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CONCEPT, DESIGN APPROACHES SUITED TO SPACE NUCLEAR POWER SYSTEMS IN THE RANGE OF 20 kWE

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ABSTRACT

Given the variety of possible missions and flight dates, it seems advisable to widen the basis for future technical choices within the French preliminary studies of 20-kWe space nuclear power systems. In addition to the fast spectrum, liquid metal-cooled reactor presently considered as a reference, shorter development term system, gas- and Na(K)-cooled thermal spectrum reactors are being investigated. The need for adequate ZrH moderator temperature conditions can be satisfied through a Brayton cycle conversion subsystem featuring two separate, high temperature-heat pipes and low temperature-pumped loop radiators. The penalty in efficiency and in radiator area, resulting from the wanted lower reactor inlet temperature, can be limited, particularly in the case of the higher temperature, gas-cooled reactor system. A multiple, pivoting tubes, low temperature radiator concept is proposed; it avoids an extension of the related structural support frame beyond the conversion subsystem region in flight configuration. Arrangements peculiar to small reactors and two-turbogenerator diagrams for reliability reasons are presented. Provisional, not yet optimized, thermal management mass estimates are evaluated.

1. INTRODUCTION

In Europe, in spite of the strong growth of the space program, on board power systems adequate for future ambitious missions remain to be developed, and particularly the potential of nuclear energy sources has still to be emphasized. Power levels of 15- to 20- kWe should be considered at first.

Moreover, the preliminary studies of space nuclear power systems carried out in France since six years have lead to a better understanding of the challenge to be taken up. This field of research should be carefully tackled and many points are worth thinking about. It is the reason why, in addition to the basic work performed within the present French program as described in the companion papers [1], [2] and in the previous papers [3], [4], [5], further investigations should be useful. The incentives for that appear in several aspects :

- the date of a first demonstration flight is not known to within five to ten years;
- the lifetime can extend from two years for a Mars exploratory trip to ten years for Earth observation or communication satellites;
- safety and public perception considerations raise issues like intact reentry, nuclear fuel inventory, proliferation risks and loss of coolant accident consequences;
- the required high reliability should determine the number of sensitive components like dynamic converters;
- the suitable adaptation of the waste heat rejection subsystem to the converters, including the generator cooling, is of paramount importance;
- given the variety of missions and the expected requirements for a minimum mass and a maximum pay load dimensions capability, the support structure associated with the larger component the radiator is, should be drastically minimized;
- thermal aggressions, including sun effects and laser beams have to be taken into account, particularly in the case of low temperature radiators.....

This paper deals with topics related to the above-mentioned points. On the basis of a Brayton cycle energy conversion, 1100-1150 K, direct cycle, medium term gas-cooled reactor systems and 900-950 K, indirect cycle, shorter term Na(K)-cooled reactor systems are considered. In both cases, the core is ZrH moderated. Several reasons prompt to use thermal spectrum reactors: a low power level, limited lifetime applications, lighter radiation shielding, small fuel inventory, easier reactor control,etc.... In order to allow an appropriate lifetime resulting from satisfactory moderator temperature conditions, a particular Brayton cycle arrangement is proposed; it involves separate high (H.T.) and low temperature (L.T.) radiators. The L.T. radiator configuration is worth being pointed out : it features a multiple, pivoting tubes concept. The reliability approach adopted for the indirect cycle system is somewhat different from the one suggested for the direct cycle case. The key thermal, thermodynamical data are given. Mass estimates especially concern the thermal management subsystem.

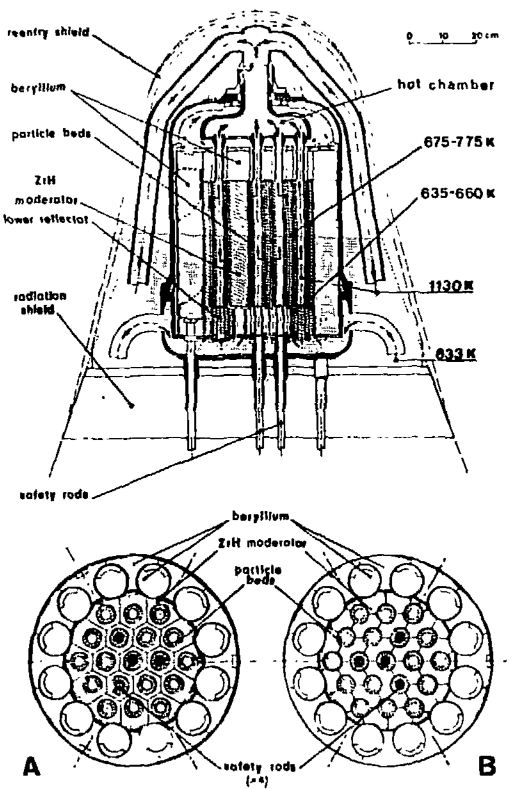
The present work is a follow-up and an expansion of the studies described in papers [6] and [7].

2. 20-kWe GAS-COOLED, DIRECT CYCLE REACTOR SYSTEM

A reactor moderator temperature conditioning, a Brayton cycle adaptation, a two-turbogenerator primary circuit, a double radiator arrangement including a L.T. radiator made of multiple, pivoting tubes, are first of all proposed for a 20-kWe intermediate temperature (1130 K), medium development term, gas-cooled reactor system owing to suitable conditions.

2-1. Reactor Concept

As shown on Fig. 1, the reactor core consists of nineteen particle bed fuel elements, each surrounded by a ZrH assembly. Two possible shapes of the latter are illustrated : a hexagonal one (A) based on the developments carried out in the USA in the sixties, and a "lozenge" one which leads to less neutron absorbing material in the core. The main feature of the core design lies in the HeXe flow arrangement which compels the gas to cool the ZrH elements, maintained in the 675-775 K temperature range, before flowing through the annular particle beds transversally. This is achieved by the use of a hot chamber located above the upper reflector. In this way, the radial beryllium reflector, the control drums and the pressure vessel including the hot gas outlet structure, are also temperature conditioned around 700-750 K. This thermal control offers a further advantage if a reentry shield covering



(a) hexagonal ← ZrH elements → (b) "lozenge"

Fig.1 20-kWe Gas-Cooled, Particle Bed Reactor

the reactor is adopted. Similarly, the shadow shield temperature conditions benefit from the location of the hot gas outlet at the opposite side of the reactor.

2-2 Brayton Cycle Adaptation

As far as the ZrH moderator temperature conditioning is concerned, Fig.2 shows two ways of adapting the Brayton cycle namely cycles (2) and (3), compared with the reference conventional cycle (1). For the three cases, the turbine inlet temperature (TIT) is 1130 K but the compressor inlet temperature (CIT) is decreased from 400 K (cycle (1)) down to 333 K (cycle (2)) and 323 K (cycle (3)). The distinctive feature of cycles (2) and (3) is the relatively low reactor inlet temperature (RIT) of 633 K. The resulting thermodynamical penalty is limited by a lowering of the CIT. Compared with the reactor thermal power (99 kWt) and the radiator area (50 m^2) of cycle (1), the corresponding values are 95 kWt and 60 m^2 for cycle (2) and 113.7 kWt and 56.5 m^2 for cycle (3). Concerning cycle (2), its high efficiency can be obtained only by increasing the compressor pressure ratio up to 2.6, a surely too high valoe for one-stage space machines; moreover, the generator cooling by a waste heat pumped loop can take place only in the CIT region, which leads to a 10 per cent increase in the radiator area. Consequently, the more flexible cycle (3) is selected. It is fairly efficient in spite of the low RIT. It exhibits a H.T. radiator (60 per cent of the rejected heat and 4.5 m^2 only) separate from a L.T. one (40 per cent of the waste heat for 52 m^2). It is compatible with an efficient, low pressure ratio turbocompressor, with a temperature level for the generator cooling limiting the relevant radiator area increase to 1.4 m^2 and with satisfactory L.T. radiator design conditions.

		①	②	③
[illegible]	K	850	633	633
[illegible]	K	[illegible]	670-770	670-770
[illegible]	m^2	50	60	56.5 (4.5 + 52)
[illegible]	kWt	99	95	113.7
[illegible]	per cent	20.2	21.1	17.6
[illegible]	kg/s	.68	.37	.44

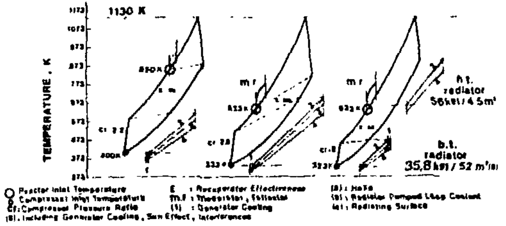


Fig.2 20-kWe, 1130 K, Direct Brayton Cycle Investigation

2-3. System Diagram and Arrangement

As shown by the system diagram of Fig. 3, the waste heat is rejected through a gas-liquid heat exchanger and two redundant NaK pumped loops downstream of the recuperator for the part concerning the L.T. radiator. It is a solution particularly suitable to a low temperature Brayton cycle heat rejection as it has been confirmed by the detailed studies carried out within the U.S. Space Station phase 2 program. The H.T. radiator is made of heat pipes directly heated by the working fluid exiting turbines. The reliability aspect is mainly expressed by the adoption of two turbogenerators because their reliability factor would not reach the one of the other components. Given the only heat source of the direct cycle, it has been estimated convenient to use one recuperator and one waste heat exchanger (WHX) of adequate manufacturing quality, and incorporated in the same casing, as developed in the U.S.A. twenty years ago. Through the WHX, the length of the primary

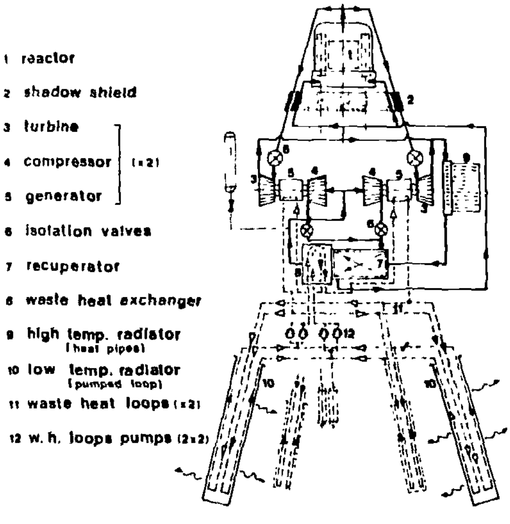


Fig.3 Gas-Cooled Reactor System Diagram

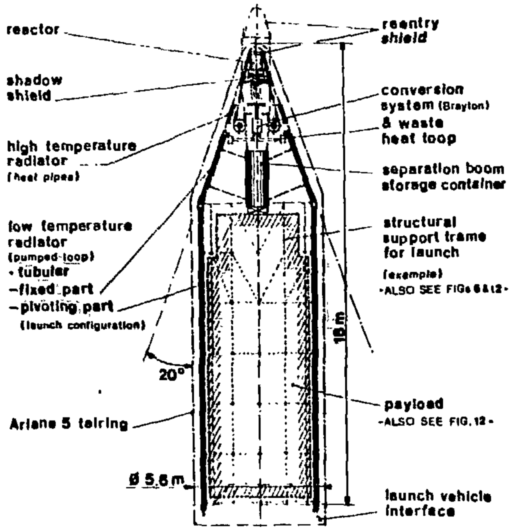


Fig.4 Gas-Cooled Reactor Power System Configuration

circuit is significantly reduced, which is beneficial to the leaktightness and to the overall reliability. Should a turbogenerator become unavailable, upstream and downstream butterfly valves would isolate it while the generator cooling would remain active. The nominal power level would be maintained by doubling the working fluid pressure. Two pumps in parallel operate on each L.T. waste heat loop.

Fig.4 is a vertical view of the power system. Except the tubular L.T. radiator, discussed in the next section, all the components are located in the upper half of the conical part which clears a maximum room for the pay load and the separation boom canister. The small H.T. radiator surrounds the conversion subsystem. Fig.5 shows details of the latter.

2-1. Low Temperature Tubular Radiator

Several reasons have lead to the concept of the *multiple, pivoting* tubes radiator shown in launch and in flight configuration on Fig.4 and Fig.5 respectively :

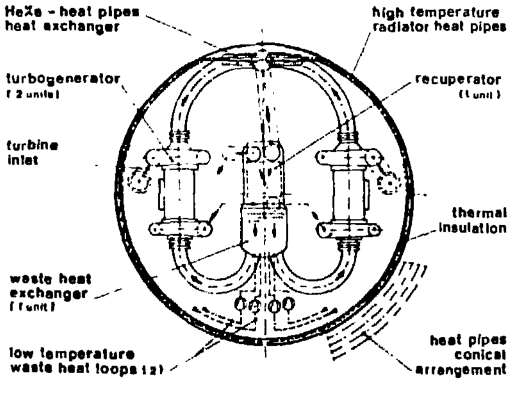


Fig.5 Brayton Conversion System with two Turbogenerators

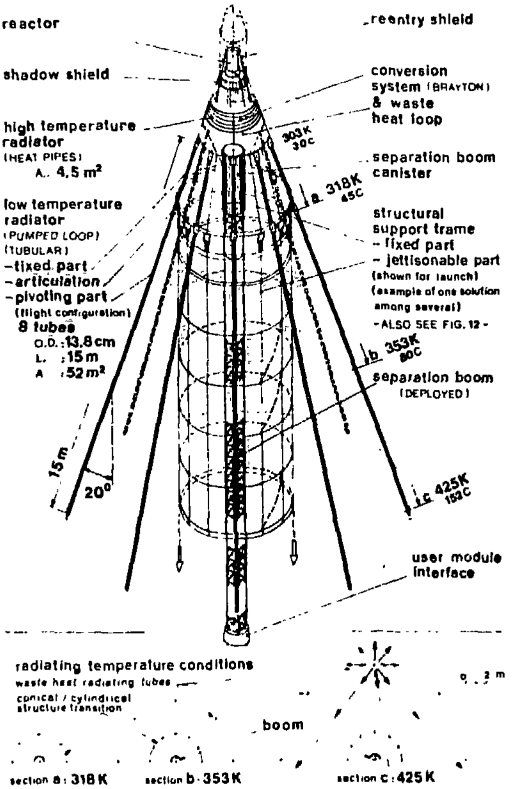


Fig.6 Gas-Cooled Reactor System. Flight Configuration

- adequate thermal conditions for a pumped loop technique and a relatively low radiation temperature range;
- the search for maximum dispersion in bulk and orientation in order to strongly reduce the effects of thermal aggressions due to the sunshine or to laser beams;
- the concern for minimizing the support structure associated with large area radiators and for avoiding the ones extending far from the conversion subsystem region;
- possible attractive mass figures.

Tubes have been selected for this purpose because cylinders offer the best self sustaining mechanical shape and can radiate their heat in all directions. As detailed on Fig.7, the intermediate coolant (NaK) is conveyed to the end of the radiator tubes and it transfers the waste heat to the radiating surface by flowing through multiple transfer pipes on its way back. Each radiator tube has a two-loop arrangement in order to practically maintain the availability of all the heat rejection capability. The radiator material is aluminium alloy or possibly beryllium. A small part of the radiator tubes is fixed and located on the conical part of the spacecraft, but in flight conditions, the longest part is moved away by pivoting according to the shadow shield angle through articulations fitted with flexible coolant pipes links. So, the main part of the support structure, which is also used for holding the radiator tubes at launch, can be jettisonsed in space. Radiator sections in three locations confirm the minimum effect of the thermal radiation on basic structures.

In the case of the 20-kWe gas-cooled reactor system, th

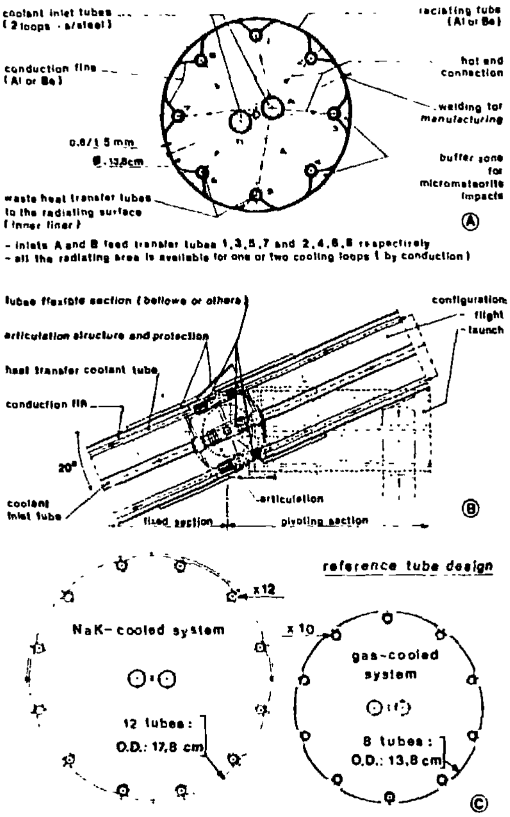


Fig.7 Low Temperature Tubular Radiator Details

L.T radiator is made of eight tubes of 13.8 cm O.D. and 15 m² overall length each, which corresponds to the required 52 m² area, including the generator cooling, sun effect and radiation interferences.
On Fig.7(C), the radiator tube section is compared with the one of the low temperature space power system discussed in the next sections.

Table 1 20-kWe Gas-Cooled Reactor System
Reactor and Thermal Management Mass Estimates
(Kg)

REACTOR	400	
SHADOW SHIELD	290	
HIGH TEMPERATURE RADIATOR(incl HeXe side)	40	
WASTE HEAT EXCHANGER	38	
// // LOOPS + PUMPS	32	
LOW TEMPERATURE RADIATOR *		
Basic Material	Al	Be
- radiating tubes (incl NaK pipes)	340	275
- articulation	20	17
- pivoting device	20	18
- launch fastening	20	15
	400 *	325 *
ASSOCIATED FRAME STRUCTURE	25	25
THERMAL MANAGEMENT TOTAL	535	460
L.T. radiator specific mass * kg/m²	7.7	6.25

2-5. Mass Estimates (Table 1)

An overall mass estimate is not available for reasons of revaluation in progress. The reactor and the shadow shield respectively weigh 400 kg and 290 kg. A detailed mass evaluation is limited to the thermal management subsystem. The total weight is of either 535 kg or 460 kg according to the use of aluminium or beryllium for the L.T. radiator. The corresponding specific masses for all the radiating tubes package are 7.7 or 6.25 kg/m , which is satisfactory, taking account that the optimum compromise between heat conduction aspects and mechanical behavior is not yet reached.

3. 20-kWe Na(K)-COOLED REACTOR SYSTEM

The arrangements described in section 2 are also applied to a 20-kWe Na(K)-cooled reactor, indirect cycle power system which is a lower temperature, shorter development term one. Comments are limited to the specific aspects of this system.

3-1. Reactor Concept

The low power level, a possible medium lifetime as well as an adapted conversion Brayton cycle would be convenient for a thermal spectrum reactor now under consideration. A tentative concept is shown on Fig.8. It features fuel elements separate from the ZrH assemblies maintained at a temperature around the relatively low RIT resulting from the Brayton cycle adaptation and from a temperature difference between the inlet and the outlet of the reactor only just larger than the one of the French Phenix breeder reactor. Adjusted fuel and moderator coolant mass flows are mixed in the upper plenum before exiting the reactor at the side opposite to the radiation shield. Two fuel and ZrH elements distribution examples among others are proposed on sections (A) and (B) of Fig.8.

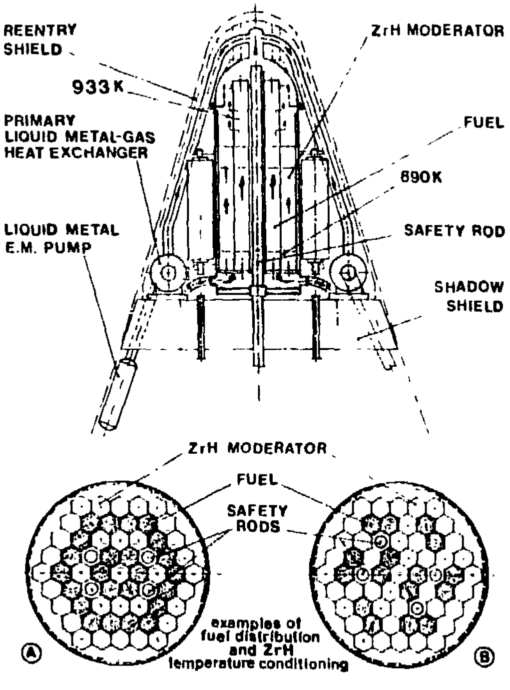


Fig.8 20-kWe Na(K)-Cooled Reactor

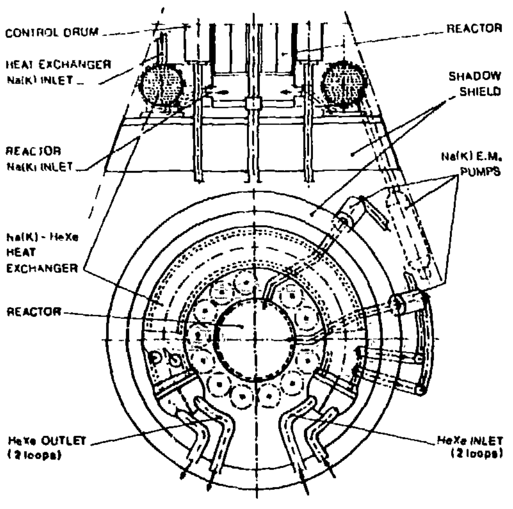


Fig.9 "C"-Shaped Na(K)-HeXe Heat Exchanger Arrangement

A distinctive feature of this low power, liquid metal-cooled reactor is illustrated by Fig.8 and by Fig.9 in more detail. It consists in the location of the primary, intermediate, "C"-shaped, Na(K)-HeXe heat exchanger around the lower part of the reactor, on the same side of the shadow shield. Only the liquid metal pumps are protected from radiations by the shield. This arrangement makes it possible a significant shortening of the primary circuit, an easier Na thawing, if this coolant is used, and a room saving beneficial to the pay load. "C"-shaped heat exchangers or steam generators have already been developed.

3-2. Brayton Cycle Adaptation

As shown on Fig.10, the study of an adequate Brayton cycle allowing a low RIT with a limited penalty is similar to the one shown on Fig.2 except the different parameters values. The TIT is 913 K; it is estimated convenient for a Na- or NaK-cooled reactor operating for several years. Cycles (5) and (6) lead to a RIT of 690 K instead of 780 K for the conventional, highly recuperated cycle (4). For radiator dimensioning reasons, the same CIT of 323 K is selected for the three compared cycles. The compressor pressure ratio is also the same (1.9); so, cycle (5) is not thermodynamically optimized.

Because the CIT of these low temperature cycles cannot be decreased further, the reactor thermal power of cycles (5) and (6) is increased by about 50 per cent in comparison with cycle (4). A noticeable feature of cycle (6), with its separate H.T. and L.T. radiators, is a total radiating area of 108 m², very close to the value of 107 m² obtained for the reference cycle (4), for similar generator cooling conditions. The heat rejection distribution between the two radiators of cycle (6) is different from the one of cycle (3) on Fig.2. Here, the H.T. radiator rejects 40 per cent of the waste heat only and its area is 7 m². Corresponding values for the L.T. radiator are 54 per cent and 101 m². Similarly to the gas-cooled reactor application, cycle (6) is selected in the present case.

3-3. System Diagram

Unlike the gas-cooled reactor, direct cycle power system, the Na(K)-cooled, indirect cycle one can be a two heat sources system through an exchanger bundle design in two parts, inside either one or two shells. It is therefore possible to adopt two separate Brayton cycle circuits, each consisting of its own turbogenerator, recuperator and WHX, as shown on Fig.11. Similarly to the procedure mentioned in section 2, the full power can be supplied by one conversion circuit operating at a double working fluid pressure. In addition, in the present case, the loss of the working fluid of one conversion loop does not jeopardize the mission. As already indicated by Fig.3, both the H.T. and the L.T. radiators are heated by the two conversion circuits in an independent way.

3-4. Power System Arrangement and Radiators

The present use of the two separate H.T. and L.T. radiators technique in order to achieve a relatively low RIT can be compared to the application of section 2. Because of the location of the Na(K)-HeXe heat exchanger on the same side of the radiation shield as the reactor, the general arrangement is similar, except that the L.T. radiator area has increased twofold, as illustrated by Fig. 12, related to Fig.6. It can be admitted that the multiple tubes L.T. radiator can still be contemplated, even its area reaches 100 m² or more.

Here, the L.T. radiator consists of twelve tubes of also 15 m in overall length, but of 17.8 cm O.D.. Twelve small inner pipes per tube transfer the waste heat to the radiating

		④	⑤	⑥
[illegible]	K	780	690	690
[illegible]	K	[illegible]	720 - 770	720 - 770
[illegible]	m²	107 [illegible]	131	108 [illegible]
[illegible]	kWt	95	145	145
[illegible]	per cent	21	14	14
[illegible]	kg/h	89	69	69

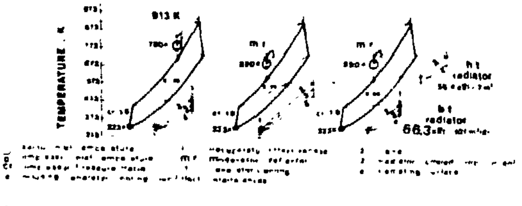


Fig 10 20-kWe, 913 K, Indirect Brayton Cycle Investigation

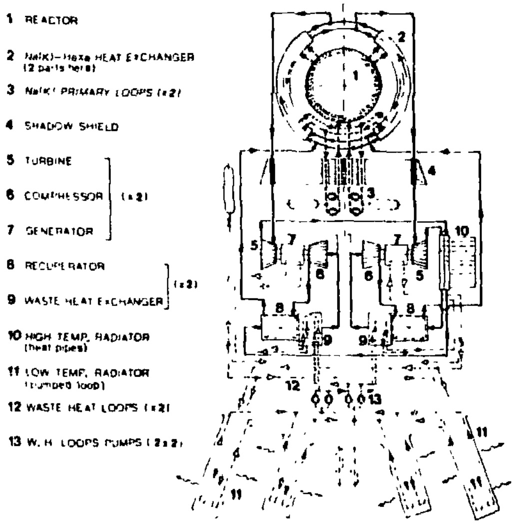


Fig.11 Na(K)-Cooled Reactor System Diagram

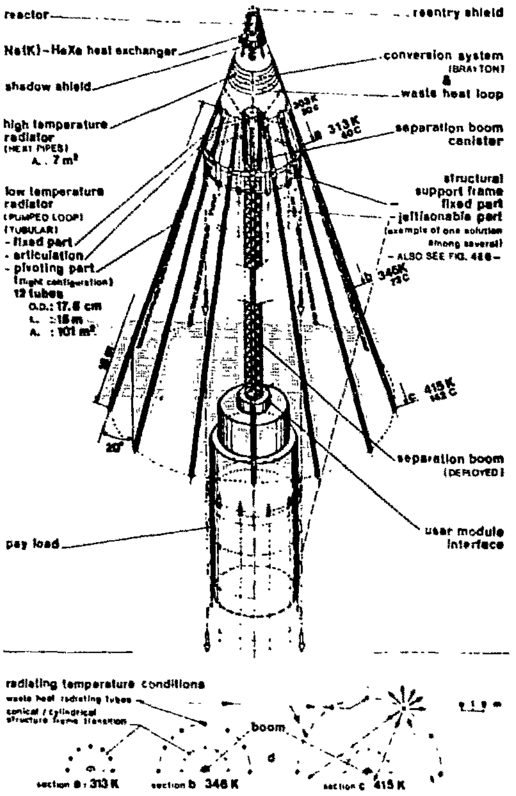


Fig.12 Na(K)-Cooled Reactor System. Flight Configuration

surface. On Fig.7, the present tube section can be compared with the one of the L.T. radiator of the gas-cooled reactor system. The tube thickness is also increased for heat conduction and structural reasons. Given its small area of 7 m², the *impact of the H.T. radiator on the system configuration remains moderate.*

3-5 Mass Estimates

Only the thermal management is concerned. If the H.T. radiator weight of about 60 kg does not burden the total mass, it turns out that the L.T. *radiator is by far the heaviest component* of all the power system. It weighs either 950 kg or 730 kg, depending on whether its basic material is aluminium or beryllium, which respectively corresponds to specific masses of 9.4 kg/m² and 7.2 kg/m², common values indeed. Mass savings can be anticipated for this not yet optimized new design.

Table 2 20-kWe Na(K)-Cooled Reactor System Thermal Management Mass Estimates (Kg)

HIGH TEMPERATURE RADIATOR (Incl. HeXe side)	60			
WASTE HEAT EXCHANGER	63			
" " LOOPS + PUMPS	42			
LOW TEMPERATURE RADIATOR *				
Basic Material	**Al**		**Be**	
-radiating tubes (incl. NaK pipes)	870	950 *	660	730 *
-articulation	30		26	
-pivoting device	25		22	
-launch fastening	26		22	
ASSOCIATED FRAME STRUCTURE		40		35
THERMAL MANAGEMENT TOTAL		**1155**		**930**
L.T. radiator specific mass * kg/m²		9.4		7.2

4. CONCLUSION

A Brayton cycle cooled by separate H.T. and B.T. radiators furthers the utilization of ZrH moderator in small space reactors by maintaining it around 700-750 K. Concerning a 20-kWe, gas-cooled reactor system, a lowering of the RIT from 850 K, for a conventional cycle, down to 633 K, results in an increase in core thermal power (113 kWt) of less than 16 per cent, and in radiator area (56.5 m²) of only 13 per cent. For a much smaller RIT decrease of 90 K, a Na(K)-cooled reactor system would suffer an increase in core thermal power (142 kWt) of 56 per cent, but, remarkably, its radiator area (108 m²) would remain almost unchanged. The multiple, pivoting tubes L.T. radiator concept allows a location of the support structures limited in the conversion system region in flight configuration, a maximum room available to the pay load at launch, and a wide dispersion of the radiating surface towards thermal aggressions including sun effects. According to preliminary estimates, the thermal management package mass is a problem for the lower temperature, liquid metal-cooled reactor system. The potential in improvement of the multitubular L.T. radiator would have to be investigated.

ACKNOWLEDGMENTS

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REFERENCES

[1] F.O. Carré, "et al", "Status of the CNES-CEA Joint Program on Space Nuclear Brayton Systems", 24th I.E.C.E. Conference, Arlington, VA, August 6-11, 1989.

[2] P. Keirle, "et al.", "Autonomous Control System Design for Space Nuclear Power Generator-Erato 20-kWe", 24th I.E.C.E. Conference, Arlington, VA, August, 6-11, 1989.

[3] F.O. Carré, "et al.", "Conceptual Design Studies of 20-kWe Nuclear Power Systems. Impact of Reactor Temperature and Technology upon Design and Performances", 5th Symposium on Space Nuclear Power Systems, Proc. pp. 489-492 , Albuquerque, NM, January 1988.

[4] F. Proust, "et al.", "Space Nuclear Studies in France. Overview of the Erato Program", 23rd I.E.C.E. Conference, Proc Vol 3, pp. 191-196 , Denver, CO, August, 1988.

[5] F.O. Carré, "et al.", "A Preliminary Assessment of Reactor Candidate Technologies for a 20-kWe Space Nuclear Brayton Cycle System", 6th Symposium on Space Nuclear Power Systems, Proc. pp. 333-338 , Albuquerque, NM, January 1989.

[6] Z.P. Tilliette, "Adaptability of Brayton Conversion Systems to Fast, Epithermal and Thermal Spectrum Space Nuclear Reactors", 23rd I.E.C.E. Conference, Proc. Vol.3, pp. 197-202 , Denver, CO, August 1988.

[7] Z.P. Tilliette, "et al.", "Brayton Cycle Conversion System and Temperature Conditioning of Small Space Nuclear Reactors", 6th Symposium on Space Nuclear Power Systems, Proc. pp. 510-513 , *Albuquerque, NM, January, 1989.*