ACCIDENTS DURING SHUTDOWN CONDITIONS FOR NPP WITH WWER-1000/428

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1 INTRODUCTION

Accidents which can arise at the reactor planned shutdown have been carefully studied over the world during a few years. The probabilistic analysis results have shown that the contribution of accident sequences to the core damage during shutdown and refuelling is comparable to that during the reactor operation on power.

Normal shutdown of the reactor with further service and refuelling consists of the following main stages:

- cooling-down at a steam-and-water stage to the cold state parameters (coolant temperature 50-60 °C)
- cold state before untightening the reactor (head removal)
- service with the head removed and refuelling
- cold state before the reactor tightening
- heating up (from the moment of the first RCP startup up to the hot state temperature)
- hot state (startup reduction of boron concentration).

It is naturally, that from the viewpoint of probability of accidenatal event arise the most attention should be paid to long-term stationary stages, such as service with the reactor head removed and refuelling.

Short-term transients from one state of the reactor into another require from the personnel to be maximum attentive in respect of following the process procedure at startup and shutdown, therefore, the effect of human factor upon the NPP safety is a subject of serious analysis.

The following important contributors to the core damage are:

- boron dilution
- loss of residule heat removal with a reduced reactor coolant system inventory
- loss of the primary circuit coolant
- loss of off-site power supply
- fires, and
- operator's errors.

This paper consideres the effect of such internal initiating events upon safety of the NPP with WWER-1000/428 as boron dilution and loss of residual heat removal at the reduced coolant inventory in the primary circuit.

2 SAFETY SYSTEM STRUCTURE

The NPP-91 design concept with WWER-1000/428 is consistent with the safety objectives for evolutionary type advanced reactors.

The active safety systems consist of 4 completely independent trains.

The train capacity, quick action and other characteristics were selected proceeding from a condition to ensure nuclear and radiation safety under any initiating events considered in the design. A high degree of the trains physical separation is achieved thanks to the location of the safety system trains in separate rooms and separate sumps within the containment.

Every safety train has an individual air cooling system with backup power supply.

3 PROBABILISTIC ANALYSIS OF EXTERNAL BORON DILUTION SCENARIOS

3.1 External dilution events analyzed

External boron dilution events in normal reactor operating conditions have been studied in [1] with probabilistic methods. No external dilution scenarios have been recognized during power and during planned cooldown. The probabilistic analyses thus concentrate on cold state events and on reactor startup events. Only core reactivity as right after refuelling has been considered.

During cold state, the following events were studied:

1) Diluted slug enters core by natural circulation when reactor is open after refuelling and maintenance
2) Diluted slug enters core by residual heat removal (RHR) system
3) Diluted slug enters core when replenishing primary coolant before pressurization
4) Diluted slug enters core by initial starting of the first RCP

During reactor startup in hot state, the following events were studied:

5) Diluted slug enters core by initial starting of startup dilution
6) Startup dilution is not interrupted when all the RCP:s stop, first RCP is started or natural circulation restarts.

These events are considered to be comprehensive as to the normal operating conditions. The numbering of events presented here differs from the one in [1].

Analysis of external boron dilution events was performed in four parts. Cold state events 1, 2 and 4 were analyzed together, and the coolant replenishment event 3 and startup events 5 and 6 alone, respectively.

3.2 Methods and assumptions

The data for the basic events was either extracted from the mini-PSA -analysis [2] or is based on expert views. In the latter case, conservatism has been tried to be followed. The probabilities are assumed to correspond to the probabilities during normal power operational states where applicable.

Rough screening limits were placed on the ground of the steady-state analyses for the eventual amount of pure water of different sources to be taken into account in the analvsis. For hot and cold state, conservative limits of 5 m^3 and 2 m^3 were introduced, respectively (neither mixing phenomena nor dynamically calculated consequences have been taken into account in these limits).

The tree of external dilution scenarios was constructed and analyzed with the help of CAFTA code. Minimum cut sets were obtained by the program in order to evaluate the probability of the scenarios. Truncation limit of 1E-10 has been applied. Complete list of the assumptions can be found in [1].

3.3 Analyses of the events

3.3.1 Cold state events 1, 2 and 4

In cold state event 1, natural circulation was studied as a potential reason to inject a slug into core. The eventual sources of the slug viewed in this event are routes from steam generator, accumulator, reactor coolant pump (RCP), fire water, decontamination and tanks of make-up water system for reactor coolant system (KBC11/12BB001).

In cold state event 2, the possibility of a residual heat removal (RHR) system to inject a slug into core was evaluated. Two scenarios were viewed:

1) the slug is situated in the RHR system at the moment of RHR system start and
2) the slug is situated in a stagnant primary loop, and is injected into core because of RHR system start in corresponding loop.

The reason to start another system was supposed to be stopping of another operating RHR system. No cases were viewed in which RHR system were taken into operation even though another operates normally. No scenarios were viewed in which pure water were injected in operating RHR system, which would then feed the slug into core.

In cold state event 4, initial startup of the first RCP was studied. Two scenarios were viewed:

1) the slug is situated in a stagnant primary loop at the moment of RCP start in that loop and
2) the slug hides in volume and boron control system and is injected into core by RCP start.

The frequency of cold state events l, 2 and 4 was calculated to be 5.17E–5 per year by the present assumptions. Frequency of event 1 alone was calculated to be 3.25E–9/ a, event 2 to be 2.11E–8 / a and event 4 to be 5.17E–5 / a. Elimination of first two minimum cutsets of event 4 would alone drop the frequency by two decades.

3.3.2 Coolant replenishment event 3

In coolant replenishment event, primary circuit coolant replenishment before pressurization and cold startup was studied. A risk of reactivity accident was studied in two scenarios:

1) Operator replenishes primary coolant from borated water storage tanks with KBB11/12AP001 pumps via startup injection line KBB22–KBA60, and there remains low–boron water in coolant storage ion exchangers KBB10ATOO1–003 due to operator backwashing during unpressurized state and

2) Operator replenishes primary coolant from make–up water tank, and a diluted boron concentration remains in KBC10 piping, there is erroneous dilution in KBC11BB001 tank or operator uses erroneously KBC12BB001 tank for dilution.

The frequency of coolant replenishment event was calculated to be 5.26E–7 per year by the present assumptions.

3.3.3 Initial starting of startup dilution event 5

In initial starting of startup dilution event, the planned way to perform startup dilution by feeding the charging pumps straight from KBC11BB001 tank with concentration which is safe as regards reactivity accidents was studied. Two scenarios were evaluated:

1) Diluted boron concentration in make–up water system enters core by initial starting of startup dilution and
2) Dilution is performed via deaerator by operator, and there remains a diluted boron concentration in deaerator which is supposed to enter to core at the moment of initial starting of startup dilution.

The frequency of initial starting of startup dilution event was calculated to be 2.74E–5 per year by the present assumptions.

3.3.4 Startup dilution event 6

In event 6, the reactor is in the hot state during startup dilution, when all RCP:s stop, and dilution is not stopped. Later on, when enough diluted water has entered in the primary circuit, the first RCP is restarted or natural circulation starts, which is supposed to inject enough diluted water into the core to induce a reactivity accident. The scenario requires operator to perform startup dilution by feeding pure or low–boron water via deaerator instead of feeding the charging pumps straight from KBC11BB001 tank.

The frequency of event 6 was calculated to be 1.50E−3 per year. In this number, factor 0.01 has been used to describe the probability of startup dilution via deaerator. Due to the truncation limit 1E−10, the calculated frequency would be slightly higher than by factor 100, namely 3.75E−10 / a, in case startup dilution were always performed via deaerator.

3.4 Results of probabilistic analysis

The overall frequency for external dilution scenarios with potential of a reactivity accident during normal reactor operating conditions was estimated to be 7.96E−5 per year by the present assumptions. Inclusion of the cutsets below the truncation limit would not have any contribution even to the last significant number of the calculated probability. The risk is dominated by few minimum cutsets, the elimination of which would drop the frequency drastically. It should be noted, that analyses of transport, mixing and consequences of diluted slug are expected to show many of the cutsets insignificant. In addition, further examination of plant characteristics and intended usage might remove many scenarios from the present model thus reducing the frequency.

The initiating event importance according to absolute and relative contribution of initiating events is presented below:

	Frequency	Contribution	
Explanation of initiating event	1 / year	1 / year	%
Natural circulation restarts, reactor open (event 1)	5.0E−3	3.25E−9	¯ 0
RHR system stops, cold state after refuelling (event 2)	2.9E−2	2.11E−8	¯ 0
Coolant replenishment before pressurization and RCP start (event 3)	1.0E−0	5.26E−7	0.7
Initial starting of 1st RCP after refuelling and maintenance (event 4)	1.0E−0	5.17E−5	65.3
Initial starting of startup dilution (event 5)	1.0E−0	2.74E−5	33.9
All RCPs fail to run during startup dilution (event 6)	1.5E−3	3.75E−10	¯ 0
		7.96E−5	100

It can be seen, that the contribution to the external boron dilution scenarios with potential to reactivity accident is almost completely caused by the initiating events of initial starting of first RCP after refuelling and maintenance (65 %) and initial starting of startup dilution (34 %), which are planned events occurring approximately once a year, and in which the actual reasons for the scenarios lie before the "initiating events".

Analysis of importance revealed that the events of coolant purification ion exchanger backwashing water, KBC12BB001 tank water or pure decontamination water entrance to core cover 99 % of the risk according to the present assumptions.

By eliminating these and some other main contributors by either physical bases or by administrational efforts, the frequency level of 1E-7 /a or lower could be achieved.

3.5 Recommendations for risk reduction

On the ground of the analysis performed, some recommendations have been presented in [1]. A few of them are briefly introduced here:

- It is recommended to evaluate, if coolant purification ion exchanger backwashing could be demanded as a prerequisite for starting boration for planned cooldown.
- Startup dilution should be performed by feeding the volume and boron control charging pumps directly from KBC11BB001 tank. Low capacity charging piston pumps are recommended to be used in the very beginning of the dilution.
- Possibility of separating the charging suction header line KBC10 from KBC12BB001 should be evaluated. Alternatively, boration of KBC12BB001 to safe concentration and boron concentration measurement to KBC10 line could be considered.
- Usage of pure water during decontamination or maintenance with potential to enter to primary circuit or associated systems should be avoided. When it is necessary to use pure water, amount of water should be controlled by appropriate means.
- Operation with two residual heat removal trains instead of one train is recommended even though it was not necessary for residual heat removal.
- Coolant storage system pumps should not be used for coolant replenishment after refuelling and maintenance. The replenishment should be done by volume and boron control pumps.

Significance of the a.m. recommendations should be evaluated separately taking into account the results of experimental and numerical studies of transport and mixing in the primary circuit together with the studies of core behaviour during injection of diluted slugs. These studies are likely to show many analyzed scenarios insignificant thus resulting in decline of the evaluated risk probability and in insignificance of some of the recommendations, too.

3.6 Conclusions on probabilislic analysis of external dilution scenarios

The analysis did not indicate any need for major modifications in the planned process systems or other technical arrangements of the plant concept. The plant design can, thus, be considered to be adequate as to the ability to prevent reactivity accidents due to external dilution scenarios, which is as expected.
Adequacy of operating manuals cannot be estimated for the time being, but the presented recommendations may be exploited when composing the manuals.

4 LOSS OF RESIDUAL HEAT REMOVAL WITH A REDUCED REACTOR COOLANT SYSTEM INVENTORY

At the planned shutdown of the reactor for refuelling and inspection of the equipment it is necessary to decrease the coolant level. In order to extract the RCP removable part for inspection and repair the level is reduced down to an elevation of the axis of the loop "cold" leg (the conditions are called "repair cooling-down"). The process of residual heat removal from the reactor is performed through the core by reverse flow, i.e. along the following circuit:

"cold" leg – RHR system heat exchanger and pump – connection pipe – l.p. safety injection system (pressure pipeline) – "hot" leg.

The causes leading to disturbances in operation of the RHR system are as follows:

- failures (damages) of pumps
- failures of the power supply system (normal and emergency)
- failures in the intermediate cooling circuit system
- failures of the service water system for safety–important consumers
- failures of I&C system
- failures of the ventilation system.

The qualitative reliability analysis has shown that the implementation of the RHR functions is carried out rather reliably.

On the base of estimates, made by the General Designer of the reactor plant – OKB "Gidropress" (Podolsk, Russia) in this case the operational personnel has enough time, till the moment of coming dangerous consequences, to take proper corrective measures. At water evaporation excessive pressure is not created in the reactor upper chamber until the steam generator warms up. The preliminary calculations have shown that the heat capacity of the reactor coolant system and SG water allows to accumulate the heat released from the reactor core during 1.5–2 hours depending on the SG initial temperature state.

The scheme process approaches permit to supply boron solution into the reactor either from the safety injection system or from the system of the primary circuit normal makeup.

Thus, it may be supposed that the complete loss of of the function of residual heat removal from the reactor with the reduced coolant inventory has a very small probability. However, taking into account the potential damage of the core under this event, it is reasonable to advice the following recommendations for consideration in design NPP–91 with WWER–1000/428:

1) To carry out the quantitative evaluation of reliable fulfilment of the RHR function

2) To specify the requirements to I&C design

3) To carry out the thermal-hydraulis analysis for proper interpretation of phenomena.

5 CONCLUSIONS

The substantiation of safety of the NPP with WWER-1000/428 requires more deep analysis of safety with the reactor shutdown.

At the present time Institute Atomenergoproekt (Saint Petersburg) and OKB Gidropress (Podolsk) began to perform systematical safety analyses for reactor of VVER-1000/428 type in regard to the reactor shutdown conditions aimed at obtaining the complete analytical results for further development of manuals and regulations for accidents of this type.

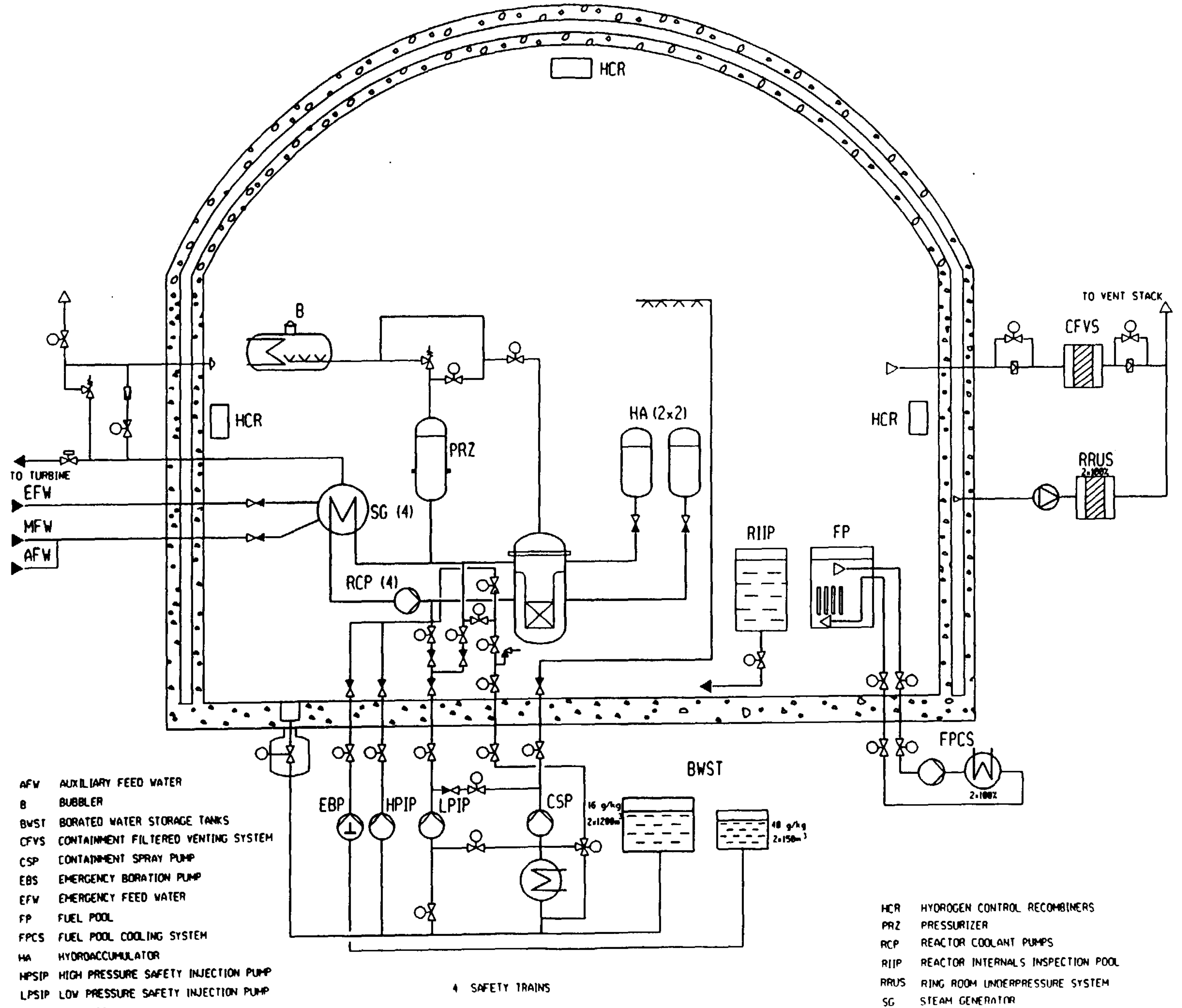
The presented results are a part of those investigations.

It should be pointed out, that the four-train structure of the safety systems has the evident advantage when substantiating the safety.

6 REFERENCES

[1] M. Kattainen, Probabilistic safety analysis of external boron dilution scenarios with potential of reactivity accident in .normal reactor operating conditions, Report CHINA-GP3-15.IVO International LTD, 16 December, 1994.

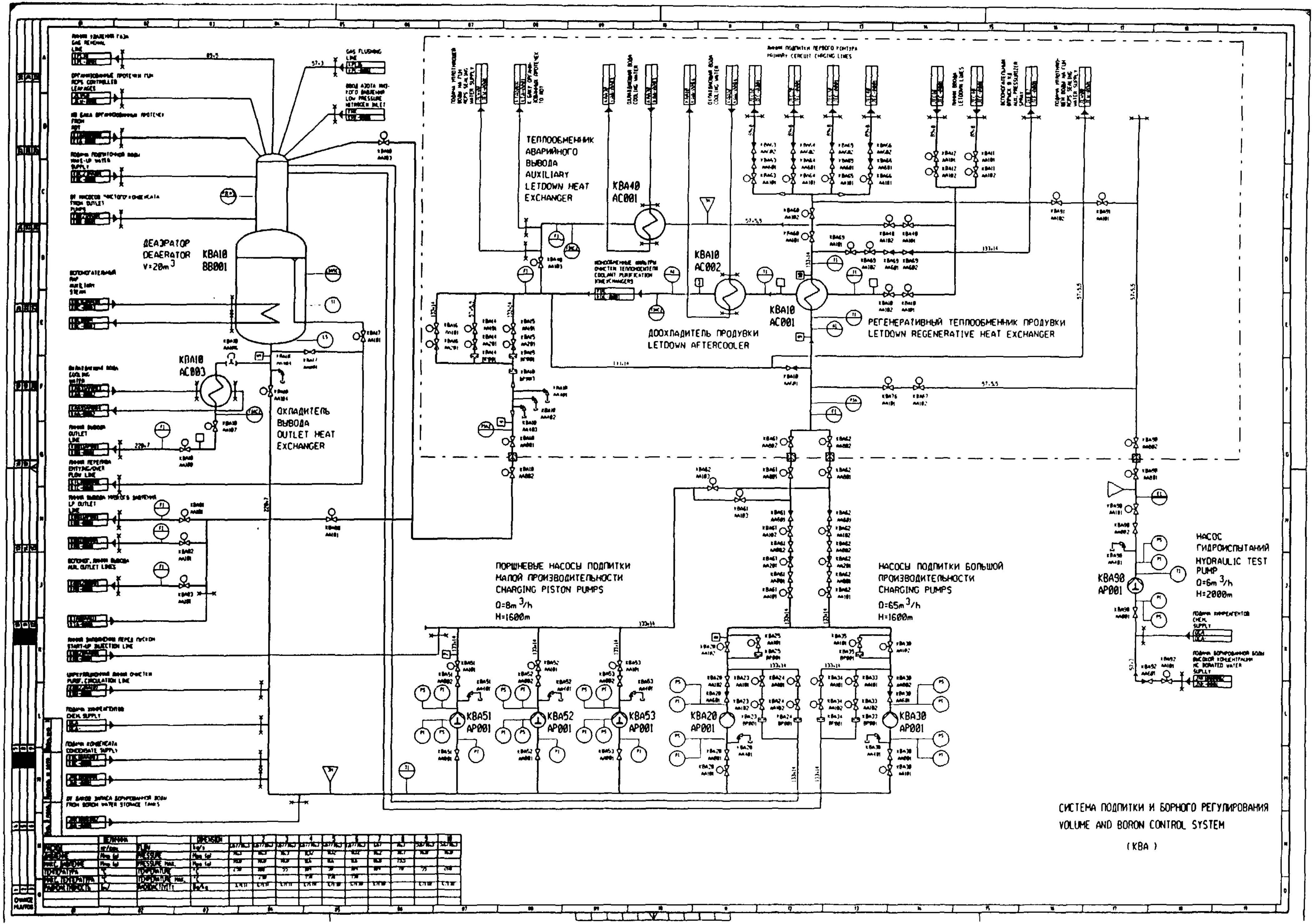
[2] A. Altshuller, Probabilistic safety analysis (Mini-PSA). VVER-1000F, Report F5-02-080-rev.1, Atomenergoproekt, 29 December, 1991.



AFW	AUXILIARY FEED WATER
B	BUBBLER
BWST	BORATED WATER STORAGE TANKS
CFVS	CONTAINMENT FILTERED VENTING SYSTEM
CSP	CONTAINMENT SPRAY PUMP
EBS	EMERGENCY BORATION PUMP
EFW	EMERGENCY FEED WATER
FP	FUEL POOL
FPCS	FUEL POOL COOLING SYSTEM
HA	HYDROACCUMULATOR
HPSIP	HIGH PRESSURE SAFETY INJECTION PUMP
LPSIP	LOW PRESSURE SAFETY INJECTION PUMP
MFW	MAIN FEED WATER

HCR	HYDROGEN CONTROL RECOMBINERS
PRZ	PRESSURIZER
RCP	REACTOR COOLANT PUMPS
RIIP	REACTOR INTERNALS INSPECTION POOL
RRUS	RING ROOM UNDERPRESSURE SYSTEM
SG	STEAM GENERATOR

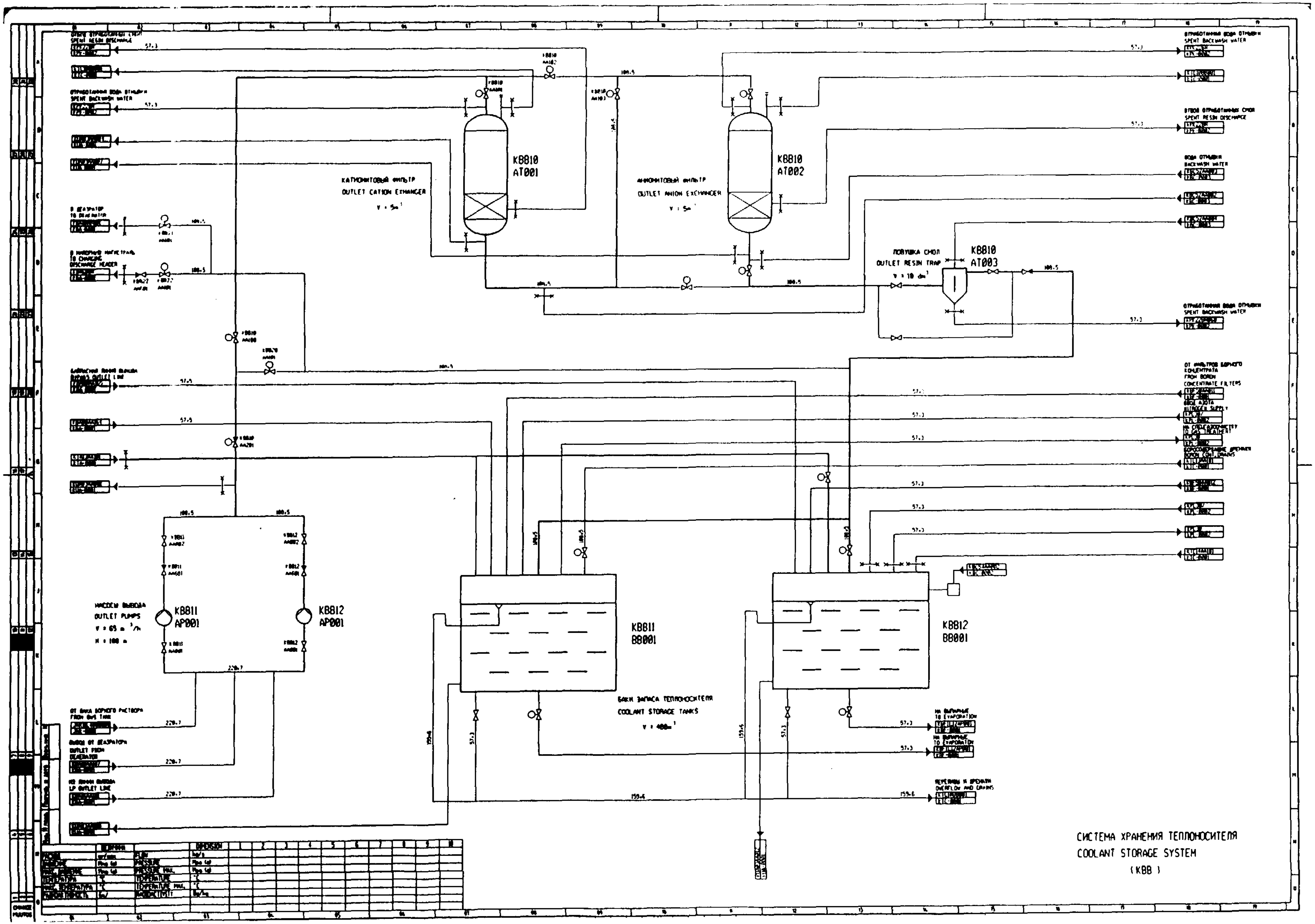
NPP-91 WITH VVER-1000/428



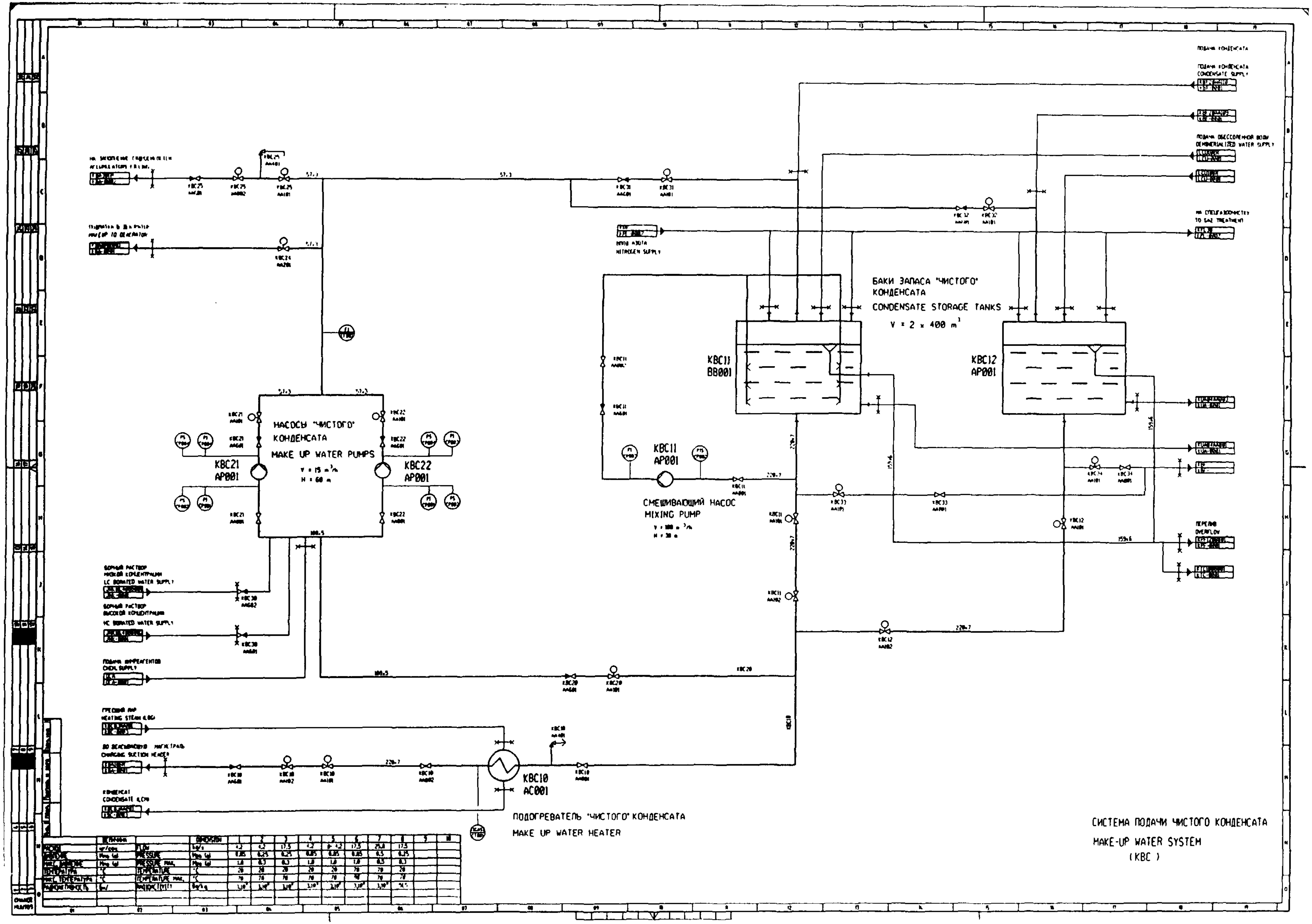
СИСТЕМА ПОДПИТКИ И БОРНОГО РЕГУЛИРОВАНИЯ

VOLUME AND BORON CONTROL SYSTEM

(KBA)



СИСТЕМА ХРАНЕНИЯ ТЕПЛОНОСИТЕЛЯ
COOLANT STORAGE SYSTEM
(KBB)

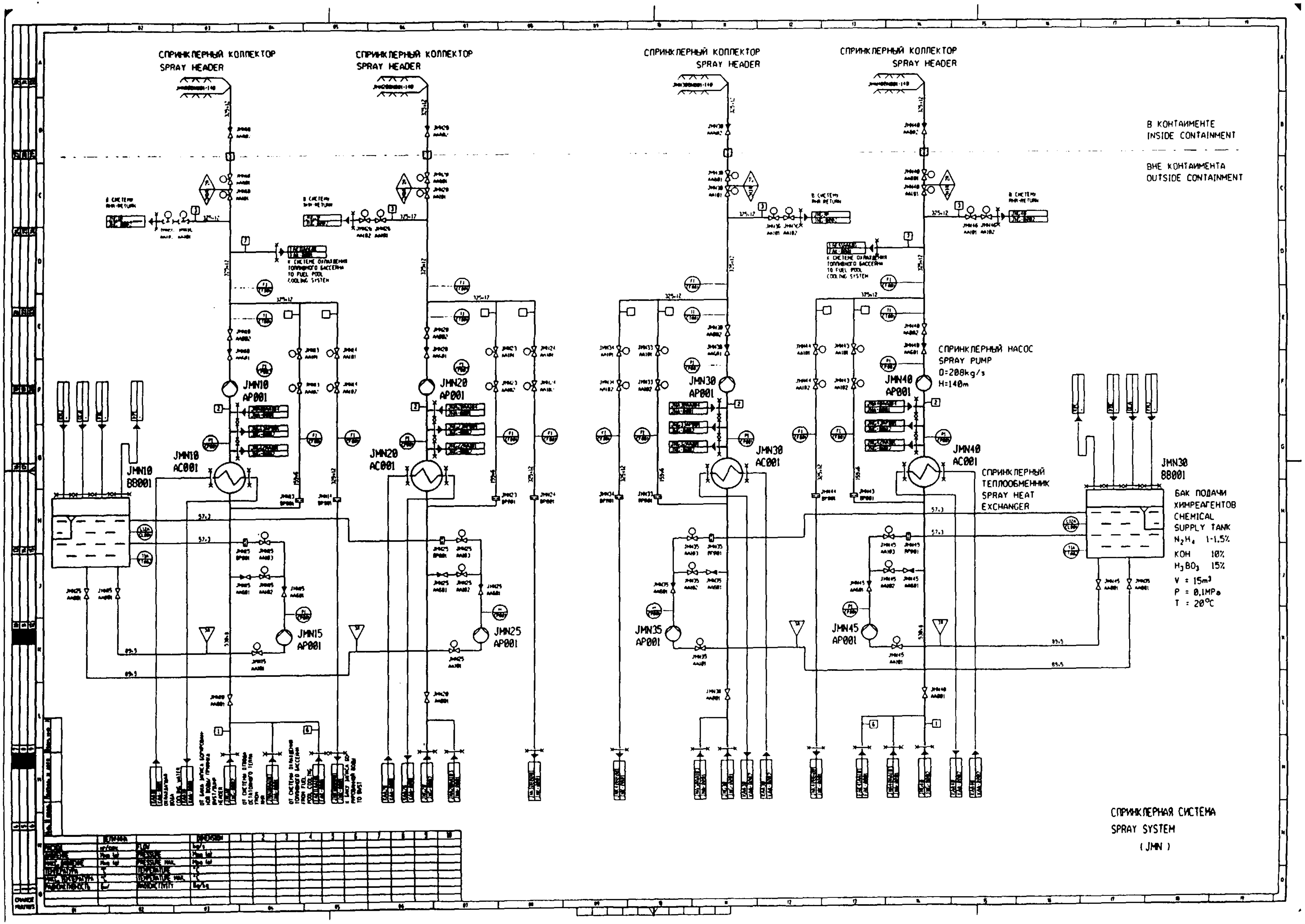


	ЕДИНИЦА		DIMENSION	1	2	3	4	5	6	7	8	9	10
РАСХОД	м³/час	FLOW	kg/s	4,2	4,2	17,5	4,2	0-4,2	17,5	25,0	17,5		
ДАВЛЕНИЕ	МПа (и)	PRESSURE	MPa (g)	0,85	0,25	0,25	0,85	0,85	0,85	0,5	0,25		
МАКС. ДАВЛЕНИЕ	МПа (и)	PRESSURE MAX.	MPa (g)	1,0	0,3	0,3	1,0	1,0	1,0	0,5	0,3		
ТЕМПЕРАТУРА	°C	TEMPERATURE	°C	20	20	20	20	20	70	70	20		
МАКС. ТЕМПЕРАТУРА	°C	TEMPERATURE MAX.	°C	70	70	70	70	70	90	70	70		
РАДИОАКТИВНОСТЬ	Бк/	RADIOACTIVITY	Bq/kg	3,10[illegible]	3,10[illegible]	3,10[illegible]	3,10[illegible]	3,10[illegible]	3,10[illegible]	3,10[illegible]	[illegible]		

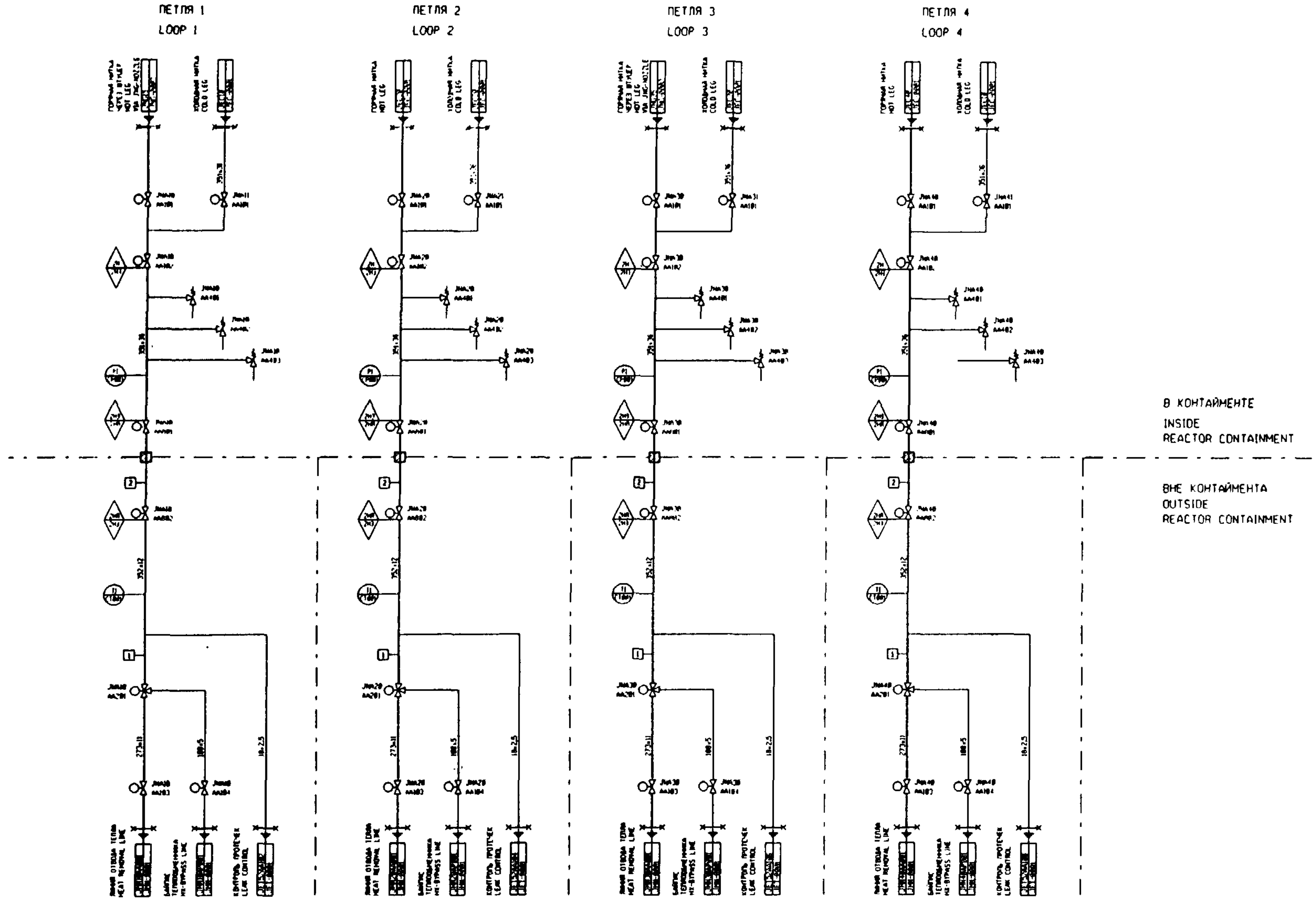
СИСТЕМА ПОДАЧИ ЧИСТОГО КОНДЕНСАТА

MAKE-UP WATER SYSTEM

(KBC)



СПРИНКЛЕРНАЯ СИСТЕМА
SPRAY SYSTEM
(JMN)



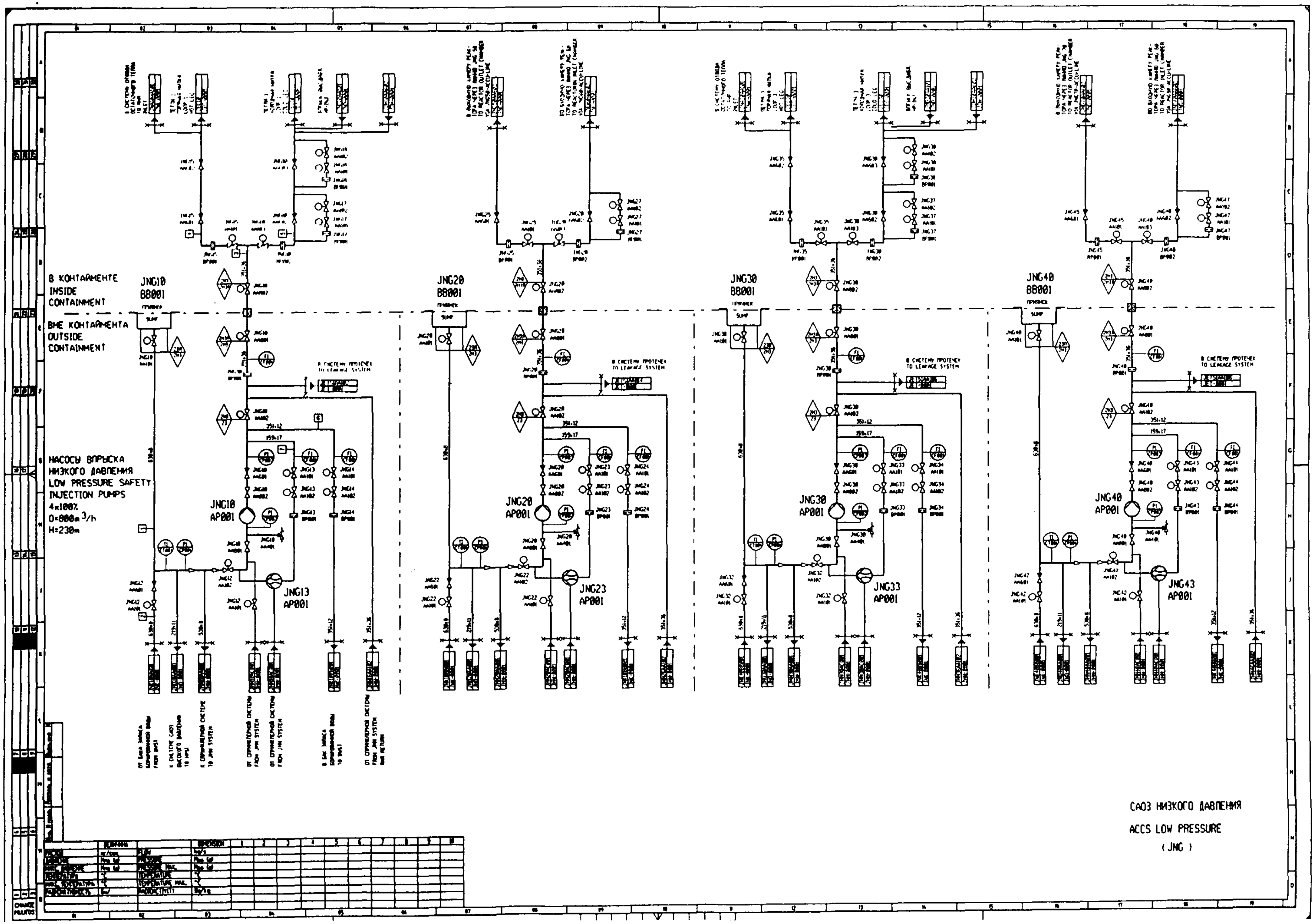
СИСТЕМА ОТВОДА ОСТАТОЧНОГО ТЕПЛА

RESIDUAL HEAT REMOVAL SYSTEM

(JNA)

	[illegible]		DIMENSION	1	2	3	4	5	6	7	8	9	10
РАСХОД	м³/час	FLOW	kg/s										
ДАВЛЕНИЕ	МПа (и)	PRESSURE	MPa (g)										
МАКС. ДАВЛЕНИЕ	МПа (и)	PRESSURE MAX.	MPa (g)										
ТЕМПЕРАТУРА	°C	TEMPERATURE	°C										
МАКС. ТЕМПЕРАТУРА	°C	TEMPERATURE MAX.	°C										
РАДИОАКТИВНОСТЬ	Бк/	RADIOACTIVITY	Bq/kg										

CHANGE NUMBERS



САОЗ НИЗКОГО ДАВЛЕНИЯ

ACCS LOW PRESSURE

(JNG)