XA9904240

International
Nuclear
Fuel
Cycle
Evaluation

INFCE

INFCE/DEP/WG.5/75

A STUDY OF SODIUM-COOLED FAST BREEDER REACTOR WITH THORIUM BLANKET FOR SUPPLY OF U-233 TO HIGH TEMPERATURE GAS-COOLED REACTOR

Contribution of Japan to INFCE WG.5/D

A STUDY OF SODIUM COOLED FAST BREEDER REACTOR WITH THORIUM BLANKET FOR SUPPLY OF U-233 TO HIGH TEMPERATURE GAS COOLED REACTOR[*]

AUGUST 1978

H. YOSHIDA, H. NISHIMURA and T. OSUGI[**]

Japan Atomic Energy Research Institute

---

[*] This paper is the personal comments of the authors and does not represent the official opinion of Japan.

[**] Tokai-mura, Naka-gun, Ibaragi-ken, Japan.

ABSTRACT

Conventional homogeneous, radial and axial heterogeneous core LMFBR concepts have been investigated to identify potential configurations of fast breeder reactor for the supply of U-233 to HTGR in the symbiotic energy system between LMFBR and HTGR. The investigation has been made considering fuel sufficiency, inherent safety and fuel cycle cost of LMFBR. It was found that the axial heterogeneous core LMFBR concept would be preferable as the LMFBR in the symbiotic energy system from its best performances to the conditions imposed.

The study presented here can prepare some data basis to compare performances of homogeneous and heterogeneous core LMFBRs with thorium blanket.

1. INTRODUCTION

There are a number of large industrial process heat applications that can utilise very high temperature gas-cooled reactor. Such multi purpose process heat production HTGR may be expected to be built, even long after the fast breeder reactor has been commercially introduced for electricity generation. It is obvious, however, that considerable amount of U-233 has to be supplied in some ways to operate the HTGR continuously, because of its conversion ratio of less than unity.

Symbiotic energy system between fast breeder reactor and process heat production HTGR appears to be promissing as an energy system self sufficient in fuels, which can generate both electricity and high temperature process heat. In the system the fast breeder reactor has to supply sufficient amount of fissile plutonium to keep the reactor itself going, and also produce U-233 neccessary to the associated U-233 fuelled process heat production HTGR. If we concern with a symbiotic energy system between electricity generating LMFBR and HTGR instead of the system mentioned above, the same considerations have to be paid for LMFBR.

Fortescue has evaluated the installed rate of HTGR to fast breeder reactor in the symbiotic system as a function of breeding ratio of fast breeder reactor and conversion ratio of HTGR(1), and also Brogli has investigated the fuel economics of the system between gas-cooled fast breeder reactor (GCFR) and HTGR(2). Their studies have indicated that the symbiotic energy system not only uses fuel very effectively, but also has lower power generating cost than for any other reactor or combined reactor systems.

The primary emphasis on the study presented has been devoted to finding out potential configurations of mixed-oxide fuelled LMFBR with thorium blanket preferable to the symbiotic energy system between HTGR and LMFBR, through investigations on fuel sufficiency in the total of the system, inherent safety such as sodium void reactivity coefficient and fuel cycle cost.

In the study three types of 1000 MWe LMFBR were chosen as basic fast breeder reactor concept. They are similar to conventional homogeneous core LMFBR, axial parfait heterogeneous core LMFBR and radial parfait heterogeneous core LMFBR, respectively. However, some parts of UO_2-blanket in the ordinary concepts are replaced by ThO_2-blanket to produce U-233.

2. MODELS OF SYSTEM AND COMPOSED REACTORS

Model of symbiotic energy system

Considering that demand of process heat energy will be significantly larger than that of electricity energy at the present, a higher installed rate of process heat production HTGR to the associated fast breeder reactor in such a system will be desirable in the future. LMFBR based on mixed-oxide fuel developed to date, however, can not be expected to have good enough breeding performance to allow such a high installed rate of HTGR in the system. Fig. 1 shows a schematic diagram of fuel flow in the equilibrium cycle of the system consisting of a LMFBR and a HTGR.

Model of HTGR

HTGR proposed to date are not designed so as to attain the best conversion ratio. Total fuel cycle cost tends at present to minimise at distinctly lower conversion ratio. According to feasibility study of steam cycle HTGR having higher conversion ratio, considerable improvement in conversion ratio, such as 0.8 - 0.9, can be attained without sacrificing fuel cycle cost too much, by increasing Th loading and reducing power density. Both changes result in reduced fuel temperature, reduced fuel burnup and reduced core pressure drop. Such performance improvement may be preferable also for process heat production HTGR. The HTGR design chosen is based on a concept with relatively high conversion ratio of 0.85. The principal parameters are listed in Table 1.

Model of LMFBR

Three basic LMFBR concepts shown in Fig. 2 were used to find out potential configurations of fast breeder reactor suitable for the symbiotic energy system by mean of supplying U-233 to the HTGR. They are distinguished in the paper by the names of "FBR-A" , "FBR-B" and "FBR-C", respectively.

"FBR-A" is similar to the conventional LMFBR. Three congigurations were chosen for this concept by varying thickness of the radial blanket. "FBR-B" is similar to the axial parfait heterogeneous core LMFBR advocated by Ducat et al.(3). Three configurations were chosen for this concept by loading ThO_2 into the external axial blanket or the radial blanket, and by varying height of the internal axial blanket. "FBR-C" is based on the radial parfait heterogeneous core LMFBR advocated by Mougniot et al.(4). For this concept two additional configurations were chosen by loading ThO_2 into the internal radial blanket or the external radial blanket.

Distinction of the eight different configurations of LMFBR are summarised in Table 2. The isotopic composition of plutonium in fresh fuel in the cores of all the configurations was assumed to be ^{239}Pu / ^{240}Pu / ^{241}Pu / ^{242}Pu = 63 / 22 / 12 / 3, which corresponds to discharged plutonium from LWR at the irradiation of about 30,000 MWD/T. The residence time of core and blanket fuel elements was also assumed to be two years at 80 % load factor.

3. CALCULATION METHOD

In order to find out the most desirable LMFBR configuration in the energy system, neutronic and fuel cycle calculations have been made. The neutronic calculation consists of burnup calculation for obtaining reactor performance at the equilibrium state and safety related physics parameter calculation.

For the neutronic calculation, the effective 6-energy group cross-sections have been provided by applying the JAERI-Fast 25-energy group cross-section set(5) to the neutron spectrum of each configuration. The burnup calculation has been made using the burnup analysis code APOLLO(6) based on two-dimensional diffusion approximation in cylindrical geometry. In the calculation, equilibrium fuelling was assumed to occur by replacing one fourth of the fuel semiannually in the core, axial blanket and internal blanket, and by replacing all the fuel in the external radial blanket after two years' irradiation. All the fuel elements, therefore, remain in the reactor for two years at 80 % load factor.

Sodium void coefficient and isothermal Doppler coefficient were chosen as safety related physics parameter of LMFBR. Sodium void coefficient was calculated as the difference between the effective multiplication factors for the reactors with and without sodium in the regions inside the axial and external blankets, using APOLLO. Doppler coefficient was also calculated in similar way for the reactors having core temperatures of 900°K and 2100°K. The calculations were made for the equilibrium state of each configuration.

Economic comparison of the eight configurations has been made using a simple formula of equilibrium fuel cycle cost which is represented by unit of \$/yr. The fuel cycle cost is composed of incomes from sale of bred fissile materials, of expenditures for fabrication and reprocessing of fuel elements, and of initial fissile inventory carring charge. The fuel cycle cost EC is written by

$$EC = Cp(Gp - \chi \cdot Ip) + Cu \cdot Gu - Cf \cdot Wf - Cr \cdot Wr ,$$

where, Cp and Cu ; unit cost of fissile Pu and U-233 (\$/kg), Gp and Gu ; annual net gain of fissile Pu and U-233 (kg/yr), Cf and Cr ; unit cost of fabrication and reprocessing (\$/kg), Ip ; initial fissile Pu inventory (kg) ,χ ; annual discount rate (1/yr), Wf and Wr ; annual amount of fuel materials to be fabricated and reprocessed. The fuel cycle cost parameters are given in Table 3.

4. RESULTS AND DISCUSSIONS

The performance of the symbiotic system may be determined by that of LMFBR chosen, because the installed HTGR is only one and also assumed to be same for every fast reactor configuration.

Comparison of fuel sufficiency

Table 4 compares initial fissile plutonium inventory and reactivity swing due to burnup during 6 months' irradiation at 80 % load factor. The minimum initial fissile plutonium inventory is attained for "FBR-A". A reason why the other concepts require larger plutonium inventory may be due to replacing fissile material from the high-worth portion of the core by a neccessarily greater amount placed in the low-worth portion of the core. The reactivity swing due to burnup is somewhat proportional to the initial fissile inventory which has direct relation with the fissile plutonium enrichment. The minimum reactivity swing is observed for "FBR-B", becuase of high plutonium buildup at the high-worth central portion of the reactor; internal axial blanket.

Table 5 shows annual gain of fissile Pu and U-233 in the equilibrium cycle. Consideration of fuel-sufficiency in the system should be paid on the points that surplus fissile plutonium is not negative and produced U-233 exceeds 135 kg necessary to HTGR every year. "FBR-A" and "FBR-B" satisfy these conditions. However, "FBR-C" considered in the study is not adequate as the fast breeder reactor in the system.

Comparison of safety-related physics parameters

Sodium void coefficient and isothermal Doppler coefficient have been caluculated as the inherent reactor safety-related physics parameters. It was assumed in the calculation that sodium voiding occurs in the regions corresponding to the core of "FBR-A" and also assumed that temperature change in fuel occurs only in the core. The calculated results are compared in Table 6.

The calculated results indicate that the positive sodium void coefficients of "FBR-B" and "FBR-C" are considerably lower than that of "FBR-A". In "FBR-A", the effect of thickness of ThO_2 blanket on sodium void coefficient is very small as found in other parameters except breeding performance. In "FBR-B", increasing height of the internal blanket, sodium void coefficient significantly decreases. In "FBR-C", sodium void coefficient strongly depends upon selection of ThO_2 or UO_2 as internal radial blanket material.

Doppler coefficient depends on the fast reactor configuration through neutron spectrum and fissile enrichment. The calculated results shown in Table 6 indicate that the Doppler coefficient of "FBR-A" is about 50 % greater than those of "FBR-B" and "FBR-C". This is because the latter two LMFBR concepts have harder neutron spectra and higher fissile enrichments, and also because temperature change resulting to the coefficient is restricted just in the core region.

Comparison of fuel cycle cost

Exact evaluation of fuel cycle cost generally requires complicated and detailed analyses, using computer codes. In the study presented here, the simple formula of eqilibrium fuel cycle cost described before was used to make it easy to look at a relative advantage or disadvantage among the eight LMFBR configurations chosen. When the eqilibrium fuel cycle cost of a reference LMFBR configuration is EC_0, the relative fuel cycle cost advantage to other configuration, LA, can be expressed as follows.

$$LA = (EC - EC_0)/ EC_0$$

Table 7 shows the calculated relative fuel cycle cost advantage, where "FBR-A-1" is the reference configuration. In the table positive values indicate degree of advantage and negative values disadvantage respectively.

It should be noted that in the calculation, the unit fuel fabrication cost for the core and internal axial blanket of "FBR-B" is assumed to be same as that for the core of "FBR-A" or "FBR-C". The other assumptions made can be seen in Table 3.

The calculated results indicate that "FBR-B" and "FBR-C" can be expected advantageous to "FBR-A" on the fuel cycle cost. In "FBR-A", increasing thickness of the radial blanket, the fuel cycle cost significantly increases. This is because increase of the expenditure of blanket fuel fabrication and reprocessing overcomes increase of the income of produced U-233, with increase of radial blanket thickness. In "FBR-B", increasing height of the internal axial blanket from 30 cm to 40 cm, the fuel cycle cost decreases, because of better breeding performance of the configuration with higher height of the internal axial blanket. And an excellent fuel cycle cost found in "FBR-C" may be simply due to considerably less core fuel reqired, compared with the other concepts. This leads to fairly low core fuel fabrication cost in "FBR-C".

5. CONCLUDINGS

Three types of LMFBR concepts with thorium blanket have been investgated to find out suitable configurations of LMFBR for the supply of U-233 to the HTGR with relatively high conversion ratio of 0.85, in the symbiotic energy system between LMFBR and HTGR. The investigations on LMFBR have been made on fuel sufficiency of the system, inherent safety such as sodium void coefficient and Doppler coefficient, and fuel cycle cost.

The followings were revealed.

(1) Conventional homogeneous core LMFBR with thorium radial blanket,"FBR-

A", well satisfies the condition of fuel sufficiency, if adequate radial blanket thickness is chosen. However, the sodium void coefficient and fuel cycle cost are inferior to the other concepts.

(2) Axial parfait heterogeneous core LMFBR can be considered as one of the best LMFBR concept installed in the symbiotic energy system, from the view points of fuel sufficiency, inherent safety and fuel cycle cost. However, further investigations would be needed on reliability and operatinability.

(3) Radial parfait heterogeneous core LMFBR seems to be inadequate as LMFBR in the system, because configurations based on this concept does not satisfy either plutonium breeding or U-233 breeding. This LMFBR, however, has excellent breeding performance in the internal radial blanket. Further parametric studies should be made, including effects of volume and position of internal radial blanket, and of core zoning with different fissile enrichments which have not been investigated yet in the paper.

ACKNOWLEGEMENT

The authours want to express their sincere thanks to K. Ikawa for his helpful comments and discussions on the computer code, APOLLO, and also to F. Ohta for performing a large number of calculations partaining to the paper.

REFERENCES

(1) Fortescue P. : Advanced HTGR system. Annals of Nuclear Energy, 2, 787 - 799, (1975).

(2) Brogli R. and Schlter G. : Fuel economics of GCFR/HTGR symbiotic system. Proceedings of the international conference on advanced reactor;

physics, design and economics, Atranta U.S., 135 -143, (1974).

(3) Ducat G.A. et al. : Evaluation of the parfait blanket concept for fast breeder reactors. COO-2250-5, (1974).

(4) Mougniot et al. : Gains de regeneration des reacteurs rapides a combustible oxyde et a refrigerant sodium. Proceedings of first european nuclear conference, Paris, (1975).

(5) Takano H., Hasegawa A., Nakagawa M., Ishiguro Y. and Katsuragi S. : JAERI fast reactor group constants set, version II. JAERI 1255, (1978).

(6) Ikawa K. : Two-dimensional multigroup diffusion burnup code APOLLO for fast reactor long-term burnup analysis. JAERI-M 5886, (1974).

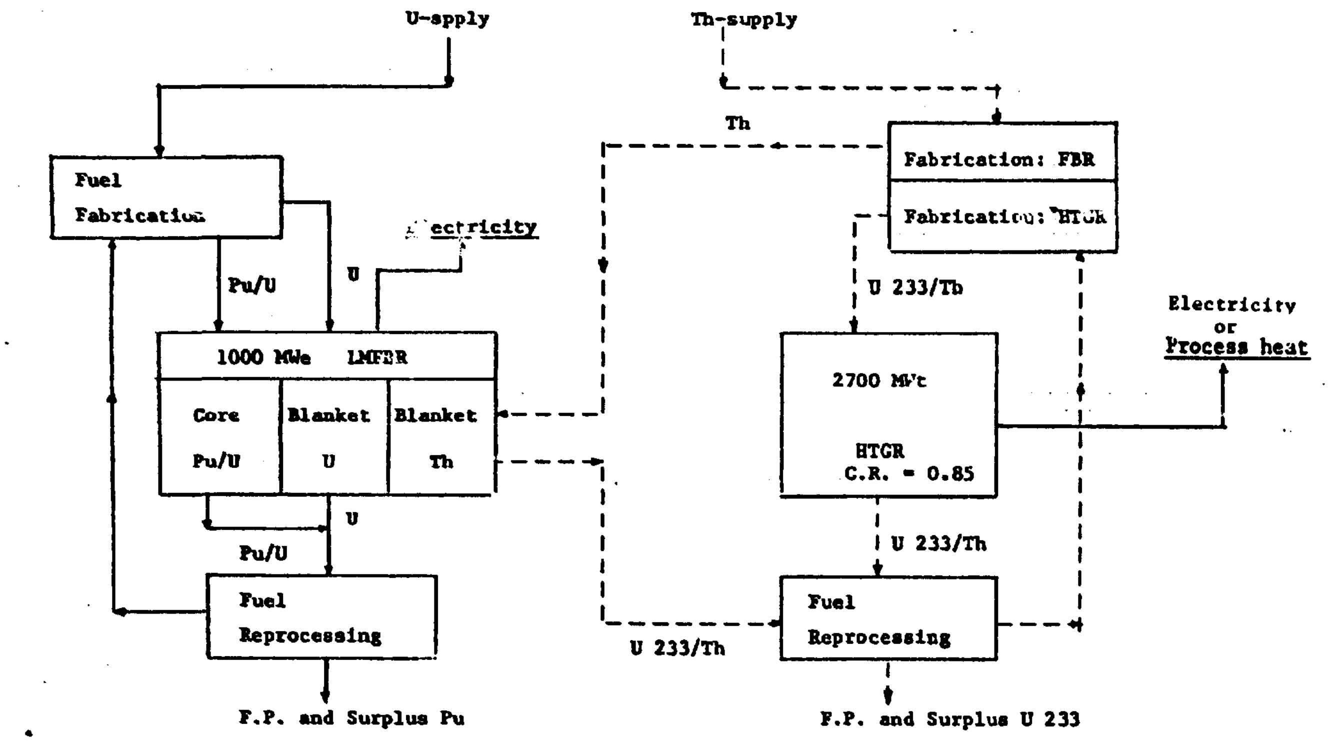
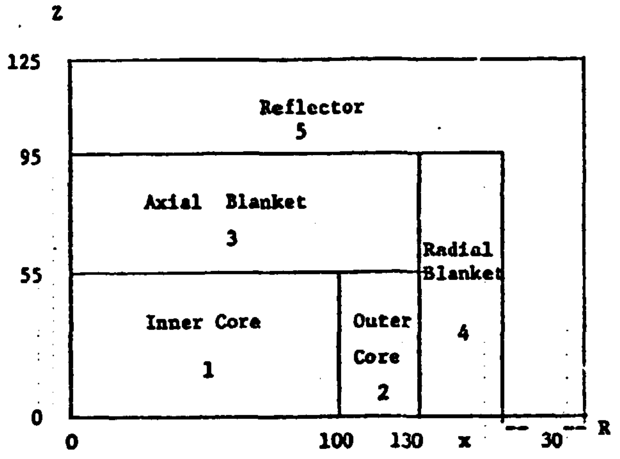
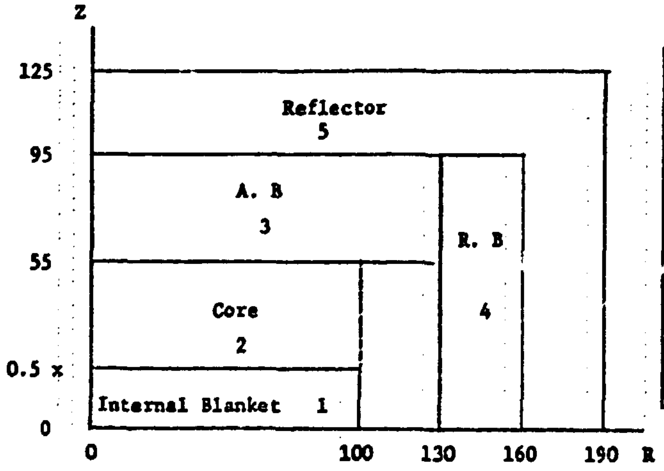


Fig. 1 Shematic diagram of fuel flow in the symbiotic energy system between sodium cooled fast breeder reactor (LMFBR) and high temperature gas-cooled reactor (HTGR).



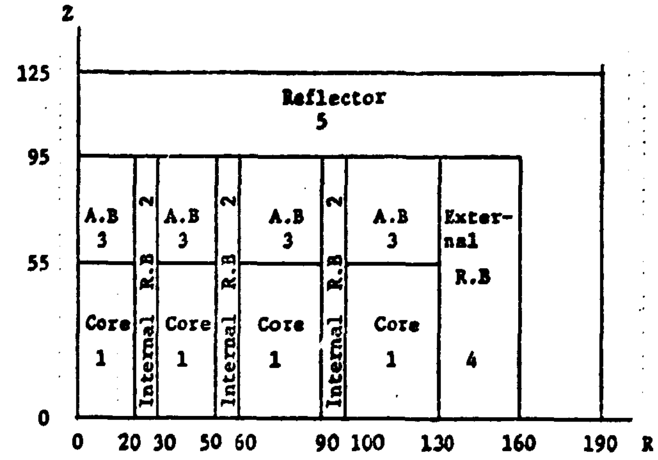
Region	Fuel	Na	S.S.
1	0.3	0.5	0.2
2	0.3	0.5	0.2
3	0.3	0.5	0.2
4	0.5	0.3	0.2
5	0	0.3	0.7

(unit : cm) "FBR-A" ; Conventional homogeneous core LMFBR



Region	Fuel	Na	S.S.
1	0.3	0.5	0.2
2	0.3	0.5	0.2
3	0.3	0.5	0.2
4	0.5	0.3	0.2
5	0	0.3	0.7

(unit : cm) "FBR-B" ; Axial parfait heterogeneous core LMFBR



Region	Fuel	Na	S.S.
1	0.3	0.5	0.2
2	0.5	0.3	0.2
3	0.3	0.5	0.2
4	0.5	0.3	0.2
5	0	0.3	0.7

(unit : cm) "FBR-C" ; Radial parfait heterogeneous core LMFBR

Fig. 2 Dimension and region composition of LMFBR concepts

Table 1 Principal parameters of HTGR selected

Thermal power	2,700 MW
Power density	5 W/cm^3
Initial U-233 inventory	1426.5 kg
Initial thorium inventory	44.5 ton
Conversion ratio	0.85
Annual consumption of U-233	135.0 kg
Fuel residence time	3 yr at o.8 L.F.

Table 2 Distinction of eight different LMFBR configuration

Configuration	Core	Th blanket	U blanket
FBR-A-1	1, 2	4(30cm)	3
FBR-A-2	1, 2	4(40cm)	3
FBR-A-3	1, 2	4(50cm)	3
FBR-B-1	2	3	1(30cm), 4
FBR-B-2	2	3	1(40cm), 4
FBR-B-3	2	4	1(40cm), 3
FBR-C-1	1	2	3, 4
FBR-C-2	1	4	2, 3

* Integers in the table stand for region-number in Fig. 1 , and values in parentheses stand for blanket thickness.

Table 3 Principal fuel cycle cost parameters

Fissile plutonium ; Cp	10 \$/gr
U-233 ; Cu	10 or 15 \$/gr
Fabrication of core fuel ; Cf,c	350 \$/kg
Fabrication of blanket ; Cf,b	70 \$/kg
Reprocessing of core fuel ; Cr,c	100 \$/kg
Reprocessing of blanket ; Cr,b	40 \$/kg
Annual discount rate ; χ	0.08/yr

Table 4 Initial fissile plutonium inventory and reactivity swing per cycle

Configuration	Fissile Pu (kg)	React. swing (% k/k)
FBR-A-1	2428.9	- 1.69
FBR-A-2	2428.9	- 1.71
FBR-A-3	2428.9	- 1.72
FBR-B-1	2581.5	- 1.60
FBR-B-2	2615.0	- 1.92
FBR-B-3	2609.1	- 1.85
FBR-C-1	2685.4	- 2.05
FBR-C-2	2520.1	- 2.01

Table 5 Annual gain of fissile plutonium and U-233

Configuration	Fissile Pu (kg)	U-233 (kg)
FBR-A-1	52.9	139.0
FBR-A-2	53.0	151.1
FBR-A-3	53.1	156.7
FBR-B-1	27.8	165.0
FBR-B-2	35.8	165.4
FBR-B-3	39.2	163.9
FBR-C-1	- 45.5	227.9
FBR-C-2	93.8	125.3

Table 6 Sodium void coefficient and Doppler coefficient

Configuration	Sodium void*	Doppler**
FBR-A-1	1.579	- 0.00527
FBR-A-2	1.576	- 0.00527
FBR-A-3	1.573	- 0.00527
FBR-B-1	1.420	- 0.00361
FBR-B-2	1.199	- 0.00329
FBR-B-3	1.253	- 0.00334
FBR-C-1	1.139	- 0.00326
FBR-C-2	1.431	- 0.00358

* % k/k, ** - T(dk/dT)

Table 7 Relative fuel cycle cost advantage of LMFBR configurations to FBR-A-1

Configuration	Unit cost of U-233	
	10 $/gr	15 $/gr
FBR-A-1	0 (%)	0 (%)
FBR-A-2	- 6.0	- 5.6
FBR-A-3	- 13.4	- 13.5
FBR-B-1	- 1.1	1.0
FBR-B-2	0.1	2.4
FBR-B-3	- 0.0	2.1
FBR-C-1	5.7	13.9
FBR-C-2	9.7	9.7