Abstract

In the period from 2012 to 2023, a specialized program (computer code) for a computer was created and modified, which currently has no analogues in the Russian Federation. **The FC-FNS code is designed to simulate fuel nuclide flows and their quantities in fuel cycle systems, taking into account the fuel cycle architecture and candidate technological solutions, including the injection system of atomic beams of various isotopic compositions, and the results of its use to determine the parameters of fuel injection, pumping and processing of a tritium-containing gas mixture at various plasma parameters of a thermonuclear facility with a blanket.**

Despite the fairly simple interface and the use of the environment instead of a specialized programming language MS Excel, the code allows simulating the coordinated operation of many fuel cycle systems, including a vacuum chamber with plasma. The peculiarity of the model is not so much the precision modeling of a single system (including plasma), as the joint operation of a large number of interconnected elements in which physical and chemical processes occur, differing by several orders of magnitude both in time and in the amount of substance. The use of a more complex mathematical apparatus (than is used) to solve the problem is not required. Further development of the approach proposed by the author using more complex and accurate models and codes is the subject of future work, requiring the involvement of a significant number of high-level specialists and the creation of a team.

FC-FNS calculation code

for modeling the distribution of hydrogen isotopes in the fuel cycle systems of a fusion reactor

To assess the tritium distribution in the controlled fusion reactor (CFR) or fusion neutron source (FNS) systems and the "tritium plant", it is necessary to model the tritium behavior in all elements of these systems, taking into account their operating mode. At the stage of developing the thermonuclear fuel cycle (FC) concept for the FNS, an analysis of available computer codes was performed. Despite the existence of computer codes in the world used for dynamic modeling of systems included in the FC, their use for the FNS project was not possible due to the insufficient level of elaboration of the FC (at the conceptual level). System codes aimed at assessing the scale of the amount of fuel for the CFR operation (for example, [1]), on the contrary, made it possible to obtain too general information about the TC. An attempt to use the FC model proposed for the DEMO reactor projects [2] showed some artificiality of the parameters for this model - the complexity of adapting the physical parameters characterizing the systems and modes of the FNS for use in modeling. At the same time, this model showed a weak dependence on the FC architecture and technological solutions for the systems. The computer codes used in the ITER project (e.g. [3]) describe the operation of the FC systems optimized for the pulsed mode of operation of the facility, which makes their application for the stationary operating FNS facility difficult. In addition, not all codes are available to Russian developers.

Commercial codes AspenPlus [4] and EcosimPro [5], COMSOL , etc. are of unconditional interest for two-dimensional modeling of FC systems and calculations of hydrogen isotope flows in them; however, the resource intensity of the created electronic models and the lack of preliminary designs of FC systems do not allow moving on to more detailed design of FC elements and modeling of the behavior of hydrogen isotopes in them even at the current stage.

In connection with these circumstances, **in 2013** it was decided to create a new computer model of the fuel cycle, allowing it to be developed as the FNS projects were developed and to use any level of detail/approximation in modeling the fuel cycle systems without compromising the result. The created model had to have sufficient "flexibility" to be able to model any fuel cycle architecture (and the ability to quickly change it) as well as to model the specified operating modes of the fuel cycle systems.

The main objectives were as follows:

- Estimation of the minimum amount of fuel (tritium) required to start the FNS facility/project,
- Selection of the optimal proportion of tritium in the plasma to reduce the amount of T in the facility as a whole while maintaining the neutron yield at the required level,

- Selection of FC technologies, including selection of the optimal gas supply scheme for the plasma beam heating system (and its replenishment with fuel particles),

- and others.

At the first stage of the TC-FNS (Tritium Cycle of Fusion Neutron Source) code development, the turnover of one component of the fuel mixture, tritium, was modeled in the FC FNS during its continuous circulation in the steady-state mode of the facility. Thus, **scenarios for putting the facility into operation were not considered, as well as all scenarios that provide for changes in values relative to the steady state.** The flow modeling was performed in zero-dimensional form.

The behavior of particles in all FC systems is described by balance equations - from the moment of particle departure from the plasma until the moment of reintroduction (into the plasma) using various injection systems. During the calculation, the particle balance as a whole is checked (for one revolution of the fuel mixture) based on the fact that **the injection systems must compensate for particle losses from the plasma as a result of burnout and carryover/diffusion losses.** When forming the lower estimate, it is assumed that fuel must be supplied to the vacuum chamber to maintain a given plasma density. Removal of particles from the vacuum chamber must ensure a regime in which fuel accumulation in it does not occur and the required operating parameters of the divertor are ensured. Using the values of the flows through all FC systems and the expected modes of their operation [6], the accumulation of T in the FC of the facility was calculated. For most systems, characteristic "residence times" of particles in the system were specified - similar to the model [2]. Meanwhile, these times were largely based on technological solutions. The TC-FNS model showed greater sensitivity to changes in process parameters and turned out to be more convenient than [2, 7], which led to its further improvement with comparable modeling results obtained [8].

Later the code was significantly developed and changed its name to FC-FNS (Fuel Cycle of Fusion Neutron Source), since it included calculations **for all hydrogen isotopes**. The code was improved both in the direction of detailing the FC systems and taking into account specific technological solutions, and in the direction of changing the architecture. The conditional stages of the development of the code functionality are presented in Table 1. A significant step was the use of agreed parameters of the core and divertor plasma for calculating flows in the FC systems. Work on the use of the model [2], taking into account its adaptation for FNS and its integration into the FC- FNS code , seems promising and is currently underway time. The algorithms used for the calculations are described in detail in [9, 10].

Table 1. Stages of FC-FNS code development [11].

Version	Year	New features
1.0	2013	Creation of an electronic model: Calculation of T-flows, assessment of T reserves
2.0	2014	Model development: T-accumulation, D:T = 1:0.05 NBI scenario
4.3	2014	T-breeding in a blanket, calculations according to the analytical model of the fuel cycle
5.0	2015	New fuel cycle layout, increasing the number of systems
5.1	2015	Changing the architecture of the fuel cycle, calculation for T, D and H
5.3	2016	Dynamics of hydrogen content in fuel, T-dynamics in injectors
5.6	2016	Changes in the approach to fuel injection
5.7	2017	Arbitrary D:T ratio in plasma
5.8.8	2017	D:T = 1:0 for NBI, arbitrary fuel flows through VV
6.0	2018	Separate injection of D_2, T_2, DT pellets, separation of gas mixture
7.0	2018	Isotopic composition of fuel in the FC - calculations by the iteration method
8.0	2019	Taking into account the influence of the neutral flow from the divertor
9.0	2019	Consistent modeling – integrating algorithms into code
10.0	2019	Splitting one working file/module into separate ones - by functions
11.0	2020	New plasma model, diffusion times for particle sources
12.0	2020	Calculations of all scenarios of gas supply to injectors in parallel
13.0	2020	The proportion of T in the divertor, the effect on the composition of the core plasma
14.0	2020	Automated calculation of pellet injection frequencies
14.2	2021	Accounting for the effect of ELM on particle loses from plasma – First Release
15.1	2021	Adaptation for FNS-ST, change of diffusion parameters
15.2	2021	T-beam modeling for FNS-ST
15.8	2021	Correct accounting of the influence of ELM, stimulation with LFS
16.0	2022	D/T Accumulation calculation algorithm in ISS
16.1	2022	Optimization of the gas neutral injection system
16.2	2022	Upgrade to use "partial times" from ASTRA
16.3	2022	Using "partial times" from ASTRA for FNS-ST

The input parameters for the code are the geometric and physical parameters of the tokamak with subsystems: the geometric dimensions of the vacuum chamber, the diffusion times of particles, the plasma density, the fusion power, the parameters of the injection systems (the dimensions of the injectors and atomic duct/pipelines , the energy and power of the neutral atom beams, the number of injectors of all types - NBI , pellet injection PIS and gas valves GIS , the efficiency of introducing the fuel mixture into the thermonuclear plasma), the duration of the fuel processing cycles in various systems of the FC and modes of pumping out the vacuum chamber and injectors and much more. Also, the parameters indicate the period of stopping the tritium reproduction systems, the proportion of deuterium/tritium in the plasma, the permissible proportion of protium in the fuel mixture.

To calculate the steady-state values of the isotopic composition of the fuel mixture, the dynamics of changes in the number of particles in the plasma and the FC as a whole are simulated for each of the isotopes. Considering that deuterium and tritium in a number of systems are presented as a mixture of isotopes (with isotopomers HT, DT and HD) as well as in the form of molecules with impurity atoms $C_n H_m$, CO etc. for all FC systems the isotopic composition of the gas and, accordingly, the share of each isotope in the gas mixture are considered. Also, steady-state values of all parameters are modeled for a given fuel injection into the chamber, burnout rate and pumping speed. For protium, among other things, the mechanisms of particle growth due to desorption processes from structural and functional materials and production as a result of fusion reactions occurring in the plasma are considered. Potential sources of protium in the form of nuclear reactions of neutrons with structural materials and diffusion through the walls of the vacuum chamber and pipelines from the atmosphere and coolants are not assessed and can be considered later after the design and materials of the facility are selected. The dynamics of the tritium share in the gas supply system of the heating injectors is modeled in a similar way. The calculations result in the values of flows returned to the injection systems after pumping/processing directly and flows requiring purification/separation – deprotization and detritization. Tritium losses due to fusion reaction in plasma, β- decay of tritium and its irretrievable losses from the FC (within the established limits) are taken into account. Tritium production is taken into account in the hybrid blanket of the facility. Due to the fact that the proportions of tritium, deuterium and protium in the fuel mixture are within known limits, the code calculates the content of all three hydrogen isotopes in each element of the FC.

Due to the fact that the fast atom beam injectors are connected to the vacuum chamber by atomic pipelines through which fuel particles can enter the injector volume, and are also consumers of gas containing hydrogen isotopes, this system is included in the FNS FC. The neutral injection system uses gas neutralizers of the ion beam, for the operation of which a large amount of gas is required. Since the isotopic composition of the neutral atom beam is determined by the composition of the ion beam formed in the ion source, **the task of matching the parameters of the plasma and injectors is**

decisive from the point of view of the efficiency of the FNS neutron source, as well as the amount of T on the facility site.

To select the best beam injection scheme (isotopic composition of the beams), the code simulates alternative schemes for providing gas to the neutral atom injectors : using a mixture of deuterium and tritium in equal proportions (which avoids isotopic separation of the flow and reduces tritium accumulation in the FC) and deuterium without tritium admixture, which implies the use of a separate gas processing circuit including gas purification systems and a hydrogen isotope separation system to maintain tritium at a low level (options I and II , respectively). The second option allows minimizing the tritium content in the gas mixture of neutral atom injectors and reducing the load on some fuel cycle systems. However, this will lead to the need for additional equipment and an increase in the capital cost of the FNS. Other modes of providing NBI with gas are also possible, which were considered in the process of searching for the best solutions. Calculations for different (three) scenarios of providing NBI with fuel are performed in parallel in the code.

Below is a description of the interface of the FC-FNS program, implemented in the Microsoft package Excel. The calculation modules are shown and the procedures for changing the parameters for calculations are described, as well as the intermediate and final results of calculations for the DEMO-FNS project are shown.

1. FC-FNS code structure, working modules and interface

The structural diagram of the code is shown in Figure 1 . The main task solved by the code is the calculation of flows and content of hydrogen isotopes in each specific fuel cycle system. For ease of use, the code is divided into separate working modules that interact with each other by means of cross-references written in the form of equations for specific cells. For the code to work, all necessary program modules must be simultaneously launched by the user.

The calculation parameters are set in the file "initial data". The file contains several working "sheets" - the first one contains a table with the calculation parameters, and most of the results are also output there. This allows the user to perform calculations using only one file as an "interface". The remaining files and their "sheets" contain intermediate results, convenient for debugging or assessing the correctness of the calculations being performed.

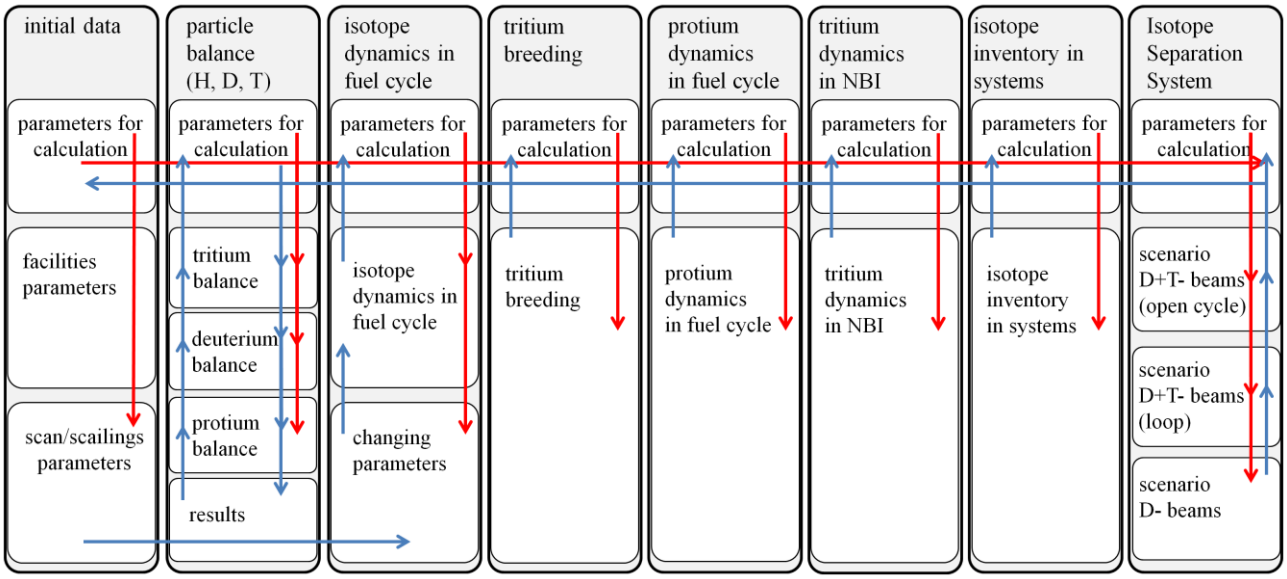


Figure 1. Structural diagram of the FC-FNS code

Figure 2 shows the table view with parameters for the DEMO-FNS project. Pellet injection frequencies are selected automatically to ensure the balance of particles in the plasma according to the equations described in [10, 12]. The color differentiation of the cells (here and below) corresponds to the type of fast atom beam under consideration – thus, green means D+T - beam, blue (in the current version of the code) D+T - beam with a closed gas supply circuit for the injectors, orange - D - beam.

A change in the set of parameters characteristic of another physical facility can be made by replacing (copying) the parameters in the table on the first sheet "parameters for calculation" from the table with a set of the corresponding parameters from the sheet "facilities parameters" (listed in the required sequence). In this case, in the corresponding cells in all files (working modules of the code), they will be automatically changed, including the name of the facility for which the calculations are performed. In a number of files, when the name of the facility is changed, the algorithms for calculating the parameter values in the corresponding cells will change (for example, for the FNS-ST facility, the heating injectors differ from the DEMO-FNS injectors in the ion type and, accordingly, the beam composition - in the form of its components with different energies, etc.). The table with parameters on the sheet "facilities parameters" contains the known parameters required for calculation for the ITER, T-15MD, JET, JT-60SA, SABR, FNS-ST and DEMO-FNS facilities. This operation is convenient for evaluating typical calculation results for facilities of different scales.

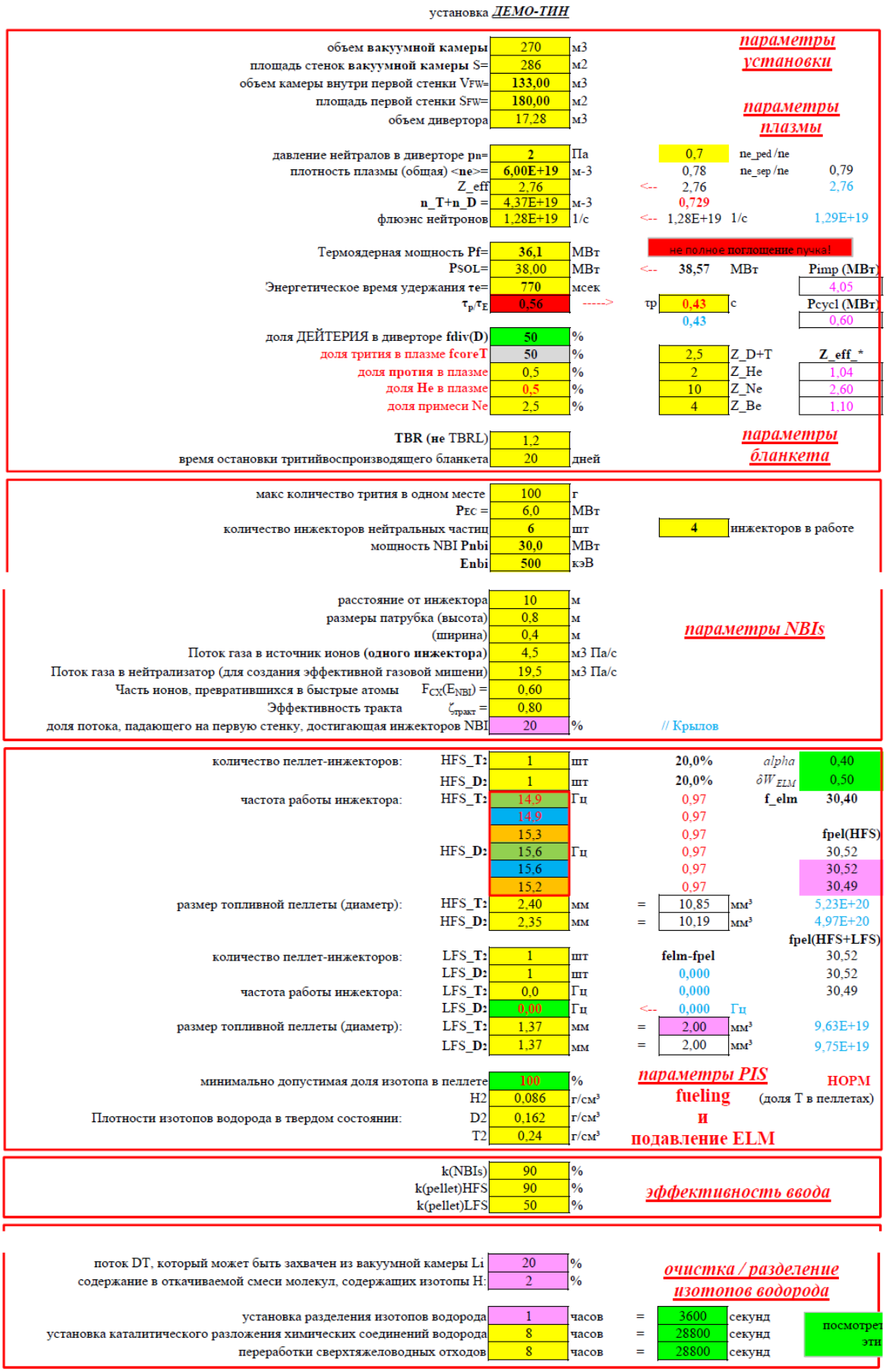


Figure 2. Interface of the module "initial data" of the FC-FNS code. Fragment with parameters of the DEMO-FNS project

Unfortunately, **such an operation cannot be correct for consistent modeling of plasma parameters and flows in the FC, since for each facility the scalings for calculating the parameters of the core and divertor plasma obtained by the SOPLPS and ASTRA codes** [9, 10, 12] **are different** and their automatic replacement cannot be implemented. The reason for this is the lack of calculations (scalings) for most of the listed facilities by the authors of the program. At the moment, for the convenience of calculations for the FNS-ST and DEMO-FNS projects, different versions of the code are used, containing the appropriate scalings and optimized taking into account the differences in the projects. If desired, the number of simulated facilities can be increased, and an interface can be organized that implies the replacement of all the main parameters, including for consistent modeling.

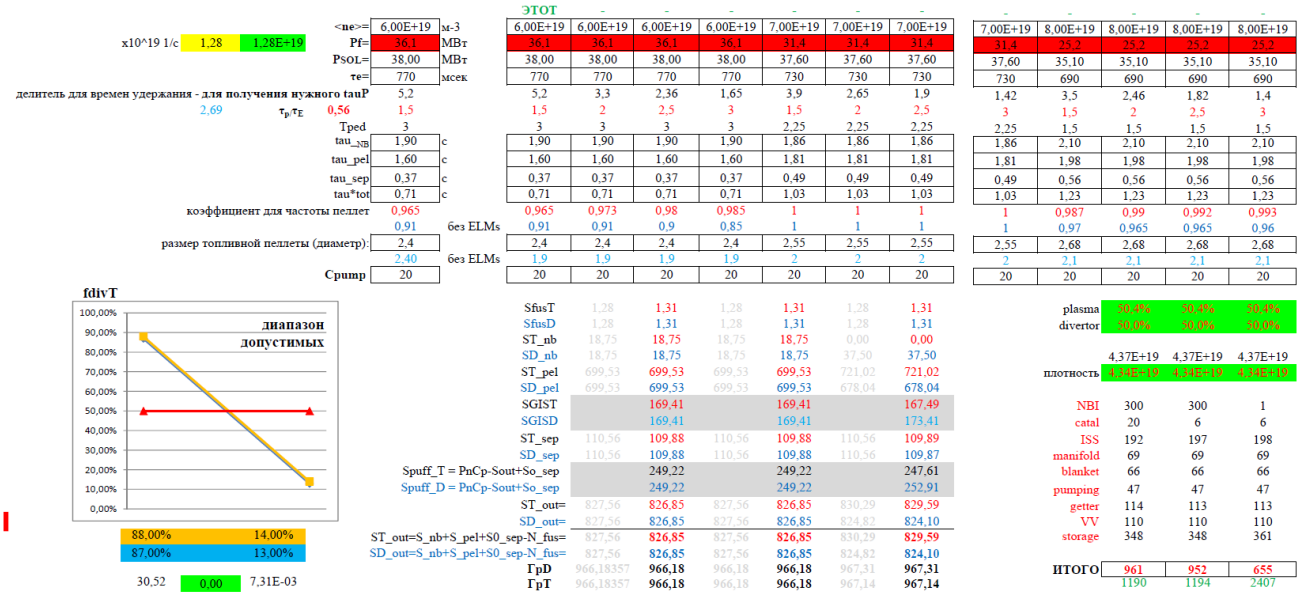


Figure 3. Interface of the module "initial data" of the FC-FNS code. Calculation results for the DEMO-FNS project

Figures 3 and 4 show additional parameters for the calculations and their results. For calculations carried out for different values of the core plasma density and particle confinement parameters, the corresponding parameters were formed in the form of a table shown in Figure 3. By copying the corresponding column with values, one of the specified operating modes (previously modeled in the ASTRA code) can be simulated. The "THIS" indicator helps the user to see the simulated mode (see Figure 3). Ease of use of the Microsoft package Excel allows you to perform the required calculations/checks in empty cells of the document during the calculation process, as well as, for example, convert values into other units if necessary. The results of the calculation of flows in the core and divertor plasma are copied from the files where these calculations are performed and are output as a table on the "parameters for calculation" sheet (see the bottom of Figure 3) - they can be copied for analysis as a block in another Microsoft Excel document.

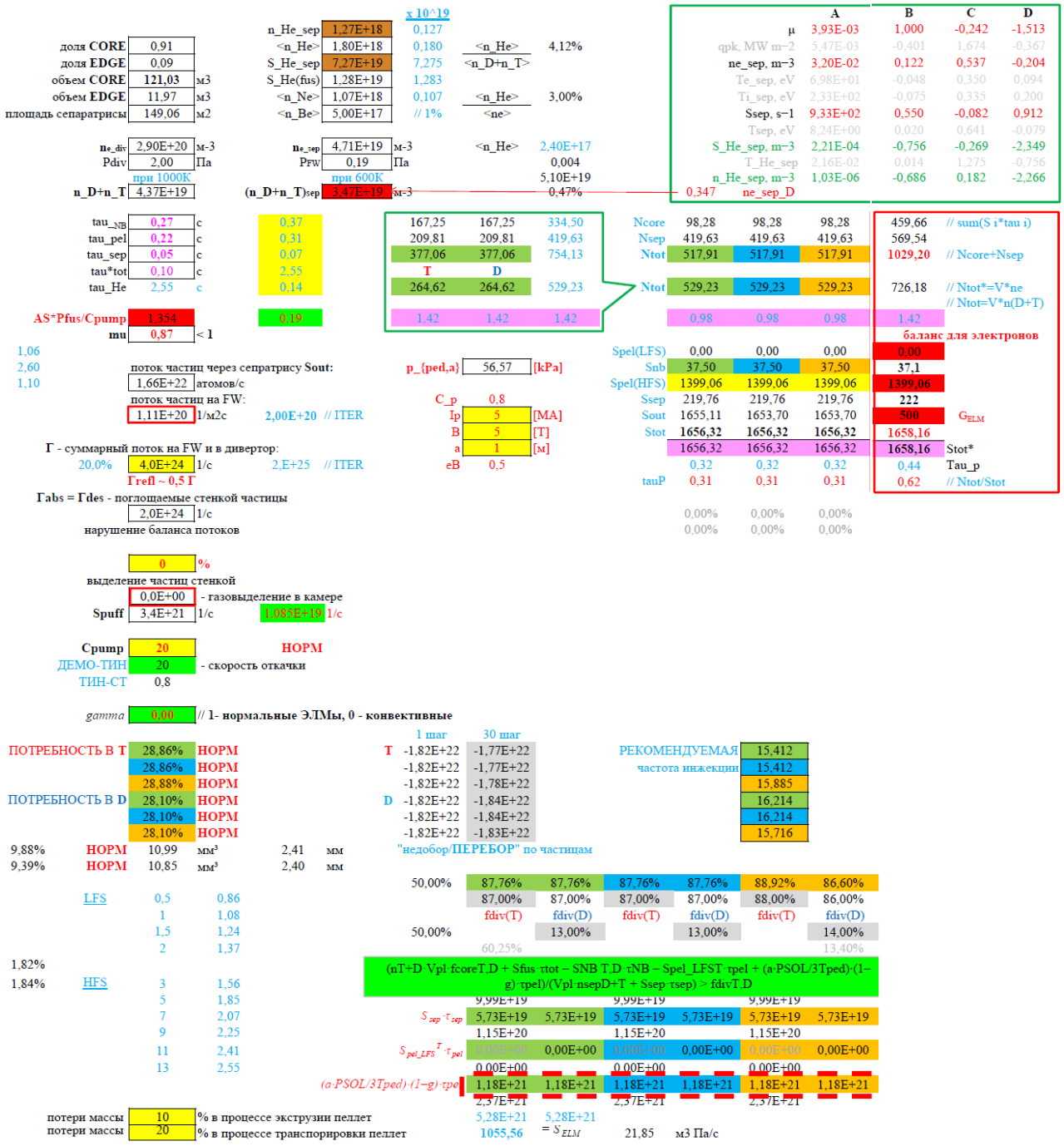
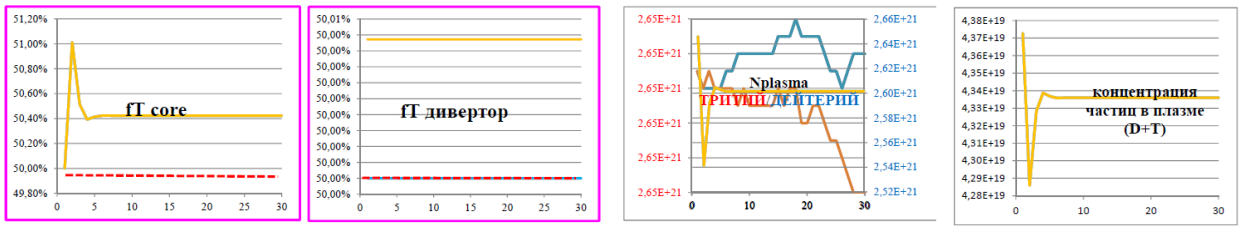


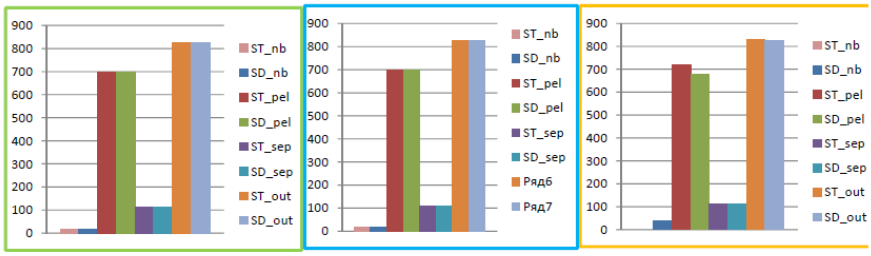
Figure 4. Interface of the module "initial data" of the FC-FNS code. Fragment. Parameters for the DEMO-FNS project and calculation results

Calculations of the main flows for the first iteration are performed in another calculation module (file) "particle balance (H, D, T)". The calculation of flows is performed separately for each of the isotopes. The first "sheet" of the file contains a table with the main input parameters required for calculations in this module. They correspond to the values in the table on the "calculation parameters" sheet of the "initial data" file (see Figure 2) and are synchronized automatically. The remaining

"sheets" contain calculations for various hydrogen isotopes and summary calculation results - on the "results" sheet.



a

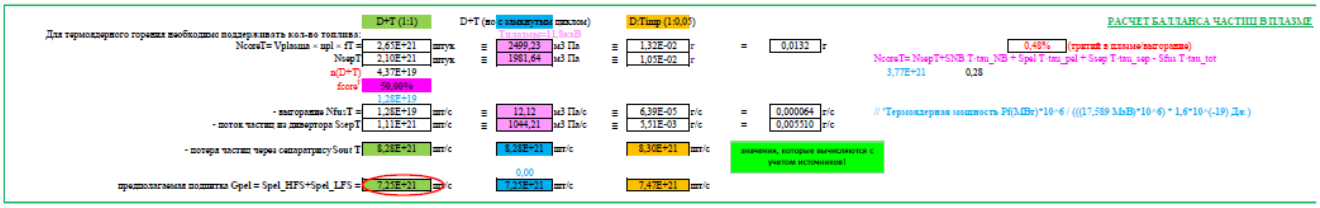


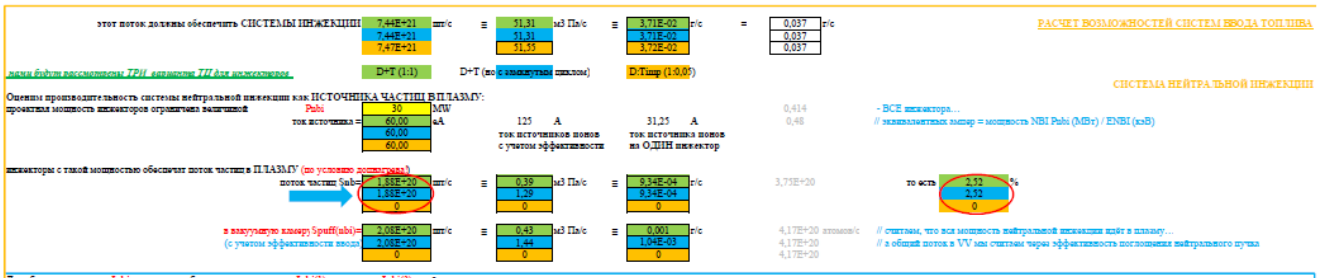
b

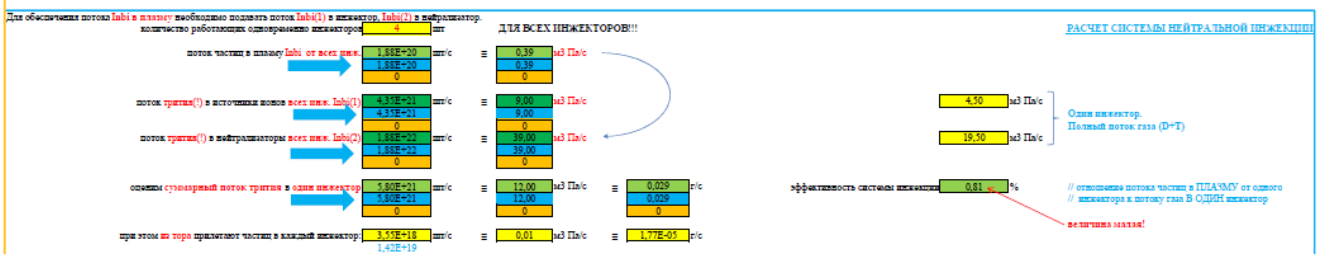
Figure 5. Interface of the "initial data" module of the FC-FNS code. Fragment. Calculation results for the DEMO-FNS project. Graphs of changes in values (by calculation iterations) for the tritium fraction in the core and divertor plasma, the total number of D+T particles in the plasma and its density – (a), as well as the fluxes of D and T particles into the plasma from various sources and the loss of particles from the plasma – (b) for different types of heating beam.

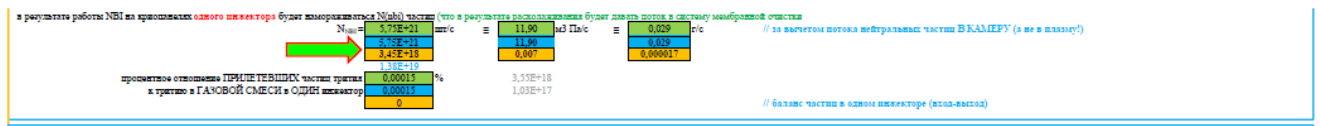
For each fuel component and initial data (plasma density and fraction of T in it), the flows are calculated sequentially in all systems of the FC, starting with the plasma and ending with the injection systems – see Figure 6 (for the tritium balance) and Figure 7. The color differentiation corresponds to that indicated above – for different types of heating beam.

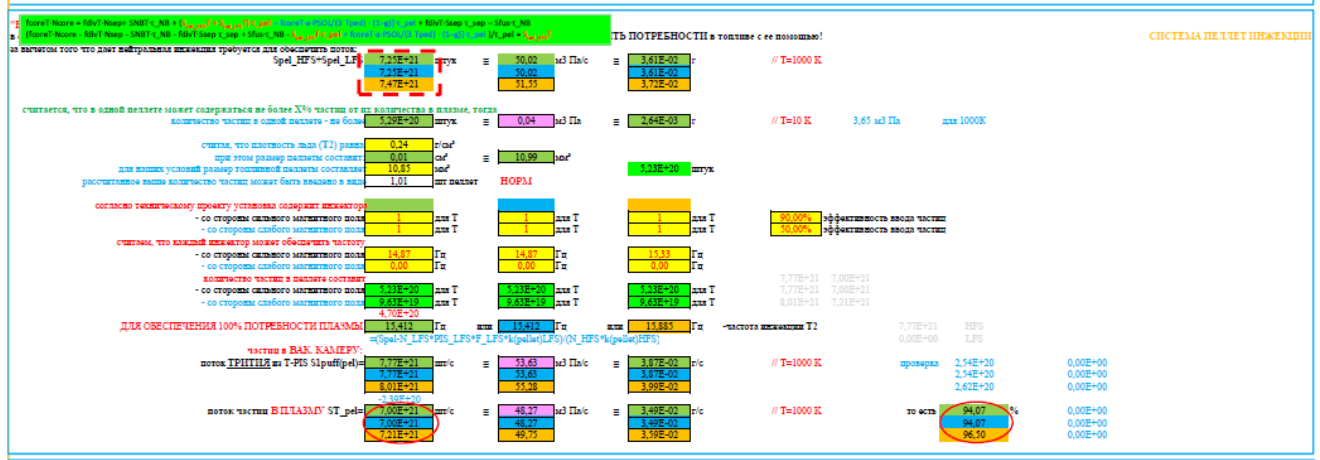
The key point of the calculation at the first iteration is the determination of the parameters (flows) of injection through the plasma pellet feeding system. Taking into account the values of other particle sources, the required fuel component injection frequencies are calculated (based on the balance equations described in [9, 10]). **The calculations performed in this module (particle balance) allow for a rough estimate of all required flows and the isotopic composition of the mixture in all FC systems. Their precise calculation by the iteration method is performed in another code module (file).**

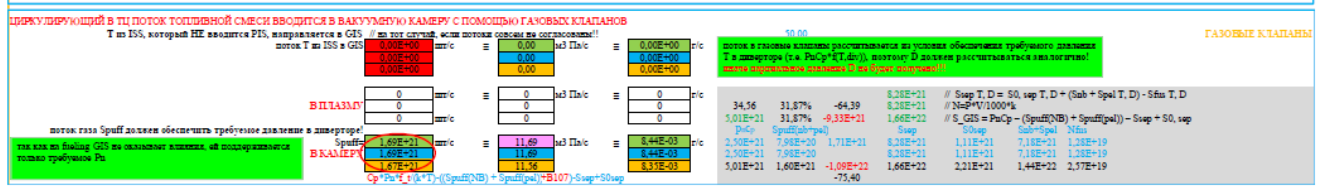

D+T (1:1)
D+T (по 6 изотопам)
D/Tпар (1:0,05)
РАСЧЕТ БАЛЛАНСА ЧАСТИЦ В ПЛАЗМЕ
Для термоядерного горения необходимо поддерживать кол-во топлива:
NcoreT= Vplasma × npl × fT
NsepT
n(D+T)
fcore
- выгорание NfusT =
- поток частиц из дивертора SsepT
- потеря частиц через сепаратрису Sout T
предполагаемым подпиткa Gpel = Spel_HFS+Spel_LFS =
0,48% (тритий в плазме/выгорание)
NcoreT= NsepT+SNB T-tau_NB + Spel T-tau_pel + Ssep T-tau_sep - Sfus T-tau_tot
значения, которые вычисляются с учетом источников!
// Термоядерная мощность Pf(МВт)*10^6 / (((17,589 МэВ)*10^6) * 1,6*10^(-19) Дж)

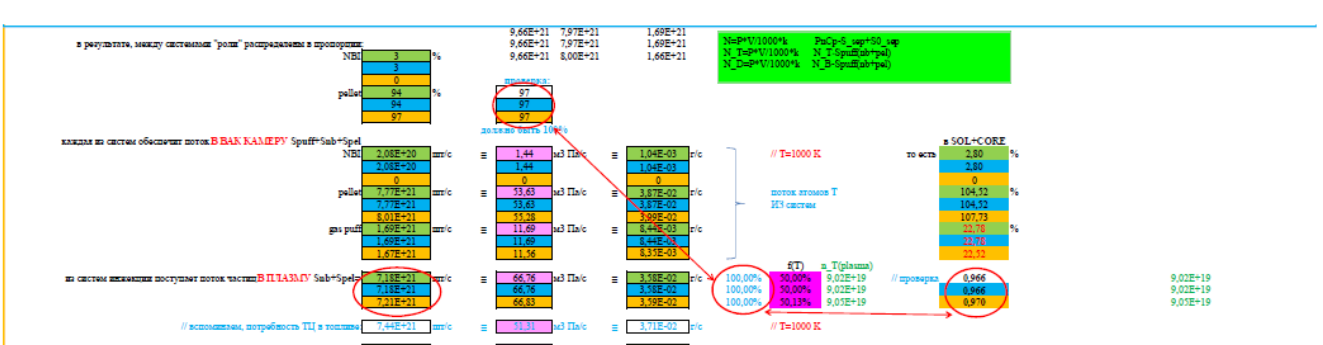

РАСЧЕТ ВОЗМОЖНОСТЕЙ СИСТЕМ ВВОДА ТОПЛИВА
этот поток должны обеспечить СИСТЕМЫ ИНЖЕКЦИИ
СИСТЕМА НЕЙТРАЛЬНОЙ ИНЖЕКЦИИ
Оценим производительность системы нейтральной инжекции как ИСТОЧНИКА ЧАСТИЦ В ПЛАЗМУ:
проектная мощность инжекторов ограничена величиной
ток источника =
ток источников ионов с учетом эффективности
ток источника ионов из ОДИН инжектор
- ВСЕ инжекторы...
// эквивалентных эмпир = мощность NBI Pnbi (МВт) / ENBI (кэВ)
инжекторы с такой мощностью обеспечит поток частиц в ПЛАЗМУ (по условию допустимых)
поток частиц Snb=
то есть
в вакуумную камеру Spuff(nbi)=
(с учетом эффективности ввода)
// считаем, что вся мощность нейтральной инжекции идёт в плазму...
// в общий поток в VV мы считаем через эффективность поглощения нейтрального пучка


Для обеспечения потока Inbi в плазму необходимо подавать поток Inbi(1) в инжектор, Inbi(2) в нейтрализатор.
количество работающих одновременно инжекторов
ДЛЯ ВСЕХ ИНЖЕКТОРОВ!!!
РАСЧЕТ СИСТЕМЫ НЕЙТРАЛЬНОЙ ИНЖЕКЦИИ
поток частиц в плазму Inbi от всех инж.
поток трития(!) в источники ионов всех инж. Inbi(1)
поток трития(!) в нейтрализаторы всех инж. Inbi(2)
оценим суммарный поток трития в один инжектор
при этом из тора прилетают частицы в каждый инжектор
Один инжектор.
Полный поток газа (D+T)
эффективность системы инжекции
// отношение потока частиц в ПЛАЗМУ от одного
// инжектора к потоку газа В ОДИН инжектор
величина малая!


в результате работы NBI на крионасосах одного инжектора будет намораживаться N(nbi) частиц (что в результате расходаживания будет давать поток в систему мембранной очистки
// за вычетом потока нейтральных частиц В КАМЕРУ (а не в плазму!)
процентное отношение ПРИЛЕТЕВШИХ частиц трития
к тритию в ГАЗОВОЙ СМЕСИ в ОДИН инжектор
// баланс частиц в одном инжекторе (вход-выход)


СИСТЕМА ПЕЛЛЕТ ИНЖЕКЦИИ
за вычетом того что дает нейтральная инжекция требуется для обеспечить поток:
считается, что в одной пеллете может содержаться не более X% частиц от их количества в плазме, тогда
количество частиц в одной пеллете - не боле
// T=1000 K
// T=10 K
3,65 м3 Па
для 1000К
считая, что плотность льда (Т2) равна
при этом размер пеллеты составит
для наших условий размер топливной пеллеты составит
рассчитанное нами количество частиц может быть введено в виде
НОРМ
согласно техническому проекту установка содержит инжекторов
- со стороны сильного магнитного поля
- со стороны слабого магнитного поля
эффективность ввода частиц
считаем, что каждый инжектор может обеспечить частоту
- со стороны сильного магнитного поля
- со стороны слабого магнитного поля
количество частиц в пеллете составит
- со стороны сильного магнитного поля
- со стороны слабого магнитного поля
ДЛЯ ОБЕСПЕЧЕНИЯ 100% ПОТРЕБНОСТИ ПЛАЗМЫ
-частота инжекции T2
частицы в ВАК. КАМЕРУ:
поток ТРИТИЯ из T-PIS S1puff(pel)=
// T=1000 K
проверка
поток частиц В ПЛАЗМУ ST_pel=
// T=1000 K
то есть


ЦИРКУЛИРУЮЩИЙ В ТЦ ПОТОК ТОПЛИВНОЙ СМЕСИ ВВОДИТСЯ В ВАКУУМНУЮ КАМЕРУ С ПОМОЩЬЮ ГАЗОВЫХ КЛАПАНОВ
ГАЗОВЫЕ КЛАПАНЫ
T из ISS, который НЕ вводится PIS, направляется в GIS // на тот случай, если потоки совсем не согласованы!!
поток T из ISS в GIS
поток в газовые клапаны рассчитывается из условия обеспечения требуемого давления
T в дивертор (т.е. PuCp*(T,div)), поэтому D должен рассчитываться аналогично!
иначе нормальное отношение D не будет получено!!!
В ПЛАЗМУ
поток газа Spuff должен обеспечить требуемое давление в дивертор
так как из Boiling GIS не оказывает влияния, он поддерживается
только требуемое Pu
В КАМЕРУ
// Ssep T, D = S0, sep T, D + (Sub + Spel T, D) - Sfus T, D
// NeP*V/1000*k
// S_GIS = PuCp – (Spuff(NB) + Spuff(pel)) – Ssep + S0, sep


в результате, между системами "роли" распределяемым в пропорции
NBI
pellet
N=P*V/1000*k PuCp-S_sep+S0_sep
N_T=P*V/1000*k N_T-Spuff(ub+pel)
N_D=P*V/1000*k N_B-Spuff(ub+pel)
проверка:
должно быть 100%
каждая из систем обеспечит поток В ВАК КАМЕРУ Spuff+Sub+Spel
NBI
pellet
gas puff
// T=1000 K
поток атомов T
ИЗ системы
в SOL+CORE
то есть
из систем инжекции поступает поток частиц В ПЛАЗМУ Sub+Spel=
// проверка
// вспомогательным, потребность ТЦ в топливе
// T=1000 K
Spuff

РАСЧЕТ СИСТЕМЫ ОТКАЧКИ

в процессе работы ВСЕХ систем ИНЖЕКЦИИ, в вакуумную КАМЕРУ будет попадать поток частиц, который должен откачиваться!

Гр_T=6puff_T+5sep_T-50_sep_T=	9,66E+21	шт/с	≡	20,00	м3 Па/с	≡	4,81E-02	г/с	100,00%	50,00%
	9,66E+21			20,00			4,81E-02		100,00%	50,00%
	9,67E+21			20,02			4,82E-02		100,00%	50,00%

// T=1000 K

20,00	м3/с
20,00	
20,02	- скорость откачки! (Ср)

- тут учитывается поток T из инжекторов за счет давления на стенки инжекторов... ('Динамика трития в инжекторах.xlsx]динамика трития в инжекторах'!F10)

СИСТЕМА ОЧИСТКИ ТОПЛИВА

В систему очистки топлива попадают потоки из:

дивертора вакуумной камеры	7,72E+21	шт/с	≡	15,97	м3 Па/с	≡	0,038	г/с	// все инжектированное минус сгоревшее	
	7,71E+21			15,97			0,038			
	7,72E+21			15,99			0,038			
с криопанелей всех инжекторов	2,30E+22	шт/с	≡	47,60	м3 Па/с	≡	0,113	г/с	// газ из инжекторов+газ из тора	
	2,30E+22			47,60			0,113			
	1,38E+19	шт/с	≡	0,03		≡	0,00007		// газ ВООБЩЕ нет	
литиевой петли	1,93E+21	шт/с	≡	8,00	м3 Па/с	≡	0,010	г/с	// T=600 K	
	1,93E+21			8,01			0,010			
	1,93E+21			8,01			0,010			
системы охлаждения дивертора и первой стенки	6,72E+16	шт/с	≡	0,0003	м3 Па/с	≡	3,35E-07	г/с	// T=600 K	
	6,72E+16			0,0003			3,35E-07			
	6,72E+16			0,0003			3,35E-07			

тогда в систему очистки входной поток:	3,26E+22	шт/с	≡	67,57	м3 Па/с	≡	0,163	г/с				
	9,65E+21			19,97			0,048					
// он же выходной	9,66E+21			19,99			0,048					

ΣT)			
50,00%	9,66E+21	9,65E+21	
50,00%	9,66E+21	-1,33E+22	
50,00%	9,67E+21	9,65E+21	

СИСТЕМА КАТАЛИТИЧЕСКОГО РАЗЛОЖЕНИЯ

в связи с тем, что тритий в химически связанном состоянии содержится в 2 % отличаемой газовой смеси:

через мембранный фильтр НЕ пройдет газ	6,53E+20	шт/с	≡	1,35	м3 Па/с	≡	3,25E-03	г/с	// для HDO, HTO, DTO, H2O, CO, D2O, T2O, Ha, Na, N2
	1,93E+20			0,40			9,62E-04		
	1,93E+20			0,40			9,63E-04		// без учета потока с КРИОПАНЕЛЕЙ ИНЖЕКТОРОВ !!!

ВЕСЬ тритий из систем химического разложения РАНО ИЛИ ПОЗДНО попадет в систему ISS

...не считая следов T (которые попадут в ISS через PERMCAT+CECE)

оставшийся газовый поток разделится:

в систему разделения ISS (для PIS)	7,77E+21	шт/с	≡	16,09	м3 Па/с	≡	3,87E-02	г/с	23,81%	100,00%
	7,98E+21			16,52			3,98E-02		82,72%	100,00%
	8,01E+21			16,58			3,99E-02		82,94%	100,00%
из системы рабливса IRS в GIS	2,49E+22	шт/с	≡	51,48	м3 Па/с	≡	1,24E-01	г/с	76,19%	
	1,67E+21			3,47			8,31E-03		17,28%	
	1,65E+21			3,41			8,21E-03		17,06%	

СИСТЕМА РАЗДЕЛЕНИЯ ИЗОТОПОВ

Для питания пеллет-инжекторов требуется дейтериевая топливная смесь!

считаем, что для изготовления пеллет (криогенной экструзией) достаточно:	100	% чистоты по изотопу
это означает, что в T-PIS будет содержаться:	0	% примеси D

в систему разделения требуется подавать поток газа, достаточный для выделения НУЖНОГО КОЛИЧЕСТВА изотопов каждого типа!

на выходе (!) системы требуется поток T	7,77E+21	шт/с	≡	16,09	м3 Па/с	≡	3,87E-02	г/с	ВХОД	
(потребность по T или по D - условно) или	7,98E+21			16,52			3,98E-02			
весь поток T со входа (!) системы (ISS) пойдет на её выход	8,01E+21			16,58			3,99E-02			

// если количество D, полученное из газовой смеси в ISS (для T-PIS) не обеспечит D-PIS, (с учетом LFS-инжекции D) тогда нужно подавать газа столько, чтобы обеспечить весь требуемый поток D

// во II случае нужно возвращать в NBI весь T, вылетевший в VV в процессе инжекции!

в ISS будет дополнительный поток T из системы NBI. Это уменьшает требуемый поток из IRS в ISS!

поток в ISS из IRS	7,77E+21	шт/с	≡	16,09	м3 Па/с	≡	3,87E-02	г/с	
	7,97E+21			16,49			3,97E-02		// тут тоже будет возврат!!!
с учетом потока T из NBI	8,00E+21			16,55			3,99E-02		

в VV будет вводиться T (поток из ISS)	7,77E+21	шт/с	≡	16,09	м3 Па/с	≡	3,87E-02	г/с	
в качестве основного топлива (с IPS)	7,77E+21			16,09			3,87E-02		=B99+B37-B99-'[динамика трития в инжекторах.xlsx]динамика трития в инжекторах'!$I$124
+ в качестве пеллет контроля ELM (с LFS)	8,01E+21			16,58			3,99E-02		=B175-B99+B108-B112-B37-B3'+B10+'[динамика трития в инжекторах.xlsx]динамика трития в инжекторах'!$I$124
									=B176-B100+B109-B113+B10+(-'[динамика трития в инжекторах.xlsx]динамика трития в инжекторах'!F12)+(-'[динамика трития в
В процессе производства (экструзии) пеллет и их ускорения		шт/с	≡	0,00	м3 Па/с	≡	0,00E+00	г/с	
часть массы пеллет будет теряться...но оставаться в системе				0,00			0,00E+00		
таким образом, PIS должна обрабатывать поток:				0,00			0,00E+00		

поток T из ISS в GIS	0,00E+00	шт/с	≡	0,00	м3 Па/с	≡	0,00E+00	г/с	// положительная величина означает что в процессе работы ISS обработала T больше чем нужно T-PIS
для Вариант II поток не в GIS а в NBI	2,09E+20			0,43			6,92E-04		// в этом случае T направляется в VV с помощью GIS для предотвращения накопления
	0,00E+00			0,00			0,00E+00		// отрицательной величины БЫТЬ НЕ МОЖЕТ!
	1,30E+19								

СИСТЕМА ХРАНЕНИЯ И ОБРАБОТКИ ТРИТИЯ

компенсация выгорания осуществляется в IRS

вентиляция VV (PUFF) + питание NBI осуществляется потоком:	2,49E+22	шт/с	≡	51,51	м3 Па/с	≡	0,12	г/с	в GIS	c(T)	NBI	-GIS
поток из выхода IRS в NBI	1,90E+21			3,94			0,01		1,69E+21	50,00%	1,69E+21	2,32E+22
и GIS	1,67E+21			3,47			0,01		1,69E+21	53,11%	1,69E+21	2,08E+20
				67,60					1,67E+21	50,23%	1,67E+21	-4,11E+17
потоки в системы инжекции:											-6,55E+06	0,00E+00
- газовые клапаны	1,69E+21	шт/с	≡	3,51	м3 Па/с	≡	0,01	г/с			-3,15E+06	-3,14E+06
	1,69E+21			3,51			0,01				-4,11E+17	-4,11E+17
	1,67E+21			3,47			0,01				-GIS	
- пеллет-инжекторы	7,77E+21	шт/с	≡	16,09	м3 Па/с	≡	0,039	г/с				
	7,77E+21			16,09			0,039					
	8,01E+21			16,58			0,040					
- система нейтральной инжекции	2,30E+22	шт/с	≡	48,00	м3 Па/с	≡	0,12	г/с				
	2,09E+20			0,43			0,001					
	0			0			0					

// тритий в NBI нужен для компенсации вылета частиц из D+T инжекторов

// для III варианта тритий НЕ нужен совсем

тритий в долговременное хранилище поступает НАПРЯМУЮ(из ближнего	1,54E+19	шт/с	≡	0,03	м3 Па/с	≡	7,67E-05	г/с	≡	2,419 кг/год
при этом считаем удовлетворение собственных потребностей в	1,54E+19			0,03			7,67E-05			
за счет сгорания (компенсируется подпиткой T в PIS)	1,54E+19			0,03			7,67E-05			

(вход-выход) < 0 (за счет потерь)

потоки в системы инжекции и из вак.камеры должны быть равны: Nfcleanup-(Nshi+Ngasp+Npellet) + Nfglobe/rwr_in = 0 // не считая воспроизводства в бланкете и Nrwr_out !!!

// где Nrwr_out - поток "излишков" во внешнее хранилище!!!

т.е. -(Nfcleanup -(Nshi+Ngasp+Npellet)) = Nfglobe/rwr_in (должно быть) // если поток из бланкета > 0, то Nfglobe д/б = 0, если = 0, то Nfglobe > 0 и ~ Nwast

// где Nrwr_in - компенсация выгорающего топлива

Nshi+Ngasp+Npellet =	3,27E+22	шт/с	≡	67,60	м3 Па/с	≡	0,16	г/с			проверка	
то есть сумма потоков на вход NBI, PIS и GIS	9,67E+21			20,03			0,05		выход	-1,28E+19	или	67,60
	9,69E+21			20,05			0,05			8,25E+06	-3,78E+19	20,03
										-1,28E+19	или	20,05
Nfcleanup =	3,26E+22	шт/с	≡	67,57	м3 Па/с	≡	0,16	г/с		1,36E+06	-1,28E+19	
то есть всё что получено в результ	9,66E+21			20,00			0,05		вход	-1,32E+19	или	67,57
// частицы из NBI возвращаются ! Либо через Pumping либо через ISS	9,67E+21			20,02			0,05			4,11E+17	-3,23E+19	20,02

										проверка	
РАСЧЕТ потоков - д.б. равна выгоранию топлива + распад	1,32E+19	шт/с	≡	2,73E-02	м3 Па/с	≡	6,57E-05	г/с	≡	2,071 кг/год	0,000 2,071 кг/год - потери за счет выгорания и распада
то есть потери частиц в ТЦ за один оборот частиц	1,32E+19			2,73E-02			6,57E-05			2,071	0,000 2,071
это поток топлива из внешнего источника (баллона/геттера)	1,35E+19			2,80E-02			6,73E-05			2,113	0,085 2,089

они компенсируются либо из стартового геттера (рассчитанного на 20 дней) либо из Т-воспроизводящего бланкета:

потребность во внешних источниках топлива составит	1,54E+19	шт/с	≡	0,03	м3 Па/с	≡	7,67E-05	г/с	≡	2,419 кг/год
например, при НЕ работающем бланкете	1,54E+19			0,03			7,67E-05			

проверка: 2,02 кг/год - выгорание в плазме!

В долговременное хранилище будет попадать поток:	2,21E+18	шт/с	≡	0,00	м3 Па/с	≡	1,10E-05	г/с	≡	0,348 кг/год
с учетом удовлетворения потребностей установки в топливе	2,22E+18			0,00			1,10E-05			0,348
	1,88E+18			0,00			9,36E-06			0,296

проверка: 0,348 кг/год - остаток произведенного T с учетом выгорания и пр.

0,348

0,301

потери формируются из распада и проницаемости	3,53E+17	шт/с	≡	7,30E-04	м3 Па/с	≡	1,76E-06	г/с	= 0,055 кг/год
	3,50E+17			7,25E-04			1,75E-06		0,055
	2,72E+17			5,62E-04			1,35E-06		0,043

...для поддержания баланса необходимо компенсировать ПОТЕРИ в ТЦ установки! и именно, проникающий поток через материалы и распад (только для T)

Предположим, что максимально допустимый проникающий поток трития через конструкционные материалы вакуумной камеры (1% от выгорания)

будет (за год):	3,27E+04	шт/год	≡	8,37E-03	м3 Па/год	≡	38,16	г/год	=	0,020 кг/год
или в секунду:	1,28E+17	шт/с	≡	2,66E-04	м3 Па/с	≡	6,39E-07	г/с		

// потери в магистралях - СОБЕРЕМ за счет двойных стенок и тп!

// расчетные ПОТЕРИ - БЕЧВОЗВРАТНО УТРАЧЕННЫЕ ЧАСТИЦЫ

Для расчета потерь за счет распада нужно СПЕРВА вычислить ЧАЛЕЖЙ трития в системах ТЦ!!!

для предварительной оценки можем считать количество частиц в ТЦ:	1,70E+26	штук	≡	6,54E+05	м3 Па	≡	847,05	г	=	0,847 кг
	1,68E+26			6,46E+05			837,57			0,838
	1,08E+26			2,24E+05			540,39			0,540

Характеристики ТЯР	ДЕМО	ТИН-СТ	ДЕМО-ТИН
	S=1200 m2 m=500-600 т	S=13 m2 m=~1 т	S=160 m2 m=~10-20 т
Допустимый проникающий поток трития через конструкционные материалы вакуумной камеры (1% от выгорания)	7×10¹⁸ T/м²с (400 г/год)	2×10¹⁸ T/м²с (1 г/год)	3×10¹⁸ T/м²с (12 г/год)

тогда:

РАСПАД с учетом "залежей" во всех системах ТЦ	2,25E+17	шт/с	≡	4,63E-04	м3 Па/с	≡	1,12E-06	г/с	=	0,035 кг/год
// сумма всех запасов во всех системах	2,22E+17			4,60E-04			1,11E-06			0,035
// * на константу распада !!!	1,43E+17			2,97E-04			7,14E-07			0,023

// доклад Спицына!..

содержание трития в каждой системе ТЦ в единицу времени (!)

система нейтральной инжекции NBI	2,30E+22	шт/с	≡	47,60	м3 Па/с	≡	1,15E-01	г/с	≡	0,11 г/с
	2,30E+22			47,60	м3 Па/с	≡	1,15E-01	г/с	≡	0,1146
	1,38E+19	шт/с	≡	0,03	м3 Па/с	≡	6,88E-05	г/с	≡	0,00
система пеллет-инжекции PIS	7,77E+21	шт/с	≡	16,09	м3 Па/с	≡	3,87E-02	г/с	≡	0,04 г/с
	7,77E+21			16,09			3,87E-02			0,04
	8,01E+21			16,58			3,99E-02			0,04
система газовых клапанов GIS	1,69E+21	шт/с	≡	3,51	м3 Па/с	≡	8,44E-03	г/с	≡	0,01 г/с
	1,69E+21			3,51			8,44E-03			0,01
	1,67E+21			3,47			8,35E-03			0,01
вакуумная камера VV	9,66E+21	шт/с	≡	20,00	м3 Па/с	≡	4,81E-02	г/с	≡	0,05 г/с
	9,66E+21			20,00			4,81E-02			0,05
включает ЧАСТИЦЫ в плазме?	9,67E+21			20,02			4,82E-02			0,05

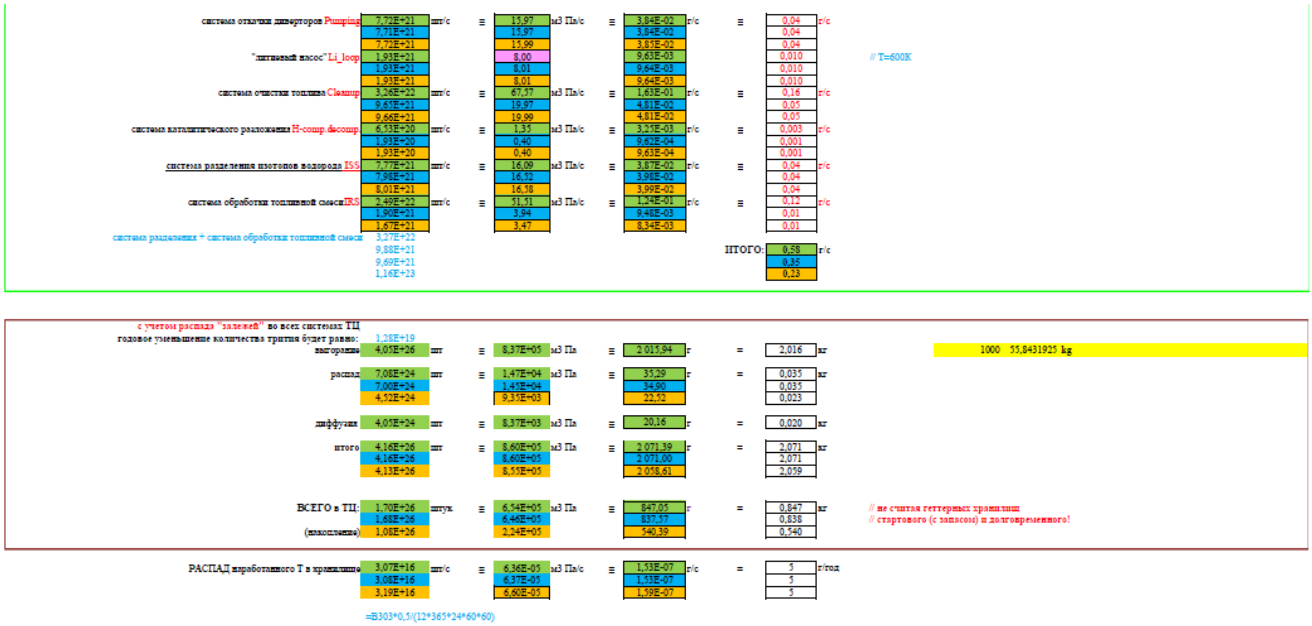
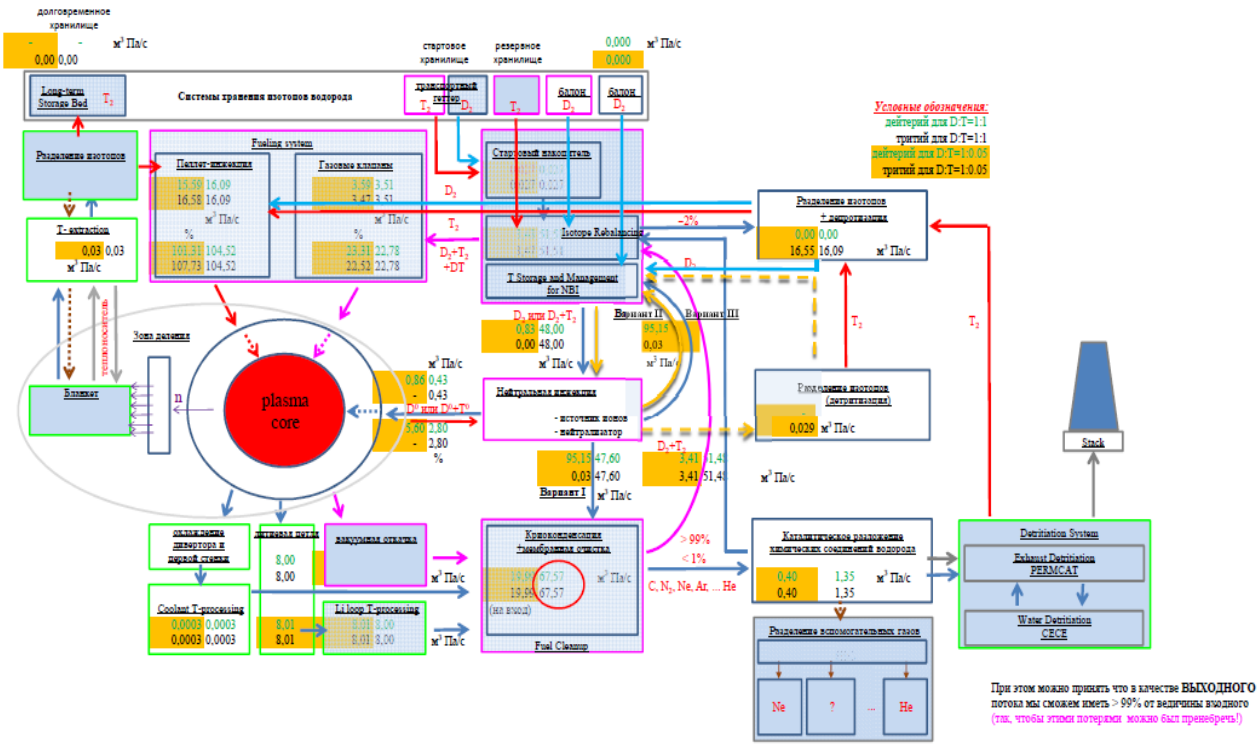


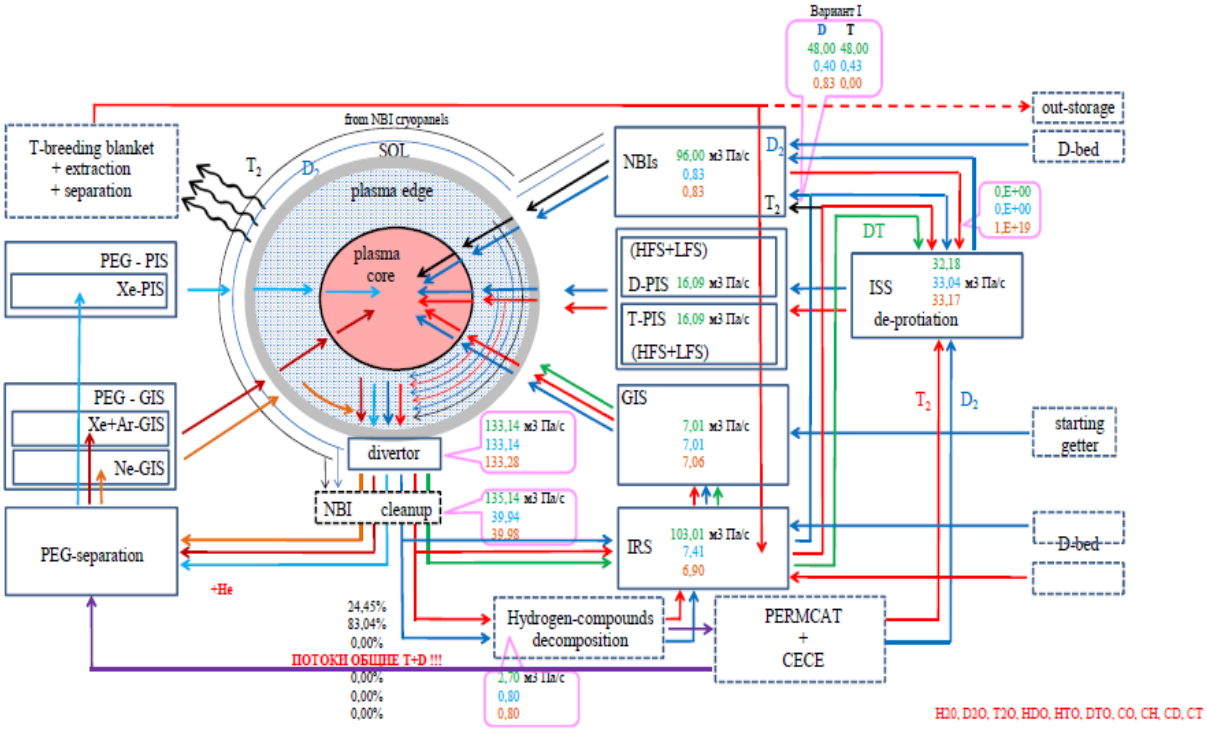
Figure 6. Interface of the module "particle balance (H, D, T)" of the FC-FNS code. Fragment. Calculations for tritium flows through the FC systems for the DEMO-FNS project

Further, all calculations are made for the specified injection parameters. The calculations are based on the physical mechanisms of burnout, particle removal from the plasma and "replenishment" due to the injection of neutral beams, pellet injection and gas puffing. The efficiency of each of the balance maintenance methods is taken into account, since not all particles introduced into the facility chamber enter the plasma and some of them are pumped out even before they are ionized. Balance equations are constructed for all systems, taking into account the input/output and the operating mode of the system or its elements. The calculation algorithm for different isotopes is identical with a difference in their chemical composition and operating modes of certain FC systems. Due to the fact that in different FC systems the fuel mixture has a different temperature and shape (atomic or molecular), the balance equations operate with the number of particles with subsequent recalculation into flows and the mass of the gas mixture.

The calculation results are summarized on the "results" "sheet" in various forms. They are displayed as hydrogen isotope flows on the conventional FC scheme (see Figure 7) and in the form of tables - see Figures 8 and 10. Figure 9 shows the flows in all the main FC systems and provides the number of T and D in these systems for various variants of heating beams. These data (as well as those presented in Figure 8) are summary, i.e. they are calculated not only in this code module, but in the others as well.

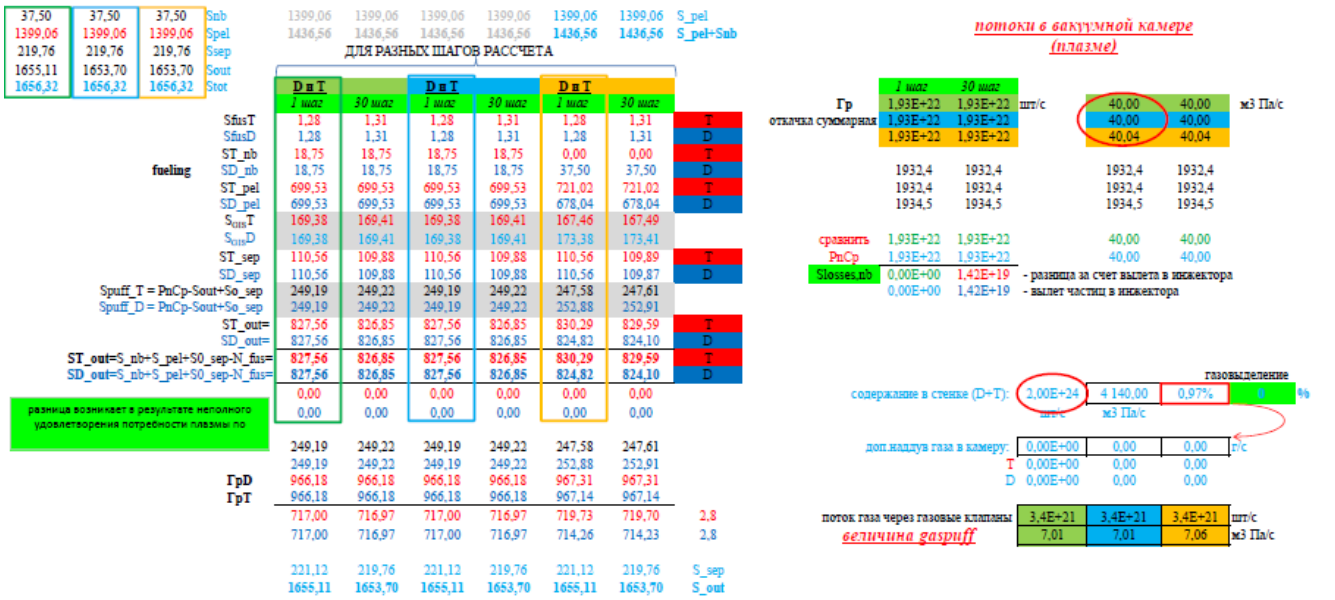


a

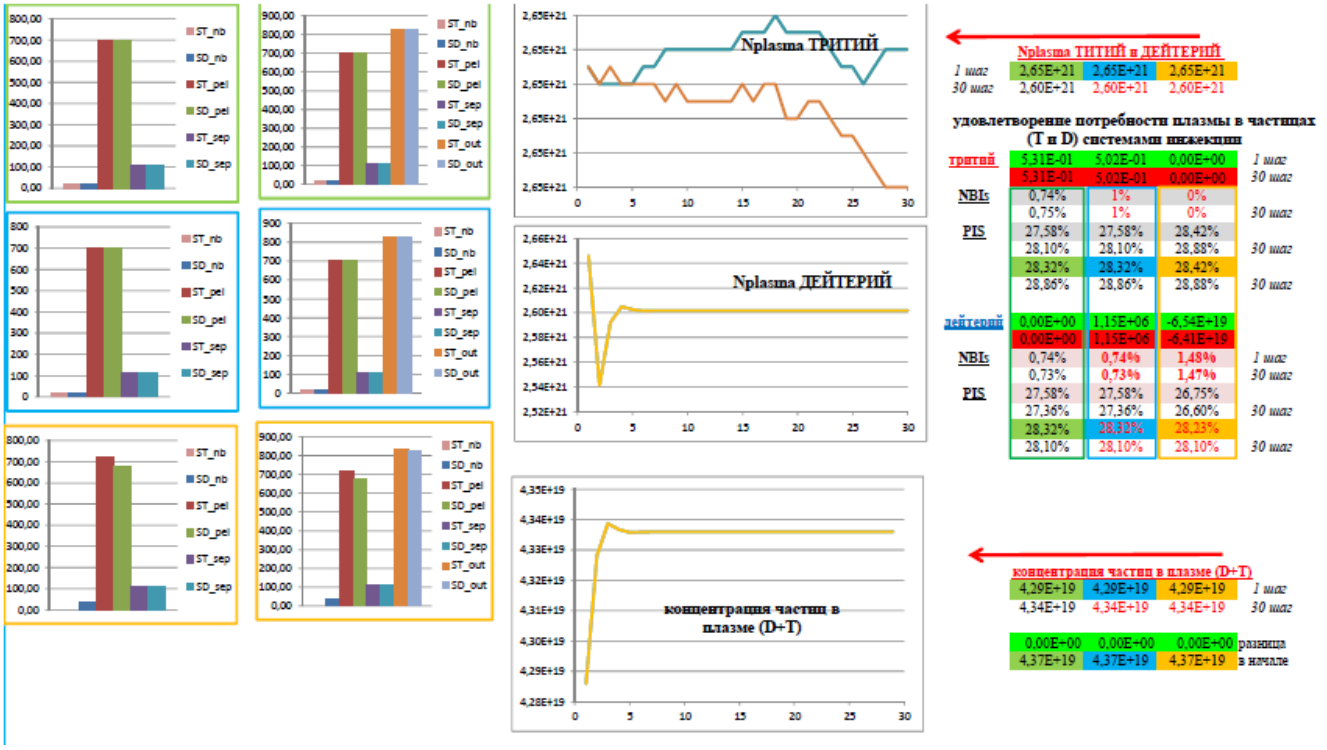


b

Figure 7. Interface of the module "balance of particles (H, D, T)" of the FC-FNS code. Fragment. Scheme of fuel cycle systems and flows of fuel components through them for different types of beam - (a), conditional scheme of movement of different fuel components through the FC systems, illustrating the FC architecture - (b) for the DEMO-FNS project.



a



b

Figure 8. Interface of the module "balance of particles (H, D, T)" of the FC-FNS code. Fragment. Results of calculations for flows of fuel components into the plasma - (a) and their role in feeding the plasma and maintaining its density - (b) for different types of heating beam for DEMO-FNS

For accurate calculations, as mentioned above, calculations are performed using the method of successive iterations in the code module "dynamics of isotopes in FC", which take into account the change in the isotopic composition of the core and divertor plasma (including the pedestal), as well as other parameters - taking into account the diffusion losses of particles from the plasma and ELM. In

this case, the first step of calculations is identical to that described above - in the module "particle balance (H, D, T)" - in it, the plasma density is specified (and not calculated), as is the isotopic composition of the plasma. At the second and subsequent steps, the values calculated according to the equations that take into account both the current values of particle sources and diffusion times for them are used to calculate the plasma density. Consequently, at the second step of calculations, the flux values for all systems differ significantly (by a jump) from those calculated at the first step and in the process of further iterations they reach a stationary state. These "stationary" values are taken into account by all other code modules in calculations (including the amount of T in the FC systems).

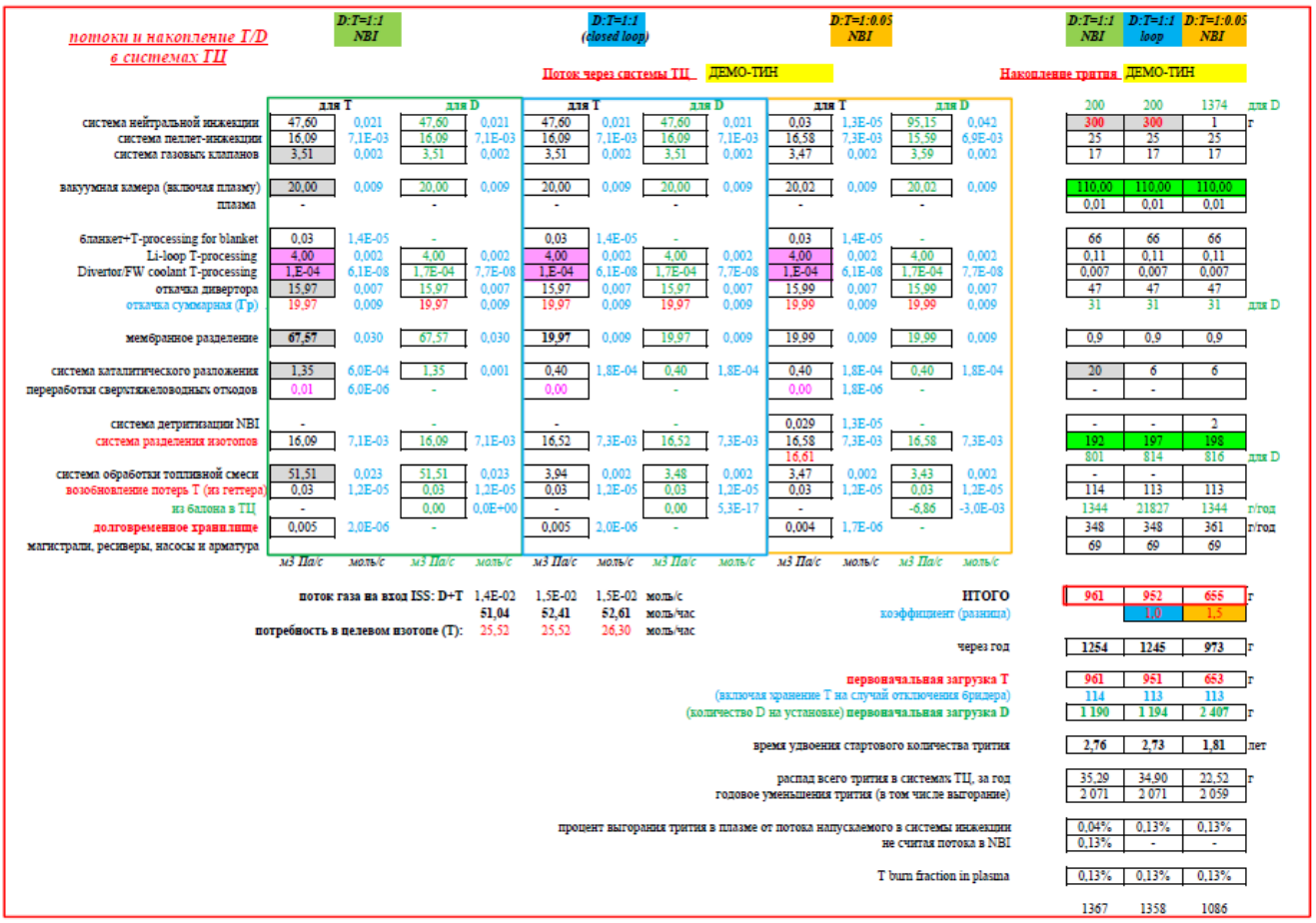


Figure 9. Interface of the module "balance of particles (H, D, T)" of the FC-FNS code. Fragment. Results of calculations of flows of fuel components into the plasma and their quantities in the FC systems for the DEMO-FNS project (for various types of heating beam)

An example of such calculations is shown in Figures 10 and 11. The calculations are performed for different fuel components (D and T) and several types of heating beam. During the calculations, the values of τ_p for hydrogen isotopes (D+T) are calculated, the pumping speed is checked for compliance with the specified value, and other procedures are performed to demonstrate the correctness of the calculations.

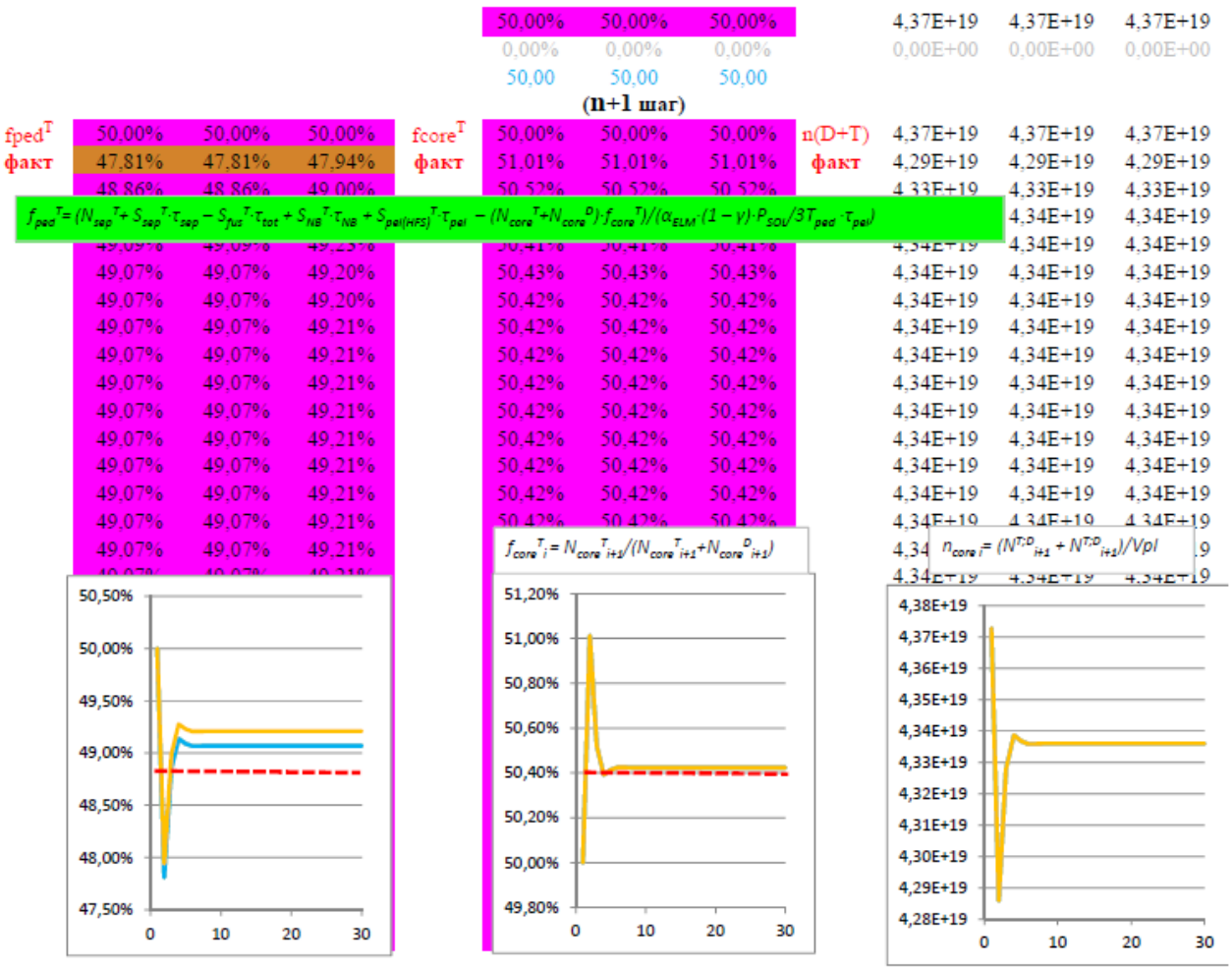


Figure 10. Interface of the module "dynamics of isotopes in the FC" of the FC-FNS code. Fragment. Calculation of the tritium fraction in the core and divertor plasma based on the calculated flows of fuel components through the FC systems using the iteration method for the DEMO-FNS project (for different types of heating beam)

In case of deviation of fuel component flows injected in the form of pellets from the required values (to ensure the required plasma density), the plasma density will change until reaching a steady-state value corresponding to the selected injection mode. In this case, a number of parameters used in calculations and being "external" for the FC-FNS code will change along with the density change. The calculation of their values at each calculation step is performed on the "parameter change" sheet based on the dependencies specified in the "initial data" module, on the "parameter scan" "sheet" - see Figure 12.

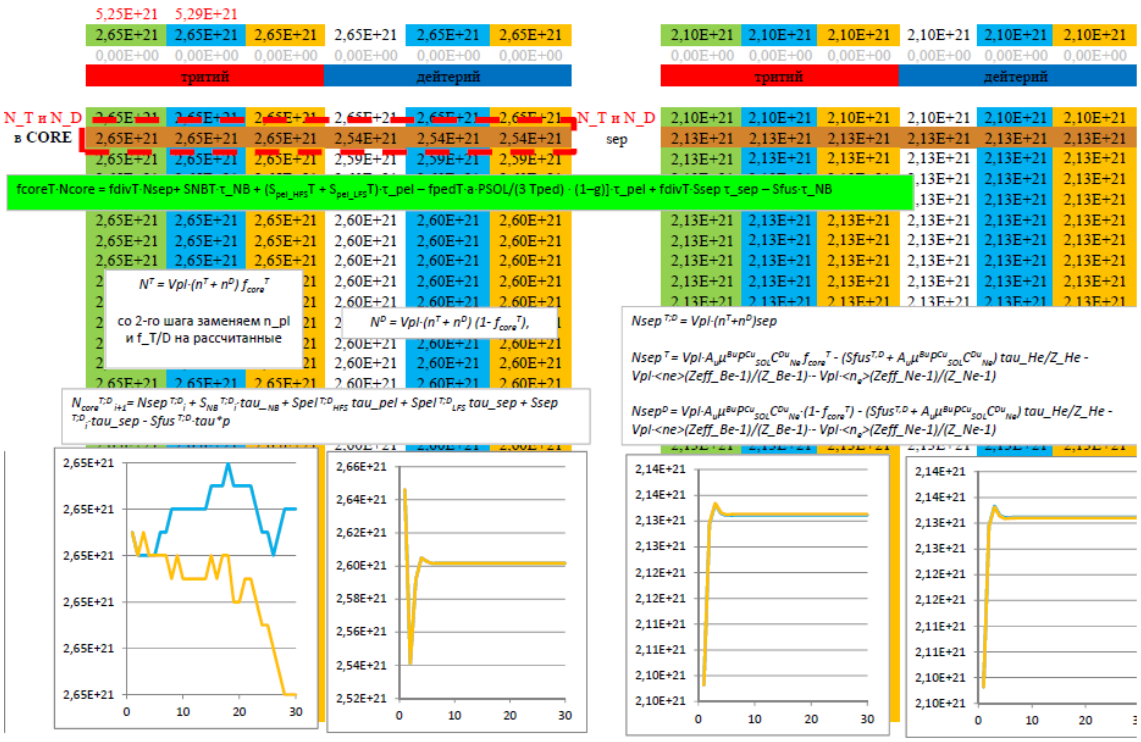


Figure 11. Interface of the module "dynamics of isotopes in the FC" of the FC-FNS code. Fragment. Calculation of plasma parameters by the iteration method for the DEMO-FNS project (for different types of heating beam)

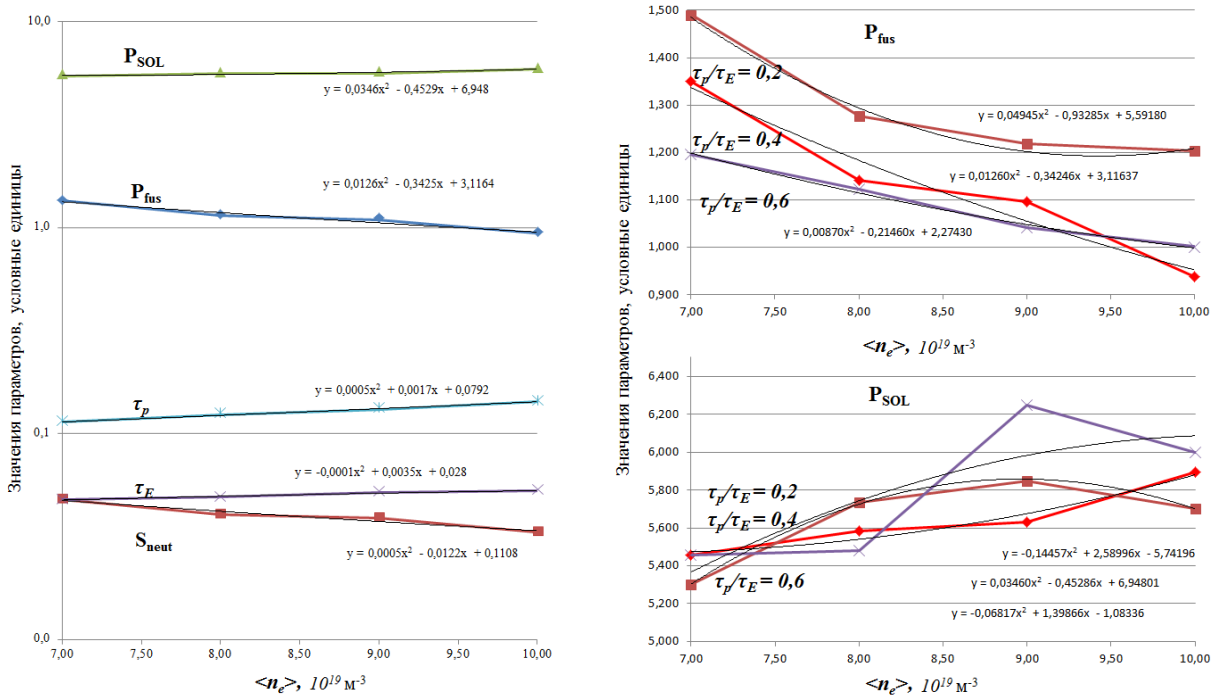


Figure 12. Dependences of plasma parameters calculated by ASTRA and used in FC-FNS in the form of scalings (from the particle confinement time and the density of the core plasma)

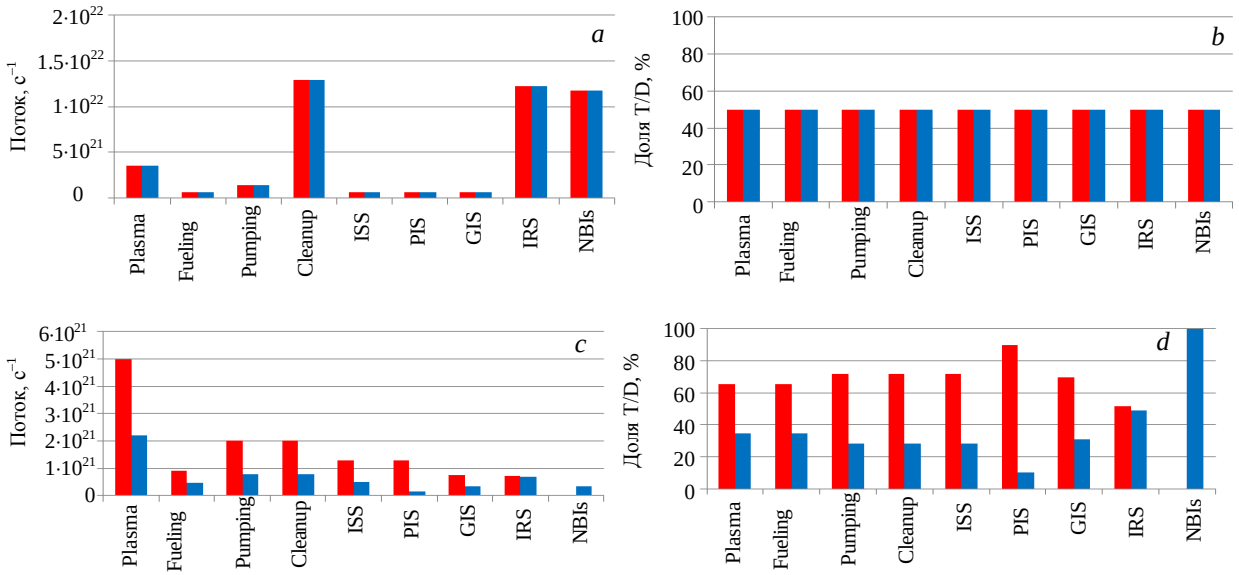
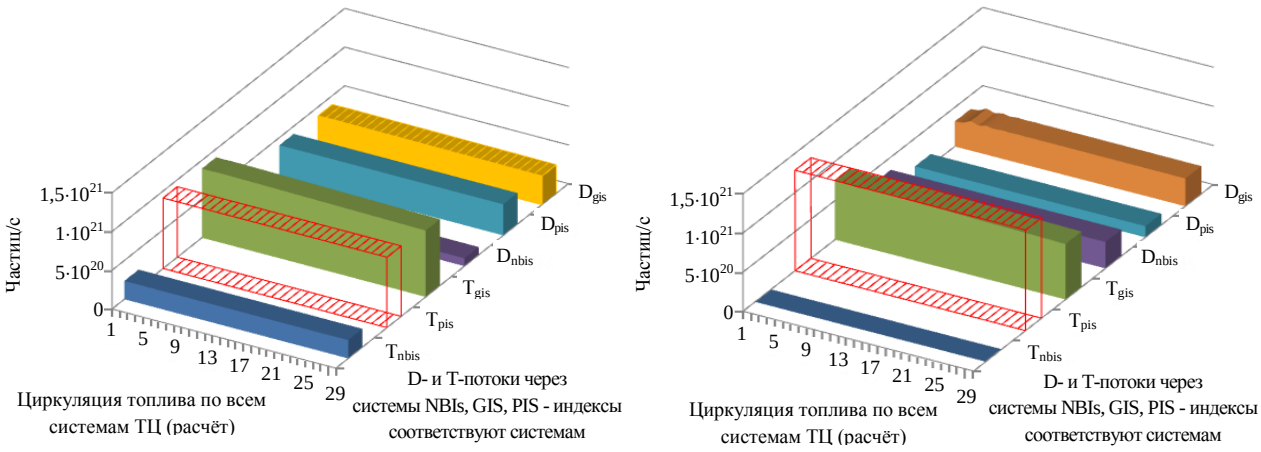


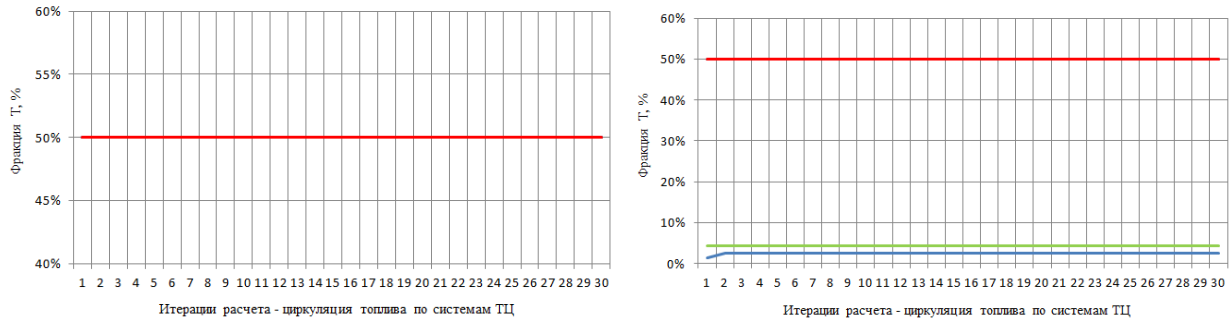
Figure 13. Flows T (——) and D (——) through the FC systems for the DEMO-FNS project (along the horizontal axis) in absolute (s^{-1}) values (*a* , *c*), as well as the isotopic composition of the gas in them ($f^{D,T}$, %) (*b* , *d*). Histograms are given for the cases of the beam $D^0 + T^0$ ($f_T = 0.5$) (*a* , *b*), beam D^0 ($f_T = 0.7$) (*c* , *d*) as the most effective from the point of view of P_{fus} and breeding T

For convenience, all parameters and results are displayed as graphs for calculation iterations - see Figures 5, 8 and 10. **The values of the isotopic composition of the gas in the main systems of the FC are displayed as summary graphs** and tables – see Figures 13-15. For verification, the total number of particles in the core and divertor plasma and the FC as a whole is monitored - see Figure 16.



(a) (b)

Figure 14. Dynamics of isotope flows in key FC systems (for DEMO-FNS) during successive circulations of fuel in the FC (s^{-1}). $D^0 + T^0$-beam - (*a*), D^0-beam - (*b*) scenarios.



(a) (b)

Figure 15 . Change in the tritium fraction in the main FC systems (for DEMO-FNS): — plasma; — pumping; — cleaning; — injection ($f_T = 0.5$ in plasma). The horizontal scale shows the calculation stages — the number of consecutive fuel supply cycles for all FC systems, the gas composition in NBIs : D + T (*a*), $D_2 + T_{2\ adm\ (5\%)}$ (*b*)

Figure 14 shows the steady-state (by iterations) values of the fuel component flows in the fuel injection and gas puffing systems (for selected operating points).

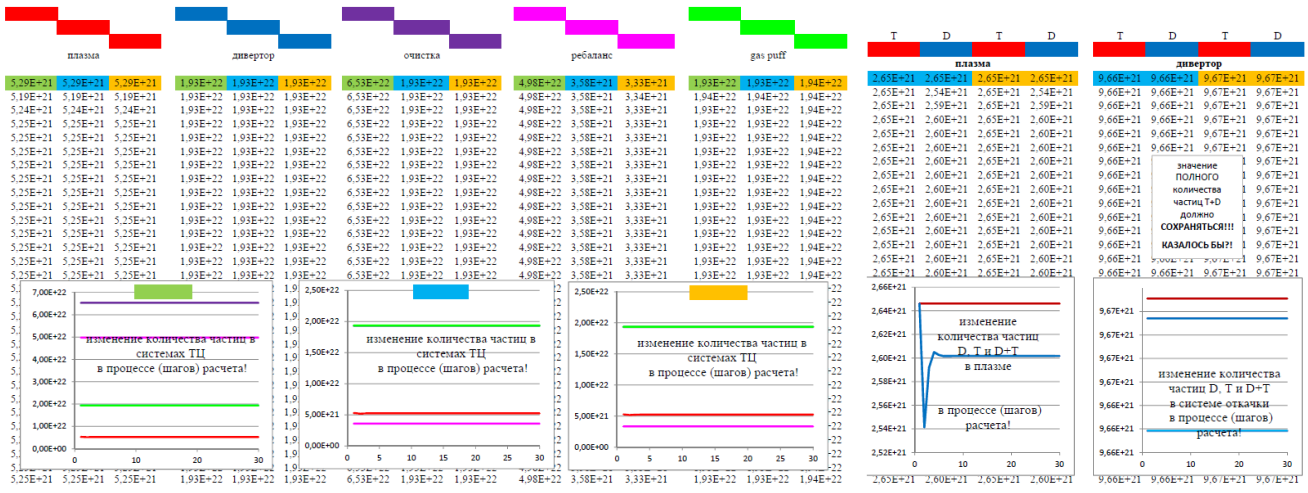


Figure 16. Interface of the module "dynamics of isotopes in the FC" of the FC-FNS code. Fragment. Checking the total number of D+T particles in the FC and in the plasma in calculations by the iteration method for the DEMO-FNS project (for different types of heating beam)

Monitoring the change in the isotopic composition of the fuel mixture in the key systems of the FC (see Figure 15) - the core plasma, pumping, cleaning, isotopic composition correction and injection systems allows us to judge the operating modes of these systems and the composition of the gas mixture in them, as well as the correctness of the modeling as a whole. A significant difference f_i^T in FC systems and plasma for D^0 -beam (Figure 15b) is explained by the regime taking into account convective ELMs - publications [10, 12] are devoted to a detailed analysis of the simulation results and a comparison of different beam compositions. During the calculation, the accumulation of particles in

the FC is monitored - so that all particles pumped out of the vacuum chamber are injected back to prevent their unjustified accumulation in any system (and all injected particles are, accordingly, pumped out).

T reproduction are made in the module « tritium breeding ». Based on the neutron yield value and blanket parameters, the breeding coefficient T (TBR) is calculated and the rate of its accumulation in the FC of the facility is calculated using two methods. The first method involves using the values calculated in the code modules described above, and the second - using a simplified FC model with analytical solutions of ordinary differential equations systems [7, 8]. The calculation results are displayed in the form of graphs for comparison (see Figures 17, 18).

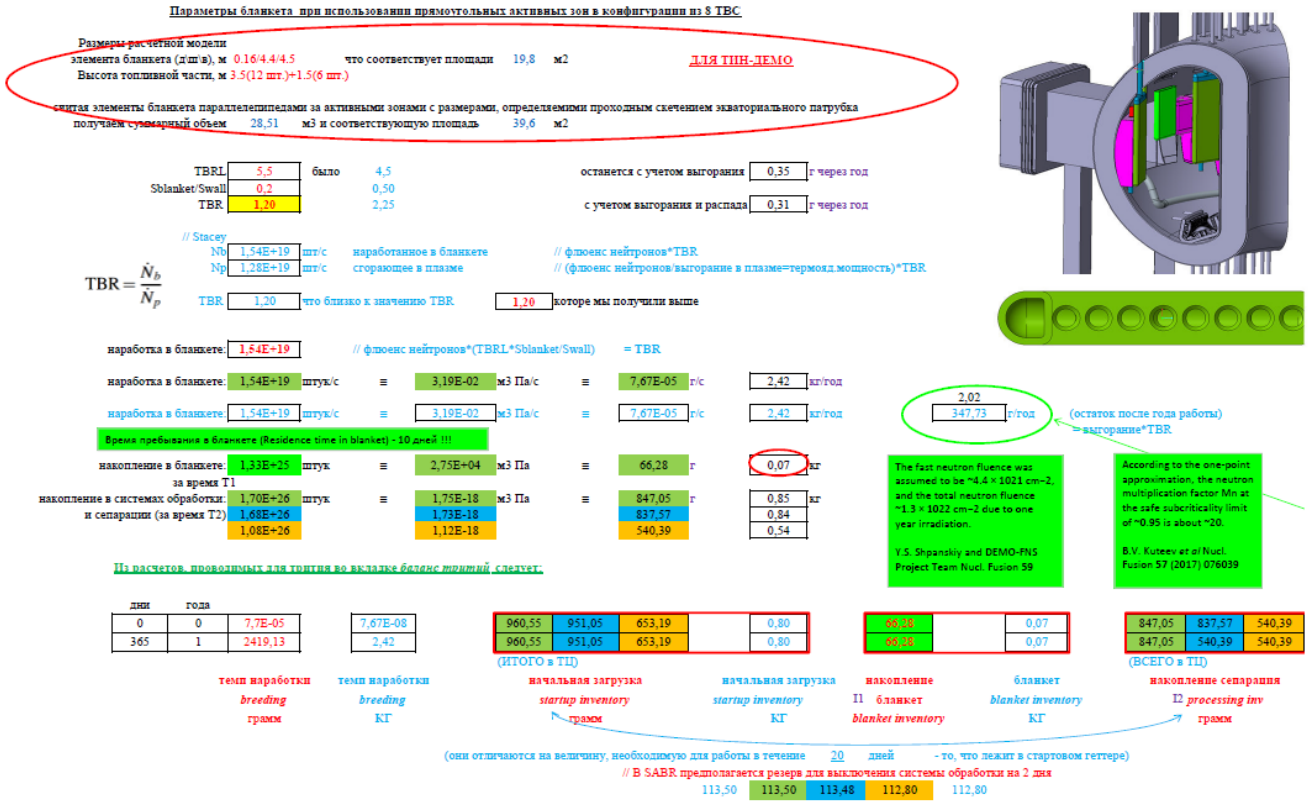


Figure 17 . Interface of the tritium module «breeding» code FC-FNS. Fragment. Calculation of the tritium production rate in the blanket of the facility for the DEMO-FNS project (for various types of heating beam)

The use of the model [7] for the FNS projects in the code is not advisable and is implemented in the code in the process of developing the modeling approach. The solutions of the ODE system are highly dependent on the characteristic "residence times" that cannot be directly related to the parameters of the FC systems, fuel flows, etc. They are largely related to the technologies used - therefore, they can be defined for the selected technologies of the FC systems. However, the choice of technologies will depend on the gas flows, its isotopic composition and take into account the integration of the systems

and their operating modes [13-15]. Meanwhile, such a model can be useful for a number of applications - for this purpose, an original system of equations was proposed that describes the FNS FC systems in which fuel flows appear instead of the "burnout fraction" value. For the calculated amount of hydrogen isotopes in the FNS FC systems (with the selected technologies), the corresponding "residence times" were found (they are in good agreement with the actual gas processing time indicators for these technologies). The solution of this ODE system is implemented separately from the code in Python and its integration into the FC-FNS code is under discussion.

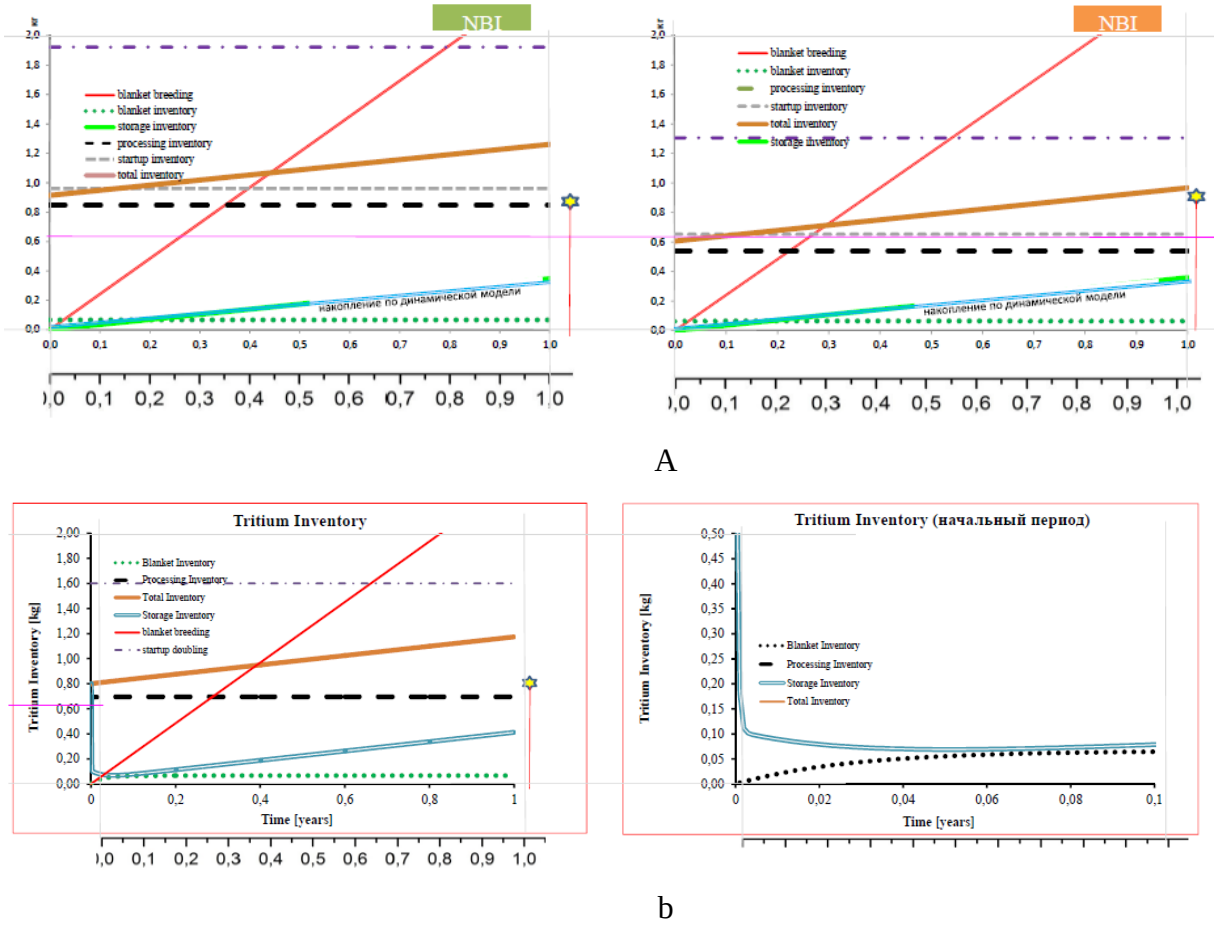


Figure 18. Interface of the module « tritium breeding » code FC-FNS. Fragment. Calculations of changes in the amount of tritium in FC systems over time for various calculation algorithms: the original algorithm of the FC-FNS code and by analytical modeling for the DEMO-FNS project (for various types of heating beam)

Based on the maximum fraction of protium in the fuel mixture specified in the initial parameters, calculations for protium are made in the "protium dynamics in the FC" module. A significant difference from the calculation for heavy isotopes is that during the circulation of the fuel mixture, it partially undergoes deprotiation in order to maintain the fraction of protium within the established limits (since exceeding its content can lead to a decrease in the neutron yield). In this module of the

code, the performance of the deprotization system (hydrogen isotope separation) is calculated to ensure the required fraction of protium in the plasma (fuel mixture) and compared with the parameters of the hydrogen isotope separation system used in the FC. The method for calculating the amount of protium in the FC is described in detail in [8, 16], in connection with this, in this chapter, minimal attention is paid to the description of the "protium dynamics in the FC" module.

The calculation of the dynamics of T in the heating injectors (which is relevant first of all for the scenario with D -beams) is performed in the module "dynamics of tritium in injectors". For this, a technique similar to that used for protium is used. For the same reason, minimal attention is paid to this module here. It should be noted that in the code module "dynamics of tritium in injectors" the particle flows into the injectors from the vacuum chamber through the beam injection channels - atomic pipelines are estimated and the conditions for gas puffing into the injector elements are calculated to form additional heating beams and ensure their neutralization - see Figure 19. These values are used in calculations by other modules of the code.

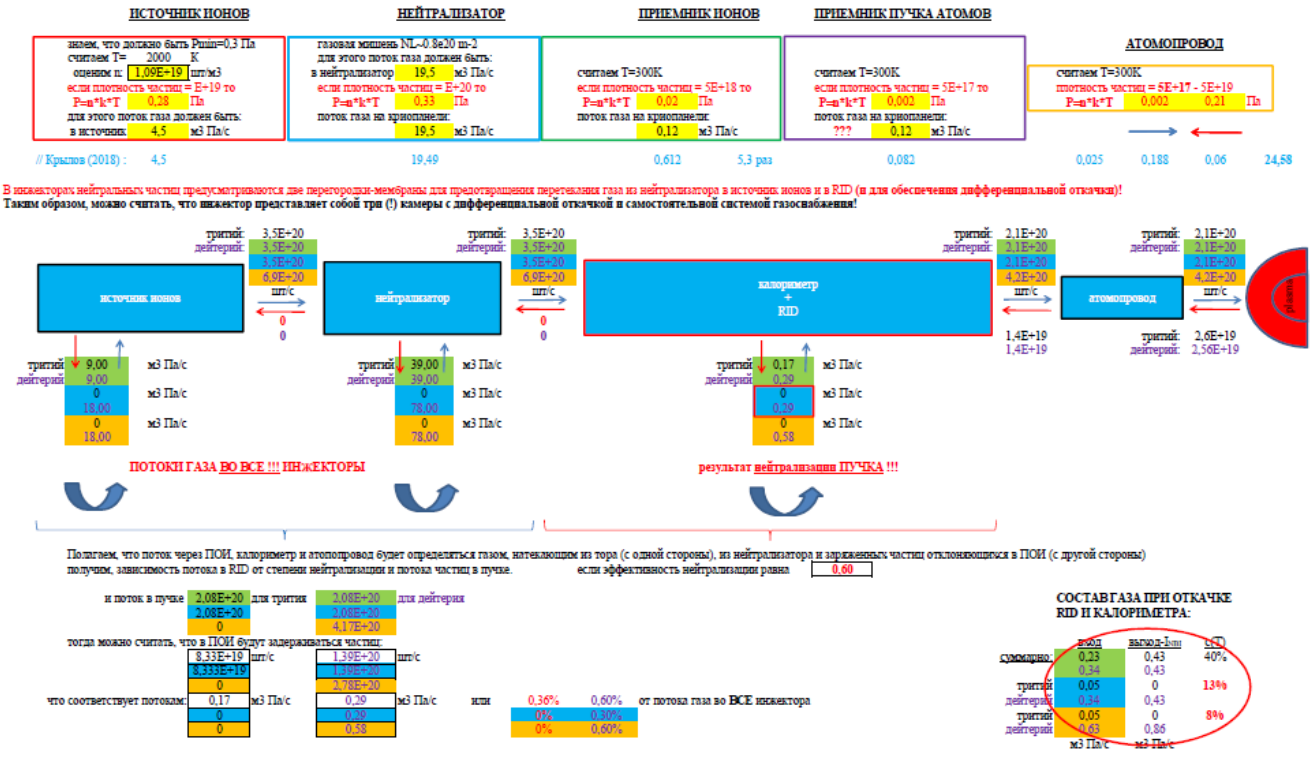


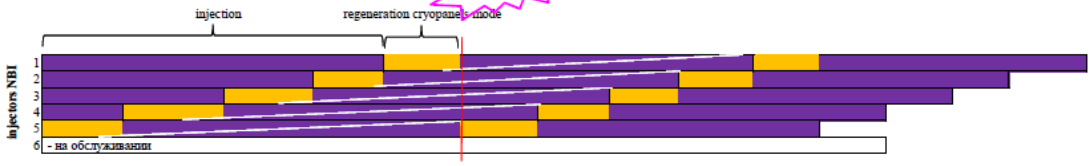
Figure 19. Interface of the module "tritium dynamics in injectors" of the FC-FNS code. Fragment. Conditions for gas injection into the injector elements to form additional heating beams and ensure their neutralization.

система нейтральной инжекции

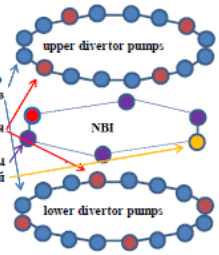
в системе нейтральной инжекции ДЕМО-ТИН предусмотрено 6 инжекторов
из которых одновременно работают 4 шт

Примем время накопления газа на криопанелях одного инжектора траб(NB) а регенерации treг(NB)
за время работы криопанели одного инжектора накопят газа Nubi=траб(NB)*Subi
где Subi-поток газа в каждый инжектор, Nubi - количество газа, накапливаемое за время работы
все инжекторы при этом будут содержать в каждый момент времени 3 *Nubi

В ТОМ СЛУЧАЕ, ЕСЛИ Treг=1/4Траб ?!



Subi= 0,03 г/с (0,03 / 0,000017) поток частиц на криопанели одного инжектора (из источника, нейтрализатора и тора)



	траб1	3 *Nubi						
	450 s	38,67	38,67	0,02	г	12,89	12,89	0,01	0,13
	600 s	51,57	51,57	0,03	г	17,19	17,19	0,01	0,17
	1000 s	85,94	85,94	0,05	г	28,65	28,65	0,02	0,28
ИТЭР:	3000 s	257,83	257,83	0,15	г	85,94	85,94	0,05	0,83
	6000 s	515,65	515,65	0,31	г	171,88	171,88	0,10	1,67
ДЕМО-ТИН	11500 s	988,33	988,33	0,59	г	329,44	329,44	0,20	3,19

= Nubi - MAX трития в одном инжекторе

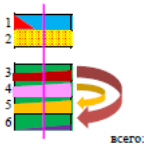
оценим накопление пленки из молекул трития на криопанелях ОДНОГО ИНЖЕКТОРА
допустимая концентрация изотопов водорода в газовой смеси 2% из соображений взрывоопасности
толщина при которой падает сорбционная способность панели 0,2 см (толщина пленки D2+T2)

тогда объем газа на поверхности криопанелей 8,00E+04 см3 или 4,05E+27 молекул D и T количество водорода в объеме инжектора 6,89E+25 молекул D2 и T2
такое количество молекул T и D будет накоплено за время 7,05E+05 секунд или 195,70 часов время из критерия сорбционной способности 11 992 секунд или 3,33 часов время из крите
(поскольку молекула T2 или D2) 7,03E+05 195,70 11 992 3,33 взрывоопасно
7,05E+05 195,74 11 994 3,33

(3,2 час / 190 мин)
за время 11 994 сек, рассчитанное для инжекторов, накопление на панелях ВСЕХ ИНЖЕКТОРОВ будет равно: 300,00 грамм для ДЕЙТЕРИЯ: 200,00 грамм
300,00 200,00
по массе
3 491 сек или 1 часов время из критерия накопления максимально допустимого количества T набрать 0,62 0,05% 1373,69
3 491 1 количество T !
5 815 821 1616 для ИТЭР 65 грамм 0,03% по частицам

система откачки из камеры

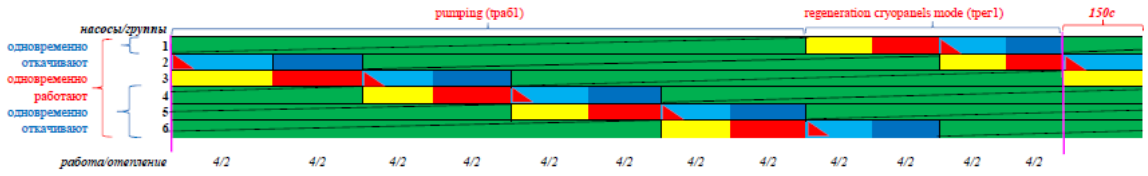
Для откачки дивертора ДЕМО-ТИН используются 36 крионасосов, объединенные в группы по 6 шт
при этом из всех 6 групп насосов одновременно в режиме откачки находятся из них 4 шт
В таком случае каждая группа насосов должна обеспечивать скорость откачки 20,00 м3/с для откачки 40,00 м3 Па/с (из камеры)



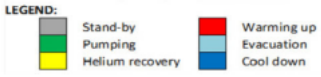
Примем время накопления газа на криопанелях одного насоса траб(рпмр) а время регенерации treг(рпмр)
считая, что ВЕСЬ поток газа из камеры (дивертора) поступает в РАБОТАЮЩИЕ насосы (группы), получим Nрпмр=траб(рпмр)*Sрпмр/Nгрупп
где Nрпмр - накопленное количество газа в одной группе насосов, Sрпмр-поток газа из дивертора
за время работы траб(рпмр) каждая группа насосов накопит количество газа Nрпмр

все насосы при этом будут содержать в каждый момент времени 4 *Nрпмр

(ИТЭР-подобный режим): pumping (траб1) = 1200 с
regeneration cryopanels mode (treг1) = 600 с



Sрпмр= 0,04 г/с (0,04 / 0,04) или 0,00 м3 Па/с



	траб(рпмр)	4 *Nрпмр			
секунд:	300	11,53	11,53	11,55	г
	450	17,30	17,30	17,32	г
	600	23,07	23,06	23,10	г
	750	28,84	28,83	28,87	г
	900	34,60	34,59	34,64	г
	1050	40,37	40,36	40,42	г
	1200	46,14	46,12	46,19	г

для ИТЭР 170 грамм при 120 м3Па/с (50/50 DT)
0,00 в пересчете на поток T у нас))

за время 1200 сек, определенное для ИТЭР-подобного режима, накопление ВО ВСЕХ насосах будет равно: 46,14 грамм 46,12 46,19 для ДЕЙТЕРИЯ: 30,76 грамм 30,76 30,79

система газовых клапанов

согласно документации ИТЭР, система газоснабжения обеспечивает поток топливной смеси в тор до 222 м3 Па/с (D+T). А также протия, дейтерия и примесных газов.

давлении подачи для примесных газов (или вообще всех) 0,09 МПа. т.е. 90 000 Па = 0,89 атм
давление в магистралях, ведущих к системе нейтральной инжекции 0,6 Мпа 600 000 Па = 5,92 атм

расход газовой смеси 125 м3 Па/с для водорода и 70 м3 Па/с для дейтерия

газовая система состоит из внешних источников газа (с Рраб =	90 000	Па	длиной	12	м	и V =	9,42E-04	м3)	2,05E+22	атомов	=	0,10	грамм
- трубопроводов (с Рраб =	600 000	Па	длиной	12	м	и V =	9,42E-04	м3)	1,37E+23	атомов	=	0,68	грамм
- газовых клапанов (GVB)	объемом до			1,74E-01	м3	корпуса и внутренним, меньшим в 10 раз			3,79E+23	атомов	=	1,89	грамм
- трубопроводов (с Рраб =	120 000	Па	длиной	15	м	и V =	1,18E-03	м3)	3,41E+22	атомов	=	0,17	грамм

суммарное содержание трития составит в 6 штук газовых клапанах для ДЕМО-ТИН ВСЕГО: 17,05 грамм 17,05 17,05 или для ДЕЙТЕРИЯ: 11,37 грамм 11,37 11,37

для ИТЭР 85 грамм
2,68 в пересчете на актуальные потоки газа

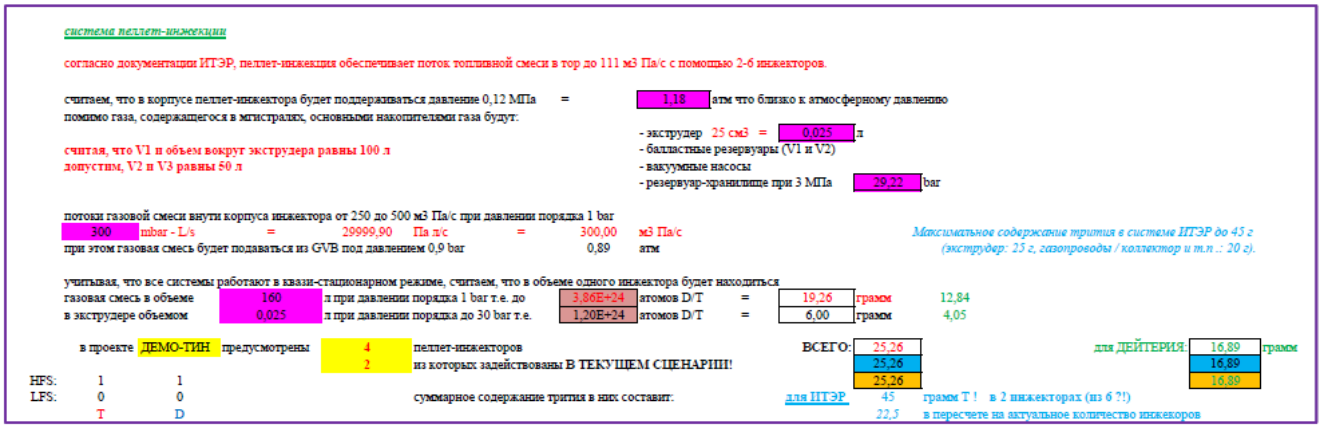


Figure 20. Interface of the module "element-by-element calculation of systems" of the FC-FNS code. Fragment.

Calculations of the amount of tritium and other isotopes accumulated during operation in the FC systems are made in the "element-by-element calculation of systems" module based on previously calculated flows of particles of the corresponding isotopes through various systems, taking into account the structure and operating cycles of these systems - the calculation method is described in detail in [17]. The systems considered are cryocondensation pumping of the tokamak chamber, cryogenic and membrane purification of spent fuel, catalytic decomposition of molecular compounds of hydrogen and processing of superheavy-water waste, separation of isotopes, deprotization, storage of hydrogen isotopes, as well as pellet injection systems and injection of particles in the form of fast atoms (heating beams). The fuel content in the main lines, FC receivers and structural materials of the vacuum chamber of the facility is also taken into account.

The calculations are carried out based on the frequency of operation of a particular system (for example, the operating mode and regeneration time of cryopumps) and the number of working elements. Thus, cryogenic and membrane isotope separation systems will include several modules operating sequentially, the loading of catalytic decomposition and superheavy-water waste processing systems will occur periodically as the gas mixture accumulates between loadings in the buffer receiver, the isotope separation/deprotization system contains several cryogenic rectification or chromatographic columns (in the case of using deuterium as the working gas for the neutral injection system), etc. The typical appearance of the interface of the "element-by-element calculation of systems" module is shown in Figures 20 and 21. The color designation of the cells corresponds to that introduced earlier - for different types of heating beam.

Information on the isotopes inventory in fuel cycle systems is also displayed in the form of histograms (Figure 22) – which is convenient for analysis and control of the calculations being carried out; they can be displayed on any sheet of any file/module (the convenience of this is ensured by the MS Excel functions) – which allows you to further consolidate and analyze information on the

calculation cycle, as well as present them in a more complex form (for example, by Origin) – see Figure 23.

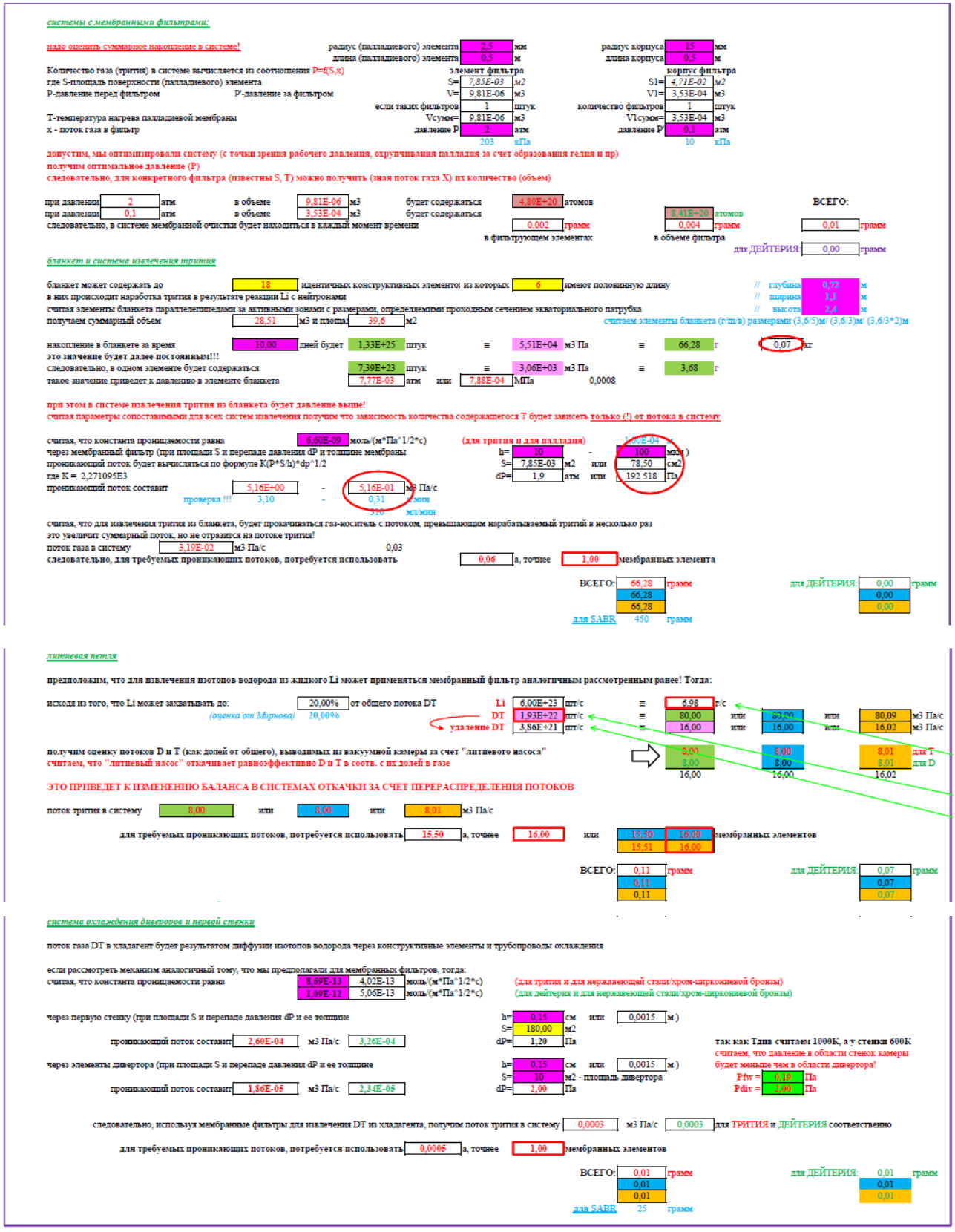


Figure 18. Interface of the module "element-by-element calculation of systems" of the FC-FNS code. Fragment.

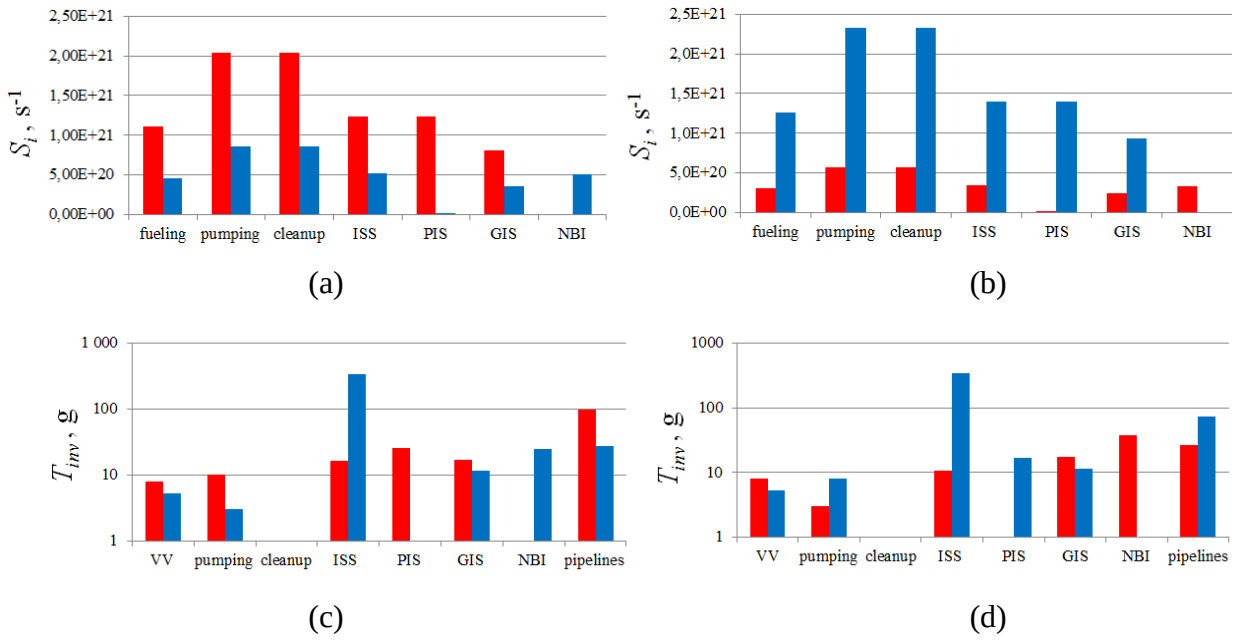
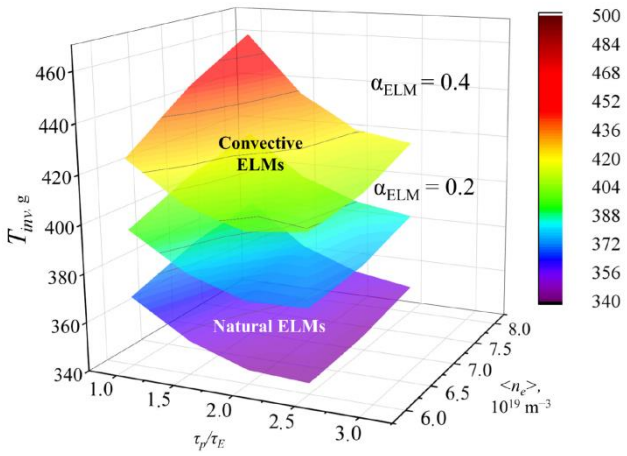


Figure 22 Particle flows T - ■ and D - ■ through the FC systems (a, b) and the amount of T in them (c, d). n_e = 10.0 10 ^{19} 1/ ^{m3} , D/χ_e = 0.6, $f_{core}^{T} = f_{div}^{T}$ = 0.7 for D -beam (a, c) and $f_{core}^{T} = f_{div}^{T}$ = 0.2 for T - bundle (b, d). PIS – pellet injection system, GIS – gas puffing system, NBI – neutral injection system, VV – vacuum vessel, pipelines – pipelines and receivers of the fuel cycle.



Drawing 23 . Tritium inventory (T_{inv}) in the FC (excluding long-term storage) taking into account particle losses in ELMs depending on the particle retention time τ_p/τ_E and plasma density $< n_e >$ (10^{19} m^{-3}) for the case D^0 - beams. The scale on the right shows the correspondence between the color on the graphs and the T inventory value.

To calculate the isotope content in the isotope separation system, the ISS code module is used, the interface of which is shown in Figure 24. For it, the main input data are flows from various FC systems, as well as actual and required (product) tritium shares. The calculation method is described in

detail in [17]. For the hydrogen isotope separation system, scenarios of various types of heating beam are calculated separately (on different "sheets").

Диапазон B	8,0E+21	1/с						
	1,7E+01	м3 Па/с						
	7,3E-03	моль/с						
	2,6E+01	моль/час						
	Основная колонна			Колонна на выходе CECE		Колонна на выходе хроматографии		
по тритию								
xb	0,99	масс доля		0,50	масс доля	0,50	масс доля	
xp	1,0E-09	масс доля		1,0E-09	масс доля	1,0E-09	масс доля	
xf (доляТ)	0,50	масс доля		8,20E-04	масс доля	0,05	масс доля	
x ср. конц.	0,75	масс доля		0,25	масс доля	0,28	масс доля	
x ср. исч.	0,25	масс доля		0,00	масс доля	0,03	масс доля	
B (выход T)	2,6E+01	моль/час		4,6E-02	моль/час	1,0E-01	моль/час	
P (выход D)	2,6E+01	моль/час		2,8E+01	моль/час	9,0E-01	моль/час	
F (входной поток)	5,2E+01	моль/час		2,8E+01	моль/час	1,0E+00	моль/час	
λисч.max	1,1E+00	—		1,4E+00	—	1,2E+00	—	
λ конц.max	9,0E-01	—		1,0E+00	—	9,8E-01	—	
Lисч.min	2,1E+02	моль/час		6,9E+01	моль/час	3,8E+00	моль/час	
Lконц.min	2,6E+02	моль/час		9,7E+01	моль/час	4,8E+00	моль/час	
θ колонны	0,80	—		0,80	—	0,80	—	
Lисч	2,6E+02	моль/час		8,7E+01	моль/час	4,8E+00	моль/час	
Lконц	3,2E+02	моль/час		1,2E+02	моль/час	6,0E+00	моль/час	
λисч	1,1E+00			1,3E+00		1,2E+00		
λ конц	9,2E-01			1,0E+00		9,8E-01		
Gисч	2,9E+02	моль/час		1,1E+02	моль/час	5,7E+00	моль/час	
Gконц	3,0E+02	моль/час		1,2E+02	моль/час	5,9E+00	моль/час	
Gисч	1,3E-04	м3/с		5,2E-05	м3/с	2,6E-06	м3/с	
Gконц	1,4E-04	м3/с		5,5E-05	м3/с	2,7E-06	м3/с	
K исч.	5,0E+08	—		8,2E+05	—	5,0E+07	—	
K конц.	2,0E+00	—		6,1E+02	—	1,0E+01	—	
n конц	5,8	шт.		23,8	шт.	16,1	шт.	
n исч	156,02	шт.		224,94	шт.	358,24	шт.	
Высота колонны конц.	0,3	м		1,4	м	1,0	м	
Высота колонны исч.	9,4	м		13,5	м	21,5	м	
Свободное сечение колонны конц	6,8E-04	м2		2,8E-04	м2	1,3E-05	м2	
Свободный диаметр колонны конц	2,9E-02	м		1,9E-02	м	4,1E-03	м	
Свободное сечение колонны исч	6,5E-04	м2		2,6E-04	м2	1,3E-05	м2	
Свободный диаметр колонны исч	2,9E-02	м		1,8E-02	м	4,1E-03	м	
Диаметр колонны конц	3,6E-02	м		2,3E-02	м	5,1E-03	м	
Диаметр колонны исч	3,5E-02	м		2,2E-02	м	4,9E-03	м	
Диаметр колонны	3,6E-02	м		2,3E-02	м	5,1E-03	м	
Объем колонны конц	3,5E-04	м3		5,9E-04	м3	1,9E-05	м3	
Объем колонны исч	9,5E-03	м3		5,6E-03	м3	4,3E-04	м3	
Статическая задержка конц. (водород)	6,7E-05	м3		1,1E-04	м3	3,7E-06	м3	
Статическая задержка исч. (водород)	1,8E-03	м3		1,1E-03	м3	8,2E-05	м3	
Статическая задержка конц. (водород)	8,03	г		7,82	г	0,44	г	
Статическая задержка исч. (водород)	215,97	г		73,84	г	9,84	г	
Динамическая задержка конц. (водород)	1,4E-04	м3		2,3E-04	м3	9,8E-06	м3	
Динамическая задержка исч. (водород)	3,6E-03	м3		2,8E-03	м3	2,2E-04	м3	
Динамическая задержка конц. (водород)	16,27	г		15,84	г	1,17	г	
Динамическая задержка исч. (водород)	437,69	г		195,93	г	26,10	г	
Общая задержка конц. (водород)	24,30	г		23,66	г	1,61	г	
Общая задержка исч. (водород)	653,66	г		269,77	г	35,94	г	
Общая задержка конц. (тритий)	18,11	г		5,92	г	0,44	г	
Общая задержка исч. (тритий)	163,41	г		0,11	г	0,90	г	
Общая задержка конц. (дейтерий)	6,20	г		17,73	г	1,17	г	
Общая задержка исч. (дейтерий)	490,24	г		269,66	г	35,04	г	
Водород в газовой фазе конц.	0,21	моль		0,36	моль	0,01	моль	
Водород в газовой фазе исч.	5,77	моль		3,38	моль	0,26	моль	
Тритий в газовой фазе конц.	0,96	г		0,54	г	0,02	г	
Тритий в газовой фазе исч.	8,66	г		0,01	г	0,04	г	
Дейтерий в газовой фазе конц.	0,22	г		1,07	г	0,03	г	
Дейтерий в газовой фазе исч.	17,32	г		13,53	г	1,03	г	
Всего трития	191,14	г		6,58	г	1,40	г	197,72 199,13
Всего дейтерия	513,98	г		302,00	г	37,27	г	815,98 853,25

Figure 19. Interface of the module " ISS " of the FC-FNS code. Fragment.

The obtained values of the amount of hydrogen isotopes in the FC systems are displayed in the form of tables on the "results" sheet of the "particle balance (H, D, T)" module and are used to estimate the losses of T due to radioactive decay (on the "tritium balance" sheet) in the same module and also in the "dynamics of isotopes in FC" module. All calculations in the code modules are organized in such a way as to avoid the occurrence of "cyclic references".

As already noted above in the text, calculations can be performed by the user using one "sheet" of the "initial data" module, while changing the facility scenarios without significantly changing its parameters. The results of the calculations are displayed on the same " sheet " with which the user works, which is convenient both for analyzing most parameters (their control) and for generating "output" - a set of results in the form of graphs and tables for copying to other documents of the Microsoft package Office, which is convenient both for data processing and for preparing presentations, etc. The formation of the content of such "outputs" is organized by copying cells (respectively, their values and "formatting") into free cells on the "sheet" from any code module.

Obviously, with a certain convenience of such an interface/calculation method, it has significant inconveniences for the developer/ user both in the development of the functional capabilities of the code and in terms of debugging. Meanwhile, the successful use of the code on this platform for almost 10 years shows that such a solution allows successfully solving the set scientific problems and developing the code (both in terms of developing the FC and additional physical phenomena).

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