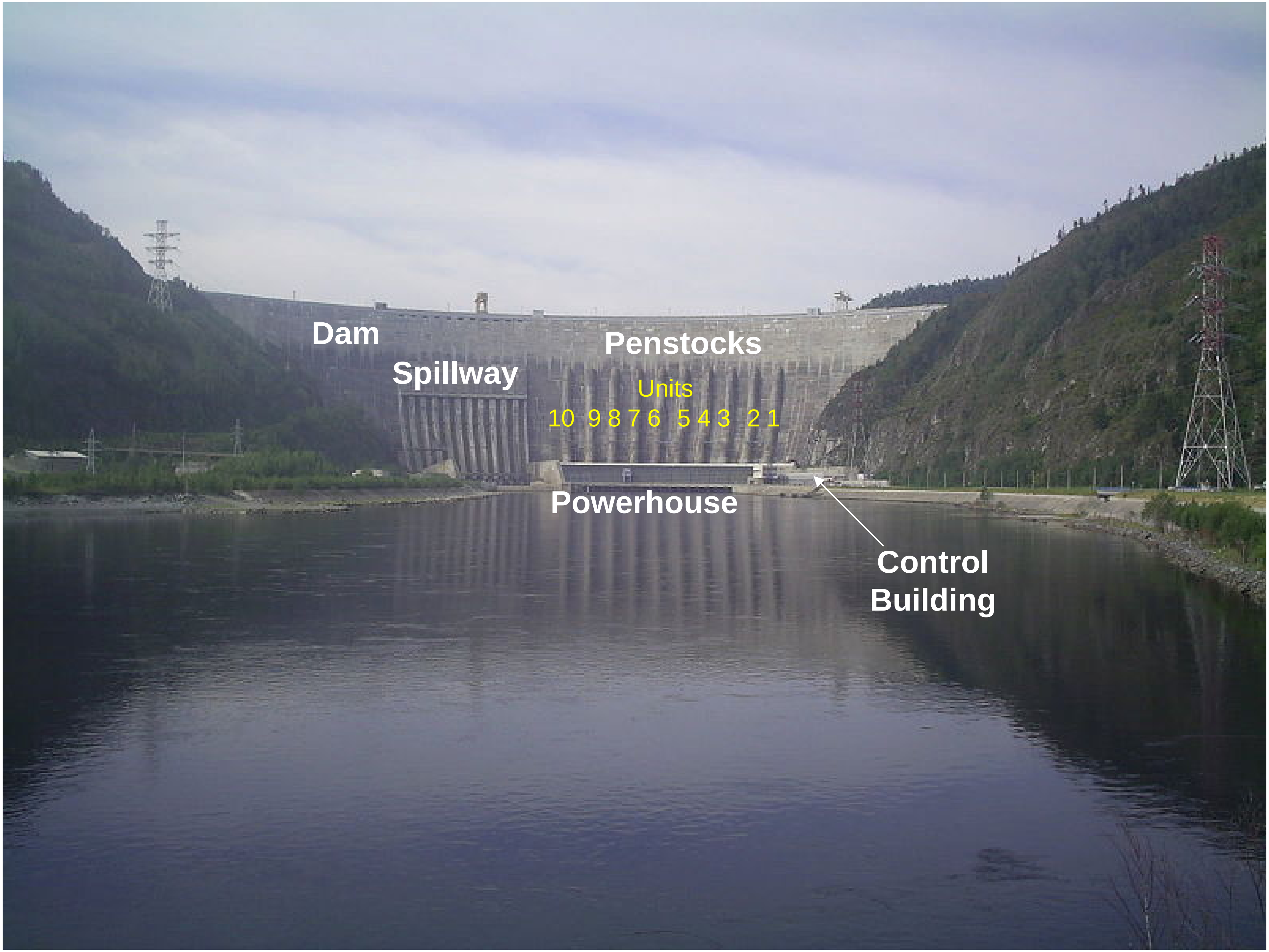
Accident at Russia's Biggest Hydroelectric Plant

Sayano-Shushenskaya – August 17, 2009


Dam
Spillway
Penstocks
Units
10 9 8 7 6 5 4 3 2 1
Powerhouse
Control Building

General View

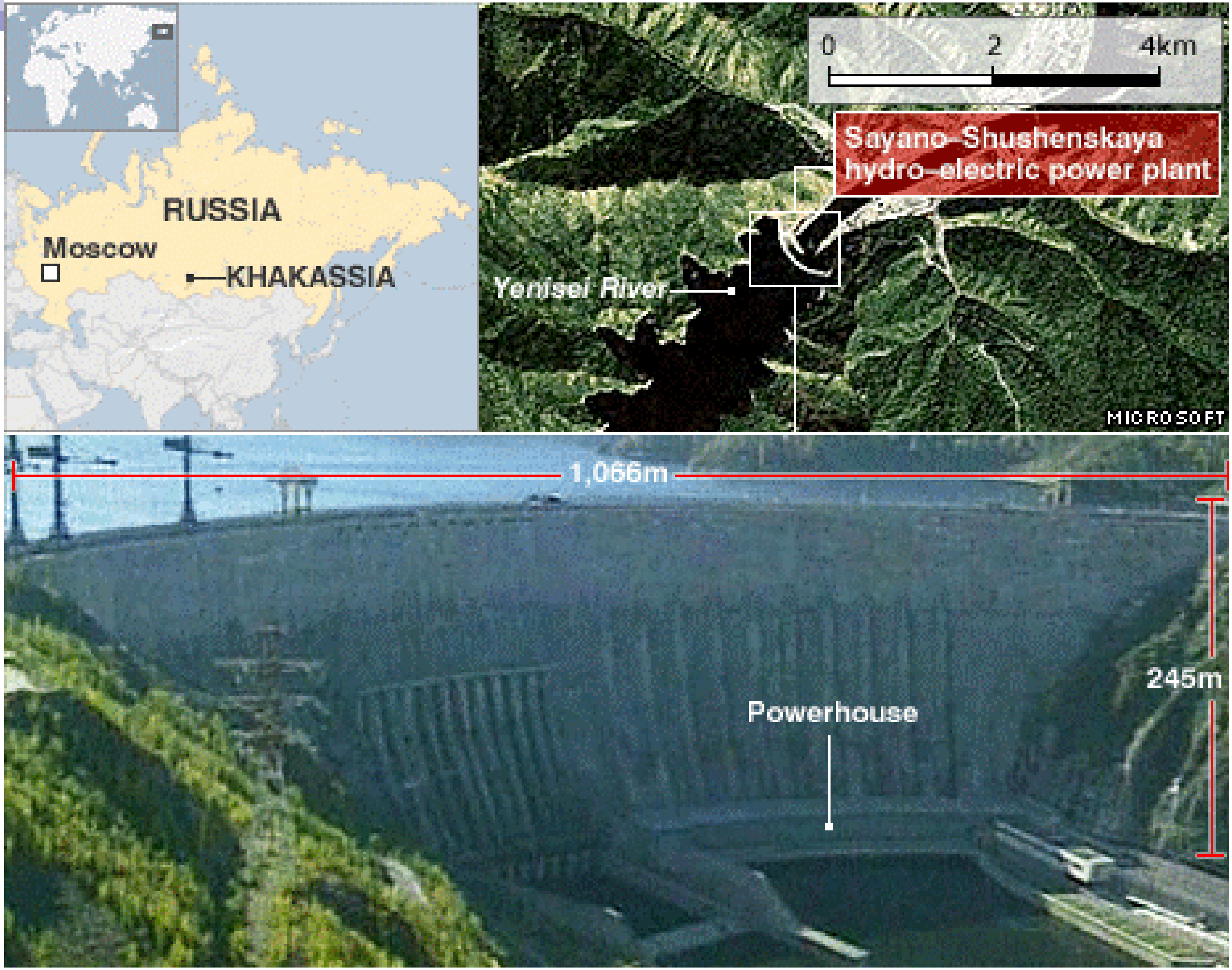
Main Characteristics

One of the world's largest hydro-electric plants, its dam is 245 m (800 ft) high and stretches 1 km (0.6 miles) across the Yenisei river.

Opened in 1978, the station provides a quarter of RusHydro output and is a major power supplier to at least two smelters owned by United Company RUSAL, the world's largest aluminum producer.

The hydroelectric power station is located on the Yenisei River, near Sayanogorsk in Khakassia, Russia. Before the accident, it was the largest power plant in Russia and the sixth-largest hydroelectric plant in the world.

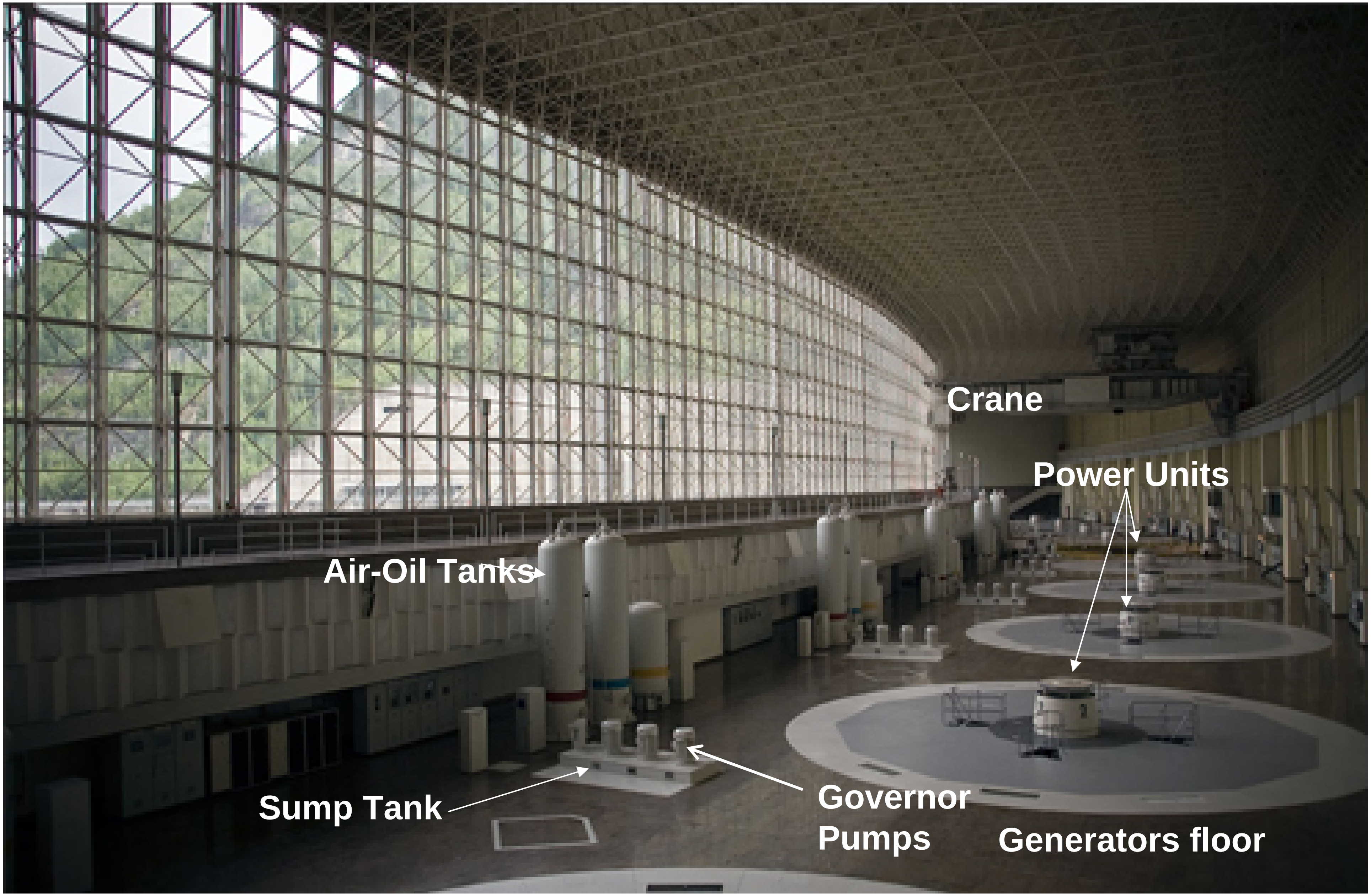
Sayano–Shushenskaya hydro–electric power plant



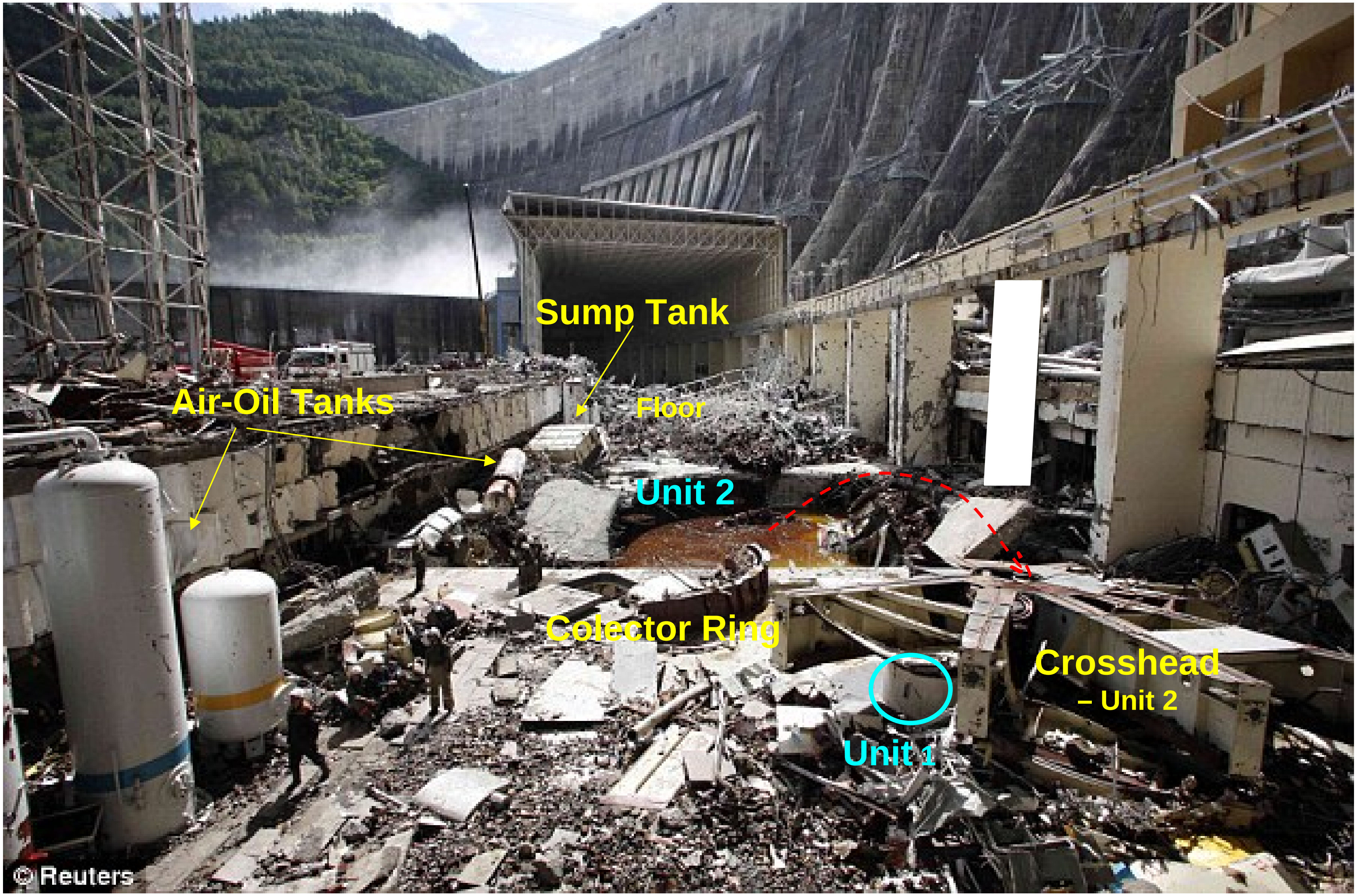
Main Characteristics (cont'd)

- Number of Units: 10
- Turbine Type: Francis (16 blades)
- Rated Power: 650 MW each
- Rated Discharge per Unit: 358,5 m^3/s
- Nominal Speed: 142,86 rpm
- Net Head: 194 m
- Operation Date: 1978
- Runner Weight: 156 ton
- Runner Diameter: 6,77 m

Before the Accident



After the Accident



Generator floor

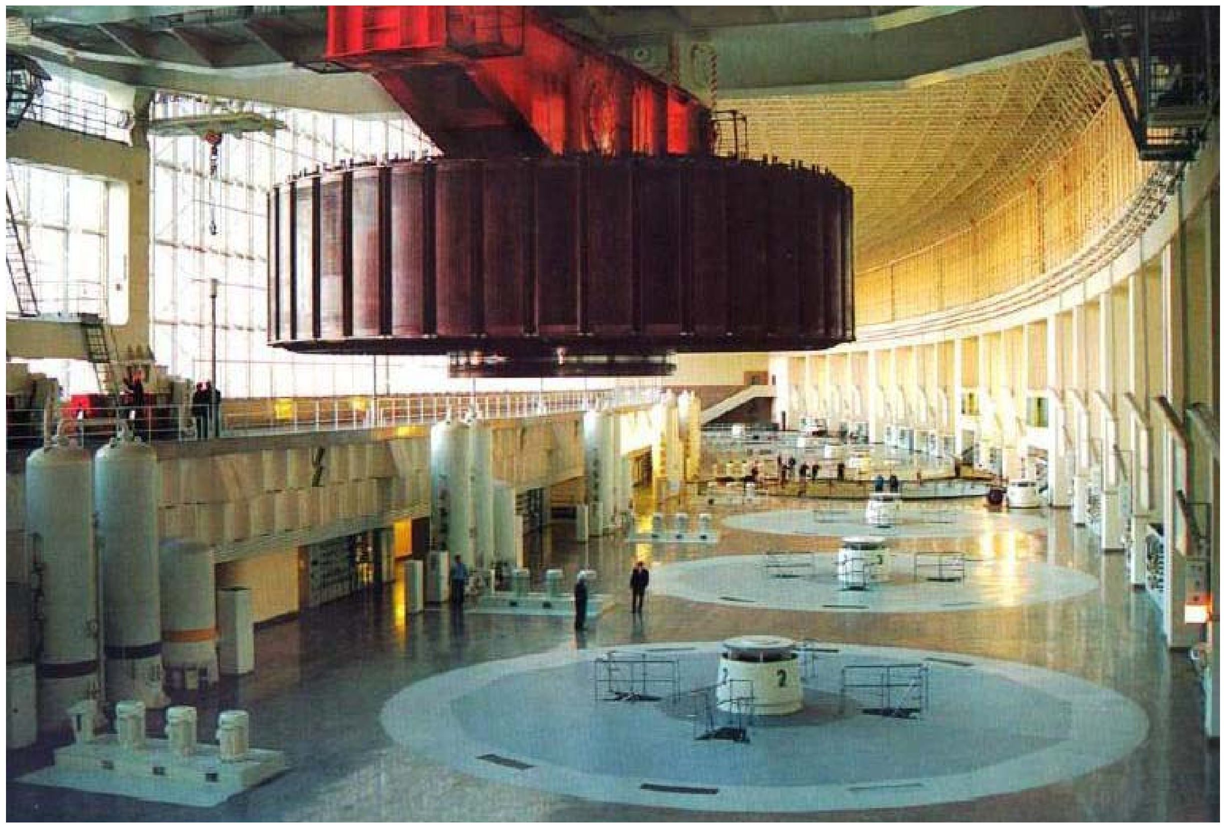
The Accident - Initial Assumptions

- At 08:13 local time (00:13 GMT) on 17 August 2009, the station suffered a catastrophic "pressure surge" in turbine known as a water hammer. The sudden water pressure surge resulted in the ejection of turbine 2 with all equipment, a total weight some 900 tons, from its seat.
- Turbines 7 and 9 also suffered from severe damage, while the turbine room roof fell on and damaged turbines 3, 4 and 5. Turbine 6, which was in scheduled repair at the time of accident, received only minor damage as it was the only one of the station's 10 turbines that did not receive electrical damage due to shorting of transformers, and it will be restarted as soon as possible.
- Water immediately flooded the engine and turbine rooms and caused a transformer explosion.
- **On 23 August 2009**, authorities said 69 people were found dead while 6 people are still listed as missing. Efforts to pump flood water from the engine room and complete a search for the missing workmen are expected to take 3 to 8 days.

http://en.wikipedia.org/wiki/2009_Sayano%E2%80%93Shushenskaya_hydroelectric_power_station_accident

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

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

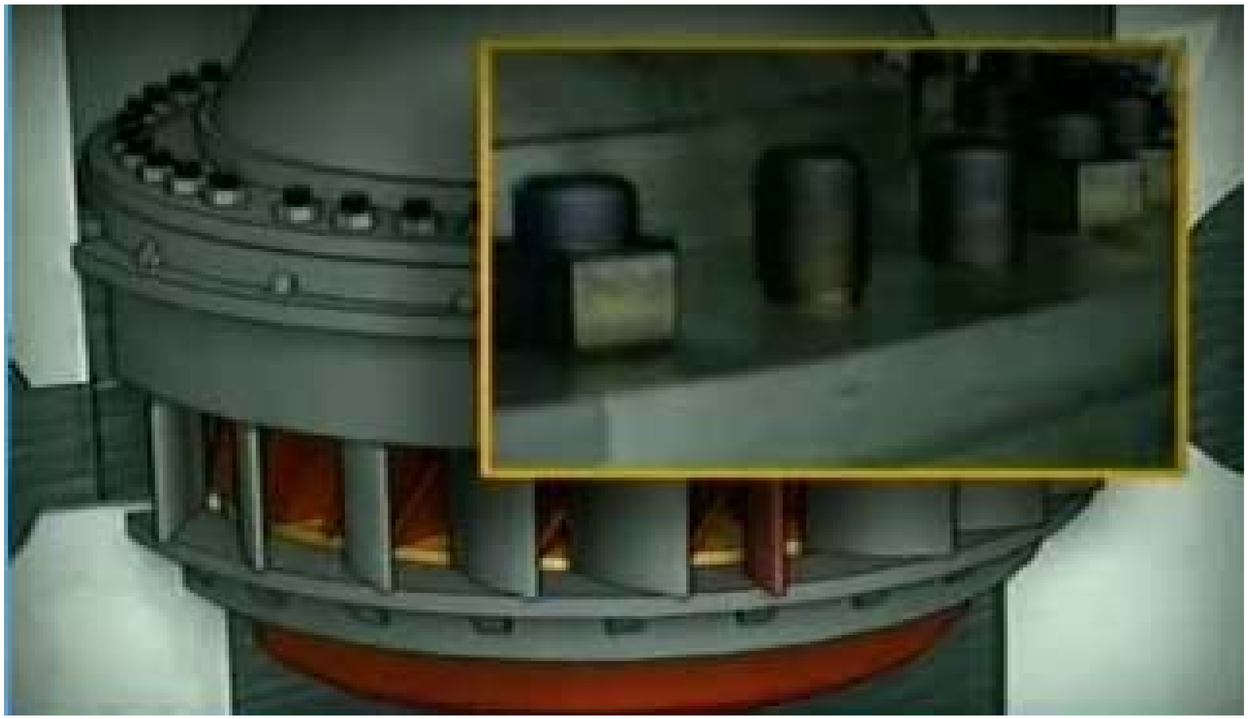


New vibration control of Unit 2 was installed in 2009 but it was out of service.

Grid regulation was accompanied by very high vibration at Unit 2.

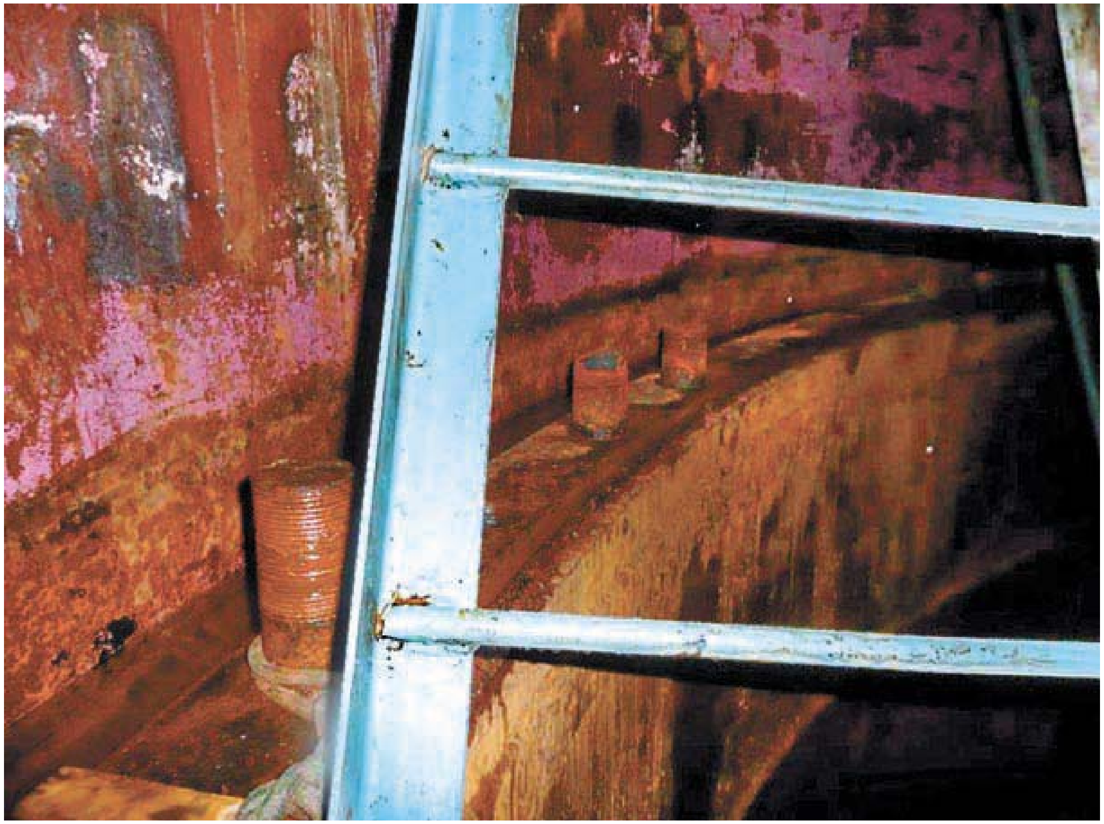
The Bolts and Vibration at Unit 2

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



At the time of the accident, the limit of vibration was exceeded 5.25 times.

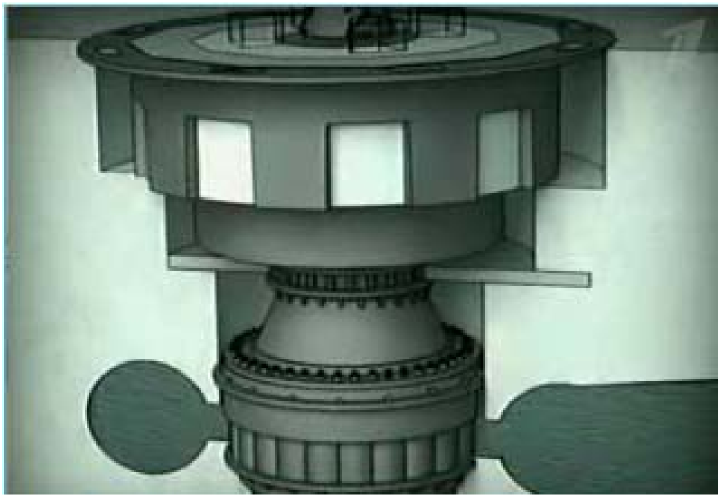
Turbine Cover Bolts Failed on Unit 2



High vibration contributed to the bolts fatigue, their functional capacity was lost, and the turbine cover was opened.

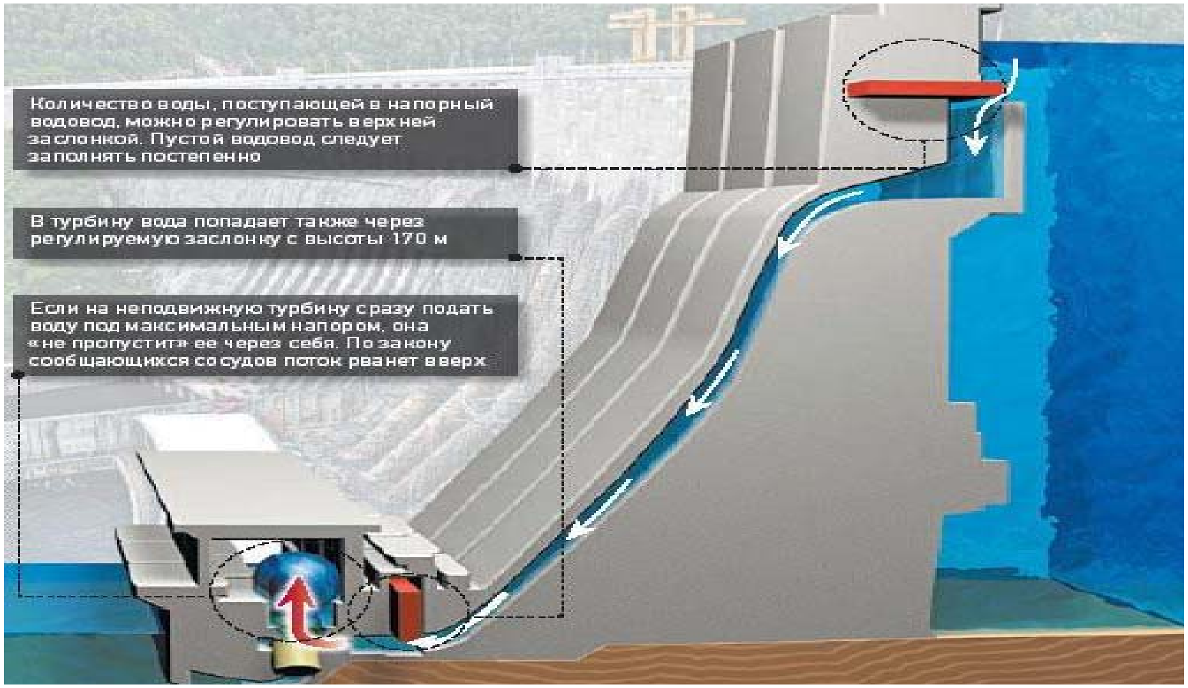
Turbine Cover Bolts Failed on Unit 2

High pressure on a large surface had created an enormous uplifting force in the unit pit.



Water under high pressure flowed into the turbine pit.

Unit 2 Was Brutally Lifted



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

Flooding of the Powerhouse Started

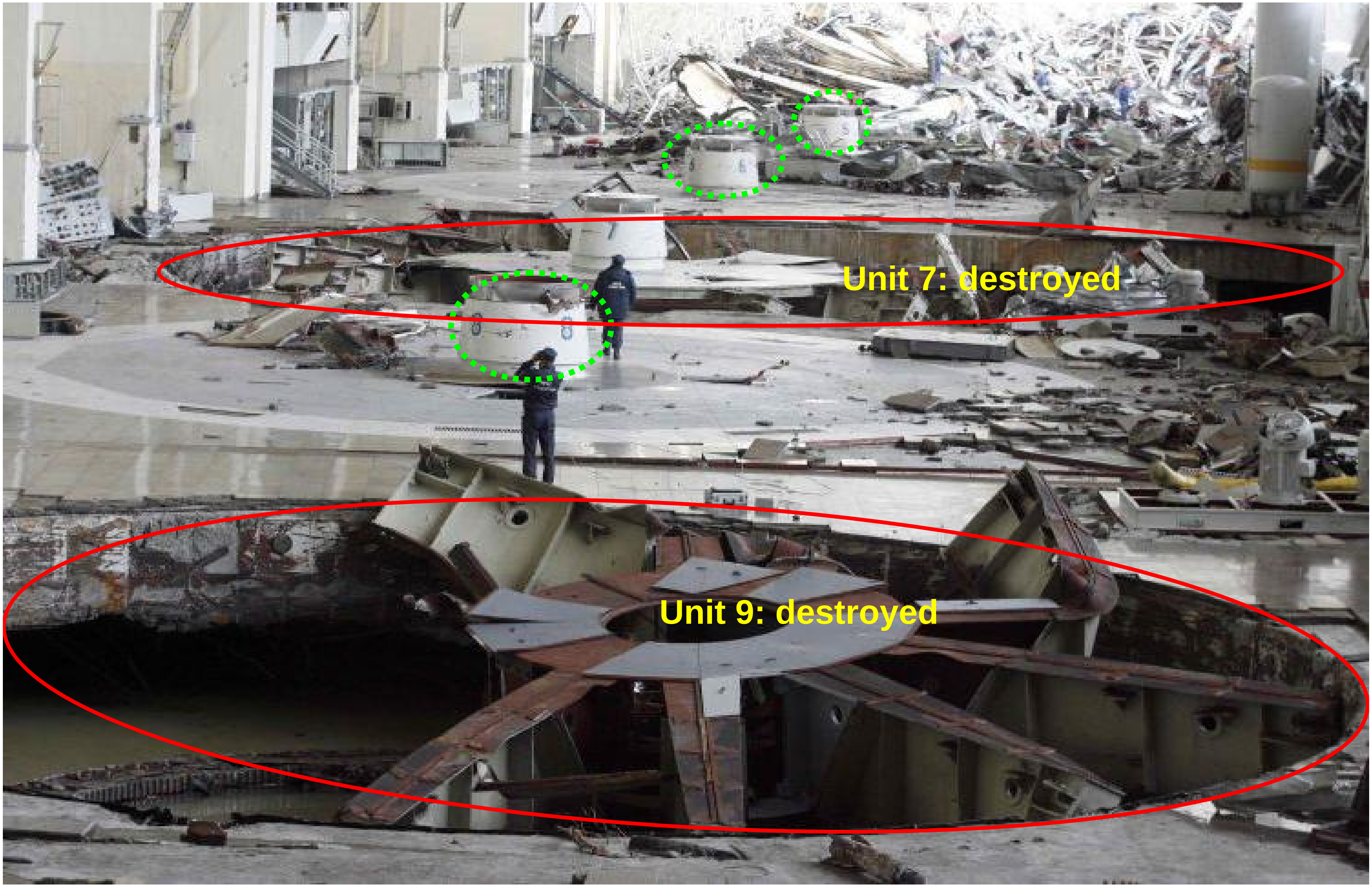
Flooding of Transformers

Section of the Powerhouse Washed Away

Sudden full flooding of the powerhouse disabled the controls and protections of the units.

The control systems stopped operating (no normal and no emergency electricity supply).


Sump Tank
(turned)
Air-Oil Tank
Crosshead


Unit 7: destroyed
Unit 9: destroyed


Unit 9
Unit 7

Some Issues During the Accident

- Emergency gates of the units failed to close automatically:
  - the outlet gates were closed manually by divers to dewater the powerhouse
  - emergency gates manual closure from 8:35-9:30 am.
- Normal electricity failed
- There was no emergency supply
- When emergency lighting failed, a pocket flashlight was used by an individual. Flashlights were not readily available
- Access door to controls of unit 2 emergency gate was closed so forced entrance was required

Emergency Plan Did Not Exist

News apparently reported 3 hours after the accident

Emergency situation lasted 1hr, 7 min. Safety Manager abandoned the plant.

Emergency Exit signs did not exist to direct people to safe places, no drills to evaluate preparedness, only oral orders were contemplated in case of emergency.

Lack of emergency procedures

Emergency Electricity Supply Did Not Function

- Manual attempt to open the gate
- The gate opened a few 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 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.

Loss Of Human Lives And Scope Of Damage

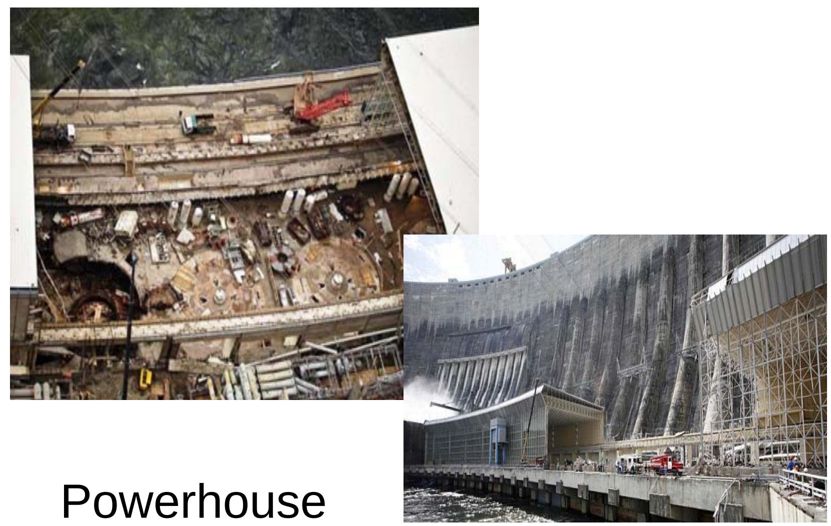
- **Total loss of equipment inside the powerhouse**
- Re-build time is 5 years - Cost over 1.3 billion USD
- Contingency Business Interruption losses for aluminum smelters
- Shutdown will push up market prices in Siberia’s grid
- Even our US Navy costs and supply availability have become issues (many aluminum engines)

Continued Scope of Damage

Unit 1

Unit 2

- Generators 7 & 9 were destroyed
- Short Circuit
- Air Oil Tanks Displaced
- Destroyed generator crosshead



Powerhouse destroyed

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 (continued)

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

Damaged Transformers

Environmental Impact

100 t of oil had been spilled into the river. The spill flowed along the river, killing the fish and causing an environmental scandal in the news.

The Focus was on the 2-days of Plant Disorganization After the Accident Versus the Good Job of the External Rescuing Teams


The Powerhouse crane is
above the assembly area


Enclosed Bus
© Reuters


Roof
Roof
© EPA

Why It Happened - Technical Causes / Hardware

- Unit 2 possibly should have been shutdown in April or May before the accident due to vibration trend. It hit the maximum technically allowed vibration and the mean vibration and stayed at that level, but there was no vibration trip, so no action was taken at that time.
- Team failure to detect critical conditions of operation.
- Poor 2009 maintenance—bolts fatigue was not corrected.
- New 2009 vibration system was out of operation.
- No response by control room to vibration.
- Numerous power swings—high vibration remained .
- New 2008 design of the grid regulator had structural deficiencies.
- Lack of criteria to operate - vibration and strange sounds noted long time before.
- Design of the bolts – no maintenance requirements, no forelock on the nuts– result was badly worn bolts, at least 6 nuts were not installed. 80 bolts X 80-mm diameter
- Worn out surfaces in the bearings including the shaft contributed to higher vibration
- Cavitation contributed to vibration/unbalanced rotor
- Unit 2 at the end of its useful life (29 years and 10 months vs. 30 years)
- Vibration after maintenance should be 38% of the limit, after 2009 maintenance was 93% of the limit

Why It Happened - Technical Causes / Hardware

- Generator breakers obsolete and not reliable.
- Cracking of the turbine blades.
- Turbine wheels had to be repaired every 10,000 hrs. because of cracking of the blades.
- Recommendation to replace the worn out wheels not implemented due to budget constraints.
- Errors in design of the plant and equipment.
- Lack of investment to replace obsolete equipment.
- Poor maintenance and operational standards.
- Gross negligence and carelessness of management at all levels.
- Significant increase in scope of maintenance—more people were required or not all work could be done.
- New instruction based on "risk" cancelled a number of previous documents related to safety standards - this was done against a general trend that equipment was getting more obsolete and deteriorated.
- Cost-cutting on safety - simplified, some documents were cancelled.

Why It Happened –
Russian Sector Issues

- 46 regional managers were fired.
- Centralized supervision had disappeared.
- Unclear rules of privatization interrupted normal rate of investment in maintenance and replacement of technology.
- Due to collapse of USSR—resultant issues with supply and quality of products and service.
- BLAME—on culture at the state, company, and plant level.
- More priority on making money, then on sound technical policy - known in the Russian press as "Factor of Successful Manager."
- Decreased efficiency of communication inside the companies and with contractors.
- Increasing lack of available qualified labor.
- High degree of technical obsolescence.
- Low technological discipline of operations and maintenance.
- Slow modernization.
- Expectations not clearly expressed or understood.
- **Criminal behavior of personnel that failed to recognize danger!!!** (per Russian Investigation Team)

Background Facts:

- Government oversight of privately managed facility.
- Great record—in fact on July 2 2009, before this incident happened in August, RusHydro announced the station's all time highest electricity output per 24 hours.
- Aging Facility—started in 1978 (though permit received in 2000), equipment had 30 year manufacturing life. The particular turbine that failed was rated for 30 years—it's life was 29 years and 10 months.
- Budget issues meant extending the life of the plant with current equipment, so planned for more repairs. Some pieces of equipment had long history of repairs - including Turbine 2. Extensive overhaul in 2000 (March-November repairs on Turbine 2), defects in bearings repaired. In 2005 similar repairs—not as extensive. Jan-March repaired and "modernized". It was the only turbine with a new electro-hydraulic regulator of its rotational speed. Wheel was not properly rebalanced after repairs were completed. (the Rotor alone weighted 920 tons). Subsequent increased vibration,but did not exceed specifications!! Yet, increased vibration of Turbine 2 was "tribal knowledge" and was going on for 10 years - well known to plant personnel. The vibration had become worse during the night and employees had tried unsuccessfully to shut the unit down. But they didn't notify the plant manager becausehe had visitors with him celebrating his 17 year success directing the plant..
- Specific direct causes—Turbine vibrations led to the fatigue damage of the mountings of Turbine #2, including the cover. Nuts on at least 6 bolts keeping the turbine cover on its place were absent. 49 bolts were investigated - 41 had fatigue cracks. On 8 bolts, the fatigue damaged areas exceeded 90% of the total crosscut area. When bolts keeping the turbine cover in place were broken, and with water pressure, the turbine with its cover, rotor, and upper parts started to move up destroying machinery. At the same time, pressurized water flooded the rooms and continued damaging plant constructions.
- Plant status: Nine out of 10 turbines were operating at the time. Turbine 6 was undergoing scheduled maintenance, but was ready for restart inspections.

Consequences:

- 74 people dead - 1 still missing. Day of mourning was declared. Area towns banned the sale of alcoholic beverages. 10% of Russia electricity not available. Aluminum smelters shut down. Using diesel generators, but anticipate losing 500,000 tons of aluminum output due to the power shortage. Electricity prices have already increased after the disaster. The accident caused an oil spill, releasing 40 tons of transformer oil spread 50 miles downstream. Killed 400 tons of cultivated trout in 2 riverside fisheries. Trading suspended for 2 days at the Moscow Interbank Currency Exchange. Compensation of 1 million rubles ($31,600) paid to each victim's family, and 100,000 rubles (US $3,100) to each survivor. The community where most of the workers were housed was flooded and destroyed - it is being rebuilt. The director of 17 years was replaced. Several people went to jail. *(Similarity to some DOE sites - did you know that certain RCRA positions, also include "jail time" for specific noncompliant actions (e.g. the Training Manager.))* Turbines 2, 7 & 9 were destroyed, additional damage to turbines 1 and 3. Less damage to 4, 5, 8, and 10. Turbine 6 which was in scheduled repair received minor damage, no electrical damage due to shorting of transformers like the others. When water flooded the engine and turbine rooms—it caused a transformer explosion. Transformers 1 and 2 were destroyed. Replacement of damaged turbines will take up to four years. Rebuilding the engine room alone will cost (US) $1.3 billion.
- Corrective Action Assigned: As work/stabilization/rebuild starts/continues, a key action is that every 2 hours a walk-down by managers (the working control of workers in their workplaces) is performed.

Lessons Learned Based on the Potential for Similarities within the DOE Complex

- **Lack of recognition of hazards including impact of aging equipment.**
- **Budget constraints meant cut back on maintenance, investment, safety, and education.**
- **Lack of recognition by employees on "needs repair" vs. "needs shutdown."**
- **Since it was "within specifications," even though vibrations were troublesome, they did not recognize the hazards of continued operation. "Within specifications" does not mean they can operate heavy loads long term in those specific ranges.**
- **Employees reluctant to complain or bring up concerns—knew work was being done as could be afforded.**
- **Tours were onsite because of beautiful view of area & a public celebration resulting in the public being in danger and lives lost, which was not part of the program/facility process.**
- **Accountability concerns—how many people were in the plant and where are the totals.**
- **Safety systems/back up systems—planning did not include catastrophic failure.**

Lessons Learned Based on the Potential for Similarities within the DOE Complex

- Emergency Planning Failures, including “failed closed” vs. “failed open,” plus manual requirements - steel gates to the water intake pipes of turbines weighed 150 tons each and had to be closed manually (opening valves with hydraulic jacks to keep them open). This took 25 minutes (record fast time but they knew how to do it, as the gates frequently had to be closed manually) This showed that “risk” factors were not a significant enough part of the planning process. Risks to include consequences for the facility as well as personnel conducting the manual action - some of these stayed and did their task, thus losing their lives.
- Early recognition of catastrophic failure and warning could have saved lives. Failures did not happen in seconds – it took 1 hr 7 minutes for consecutive failures to fully launch. They were involved in the actions of the moment, without looking ahead for resulting consequences.
- Did not have “operational drills”, such as this piece of equipment failed, now what actions need to be taken, what are the impacts. Did have some emergency drills focused on fires, but not on equipment, operational aspects with series of actions/consequences to recognize when they had reached full “emergency” mode.
- Emergency Egress Barriers
- No continuity of operations business plan to assist in impact to company, surviving employees, etc. This had a great impact as personnel lived in the “company town” which was destroyed by the flood so, as an example, they had no way to receive pay checks.

Lessons Learned Based on the Potential for Similarities within the DOE Complex

- No good system for how to control/operate immediately following a disaster; very poor organization which was evident in the news reports. This is the steps between emergency and recovery planning. What is done, by whom, who is the back-up if those key personnel are no longer available?
- Impacts of new designs, controls, and grid changes not recognized.
- Not learning from past lessons (such as continued cracks identified during each Unit 2 maintenance activity).
- Not appropriately identifying risk and maintenance priorities fits in with some current DOE complex concerns.
- Poor post maintenance inspection and testing programs.
- OEM did not specify requirements for bolts maintenance and inspections, thus not done (focused on compliance requirements only vs. good practice implementation).
- Mgmt negligence and carelessness - Though this was determined as a factor, and some personnel were put in jail accordingly, it would be difficult to assess. They had a great reputation; less then a month before they had received national kudos and they weren't truly aware of the site's equipment issues.
- Increased scope (more maintenance required), meant more people needed, which would again take more budget.
- Safety standards had been simplified and cut back.
- Didn't learn from previous lessons—flooded 2 times previously. (1979 and 1985).

Lessons Learned Based on the Potential for Similarities within the DOE Complex

- Technically obsolete, slow to modernize.
- Operational and maintenance requirements were not understood and expressed clearly.
- OEM recommendations not followed.
- Vulnerability of plant - units have different architecture, as a consequence of modernization.
- Existence of “BLAME” environment—can’t really do anything about it due to……..

DOD Lessons Learned from this Accident

- The DOD had continued to use NDT or “hammer ping” for checking bolts, etc. A newer standard operating procedure is now being used for vibration. Though components of the procedure have been in place for some time, it was reviewed and updated as a result of discussions of the Sayano-Shushenskaya Hydro accident.
- Lessons on Critical Parts Availability - Naval use of aluminum engines, spare parts will be critical. Happened in August – the end of the fiscal year is not a good time to be trying to purchase spares before market jettisons due to aluminum availability challenges.
- See Vibration notes (handout).

Additional Questions to be Asked

- What is the percentage of the obsolete equipment (per OEM manual) that the plant has at the present time?
- Is all the obsolete equipment currently on a modernization list?
- Are there pieces of equipment with a "history" of problems?
- Critical Spare Parts list?
- Do employees recognize when it has crossed the "needs repair" stage vs. "needs shutdown" mode - is there any criteria available for them to make that determination…
- Are there pieces of equipment with higher than normal machinery breakdowns? What is the plan?
- Have you fully identified the vulnerabilities associated with modernization (change management).
- Manual controls (vs. automatic controls) during emergency---how often during drills? Is there a setpoint established where this is too high risk; any alternatives that need to be considered?
- Do maintenance subcontracts clearly specify quality control of works (including bolt inspections, etc.)? Do they state what is to be done if defects are identified during maintenance?
- What are the dynamics and execution of your modernization program/percentage of investment, availability of the budgeted funds—does it align with actual risk?
- When design errors are identified, are mitigation plans put in place?

Additional Questions to be Asked

- What is your site history on responding to Critical items? Do you maintain a punch-list; what is the history of the quality of solutions?
- Are you maintaining critical spare parts? In the current economy, just as in Russia, the supplier could go under with no warning. Do you have alternative suppliers identified?
- For normal vs. emergency electric supply systems, are they separated at all levels, including cable routing?
- Have you determined the need for and taken action accordingly for dust and water proofing of key panels, cabling, etc. related to plant critical protection?
- If your turbines (hydro, steam, or gas) do not have automatic vibration trips, then do you have clear instructions on the action to be taken and at what vibration levels?
- When was the last time you evaluated your maintenance standards to ensure they meet your needs?
- What is the accessibility to critical equipment in case of emergency? Are emergency work packages pre-built so that you can get the job done with appropriate controls?
- Is existence of complacency or general blame (e.g., it’s due to…can’t fix it now…) hampering your programs?