)

IMPETUS FOR A LIQUID METAL COOLED REACTOR AS A HEAT SOURCE FOR ANY TYPE OF SEPARATE CONVERSION LOOP

<table>
<tr><th><u>ADVANTAGES</u></th><th colspan="2">LIQUID METAL COOLED REACTOR</th><th>DRAWBACKS</th></tr>
<tr><td colspan="2">. AVAILABLE EXPERIENCE FROM TERRESTRIAL PLANTS (EXTRAPOLABLE ?)</td><td colspan="2">. SOLID COOLANT AT ROOM TEMPERATURE NEED FOR PREHEATING BEFORE START UP</td></tr>
<tr><td colspan="2">• WELL ADAPTED TO A WIDE RANGE OF THERMAL OUTPUT</td><td colspan="2">. CORROSIVE AND PYROPHORIC COOLANT</td></tr>
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   . SEPARATION AND PURGE OF THE GASEOUS PRODUCTS (HELIUM FROM (N, α) REACTIONS)
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<tr><td colspan="2">. LARGE COOLANT HEAT CAPACITY AND CONSEQUENT SIGNIFICANT CORE THERMAL INERTIA</td><td colspan="2" rowspan="3">. ALL CORE INTERNAL AND SUPPORT STRUCTURES WORK AT A TEMPERATURE EXCEEDING 1 200°C
   . COMPATIBILITY WITH AN ALLOWABLE CREEP RATE OF THE VESSEL ?
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IMPETUS FOR A LIQUID METAL COOLED REACTOR AS A HEAT SOURCE FOR ANY TYPE OF SEPARATE CONVERSION LOOP

LIQUID METAL COOLED REACTOR

ADVANTAGES	DRAWBACKS
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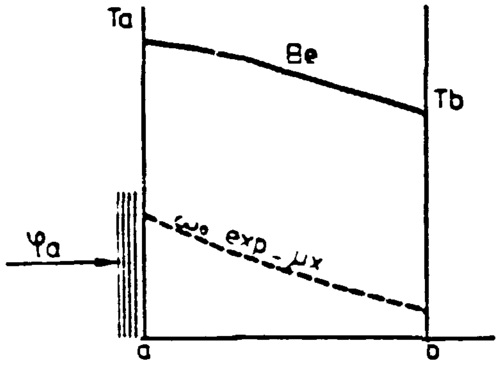
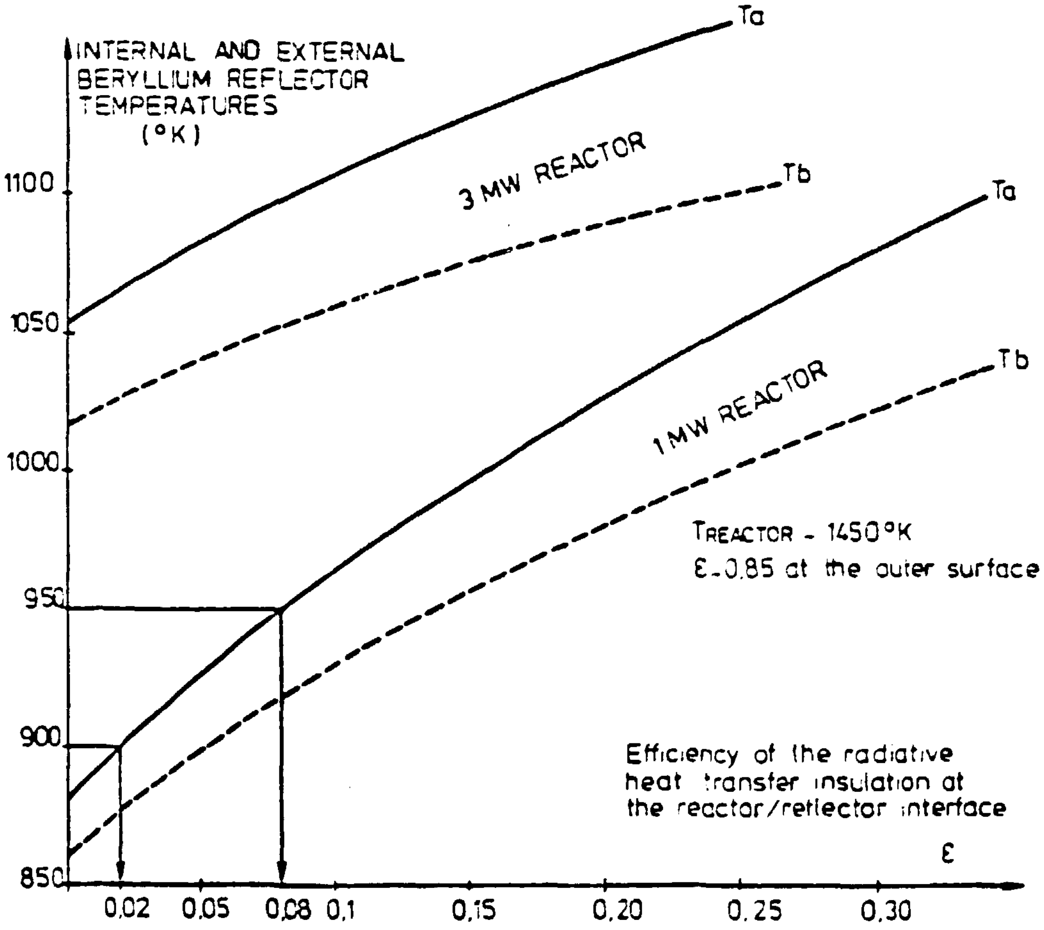
RADIAL REFLECTOR THERMAL BALANCE



BERYLLIUM TECHNOLOGICAL LIMITATIONS
→ Ta<950°K $\Phi .t < 5 - 10^{21}$ n/cm2
→ Ta<900°K $\Phi .t < 10^{22}$ n/cm2

→ Restriction on the radiative heat transfer from the reactor vessel / minimum required efficiency of the multifoil insulation

→ Restriction on the thickness of the reflector trade off with the desired neutronic efficiency



A passively cooled beryllium reflector may be considered for a 1MW reactor, provided a multifoil insulation efficiently limit the flux radiated by the reactor vessel(W,Mo,C,j)

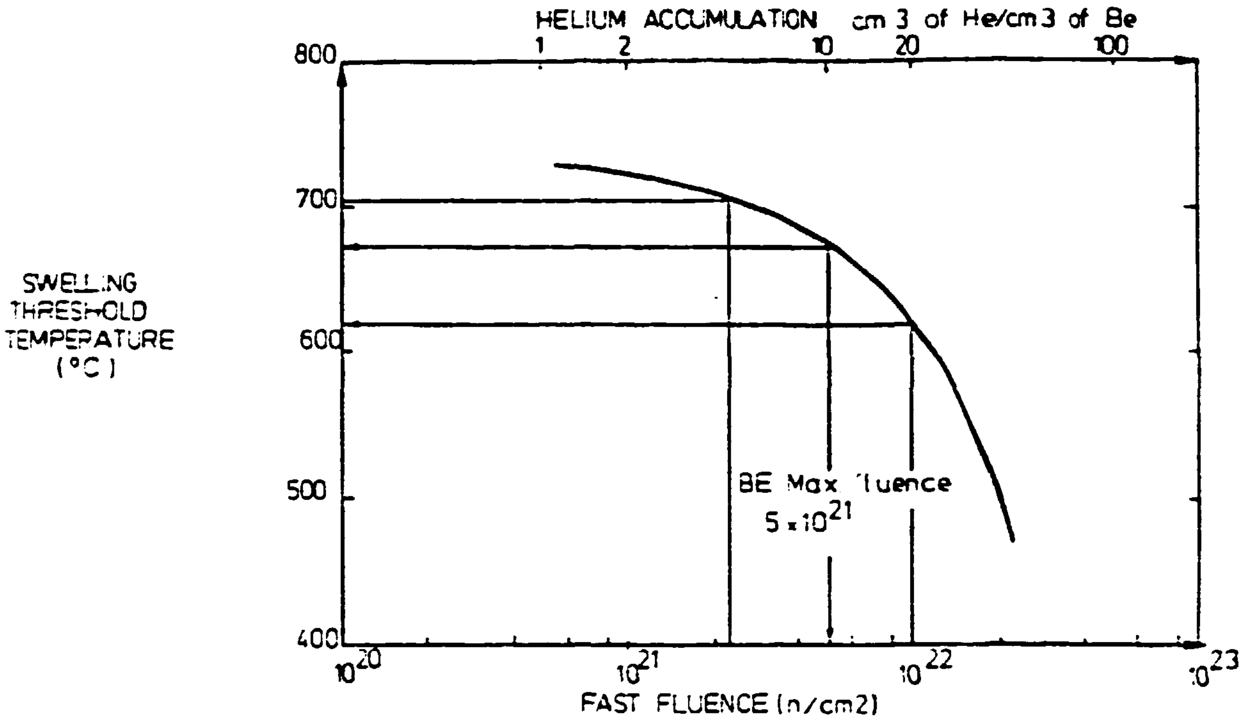
T < 900°K → { ε<0.02 FOR TREACTOR - 1450° K
ε<0,1 FOR TREACTOR - 1100° K

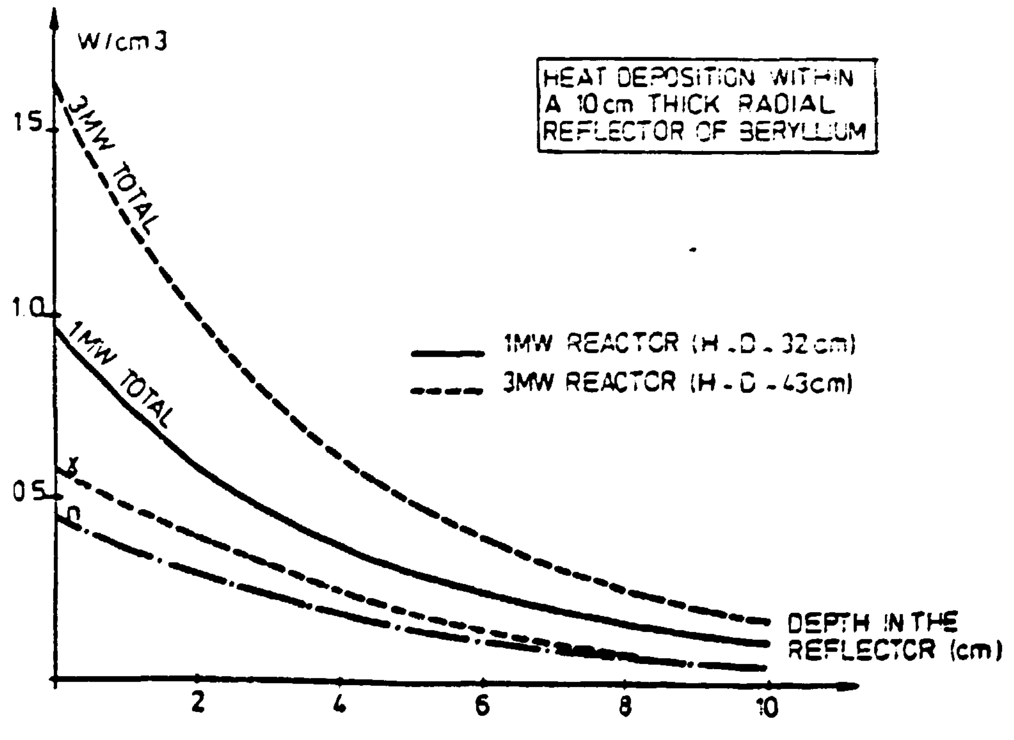
Alternative reflector materials (BeO) featured by extended technological performances should be considered for a reactor power exceeding 2MW

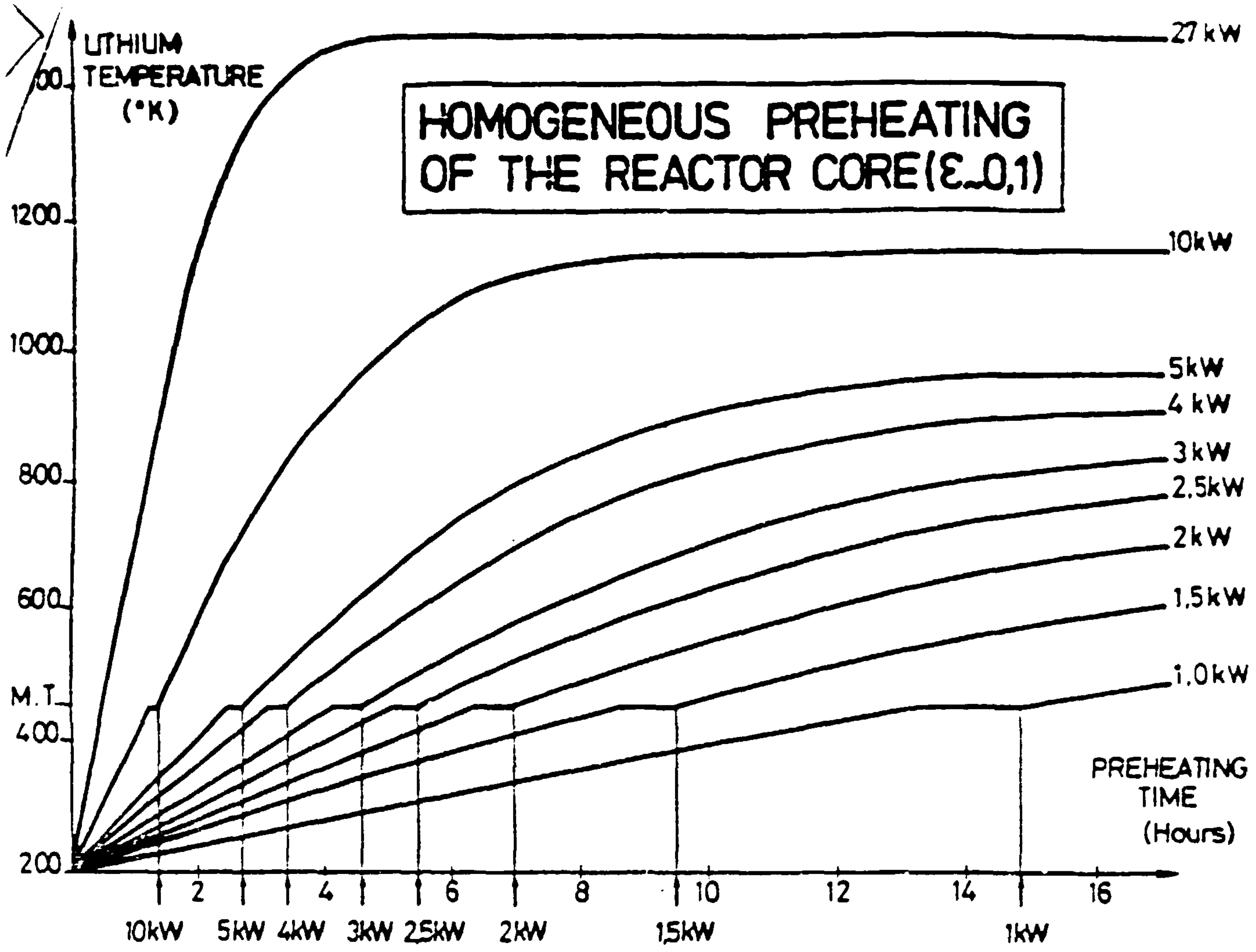
→ Mass penalty
→ Impact upon the available control worth ?

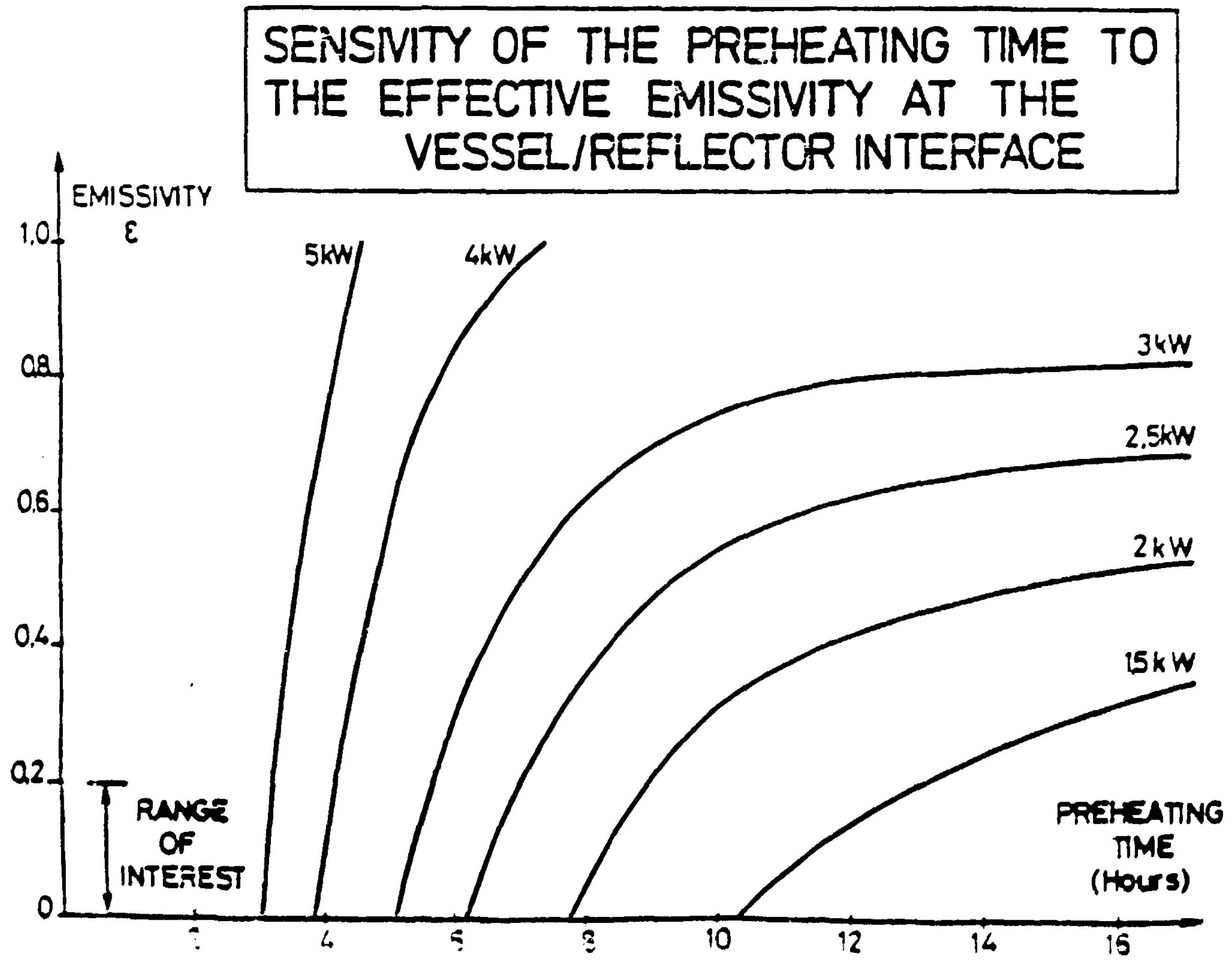
IMPACT OF THE BERYLLIUM TECHNOLOGICAL LIMITATIONS UPON THE DESIGN OF THE RADIAL REFLECTOR

BERYLLIUM TEMPERATURE LIMITATION AS A FUNCTION OF THE FAST FLUENCE





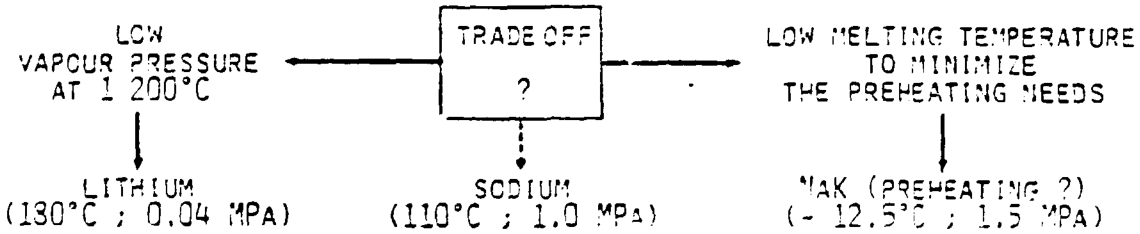

HOMOGENEOUS PREHEATING OF THE REACTOR CORE (ε~0,1)


SENSIVITY OF THE PREHEATING TIME TO THE EFFECTIVE EMISSIVITY AT THE VESSEL/REFLECTOR INTERFACE

LIQUID METAL COOLED REACTOR CONCEPT

REVIEW OF THE MAIN CANDIDATE COOLANTS

PRESSURE (MPA)	LITHIUM	SODIUM	POTASSIUM	EUTECTIC NAK	MERCURY
MELTING T(°C)	180.54	97.81	63.25	- 12.5	
500°C		5.3×10^{-4}	4.0×10^{-3}	2.9×10^{-3}	1.037
750°C	2.3×10^{-4}	2.59×10^{-2}	9.37×10^{-2}	7.09×10^{-2}	
1 000°C	6.7×10^{-3}	0.267	0.604	0.491	28.61
1 250°C	6.55×10^{-2}	1.255	2.054	1.785	
1 500°C	0.340				



LOW
VAPOUR PRESSURE
AT 1 200°C

TRADE OFF
?

LOW MELTING TEMPERATURE
TO MINIMIZE
THE PREHEATING NEEDS

LITHIUM
(180°C ; 0.04 MPA)

SODIUM
(110°C ; 1.0 MPA)

NAK (PREHEATING ?)
(- 12.5°C ; 1.5 MPA)

THE LOW LITHIUM VAPOUR PRESSURE AT THE OPERATING TEMPERATURE IS ONLY BENEFICIAL, IF THE HELIUM PRODUCED BY (N, α) REACTIONS CAN BE EFFICIENTLY SEPARATED FROM THE COOLANT AND PURGED TO PREVENT ANY PROGRESSIVE PRESSURIZATION OF THE PRIMARY CIRCUIT.

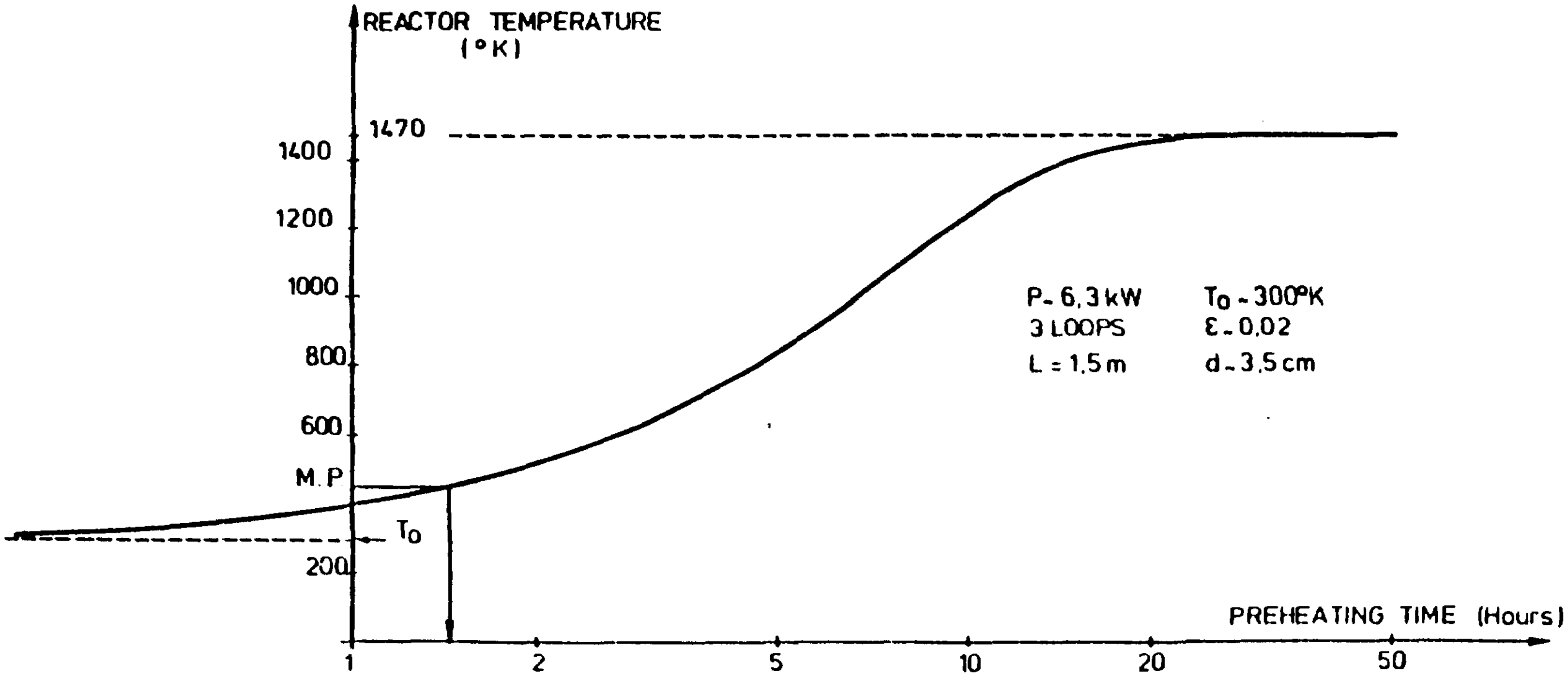
$$({}^{6}\text{LI} + \text{N} \longrightarrow {}^{4}\text{HE} + {}^{3}\text{H} + 4.8\ \text{MEV})$$
$${}^{7}\text{LI} + \text{N} \longrightarrow {}^{4}\text{HE} + {}^{3}\text{H} + \text{N}' - 2.5\ \text{MEV})$$

$$\begin{array}{c} \text{TOTAL} \\ {}^{7}\text{LI CONVERSION} \\ \text{IN A 10Y LIFETIME} \end{array} \left\{ \begin{array}{ll} 450\ \text{APPM} & \text{CORE} \\ 125\ \text{APPM} & \text{REFLECTOR} \\ 40\ \text{APPM} & \text{PLENUM} \end{array} \right\} \sim \begin{array}{c} 0.02\ \% \\ \text{OF THE } {}^{7}\text{LI} \\ \text{REACTOR CONTENT} \end{array}$$

0.047 M^3 OF HELIUM AT 1 200°C UNDER 0.1 MPA

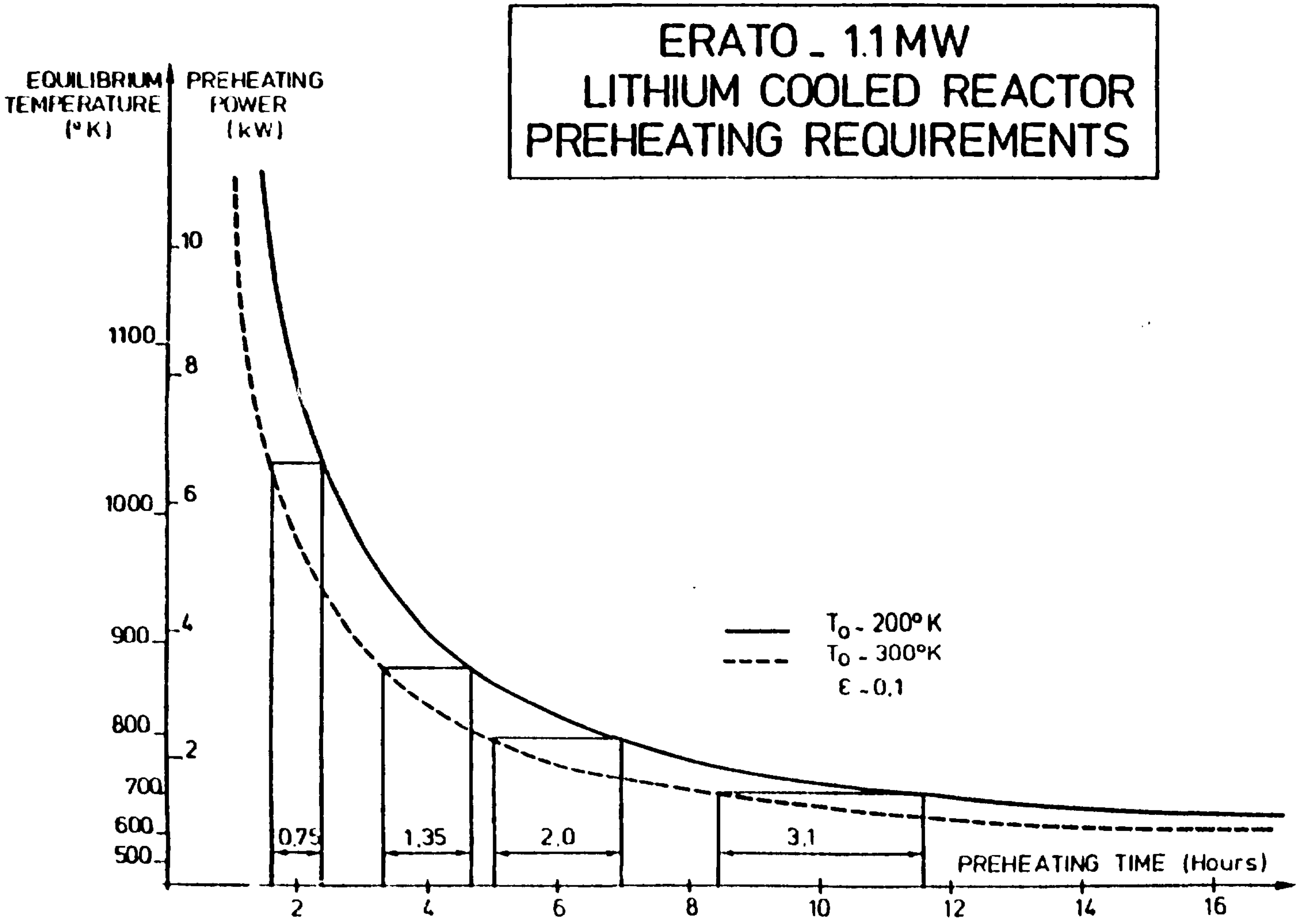
THAWING OF THE LITHIUM LOOPS BY THERMAL CONDUCTION OF THE HEAT GENERATED IN THE REACTOR

REACTOR TEMPERATURE EVOLUTION DURING THE FASTEST REALIZABLE PREHEATING TRANSIENT



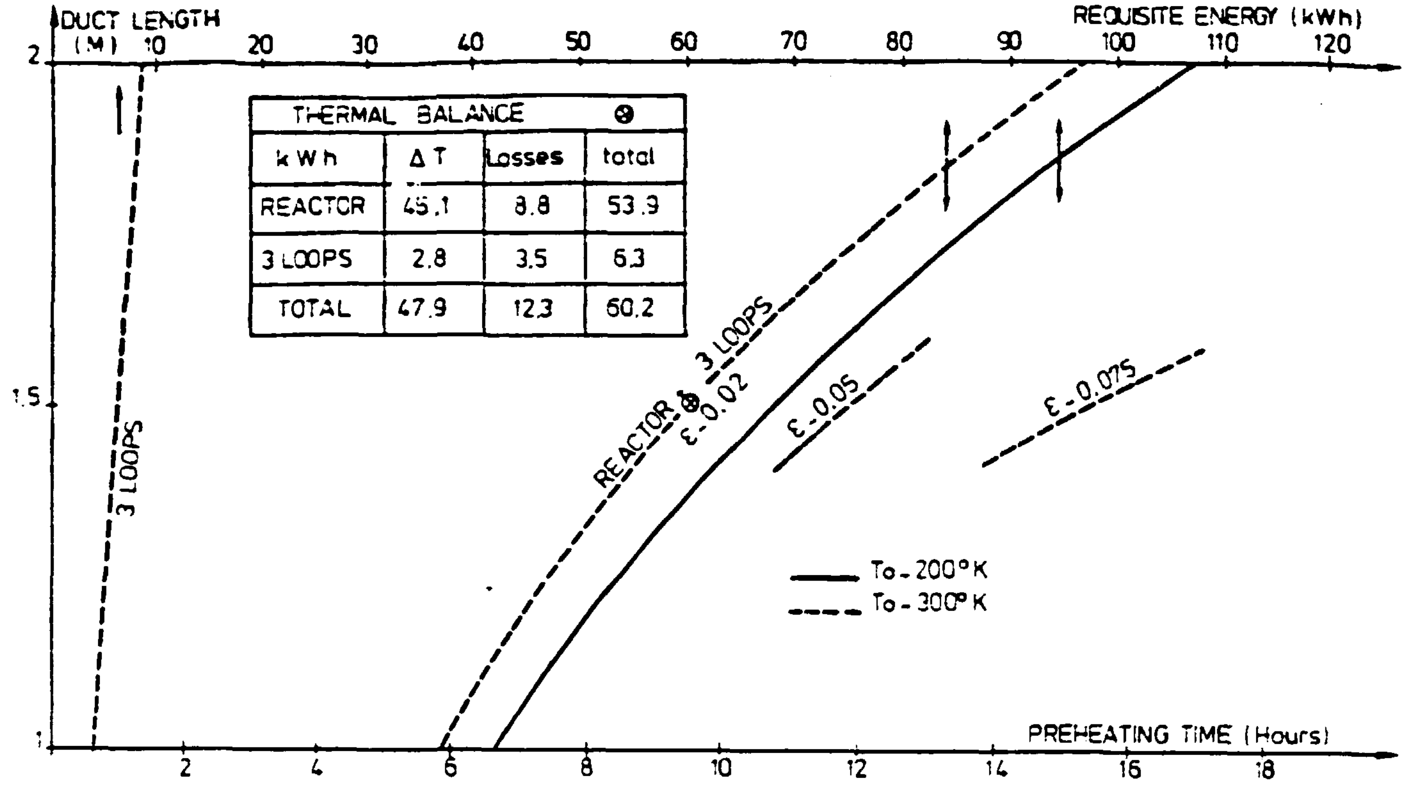
The reactor power is selected so that the maximum temperature in the core never exceeds the nominal operating conditions

$P \leq 6,3$ kW for $T \leq 1470$°K


ERATO - 1.1 MW
LITHIUM COOLED REACTOR
PREHEATING REQUIREMENTS
EQUILIBRIUM TEMPERATURE (°K)
PREHEATING POWER (kW)
1100
1000
900
800
700
600
500
10
8
6
4
2
0.75
1.35
2.0
3.1
T_0 - 200°K
T_0 - 300°K
ε - 0.1
PREHEATING TIME (Hours)
2
4
6
8
10
12
14
16

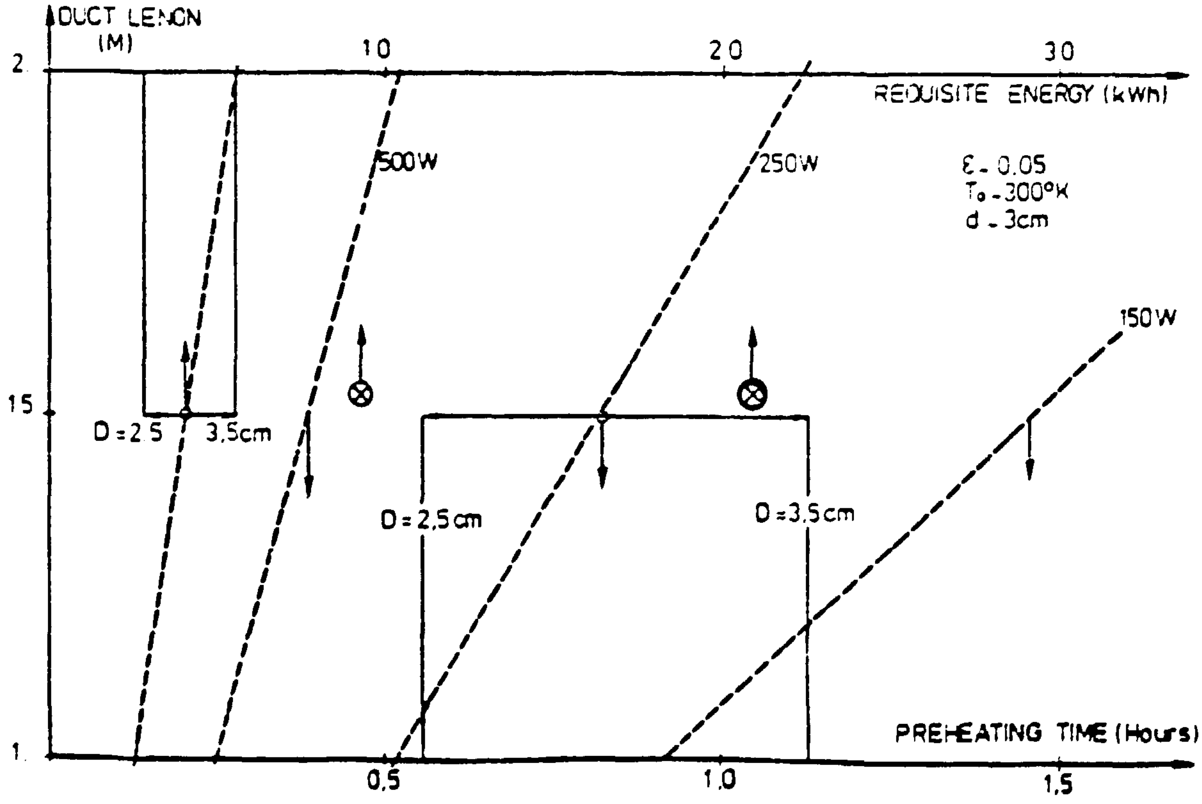
TIME AND ENERGY REQUIREMENTS FOR THAWING THE LITHIUM LOOPS BY CONDUCTION OF THE HEAT GENERATED IN THE REACTOR

PREHEATING REQUIREMENTS WITH THE REACTOR OPERATING ΔT 6,3kW AS UNIQUE HEAT SOURCE



THERMAL BALANCE			⊗
kWh	ΔT	Losses	total
REACTOR	45.1	8.8	53.9
3 LOOPS	2.8	3.5	6.3
TOTAL	47.9	12.3	60.2

PREHEATING REQUIREMENTS WITH AN ACTIVE HEATING OF EACH SINGLE LITHIUM LOOP

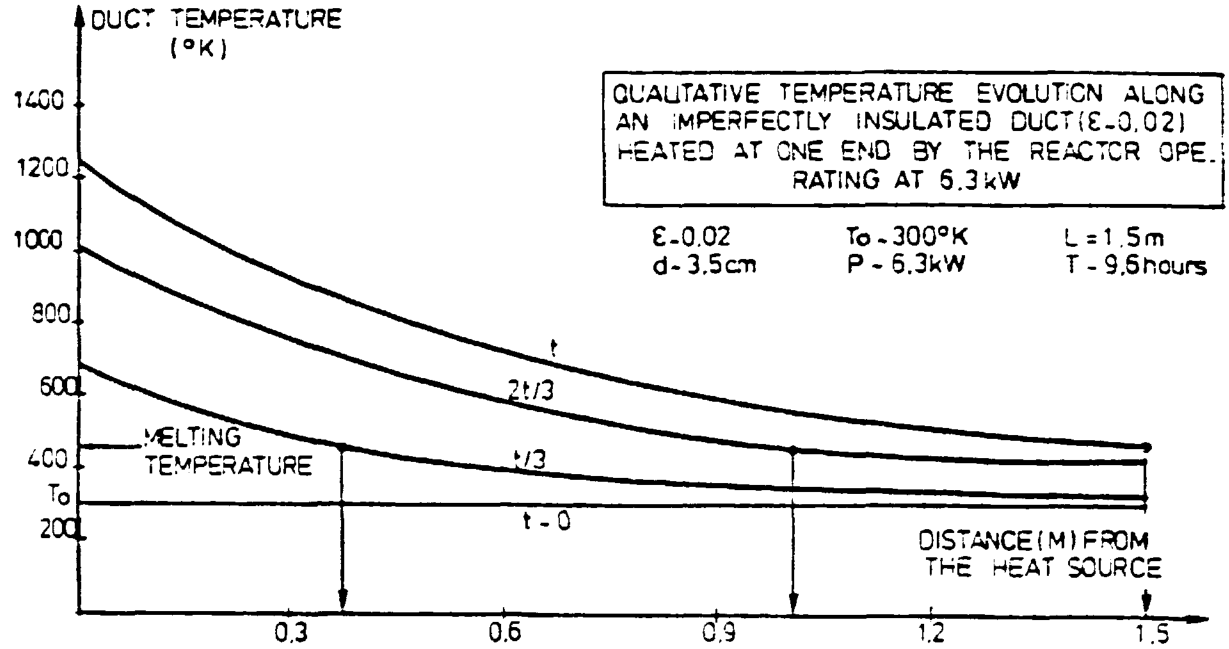


⊗ Useful and ⊗ total energy requirement for conductive heating (ε - 0,02, d - 3,5cm)

THAWING OF THE LITHIUM LOOPS BY THERMAL CONDUCTION OF THE HEAT GENERATED IN THE REACTOR

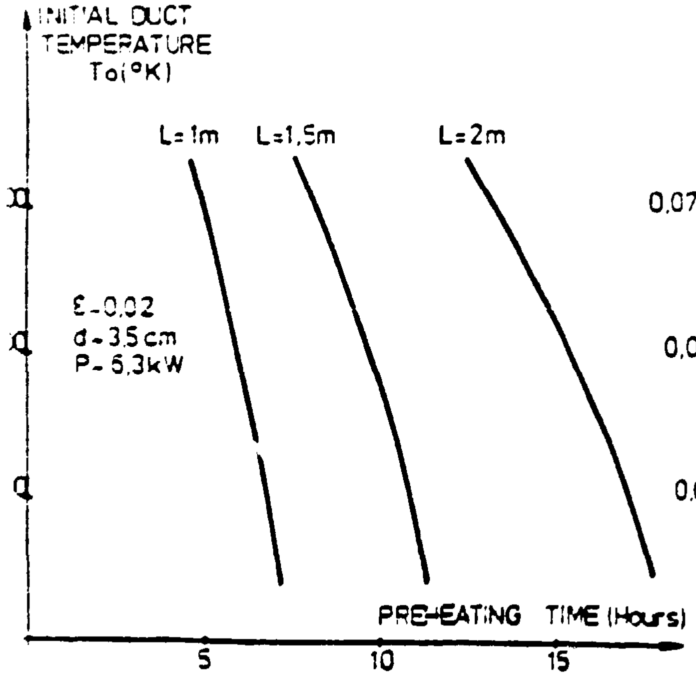
SENSITIVITY OF THE PREHEATING REQUIREMENTS TO THE DUCT CHARACTERISTICS

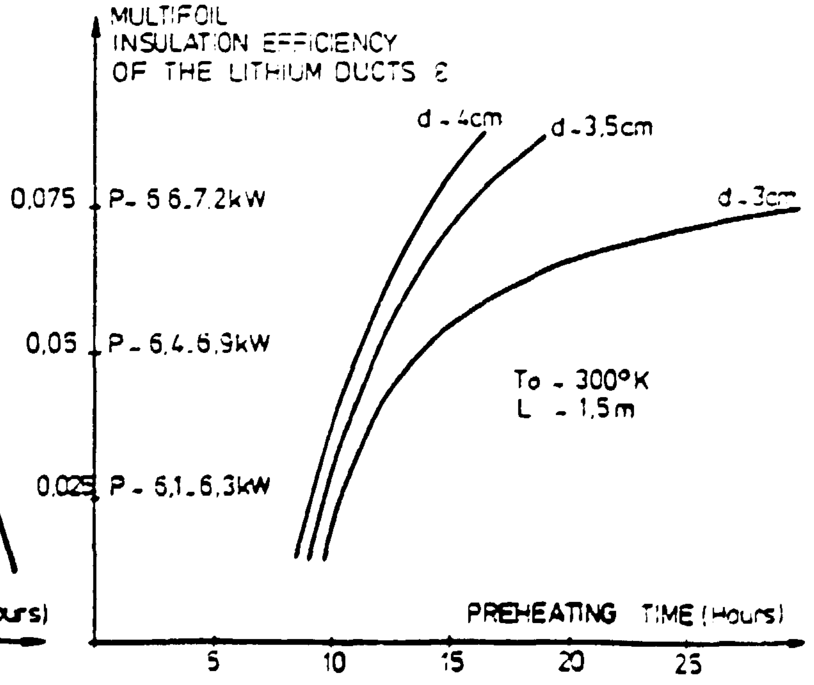
- GEOMETRY (DIAMETER, LENGTH) d, 2 × L
- MULTIFOIL INSULATION EFFICIENCY ε
- INITIAL TEMPERATURE T_0



QUALITATIVE TEMPERATURE EVOLUTION ALONG AN IMPERFECTLY INSULATED DUCT (ε - 0.02) HEATED AT ONE END BY THE REACTOR OPERATING AT 6.3 kW

ε - 0.02 To - 300°K L = 1.5 m
d - 3.5 cm P - 6.3 kW T - 9.6 hours





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• QUASI ISOTHERMAL HEAT TRANSFER TO ANY TYPE OF SEPARATE CONVERSION LOOP
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LIQUID METAL COOLED REACTOR CONCEPT PREHEATING OF THE PRIMARY LOOPS

<table>
<tr><th></th><th>PREHEATING REQUIREMENTS</th><th colspan="2">OPTIONS</th><th>COMMENTS</th></tr>
<tr><td rowspan="5">REACTOR ONLY</td><td rowspan="5">START UP ≤ 1 DAY
LIMITED UNCERTAINTY ON THE THAWING TIME
REASONABLE MARGIN OF EQUILIBRIUM TEMPERATURE ABOVE 500°K
} P ≥ 1 KW
$T_\infty \leqslant 1470$°K WITH $\varepsilon \sim 0.02 \rightarrow P \leqslant 5.4$ KW
P ∿ 3 KW { 12 KWH 300 → 500°K
16 KWH 200 → 500°K</td><td colspan="2">REACTOR DIVERGENCE</td><td>POWER CONTROL ? (≤ 5 KW)</td></tr>
<tr><td rowspan="2">ELECTRIC PRE-HEATING</td><td>APU</td><td>RESTARTABLE ?</td></tr>
<tr><td>RTG</td><td>$\eta \sim 5$ % 150 KG $^{8}PuO_2$?
COST</td></tr>
<tr><td rowspan="2">RADIOISOTOPES $^{8}PuO_2$ AS HEAT SOURCE</td><td>FUEL</td><td>7.5 KG $^{8}PuO_2$ (7 % PuO_2 IN UO_2
CONDITIONING ? VENTING ?
FUEL DISPERSION ?
HANDLING A REACTOR AT 500°</td></tr>
<tr><td>SPECIAL DEVICES</td><td>HEATING RODS ?
HEATING CENTRAL PLUG ?</td></tr>
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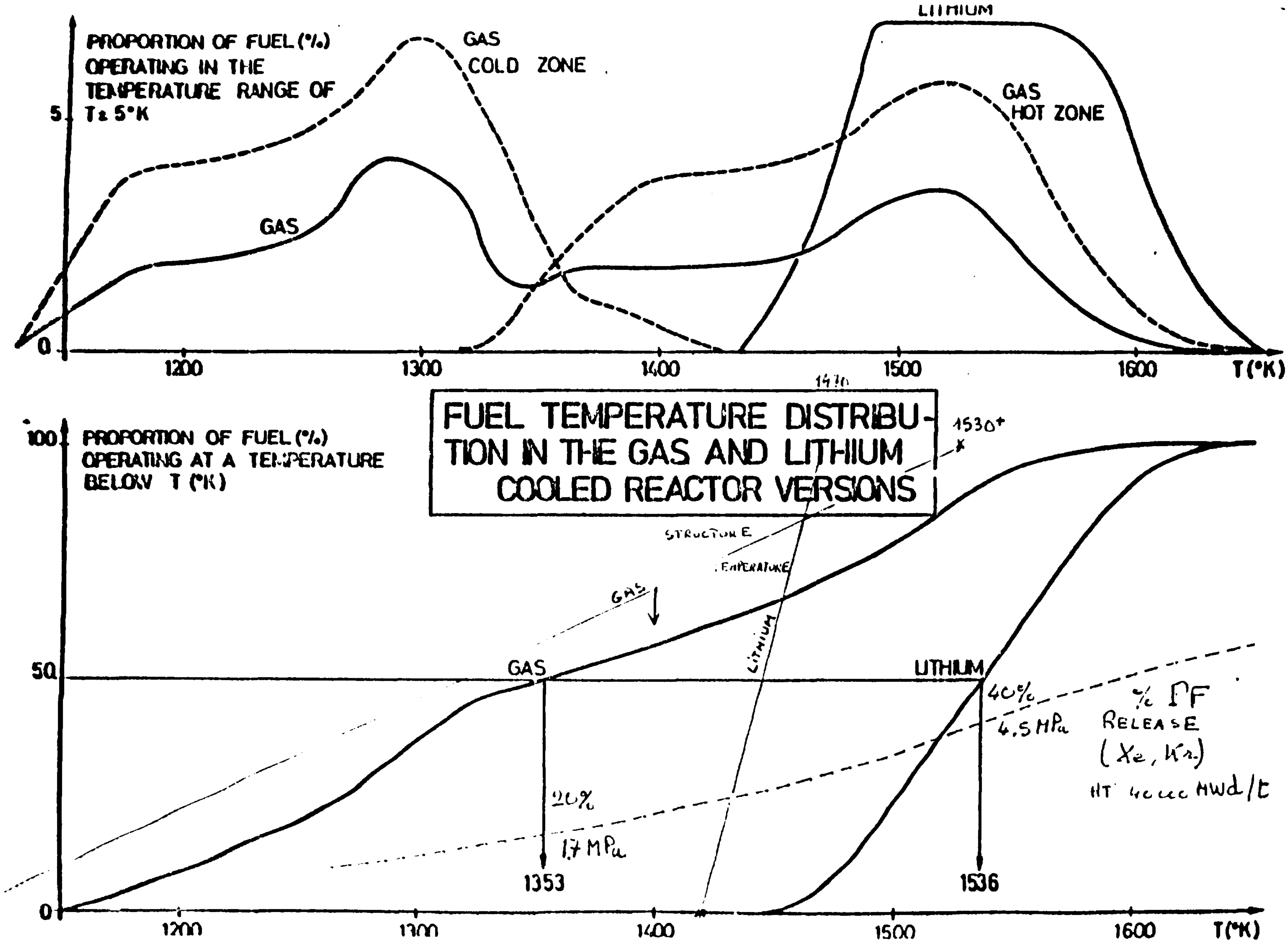
$\varepsilon \sim 0.02$.
THAWING TIME ∿ 9.6 HOURS.<table><tr><th>KWH</th><th>HEATING</th><th>WASTE</th><th>TOTAL</th></tr><tr><td>REACTOR</td><td>45.1</td><td>8.8</td><td>53.9</td></tr><tr><td>3 LOOPS</td><td>3 x 0.93</td><td>3 x 1.17</td><td>3 x 2.1</td></tr><tr><td>TOTAL</td><td>47.9</td><td>12.3</td><td>60.2</td></tr></table></td><td colspan="3">NECESSITY OF AN EXCELLENT DUCT MULTIFOIL INSULATION ($\varepsilon \leqslant 0.05$).
CONSTRAINTS UPON THE DUCT DIAMETER AND LENGTH.
TIME AND ENERGY REQUIREMENTS FOR A SINGLE LOOP ($\varepsilon \sim 0.02$, L = 2 x 1.5 M, D ∿ 3 TO 4 CM)
8 - 10 HOURS AND 2. TO 3 KWH WITH AN EFFICIENC OF 40 % TO HEAT THE LITHIUM.
ABOUT PROPORTIONAL TO $L^{1.4}$.</td></tr>
<tr><td rowspan="4">THAWING BY DIRECT HEAT DEPOSITION WITHIN THE LITHIUM LOOPS.</td><td rowspan="4">ENERGY REQUIREMENT FOR A SINGLE LOOP
($\varepsilon \sim 0.02$, L = 2 x 1.5 M, D = 3 TO 4 CM)
0.5 KWH WITH AN EFFICIENCY OF 90 % TO HEAT THE LITHIUM.
ABOUT PROPORTIONAL TO L.</td><td rowspan="2">ELECTRIC PRE-HEATING</td><td>APU</td><td>RESTARTABLE ?</td></tr>
<tr><td>RTG</td><td>$\eta \sim 5$ % 75 KG $^{8}PuO_2$?
COST</td></tr>
<tr><td colspan="2">$^{8}PuO_2$ COLLARS</td><td>2 TO 4 KG $^{8}PuO_2$?</td></tr>
<tr><td colspan="3">HEAT TRANSPORT FROM THE REACTOR BY HEAT PIPES</td></tr>
<tr><td rowspan="2">PRIMARY HEAT EXCHANGER</td><td rowspan="2">A FEW KWH.</td><td colspan="2">ELECTRIC PREHEATING</td><td>APU</td></tr>
<tr><td colspan="2">$^{8}PuO_2$ HEAT SOURCE</td><td>2.5 KG $^{3}PuO_2$/KW</td></tr>
</table>

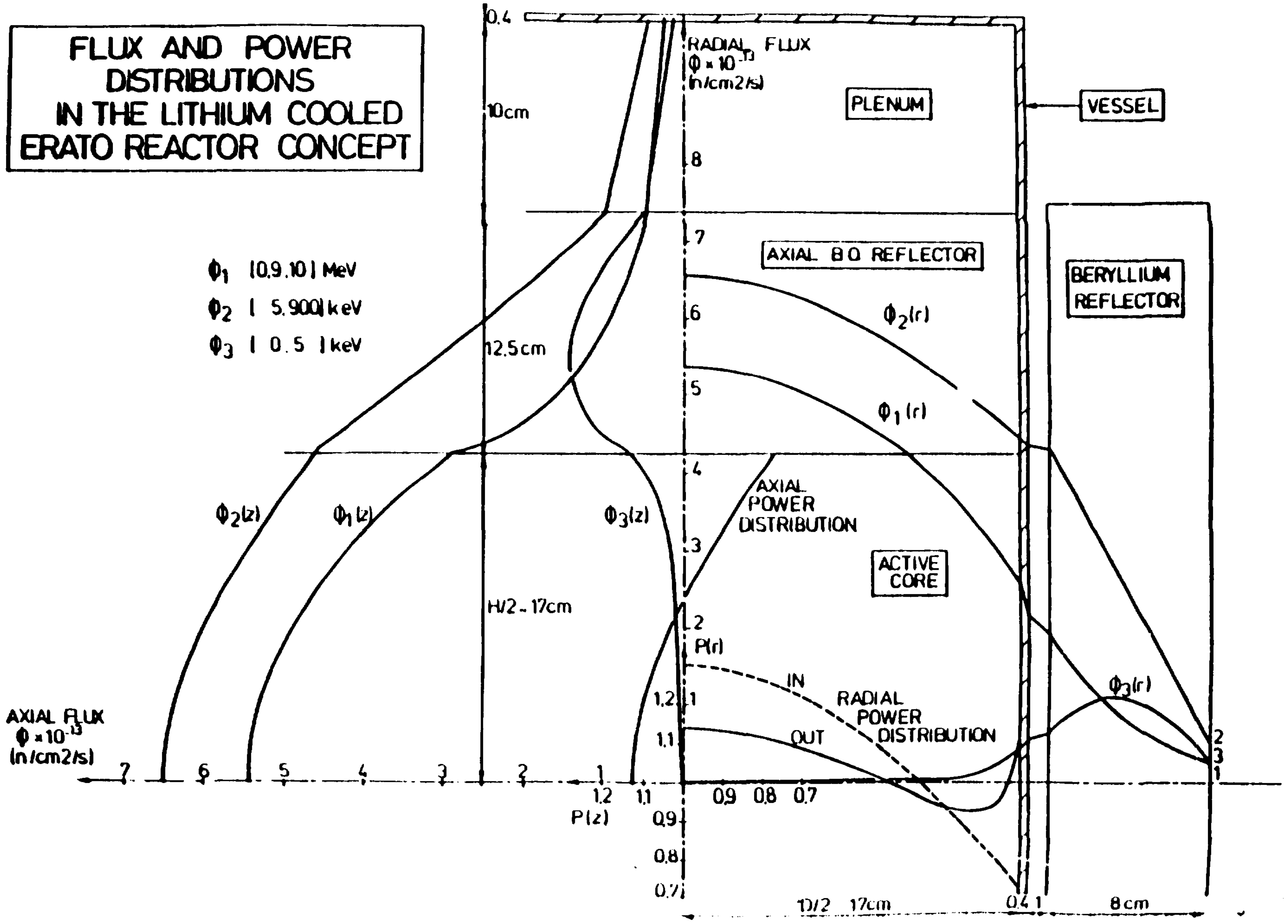
PRESENTLY CONSIDERED PREHEATING SCENARIO :

- THAWING OF THE REACTOR CONTENT BY DIVERGENCE AND STABILIZATION AT LOW POWER (≤ 5 KW)
- ELECTRICAL HEATING OF THE LITHIUM LOOPS AND OF THE PRIMARY HEAT EXCHANGER AUXILIARY POWER UNIT TO BE DEFINED.



FUEL TEMPERATURE DISTRIBUTION IN THE GAS AND LITHIUM COOLED REACTOR VERSIONS

FLUX AND POWER DISTRIBUTIONS IN THE LITHIUM COOLED ERATO REACTOR CONCEPT



REACTOR CONTROL AND MASS BALANCE

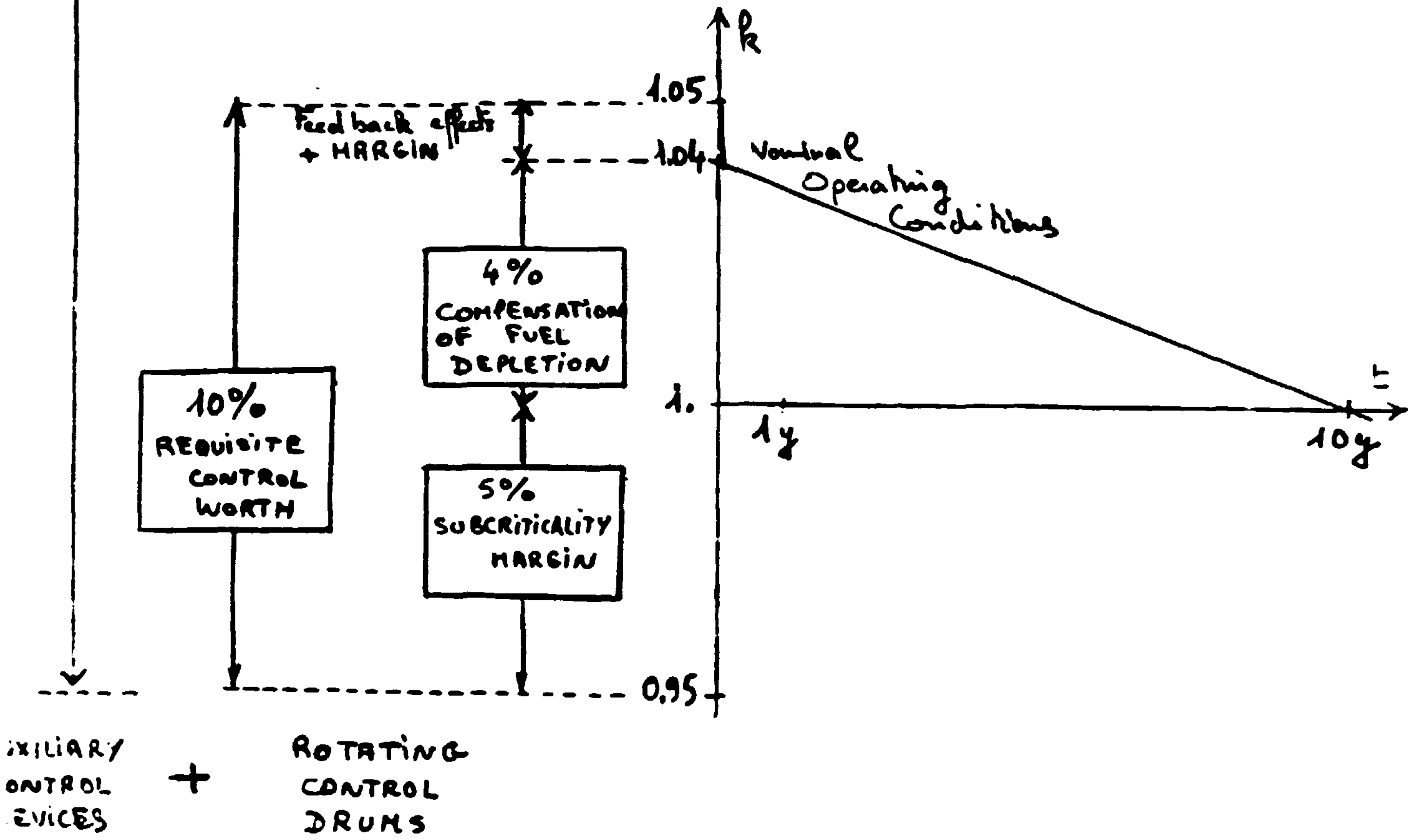
$k \sim 1.05$
OUT

0.95×0.98 UO_2 t_D	CORE RADIUS (cm)	k DRUMS IN	IMMERSION		Δρ IMMERSION	GAIN ON Δρ	POISON WORTH		GAIN ON Δρ / MASS PENALTY	REACTOR MASS (kg)
			OUT	IN			NOMINAL	IMMERSION		
44.4% UO_2	36.75	0.946	1.213	1.174	+14.5 %					460
40.6% UO_2 + 3.8% $^{10}B_4C$	48.1	0.978	0.938	0.920	−11.3 %	25.8 %	18.2 %	35.0 %	60 pcm/kg	890
38.2% UO_2 + 6.2% Gd_2O_3	42.1	0.955	1.132	1.102	+7.5 %	7.0 %	9.8 %	12.1 %	40 pcm/kg	640
49% UO_2	33.9	0.944	1.191	1.145	+12.5 %					400
44.8% UO_2 + 4.2% $^{10}B_4C$	44.6	0.977	0.957	0.935	−9.3 %	21.8 %	17.9 %	32.2 %	60 pcm/kg	770

EXTRAPOLATED DESIGN FEATURES FOR $k \sim 1.05$ (OUT) IN NORMAL CONDITIONS
AND $k \sim 0.95$ (IN) IN CASE OF IMMERSION

	44.4% UO_2	44.4% {UO_2 + $^{10}B_4C$}	44.4% {UO_2 + Gd_2O_3}	49% UO_2	49% {UO_2 + $^{10}B_4C$}
FUEL POISONING (V_p/V_F)%	ACTIVE AUXILIARY CONTROL DEVICE	7.5%	30%	ACTIVE AUXILIARY CONTROL DEVICE	8%
CORE RADIUS (cm)	36.75	46.8	53.5	33.9	43.9
REACTOR WEIGHT (Kg)	460 +	845	1025	400 +	745

SPACE REACTOR REACTIVITY BALANCE



INVESTIGATION OF LEADING PARAMETERS FOR THE REACTOR CONTROL AND MASS BALANCE

- FUEL FILLING FACTOR (NEUTRON LEAKAGE → >40% UO_2)

CONTROL WORTH IN NORMAL OPERATING CONDITIONS

- ABSORBER SEGMENTS GEOMETRY AND ^{10}B CONTENT
- REACTOR VESSEL THICKNESS

CONTROL WORTH IN CASE OF IMMERSION

- POROSITY OF THE CORE/REFLECTOR INTERFACE
- EFFECT OF DISPERSED POISON (Gd_2O_3 – $^{10}B_4C$ IN THE CORE LATTICE) AND ASSOCIATED REACTOR MASS PENALTY
- EFFECT OF HETEROGENEOUS CONTROL DEVICES (CENTRAL PLUG/ CONTROL RODS ---)

REACTOR CONTROL AND MASS BALANCE

k∼1.05
OUT

0.95×0.98 UO_2 t_D	CORE RADIUS (cm)	k DRUMS IN	IMMERSION		Δρ IMMERSION	GAIN ON Δρ	POISON WORTH		GAIN ON Δρ / MASS PENALTY	REACTOR MASS (kg)
			OUT	IN			NOMINAL	IMMERSION		
44.4% UO_2	36.75	0.946	1.213	1.174	+14.5%					460
40.6% UO_2 + 3.8% $^{10}B_4C$	48.1	0.978	0.938	0.920	−11.3%	25.8%	18.2%	35.0%	60pcm/kg	890
38.2% UO_2 + 6.2% Gd_2O_3	42.1	0.955	1.132	1.102	+7.5%	7.0%	9.8%	12.1%	40pcm/kg	640
49% UO_2	33.9	0.944	1.190	1.145	+12.5%					400
44.8% UO_2 + 4.2% $^{10}B_4C$	44.6	0.977	0.957	0.900	−9.3%	21.8%	17.9%	32.2%	60pcm/kg	770

EXTRAPOLATED DESIGN FEATURES FOR k∼1.05 (OUT) IN NORMAL CONDITIONS
AND k∼0.95 (IN) IN CASE OF IMMERSION

	44.4% UO_2	44.4% $\left\{ UO_2 + {}^{10}B_4C \right.$	44.4% $\left\{ UO_2 + Gd_2O_3 \right.$	49% UO_2	49% $\left\{ UO_2 + {}^{10}B_4C \right.$
FUEL POISONING (V_P/V_F)%	ACTIVE AUXILIARY CONTROL DEVICE	7.5%	30%	ACTIVE AUXILIARY CONTROL DEVICE	8%
CORE RADIUS (cm)	36.75	46.8	53.5	33.9	43.9
REACTOR WEIGHT (Kg)	460 +	845	1025	400 +	745

LEADING PARAMETERS FOR REACTIVITY CONTROL AND MASS BALANCE

44.4% UO_2 $\frac{V_m}{V_f} \sim 0.94$ 49% UO_2 $\frac{V_m}{V_f} \sim 0.75$		MASS BALANCE	CONTROL WORTH CONTROL DRUMS + AUXILIARY DEVICES NORMAL CONDITIONS	 IMMERSION	COMMENTS	G	L
FUEL FILLING FACTOR (V_{fuel}/V_{core})		-60 kg/4.6%	Weakly dependent (Same reactivity → same leakage)	POROSITY	Search for maximum UO_2% compatible with cooling conditions	? cooling	!
MODERATOR TO FUEL RATIO (V_m/V_f)				2% (0.94 → 0.75)	Easier control of the immersed reactor with a lower porosity, provided the integrity of the core geometry be kept		!
DISPERSED CORE POISONING	$^{10}B_4C$ 2% in UO_2	+430 kg/10.2% +370 kg/17.9%	-3.3%/18% ($\frac{V_p}{V_f} \sim 85\%$) (-20%) DROP OF k_∞ AND LEAKAGE	25.8%/10.2% 21.8%/17.9%	• Inherent safety $(V_m/V_f)\uparrow$ $k\downarrow$ • Excessive mass penalty for low power reactors (1MW) → Low specific power	? Flooding of the bypass channel	
	Natural Gd_2O_3 10% in UO_2	+120 kg/9.2%	-0.9%/10% ($\frac{V_p}{V_f} \sim 11\%$) (-6%) SLIGHT DROP OF CORE LEAKAGE	7%/9.2%	Minimum penalty → Increase % UO_2 → ^{10}B or ^{157}Gd		
HETEROGENEOUS CONTROL DEVICES	CENTRAL PLUG $\phi \sim 7.5$ cm	+60 kg/460 kg +50 kg/400 kg	~ + 20%		• Upper limit upon the acceptable porosity of the fuel lattice + core/plug interface • Complexity of a toric vessel		
	CONTROL RODS				• Complexity of rod actuators and mechanisms • Penetrations across the reactor vessel		

Poisoning of the Radial baffle

PRESENT TRENDS :
- INCREASE THE FUEL PROPORTION BEYOND 50%
- REDUCE THE CORE POROSITY + THAT OF CORE/REFLECTOR INTERFACE
- THE CHOICE OF THE CANDIDATE OPTIONS TO MAINTAIN THE REACTOR SUBCRITICAL IN CASE OF IMMERSION REMAINS OPEN

LIQUID METAL VERSUS GAS COOLED REACTOR AS HEAT SOURCE FOR A REFERENCE BRAYTON CYCLE

GAS [733; 1127] °C 2.25 MPa	LITHIUM COOLED REACTOR		GAS COOLED REACTOR	
START UP	?	PREHEATING - THAWING	!	IMMEDIATE READINESS
ADAPTABILITY TO VARIOUS CONVERSION SYSTEMS	!		?	PRIVILEGED ADAPTATION TO DIRECT GAS CYCLES
FUEL ELEMENT OPERATING CONDITIONS : T	?	Whole structure > 1200°C	?	Peak 1260 °C
ΔT	!	Quasi isothermal		Axial gradients (~200°C)
Pressure	?	Fission Gas Release		Coolant
Corrosion	?			
CONSEQUENCE OF CLAD FAILURE	?	UO_2 / Li → UN ?	—	
COOLANT PURIFICATION	?	HELIUM COLD TRAP (Corrosion products)	!	
STRUCTURE OPERATING T	?	T > 1200°C { Creep rate ? Multifoil insulation ?	?	< 30% T > 1200 C Control of peak Temperature ?
PRESSURE	—	Low vapour pressure (+He ?)		Heat Transfer versus pumping power
HEAT TRANSFER	!	Quasi isothermal	?	
POTENTIAL FOR EXTRAPOLATION	!	Well adapted to a wide range of thermal output	—	Limited potential for an increased specific power beyond 10 W/gU
THERMAL INERTIA	!			
REMOVAL OF AFTER HEAT	—	Passive (TEM Pumps)	—	Active (Compressors)
PUMPING POWER RATIO	!	Low	—	High
DESIGN COMPLEXITY			?	Double passes
SUBCRITICALITY IN CASE OF IMMERSION	—		?	
VESSEL THICKNESS FUEL DISPERSION (REENTRY) DRUMS CONTROL WORTH	—		?	Questionable compatibility of 2-3 MPa pressurized vessel with allowable Creep rate Thickness ↑ Control worth ↓
DESIGN OF REFLECTOR AND NEUTRON SHIELD COMPATIBLE WITH THE MATERIALS TECHNOLOGICAL LIMITS	—			

CRUCIAL ISSUES COMMON TO BOTH LITHIUM OR GAS COOLED REACTORS

- START UP
- REACTOR SUBCRITICALITY IN TYPICAL LAUNCHING CONDITIONS AND IN ACCIDENTAL CONFIGURATIONS (IMPACT, IMMERSION)
- REMOVAL OF THE AFTER HEAT
- COOLING ACCIDENTS
- DIVISION AND DISPERSION OF THE FUEL ELEMENTS IN CASE OF REENTRY
- DESIGN OF THE REFLECTORS AND NEUTRON SHIELD COMPATIBLE WITH THE MATERIALS TECHNOLOGICAL LIMITS

TECHNOLOGY DEVELOPMENTS

- MATERIALS
    - FUEL (REFRACTORY ALLOYS, FUEL/CLADDING/COOLANT INTERACTION)
    - STRUCTURE
    - LITHIUM (CORROSION)
    - MULTIFOIL INSULATORS (COMPATIBILITY WITH HIGH TEMPERATURE)
    - REFLECTOR (BE, BEO, B_4C, GRAPHITE)
- INSTRUMENTATION
    - COMPATIBILITY WITH THE REQUISITE OPERATING TEMPERATURE
    - MINIATURIZATION
    - LOW POWER RESPONSE
- METAL/GAS SEPARATION (SPECIFIC TO LITHIUM COOLED CONCEPTS)