REFLECTIONS ON RUSSIAN ACCIDENT ON AUGUST 17th 2009

6,400-MW SAYANO-SHUSHENSKAYA HYDROELECTRIC POWER PLANT

Purpose of presentation is to learn from the accident and use this experience in the insurance engineering surveys.

The official report was used, as well as Russian Internet information

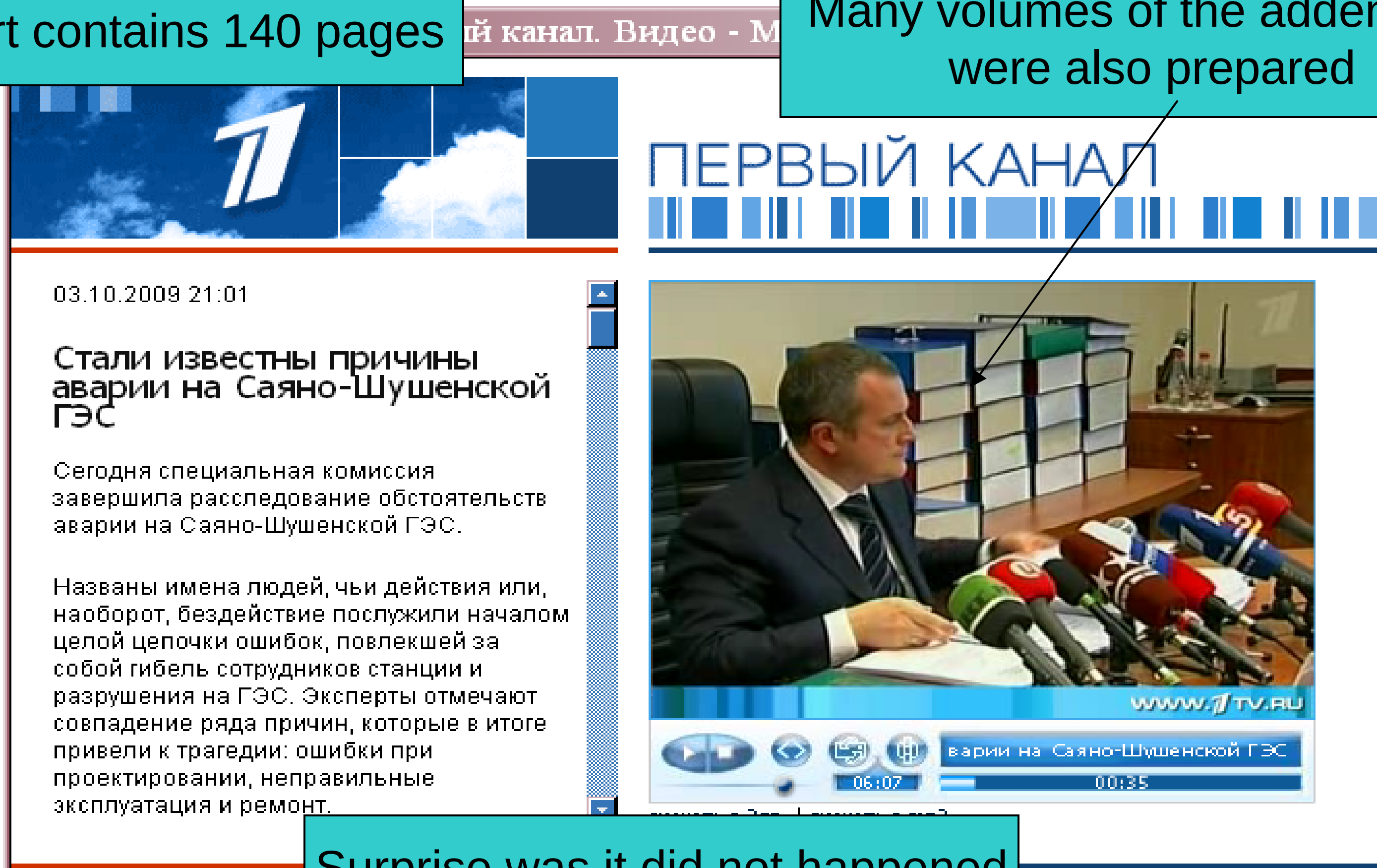
By Eugenio Kolesnikov – Miami October 12 2009; revised on October 20.

www.rudhydro.ru - official site of the owner
http:// www.1tv.ru – Russian TV channel 1
http://forums.drom.ru/hakasiya – discussion web site
http://www.1tv.ru/news/techno/152840 - final report

Officially the loss report was presented on October 3rd 2009

The report contains 140 pages

Many volumes of the addendum were also prepared



Surprise was it did not happened earlier / see slide 39 for details

General Information

- 6th world largest power plant.
- Useful life of the units is 30 years by design
- 10 x 640-MW units were installed
- 24 billion KWt / year = 10% of Siberian need
- December 1978 – first unit in operation
- December 1985 – 10th unit in operation
- 2000 – plant officially commissioned
- 2007 – 2011: 2nd plan of the plant modernization / refurbishment
- 2005 – 2010: Massive replacement of control and protection systems on all units / installation of DCS

SEQUENCE
OF THE ACCIDENT

Fire at Other Plant started sequence of the events resulted in the accident

There was fire in a communication room at Bratskaya hydro

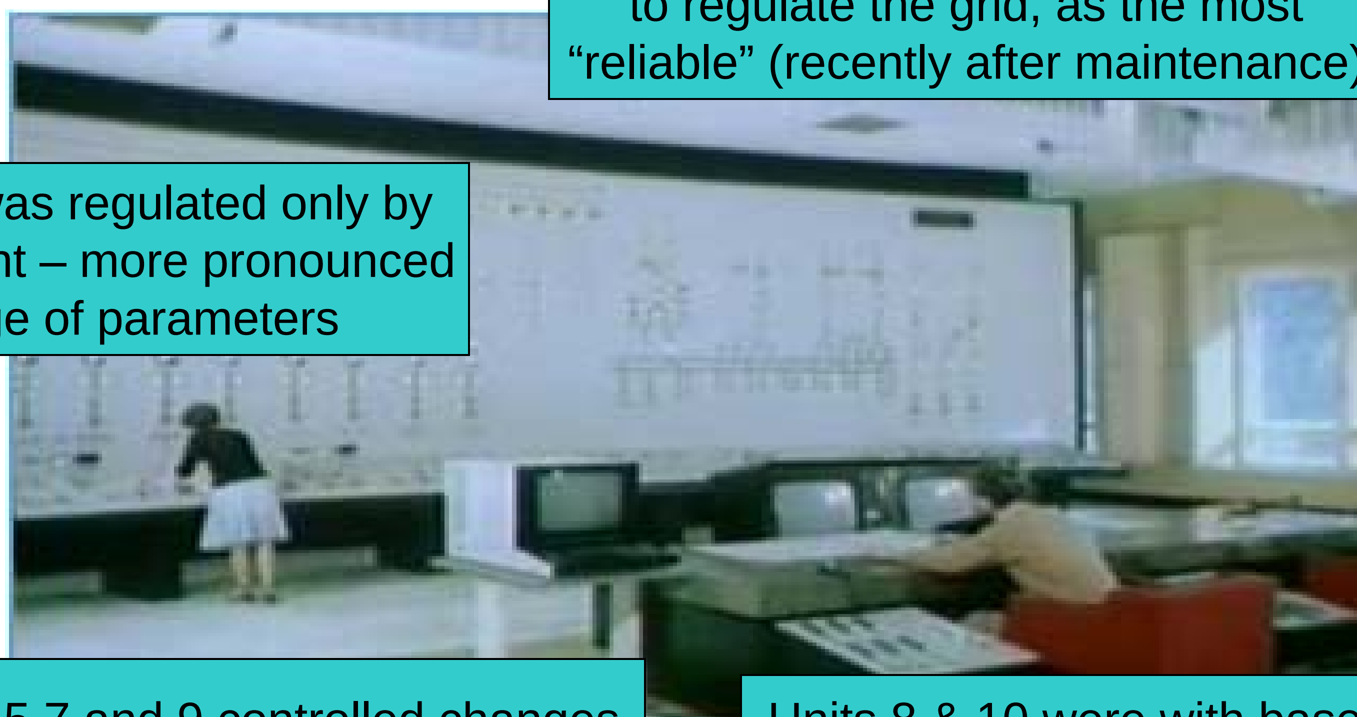
Communication with Dispatch Center was interrupted for 30 min

There was order to use Sayano for the grid regulation

Several Invalid Assumptions During Operation Of The Plant

Unit 2 was selected as the leading to regulate the grid, as the most “reliable” (recently after maintenance)

The Grid was regulated only by Sayano plant – more pronounced Change of parameters



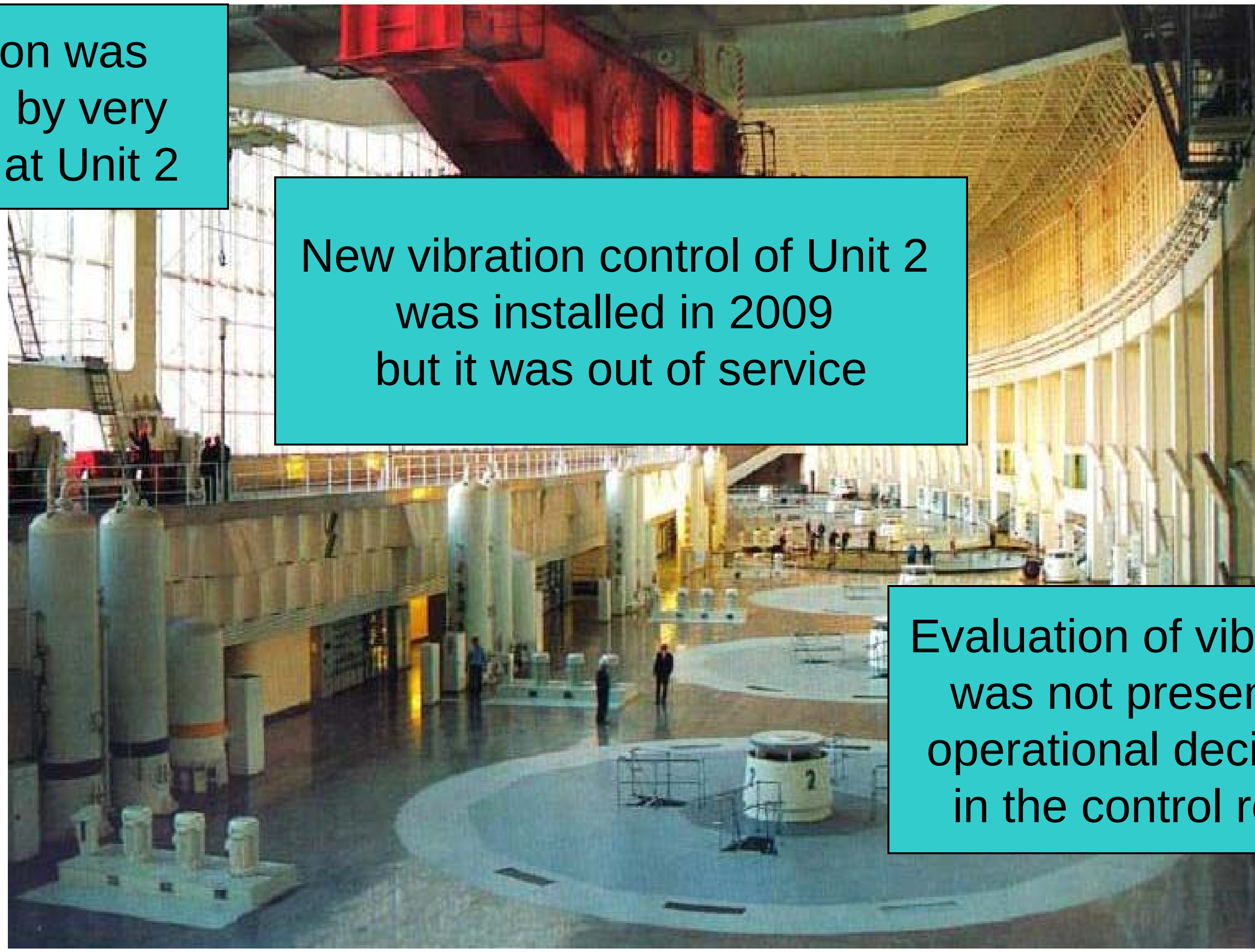
Units 1,2,4,5,7 and 9 controlled changes of MW demand & frequency of the grid

Units 8 & 10 were with base load
Unit 6 was in stand-by

Before accident Unit 2 six times was in non-recommended Zone swinging from 170 to 600-MW

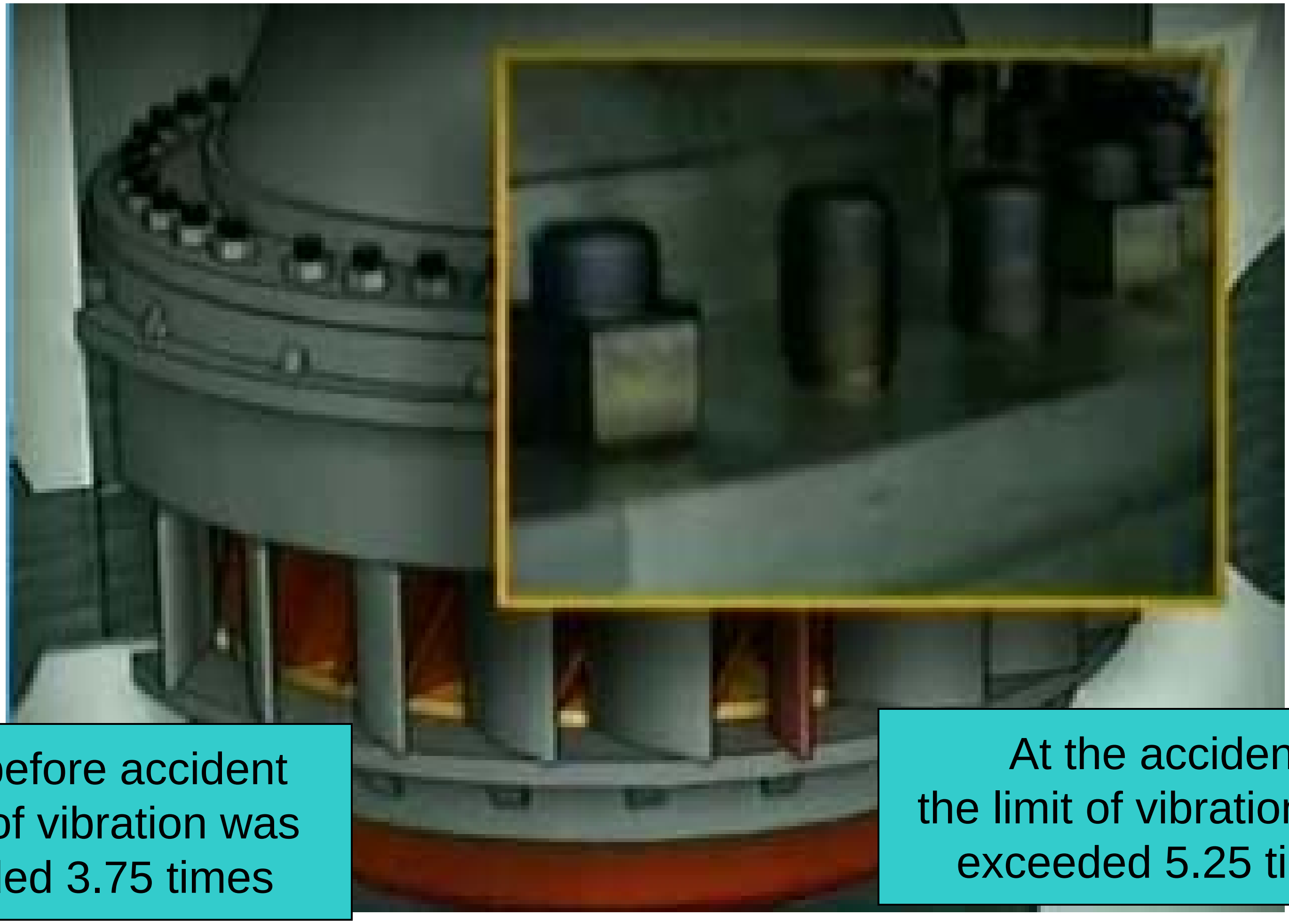
Grid regulation was accompanied by very high vibration at Unit 2

New vibration control of Unit 2 was installed in 2009 but it was out of service



Evaluation of vibration was not present in operational decisions in the control room

The Bolts and Vibration at Unit 2

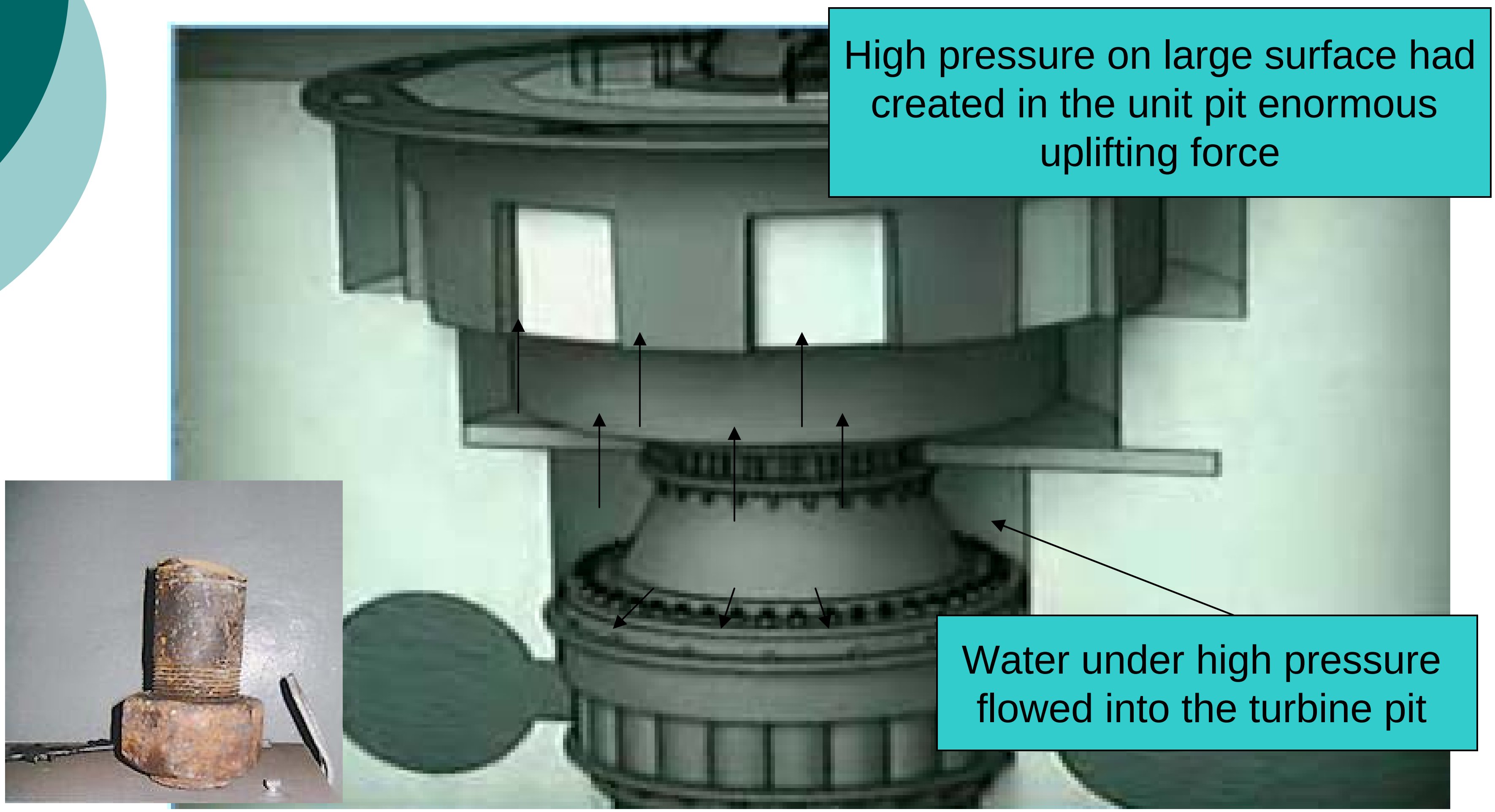


13 min before accident
the limit of vibration was
exceeded 3.75 times

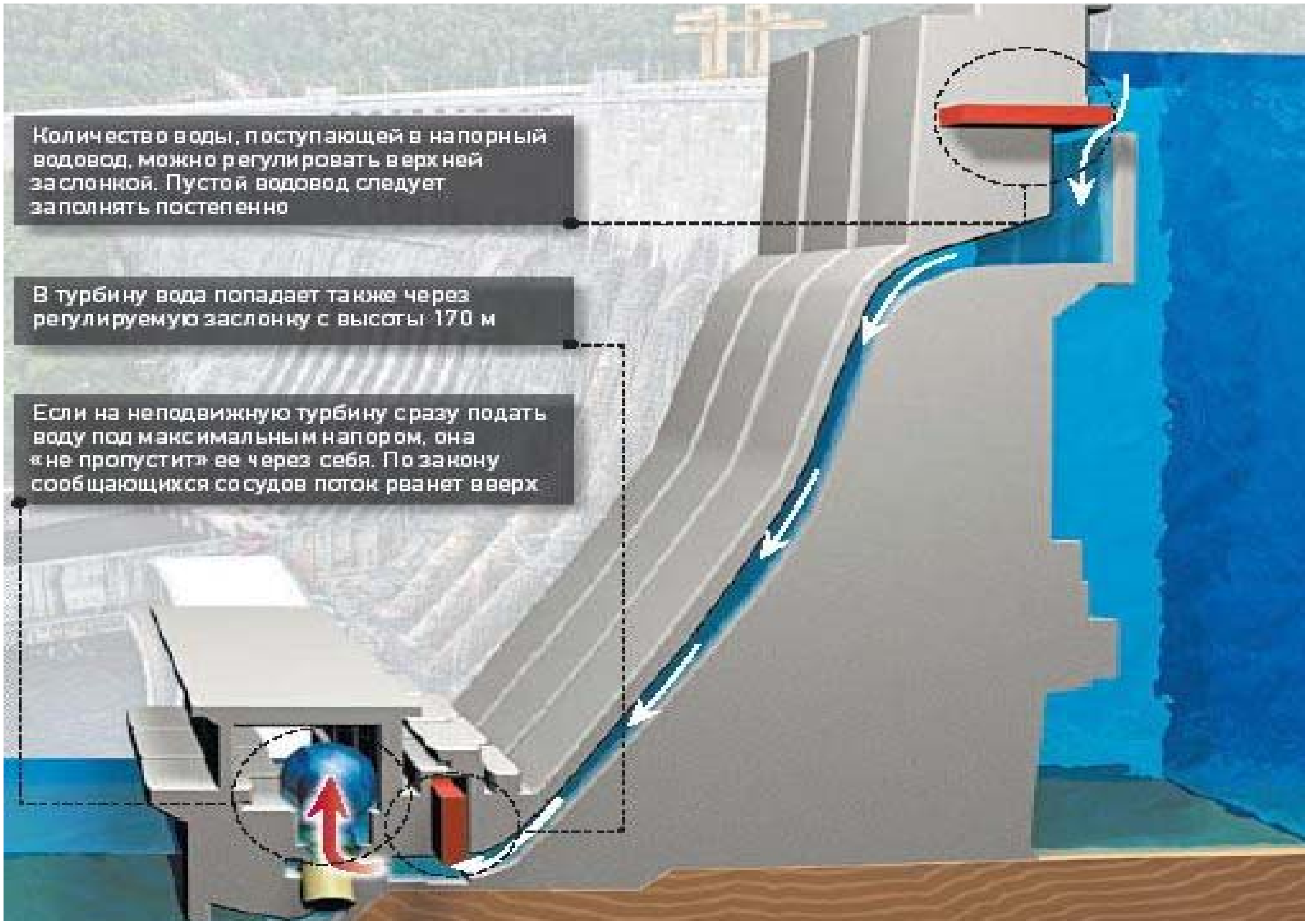
At the accident
the limit of vibration was
exceeded 5.25 times

Turbine Cover Bolts Failed on Unit 2

Turbine Cover Bolts Failed on Unit 2

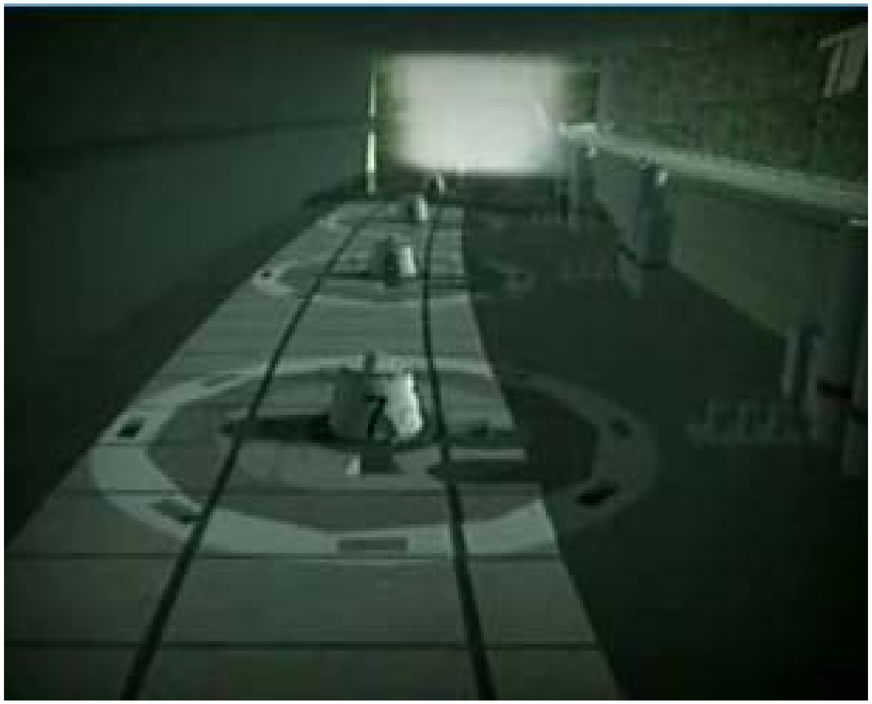


Unit 2 Was Brutally Lifted



The unit weight is 2,691-t, the rotor weight is 900-t

Flooding of the Powerhouse Started

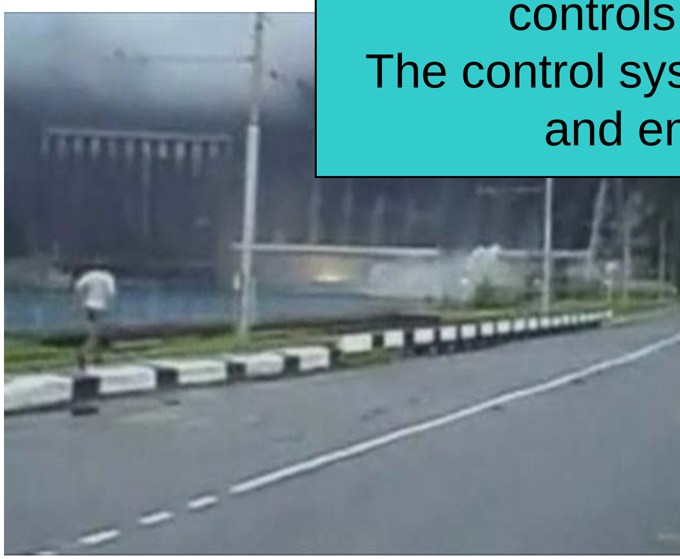


Flooding of Transformers

Section of the Powerhouse has been Washed Away

Short Circuits Caused by Water

Sudden full flooding of the powerhouse disabled controls and protections of the units;
The control systems stopped operating (no normal and emergency electricity supply)



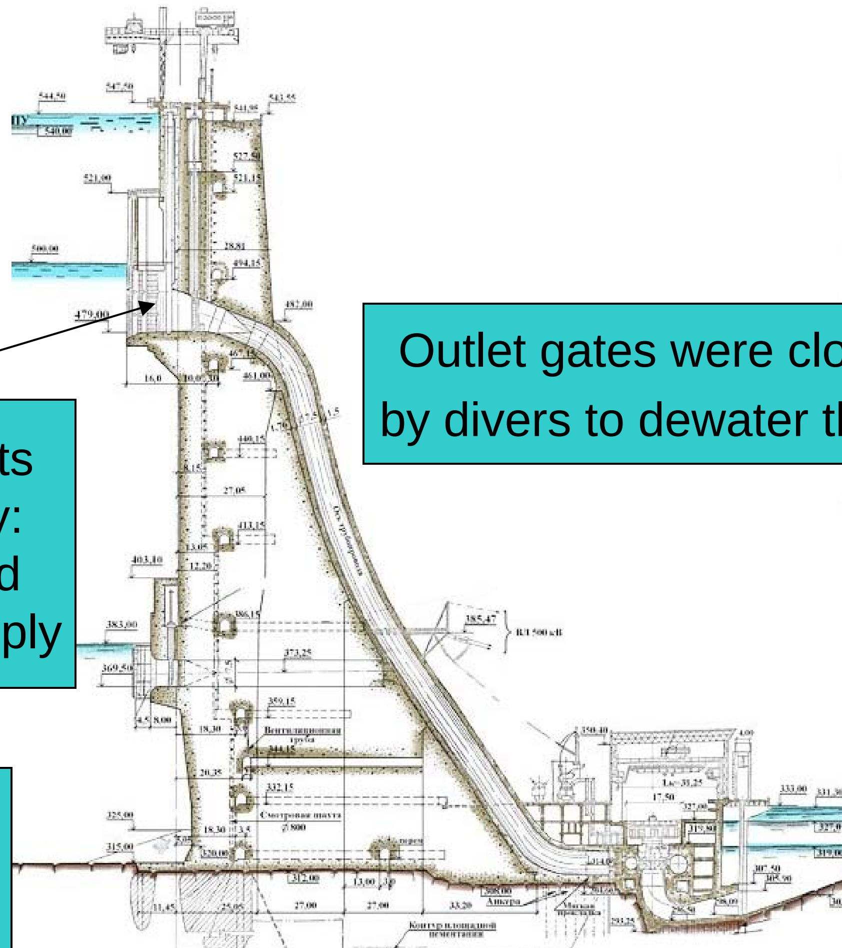
Overtopping Exposure in 2 days

All spillway gates were opened after 2-day effort: from 11:32 am

Electric generator was borrowed to open the spillway gates

Apparently the reservoir could reach overtopping exposure in 2 days after the accident, if the spillway would not be opened completely

Some Issues During the Accident



Outlet gates were closed manually by divers to dewater the powerhouse

Emergency gates of the units failed to close automatically: normal electricity failed, and there was no emergency supply

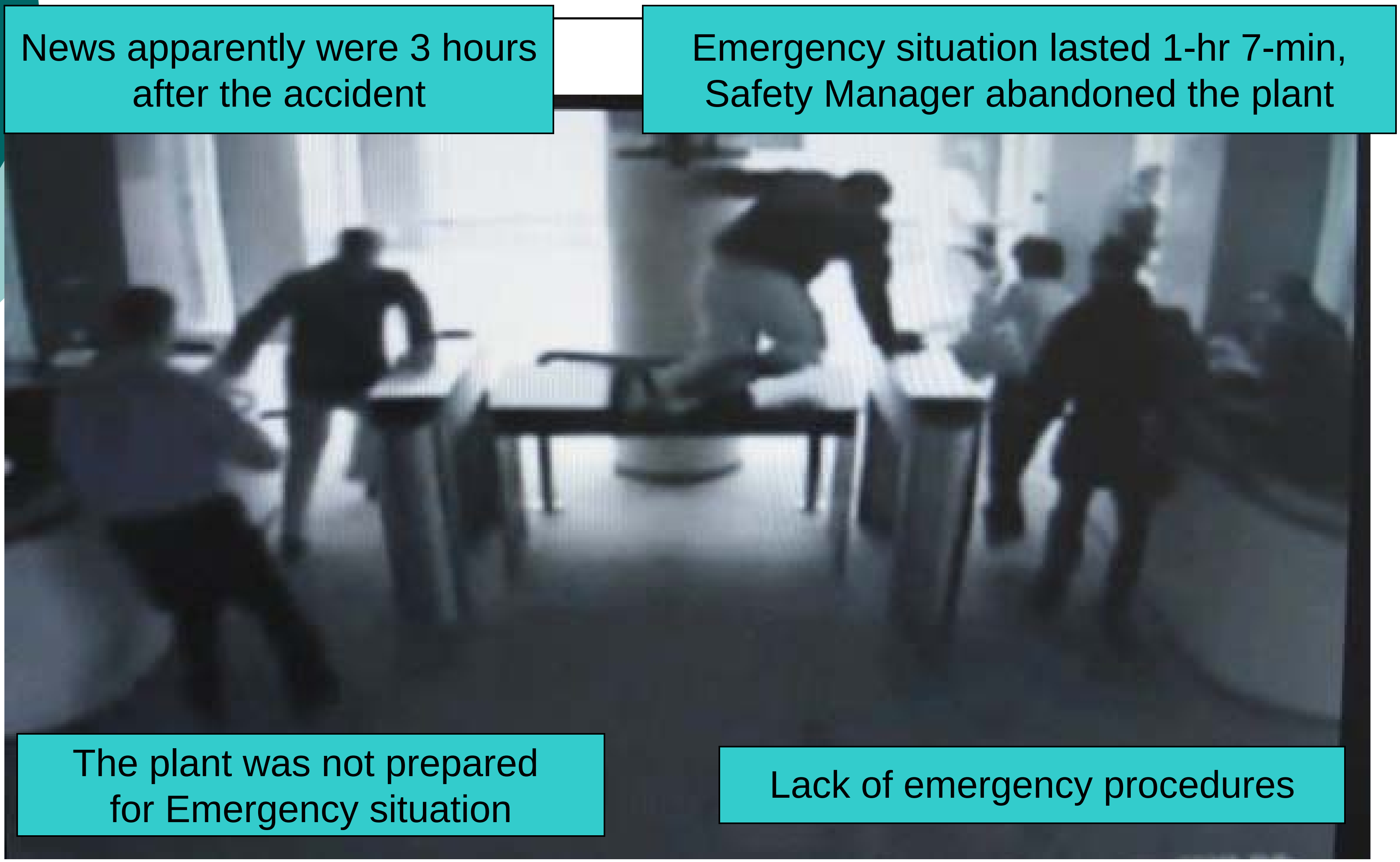
Emergency gates manual closure: From 8:35 to 9:30 am

Some Issues During the Accident

Access door to controls of the unit 2 emergency gate was closed – forced entrance was required

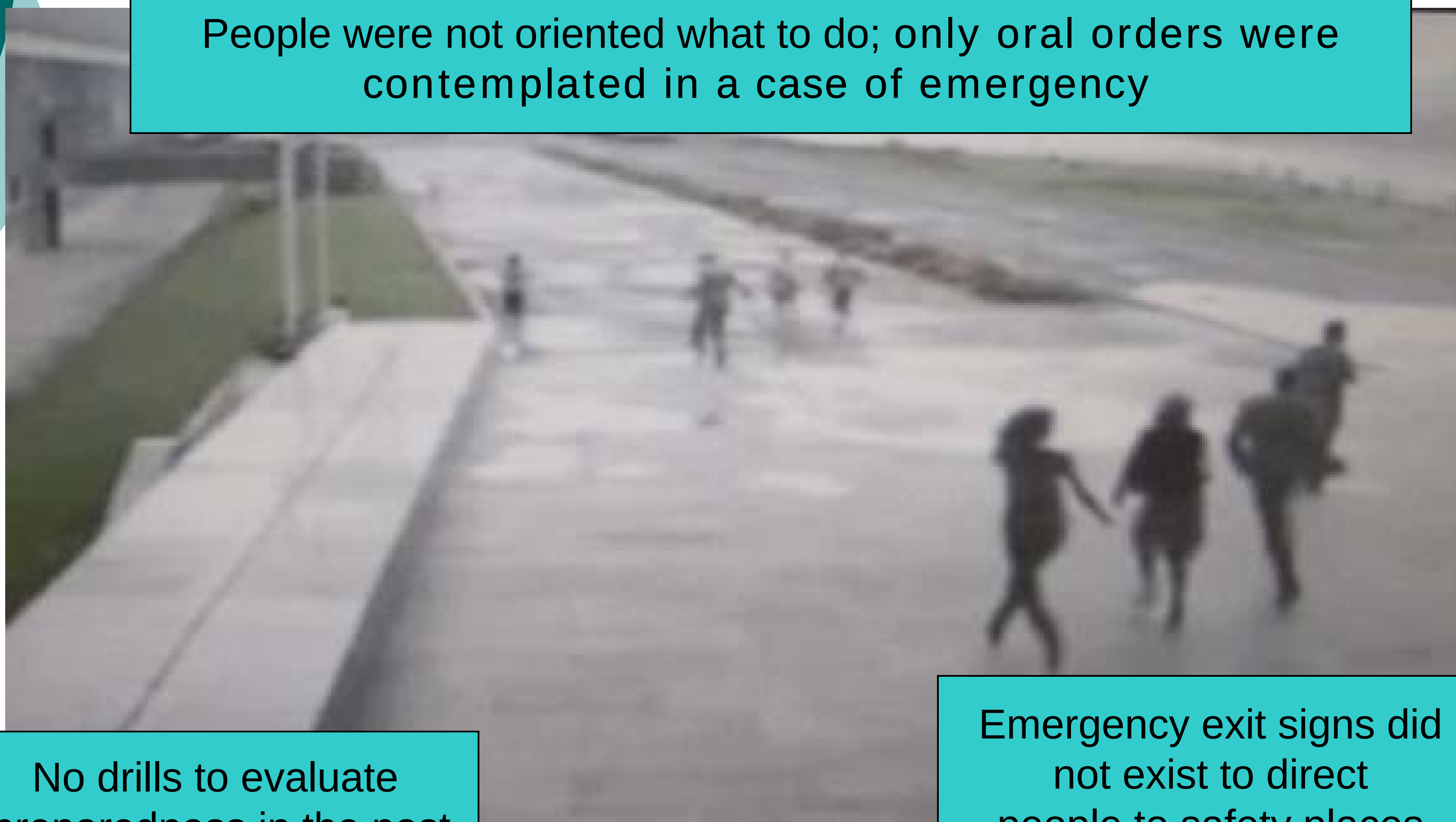
Emergency lighting failed – a pocket flashlight was used

Emergency Plan Did Not Exist



Evacuation Of People

People were not oriented what to do; only oral orders were contemplated in a case of emergency



No drills to evaluate preparedness in the past

Emergency exit signs did not exist to direct people to safety places

Emergency Electricity Supply Does Not Function – Manual Attempt To Open The Gate

The Gate Area Several Minutes Later

LOSS OF HUMAN LIVES AND SCOPE OF DAMAGE

75 Persons Died

- All persons who were inside the powerhouse at elevation 335-m a.s.l. and below have been perished.
- 10 persons from the plant and 65 maintenance contractors died.
- There were app. 300 persons at the plant at 8:13 a.m. (at the time of accident).
- Normal plant shift is app. 12 persons.

Powerhouse Before & After Accident

Total loss of equipment inside the powerhouse

Re-build time 5 years, Costs over 1.3 billion USD

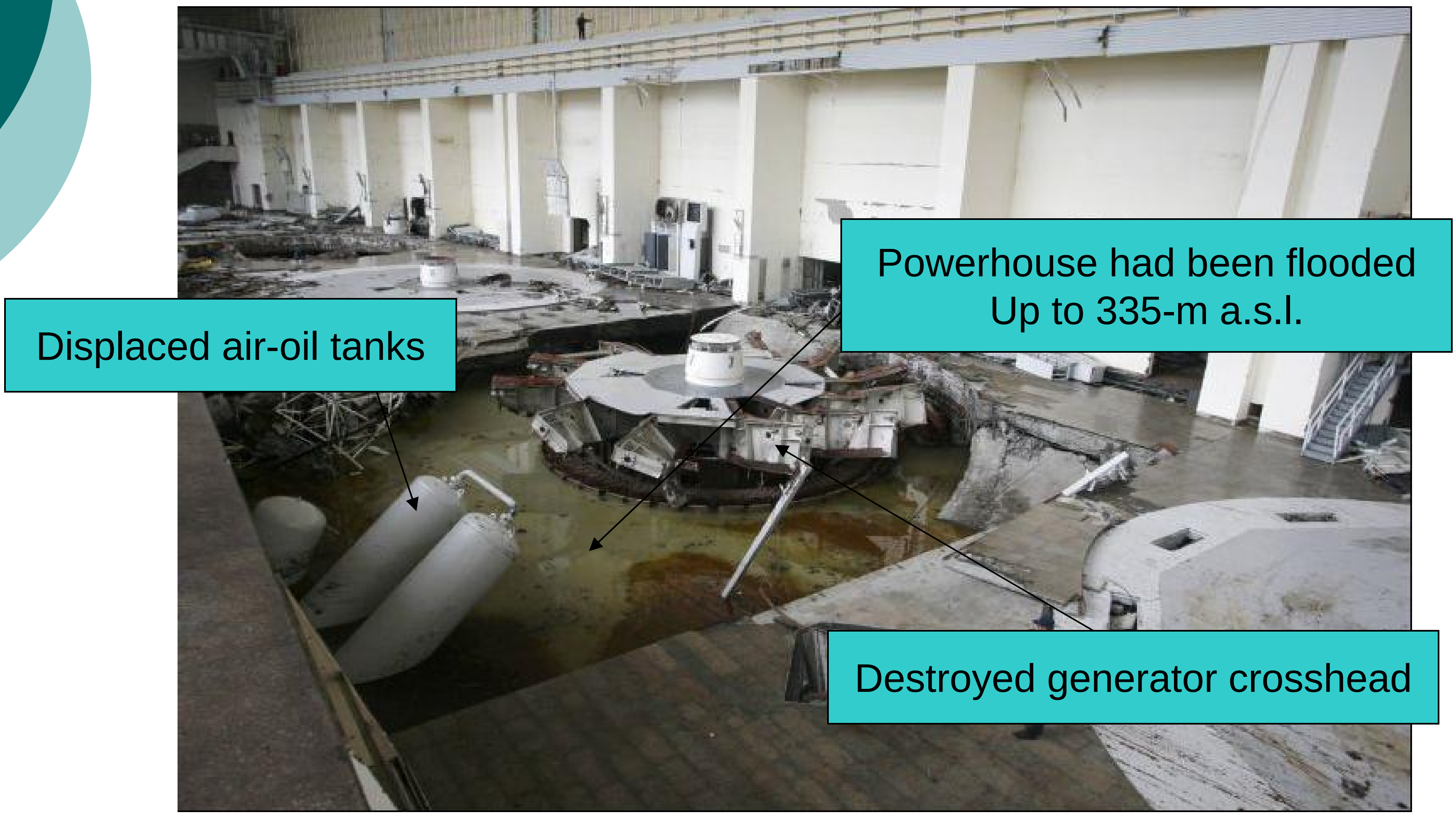
Unit # 1

CBI / Contingency Business Interruption losses for aluminum smelters

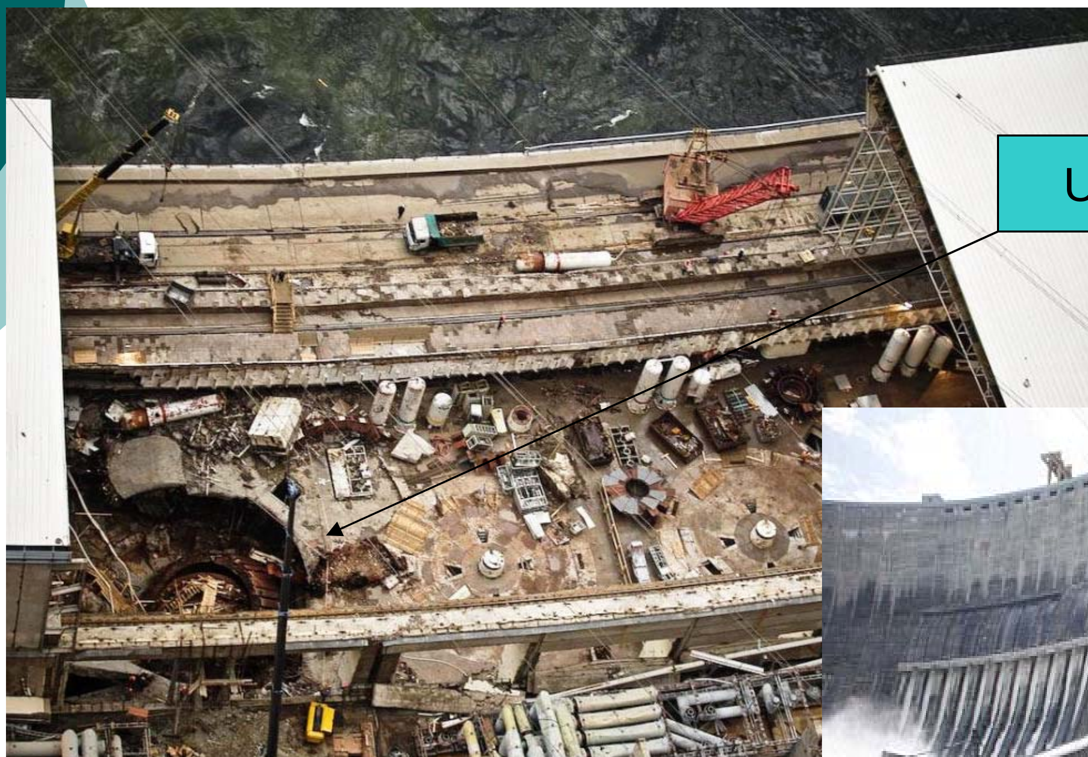
Shutdown will push up market prices in Siberia’s grid

Total Destruction of Unit # 2

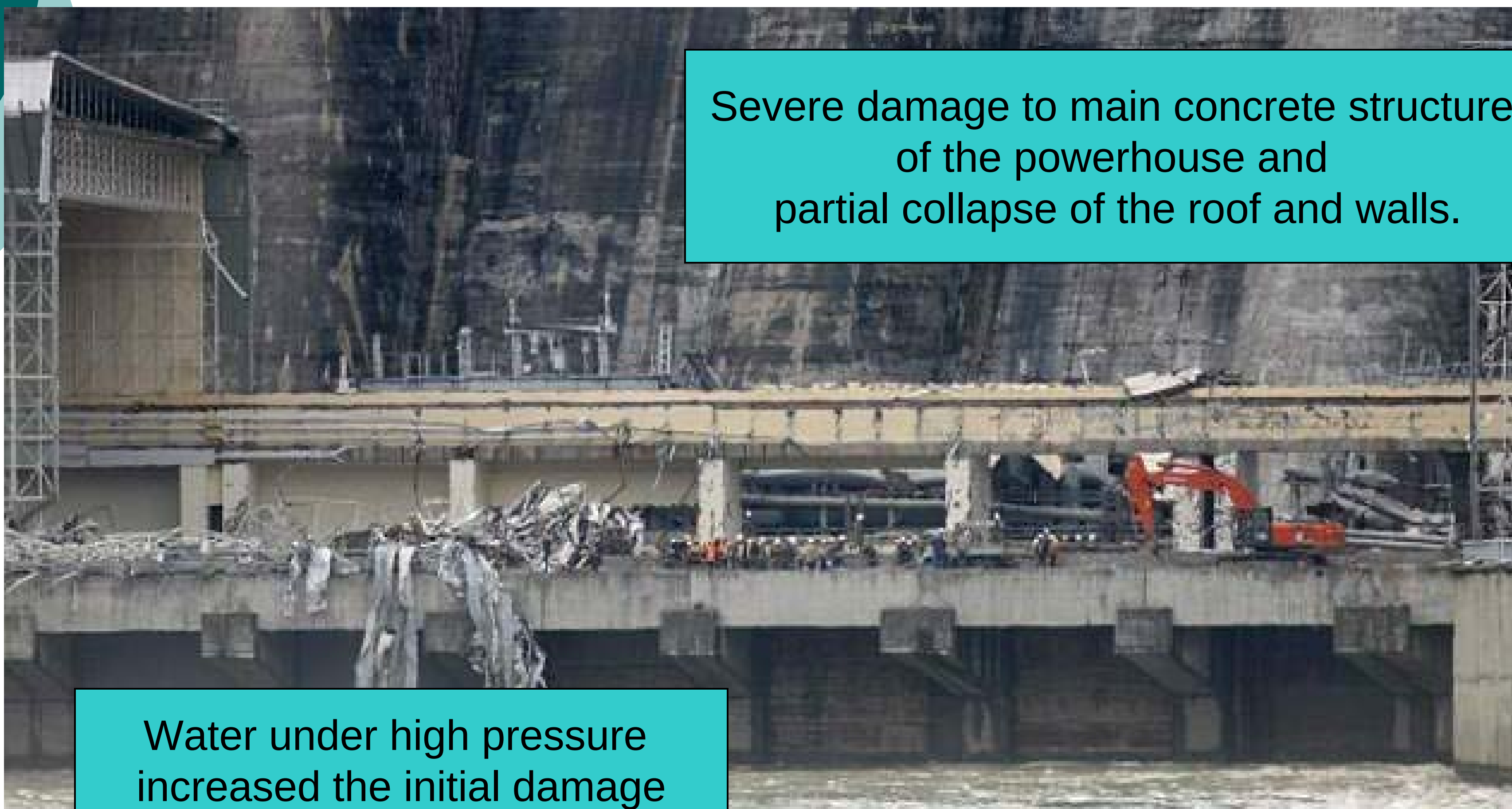
Generators 7 And 9 Destroyed By Short Circuits



Area Of The Disappeared Section Of The Powerhouse



Major Losses



Severe damage to main concrete structure of the powerhouse and partial collapse of the roof and walls.

Water under high pressure increased the initial damage

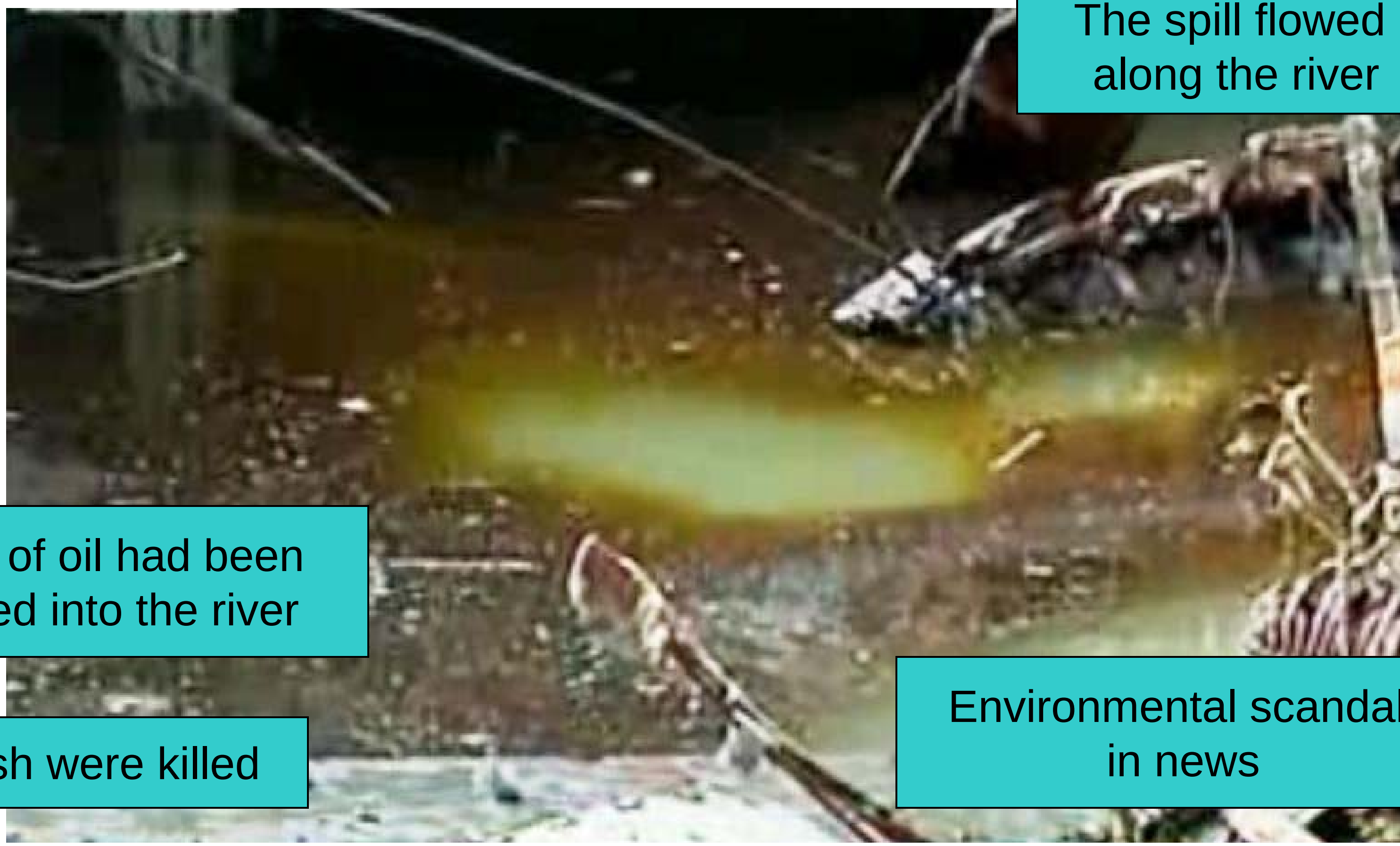
Major Losses (cont.)

Concrete elements were destroyed by brutal destruction caused by elevation of unit 2, high pressure jet streams and collapse of the structure

Damaged Transformers

After and during the accident

Environmental Impact



The spill flowed along the river

100-t of oil had been spilled into the river

Fish were killed

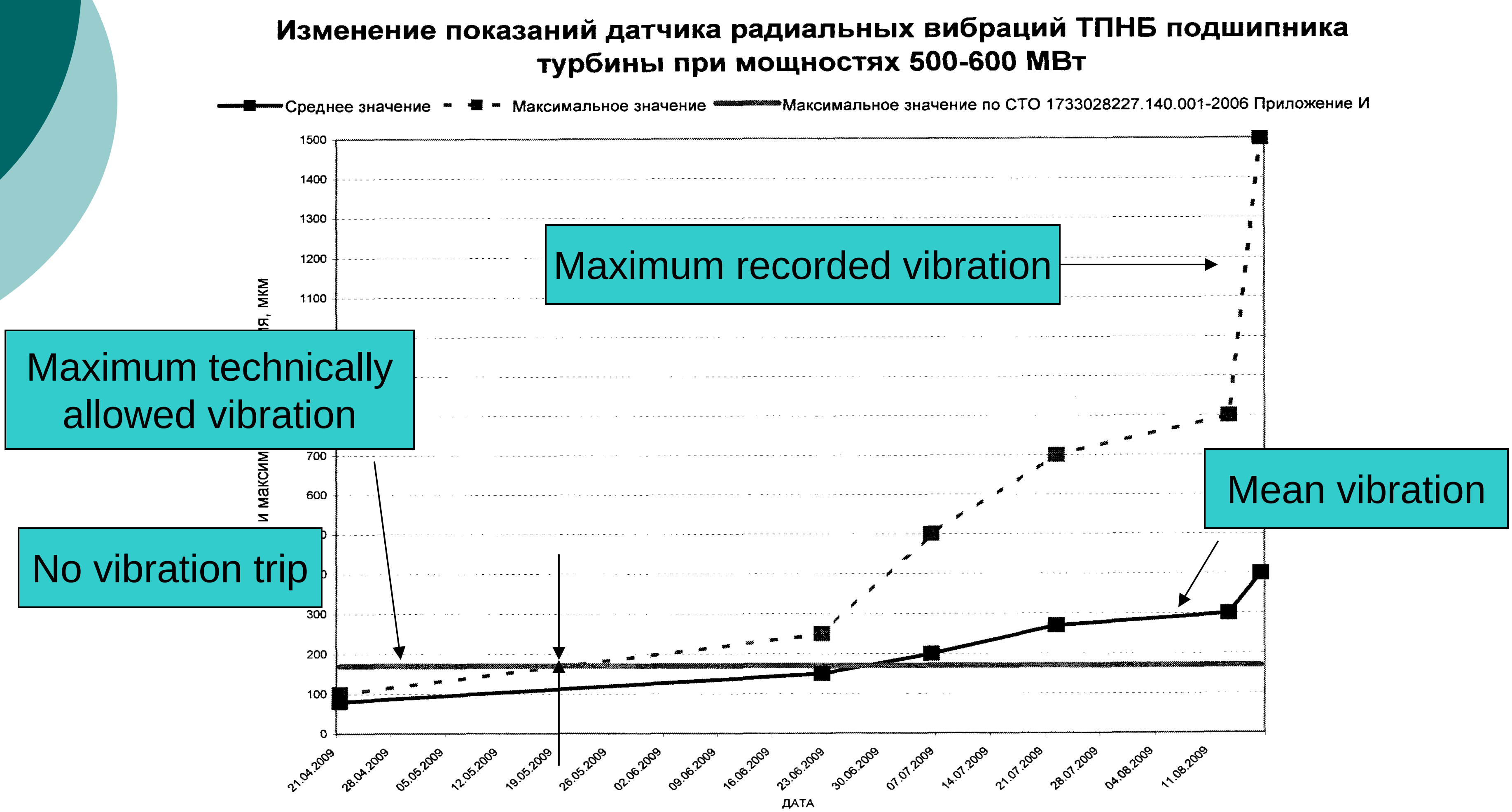
Environmental scandal in news

2-days Plant Disorganization After The Accident Versus Good Job Of External Rescuing Teams

WHY IT HAPPENED?

TECHNICAL CAUSES / HARDWARE

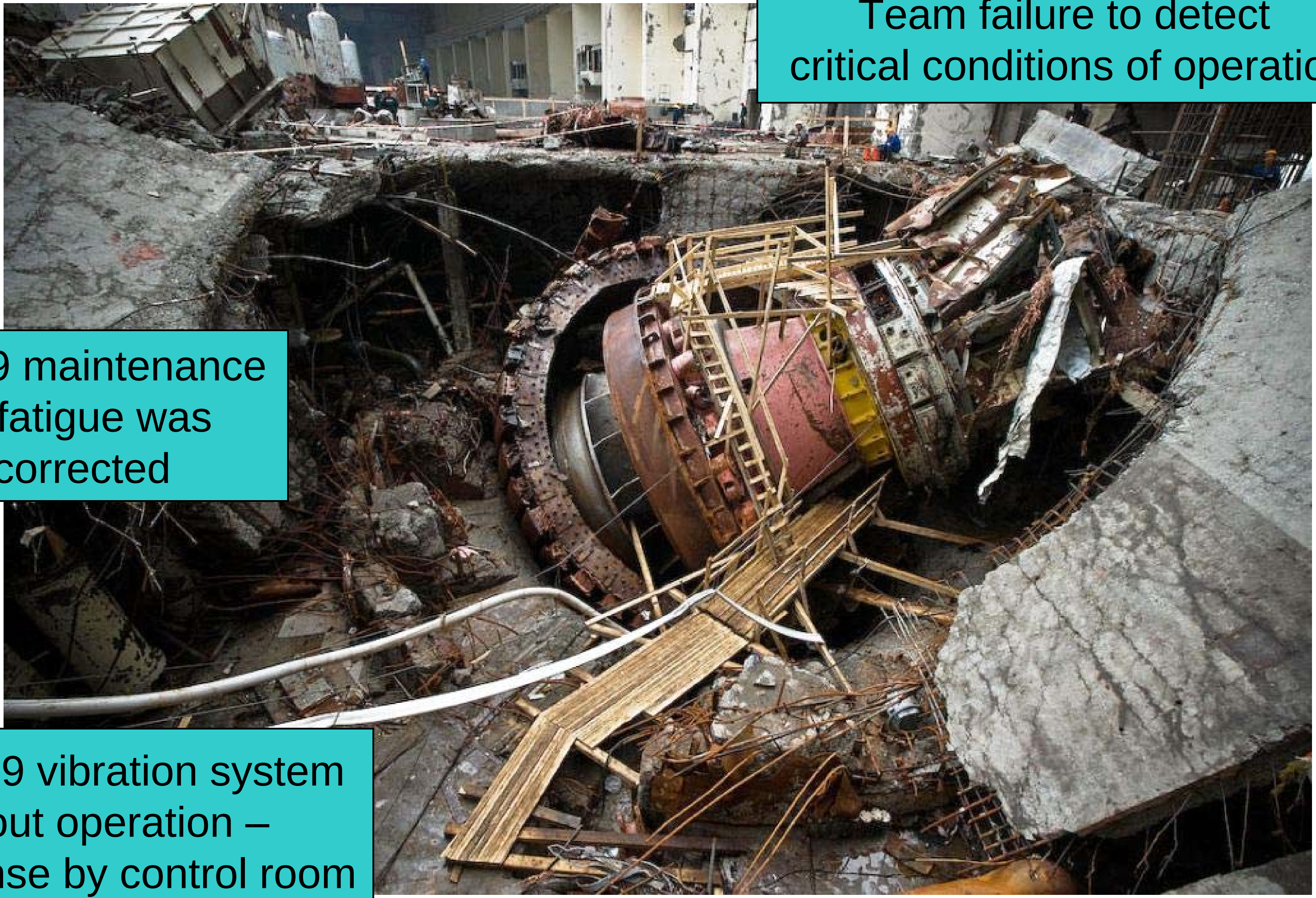
Unit 2 Should Be Shutdown In April Or May 2009



Vibration trend before the accident

Causes Of The Unit 2 Failure

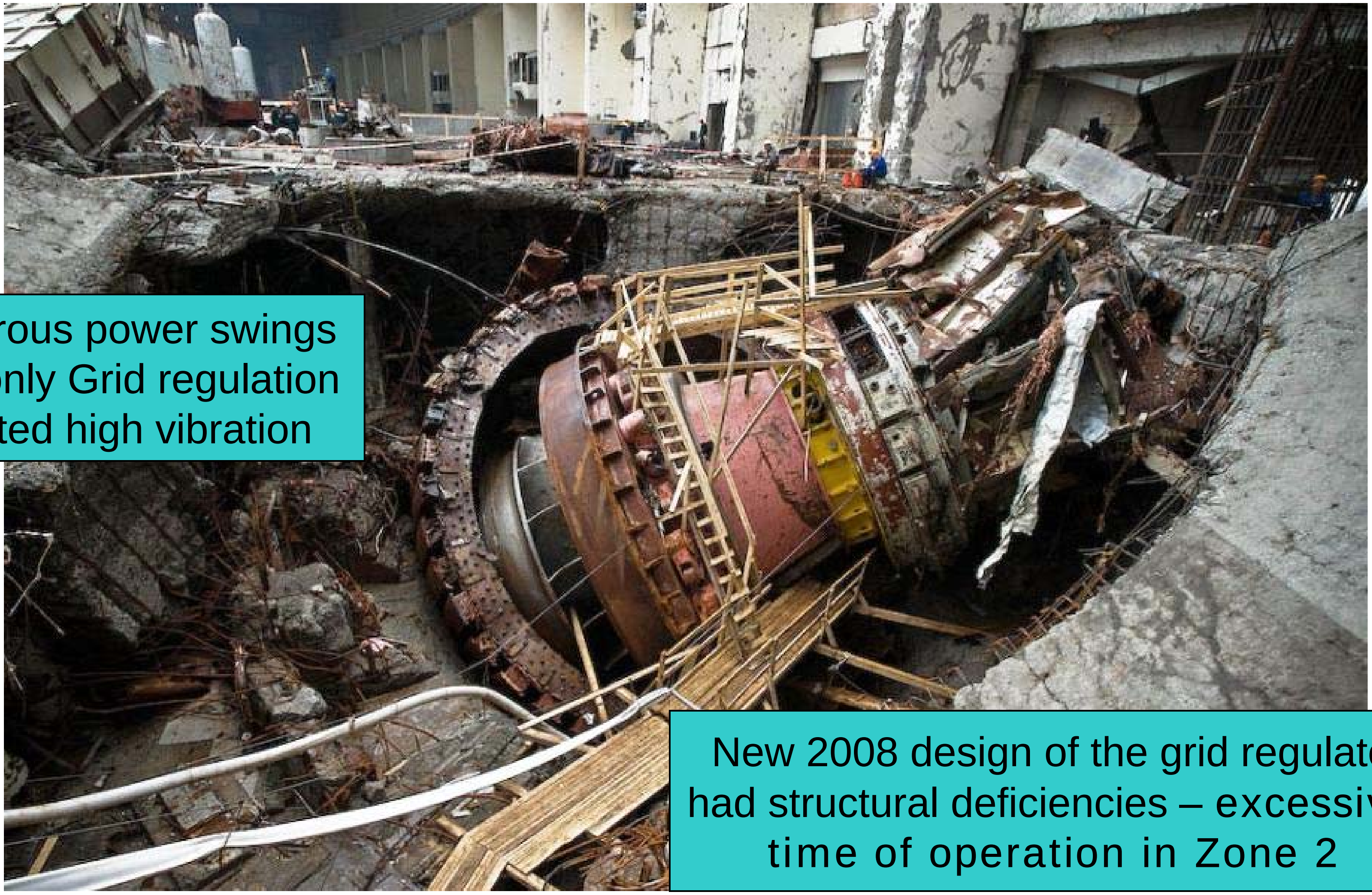
Team failure to detect critical conditions of operation



Poor 2009 maintenance - bolts fatigue was not corrected

New 2009 vibration system was out operation – No response by control room

Causes Of The Unit 2 Failure (Cont.)



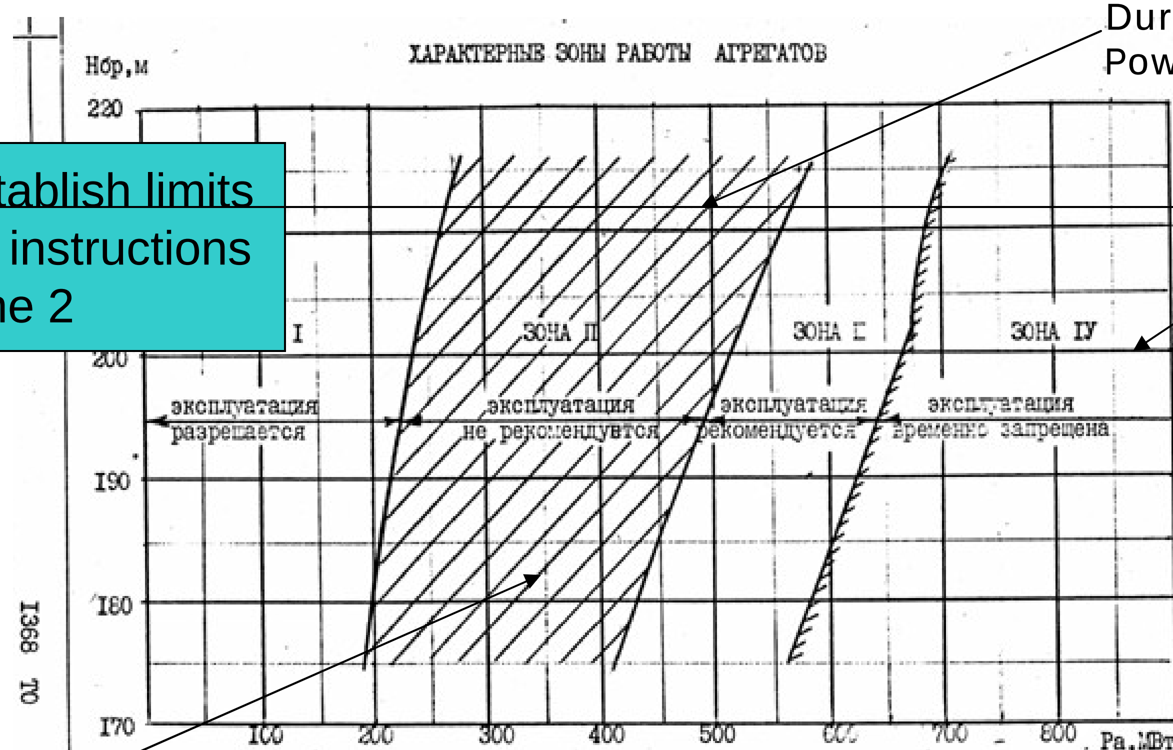
Numerous power swings being only Grid regulation - lasted high vibration

New 2008 design of the grid regulator had structural deficiencies – excessive time of operation in Zone 2

Aggravating Factors Before The Accident

- Prototype character of the Grid regulator (operational test in 2008; commissioned on 21.07.2009)
- No vibration trip
- 212-m reservoir level above designed 197-m made operation longer in Zone 2 of high vibration.
- Lack of criteria to operate / vibration and strange sounds were noted long time before
- Design of the bolts – no maintenance requirements, no forelock on the nuts
- New controls of the wicket gate at Units 2, 5 & 6 from 2009 (prototype?)
- Worn out surfaces in the bearings including the shaft contributed to higher vibration
- Cavitation had contributed to vibration / unbalanced rotor
- Unit 2 was at the end of its useful life (29 years and 9 months vs. specified 30 years)
- Useful life of the failed turbine bolts was also 30 years.

Fatigue Appeared And Developed When Units Worked In Zone 2



During accident Power=475-MW

Head = 212-m

design = 197-m

OEM did not establish limits and operational instructions for Zone 2

Operation in Zone 2 was associated with high vibration caused by hydrodynamic fluctuations in the turbine

Bolts' fatigue cracks were forming during operation in Zone 2 – a moment of failure was question of time

All Plant Units Operated In Zone 2

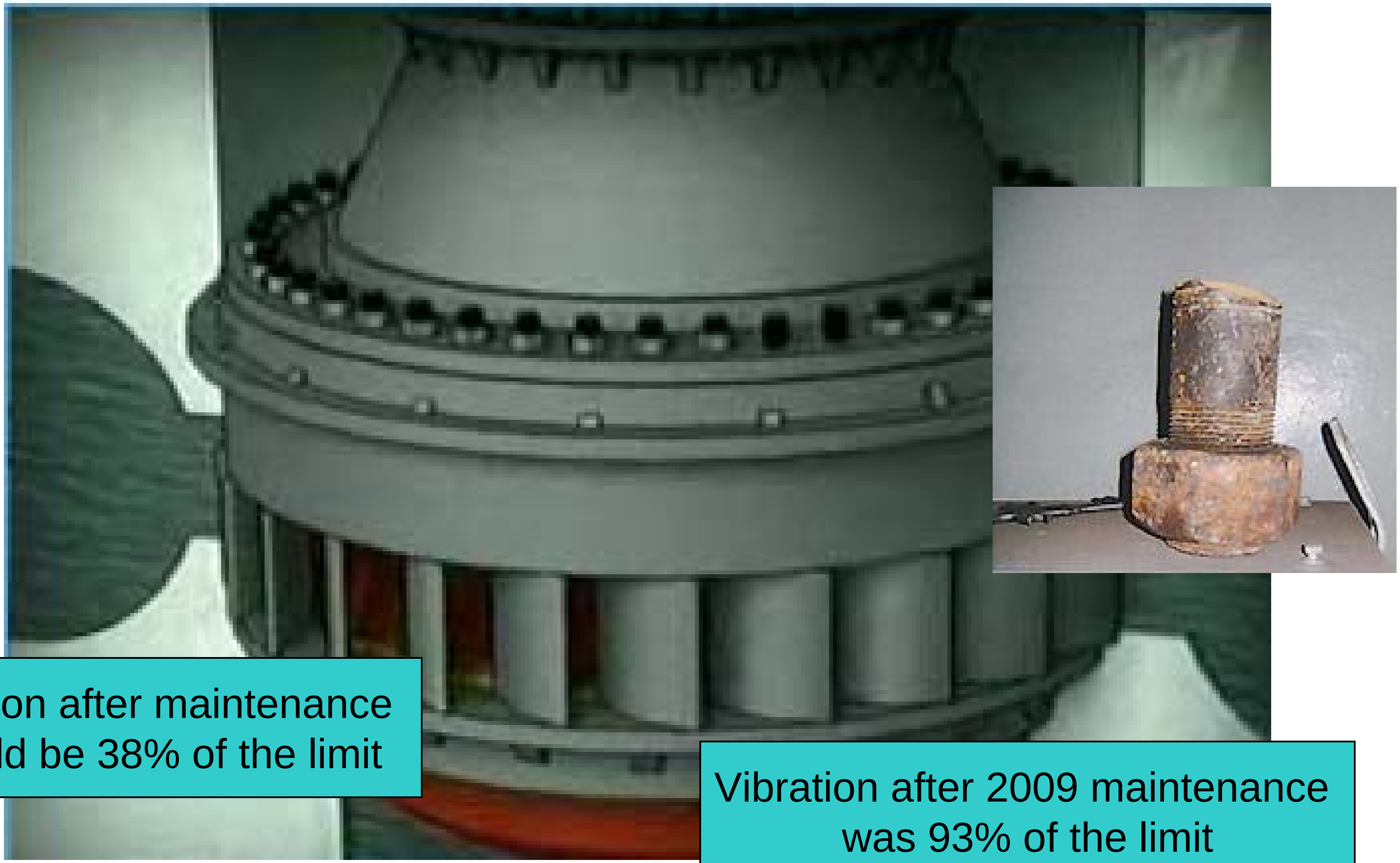
In 2009 unit 2 was
232 times in zone 2
totaling 46 minutes

In 2009 unit 4 was
490 times in zone 2
totaling 1-hr 38 minutes

Was The Grid Regulator “GRARM” Forcing Units To Work In Zone 2?

- OEM had not approved algorithm of the grid regulator
- Criteria for work priorities in the group regulation were not established
- No criteria for selection of the leading unit neither how long to maintain it regulating
- Specific design and the camp of operational characteristics of the units were not considered
- Individual power limits and specific physical conditions and vibration behavior of each unit in zone 2 were not considered

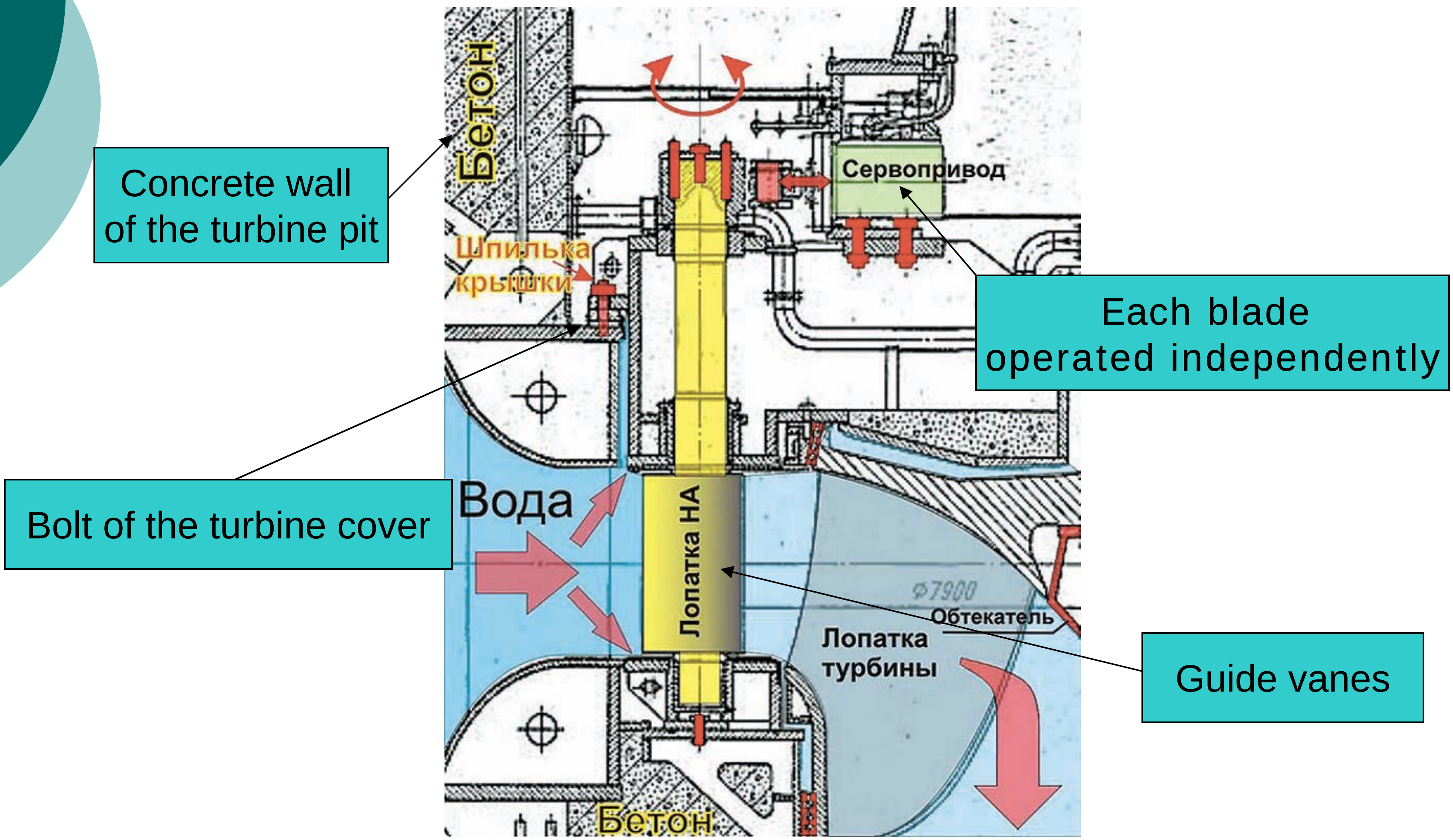
High Vibration Was From 1982



Vibration after maintenance should be 38% of the limit

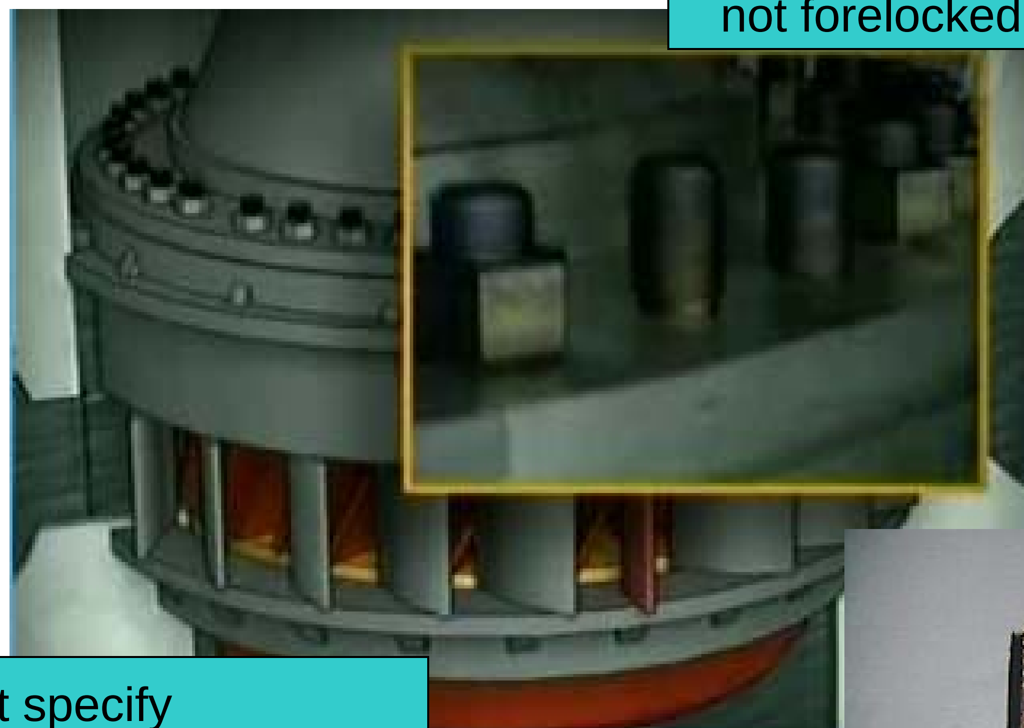
Vibration after 2009 maintenance was 93% of the limit

Turbine Pit, Turbine Cover and the Bolts



At Least 6 Nuts Were Not Installed, Total 80 Bolts X 80-mm Diameter

The nuts were
not forelocked by design



OEM did not specify
requirements for the bolts maintenance
and inspections: result-badly worn bolts

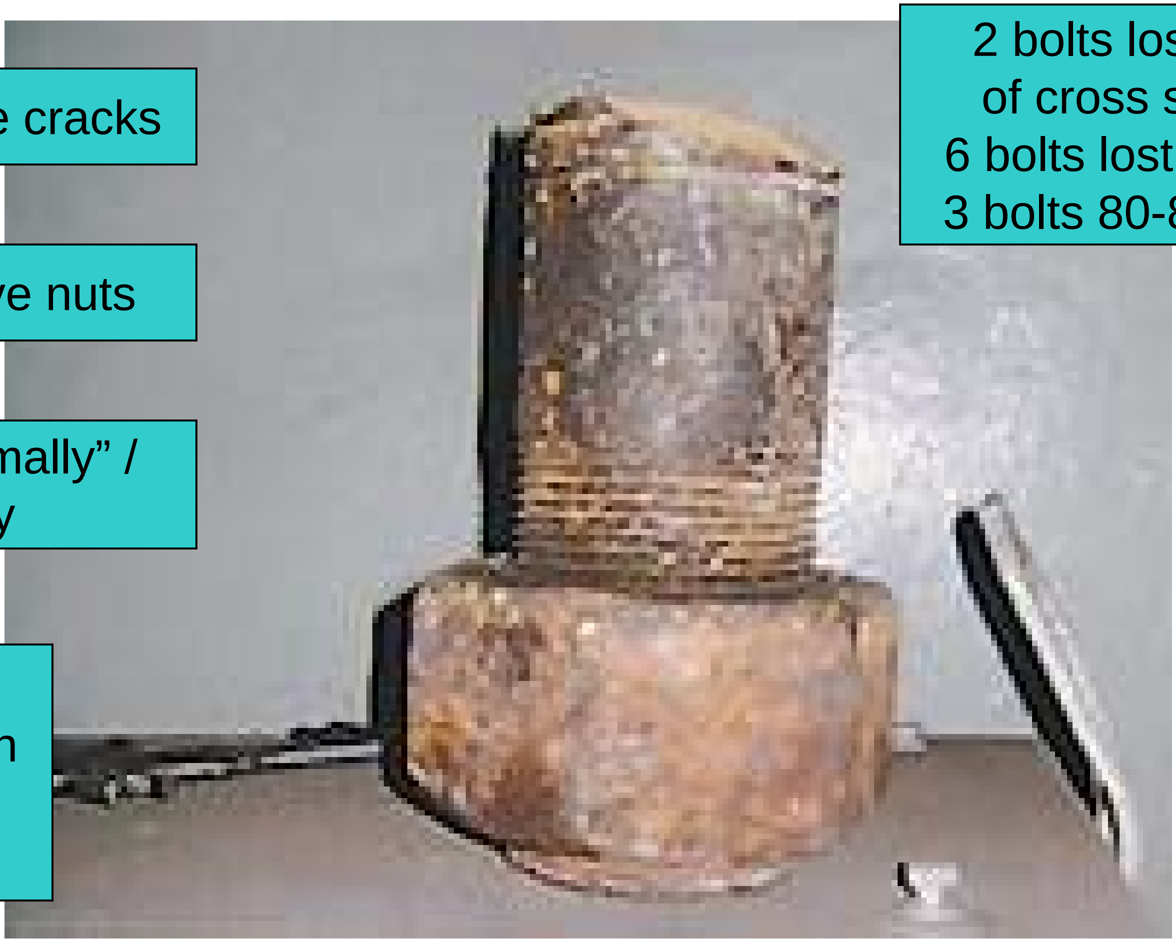
47 Bolts Of 49 Laboratory Tested Were Defective (All From Unit 2)

41 bolts had fatigue cracks

6 bolts did not have nuts

2 bolts failed “normally” / mechanically

49 bolts lost 65% of their cross section because of the fatigue cracks



2 bolts lost 96% of cross section
6 bolts lost 90-95%
3 bolts 80-85% etc.

Picture is shown for reference only as example

Issues With Design Of The Units

Cracking of the turbine blades. Cracks up to 130-mm

Cavitation loss up to 12-mm

Not reliable generator breakers

Obsolete and not reliable control systems that had 10-year useful life

Issues With Design - Conditions Of The Turbine Wheels

- The turbine wheels had to be repaired every 9k to 10,000 hours because cracking of the blades is permanent.
- Use of welding was required to repair cracks up to 130-mm and cavitation loss of metal up to 12-mm deep.
- More repairs mean higher exposure to breakdown. There should be limits how many times the turbine wheels may be repaired.
- Recommendation to replace the worn out wheels was never implemented.

WHY IT HAPPENED?

HUMAN ELEMENTS / SOFTWARE

Aggravation Factors Of The Accident

1. Errors in design of the plant and equipment
2. Lack of investment to replace obsolete equipment
3. Poor maintenance and operational standards
4. Gross negligence and carelessness of management at all levels

Design Errors

- Plant had no facility to close from the control room the emergency gates at the penstocks (no manually operated button).
- Emergency gates at the penstocks did not close when electricity supply fails (in case of over speed-yes).
- Wicket gates did not close when electricity supply fails.
- There was no separate and totally independent back-up electricity supply system installed.
- Architecture of the control systems was not uniform for all units.
- No trip on high vibration
- Protection devices and circuitry was not dust- and water-proofed

Design and Operational Issues

- Significant increase of scope of maintenance work was noted after 50,000-hr of unit operation. As consequence more people were required or not all work done.
- New instruction to evaluate the risk of operation has canceled a number of previous documents related to safety standards. That was against a general trend that equipment was getting more obsolete and deteriorated.
- Cost-cutting on safety: Safety standards had been simplified and several safety documents are not anymore in use from 2006.

Poor Conditions Of The Plant Were Well Known

- Ex-General Manager denounced the critical condition of the plant many years ago.
- 2007 survey of the Russian Accounting Chamber: use of the plant is dangerous, the prosecutor general's office was approached
- 2007 info warned: 85% of the equipment was obsolete; most of the equipment was worn-out.

Poor Conditions Of The Plant Were Well Known (cont.)

- Before 2000 Rostechnadzor (jurisdictional body) had stated that the operation was unsafe
- 2007 and 2008 surveys done by Rostechnadzor could not prevent the accident (no issues found – suspected corruption)
- Plant was commissioned officially only in 2000 because of problems to finish project but commercial operation started in 1978
- 2000 reception of the plant was based on 1989-1991 documentation: real conditions were not documented
- General quality of the project and equipment was declared in 2000 as “**GOOD**”

It Was A Stockholders Business
To Maintain The Plant In Safety Conditions

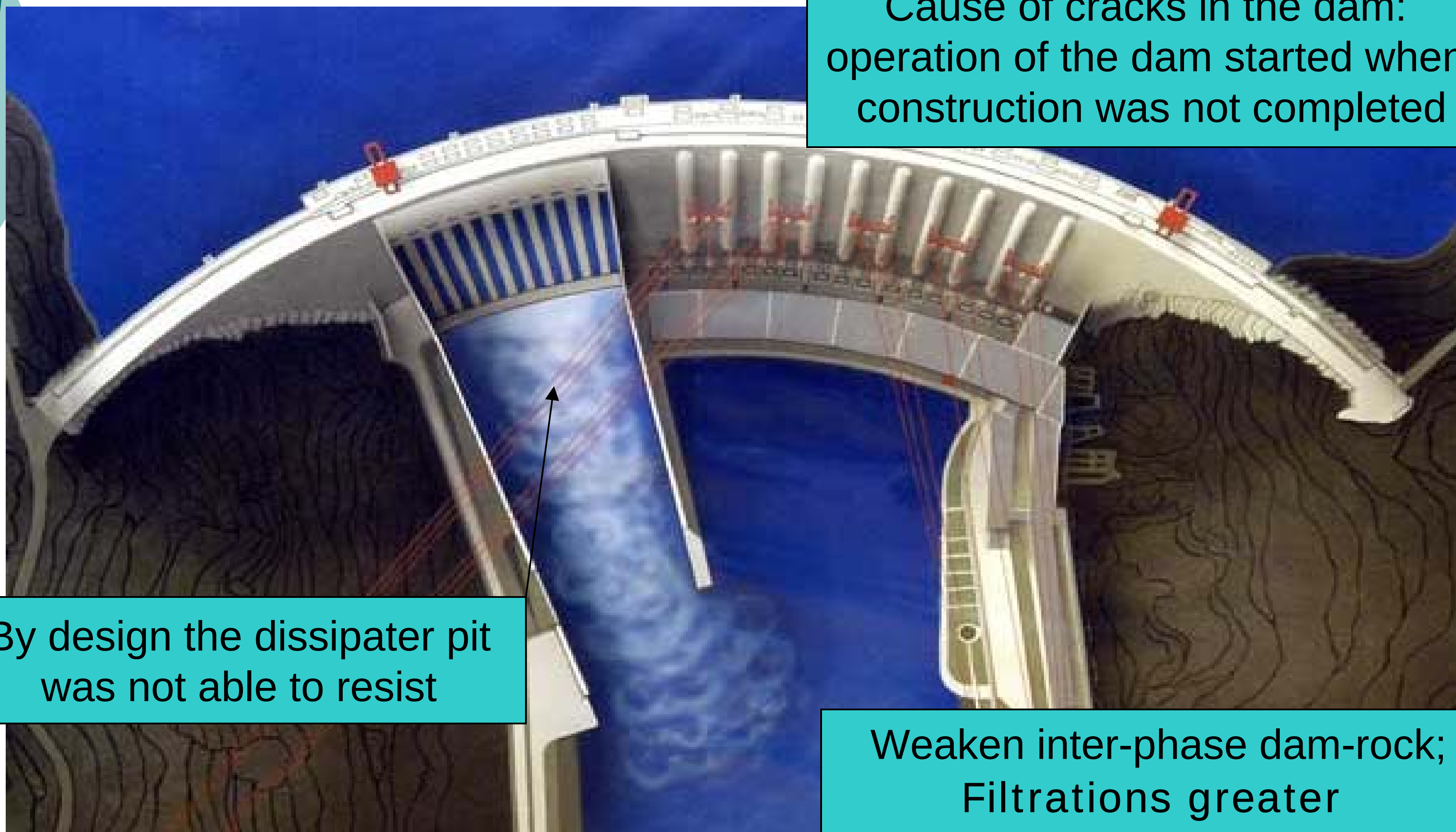
(reply of the prosecutor general's office in 2007)

Jurisdiction surveys responsible to supervise safety were misleading due to corruption

THREE MAJOR ISSUES WITH THE DAM AND SPILLWAY

Major Issues of the Dam

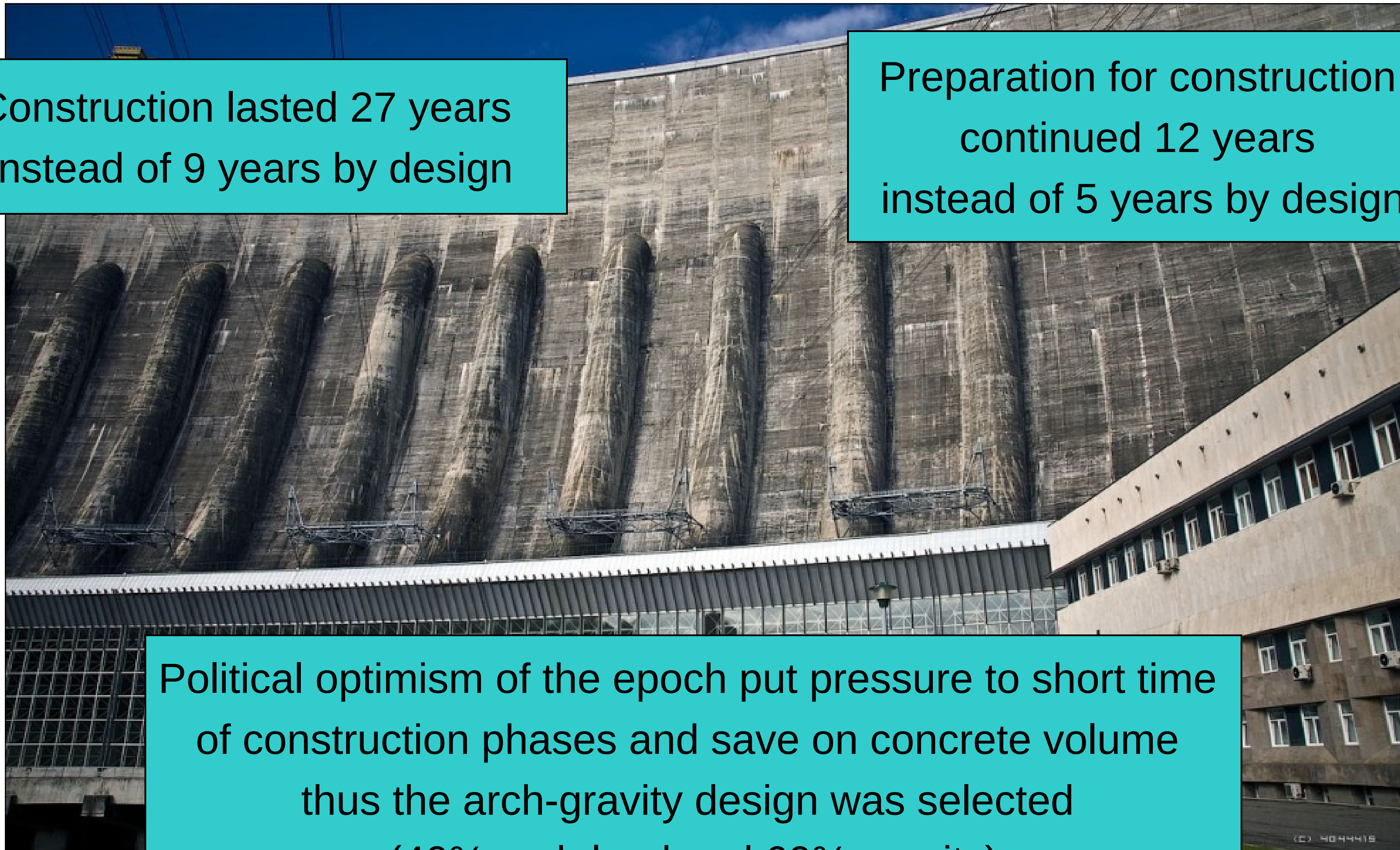
Cause of cracks in the dam: operation of the dam started when construction was not completed



By design the dissipater pit was not able to resist

Weaken inter-phase dam-rock; Filtrations greater than estimated by design

Deterioration Of The Dam Had Started During Construction



Construction lasted 27 years instead of 9 years by design

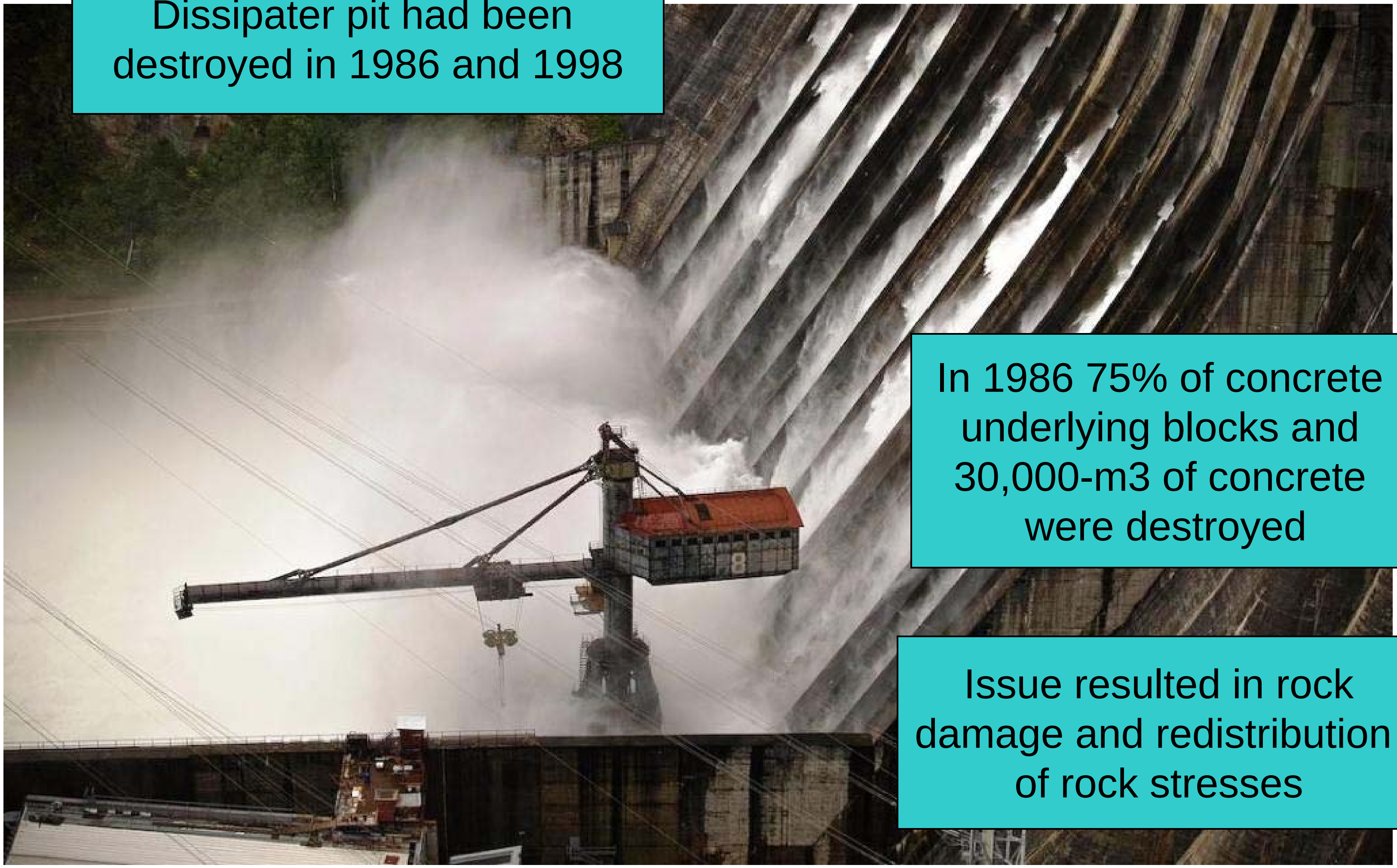
Preparation for construction continued 12 years instead of 5 years by design

Political optimism of the epoch put pressure to short time of construction phases and save on concrete volume thus the arch-gravity design was selected (40% arch load and 60% gravity)

Dam Was Repaired In 1996 & 1998

The Energy Dissipater Requires Repair Now!

Dissipater pit had been destroyed in 1986 and 1998



In 1986 75% of concrete underlying blocks and 30,000-m3 of concrete were destroyed

Issue resulted in rock damage and redistribution of rock stresses

Solution of the Spillway Issue

Additional lateral spillway is
under construction at the present time

The Plant Had Been Flooded Twice In The Past : in 1979 and 1985

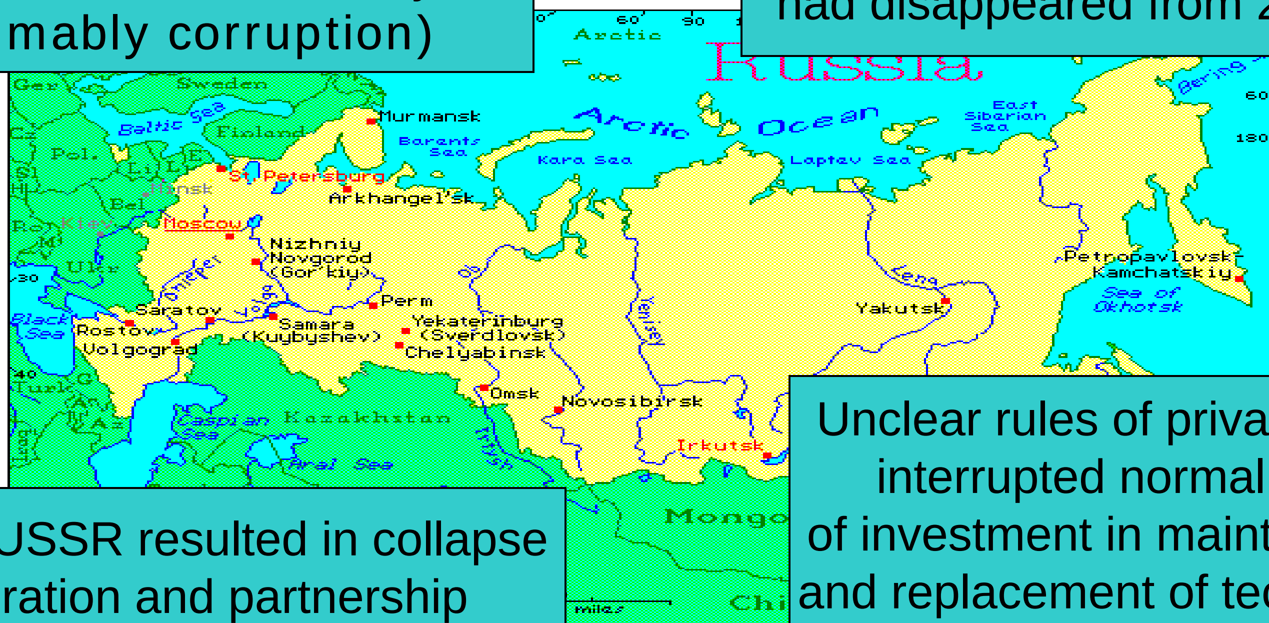
ISSUES WITH ELECTRICITY SECTOR

- In Russia
- In the company
- At the power plant

Some Issues in Russian Electricity Sector

46 regional managers of 84 in Rostechnadzor (jurisdictional body) were fired recently (presumably corruption)

Efficient State Centralized Supervision for Hydros had disappeared from 2000



Collapse of USSR resulted in collapse of cooperation and partnership with issues of supply and quality of the products and service

Unclear rules of privatization interrupted normal rate of investment in maintenance and replacement of technology

Blame-on environment at state, company and plant level

Some Issues in Russian Electricity Sector (cont.)

Major accent on making money then on sound technical policy; this is known in the Russian press as “Factor of Successful Manager”

Decreased efficiency of communication inside the companies & with contractors

Interrupted continuity of operational standards between old & new generation of specialists

Increasing lack of qualified labor for operation and maintenance

Some Issues in Rushydro

High degree of
technical obsolescence

Slow modernization

Location

Potential corruption – company
personnel was stockholders
of the contracted companies

Low technological discipline
of operation and maintenance

Issues at the Plant

- Extended life of some elements beyond recommendations of OEM (i.e. control systems)
- OEM / LMZ was excluded to provide maintenance to the plant (local companies were benefited)
- Careless and greedy plant management (conclusions of the commission) who was shareholders of the contracted local companies.
- Manufacturer of the turbine bolts that failed was not invited to diagnostic their conditions (Unit 2 from 1979)
- Operational and maintenance requirements were not understood and clearly expressed

Negligence At The Plant

- Criminal behavior of personnel that failed to recognize danger – formal accusations had been presented to the court.
- Fatigue cracks in the bolts had been reported but corrective measures were not taken. No NDT applied for evaluation.
- Maintenance contracts did not specify requirements for quality control of works.
- Failure to comply with technical instructions. During maintenance works some defects were not repaired.

CONCLUSIONS

Specific points to be discussed during Power Gen engineering surveys in Russia /

From insurance point of view

Consequences Of The Accident

- Total loss of the powerhouse is now a real loss scenario for large plants (before total flooding of the powerhouse was related probably with a dam break).
- Cost of human error may be significantly higher for large plants then for small ones.
- Lack of the loss control programs and emergency plans is significant deficiency.
- Permanent drills are required to know real preparedness.

Background of the Russian Generation Industry

- Obsolete critical equipment is in use beyond the useful life specified by OEM - higher that normal Machinery Breakdown (MB) exposure.
- Vulnerability associated with quality of modernization including gross negligence.
- Prototype character of the critical items during modernization of large power plants - issues with quality of supplied items increase MB exposure.
- Impact of poor technological discipline (misleading certificates and misrepresented evaluations, quality control, qualification of labor and other issues).

Specific Check Points For The Bolts Of The Hydraulic Turbine Covers

- Useful time of life, scope of maintenance and NDT inspections of the bolts.
- Operational instructions and limits to work in the non-recommended zones of the unit to avoid initiation of the fatigue cracking (swing of power, vibrations limits).
- Installed system of the Grid regulation: behavior in the non-recommended zones, manufacturer, when installed and upgraded, OEM approval.

Specific Check Points For The Bolts Of The Hydraulic Turbine Covers (Cont.)

- Control of number of the operations and time of operation inside the non-recommended zone to adjust frequency of inspections and maintenance
- Operational vibration system with capacity for vibration analysis (vibration spectrum, recording of the data etc.)
- How the grid regulation facility takes into consideration real physical conditions of the unit (levels of vibration, hydrodynamic unbalance in the turbine, conditions of the turbine wheel / cracks, number of repairs and vulnerability to cracking, loss of metal by cavitation and erosion, conditions of bearings and other factors)

Specific Check Points For The Bolts Of The Hydraulic Turbine Covers (Cont.)

- Independent emergency generator for activation of the spillway gates and units' emergency gates at water conducts.
- Independent emergency generator for the powerhouse in addition to battery supported systems
- Emergency closing (trip) of the guide vanes / wicket gates and the units emergency gates when electricity supply failed
- Remote manual closing of the units emergency gates from the control room (stop water flow)
- Other important points not mentioned here.

Specific Check Points For the Plant Equipment

- List of equipment and critical elements with expired useful life defined by OEM specification in order to control obsolescence and extreme degradation
- What is percentage of the obsolete equipment that the plant has at the present time?
- Do all obsolete equipment included into the modernization programs?
- What are prototype solutions during upgrading, refurbishing and modernization (whose failure may result in major loss)?

Specific Check Points For the Plant Equipment (cont.)

- Dynamics and execution of the modernization program / percentage of investment, availability of the budgeted funds
- Spill capacity of the dam versus updated flood flows for specific return periods (recommended update every 10 years). Emergency watershed regulation should be in use when there is an issue with spill capacity – this is in function of social risks downstream the dam.
- Conditions of Interfaces dam-rock: injection screens that control filtrations under the dam and through the dam abutments on both banks. Alarm when filtrations are higher than the design parameters.

Specific Check Points For the Plant Equipment (cont.)

- Identified the design errors and mitigation actions; what was done?
- History to respond to the Critical items that were on the punch-list and quality of solutions.
- List of the Critical spare parts in warehouses and their supply from OEM (collapse of previous scheme of cooperation may result in long time of supply and non-existence of providers).
- What is useful life of the turbine wheel and what is its vulnerability in function of the number of the turbine wheel repairs?

Specific Check Points For the Plant Equipment (cont.)

- Normal and emergency electric supply systems separated at all levels including cable routing.
- Preferable dust- and water-proof execution of the elements, devices, panels and cabling related with the plant critical protection.
- Cable routing and potential impact of fires on reliability of the protection systems.
- Vulnerability of the plant when the units have different architecture of the control systems, as consequence of modernization.

Specific Check Points For the Plant Equipment (cont.)

- Where turbines (hydro, steam or gas) have no automatic vibration trips then there should always be clear instructions on the action to be taken and at what vibration level.
- The operator should always have full trip authority when the vibration reaches the clearly identified ‘advise trip’ level.

Human Elements / Software

- What are the documents to evaluate the risk of the plant operation; when there were modified? Were they simplified at some point?
- Modification of the safety standards: were they simplified? date of the last revision.
- Desk top simulations of the emergency situations to prevent the team failure to make adequate critical decisions.
- Quality of the Emergency plans: major loss scenarios covered, instructions in written, personnel trained, external help, etc.
- Quality of drills.

Human Elements / Software (cont.)

- Emergency training of the personnel based on identification of all critical loss scenarios.
- Impairment controls applied for protection systems to assure permanent protection.
- Maintenance standards and how they are controlled.
- How maintenance contracts specify procedures of the Quality Control and how it is supervised?

Human Elements / Software (cont.)

- Latest jurisdictional documents of Rostechnadzor (note: in the past the conclusions were misleading and misrepresented).
- Supervision of overhauls by OEM.
- Quality of the new service providers and equipment suppliers / screening.
- Qualification and certification of labor at the present time: educational background, training, experience, turn over.
- Quality of LOTO: logout / tagout procedures; closed doors to critical equipment and accessibility to it in case of emergency, etc.

Human Elements / Software (cont.)

- Escape routes clearly marked, emergency lighting available (autonomous with own batteries and connected to the emergency supply circuit), portable flashlights available.
- Vulnerability of communication with the dispatch center, watershed regulating authority for floods control, external help.
- Existence of Blame-on environment.
- Other missed points.