~~FR8605749~~
FR8700739

COMMISSARIAT A L'ENERGIE ATOMIQUE

CENTRE D'ETUDES NUCLEAIRES DE SACLAY
Service de Documentation
F91191 GIF SUR YVETTE CEDEX

CEA-CONF -- 8604

R3

ADVANCES IN DEFINING A CLOSED BRAYTON CONVERSION SYSTEM FOR FUTURE ARIANE 5 SPACE NUCLEAR POWER APPLICATIONS

TILLIETTE, Z.P. CEA CEN Saclay, 91-Gif-sur-Yvette (France). IRDI, DEMT

Communication présentée à : 31. International conference on gas turbine
Duesseldorf (Germany, FR)
8-12 Jun 1986

ADVANCES IN DEFINING A CLOSED BRAYTON CONVERSION SYSTEM FOR FUTURE ARIANE 5 SPACE NUCLEAR POWER APPLICATIONS

Z.P. TILLIETTE
COMMISSARIAT A L'ENERGIE ATOMIQUE
Centre d'Etudes Nucléaires de Saclay
91191 GIF-SUR-YVETTE - FRANCE

*

ABSTRACT

The present european ARIANE space program will expand into the large ARIANE 5 launch vehicle from 1995. It is assumed that important associated missions would require the generation of 200 kWe or more in space during several years at the very beginning of the next century. It is the reason why, in 1983, the French C.N.E.S. (Centre National d'Etudes Spatiales) and C.E.A. (Commissariat à l'Energie Atomique) have initiated preliminary studies of a space nuclear power system.

The currently selected conversion system is a closed Brayton cycle. Reasons for this choice are given : high efficiency of a dynamic system ; monophasic, inert working fluid ; extensive turbomachinery experience,etc... A key aspect of the project is the adaptation to the heat rejection conditions, namely to the radiator geometry which depends upon the dimensions of the ARIANE 5 spacecraft.In addition to usual concepts already studied for space applications, another cycle arrangement is being investigated which could offer satisfactory compromises among many considerations, increase the efficiency of the system and make it more attractive as far as the specific mass (kg/kWe), the specific radiator area (m^2/kWe) and various technological aspects are concerned. Comparative details are presented.

INTRODUCTION

The european space program becomes significant and well known, particularly through the launch of several satellites, mainly geosynchronous, per year for various countries by using the ARIANE rocket. ARIANE is a wide family of launch vehicles, as illustrated in Fig. 1. ARIANE 1 was qualified in 1981. ARIANE 3 is in operation since the end of 1984. Several models of ARIANE 4 will be used these next years. An important stage was reached in 1984 with the decision of the european Governments to study and develop the large ARIANE 5 launch vehicle for operation from 1995. Fig. 2 shows some versions of ARIANE 5 which is designed to launch a payload of 17,000 kg in 400 km low earth orbits and of about 5000 kg in geosynchronous orbits. Several large launchers are compared in Fig. 3.

With ARIANE 5, important space missions are made possible around the end of this century, such as Orbital Transfer Vehicles,(O.T.V.) communication satellites, earth observation, space stations. It is now admitted that, within about fifteen years, a power generation of 50 kWe to 400 kWe during several years would be required in space. Because of these relatively high power levels and extended operation time requirements, the heat source would necessarily be a nuclear reactor. It is the reason why, in France, the study of a space nuclear power system has been initiated ; it is co-sponsored by the "Centre National d'Etudes Spatiales"(C.N.E.S.) and the Commissariat à l'Energie Atomique" (C.E.A.). Following preliminary investigations (1983-1984), a two-years (mid 1984-mid 1986) phase of assessment studies is in progress (1) (2) (3). The purpose of the present phase is to estimate the technical feasibility and the cost of the program with a view to decisions around the end of 1986. The reference application precisely is an electrical O.T.V. which is the most demanding form the specific mass point of view.

It is clear that the development of a space nuclear power system corresponds to a very ambitious program within reach of very few industrially advanced countries. Europe could certainly manage such a program because its present space program is already significant and expands (COLUMBUS, HERMES Projects). Moreover, as far as nuclear energy is concerned, France is one of the leading countries all over the world

SELECTED SPACE CONVERSION SYSTEM

In the preliminary phase, several space related energy conversion concepts were investigated and compared. For the present two-year phase, a system selection has been made as shown in Fig. 4. It concerns a closed Brayton Cycle of which the basic principles are given by Fig. 5. This present choice is based on several attributes of the system :

- relatively high efficiency ;
- moderate reactor thermal power level ;
- extensive industrial turbo-machinery experience ;
- already well developed components ;
- clean, non-corrosive working fluid (He-Xe mixture) ;
- relatively low temperature level at one end of the cycle ;
- easy power conditioning.

Brayton cycles have been studied and developed for many space power systems these last twenty years. The reliability of the compressor-generator-turbine assembly has been demonstrated in space conditions by a unit at NASA Lewis Research Center (LeRC) that successfully operated essentially unattended for almost 40,000 hours (4) (5). Some past projects are worth mentioning : the 50 kWe 1971 space station (5), the 400 kWe nuclear electric propulsion (NEP) project (O.T.V.) (6), the SP-100 Westinghouse direct cycle (7) and Rockwell indirect cycle (8) projects. More recently, a closed gas cycle "solar dynamic" system is being considered for the future U.S. space station program (9). Concerning the preliminary French studies, some investigations have been carried out (3), (10).

It appears from these works that the Brayton cycle unquestionably is a possible space power generation system. It compares with the main other candidates. However, it has to be carefully studied for improving its potential.

POWER SYSTEM CONDITIONS

In space, the power system is determined by both the required power level and the heat rejection capacity, namely the possible area of the radiator.

Considering that the future power needs in space at the beginning of the next century could range from about 50 kWe to 400 kWe, a reference power level of :

200 kWe net

has been adopted for the present assessment study. According to Fig. 6, it corresponds to an acceptable transfer time from a LEO to a GEO orbit in the case of an electrical O.T.V. adapted to ARIANE 5.

The available radiator area is a basic conversion system condition. Not only the power level, the efficiency but also the technology, more precisely the upper temperature level, directly depends upon it.

In order to illustrate in more detail the possible radiator areas offered by the ARIANE 5 spacecraft already shown by Fig. 2, Fig. 7 has been drawn. Up to now, only the fixed peripheral part of the space vehicle is used for the radiator which extends on both the cone and the cylinder. The two radiator diameters of 4,6 m and 5 m are considered. According to the appropriation of either a large or a small area at the bottom of the cylinder for the waste heat rejection from power processing and payload, either a reduced or an extended coverage of the cylinder are possible for the main radiator. It follows that two radiator areas can be taken into account in the present investigation :

$$135\ \text{m}^2 \qquad \text{and} \qquad 190\ \text{m}^2.$$

These two values permit to get a satisfactory preliminary estimate of the ARIANE 5 power system capacity in different cases.

It is sure that deployable radiator concepts, conceivable in the future, would significantly increase the power generation capacity.

INVESTIGATED CLOSED BRAYTON CYCLES

The basic space closed Brayton cycle is the simple, recuperated one as shown in Fig. 5. It is the cycle adopted for the first preliminary studies and the reference French project.

Given the need to enlarge the scope of the investigation and following a better understanding of the space power generation problems, other closed gas cycles have also been examined, as illustrated in Fig. 8. This additional cycle investigation has been carried out by taking account of the leading parameters of a space power system, namely :

- the technology ;
- the specific mass (kg/kWe) ;
- the specific radiator area (m^2/kWe).

For the temperature levels presently considered, only recuperated cycles are studied. So, the possible cycle modifications involve intercooling or reheat.

The non-reheat, intercooled cycle (B) of Fig. 8 is not a satisfactory solution for space applications. The increase in efficiency and the relative decrease in working fluid mass flow are largely offset by an increase in the radiator area because of a lower mean heat rejection temperature. The reheat, intercooled cycle (C) is the most efficient and leads to the minimum working fluid mass flow. Comparisons also show a decrease of almost 10 per cent in the radiator area. This cycle could nevertheless offer no advantage in space because the above-mentioned gains are probably offset by the circuit complications concerning not only the high temperature end but also the more extended low temperature part. As a matter of fact, it is superseded by the reheat, non-intercooled cycle configuration (D) which combines an increase in efficiency, a decrease in working fluid mass flow with a more significant decrease in radiator area ranging from 15 to 20 per cent. This result is a logical consequence of the smaller waste heat amount resulting from the reheat and the higher pressure ratio combined with a moderate increase of the radiator temperature range only towards the higher values of the latter.

Consequently, results have been obtained and compared for the simple, reference, non-reheat, non-intercooled (A) cycle and the reheat, non intercooled (D) cycle of Fig. 8.

EXAMPLE OF COMPARED CONVERSION CIRCUITS

Before presenting the results of the cycle investigation, it is necessary to somewhat detail the arrangement of the compared circuits as they are shown in Fig. 9.

In both cases, the heat source is a fast spectrum, lithium cooled (for higher temperatures) reactor. The primary circuit consists of two loops. Heat is transfered to the conversion circuit through a liquid metal-gas heat exchanger. The secondary circuit also consists of two loops, each essentially comprising a combined rotating assembly, a recuperator and a radiator made of three panels of heat pipes in series. Provision is made to supply full power in the case of the unavailability of one turbogenerator by doubling the gas inventory in the operating loop and using all the radiator area.

The (A) diagram of Fig. 9 represents the reference, non-reheat, non-intercooled cycle version. In this case and before a more detailed study, a configuration has been adopted which probably is pessimistic from the mass balance point of view but is more satisfactory as far as the combined rotating units are concerned. Two separate turbocompressor-generator assemblies have been adopted for each loop in order to avoid a two large departure from the present concepts of space rotating units. In this way, reheat between the two turbines in series is achieved relatively easily. In addition, the optimum higher pressure ratio is also more easily obtained by two separate compressor stages with a better efficiency than by one stage only. One turbomachine with two turbine stages and one or two compressor wheels could be lighter but would certainly be judged complicated for space applications. Moreover, given their lower power level and their lower pressure ratio per stage, the rotation speed of each unit could be increased, which would reduce their mass.

The two associated turbogenerator units rotate in reverse directions in order to minimize the stability problems of the spacecraft. It is assumed that two such units in series on the gas circuit could operate in parallel concerning the power utilization. For this purpose, a power adaptation exists between each generator and the power conditioning.

The aspects of this concept are being investigated in more details.

A careful look at Fig. 9 makes it possible to roughly appreciate the differences between the circuits (A) and (D). The latter has four smaller turbogenerators instead of two larger ones, but all the other components are smaller ; in addition, ducts have smaller diameters, particularly the long ones of the cold end to the radiator. The heat exchangers between the working fluid and the radiators panels are also reduced.

Fig. 10 also gives an idea of the differences between the two concepts. It superimposes the circuit diagram to the ARIANE 5 spacecraft geometry, which corresponds to a more accurate representation of the ducts network.

COMPARATIVE RESULTS

Results are essentially given in a comparative form between the reference, non-reheat, non-intercooled simple cycle (A) and the reheat, non-intercooled cycle (D).

In each case, four turbine inlet temperatures(T.I.T.) are considered :

- 1400°K / 1127°C ;
- 1290°K / 1017°C ;
- 1173°K / 900°C ;
- 1073°K / 800°C.

The two first temperature levels imply the use of refractory alloys for both the primary lithium circuit and the secondary gas circuit. The third temperature level implies the use of refractory alloys for only the primary lithium circuit but makes it possible to use superalloys for the gas circuit. The 1073°K T.I.T. level could also allow the utilization of superalloys for both the secondary and the primary circuit, the adoption of liquid sodium instead of liquid lithium becoming possible for the latter.

Variation of the Radiator Area

Firstly, a sensitivity study of the variation of the radiator area as a function of the compressor inlet temperature (C.I.T.) is illustrated by Fig. 11. It appears that the radiator area varies relatively slightly within the considered C.I.T. range. This can be explained by the regular increase in pressure ratio and the relatively significant decrease in cycle and radiator thermal power, in working fluid mass flow, in parallel with an increase in efficiency in proportion as the C.I.T. decreases, as shown by Fig. 12. It has been taken into account of the variation of the heat transfer conditions between the working fluid and the radiator.

Fig. 11 makes it possible to quickly estimate the gain in radiator area expected with the reheat, non-intercooled Brayton cycle. This area reduction is of the order of 16 to 20 per cent, a very noticeable value.

In Fig. 11, the strong effect of the T.I.T. on the value of the radiator area appears also. In comparison with a 1400°K (1127°C) T.I.T. conversion system, and for the specified pressure ratios, 1290°K (1017°C) - 1173°K (900°C) - 1073°K (800°C) T.I.T. cycles need about 1.28, 1.7 and 2.4 more radiator area respectively.

Comparative Brayton Cycle Results

Table 1 and Table 2 give the significant, comparative values about the two considered Brayton cycles. The main parameters are :

- the "conversion in" temperature (T.I.T.) ;
- the main radiator area ;
- the net power level ;
- the main radiator specific area ;
- the power system net specific mass.

The two main radiator areas of 135 m^2 and 190 m^2 are considered, except for the T.I.T. value of 1073°K. All the mass estimates, including all the power system, are made in the same conditions. In this way, they are comparable, although further estimates would have to be carried out as the project develops. It must be taken into account that the neutron and gamma shield is designed for a low radiation dosé on the equipment.

For a T.I.T. of 1400°K, and a radiator area of 135 m^2, a simple cycle conversion system meets the requirement of supplying a net power of 200 kWe. However, for the same power level, the use of a reheat, non-intercooled cycle results in a decrease in the net specific mass by about 12 per cent (22.5 kg/kWe instead of 25.5 kg/kWe). In this case, the reheat cycle is a very efficient one but its conditions are far from corresponding to the minimum radiator area requirements, because a low C.I.T. can be adopted.

For the same T.I.T. of 1400°K and C.I.T. values almost squaring with the minimum radiator area conditions, an available radiator area of 190 m^2 would make it possible to obtain net power levels of 280 kWe and 355 kWe with a simple cycle and a reheat cycle respectively. Correlatively with this increase in power level by more than 26 per cent, a reduction of about 17 per cent in the net specific mass (18,4 kg/kWe instead of 22.3 kg/kWe) would be possible by utilizing a reheat cycle.

The 1290°K T.I.T. is 110°K lower than the previous one. For such a noticeable decrease in temperature level, the simple cycle system generates only 160 kWe net, where as it remains possible to meet the 200 kWe requirement with the reheat cycle, which, furthermore, offers an advantage in specific mass of about 15 per cent.

The T.I.T. value of 1173°K would make it possible to use superalloys instead of more sensitive, exacting refractory alloys for the conversion system. It appears that the 200 kWe power level can still be reached for a radiator area of 190 m^2 but only with a reheat cycle. The capacity of the simple cycle is limited to 172 kWe and its specific mass would again be about 15 per cent higher.

The comparison also concerns the T.I.T. of 1073°K, which corresponds to the possible use of superalloys instead of refractory alloys for both the primary and the secondary circuits. For the reference power level of 200 kWe net, the needed radiator area is 315 m^2 for the simple cycle, but only 255 m^2 for the reheat cycle, which is a reduction of almost 20 per cent. (Sodium could also be used instead of Lithium).

All the others data given by Table 1 and Table 2, particularly the various thermal powers and the working fluid mass flow, make it possible to appraise the differences in dimensioning conditions between the considered circuits.

Brayton Cycle - Stirling Cycle Comparison

The Stirling cycle conversion system is considered as another potential solution for future space applications. Some papers have been published. One of them (11) gives some characteristics available for a comparison. In Table 3, this 1050°K space Stirling cycle is compared with the abovementioned two versions of a 1073°K Brayton cycle. The two "conversion in" temperatures can be considered as similar, given the differences existing between the engine concepts.

The comparison is made for the power level of 100 kWe of U.S. SP-100 project. For the moment, only the system efficiency and the radiator specific area are mentioned. A mass comparison would need further studies ; for instance, the dimensioning of the neutron and gamma shield of the SP-100 project is made for a significantly higher radiation dose on equipment than in the french project.

It appears, as it is generally thought, that the simple Brayton cycle has performances somewhat lower than the Stirling cycle, but the Brayton reheat cycle compares favourably with the latter at least from a thermodynamical point of view for space power systems.

SUMMARY

Preliminary studies of a closed Brayton cycle conversion system for ARIANE 5 nuclear power applications are initiated in France. An adequate adaptation to possible radiator areas is searched. Power level and mass requirements can be met by using a simple cycle but it appears that another interesting solution could be a reheat, non-intercooled cycle which presents some favourable aspects for space.

It is sure that several questions in this field have to be discussed with conversant specialists.

Unless deployable radiators could be used, power levels higher than about 150 kWe would require high temperature systems involving the utilization of refractory alloys.

ACKNOWLEDGEMENTS

The two first phases (1983-1984 ; 1984-1986) of the French space nuclear power studies are co-sponsored by the Government Agencies "CENTRE NATIONAL D'ETUDES SPATIALES" and "COMMISSARIAT A L'ENERGIE ATOMIQUE".

The sponsoring Agencies and the author wish to gratefully acknowledge the Garrett Corporation, Phoenix, Az, and particularly Mr. A. PIETSCH, for information about various advanced Brayton Cycle power systems.

REFERENCES

1. Poher C., Cacheux J., Bliaux J., Tilliette Z.P.,
"Space Electronuclear Generators : Comparison between different Kinds of Energy Conversion Methods", I.A.F. Conference, Lausanne, 1984
Paper n° 285.

2. Poher C. et al,
"French Activity on Space Nuclear Power Systems", 2d Symposium on Space Nuclear Power Systems, Albuquerque, NM, January 14-16, 1985,
Paper n° MS-2.

3. Carré F., Proust E., Schwartz J.P.,
"Liquid Metal Versus Gas-Cooled Reactor Concepts for a Turbo-Electric Powered Space Vehicle", 2d Symposium on Space Nuclear Power Systems, Albuquerque, N.M, January 14-16, 1985,
Paper n° RS-1.

4. English R.E.,
"Power Generation from Nuclear Reactors in Aerospace Applications", NASA Technical Memorandum 83342, Symposium on Advanced Compact Reactors, Washington D.C., November 15-17, 1982.

5. Garrett Corporation,
"Closed Brayton Cycle Applications", Garrett C° Reports, Phoenix, Az, 1979-1983.

6. Layton J.P.,
"Reactor/Brayton Power Systems for Nuclear Electric Spacecraft (NEP 400 kWe Project, Garrett Power System)", 15th Intersociety Energy Conversion Engineering Conference, Seattle, WA, August 18-22, 1980,
pp. 732-737.

7. Parker G.H., Pierce B.L., Thompson R.E.,
"Design Considerations for Nuclear Reactor Gas Turbine Space Power Systems", ASME Gas Turbine Conference, Phoenix, AZ, March 1983,
ASME Paper n° 83-GT-20.

8. Anderson R.V.,
"A Lithium-Cooled Reactor-Brayton Turboelectric Power Converter Design for 100 kWe Class Space Reactor Electric Systems", 19th Intersociety Energy Conversion Engineering Conference, San Francisco, C.A., August 18-24, 1984,
pp. 481-486.

9. Pietsch A., Trimble S.,
"Space Station Brayton Cycle Power System", 20th Intersociety Energy Conversion Engineering Conference, Miami Beach, FL., August 18-23, 1985.

10. Tilliette Z.P.,
"Utilization of a Brayton Cycle Energy Conversion System in Space Nuclear Power Applications", 2d Symposium on Space Nuclear Power Systems, Albuquerque, NM, January, 14-16, 1985,
Paper n° EC-8.

Table 1 Key Data of Non-Reheat and Reheat Brayton Systems for 1400°K and 1290°K Turbine Inlet Temperatures and for 135 m² and 190 m² Radiator Areas

Technology									
- Primary Circuit - Conversion System.		Refractory Alloys / Liquid Lithium Refractory Alloys / He - Xe							
Turbine Inlet Temperature	°K/°C	1400 / 1127				1290 / 1017			
Radiator Area (2) (3)	m²	135		190		135		190	
Cycle : Reheat or not		NO	YES	NO	YES	NO	YES	NO	YES
Net Power	kWe	200	200	280	355	160	200	200	260
Compressor Inlet Temperature	°K	513	368	473	453	473	473	413	413
	°C	240	95	200	180	200	200	140	140
Pressure Ratio		2.1	3.8	2.2	3.2	2	3	2.2	3.2
Recuperator Effectiveness		0.80	0.85	0.80	0.85	0.85	0.85	0.85	0.85
Reactor Thermal Power	kWt	1036	588	1211	1339	758	940	754	963
Efficiency - Cycle	per cent	23	40.4	27.7	31.6	25.2	25.4	31.6	32.2
Efficiency - Net		19.3	34	23.1	26.5	21.1	21.3	26.5	27
Working Fluid Mass Flow (He-Xe)	kg/s	5.3	1.8	5.8	4.65	4.6	3.8	4.1	3.6
Outlet Temperature - Turbine(1)	°K	1103	1120	1083	1155	1033	1076	998	1064
Outlet Temperature - Compressor	°K	724	680	679	769	651	780	593	700
Recuperator -Thermal Power	kWt	831	355	971	800	780	505	726	644
Recuperator -Temperature Difference	°K	76	68	80	59	57	45	61	55
Main Radiator - Thermal Power	kWt	787	346	863	903	565	697	509	644
Main Radiator - Temperature Range (Metal)	°K	495-712	362-671	460-685	442-730	460-648	460-729	405-607	405-682
Main Radiator - Specific Area	m²/kWe	0.67	0.67	0.68	0.53	0.84	0.67	0.95	0.73
Power System - Total Mass (4)	kg	5100	4500	6250	6550	5000	5350	5400	5900
Power System - Net Specific Mass	kg/kWe	25.5	22.5	22.3	18.4	31.3	26.7	27	22.7
		(2)	(5)	(3)	(3)	(2)	(2)	(4)	

(1) Mean Temperature
(2) Minimum Radiator Area } Emissivity : 0.85
(3) Almost Minimum Radiator Area }
(4) Non Efficiency - optimum pressure ratio
(5) High Efficiency Conversion System
(6) Reactor + Shield + Conversion System + Radiator + Power Conditionning + Structures (shielding for low radiation dose)

Table 2 Key Data of Non-Reheat and Reheat Brayton Systems for 1173°K and 1073°K Turbine Inlet Temperatures and for various Radiator Areas

Technology { - Primary Circuit - Conversion System		Refractory Alloys/Liq.Lithium Super Alloys / He - Xe				Liquid Sodium Super Alloys	
Turbine Inlet Temperature	°K/°C	1173/900				1073/800	
Radiator Area (2) (3)	m^2	135		190		315	254
Cycle : Reheat or not		NO	YES	NO	YES	NO	YES
Net Power	kWe	122	142	172	200	200	200
Compressor Inlet Temperature	°K	423	398	423	398	393	383
	°C	150	125	150	125	120	110
Pressure Ratio		2.2	3	2.2	3	2.2	2.75
Recuperator Effectiveness		0.90	0.90	0.90	0.90	0.85	0.85
Reactor Thermal Power	kWt	533	553	748	775	952	847
Efficiency - Cycle	per cent	27.3	30.7	27.4	30.8	25	28.1
Efficiency - Net		22.9	25.7	23	25.8	21	23.6
Working Fluid Mass Flow (He-Xe)	kg/s	3.45	2.5	4.85	3.5	6.4	4.3
Outlet Temperature - Turbine (1)	°K	908	979	908	979	817	907
Outlet Temperature - Compressor	°K	608	656	609	656	577	608
Recuperator -Thermal Power	kWt	481	380	680	535	750	575
Recuperator -Temperature Difference	°K	30	33	30	33	40	45.5
Main Radiator - Thermal Power	kWt	384	379	540	530	706	605
Main Radiator - Temperature Range (Metal)	°K	414-594	391-634	414-594	391-634	386-569	377-607
Main Radiator - Specific Area	m^2/kWe	1.11	0.95	1.10	0.95	1.58	1.27
Power System - Total Mass (4)	kg	4450	4600	5600	5560	6400	5800
Power System - Net Specific Mass	kg/kWe	36.5	32.4	32.6	27.8	32	29
		(2)	(3)	(2)	(3)	(3)	(3)

(1) Mean Temperature
(2) Minimum Radiator Area } Emissivity : 0.85
(3) Almost Minimum Radiator Area }
(4) Reactor + Shield + Conversion System + Radiator + Power Conditioning + Structures (shielding for low radiation dose)

Table 3 Performance Comparison between Non-Reheat and Reheat Brayton Cycles and a Stirling Cycle for Space Applications

Conversion Cycle		BRAYTON		STIRLING (1)
		No Reheat	Reheat	
Temperature				
- Reactor Outlet	°K	1110	1110	1100
	°C	837	837	827
- Conversion In	°K	1073	1073	1050
	°C	800	800	777
- Radiator	°K	386 - 569	378 - 608	~ 500
	°C	113 - 296	105-335	~ 227
Reactor Thermal Power	kWt	476	424	450
Net Efficiency	per cent	21	23.6	22.2
Radiator Area	m²	158	127	128
Radiator Specific Area	m²/kWe	1.58	1.27	1.28
Net Power	kWe	100		

(1) ROCKWELL/ROCKETDYNE,SP-100 Project, Space Nuclear Power Systems Symposium, ALBUQUERQUE, January, 1985, Paper N° TM-3.

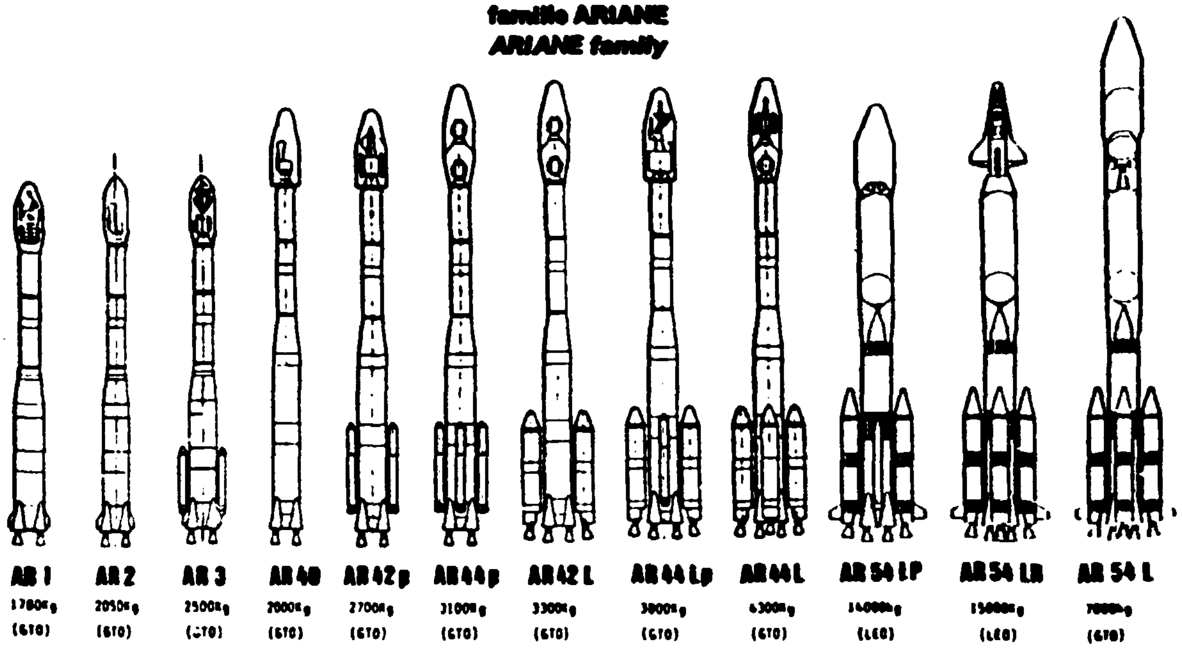


Fig. 1. Ariane Family of European Launch Vehicles

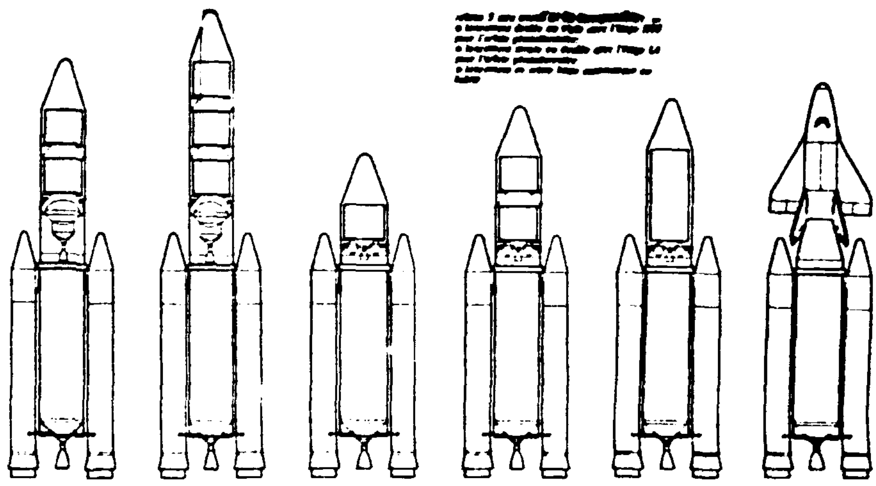


Fig. 2. Outline of Possible Models of the Future ARIANE 5 European Launch Vehicle

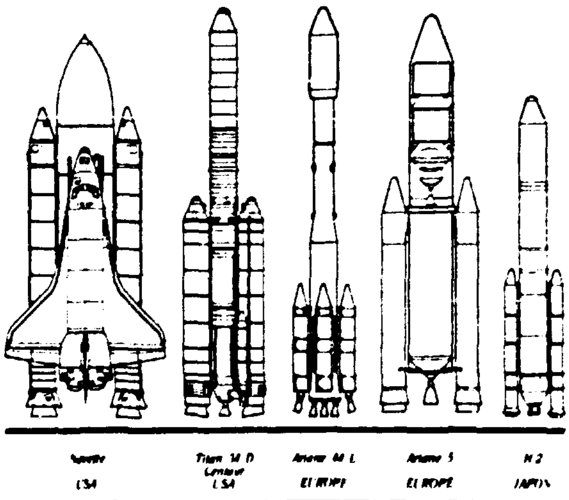


Fig. 3. Comparison of several Large Launch Vehicles

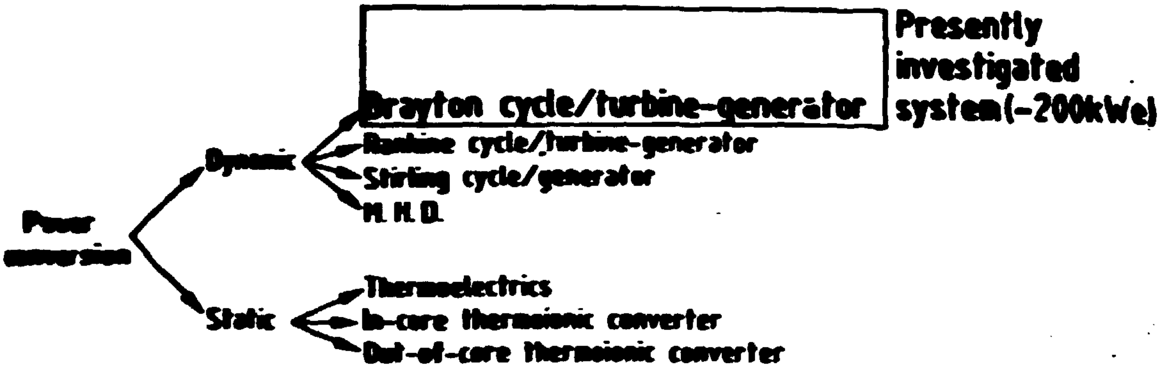


Fig. 4. Present French Selection of a Space Nuclear Power Conversion System

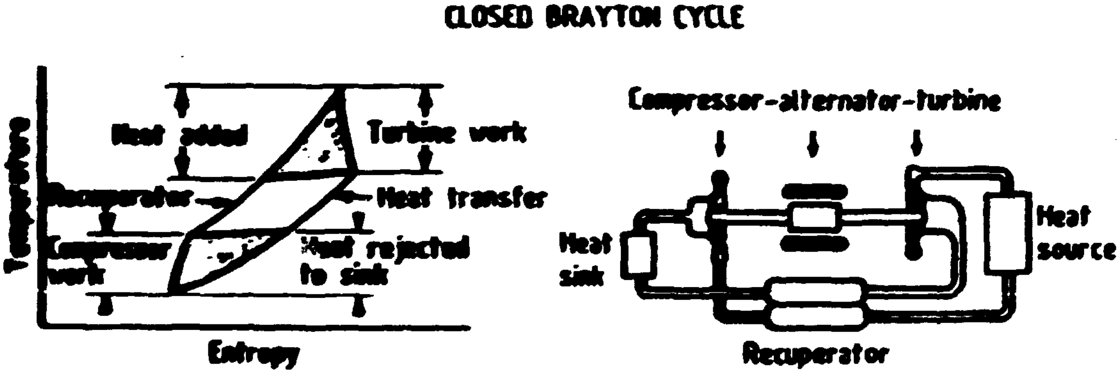


Fig. 5. Principle and Arrangement of a Recuperated Closed Brayton Cycle

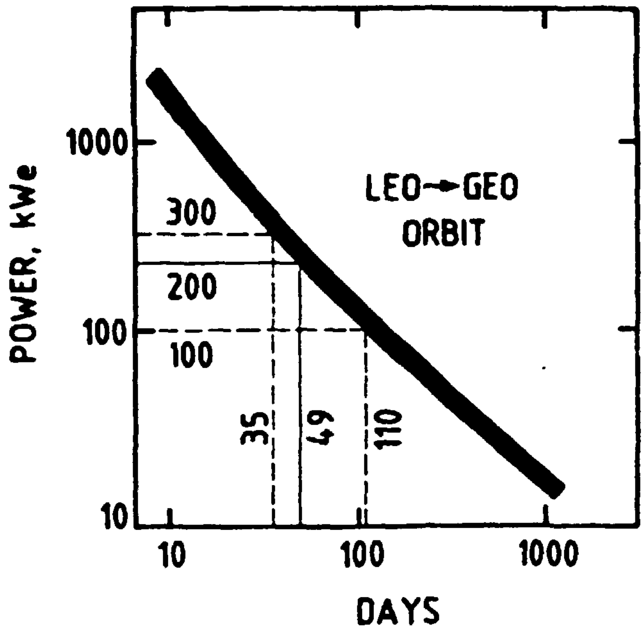


Fig. 6. Needed Electric Power Versus LEO-GEO Orbits Transfer Time for ARIANE 5 Applications

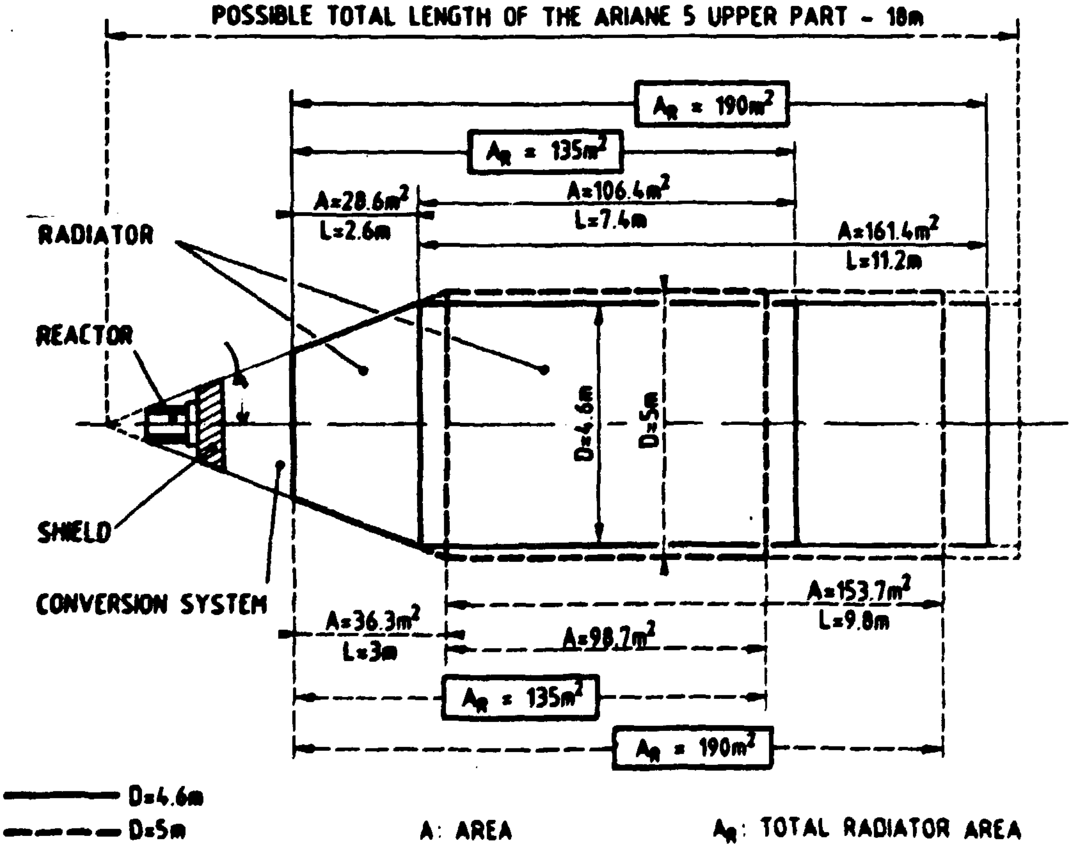
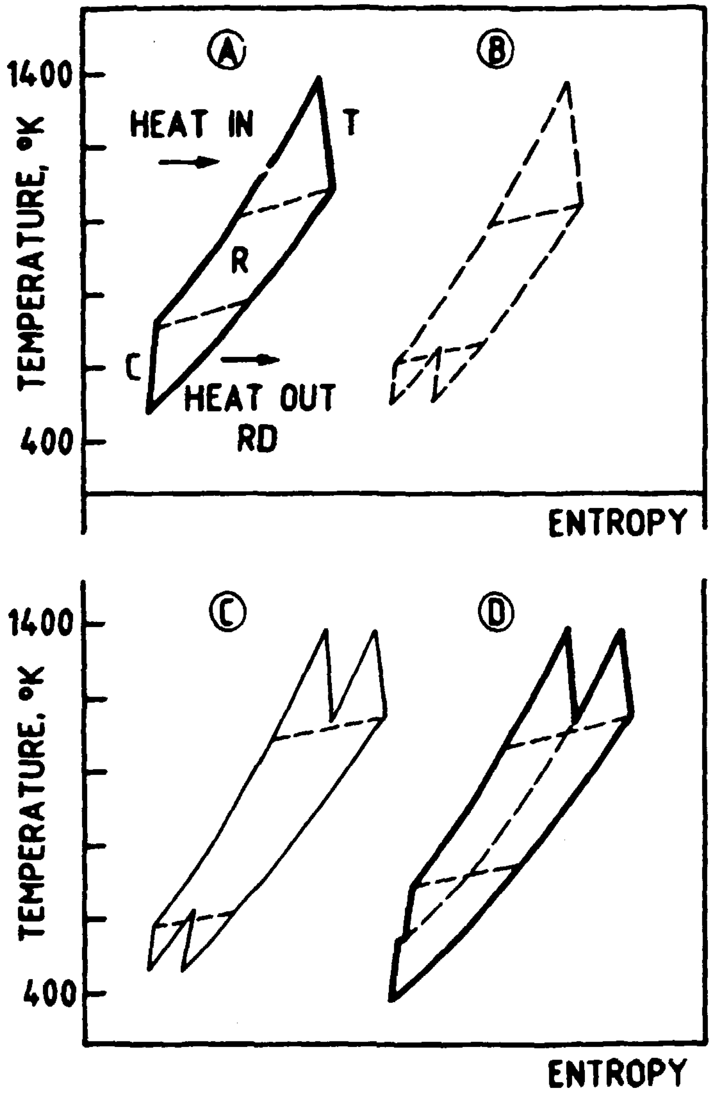


Fig. 7. Reference and Extended Radiator Areas of a Future ARIANE 5 Spacecraft

CLOSED BRAYTON CYCLES:

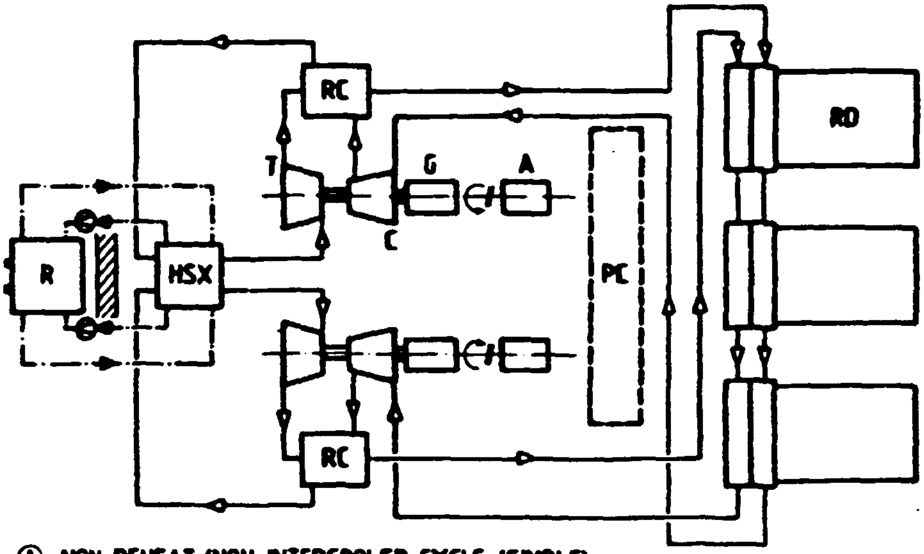
Ⓐ NON REHEAT/NON INTERCOOLED (SIMPLE)
Ⓑ NON REHEAT/INTERCOOLED
Ⓒ REHEAT/INTERCOOLED
Ⓓ REHEAT/NON INTERCOOLED



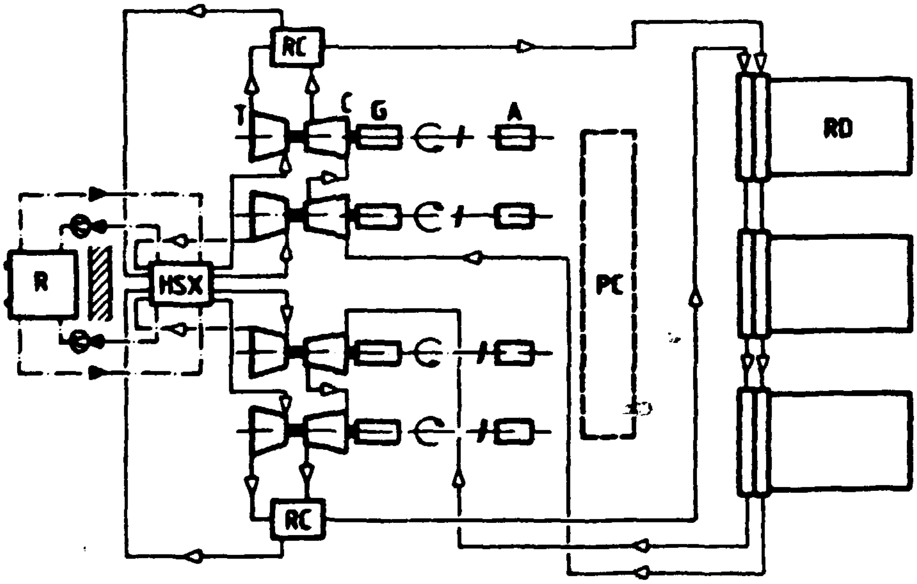
T : TURBINE
C : COMPRESSOR
R : RECUPERATOR
RD : RADIATOR

Fig. 8. Brayton Cycles Investigated for Space Energy Conversion Applications

- R : REACTOR
- HSX : HEAT SOURCE HEAT EXCHANGER
- T : TURBINE
- C : COMPRESSOR
- G : GENERATOR
- RC : RECUPERATOR
- RD : RADIATOR PANELS
- A : POWER ADAPTATION
- PC : POWER CONDITIONING



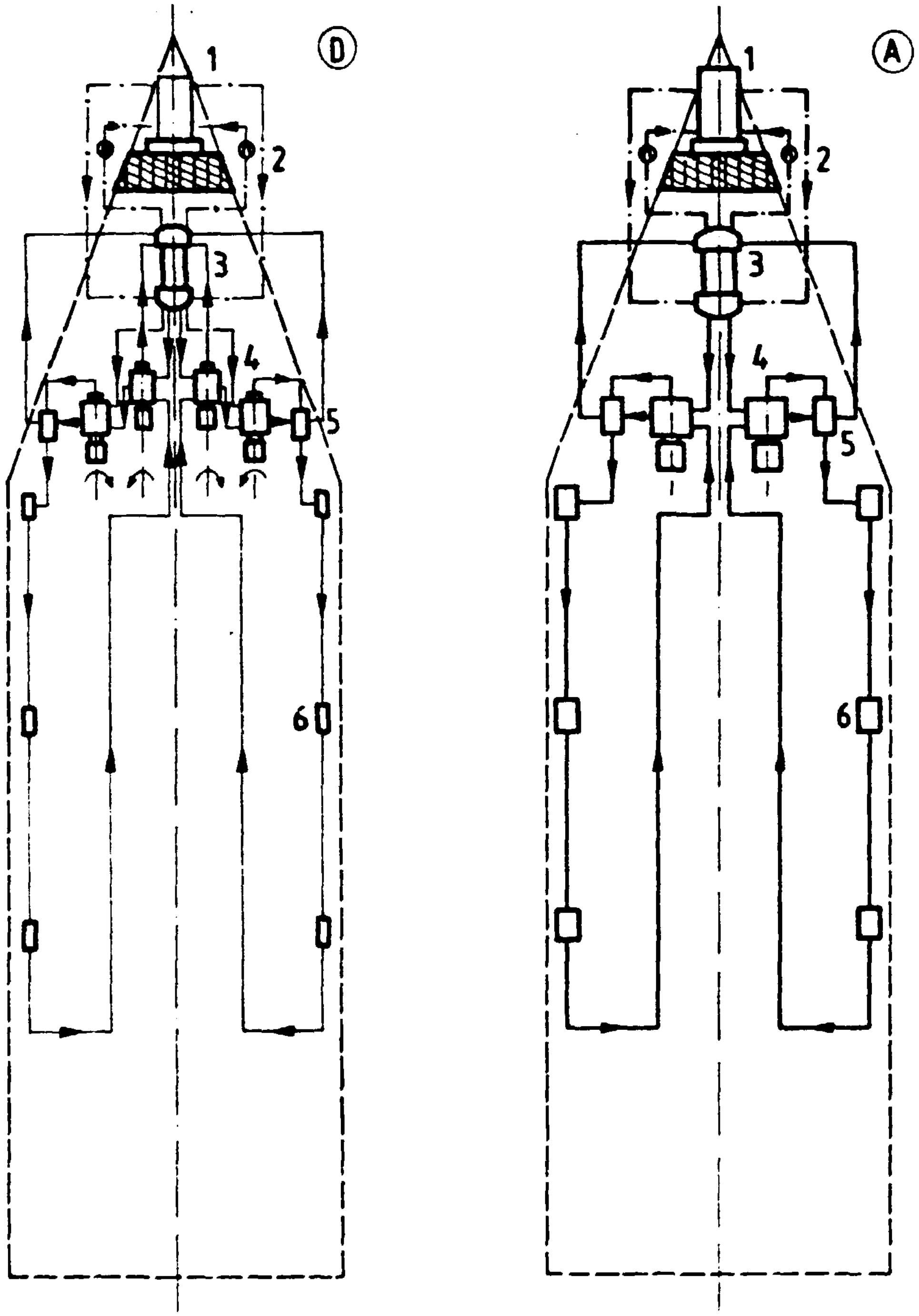
Ⓐ NON REHEAT/NON INTERCOOLED CYCLE (SIMPLE)



Ⓓ REHEAT/NON INTERCOOLED CYCLE

Fig. 9. Comparative Diagrams of Non-Reheat and Reheat Brayton Cycle Systems for Space Applications

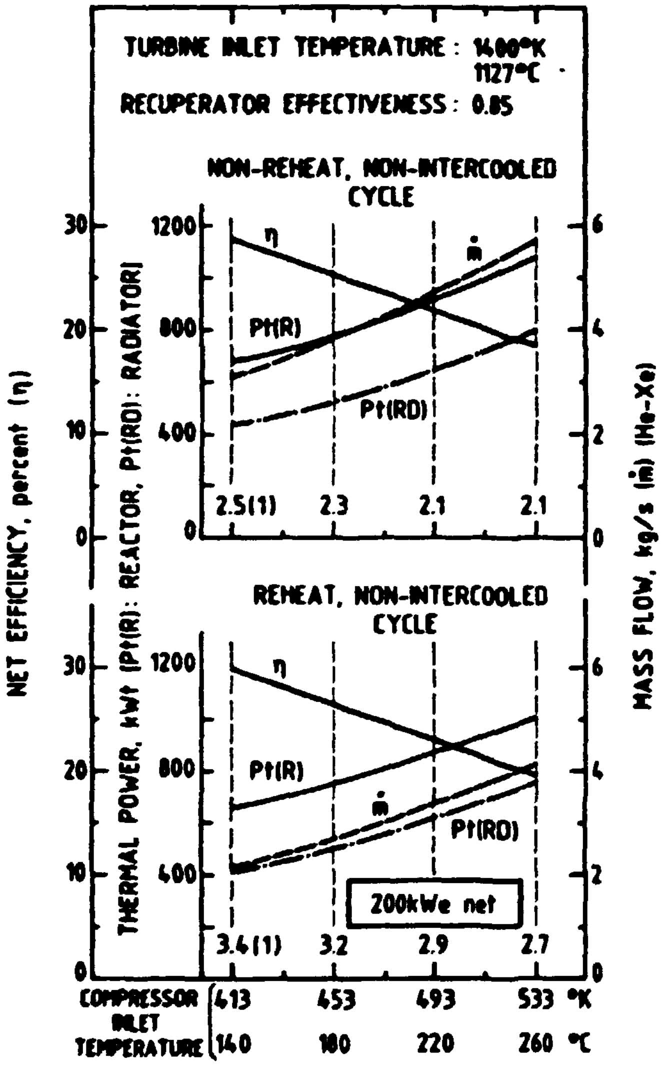
1 : REACTOR
2 : SHIELD
3 : HEAT SOURCE HEAT EXCHANGER
4 : TURBINE-COMPRESSOR-GENERATOR UNITS
5 : RECUPERATOR
6 : RADIATOR



REHEAT, NON-INTERCOOLED CYCLE

NON-REHEAT, NON-INTERCOOLED CYCLE

Fig. 10. Comparative Schematic Arrangements of Non-Reheat and Reheat Brayton Cycle Systems for Space Applications



(1) COMPRESSOR PRESSURE RATIO

Fig. 11. Typical Variation of the Main Power System Characteristics as a function of the Compressor Inlet Temperature

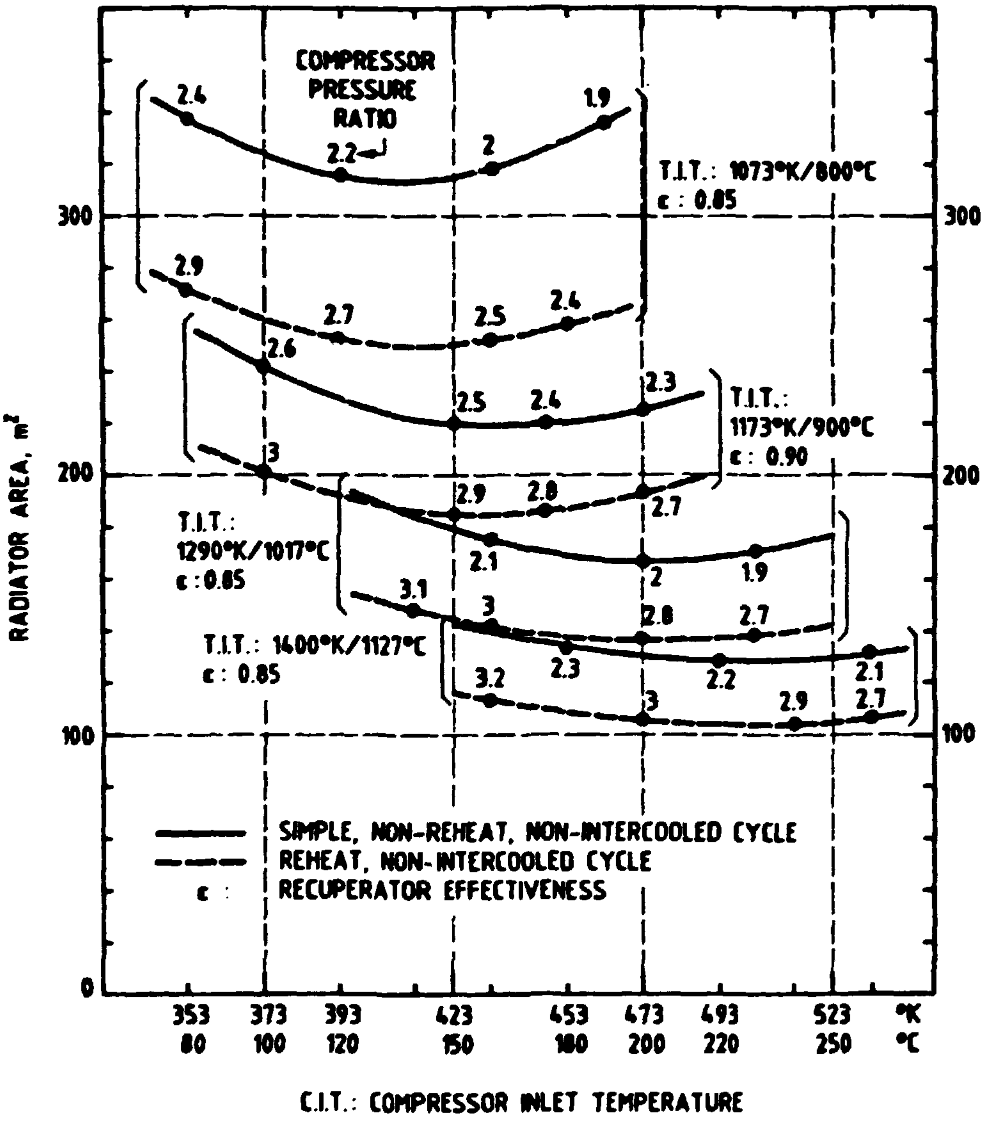


Fig. 12. Variation of the Radiator Area as a function of the Turbine and Compressor Inlet Temperatures