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A FOUR-YEAR INVESTIGATION OF BRAYTON CYCLE SYSTEMS FOR FUTURE FRENCH SPACE POWER APPLICATIONS

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A FOUR-YEAR INVESTIGATION OF BRAYTON CYCLE SYSTEMS FOR FUTURE FRENCH SPACE POWER APPLICATIONS

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ABSTRACT

Within the framework of a joint program iniated in 1983 by the two French Government Agencies C.N.E.S. (Centre National d'Etudes Spatiales) and C.E.A. (Commissariat à l'Energie Atomique), in order to study space nuclear power systems for future ARIANE 5 applications, extensive investigations have dealt with the Brayton cycle which has been selected as the energy conversion system.

Several aspects can be mentioned in this field : the matching of the power system to the available radiator dimensions up to 200 kWe, the direct or indirect waste heat transfer to the radiator, the use of a recuperator, the recent work on moderate (25 kWe) power levels, the simulation studies related to various operating conditions and the general system optimization. A limited experimental program is starting on some crucial technology areas including a first contract to the Industry concerning the turbogenerator.

Particular attention is being paid to the significance of the adoption of a Brayton cycle for space applications involving a nuclear heat source which can be either a liquid metal-cooled or a gas-cooled reactor. As far as a gas-cooled reactor, direct cycle system is concerned, the relevance to the reactor technology and the concept for moderator thermal conditioning, is particularly addressed.

NOMENCLATURE

NaK	Eutectic sodium-potassium
TIT	Turbine inlet temperature
CIT	Compressor inlet temperature
ZrH	Zirconium hydride
LiH	Lithium hydride
HP	High pressure
Pt	Thermal power

INTRODUCTION

The European space program is presently based on the use of the ARIANE 2, 3 and 4 launch vehicles for communication and television satellites. The earth observation is also considered, the first application being SPOT 1 shown in Fig.1 and in operation since 1985. After 1995, the availability of the heavy launcher ARIANE 5 (Fig.2) will permit more ambitious missions.

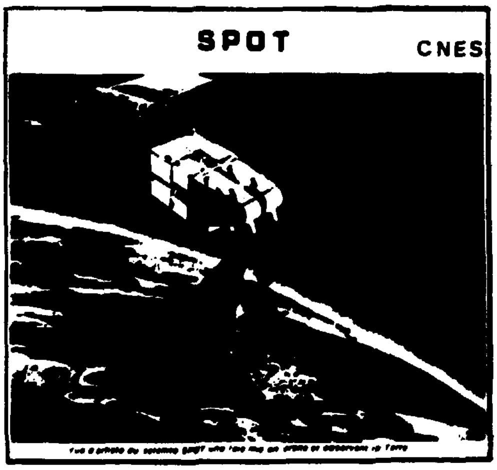


FIG. 1. " SPOT " OBSERVATION SATELLITE LAUNCHED BY "ARIANE" (1985)

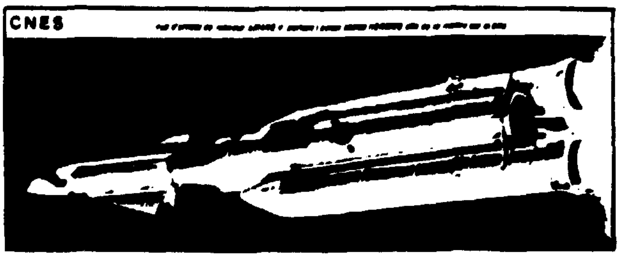


FIG. 2 . FUTURE "ARIANE 5" LAUNCH VEHICLE WITH THE "HERMES" SPACE PLANE

Higher on board energy levels will be needed at the turn of the century for long periods and it is the reason why nuclear energy will probably be required. Several papers (1) to (12) report on the main aspects of this program. They deal with program considerations (1), (2), (5), reactor and system concepts (3), (6), (10), (12), Brayton cycle conversion (4), (7), (8), (11) and radiator (90).

The selection of the Brayton cycle conversion system has been confirmed ; it takes account of common reasons and of particular French, European space technical considerations. Several investigated aspects can be mentioned in this field : a first assessment of a reference 200 kWe system with a view to the matching of the power system to the available radiator dimensions, the direct or indirect waste heat transfer to to the radiator, the recent work on moderate power levels of the order of 25 kWe, the simulation studies related to transient and various operating conditions and some activity on a general system optimization and on the parameters sensitivity to modified conditions. In addition to the studies carried out up to now, a limited experimental program is starting in some crucial areas. As far as the turbogenerator is concerned, a first contract has been awarded to the Industry for a preliminary definition.

With regard to the moderate power level (20-30 kWe) systems, the current study deals with both liquid metal-cooled fast spectrum and gas-cooled epithermal spectrum reactors for comparison purposes.

The interest in a gas-cooled reactor direct cycle concept stands to reason if a Brayton cycle is used. This close, natural combination with the heat source prompts an investigation on the utilization of the closed-cycle gas turbine conversion system. There are naturally consequences of the selection of a gas cycle on the reactor technology and concept. An additional approach is being considered. It concerns thermal spectrum gas-cooled reactors and particularly ways of achieving satisfactory temperature conditions, making it possible to use efficient moderator and reflector materials like the ZrH and Li_7H metal hydrides for a long period. Only the Brayton cycle aspects of the topic are addressed in this paper.

WASTE HEAT REJECTION . RADIATOR

The heat rejection studies deal with the transfer of the Brayton cycle waste heat to the radiating area. It is a point of prime importance, given the length of the cooling circuit, as illustrated by Fig.3, the extension of the radiator heat exchange surface, and the resulting greater sensitivity of these components to a possible aggressive environment, and to an inadequate structural behavior. It is wise to keep the length of the working fluid circuit of dynamic conversion systems as short as possible in order to lower the gas pressure drop, to make the gas pressure control and the achievement of an absolute leak tightness easier, to make the radiator heat exchanger much more compact and to prepare the way to possible satisfactory deployable radiator techniques.

In parallel with the transfer of the waste heat to the radiator heat pipes directly by the working fluid, a version featuring an intermediate cooling liquid under a very low pressure is considered (Fig.4). Two cooling loops are provided for redundancy purpose and either the eutectic NaK(78) or an organic fluid could be utilized, according to the temperature range. The use of an intermediate cooling circuit makes it

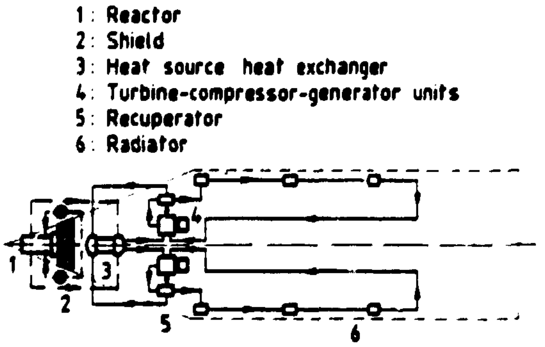


FIG. 3. SCHEMATIC ARRANGEMENT OF AN "ARIANE 5" GAS-COOLING CIRCUIT, BRAYTON CYCLE NUCLEAR POWER SYSTEM

(cf. (8),(11) for working fluid-directly heated radiator)

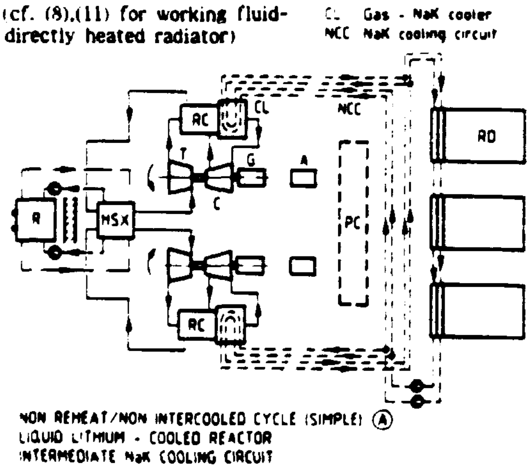


FIG. 4. POWER SYSTEM DIAGRAM : INTERMEDIATE WASTE HEAT CIRCUIT AND HEAT PIPES RADIATOR

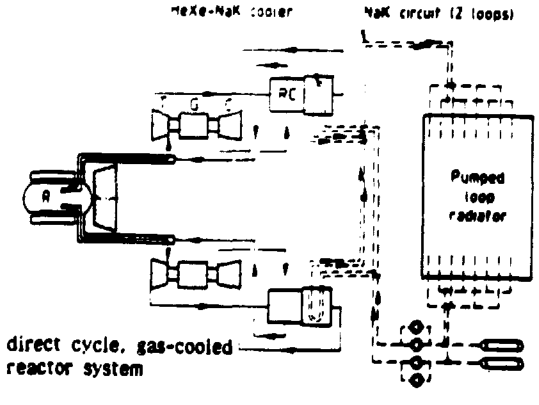
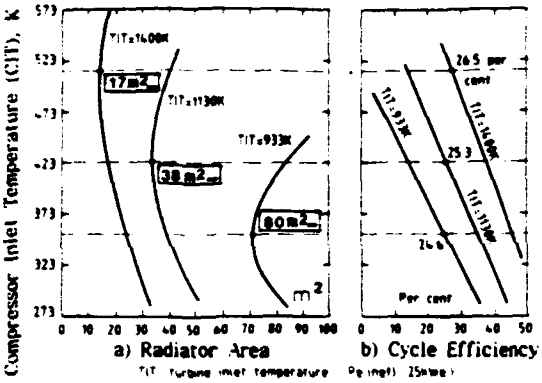


FIG. 5. POWER SYSTEM DIAGRAM : INTERMEDIATE WASTE HEAT CIRCUIT AND PUMPED-LOOP RADIATOR



a) Radiator Area b) Cycle Efficiency

TIT turbine inlet temperature Pe(net) 25kWe)

FIG. 6. RADIATOR AREA AND CYCLE EFFICIENCY VARIATION OF 25 kWe SYSTEMS

convenient to adopt a pumped-loop radiator, as shown by Fig.5. These two techniques are compatible with a Brayton cycle conversion system because heat is transfered through a large temperature change which involves limited fluid mass flows.

The preliminary studies carried out so far in this field lead to sufficiently positive conclusions for pursuing this investigation (8), (11).

LOW POWER LEVEL APPLICATIONS

Presently, moderate power levels of around 25 kWe are being investigated. Some first results were presented in (8) and (11). Three turbine inlet temperature (TIT) values are being considered recently :

- 933 K (short-term liquid sodium- or NaK-cooled reactor),
- 1130 K (medium-term direct cycle, gas-cooled reactor),
- 1400 K (long term high temperature lithium-cooled reactor).

TABLE 1. KEY DATA OF 25 kWe SYSTEMS
(Values for minimum radiator area)

Turbine inlet temperature	K	1400	1130	933
Compressor inlet temperature	K	513	423	353
Pressure ratio (compressor)		1.90		
Cycle efficiency	per cent	26.5	25.3	24.6
Net efficiency	per cent	21	20	19.5
Reactor thermal power	kWt	119	125	128
He-Xe (40) mass flow	kg/s	0.73	0.97	1.20
Recuperator dimensioning factor		1.33	2.18	3.20
Radiator thermal power	kWt	83.5	89	92
Radiator area	m²	17	38	80
Radiator specific area	m²/kWe	0.68	1.52	3.20
Total power system mass (round)	kg	1700	2000	2400

Fig.6(a) shows the variation of the radiator area of these 25 kWe systems as a function of the compressor inlet temperature (CIT). For the 933 K, 1130 K, 1400 K cycles, the minimum radiator area respectively corresponds to 80 m², 38 m², and 17 m². The minimum of the curves is all the more marked as the TIT is lower. Fig.6(b) presents the corresponding variation of the cycle efficiency, the value of which changes only from 24.6 per cent to 26.5 per cent for the minimum radiator area conditions. Additional results are given in Table 1. The total power system mass is worth mentioning ; it is of the order of 2400 kg, 2000 kg, 1700 kg respectively for the 933 K, 1130 K, 1400 K TIT cycles.

These low power level applications are being studied more in depth.

SIMULATION STUDIES

The first applications of this work concern the previous 200 kWe reference project. The analysis of the transient behavior of the system, via computer simulation, is intended to validate, detail or modify preliminary selected basic options regarding :

- the operating transients scenarios and the associated regulation,
- the reactor control and the protective actions in the case of abnormal transients.

In the 200 kWe project, power is generated by two pairs of 50 kWe Brayton rotating units. Several operating procedures for the successive run-ups of both pairs of 2 x 50 kWe converters have been analyzed (Fig.7).

The energy needs and time scale involved in the start-up scenario with frozen coolant were estimated by the numerical simulation of the primary loop thermal response to a monitored reactivity insertion (Fig.8).

As the restart procedure is expected to be long and difficult, control and protective actions have been developed which aim at avoiding the complete stopping of the rotating units. The capacity of the proposed regulation system for stabilizing the reactor operation

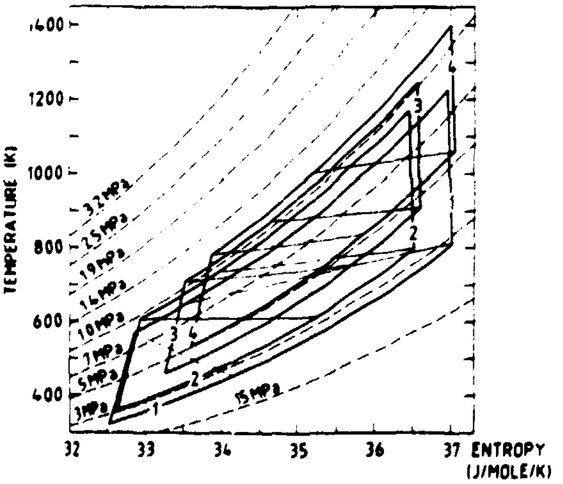


FIG. 7. BRAYTON CYCLE EVOLUTION DURING THE RUN-UP OF ONE PAIR OF CONVERTERS

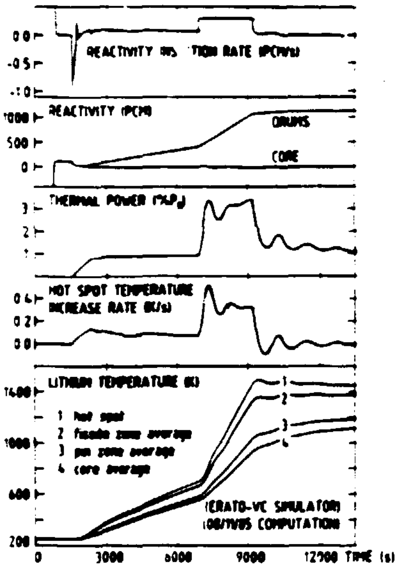


FIG. 8. REACTOR RESPONSE TO THE START-UP PROCEDURE

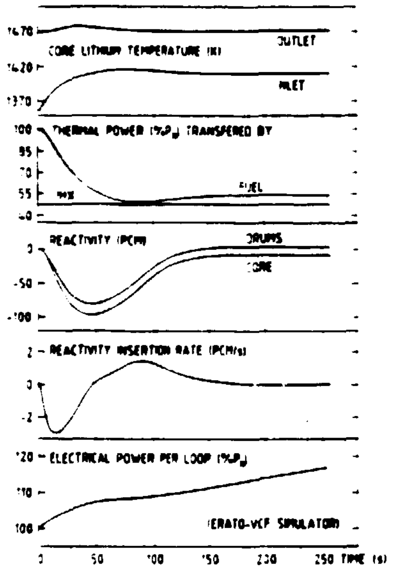


FIG. 9. REGULATION RESPONSE TO THE FAILURE OF ONE PAIR OF CONVERTERS

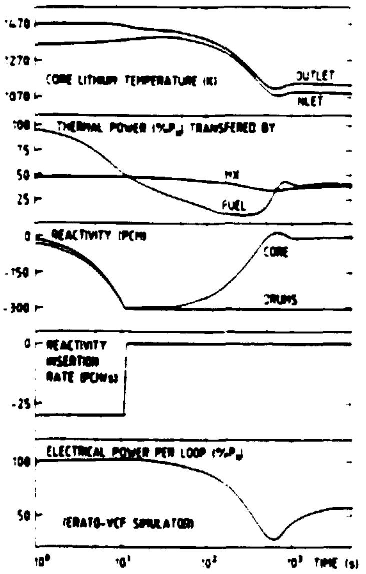


FIG. 10. PROTECTIVE RESPONSE TO THE FAILURE OF ONE PAIR OF CONVERTERS (Automatic power reduction down to 50% Pn)

and for damping the power and temperature swings has been demonstrated by the numerical simulations of various cooling accidents scenarios (Fig.9). Simulation studies are currently applied to check the possibility of reversible protective actions, and to define the procedure of automatic reactor power reduction in particular, so as to keep one of the two pairs of converters running at least (Fig.10).

These studies will be extended to future sensitivity analyses, in order to assess the advisability of departure from the reference design and operating conditions.

POWER SYSTEM MASS OPTIMIZATION

Within the scope of the studies on the 200 kWe reference system , computer programs and procedures are being developed for performing an automatized optimization of components and system design parameters. This optimization aims at minimizing the total mass under the constraints set by the integration into the ARIANE 5 launch vehicle.

In order to make the procedure more flexible, the global system is split into three weakly coupled subsystems, namely :

1 : reactor + shield,
2 : primary circuit,
3 : conversion system + primary heat exchanger.

Fig.11 presents the architecture of the program optimizing the third subsystem. Fig.12, drawn from results obtained with a preliminary version of the program, illustrates the consequences, on the reference system mass, of a slight departure from their optimum values of the major thermodynamic cycle parameters.

This work is expected to be extended in the near future to the optimization of low power (20-30 kWe)

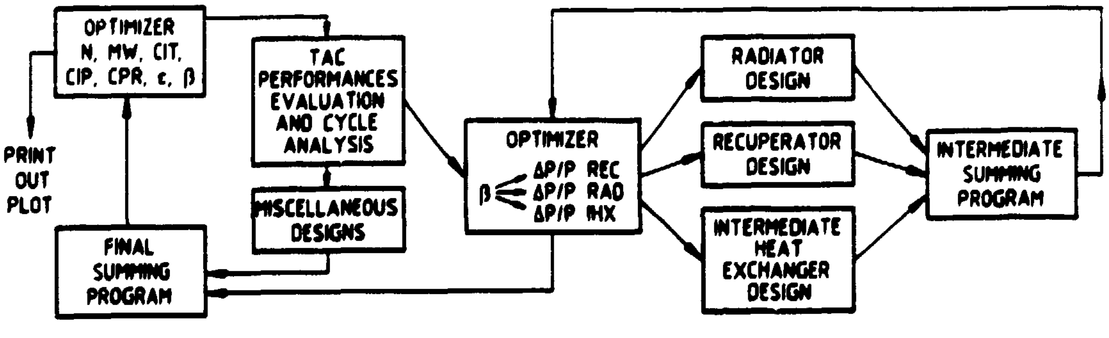


FIG. 11. CONVERSION SUBSYSTEM OPTIMIZATION PROGRAM ARCHITECTURE

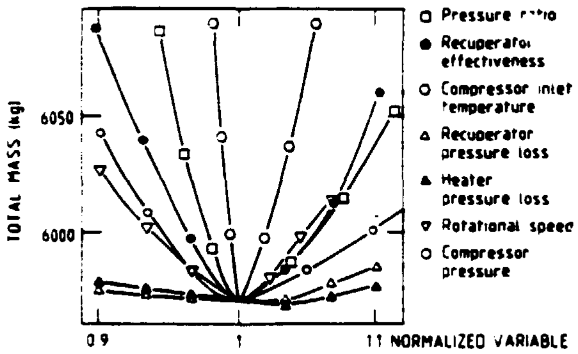


FIG. 12. SENSITIVITY OF THE POWER SYSTEM MASS TO THE DEPARTURE OF SOME KEY PARAMETERS FROM THEIR OPTIMUM VALUES

space systems associated with both a liquid metal-cooled nuclear reactor and a gas-cooled one with a gas turbine conversion system.

REACTOR TECHNOLOGY AND CONCEPT

By going more closely into the significance of the utilization of the Brayton cycle for space power systems, it is essential to consider the possible consequences on the nuclear heat source technology and concept.

Reactor Technology

Fig.13 makes it possible to compare three investigated concepts.

A liquid metal-cooled reactor implies an intermediate liquid-gas heat exchanger and an almost isothermal high temperature primary circuit, including the structural materials.

The direct cycle gas cooled reactor is naturally suited to a Brayton cycle conversion system. In that case, the thermal conditions of most of the structures under pressure turn out to be quite different. Internal thermal insulation can be used in a gaseous environment in such a way that the piping and pressure vessel temperatures can be maintained at a moderate level. Another solution features a concentric flow technique which keeps the main part of the circuit at the reactor inlet temperature. This point is worth noting because it is a question of technology readiness and also of the technical capability of European countries, given t[illegible]rate temperature level of the pressurized vess[illegible] piping.

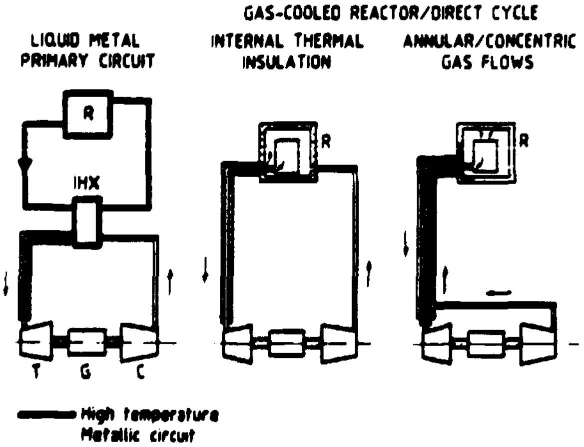


FIG. 13. HIGH TEMPERATURE, BRAYTON CYCLE SPACE NUCLEAR POWER SYSTEMS CONCEPTS

Attractive developments in this field can result from the temperature conditioning of moderated reactors discussed in the next section.

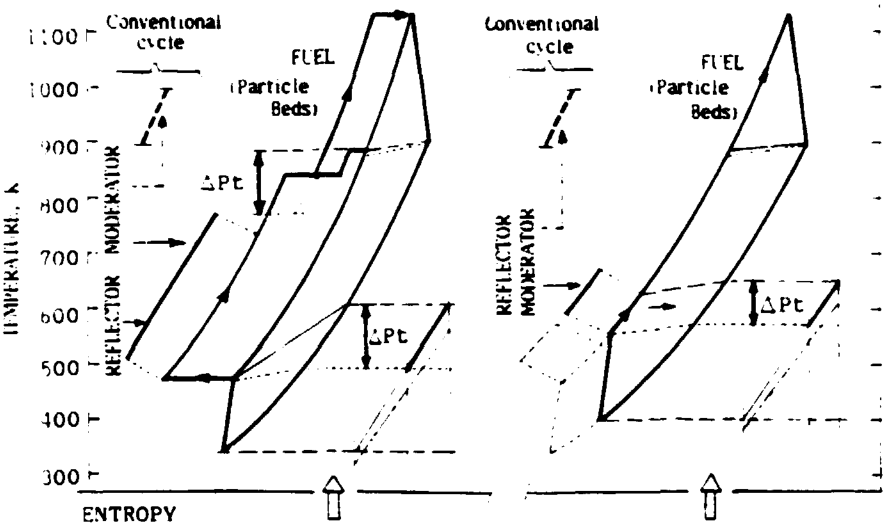
Reactor Concept

Another aspect has to be emphasized. In a direct cycle arrangement, it amounts to the investigation of an as adequate as possible utilization of the conversion system, supposing that a satisfactory space system should probably feature a right match and an actual symbiosis between the heat source and the conversion sub-system. This aspect concerns the possibility of contemplating a thermal spectrum gas-cooled reactor for moderate power level, long lifetime space applications. Consequences would be of the utmost importance from the points of view of fissile material inventory, safety, shielding, weight, control and structures irradiation. A condition has to be fulfilled for that ; the temperature level must allow use of efficient moderator and reflector materials like the ZrH and Li_7H metal hydrides for a long period ; it must be relatively low. In a first approach, the gas cycle makes it possible to use a convenient moderator by maintaining it at the reactor inlet temperature in normal operating conditions. But, in addition, more promising arrangements can be suggested and this topic is addressed in the following section.

MODERATED REACTOR TEMPERATURE CONDITIONING

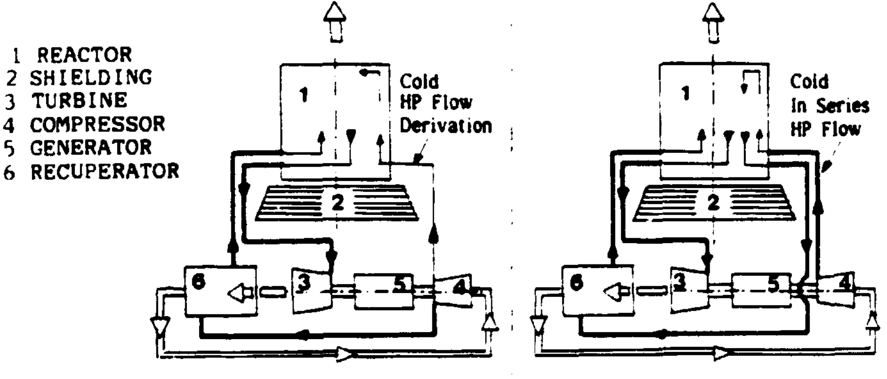
As far as thermal spectrum nuclear reactors are concerned, the required long lifetime use of the needed efficient ZrH and Li_7H moderator and reflector materials depends upon sufficiently low temperature and power levels. This section is devoted to the Brayton cycle aspects of the problem. The reactor design is a key factor of the study, but its presentation is beyond the scope of this paper. Ways of controlling the moderator and reflector temperature can be offered by a Brayton cycle directly combined with a gas-cooled reactor, typically a particle bed one. The two means presented in this paper imply the use of the high pressure (HP) flow at the compressor exit, either partially or totally.

In the first arrangement, a certain amount, roughly 25 to 35 per cent, of the HP flow leaving the compressor shunt the HP side of the recuperator and cools the reflector and the moderator before being mixed with the remaining part of the flow which has been preheated through the recuperator, as shown by Fig.14(a). There is obviously a penalty in energy conversion efficiency because the increase in the heat source thermal power ΔPt must be rejected by the radiator. However, a significant comment has to be pointed out : the thermodynamic loss does not at all correspond to the characteristics of a conventional cycle of the same derated efficiency. As a matter of fact, in the shunt cycle arrangement, the working fluid mass flow and pressure drop are not modified and, what is of prime importance for space applications, the additional radiator thermal power ΔPt is



(a) Brayton Cycle and Temperature Conditions

(c) Brayton Cycle and Temperature Conditions



(b) Circuit Diagram

(d) Circuit Diagram

SHUNT HP FLOW ARRANGEMENT

IN SERIES HP FLOW ARRANGEMENT

FIG. 14. TWO EXAMPLES OF BRAYTON CYCLE ADAPTATION FOR MODERATOR, REFLECTOR, STRUCTURES COOLING

rejected at a temperature higher than the one of the usual configuration and, consequently, the radiator size penalty is limited. For the example given in Table 2 the amount of heat transfered by the radiator increases by 70 per cent but the corresponding radiating area extension does not exceed 22 per cent.

The basic findings of Fig.14(a) consist of the resulting much lower moderator and reflector temperature range in comparison with the conventional conditions. This temperature range goes from about 900 - 1000K down to 520 - 760K.

The power system circuit diagram of the shunt arrangement is shown by Fig.14(b), the main feature of which is a small, cold, relatively short pipe connecting the compressor outlet to the reactor inlet.

Fig.14(c) shows the cycle and temperature conditions of the second arrangement which features utilization of the whole HP flow coming from the compressor for cooling the reflector and the moderator. In this in-series configuration, the HP working fluid is directed to the reactor, cools the reflector and the moderator separately and has to leave the reactor in order to flow through the recuperator before being finally heated in the core. As illustrated by the circuit diagram of Fig.14(d), a double pipe has to be added between the reactor and the recuperator but it is a cold one and it can be of a concentric design.

It is more important to emphasize the consequences from thermal and thermodynamic points of view. The reflector and moderator temperature range is reduced, lowered and extends from 600K to 670K only, compared with the previous case. In relation with a conventional cycle concept, the temperature drop reaches 300K as shown by Fig.14(c). Because of this coo-

TABLE 2. COMPARISON OF TWO MODERATOR. REFLECTOR. STRUCTURES COOLING ARRANGEMENTS

Moderator. Reflector. Structures Cooling Arrangements	SHUNT	IN SERIES
Turbine Inlet Temperature	1130 K	
Recuperator Effectiveness	0.93	
Compressor Inlet Temperature	345 K	400 K
Cooling HP Gas Flow Percentage	30 % (1)	100 %
Cooling HP Gas Inlet Temperature (2)	475 K (3)	550 K (4)
Reflector. Moderator. Temperature Range	520 - 760 K	600 - 670 K
Power System Relative Pressure Loss	7 %	8,4 % (+20%)
Pressure Loss Conversion Efficiency Penalty	NIL	- 1,6 pt.(-5%)
Reference Radiator Area (Conventional Cycle)	1,2 Sr	Sr (5)
Radiator Thermal Power Increase	+ 70 %	+ 36 %
Radiator Area Increase	+ 22 %	+ 13 %

(1) Hypothesis for a given moderator+reflector thermal power.
(2) Compressor exit
(3) Lower than the required value for a minimum radiator area.
(4) Close to the required value for a minimum radiator area.
(5) Pressure loss penalty taken into account.

ling upstream of the recuperator, the corresponding amount of heat ΔPt must be additionally rejected by the radiator, but only in the higher temperature region. For the example of Table 2, which concerns the same power level as previously, the increase in radiator thermal power is 36 per cent but the extension of the radiator area is limited to 13 per cent. These values take an increase in circuit pressure drop into account. As already mentioned, the working fluid mass flow is not modified at all. A further feature of this in-series arrangement is that the compressor inlet temperature is not lower than the value corresponding to the minimum radiator area for moderator temperature reasons.

Both shunt and in-series arrangements make it possible to condition the main pressurized structures like the reactor pressure vessel at an appreciably low temperature.

As far as the reactor is concerned, it can be said for the moment that the multiple particle beds concept offers ways of separating reflector, moderator and fuel cooling areas.

The thermal and thermodynamic aspects of the separate moderator and reflector cooling are proven attractive given the basic advantages it offers for the adequate utilization of ZrH and Li_7H and for the necessary hydrogen containment. The related reactor design studies, which are presently in progress, tend to confirm the practicability and the interest of such moderated space nuclear power systems, at least for low or intermediate power levels. The in series arrangement could be preferred.

CONCLUSIONS AND SUMMARY

In addition to the extended, corresponding development carried out in this field during many years in the U.S.A., the four year investigation of Brayton cycle power systems reported in this paper can be considered as conclusuve for space applications. Results are estimated satisfactory from efficiency, compactness, weight, power level range, waste heat rejection conditions, flexibility, heat source adaptation and technology points of view.

There are reasons for carrying on with the study of this conversion system. However, it is judicious to try to determine an as satisfactory as possible utilization of the Brayton cycle through an adequate association and match with the heat source. The temperature conditioning of a moderated reactor is an example of what could be made in this domain.

ACKNOWLEDGEMENTS

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