Experiences with loss of natural circulation events, performed experiments, analysis, computations and development of operational documents.

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Abstract:

The refuelling of the unit 4 was started on 18. June, 1988.. At the time of the event the reactor was in cold shutdown state, with atmospheric pressure, the reactor head was removed. On. June 30 the operational personnel performed a planned switch over of natural circulation from loops 4., 6. to loops 1., 3.

In the meantime the effectiveness of the core cooling by natural circulation decreased sharply for about 3 hour-period. After switching over the natural circulation among the loops the operating personnel isolated the loops 4., 6. and started to drain them. Nitrogen used to drain the loops was unintentionally injected into the loops in operation and large amount of primary coolant was pushed out from the SG primary side to the reactor vessel.

The operators tried to stop the disturbance of natural circulation by starting the booster pump of make-up system periodically to the working loops. During this injection the personnel performed venting few times to take away the gas-air mixture from the top of the SG primary headers. After all the restoration of the natural circulation was achieved by continuous venting the SG headers.

During 1993 annual refuelling outage of Unit 2 at Paks NPP a deterioration of natural circulation in reactor coolant system occurred.

A special maintenance task was being performed to repair the cladding of the sealing bellows between the reactor vessel and reactor cavity. For this work the reactor was covered by the dummy cover, used during pressure tests, and pressurised by air for 50 mbar. During the cladding process the workers recognised a significant temperature increase of the surface of the sealing bellows and the reactor dummy cover. However, the control room instrumentation did not reflect any temperature changes. Later, when the cladding had been finished, the reactor was still closed but the pressure was already released, control room operators noticed the increase of reactor coolant temperature and temperature difference in loops and recognised the deterioration of natural circulation in reactor coolant system. The necessary actions required by the emergency procedures were taken and the natural circulation was restored. The deterioration of natural circulation was caused by uncontrolled decrease of. water level in reactor.

1. Degradation of the natural circulation of the Unit 4

1.1. Event description

The unit 4 of Paks NPP was in cold shutdown condition for refuelling. Reactor pressure vessel was depressurized, in cold condition with average coolant temperature $T_{avg.}$ of 42 °C, reactor cover was removed. Decay heat was being removed by two loops' (4. and 6.) natural circulation. Average differential temperature ΔT in the loops was 12 °C.

Sequence of events:

00:40	Operational personnel started a planned switch over the natural circulation from loops 4. and 6. to 1. and 3.
01:30	The switchover of the loops was performed, natural circulation started to develop in the newly operational loops. Then loop 4. and 6. were isolated by main gate valves (MGV)and started to drain.
01:45	To increase of the speed of draining of the loop 4, 6 the 5 bar's. nitrogen system was connected to the SG primary headers. At the same time the water level in the reactor pressure vessel increased quickly and bubbles appeared on the surface of water.
02:00	Nitrogen was disconnected and an attempt was made to tighten the main gate valves of loop 4., 6. Due to it was believed that the main gate valves had a leak through. Operational personnel performed the-venting of main steam headers. The ΔT continually decreased, T slowly increased.
02:35	The reactor water level was reduced to the original level by draining of loop 1, 3.
02:50	ΔT further decreased, for this reason the draining was stopped.
02.55	ΔT practically reached 0 °C. Loop 1 and 3 and steam generators were vented. According to this interaction the ΔT increased to the value of 5 °C but the natural circulation remained unstable.
03:05	Operators started the booster pump of make-up system periodically to improve the natural circulation effectiveness while the field operators performed periodical venting at the SG primary headers.
03:45	Personnel noticed the steaming on the water surface of the reactor in reactor hall.
04:00	Operators increased the flow rates of the coolant at secondary sides of the steam generators and of the component cooling water of the residual heat removal (RHR) heat exchangers.
04:55	The venting of the loops 1., 3. was resumed, and the valves were left in that position. ΔT began to increase.
05:10	The ΔT differential temperature in loops 1., 3. increased up to 39,5 °C and average coolant temperature increased up to 57 °C, then decreased.
05:45	The effective natural circulation gradually stabilised with differential temperature in the loops of 19 °C, average coolant temperature of 38 °C. The situation had been under control.

1.2. Safety assessment:

The main cause of the event was the mishandling of the venting valves by field operator during connection of the nitrogen to the loops. The nitrogen unintentionally was injected into the loops on natural circulation and the coolant was forced out of the SG primary headers, which is resulted in drying out of the heat transfer tubes of steam generators. Due to that the circulation was blocked.

Consequence of the event and influence to the safety:

- The recorded hot leg temperature in the loop 1 increased up to 88 °C and in the loop 3. up to 77 °C.
- Investigations and analysis (radiochemistry, reactorphysics) performed immediately after the events stated that the heat-up of reactor core did not mean any risk to the fuel assemblies. The follow-up analysis, made by KFKI (Central Research Institute of Physics) showed that the maximum fuel cladding temperature was 114,5 °C.

The evaluation of personnel activities

- Root cause of the event was the lack of the QA activities during operation with natural circulation. There were found several improper activities, such as: valve opening-closing without independent review, decision making based on the short term change of the parameters. Contrary to the often used manner of the natural circulation the related parts of the operation and safety instructions proved to be in poor quality.
- The operational personnel in the first time misunderstood the situation, did not realise that the cause of the problem could have been the presence of a nitrogen cushion in the upper region of operational loops (SG primary headers). Operators were misled by events because they believed the main gate valves of the loops 4., 6. had a leak through.
- After the incorrect evaluation of the event's nature wrong interventions had been made with starting to drain the loops in natural circulation followed by reduction of the reactor water level to the initial value. Hereby the natural circulation suffered a new disturbance.

The natural circulation was restored when the nitrogen cushion was blown out of SG primary headers.

1.3. Corrective Measures

- The influence to safety of the poor quality of operational activities: namely interactions without written authorisation and the lack of the independent review was stressed during the operational personnel retraining..
- The operational and emergency procedures had been verified and the inadequate parts completed and improved.
- A series of experiments were conducted to gain more detailed data on natural circulation behaviour under different disturbances.
- Analysis of available information on the similar events at other VVER plants was performed. Lessons learned from these events also was used to improve the quality of operational documents

2. *Degradation of natural circulation on Unit 2*

2.1. *Event description:*

Prior to the event Unit 2 of Paks NPP was shut down for annual maintenance and refuelling. The reactor was disassembled and reactor cooling was provided by natural circulation, maintained in the reactor coolant loops 1 and 5. Decay heat was being removed from primary circuits via steam generators secondary side by forced circulation.

On 12 September 1993 preparation of a special task, Ni-cladding of sealing bellows between the reactor vessel and the reactor cavity, was being performed upon an approved program. The reactor was filled up to 200 mm below the reactor flange level and the reactor dummy cover, used during pressure tests, was installed on the reactor. Beyond that, in order to prevent penetration of liquids used during maintenance into the reactor vessel, a small overpressure (50 mbar) was created by compressed air injection below the reactor dummy cover according to the repair programme.

On 14 September the workers performing the cladding recorded in their log the increase of metal temperature of the sealing bellows. At 10:00 the temperature was 31 °C, at 14:00 it was 38 °C and at 17:00 it was 42 °C according to the contact thermometer measurements. On 15 September the workers acting on the reactor experienced that the sole of their plastic protecting shoes had melted. This indicated a significant temperature increase of the reactor dummy cover and respectively the water in the reactor. Maintenance staff did not consult the anomaly with control room operators. No reactor coolant temperature change was noticed in control room at that time. At 19.30 the cladding work had been finished and the pressure release from reactor was started.

At 23.35 the instrumentation in control room reflected primary coolant temperature and temperature difference increase. The personnel conducted the necessary inspections: checking the venting of loops 1 and 5, the absence of nitrogen supply and the cooling from secondary side. No anomaly and no explanation for malfunction of the natural circulation was found. To restore natural circulation the reactor dummy cover had to be removed. In order to decrease the water level in reactor, which was above the flange level, operators opened the drains in loop 1. According to the requirements of emergency operating procedures after removing the reactor dummy cover personnel isolated and then reconnected the loops one by one. Finally the circulation in loops 1 and 5 was restored.

According to the temperature records the highest temperature reached during the event was 99 °C. It has to be noted, that the limited number of monitored parameters during refuelling outage caused difficulties for the personnel. The only parameters that could be monitored by the operators in the control room were the average coolant temperature and the temperature difference. The work of reactor water level sensors and the reactor pressure sensors was not reliable during the event.

2.2. *Safety assessment:*

The temperature limitation prescribed in Technical Specifications was exceeded. Reactor coolant temperature increased above 70 °C for a period of 1 h. According to the temperature measurements the violation occurred between 03:30 and 04:30 on 16 September, 1993. Relying upon the reports written by the personnel it seems that the violation lasted longer in reality, however the exact duration of it could not be defined due to lack of readings of the hot leg temperature values.

After the reactor dummy cover was removed steaming from the reactor was observed and γ - dose rate at upper level of spent fuel pool increased to threefold of the value before and reached 100-150 µGy/h. After 4 hours it dropped to 60-120 µGy/h. Increase of surface contamination in reactor hall and on reactor platform could not be observed. No rise of activity concentration in atmosphere of the reactor hall could be detected. Airborne radioactive emission of first twin units did not rise either. During the event no personal contamination and no overexposure occurred to personnel performing operation and maintenance activities in the reactor hall.

An analysis was conducted to determine if damage to the fuel occurred. Checking, performed after the event by Chemistry laboratory confirmed that no fuel damage occurred.

The information provided by instrumentation and measurements in course of event was very limited. It caused difficulties for personnel coping with the malfunction and made very difficult to analyse the event and find the causes afterwards. The ongoing modification activities and maintenance work during the outage put most of the measurement and data recorders out of service.

a. Temperature measurement:

   Only average coolant temperature which formed from reactor inlet and outlet temperature measurement (loop cold leg and hot leg) and the loop temperature difference were available for operators. Recording of these parameters was not permanent either. There is no permanent temperature measurement in the reactor at the core outlet when the reactor head is removed. When natural circulation is deteriorated, mean coolant temperature and temperature difference between cold and hot legs do not provide sufficient information about the temperature in the reactor core itself.

b. Water level measurement in the reactor:

   The design of reactor does not include instrumentation for water level measurement. For such purposes in shutdown conditions the sensing-lines of core pressure difference instrumentation are used. Unfortunately, because of the reactor construction characteristics and unreliable performance of instruments conflicting water level values were measured during the event, especially at closed and pressurised reactor. Therefore those readings could not be given much credit during event analysis.

c. Pressure measurement under reactor cover

   Reviewing the available pressure readings the measurement did not seem reliable during the event.

   Inspection of the reducer-manometer device used for pressurising the reactor revealed a significant defect. The reducer-manometer during the inspection performed in laboratory indicated 80 mbar while real pressure was 15 mbar. According to the report of the foreman performing the pressurisation before cladding the manometer indicated 60 mbar while there was atmospheric pressure. This coincided with the laboratory test.

Information available for personnel during the event and afterwards, during the investigation, was not comprehensive enough to make firm conclusions. To collect more information for event analysis a special program, "Disturbance of Natural Circulation", was developed and carried out. It was performed after refuelling, during the decontamination of spent fuel pool, when the conditions were similar to those existing during the event, but differed in the following:

a) During the event natural circulation was maintained in two loops but the experiment provided circulation only in one loop, the other loops were in standby condition.

b) The experiment lasted for 16 hours, while repair of the sealing bellows was conducted during 3 days.

c) Decay heat rate during the experiment corresponded to half of the heat power produced during the event.

After evaluation of the performed program the following conclusions could be drawn:

- Pressurisation and depressurization of the reactor (in the course of experiment) was a much faster process than it was during repair of sealing bellows. Prior to the event it took 45 minutes for the prescribed pressure to develop, while during the experiment it took only a few minutes.

- During the program a pressure increase under the reactor dummy cover occurred. It could be caused only by the leakage of pressurised air into the reactor through the reducer-manometer device.

- Natural circulation seemed to be a rather stable process. It compensated minor disturbances smoothly. Injection of cold water into the hot leg of the loop with natural circulation did not affect the circulation significantly. Circulation was not deteriorated by connecting the draining systems of cold and hot leg of the loop either.

- Considering the experiment and event conditions, loss of the natural circulation can be explained only by decrease of water level in the reactor below the hot nozzle level.

Since the cause of the event could not be firmly identified during the investigation on site, Paks NPP applied to the Central Research Institute for Physics (KFKI) in Budapest for analysis of the event. Beyond the analysis of reports and records available at the site, experiments were performed on the Integral Test Facility for VVER 440/213 Safety Studies (PMK-2) at the institute. The objective of the experiments was to simulate the event and to carry out a wider analysis of natural circulation mode.

2.3. Event cause, corrective actions:

Based on the facts discovered during the investigation and the results of the analysis carried out by KFKI the following conclusions were made. The deterioration of natural circulation was caused by uncontrolled decrease of water level in reactor. The possible contributors to the low level in reactor are listed below:

- pressurisation under the reactor dummy cover having unreliable instrumentation (pressure and level measurement problems, leaking reducer-manometer device)

- leakage of coolant from reactor to the isolated loops
- drainage of reactor before removal of dummy cover supposing high level in the reactor

However none of the above listed assumption could be confirmed by the investigation or analysis due to lack of adequate information.

The investigation could not find the explanation for the reported rapid temperature increase of the sealing bellows and the reactor dummy cover during the cladding process.

Analysing the activities performed by maintenance personnel, the fact should be considered that the repair program did not include the necessary instructions for elimination of a possible anomaly. For operational personnel the clear understanding of the event was hindered by insufficient and unconfirmed information available on instruments in unit control room.

To prevent the recurrence of similar events during natural circulation mode the investigation team proposed the following corrective actions

- The decontamination of refuelling pond and pressurisation under reactor head prescribed in the technology of the silfon repair and cladding will not be allowed to be performed in the future. Possible actions for compensating this have to be defined, elaborated and approved by the Nuclear Safety Inspectorate.
- The possible improvement of the reactor level instruments reliability have to be examined.
- The possible introduction of temperature measurement of the upper plenum at sealed reactor has to be examined .
- List of parameters required for natural circulation mode has to be set up and they should be incorporated into the related operating procedures.
- It has to be examined whether spare thermocouples of the loop could be used for measuring temperature in narrow range.

3. *Experimental programs for filling in the gaps in knowledge revealed during natural circulation incidents as well as their scope, results and consequences*

In the nuclear power plant the mathematical modelling of the natural circulation processes was commenced already in 1985. A simplified model was elaborated which certain processes could be simulated with.

In order to realise the six-loop simulation the model was improved by building in of a mixing model.

The 1988's cause of the natural circulation incident was identified by the personnel as late as 3.5 hours after beginning of the event. It can be said that the procedural deficiencies and the gaps in the personnel's knowledge were important contributors of the emergency situation.

Following the incident, in order to become acquainted with the natural circulation processes experiments were conducted the experience of which was included in the emergency operating procedure. It became clear however, that in shutdown state of the reactor only a low number of measuring systems are in operation and so the incidents can't be identified. Therefore the computer simulation of the processes is essential for exact knowledge of them.

The 1993's supposed cause of the natural circulation incident was the pressure created under the provisional reactor head without control led to decreasing of the water level fall below the hot leg nozzles. An experimental program was prepared for reveal of the incident causes. In the course of the program the incident cause couldn't be established.

After investigation of the incident the Nuclear Power Research Institute of the Central Research Institute for Physics (KFKI AEKI) conducted physical model experiments in order to acquire knowledge about the natural circulation disturbances and to reveal the cause of the incident. The experience of the experiments was summed up in a research report.

It was established that the code RELAP is suitable for mathematical modelling of the natural circulation incidents only to a limited extent.

Simultaneously the improvement of the mathematical model created in the plant before was given priority. As a result of the development the code CRUISE was elaborated which is fully suitable for dynamic simulation of the one-phase, six-loop natural circulation processes. By applying this model any feasible activity characteristically of a given operating mode can be simulated as well as transients (change of loops, loss of cooling, level falls etc.) can be followed. In March 1994, for validation of the model experiments were conducted in unit 4.

3.1. Results of the experiment performed after the natural circulation incident on 30 June 1988:

Aim of the experiment:

To acquire knowledge about how the changes occurring at natural circulation, with depressurized and open reactor drained under the flange affect the parameters shown by the primary circuit measurements as well as what the indications are from which the operator can conclude abnormalities in the circulation.

Method of the experiment.

Creating of transients on the reactor by affecting the flowrate in the primary circuit and the cooling system:

- closing of the hot leg main gate valve on one of the two operating loops,
- simultaneous termination of the secondary side circulation on two operating loops,
- increase of the secondary side cooling water flowrate (taking of the standby cooling pump into operation).

Performance of the above activities in three different process conditions:

- water level in the reactor: flange-200 mm, SG headers vented, water level in the headers and in the reactor is the same,
- water level in the reactor: flange-1050 mm, SG headers vented, water level in the headers and in the reactor is the same,
- water level in the reactor: flange-200 mm, primary SG headers of one loop filled up fully and vented (in this SG the water level is higher than in the reactor).

Experience:

- In the course of performance of the experiment it became clear that the personnel doesn't know what reactor level is required in the SGs if the reactor is drained under the flange (should it be filled up fully or should it be equalised with the reactor level).There is no clear description about what in this case by venting of the SG is meant. (Later on it was proved that for maintaining of the natural circulation one part of the SG cooling surface is sufficient, at the reactor drained under the flange it is safer to maintain a SG water level equalised with the reactor).

— The third operating condition couldn't be created during the experiment since the filling up of the SGs would have required closing of the main gate valves on the given loop however, the main gate valves couldn't be operated during the measurement.

— The loop thermometers showed significant calibration deficiency in the given temperature range (This has been solved since then.)

— The system participating in the natural circulation gives a relative prompt response on the different interventions however, the temperature changes are slow..

— At suspension of the circulation the temperatures on the section not isolated by the suspension don't change while on the isolated section there is a severe cooling.

— The observation of ΔT and the average temperature during the transient gives no clear information. The cold leg and hot leg temperatures are to be followed separately. --

— If at operation with two loops the value of the ΔT held stable has changed by more than 25 %, it always indicates a severe disturbance of the natural circulation. (For example the loss of circulation on one loop.)

— According to measurement of the wall temperature of the provisional loop no stratified flow can be supposed.

3.2. *Results of the experiment performed after the natural circulation incident on 15 September 1993:*

Aim of the experiment:

Reveal of the conditions which have led to disturbance of the natural circulation during the silfon nickel plating.

Method of the experiment.

Pressure test head on the reactor, water level in the reactor flange-380 mm, loop 2 in natural circulation, loop 4 in standby operation. Interventions performed during the program:

— Pressurisation of the space under the pressure test head, data collection at 20, 50 and 70 mbar.

— Increase of water level in the reactor by 200 mm, the coolant is to be injected through the pressurizer.

— Restoring of the reactor water level to the initial value.

— Opening of the drain lines of the loops participating in the circulation, draining for 4 hours.

— Injection of water into hot leg of the operating loop for 30 minutes.

— Release of pressure under the pressure test head.

On basis of the experimental results the cause of the incident occurring during the silfon nickel plating couldn't be established.

3.3. *Results of the experiment performed by KFKI-AEKI on the physical model PMK after the natural circulation incident on 15 September 1993:*

Aim of the experiment:

Investigation of the scope of interventions causing the disturbance of natural circulation. Investigation of the incident occurring during the silfon nickel plating. Presentation of suggestions for provisional change of the operating procedures, drawing of consequences. Investigation of the suitability of the code RELAP for modelling of natural circulation incidents. .

Scope of the experiment.

During the model experiments every incident is to be continued until the boiling of water.

- Reconstruction of the plant incident.
- Injection of cold water into the hot leg at different flowrates.
- Injection of gas into upper part of the reactor.
- Injection of gas into the SG headers.
- Closing of main gate valve in the cold leg.

Experience:

Reconstruction of the incident:

It can be supposed that the incident was caused by uncontrolled injection of gas and as a consequence of this by decrease of the water level in the reactor vessel. The water level may have been reduced to such an extent that the water level fell below the hot leg nozzle. Based on the experiment results it can be established as follows:

- natural circulation stops only in the case when the coolant level falls below the hot leg nozzle,
- the gas doesn't reach the SG headers,
- there is volumetric boiling in the reactor for long time however, the loop temperatures don't change and therefore the operating personnel doesn't notice the incident,
- after the gas isolation the circulation starts.

General conclusions on basis of the performed measurements:

- In the case of the pressure test head put on the reliable measurement of the pressure of gas (with two calibrated manometers) injected into the upper plenum is a basic requirement. Prior to the injection of gas the condition of the vent lines of the system is to be known. (The pressurisation of the reactor closed with a provisional head is an forbidden activity since the incident.)

  The reliable measurement of the reactor water level at closed reactor vessel is a basic requirement, the measurement of the water level is to be ensured by a technical solution.
- The coolant temperature in the upper plenum is to be known as the loop temperatures aren't suitable for detection of suspension of the natural circulation.
- The uncontrolled ingress of gas into the SG headers is to be prevented by a technical solution. (Made.)

It was established that the code RELAP is suitable for modelling of the natural circulation incidents only to a limited extent.

3.4. *Experiment results required for validation of mathematical model of the natural circulation* (21-23 March 1994):

Aim of the experiment:

Determination of thermohydraulic parameters of the mathematical model to be established for investigation of the natural circulation, investigation of characteristics of the natural circulation operating mode.

Scope of the experiment:

Creating of transients on the reactor:

- closing of the hot leg main gate valve on one of the two operating loops,
- increase of the secondary side cooling water flowrate,
- restoration of the secondary side cooling water flowrate,
- partial opening of the hot leg main gate valve of the isolated loop,
- restoration of the two-loop circulation

The operations listed above were performed at a refuelling water level of flange-200 mm.

Experience:

- In the course of the experiment the hot leg temperature of the loop isolated from the natural circulation decreased under that of the cold leg. Despite that, after partial opening of the main gate valve the circulation started not in the opposite direction. This is possible because the pressure difference required for circulation is determined by density of the hot leg hot water in the reactor and by density of the colder water in the hot leg loop above that as well as by density of the cold leg water which is hotter than that of the hot leg. Since in the hot leg loop the distribution of the water column heights required for the pressure difference shows that there is hot water in the main part of it (in the reactor), the average water density in the hot leg will be below that of the cold leg and as a consequence of this the circulation can start only in the normal direction.
- In both experiments it could be seen that after reopening of the hot leg main gate valve to 200 turns a steady circulation is established also in these loops. The flowrate is in this case a little lower than at fully opened main gate valve but it can be explained by the fact that the discharge area of the main gate valve reopened to 200 turns is only a portion of that of the fully opened valve.
- The series of experiments had to be repeated at refuelling water level because during performance of the program other activities beyond the program caused disturbance of the natural circulation. About the first, unsuccessful performance of this series of measurements it can be said as follows:

The disturbance of the natural circulation was caused not by closing of one of the main gate valves as in the repeated experiment no occurrences similar to those in the first one could be noticed.

Since in the unit two interventions were performed simultaneously (closing of the main gate valve and lifting out of the sluice gate between the spent fuel pool and the refuelling pool), it can't be decided whether the disturbance of natural circulation was caused by simultaneous effect of these or by lifting out of the sluice gate. The lifting out of the sluice gate may be taken into consideration because the spent fuel pool had been filled up to the refuelling water level earlier, the steady temperature conditions had been already established and these were certainly not the same as at opened sluice gate. Furthermore, the mixing processes after the lifting out aren't known. The closing of the main gate valve on one of the loops opposite to each other led also to distortion of the core cooling symmetry therefore it may be supposed that both interventions contributed to the disturbance simultaneously.

Based on the facts described above it isn't suggested that in the unit operating in natural circulation mode more than one activities affecting the circulation are performed simultaneously. For ensuring the symmetrical cooling of the core it is advisable to maintain the natural circulation on two loops being opposite to each other in every case.

Since the loop temperature measurements don't supply satisfactory information about the existence of the natural circulation, during performance of the experiment, based on the measurements of Δt and prior to acquiring knowledge of the emerging processes the series of measurements had to be stopped. It is essential to implement measurements which give exact information about the existence of the circulation and the safe cooling.

4. Optimised emergency operating procedure for managing the disturbances of the natural circulation

4.1. Required scope of the emergency operating procedure:

In case of a disturbance of the natural circulation one chapter of the emergency operating procedure is to be applied. The chapter "Loss of the natural circulation during residual heat removal from the core of the procedure gives the operating personnel instructions to reveal and eliminate the causes.

The emergency operating procedure is aimed to be of aid for the operating personnel in revealing the causes of the incidents and to offer proposals for elimination methods of these with possible consideration of all the circumstances which may affect the occurrence and sequence of the incident.

On basis of that, for managing of a given accident the emergency operating procedure should consider following factors:

1. Possible causes of the disturbance of the natural circulation
    - Reactor level fall below the hot leg nozzles,
    - Level fall in the steam generator's primary headers,
    - Closing of the hot leg main gate valve,
    - Closing of the hot leg main gate valve,
    - Closing of the cold leg main gate valve
    - Closing of both main gate valves,
    - Deterioration of the secondary cooling.
2. According to the Reactor Operating Procedure the following natural circulation operating modes are possible:
    - natural circulation on two loops
    - natural circulation on one loop

- change of loops in the case of a natural circulation on two loops
- change of loops in the case of a natural circulation on one loop

In the present emergency operating procedure there is no differentiation of the disturbances occurring during the different modes of operation however, the incidents can be identified on basis of the parameters measured, the way of reveal and elimination of the causes differ in every operating mode.

3. Based on the paragraph above, the parameter changes occurring during the different operating modes have to be evaluated in the case of every circulation disturbance separately. For example:

   - decrease or loss of circulation on one of two operating loops,
   - decrease or loss of circulation on two of two operating loops,
   - decrease or loss of circulation in the case of one operating loop.

   In the situations not mentioned there are conditions which are similar to those listed above.

4. In the present emergency operating procedure the note "validate by measuring" is included in several paragraphs what indicates that at time of elaboration of this procedure there were still indefinite parts.

5. Based on this consideration the paragraph describing the personnel's activity in the situations listed above is to be revised as well.

6. The loop change activities dealt with in the reactor operating procedure are to be investigated with consideration of the experience gained during the circulation measurements and the different incidents as well.

4.2. Necessity of optimised algorithm of the emergency operation:

On basis of the operating experience and the experience gained so far during the incidents at natural circulation as well as the physical experiments conducted on model PMK of the Central Research Institute for Physics (KFKI) and on units of the Paks NPP and further on based on the mathematical model experiments with code Cruise the algorithm of the emergency operating procedure can be elaborated.

The optimised algorithm is given both in text and in the form of flow diagram. The personnel acting according to the algorithm is certain to make all the required decisions and at the same time excludes all the activities which aren't inevitably required for the urgent emergency operation. This way the algorithm not only directs and facilitates the decision-making but for reducing the time required for emergency operation optimises the number and sequence of activities to be performed to some extent.

On basis of the conducted mathematical model experiments it can be established that because of large number of the emergency situations at natural circulation and the limited number of real measurements performed that time, in most cases the cause of disturbance can't be identified based on the unit parameters.

After identification of the abnormal situation, the personnel establishes the cause of natural circulation disturbance - in contrary to the previous practice - not on the basis of the parameter changes. At important points of divergence of the algorithm the operator takes a decision on basis of the condition of the process systems and equipment and in most cases based on the report of the shift operator sent to the place. (For example, the following parameters characteristic of the equipment condition serve as basis of the decisions: pump in operation / out of operation, valve closed / not closed./

Anticipated changes of the parameters established on basis of the experiment and calculation results are given in the algorithm, on the line of the cause inducing incidents (only) for information. The required actions to be performed in order to eliminate the cause are listed for every case. The process trend is reviewed on basis of the most important temperature measurements. The flow diagram can't be escaped from until all of the causes are eliminated. In the case when more than one causes of the circulation disturbance have been identified, the personnel can localise every of them on basis of the flow diagram.

5. Current situation:

In order to gain more complete information during operation in future it was examined, if it was possible to improve RPV level measurement reliability and introduce temperature measurement in the upper plenum at sealed reactor. Different technical solutions were reviewed, however the reactor equipment design did not allow any of them to be installed. Therefore the possibility of some administrative measures was reviewed. In 1994 two other VVER units had similar problems with natural circulation and in both cases one of the contributors was the pressurised air or nitrogen under reactor head or in the steam generators. The Safety Committee of Paks NPP has recently decided to prohibit using pressurised gases (nitrogen or air) when the primary coolant pressure is less then 10 bar.

A list of parameters required to be continuously monitored and recorded during natural circulation mode was set up and incorporated into the related operating procedures.

During event analysis a new mathematical model of natural circulation on VVER-440 reactors was developed. Using the computer code the event was modelled. Using this tool a new - similar to those symptom oriented - emergency procedure has been developed to handle the events during natural circulation. The emergency procedure is in the phase of validation and verification now.

References: **István Lenkei:** Degradation of the natural circulation of the Unit 4 at the Paks NPP (IAEA IRS report)

István Szabó: Loss of natural circulation in reactor coolant system (WANO EAR report)

Operational personnel activities in case of natural circulation deterioration

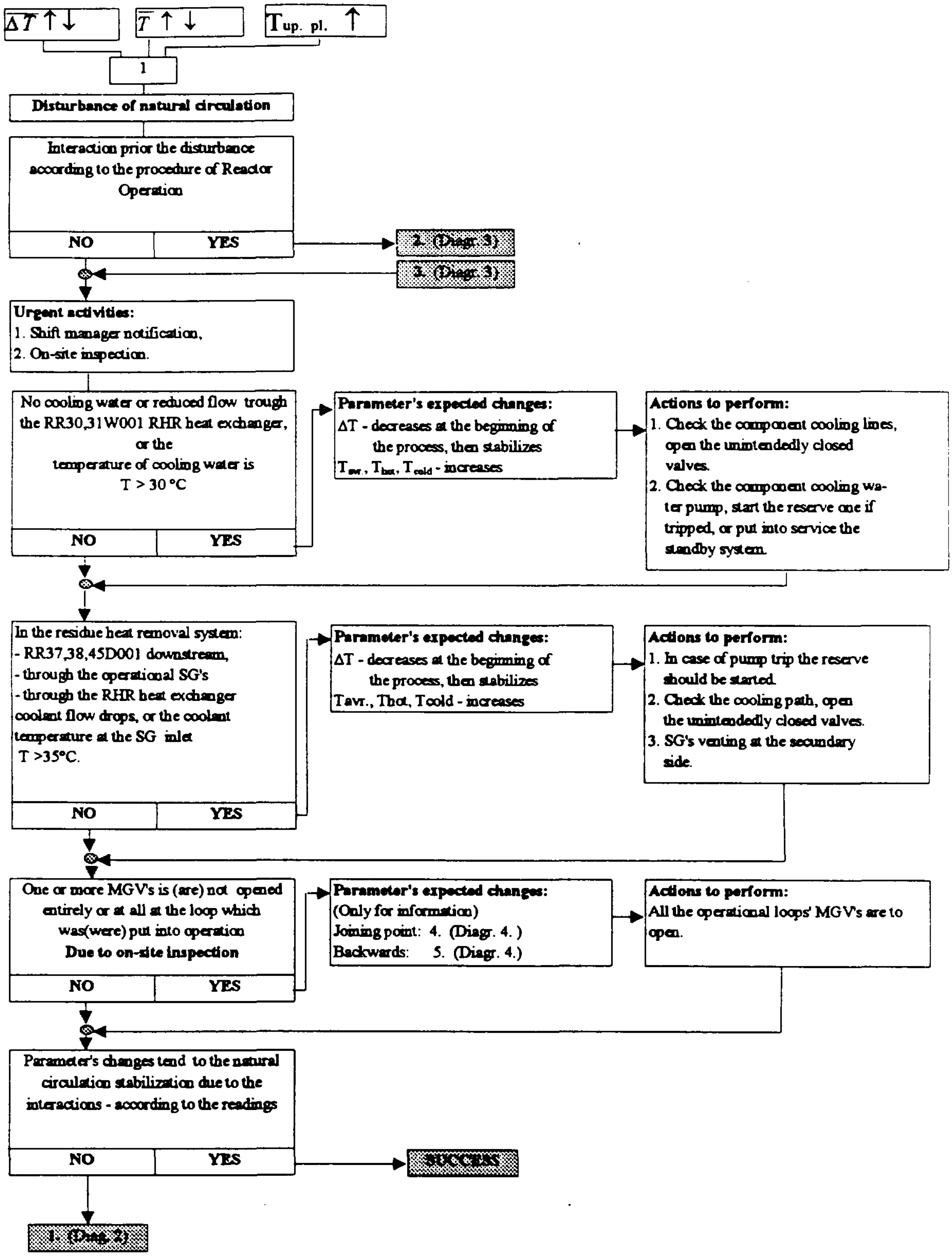
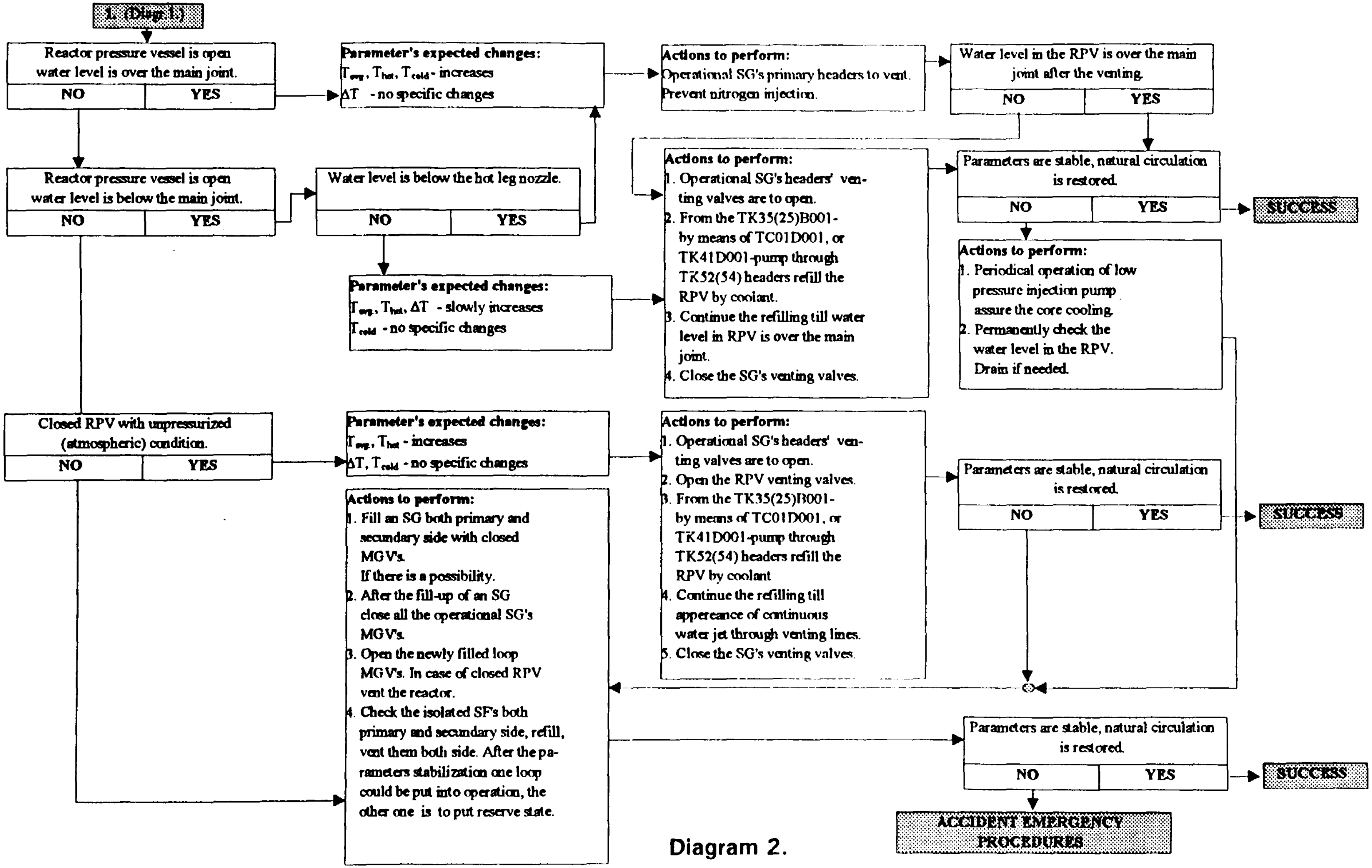


Diagram 1.



1. (Diag 1.)
Reactor pressure vessel is open water level is over the main joint.
NO
YES
Parameter's expected changes:
Tavg, Thot, Tcold - increases
ΔT - no specific changes
Actions to perform:
Operational SG's primary headers to vent.
Prevent nitrogen injection.
Water level in the RPV is over the main joint after the venting.
NO
YES
Reactor pressure vessel is open water level is below the main joint.
NO
YES
Water level is below the hot leg nozzle.
NO
YES
Parameter's expected changes:
Tavg, Thot, ΔT - slowly increases
Tcold - no specific changes
Actions to perform:
1. Operational SG's headers' venting valves are to open.
2. From the TK35(25)B001- by means of TC01D001, or TK41D001-pump through TK52(54) headers refill the RPV by coolant.
3. Continue the refilling till water level in RPV is over the main joint.
4. Close the SG's venting valves.
Parameters are stable, natural circulation is restored.
NO
YES
SUCCESS
Actions to perform:
1. Periodical operation of low pressure injection pump assure the core cooling.
2. Permanently check the water level in the RPV. Drain if needed.
Closed RPV with unpressurized (atmospheric) condition.
NO
YES
Parameter's expected changes:
Tavg, Thot - increases
ΔT, Tcold - no specific changes
Actions to perform:
1. Operational SG's headers' venting valves are to open.
2. Open the RPV venting valves.
3. From the TK35(25)B001- by means of TC01D001, or TK41D001-pump through TK52(54) headers refill the RPV by coolant
4. Continue the refilling till apperеance of continuous water jet through venting lines.
5. Close the SG's venting valves.
Parameters are stable, natural circulation is restored.
NO
YES
SUCCESS
Actions to perform:
1. Fill an SG both primary and secundary side with closed MGV's. If there is a possibility.
2. After the fill-up of an SG close all the operational SG's MGV's.
3. Open the newly filled loop MGV's. In case of closed RPV vent the reactor.
4. Check the isolated SF's both primary and secundary side, refill, vent them both side. After the parameters stabilization one loop could be put into operation, the other one is to put reserve state.
Parameters are stable, natural circulation is restored.
NO
YES
SUCCESS
ACCIDENT EMERGENCY PROCEDURES

Diagram 2.

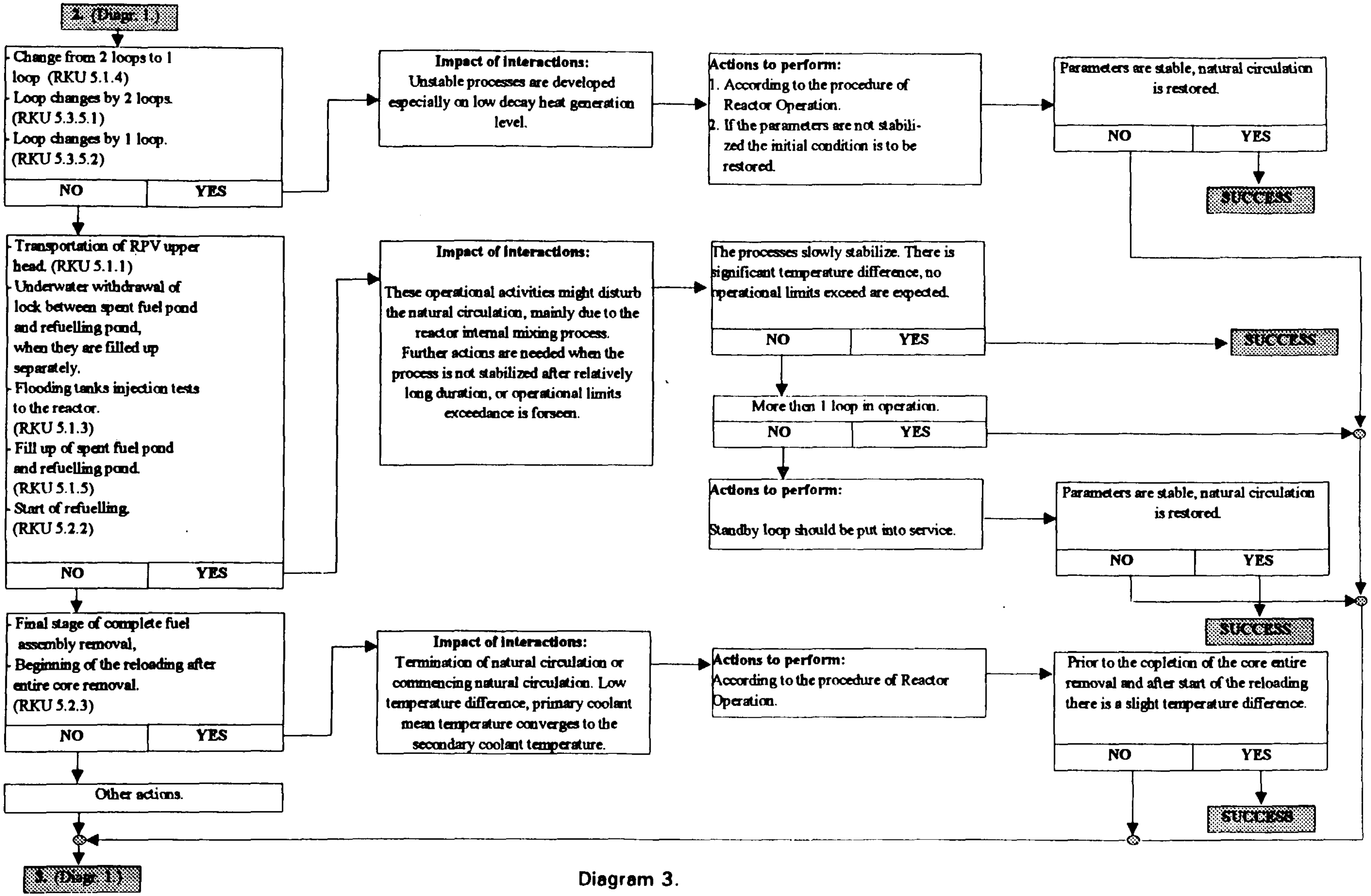

2. (Diagr. 1.)
- Change from 2 loops to 1 loop (RKU 5.1.4)
- Loop changes by 2 loops. (RKU 5.3.5.1)
- Loop changes by 1 loop. (RKU 5.3.5.2)
NO
YES
Impact of interactions:
Unstable processes are developed especially on low decay heat generation level.
Actions to perform:
1. According to the procedure of Reactor Operation.
2. If the parameters are not stabilized the initial condition is to be restored.
Parameters are stable, natural circulation is restored.
NO
YES
SUCCESS
- Transportation of RPV upper head. (RKU 5.1.1)
- Underwater withdrawal of lock between spent fuel pond and refuelling pond, when they are filled up separately.
- Flooding tanks injection tests to the reactor. (RKU 5.1.3)
- Fill up of spent fuel pond and refuelling pond. (RKU 5.1.5)
- Start of refuelling. (RKU 5.2.2)
NO
YES
Impact of interactions:
These operational activities might disturb the natural circulation, mainly due to the reactor internal mixing process. Further actions are needed when the process is not stabilized after relatively long duration, or operational limits exceedance is forseen.
The processes slowly stabilize. There is significant temperature difference, no operational limits exceed are expected.
NO
YES
SUCCESS
More then 1 loop in operation.
NO
YES
Actions to perform:
Standby loop should be put into service.
Parameters are stable, natural circulation is restored.
NO
YES
SUCCESS
- Final stage of complete fuel assembly removal,
- Beginning of the reloading after entire core removal. (RKU 5.2.3)
NO
YES
Impact of interactions:
Termination of natural circulation or commencing natural circulation. Low temperature difference, primary coolant mean temperature converges to the secondary coolant temperature.
Actions to perform:
According to the procedure of Reactor Operation.
Prior to the copletion of the core entire removal and after start of the reloading there is a slight temperature difference.
NO
YES
SUCCESS
Other actions.
3. (Diagr. 1.)

Diagram 3.

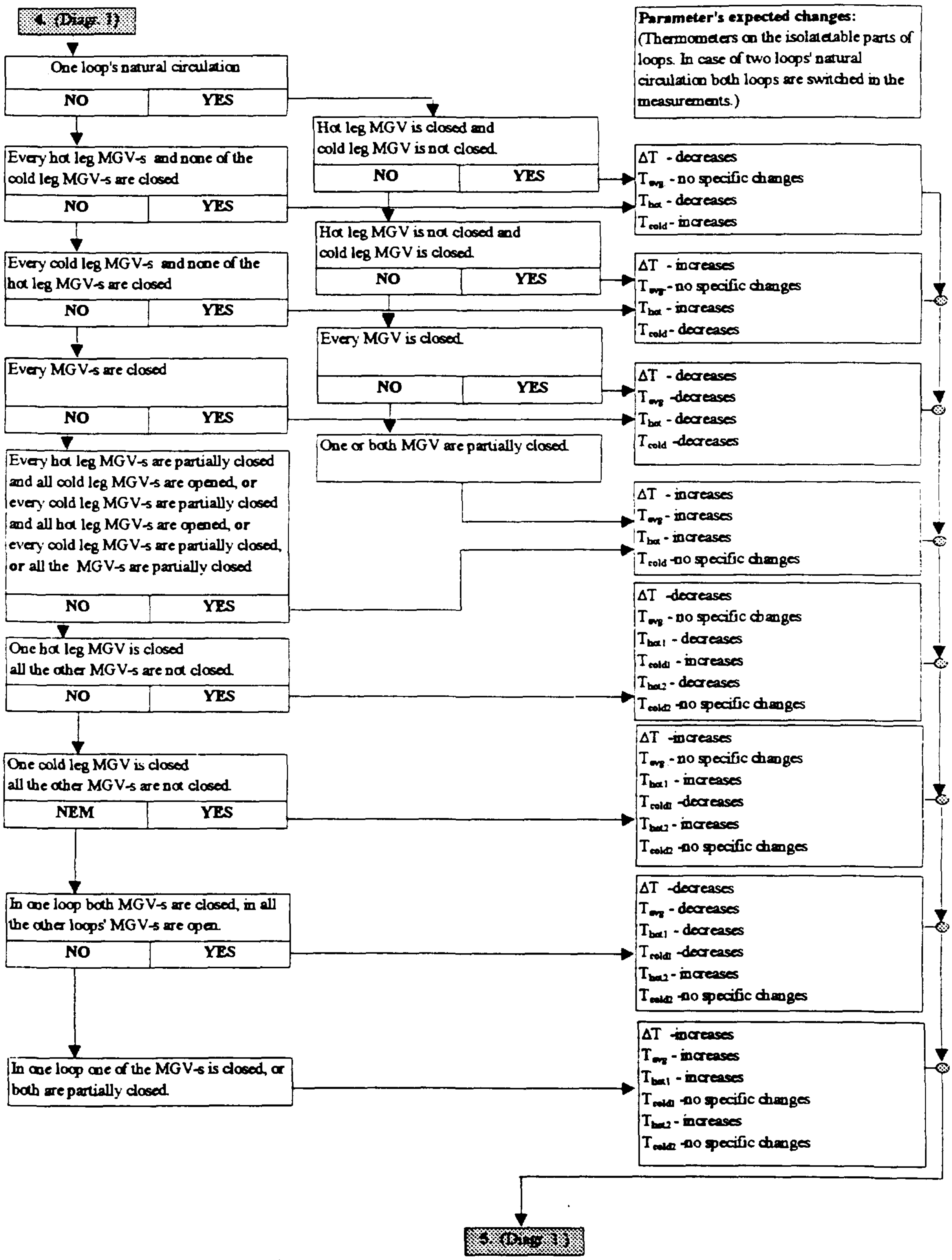


Diagram 4.

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