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The cleaning tank incident, current status and recovery plan[1]

Prepared for the the USNRC-HAEA consultations
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HAEA-NSD
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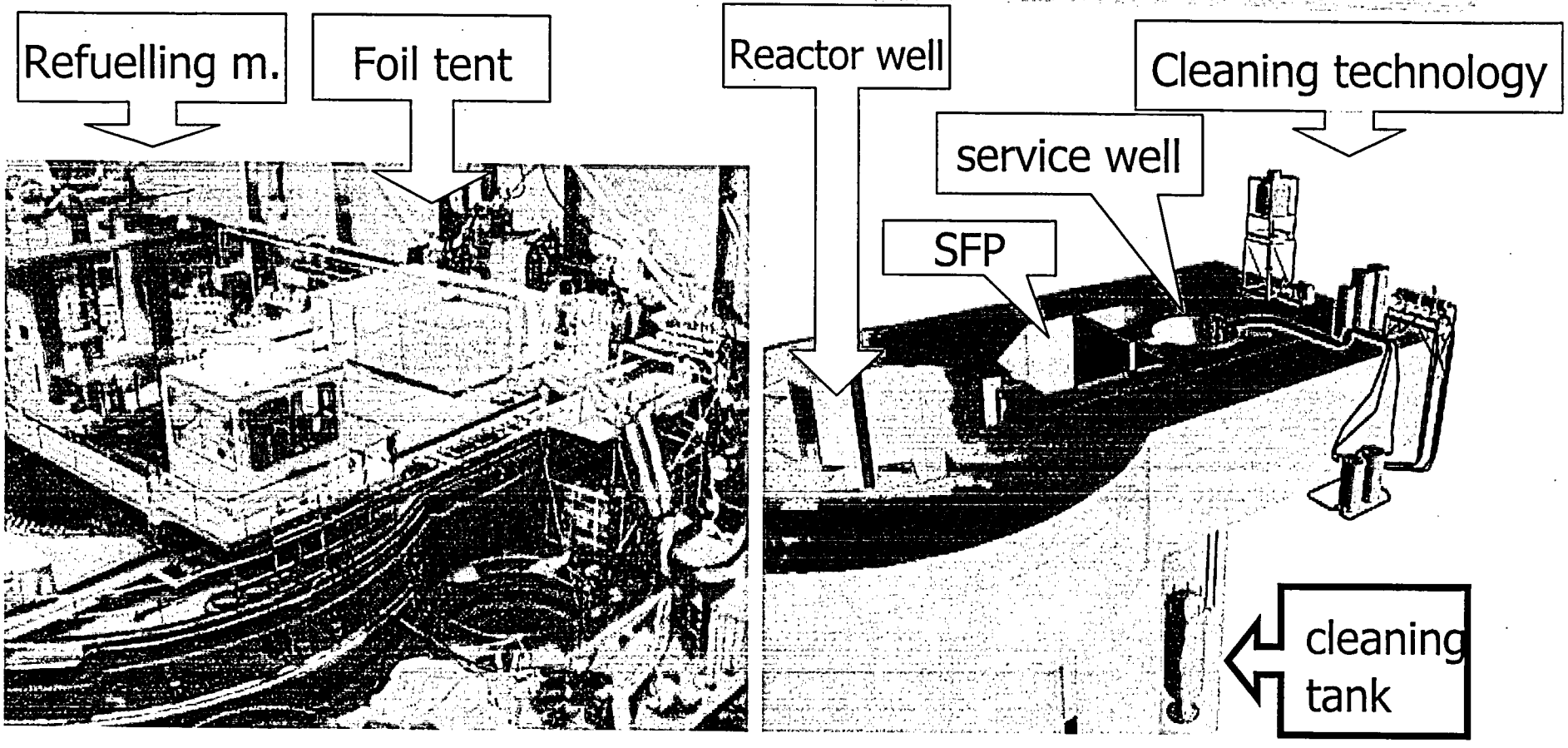
[1] Based on different materials from the HAEA-NSD, the Paks NPP and from Nuclear Institute of BUTE

Release (4)

The Scene: Unit No.2 – photo, 3D CAD



The milestones on the road toward the incident (1)

- By neglecting the international VVER-440 experience for a long time, the replacement of the aging SG feed water distributors was postponed
- By the year 2000, four out of the 6 SGs at unit 2 the replacement could not be delayed anymore, therefore the work had to be carried out during a single outage
- Crud deposition on fuel assemblies after the SG decontamination had already been experienced, and the more SGs were involved, the more crud could be expected
- The alternative option of shielding by lead cushion was not considered for ensuring the working conditions inside the SG
- Unproven indications of imprecise application of the decontamination technology

The milestones on the road toward the incident (2)

- Due to similar scenarios, 3 out of the 4 units suffered severe crud deposition on the fuel surfaces for the last few years
- These units could not operate at 100% rated power, to satisfy the cladding temperature and other limitations
- The allowed maximum power of these units varied during the last two years between 84-98% of design power (determined according to a detailed conservative analysis from the side of the Russian fuel supplier)
- The plant personnel expected to get rid of the crud deposition gradually when about 1/3rd of the assemblies is replaced by fresh fuel at every refuelling but the expectations were not satisfied
- An agreement had been reached between the Regulator and the Plant that during the year of 2003 the problem should be resolved

The milestones on the road toward the incident (3)

- Two options were considered: internal cleaning (in the RV) and external cleaning
- The former had no reference at all, while the latter had a single (incomplete) reference (yr. 2001 at Paks cleaning of 150 assemblies by Siemens)
- Decision was made in Sept. 2002 for external cleaning of the fuel during the next outages of the units 1 through 3
- The original cleaning equipment had to be re-designed: 7→30 and from cool to hot (freshly removed) assemblies
- The design considered the removal of the max. 300kW as no challenge and no safety issue, at all

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The milestones on the road toward the incident (4)

- The design documentation completed on 12/18/2003 and submitted for approval to HAEA-NSD on Dec. the 18th of 2002 and approved by Jan. the 24th
- The plant initiated the import of the equipment the same day
- After an unsuccessful SAT on 02/20/2003, design modifications and successful SAT on 03/03/2003
- On 03/10/2003 the Procedures for cleaning were submitted to the Regulator
- On 03/16 the first loading of the equipment with cool assemblies (after 1 year cooling). Then cleaned yet another such set.

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The milestones on the road toward the incident (5)

- On 03/29/2003 unit 2 was shut down
- On 04/04/2003 the cleaning tank was loaded with the first set of freshly removed fuel, cleaning ready in ~20 hours
- Three further sets were cleaned before 04/10, while some minor signs of abnormal behaviour were disregarded (repeated I^{131} spiking)
- When cleaning of the load number 6 was completed (04/10 4 p.m.), the crane was engaged in other work, thus the opening of the tank lid was postponed and the cooling went on in mode "B"
- Before 7 p.m. the pool level rose by ~70 mm (undetected)
- Around 9:50 p.m. sharp increase in the Kr^{85} measurement

The incident

- 10 p.m.: The radioactive noble gas concentration in the reactor hall is 3.7MBq/m^3 - the hall evacuated
- due to false data in the procedures, the FANP expert evaluated the case as "one or two inhermetic fuel pins".
- An "Extraordinary Maintenance Committee Mtg." was set up at 1 a.m. 04/11 to decide the next step
  - very limited information
  - false evaluation
  - some of the worrying information was neglected
  - mostly dealing with the problem of identifying and storing the assumed couple of inhermetic assemblies
- Decision: the tank has to be opened!

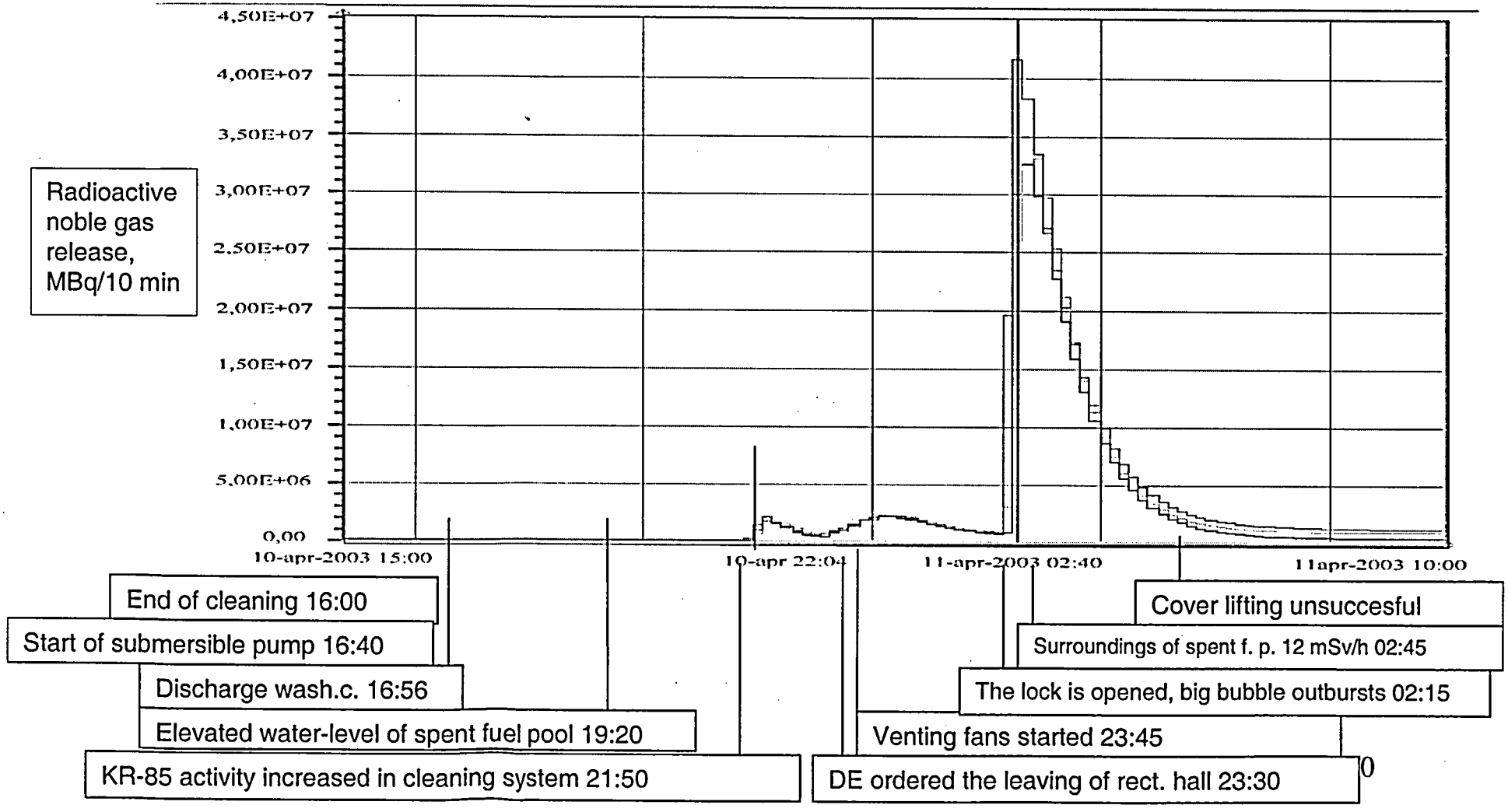
Opening the tank

- At 2 a.m. the hydraulic lock of the lid was released
  - very sharp increase of radioactivity in the hall and also in the ventilation stock ($4.2 \cdot 10^{13}$Bq/10 min)
  - drop of the pool level by 70 mm
- When the crane started to lift the lid, the rope broke and the lid stuck partly open (tilted)
- Nuclide concentration in the coolant:

Cs-134	$1.04*10^6$ Bq/kg
Cs-137	$8.60*10^5$ Bq/kg
I-131	$1.44*10^7$ Bq/kg
I-132	$2.01*10^6$ Bq/kg
Te-132	$1.32*10^5$ Bq/kg
Te-131m	$3.08*10^6$ Bq/kg
La-140	$1.64*10^5$ Bq/kg
Sr-92	$1.65*10^4$ Bq/kg
Ce-141	$1.12*10^5$ Bq/kg

Noble gas emission

Stack measurements



The day after

- The incident was reported and classified as INES-2
- The plant leaders maintained the "couple of inhermetic pins" theory - any more pessimistic evaluation was disregarded
- No more significant release after the maximum occurred at 2 a.m. for a duration of ~20 minutes:
  - noble gas: $4.17*10^{13}$ Bq/10 min
  - Iodine: $1.9*10^{10}$ Bq/10 min.
- Special committies were set up both at the plant and at the Regulator; daily video-conferencing

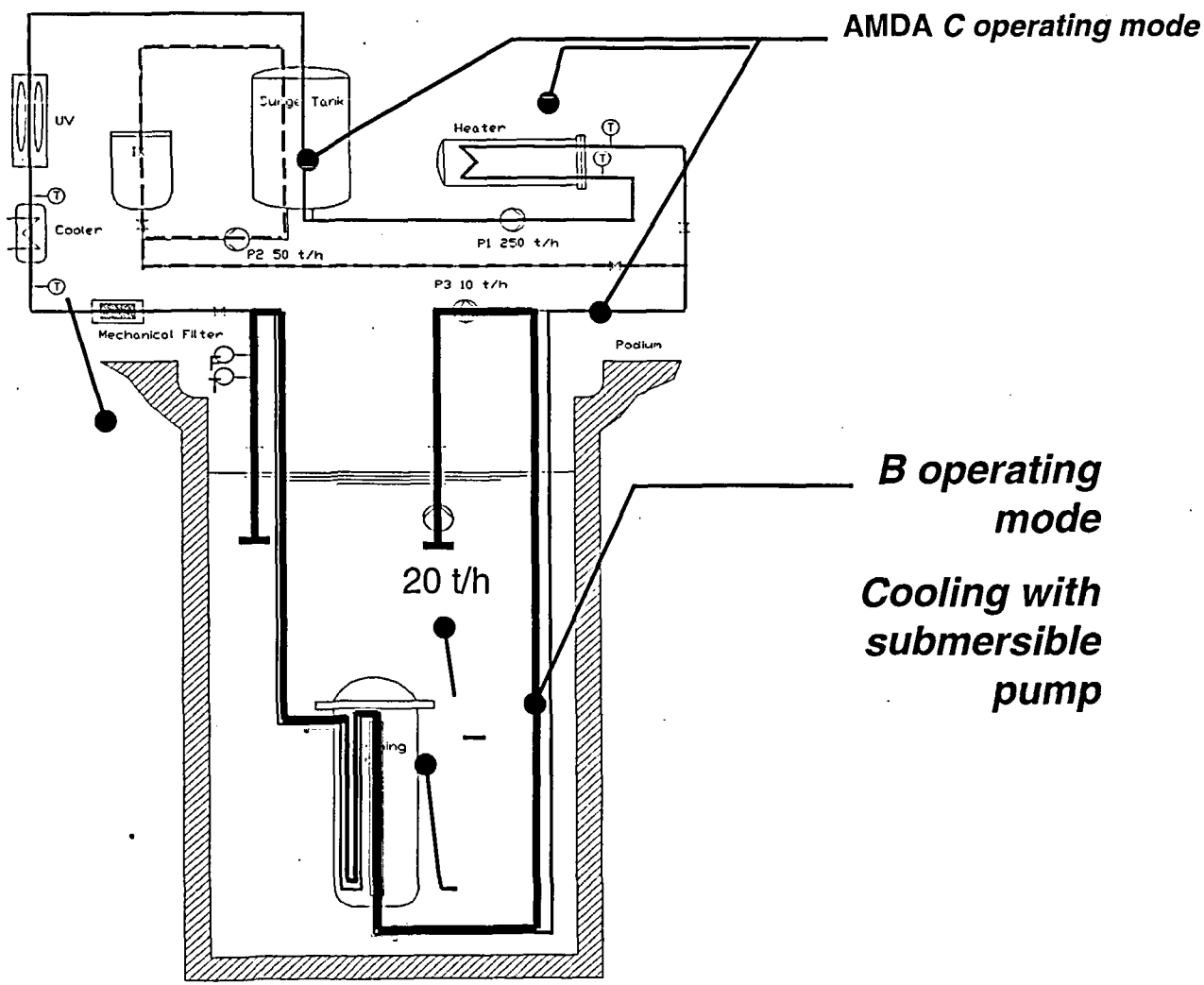
Further developments

- After repeated unsuccessful attempts of opening the lid, on the 16th of April the lid was removed
- The same day the underwater video imaging revealed extensive damage of the assemblies:
  - completely broken assemblies
  - pieces of assembly wall torn off
  - free, partly broken fuel pins, free pellets, debris, etc.
- Upgrading the event to level 3 in the INES scale

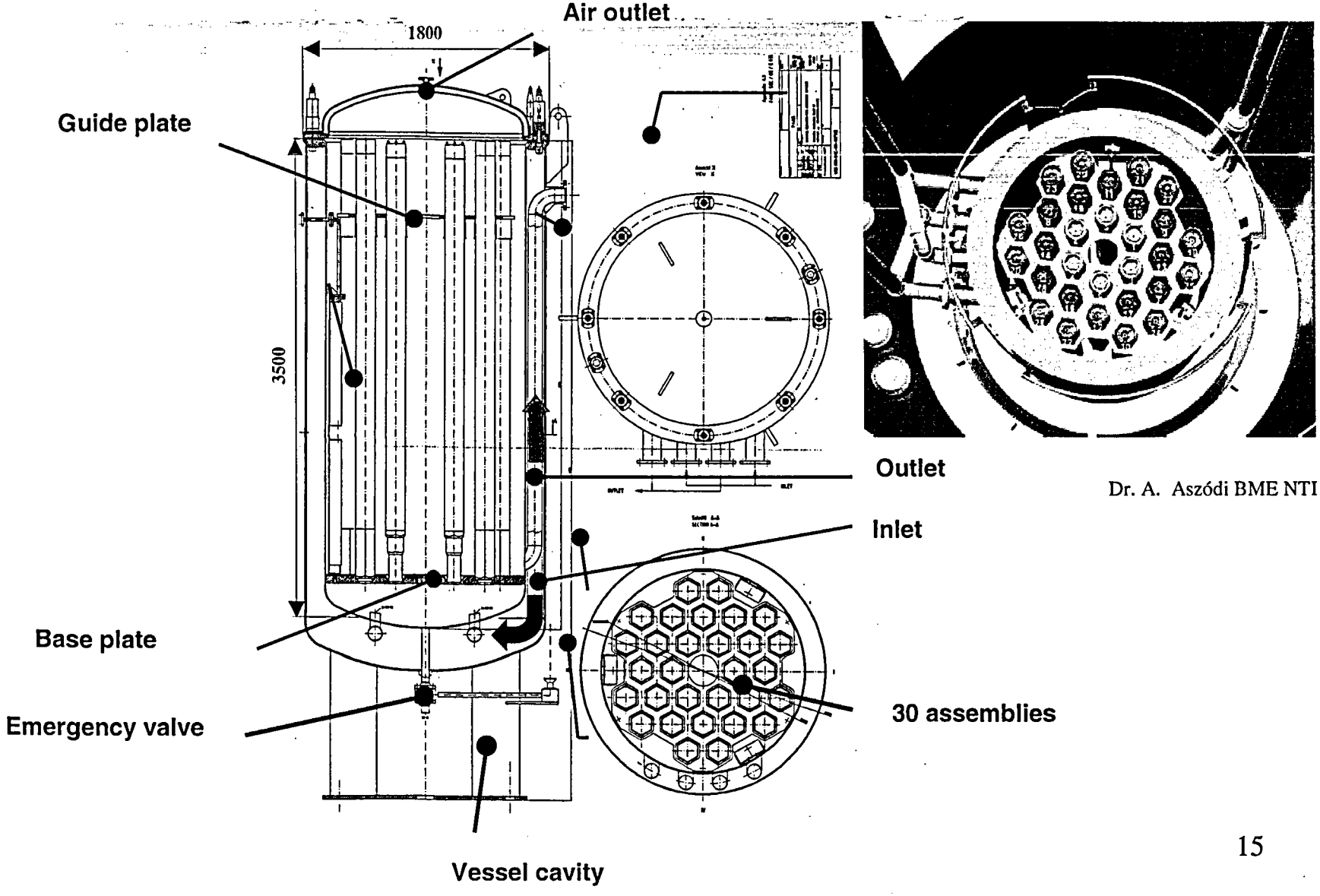
Reconstruction of the physical process (1)

- In mode B a single submersible pump cooled the tank by re-circulating the pool water
- Flow and temperature gauges installed in the exit line (no recording, hourly manual reading)
- The flow rate is ~20t/h, about 5 times the necessary amount to remove the heat (~270kW) without boiling
- But, no bypass flow was taken into account in the design and analysis. Possible bypass routes:
  - holes on the assembly walls (12 times 9 mm diameter)
  - incorrect sealing at the bottom plate, imperfectly seated assemblies
- Developing temperature stratification inside the tank due to bottom outlet

Reconstruction of the physical process (2)



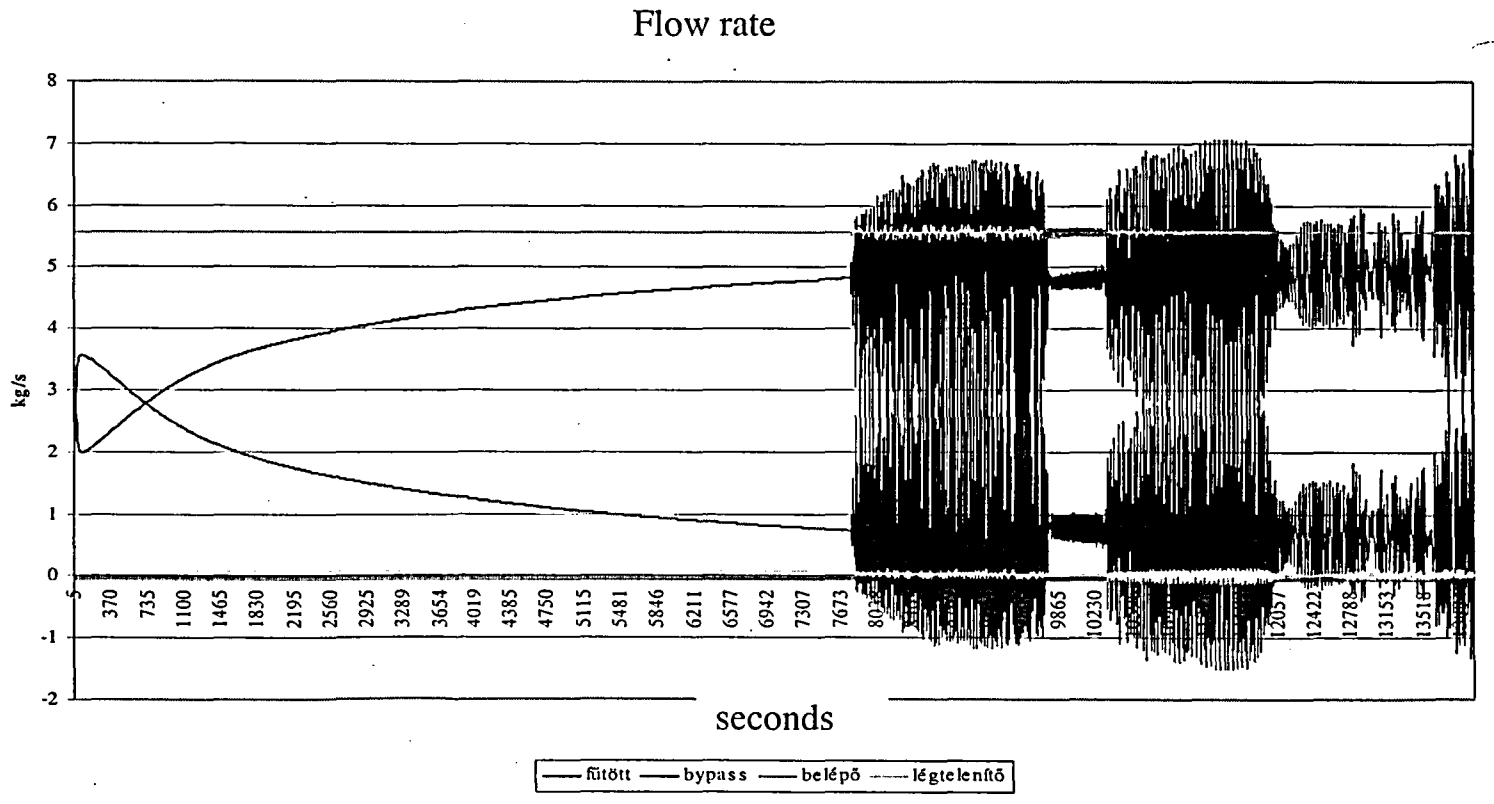
Reconstruction of the physical process (3)



Dr. A. Aszódi BME NTI

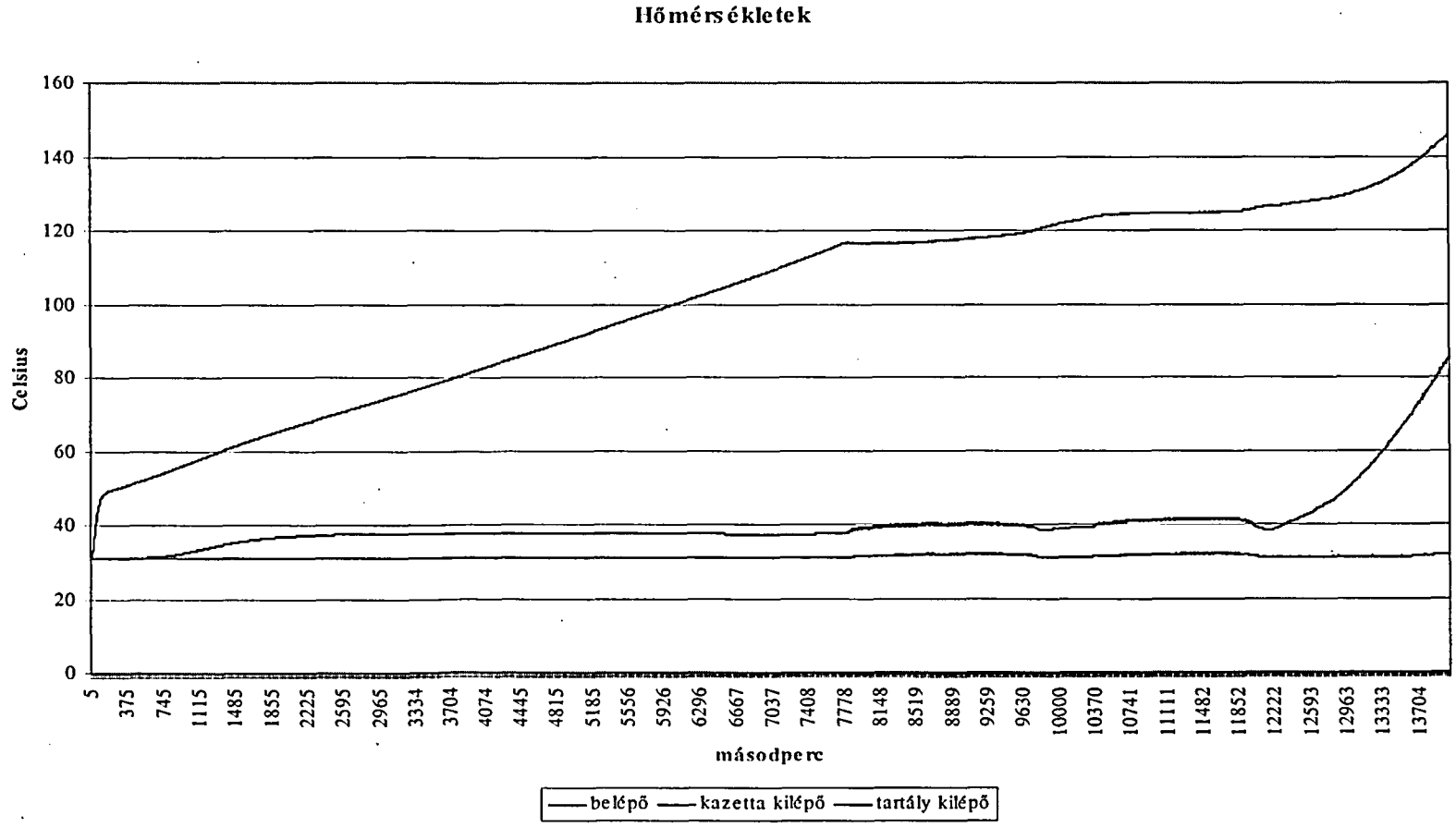
Reconstruction of the physical process (4)

Positive feed-back: the increasing temperature difference between the lower and the upper range of the tank caused decreasing flow rate through the assemblies



Reconstruction of the physical process (5)

The temperature behavior: assembly outlet: red, tank outlet: blue



Reconstruction of the physical process (6)

- When the coolant started boiling, a steam cushion developed at the top
- Soon after the steam cushion reached the upper head of the assemblies the flow through the assemblies practically stopped and in the course of 20 minutes the cushion filled almost the whole tank (increase of pool level by 70 mm)
- Further heat removal from the assemblies was restricted to radiation, steam-water heat-exchange (the exit temperature of the tank remained stable)
- Detailed severe accident codes confirmed (ATHLET, MELCORE) that in about 2-3 hours the fuel reached a temperature of ~1200K → first detection of Kr-85 at 10 p.m.

Reconstruction of the physical process (7)

- There are known indications that around midnight the rubber sealing between the tank and its lid gave up and started to blow out some steam. This possibly enhanced the cooling somewhat.
- When the hydraulic lock of the lid was released at 2 a.m., the Δp of the pump was enough to lift the lid by a few mm, then the cold water suddenly flooded the overheated assemblies while a series of small steam explosions and the thermal shock crushed the assemblies...

The investigation

- The event was investigated in parallel both by the plant and by the Regulator
- In May an IAEA expert mission was invited to review the investigations
- The regulatory investigation revealed several flaws in the design and also in the safety analysis, as well as several organisational problems. In addition to this, some inadequate regulations and regulatory practices were identified.
- The main cause of overlooking the shortcomings during the regulatory approval was the time pressure and the misleading reference to the former successful cleaning program (7-assembly tank for cooled assemblies in 2001)

Major design deficiencies

- The holes on the assembly wall were not taken into account (Cause: the designer of the 7-assembly tank resigned from the company, the drawings provided by the plant did not show the holes).
- The designer assumed no by-pass flow at the base plate connection of the assemblies - inadequate criterion for positioning.
- The designer did not consider the possibility of steam cushion build-up due to bottom outlet.
- Designing a closed tank with freshly unloaded spent fuel without direct temperature gauges
- Wrong estimation of the time to boiling in case of a pump failure (assumed 9 minutes, in fact ~50 sec) → no back-up pump. The 9 minutes was assumed to be enough to open the lid (also unrealistic).
- Wrong methodology for evaluating the built in Kr-85 measurement reading for estimating the number of failed fuel rods (by 3 orders of magnitude)

Major organizational deficiencies

- Designing on the basis of incorrect documentation
- Referring to former case without systematically studying the differences and changes
- No design review at the licensee, who ordered the equipment
- No independent review of the safety analysis
- Precedence of the economic short-term interests over the safety issues
- Unlimited trust toward an experienced supplier, contractor (Framatome ANP)
- Allowing to carry out a safety relevant process by a contractor without technical and safety supervision from the side of the licensee

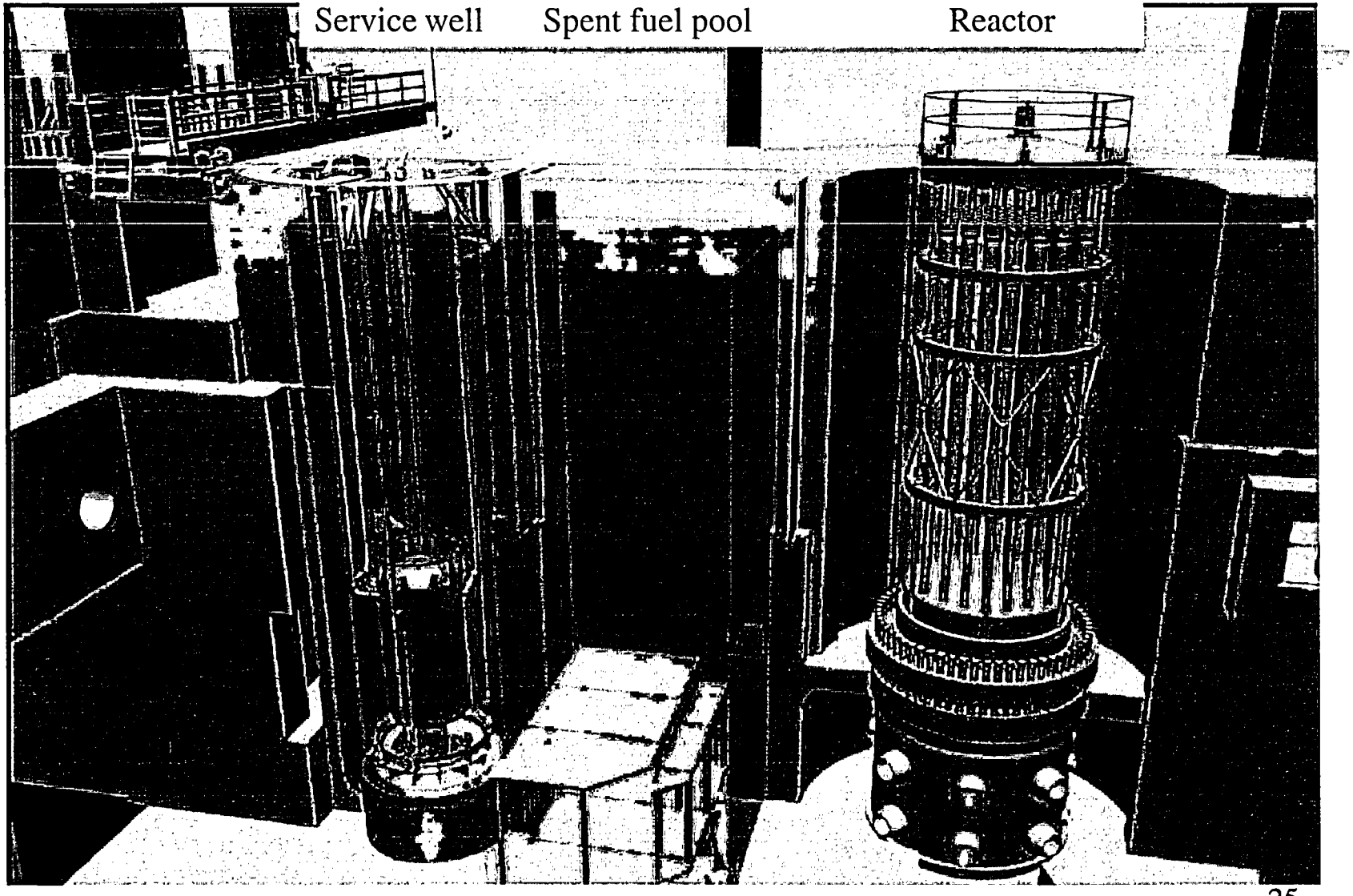
Major deficiencies in the licensing and in the regulations (1)

- Handling the case as a routine modification approval in the process of "spent fuel handling" (safety class 3) without taking into account the "first-of-a-kind" character of the process
- Accepting the reference to the successful former cleaning process by the 7-assembly tank without seriously scrutinizing the changes, differences
- Concentrating on the chemical cleaning process without considering all the operational modes of the equipment
- Requesting no thermal-hydraulic expert (internal or external) in the review of the submission - assuming no safety relevance in this field

Major deficiencies in the licensing and in the regulations (2)

- There are no specific licensing requirements for a non-standard process
- The regulations are too specific: e.g. concerning the spent fuel only the storing and the transportation are regulated, therefore there are no well defined regulations for a case, when some of the spent assemblies are handled together for some specific purpose
- There are no clearly defined conditions, guidelines for the reviewing process
- There are requirements for the design basis of the plant but no such thing is required in case of a separate equipment, when it is loaded with nuclear fuel

A cut-away picture of the current layout



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What happened since (1)

- There was some concern about the reactivity of the damaged fuel: in the original pattern it was strongly over-moderated, now the fuel is much more dense → certainly there exists a positive critical boron concentration!
- It is a difficult task to find a bounding estimate, since the geometry is unknown and is extremely complicated:
  - two independent TSOs made estimations assuming "worst case configuration" (difficult to prove!)
  - The finding is that it is highly probable that the critical boron concentration is below 16 g/kg (1,6% wt boric acid)
  - To maintain the required shut-down margin at least 20 g/kg boric acid is necessary

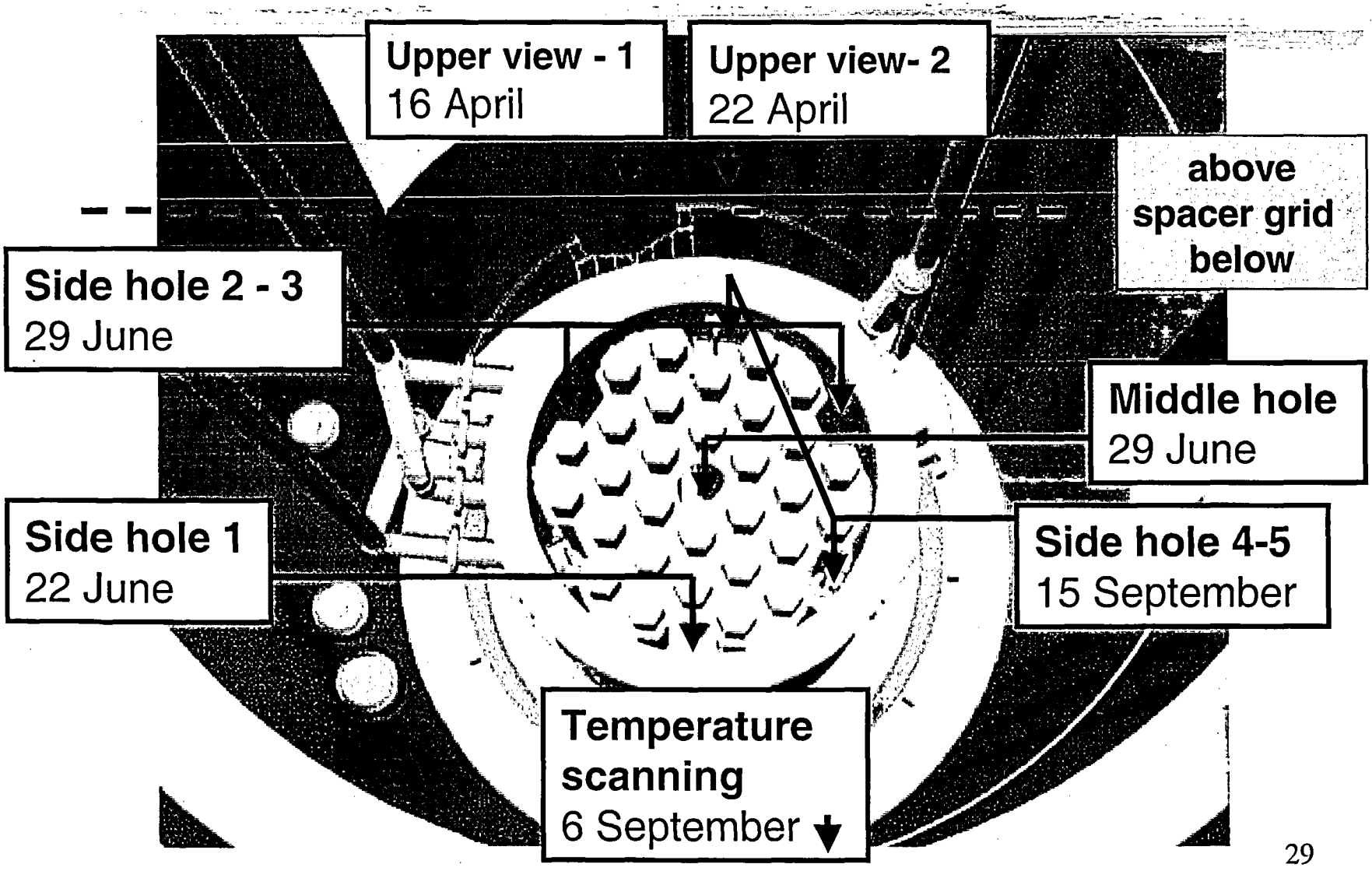
What happened since (2)

- The reactor remained shut down. Reason:
  - to complete the re-fuelling without the damaged fuel and the fuel assemblies with crud deposition, several assemblies have to be removed from the spent fuel pool and this requires the service well
  - there is significant but not completely known Uranium and trans-uranium deposit in the primary circuit which may cause significant activity in the primary loop
- The cleaning tank is supplied with a temporary emergency boration system
- Several underwater camera explorations were carried out (see later)

Current status of the damaged fuel

- Boric-acid concentration: >20g/kg (~3500ppm B_{nat})
  - estimated k_{eff}<0.85
- 4 redundant re-circulation pumps for the tank cooling
- The well is not yet separated from the spent fuel pool
  - proposal for the separation and for the solution of autonomic cooling of the service well is currently under regulatory review
- Measurements installed:
  - 3 independent n detectors
  - temperature gauges
  - level gauge
- A relatively detailed 3D mapping of the damaged material is available

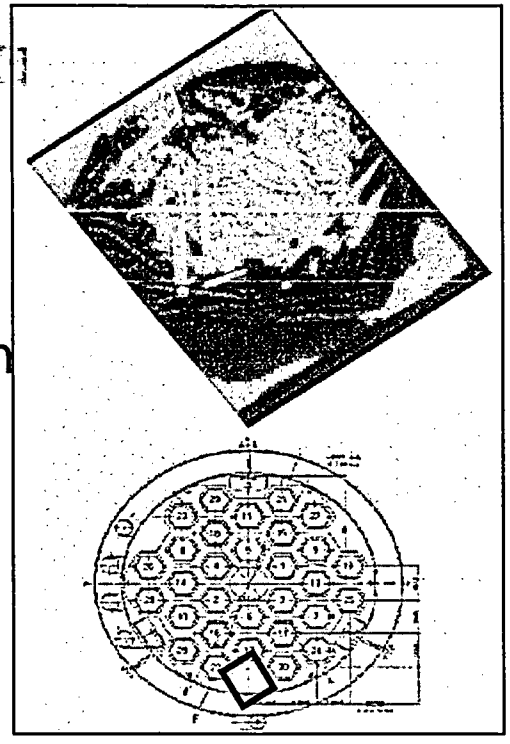
Visual inspection and mapping (1)



Visual inspection and mapping (2)

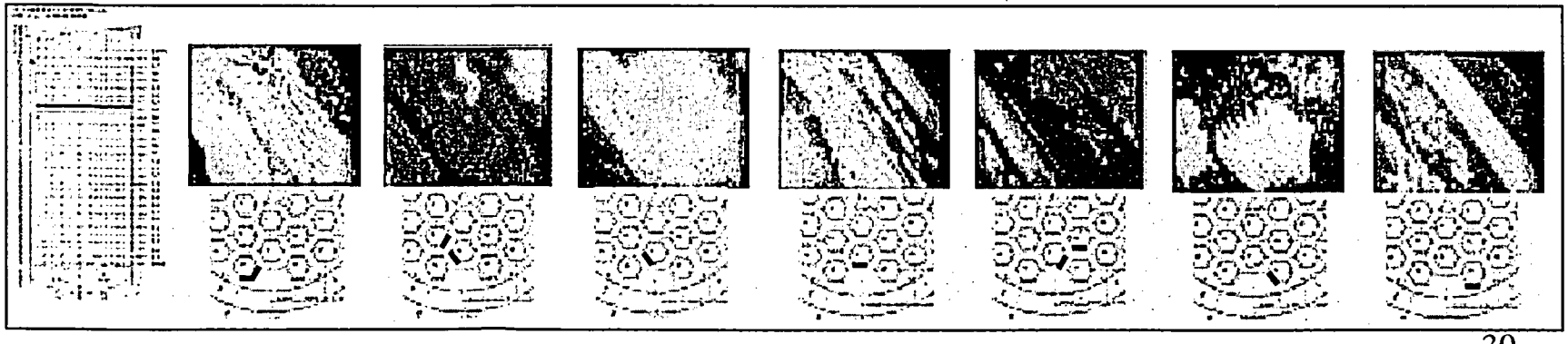
Evaluation

- damage assessment of every assembly
- determination of the distribution of bottom debris
- assessment of failure modes, mechanisms
- Temperature assessment based on color information



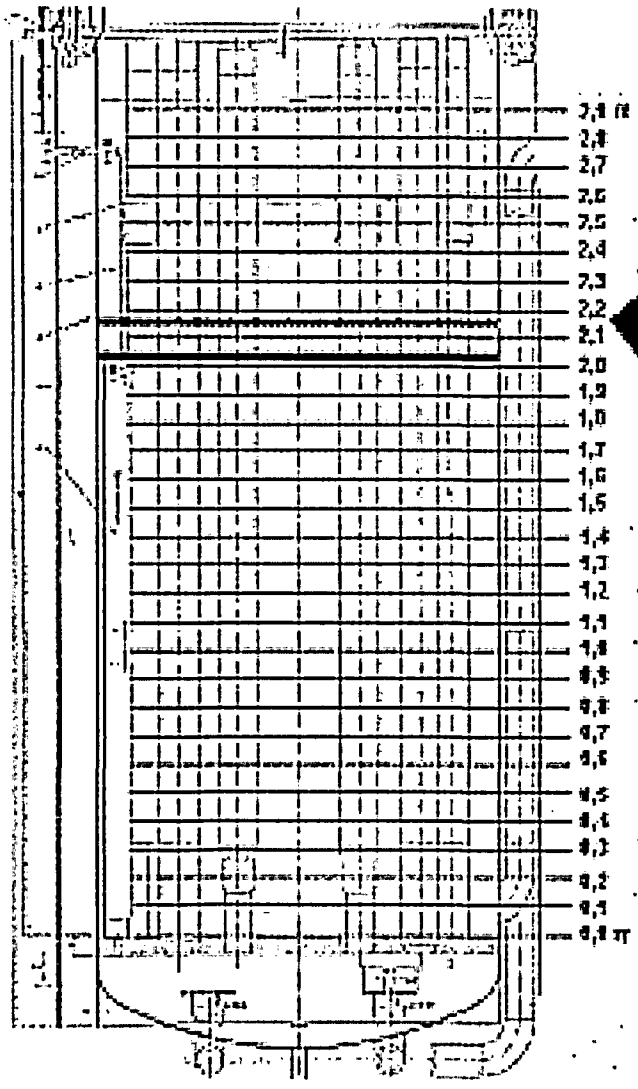
Spatial 3D mapping

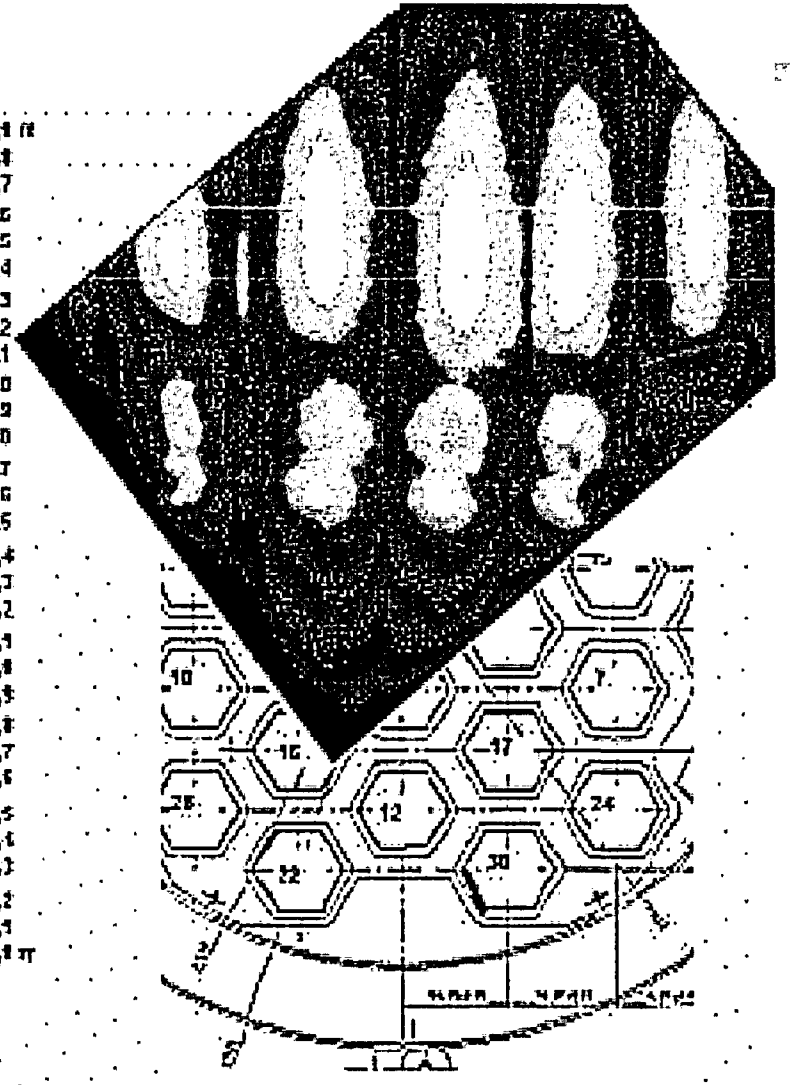
3D CAD model



Visual inspection and mapping (3)

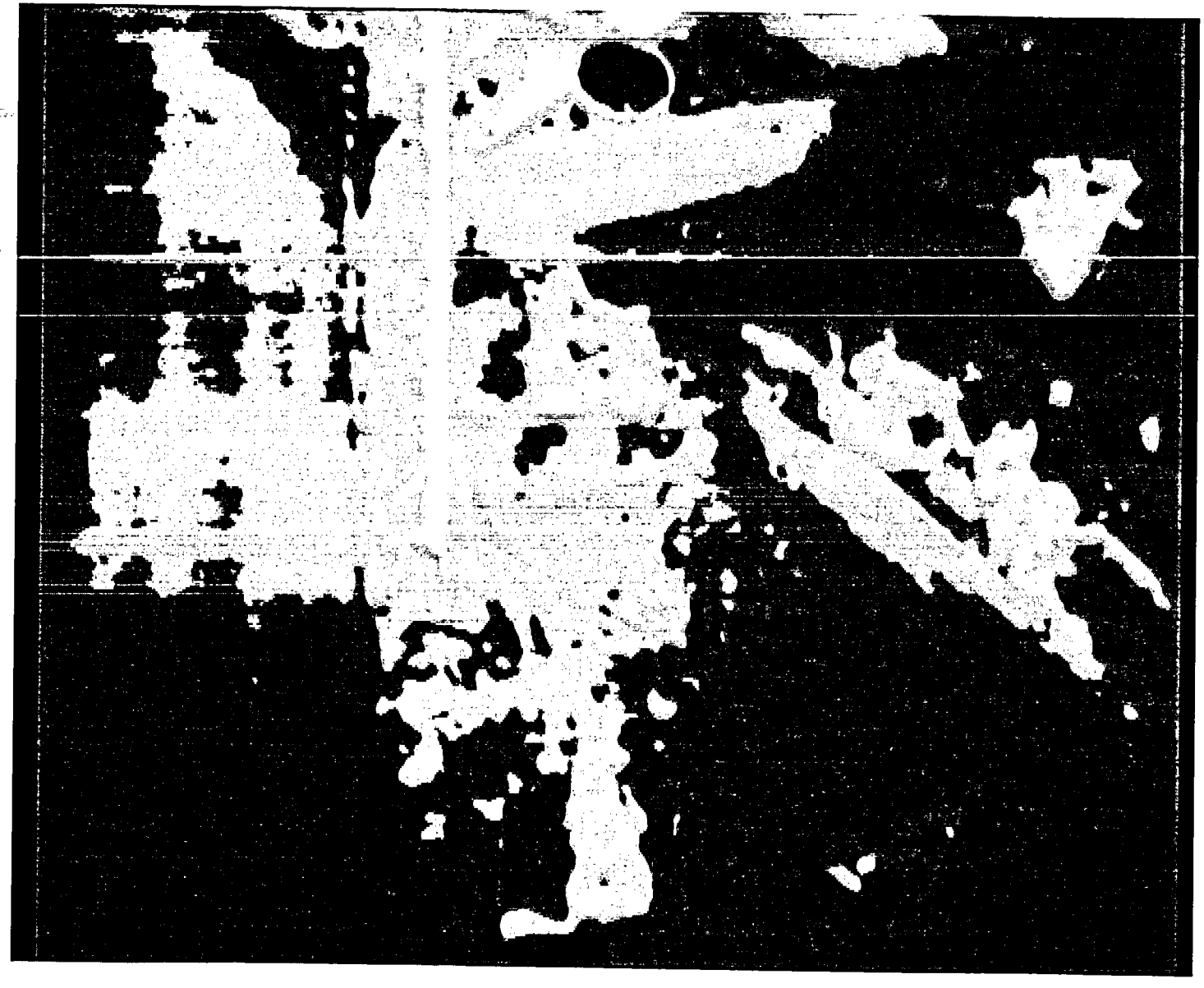
Assembly-walls broken, fuel pins swollen





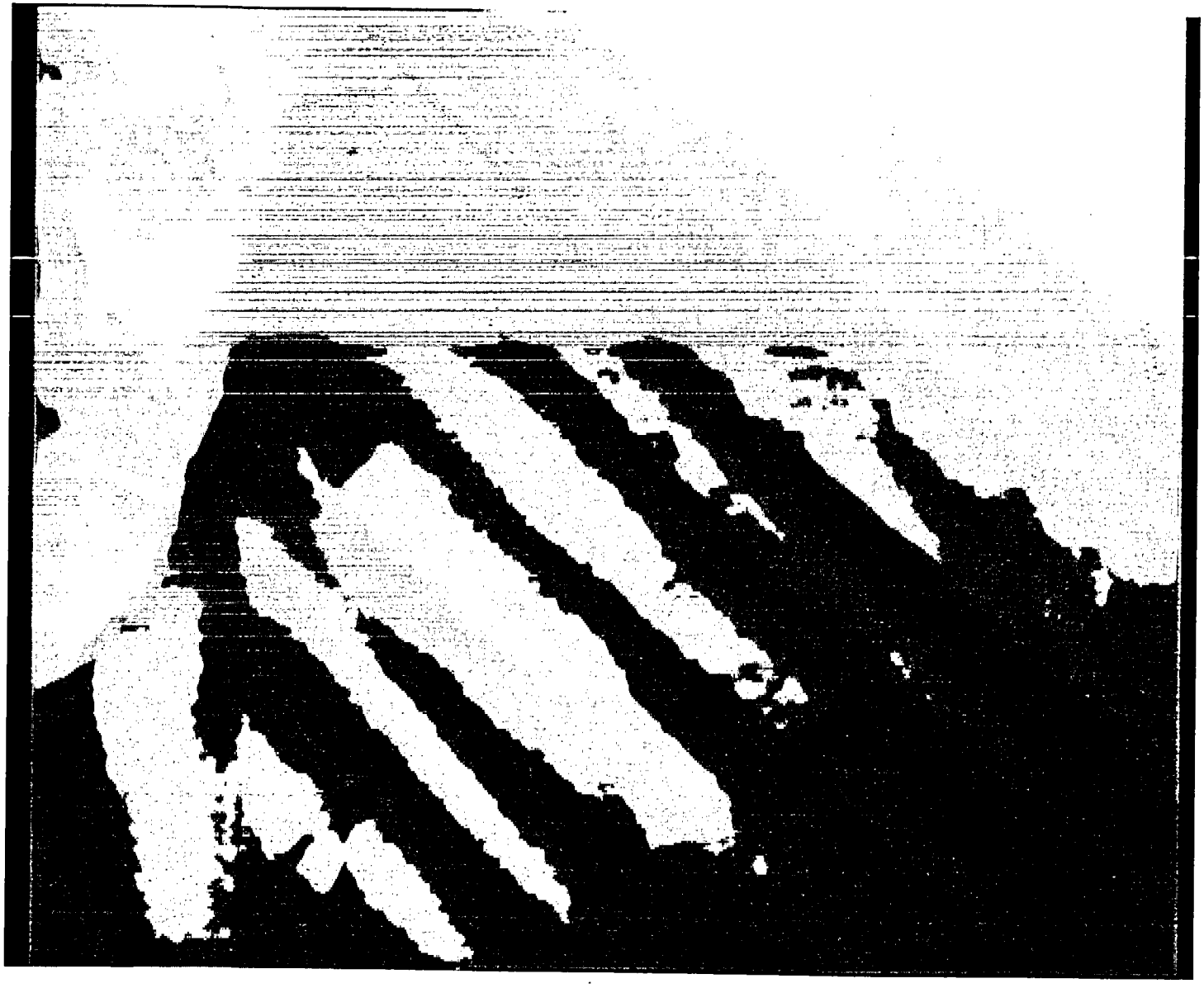
Close up (1)

Upper view of the bottom debris



Close up (2)

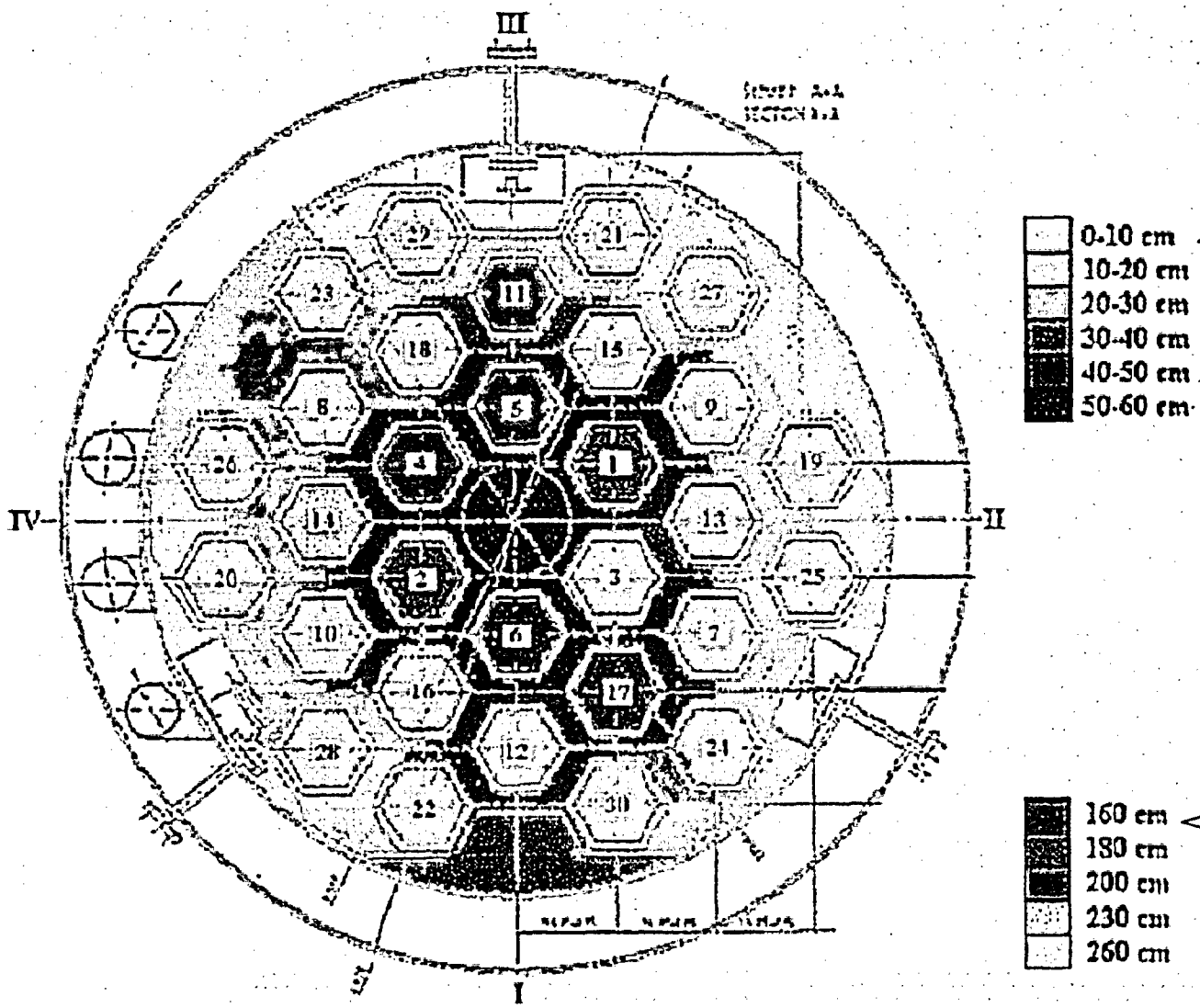
A typical damaged assembly in the upper region



Close up (3)

Swollen and oxidized fuel pins

Mapping summary (radial)



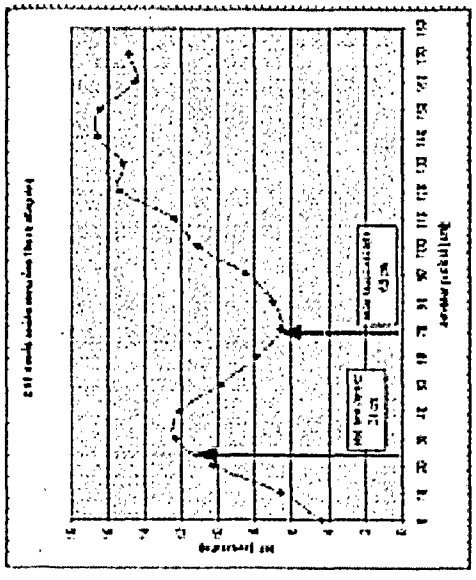
Thickness of the debris on the base plate

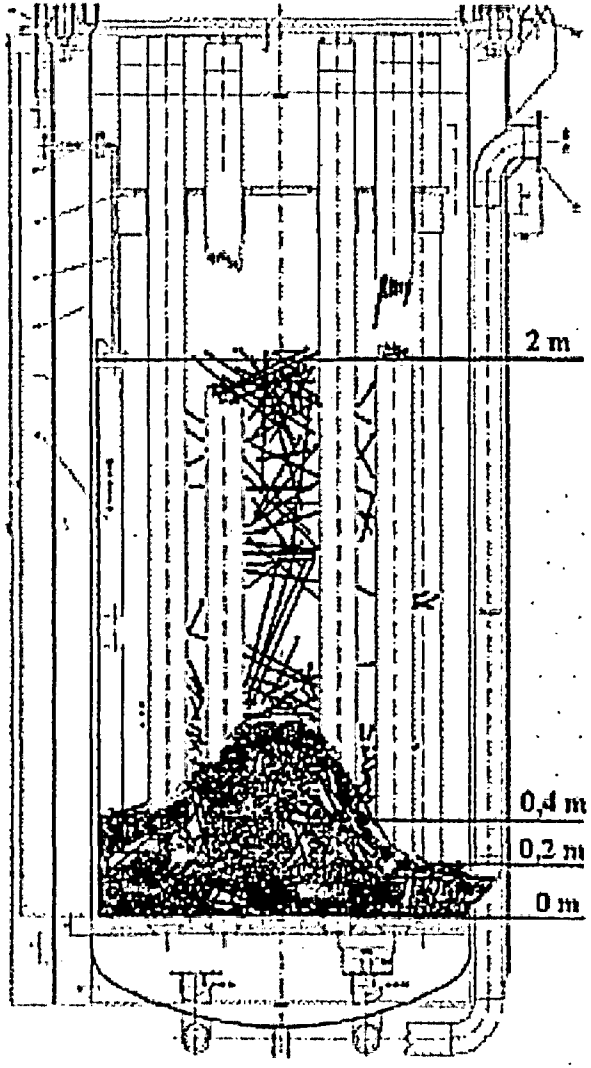
Height of solid part of the assemblies

Mapping summary (axial)

The estimation is based on:

- video recordings
- neutron flux distribution



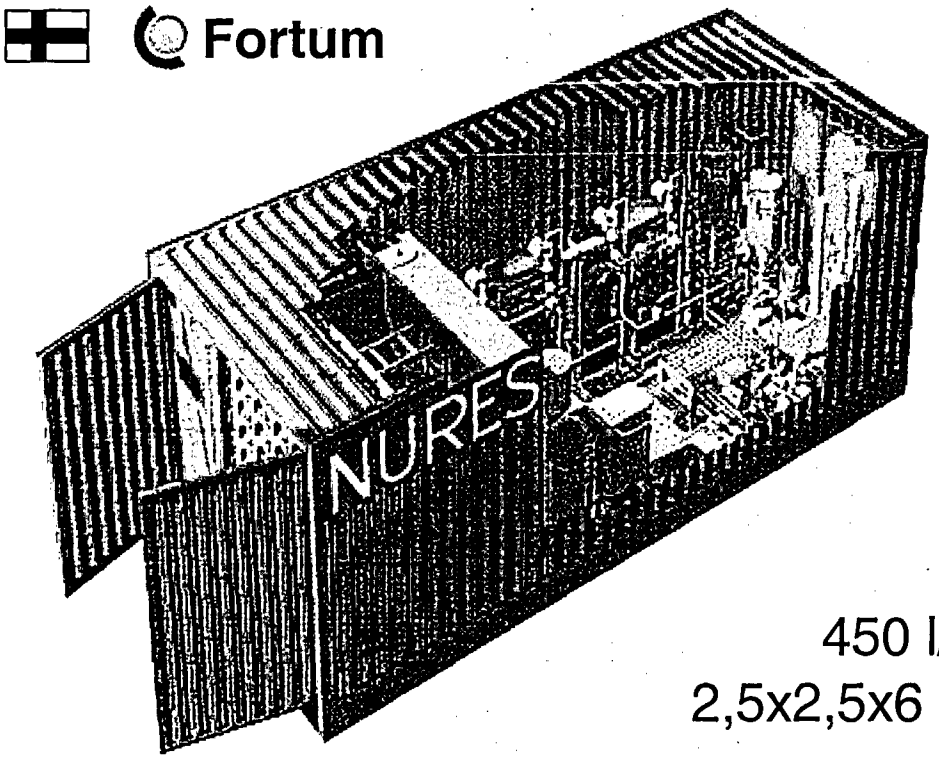


Modifications: mobile coolant filtering

Filter No. 4

Mobile filter

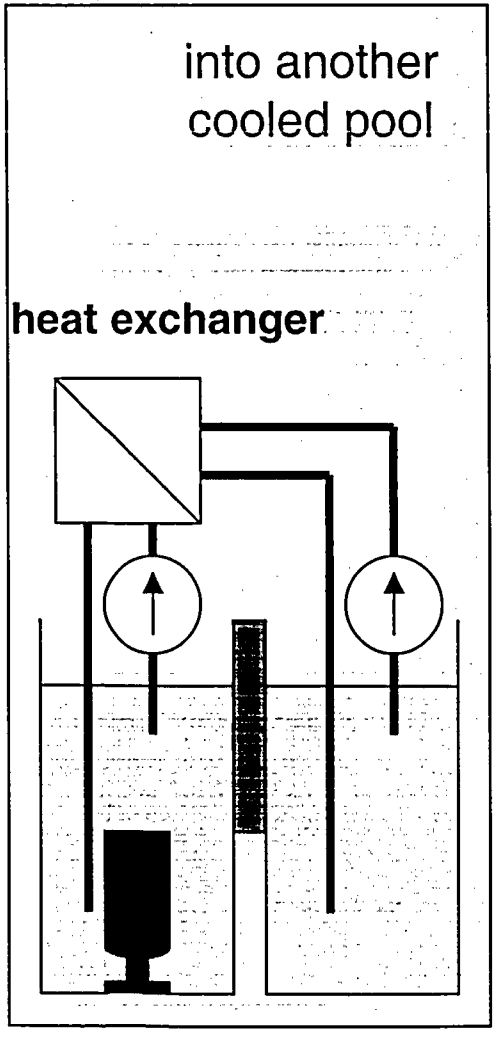
Fortum

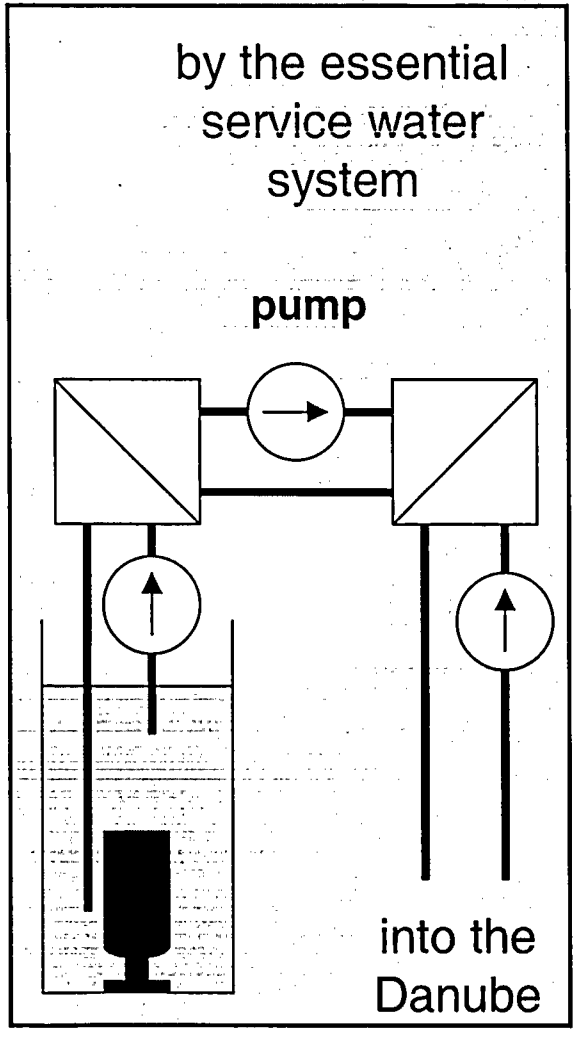


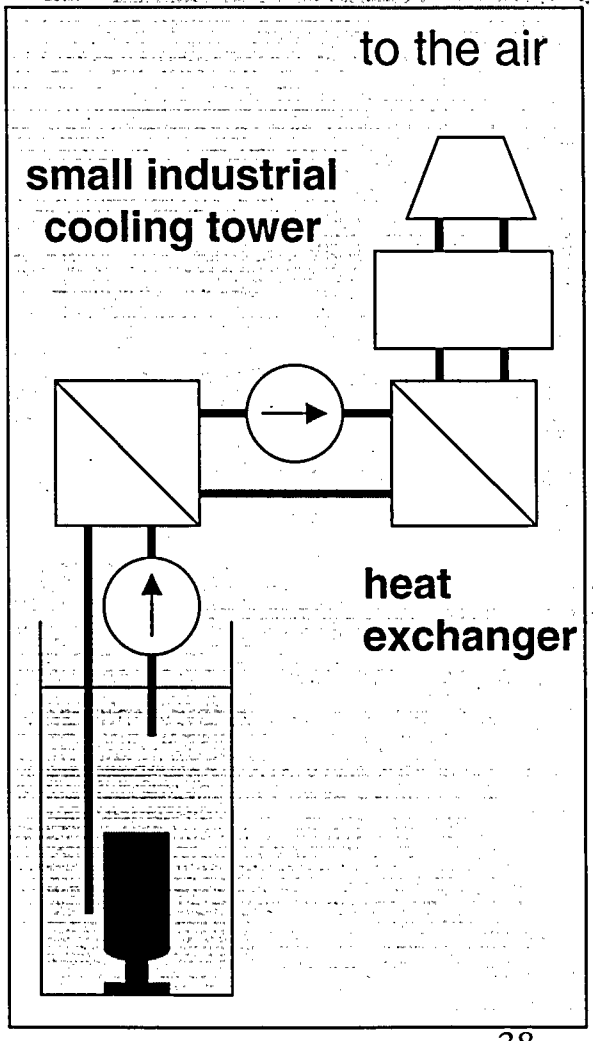
450 l/h
2,5x2,5x6 m

- Filter No. 4
- **branch 1: SFP**
- **branch 2: service well**
- Mobile filter for α contaminants
- **connected to Filter No. 4**
- **- autonom. cooling**
- **independent**

Modifications: independent cooling circuit for the well





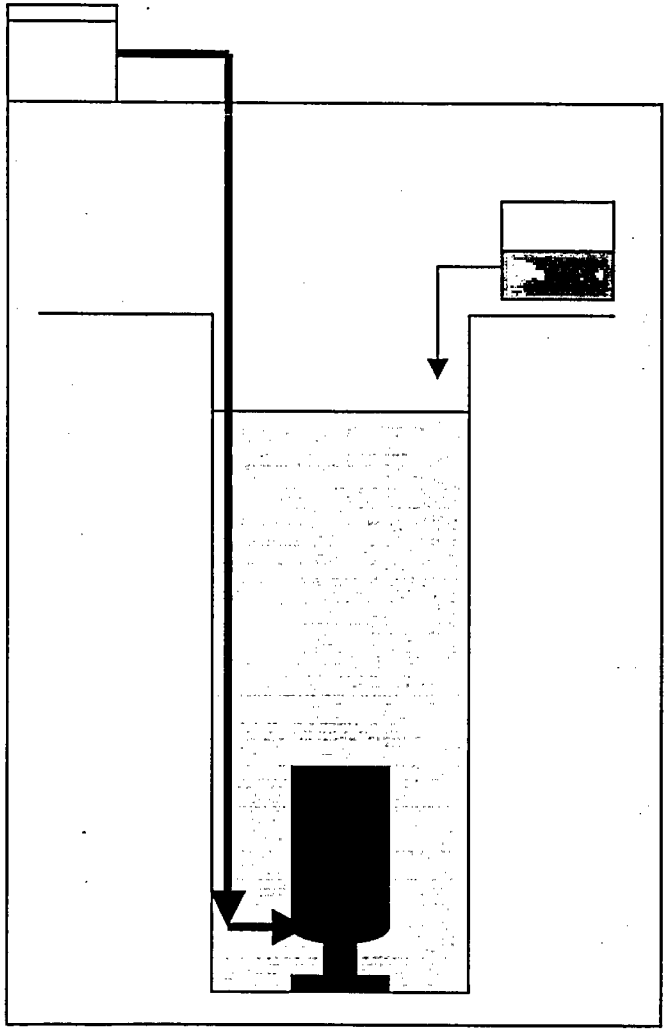


Selected variant

Other systems

Emergency boration

Passive gravitational injection system



Chemical maintenance system

Connected to the primary loop of the independent cooling circuit

+ also applicable to supplement the evaporation loss

Proposal for solving the fuel shuffling dead-lock (1)

- The dedicated position of the transfer cask for loading is the „service well" (now unaccessible).
- Currently the reactor is loaded with a full load of assemblies (349) but the configuration is not suitable for operation. The SFP is almost full.
- Free positions are necessary both for reshuffling the reactor core and also for storing the capsules with the damaged fuel.
- There is a significant amount of cooled down assemblies in the SFP which are suitable for transferring to the Intermediate Dry Storage Facility. Two main challenges:
  - Where can we stand the transfer cask?
  - The assemblies in the SFP are contaminated from outside.
- Proposition: a special stand for holding the transfer cask on top of the open reactor pressure vessel. (One such submission has already been rejected by HAEA-NSD.)

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Proposal for solving the fuel shuffling dead-lock (2)

- The transfer cask is moved by the main crane in the reactor hall. But it has already determined more than two years ago that the crane in not compliant with the NUREG-0614 and with the NUREG-0554.
  - no co-ordinate and path control (only manually controllable)
  - the required safety factor is not matched
- The decided modifications have to be completed.
- Placing the cask onto a stand resting on the reactor vessel may only be approved if there is no fuel in the vessel. Our concern is the assurance of causing no harm to the vessel, especially not in an undetectable way.

Operation of unit 2 before liquidation

- The fuel shuffling problems must be resolved
- The liquidation project must have priority
- Every safety code and TechSpec requirement must be fulfilled
- No fuel with substantial crud deposition may be used
- No fuel involved in the cleaning tank batches 3-5 may be applied
- Any kind of unfavorable interaction - either in normal or in abnormal operational conditions - must be excluded (including DBA handling for the operational unit).
- The unit must not operate during the effective liquidation activities

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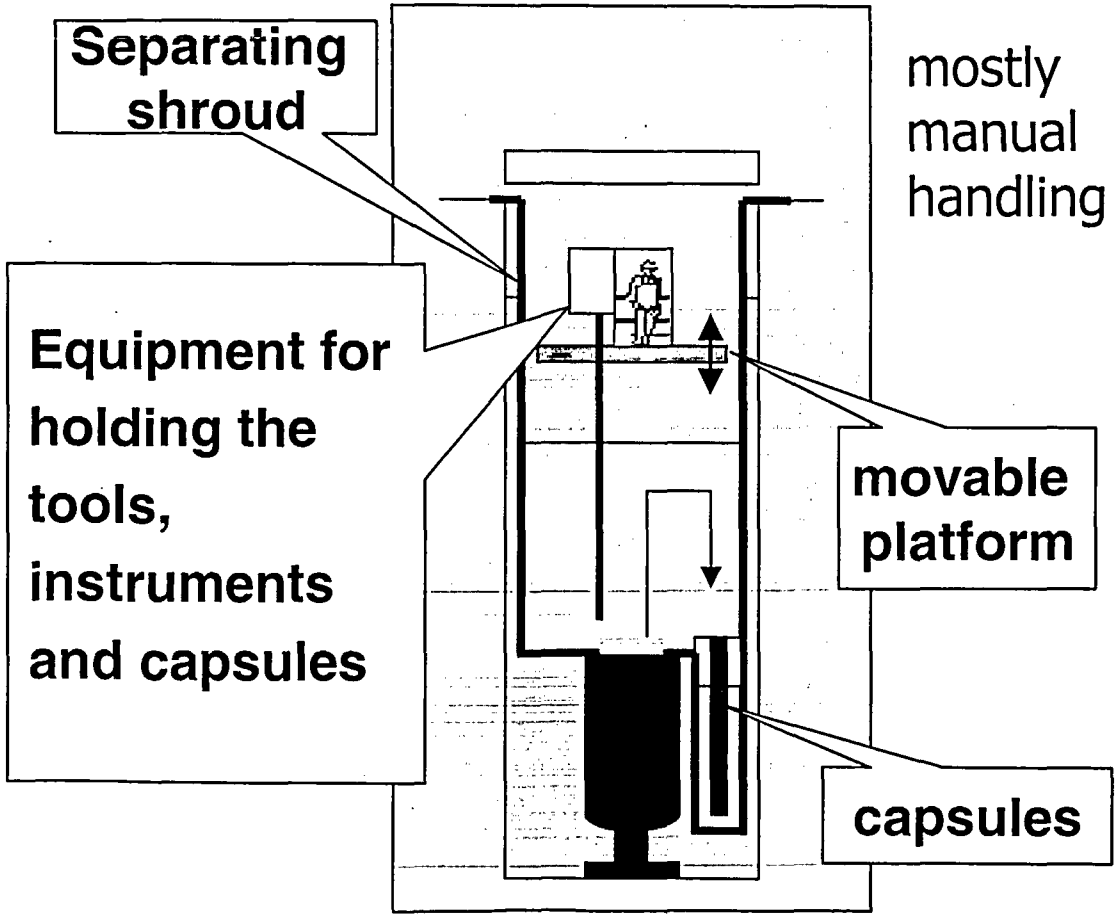
Liquidation layout



Liquidation: licensing

- Licensing
  - Elaboration of regulatory requirements (in progress)
    - appropriate adaptation of the nuclear safety codes
  - Time schedule of licensing activities
    - license in principle
    - licensing of the equipment
    - general license for performing the liquidation activities
- Additional licensing issues:
  - waste management
  - long term handling of externally contaminated assemblies
  - conditions of re-starting the power unit

Liquidation: safety analysis, design (1)

- Detailed survey of the initial conditions
  - condition of the fuel and of the coolant
  - subcriticality
- Radiation protection
  - Selection of the best possible approach (ALARA). The requirements must be clearly defined.
- A specific TechSpec must be elaborated and approved
- Specific emergency preparedness plan must be elaborated
- Several special capsules must be designed and approved (e. g. for complete damaged assemblies, for larger fragments, for small fragments etc.)

Liquidation: safety analysis, design (2)

- Design of specific tools, verification of their applicability
- Due to the excessive human involvement of the planned activities, very elaborated procedures are required
- The actual and potential surface contamination must be assessed
- Appropriate technologies must be elaborated and validated for surface decontamination
- The expected amount of different kinds of rad-waste must be assessed and the handling and storing conditions and methods must be elaborated and provided
- **All the assessments and plans must be reviewed by independent experts**

Liquidation: fabrication, mantling, training (1)

- Fabrication of well shroud, movable platform, special tools, capsules and containers and other accessories.
- Delivery of the above to the plant site
- Elaboration of the operation manual
- Fabrication of a mock-up of the cleaning tank, including the damaged fuel inside
- Mantling an inactive configuration with the mock-up and the other equipment for
  - validating the tools and the methodology
  - training the personnel
- Feed-back and finalization
- Completion of the documentation

Liquidation: fabrication, mantling, training (2)

- The complete documentation to be submitted for regulatory approval shall include
  - the equipment design documentation,
  - the plans for installation, operation manual,
  - QA plan,
  - malfunction and emergency handling.
- Fabrication of the "real" equipment
- Training of all the personnel according to the finalized and licensed methodology, including the emergency handling
- Preparing the real site for accepting the equipment
- Mantling and installation of the equipment at the active site

Liquidation: training

- The dedicated training program must include
  - classroom training to make the affected personnel acquainted with all the relevant and related information
  - practical training by using the mock-up and the real tools (along with the manuals and procedures) to make the personnel skilled
- The practical training programs must be arranged to allow practicing the necessary team work according to the different tasks
- Special training must be arranged for the malfunction and emergency handling

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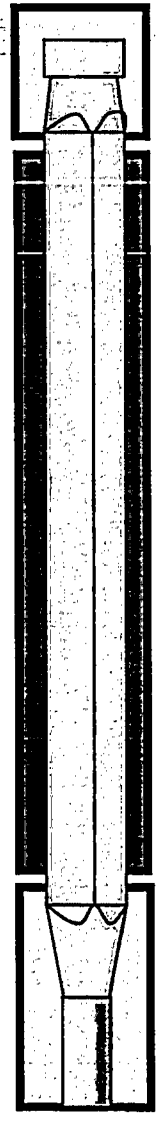
Liquidation: the main steps

- Setting up the control system for the criticality and for radiation protection and monitoring
- Loading the different capsules with pieces of broken fuel
- Transferring the capsules into the Spent Fuel Pool
- Storing and handling the non-fissile rad-waste
- Dismantling the cleaning tank and storing the pieces which can not be decontaminated
- Doing the same with all the affected equipment
- Cleaning, decontaminating the service well and any affected area. Restoring the original conditions as much as possible.

Some details of the methodology

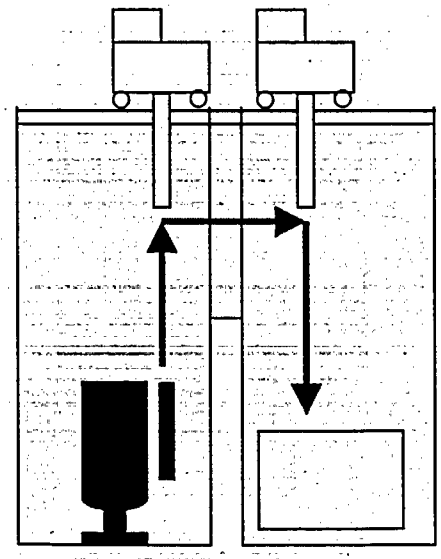
- The large, medium and small pieces will be separated
- Removal of the assemblies:
  - The head and foot part will be cut off
  - if possible, cutting of the active part of the fuel will be avoided
- The pieces will be encapsulated separately

What?	Fissile material	Highly active rad-waste
Where?	Spent fuel pool	Storage wells
When?	After sufficient cooling (reprocessing or DSF)	Recoverable at the decommissioning phase

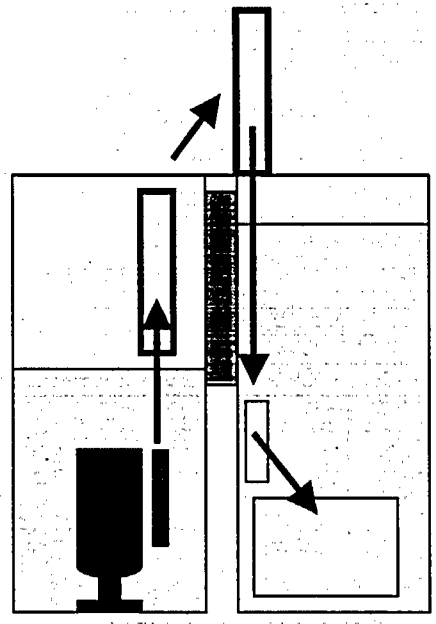


Options for transferring the capsules to the SFP

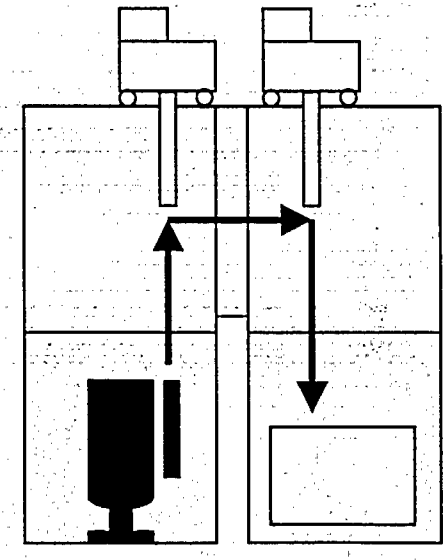
wet
refuelling m.



dry
container, crane



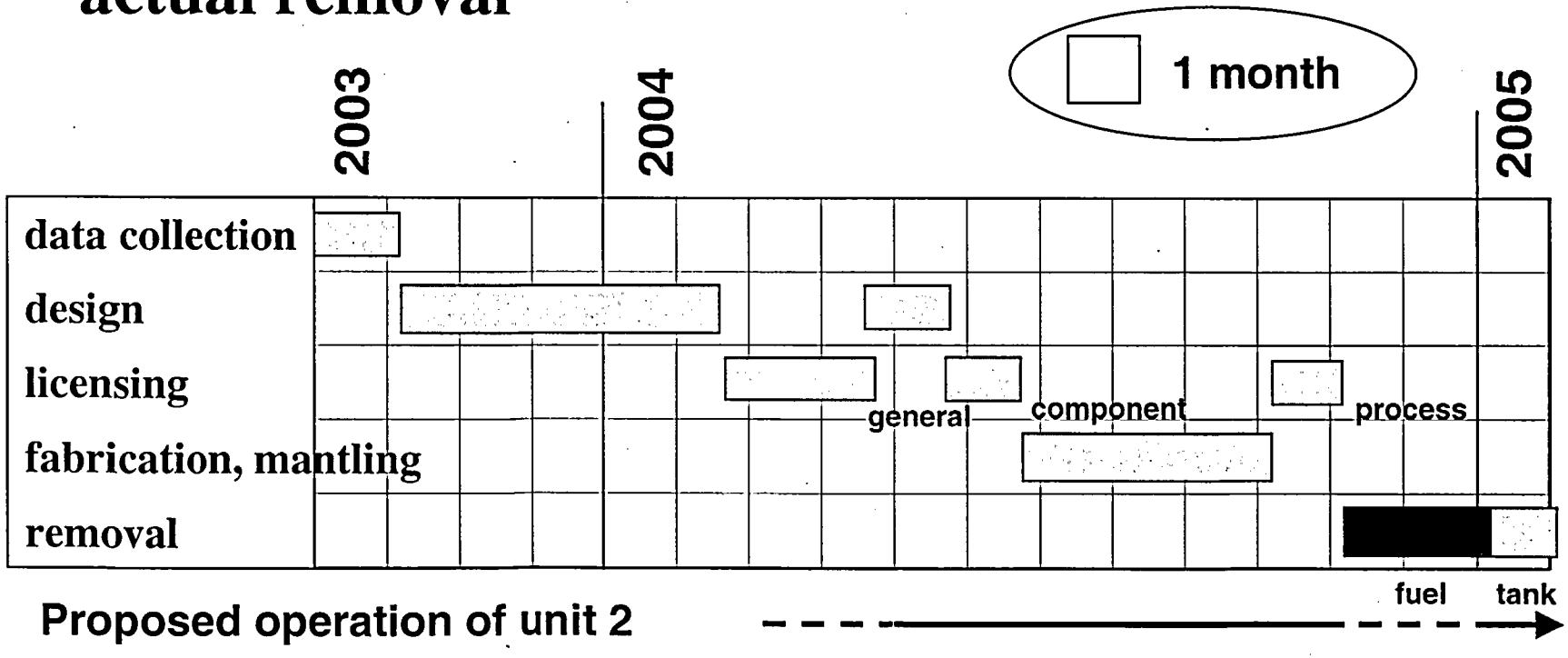
„demi-sec"
refuelling m.



- (+) usual manip.
- (-) water-mixing
- (-) level-change, decontam

- (+) low pool-level
- (+) clean
- (-) complicated

- (+) separeted pools
- (+) simple
- (-) high radiation

Planned time schedule

- **preparation,**
- **licensing,**
- **actual removal**