Incident

Chernobyl – 30 years on

Fiona Macleod

On Saturday 26 April 1986 the citizens of Pripyat were outside enjoying the hot weather — in the school playground, planting out the garden, fishing in the river, sunbathing in the park, completely oblivious to the plume of radioisotopes drifting towards them from the nearby Chernobyl nuclear power plant.

After Saturday lessons finished, a few enterprising children cycled up to the overpass to get a better look at all the excitement a mile away. Across the lake — an artificially created cooling pond for the power plant — they watched fire engines, planes, helicopters, and truckloads of soldiers. In the evening people came out onto their balconies to marvel.

> *"I can still see the bright crimson glow...We didn't know that death could be so beautiful".*[1]

At 01.23, earlier the same day, No 4 reactor had exploded during a safety test that went horribly wrong. A series of explosions led to the rupture of the containment and fifty tonnes[3] of nuclear fuel were ejected from the core of the reactor, hurling uranium dioxide, iodine, caesium, strontium, plutonium and neptunium radioisotopes into the air — orders of magnitude greater than the radioactive release after the bomb dropped on Hiroshima. And the fires were still burning, yet no one had alerted the population or evacuated the town that lay only one mile away.

Before his suicide on the second anniversary of the accident, one of the expert investigators, Valery Legasov, wrote:

> *"... the (Chernobyl) accident was the inevitable apotheosis of the economic system ... in the USSR ... Neglect by the scientific management and the designers ... When one considers the chain of events ... it is impossible to find a single culprit, a single initiator of events, because it was like a closed circle."* [2]

So was this accident unique to the nuclear industry of former Soviet Union at the height of the Cold War? Or are there wider lessons to be learned?

Too much haste, too little speed

Picture the scene: a meeting between a project team and the sponsors. The Chairman opens the meeting.

> *"Give us an update on progress."*

The project manager rolls out a plan and begins his presentation on the critical path for completion. After two minutes, he is interrupted.

> *"When will you start up?"*
> *"No earlier than August."*
> *"That is unacceptable. The deadline for start-up is May."*

The project manager bites his tongue. He is not going to remind the steering group that the original project plan showed start-up in December, that a May deadline was imposed by someone in a remote office without any conception of what needed to be done. Instead, he shrugs his shoulders and spreads his hands.

> *"Some equipment will only be delivered in May."*

The Chairman slams a fist on the table.

> *"Then make sure it is delivered earlier!"*

He turns to the boss of the project manager.

> *"Your project team has failed again."*

The project manager is side-lined and new blood is brought into the team.

The plant starts up in December.

That was the gist of an exchange in the Kremlin in 1986, discussing another nuclear plant project, reported by Grigori Medvedev[3] because it was so unusual for a chief of construction to challenge unrealistic deadlines in front of ministers. After his dressing down, the project manager was reported to mutter:

> *"We lie and teach others to lie. No good will come of this."*

Such an exchange could never happen today in the board room of a multinational chemical company. Senior leaders may not know the fine detail of every complex project, but they always hire, trust and empower people who do.

Or do they?

Start up first, test later

Chernobyl Reactor 4 started up before the end of 1983 in order to meet a deadline for energy production targets. Because some of the commissioning tests were bypassed, a worrying problem emerged. How to run the main water circulation pumps in the event of a loss of power.

Active cooling is required in nuclear reactors, running or idle, to remove the heat generated by radioactive decay. In the event of a reactor shutdown, back up diesel generators were designed to start up automatically in order to provide power to the instruments and main water circulation pumps, however they took over 60 seconds to reach full speed. Too long for the core to be without cooling.

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[1] *Nadezhda Vygovskaya quoted in Voices from Chernobyl*

[2] *Testament - Valery Legasov, leader of the Soviet delegation to the IAEA Post-Accident Review Meeting*

[3] *G. Medvedev Chernobyl Notebook*

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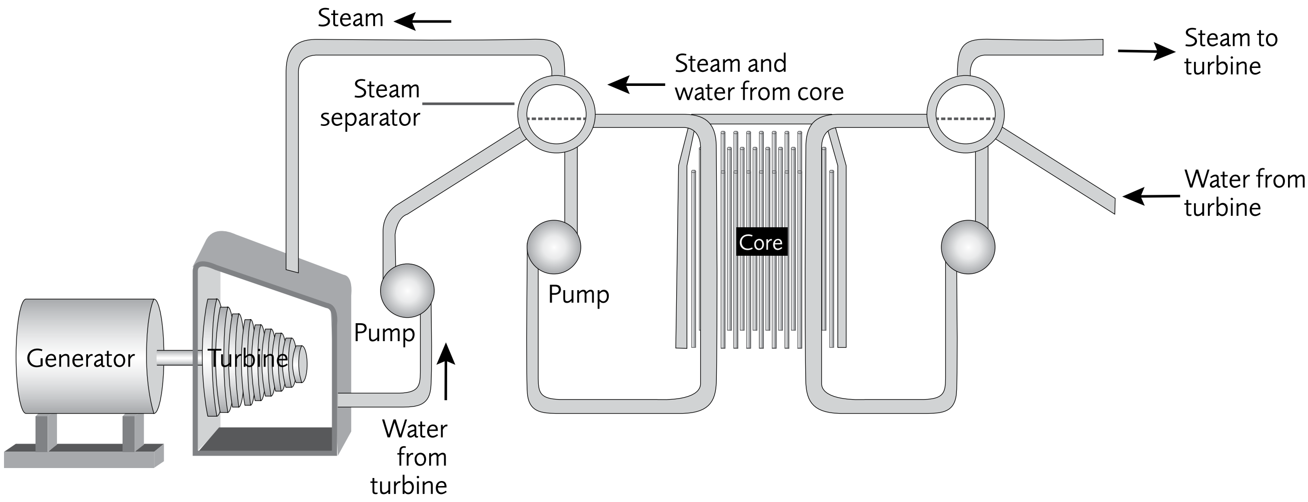

It was suggested that the steam turbines, which would continue to spin after a reactor shutdown, might generate enough electrical power as they were coasting down to run the main water circulation pumps while the back-up diesel generators were winding up, elegantly bridging the power gap.

Previous tests had proved unsuccessful, but a fourth test was scheduled for 25 April 1986, in advance of a planned shutdown on Reactor 4.

Opinions are divided on the risk of running such an experiment on a nuclear power plant. However the additional measures that the plant management took in order to make the experiment "pure"[3] added the most extraordinary risks.

The emergency cooling system was disabled: the pump fuses removed and the valves chained and padlocked shut. This seems to have been due to a belief that there was a danger of heat shock if cold water was allowed to rush into the hot core of the reactor, despite the fact that this was a fundamental part of the design.

The test was to be carried out live. Instead of shutting down the reactor and measuring the electrical energy generated by the coasting steam turbine, the plan was to keep the reactor operational so the test could be repeated if necessary.

Most of the reactor emergency shutdown systems were disabled. In part this was to allow the test to be repeated if it failed the first time.

These extraordinary violations, the removal of the very back-up systems on which the safety of the plant depended, were planned and documented and sent to the government regulator in January 1986, well in advance of the test[3]. The plant management took the lack of reply as tacit approval to proceed. It became clear after the accident that nobody who understood the operation of a nuclear reactor had reviewed or understood the planned tests.

According to the expert investigator, Valery Legasov[2], the test was

> *"like airplane pilots experimenting with the engines in flight"*

But even with these fundamental systems overridden, the test might just have proceeded without incident, had it not been delayed from day shift to night shift.

Before looking at what else went wrong, it is worth taking a moment to understand the fundamental design flaws of the RBMK nuclear reactor.

The difficult we do right away, the impossible takes a little longer

The experts recommended a pressurised water reactor design (VVER) for the Chernobyl complex. The VVER design was said to be superior — intrinsically safer with lower emissions than the boiling water graphite moderated reactor (RBMK). See Table 1 for a comparison of the two technologies.

The technology chosen by the expert design team was rejected. Why? Was it just a question of cost? Rouble per kilowatt? Bang for Buck? It appears not.

By 1965 it was clear that mass production of the VVER reactor would be difficult. Only one factory, the Izhora works in Leningrad, had the necessary technical expertise to manufacture such large and complex pressure vessels. On the other hand the inferior RBMK could largely be constructed on site with local suppliers of concrete and piping. Even the graphite blocks could be transported and assembled from modules.

> *"Soviet scientists, engineers and planners did not take decisions of such magnitude lightly (but)...instead of choosing technically outstanding designs...they chose designs they thought would meet ambitious plan targets for nuclear power generation"*[4]

In the end, one overriding factor trumped all the others. How fast could the nuclear energy program be implemented?

The decision was made. The council of ministers approved the RBMK, declaring it the safest and most economical. An aspiration rather than a fact.

"*No matter, we will adopt it...The operators have to work it out so that ...* (the RBMK design) *is cleaner and safer than the Novovoronezh* (VVER) *design*." (Reference 3).

Such an impossible task — take an inferior design which can be built faster and magically remove the flaws — would never be given to the design engineers in a modern chemical company.

Or would it?

[4] *Producing Power: The Pre-Chernobyl History of the Soviet Nuclear Industry by Sonja D. Schmid*

engineering and design

systems and procedures

culture

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Technology[5]	VVER	RBMK
	Pressurised water reactor	Graphite moderated water cooled reactor
	Novovoronezh Водо-водяной энергетический реактор	Reaktor Bolshoy Moshchnosti Kanalniy Реактор Большой Мощности Канальный
Emissions	100 curies/day	4,000 curies/day
Turbine driven by	Steam from Secondary circuit – primary water is pressurised to remain liquid in core and exchanges heat with water in secondary circuit which boils to drive turbine	Steam from Primary circuit – water boils in core and drives turbine
Moderator	Water	Solid Graphite
Coolant	Water	Water
Loss of coolant	Intrinsically Safer - The neutron moderation effect of the water diminishes, reducing reaction intensity	Unstable - The neutron moderation by graphite continues, no loss of reaction intensity leading to overheating
Void coefficient of reactivity[5]	Negative (good)	Positive (bad)
Fuel	Enriched Uranium dioxide	Enriched Uranium dioxide
Refuelling	Full shutdown required	On-line. Multiple independent fuel channels.
Containment	Steel pressure vessel	Leak-tight (explosion prone) concrete box with bubbler pool underneath
Other	Design favoured outside USSR	Originally designed to provide Plutonium for military use
Construction	Construction in specialised fabrication shop. High quality factory based steel forging	Modular. Assembly on site. Graphite, cement and piping
Capital Cost Rouble/ kW Power output	190-210[6]	250-270[6] (actual) 190[7] (aspirational)

Table 1: Comparison of VVER and RBMK designs

RBMK design flaws

Design flaw 1 – positive void coefficient of reactivity

In a nuclear chain reaction, a neutron collides with a nucleus, splitting it to release heat and more neutrons (nuclear fission). The neutrons must be slowed down (moderated) to increase the probability of the next fission and sustain the chain reaction. Extra neutrons must be removed (absorbed) to prevent a runaway reaction and core meltdown. The power of the reactor is controlled by inserting and withdrawing control rods containing a neutron absorber, in this case boron.

In the RBMK design, the moderator and coolant are of different materials. Water is a more efficient coolant and a more effective neutron absorber than steam (see Table 2) Excess steam reduces the cooling of the reactor, but the graphite moderator allows the nuclear chain reaction to continue. As steam bubbles (voids) form, the reactor power increases, releasing more heat and more steam and so power continues to increase in a vicious spiral. This is known as a positive void coefficient of reactivity.

In the VVER design where the water circuit is both moderator and coolant, excess steam generation reduces the slowing of neutrons necessary to sustain the nuclear chain reaction. More steam means lower reactor power, less heat and less steam, returning the reactor to stability. This is known as a negative void coefficient of reactivity.

	Neutron scattering Cross-section (σs) in barns Moderates speed of neutron, Promotes fission	Neutron absorption cross-section (σc) in barns Stops fission	Moderating Ratio[8] (Slowing down power vs Macroscopic absorbtion cross section)
Water (H_2O)	~100	0.66	70
Graphite (C)	4.8	0.004	170
Boron 10	~0	3800	~0

Table 2: Properties of water, graphite and Boron 10

Design flaw 2 – Control rods

The designers of the RBMK understood the first design flaw. A supervisory control system continuously calculated and displayed the operating reactivity margin (ORM). The secondary safety systems were beefed up — a minimum number of control rods were to remain in the core at all times, the AZ-5 emergency button which inserted further control rods in 20 seconds and independent emergency cooling.

But there was another problem with the RMBK design that was less well known, a design flaw that was first noticed in December 1983 during the commissioning of Ignalina Unit 1 (Lithuania was then part of the USSR). As the control rods descended into the core, the operators observed a surge in the power. The tip of the control rod was made of graphite. As the control rod descended it displaced water, so instead of

[5] *http://users.owt.com/smsrpm/Chernobyl/RBMKvsLWR.html*
[6] *The Economics of Nuclear Power in the Soviet Union. William J. Kelly, Hugh L. Shaffer and J. Kenneth Thompson, Soviet Studies. Vol. 34, No. 1 (Jan., 1982), pp. 43-68*
[7] *Semenov*
[8] *Nuclear Power Generation: Incorporating Modern Power System Practice edited by P.B. Myerscough*

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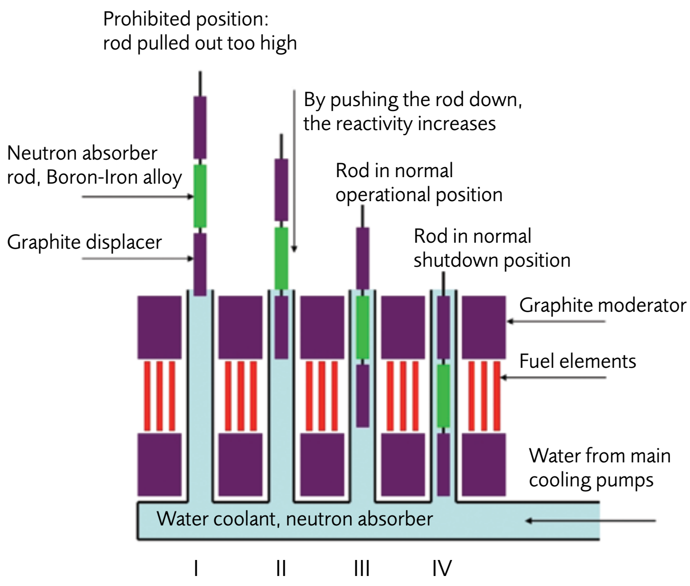

Diagram from http://consumedland.com/page_06_en.html

reducing the power of the reactor, the power increased.

In 1983 in Ignalina Unit 1, the reactor was stable; the cooling water was flowing and the automatic control was regulating. The temperature and pressure did not soar, the channels did not warp, the control rods did not get stuck and over 20 seconds the graphite tip continued to descend beyond the core allowing the boron section of the control rods to slip into place and stop the nuclear reaction.

But in 1986 in Chernobyl the reactor was unstable; the incoming night shift had allowed the power to drop to a dangerously low level and the primary water circuit was surging uncontrollably. The reactor operator attempted to stabilise the reactor manually. When his supervisor realised that control had been lost, he hit the emergency AZ-5 button. The control rods started to fall. The entry of the graphite tip of the control rod into an already unstable reactor was the final straw.

The first explosion happened seconds later.

Не пили сук, на котором сидишь – Don't saw through the bough you're sitting on

Plant Manager Bryukhanov (a turbine specialist) and Chief Engineer Formin (an electrical engineer) had approved the unsafe-safety test. It appears that their interest in assessing the electrical power from a coasting turbine had blinded them to the dangers of operating of a nuclear reactor with safety systems disabled. Formin had only recently returned to work after major spinal surgery as a result of a serious car accident and was reported to be distracted and in constant pain (Reference 3).

The unsafe-safety test was ready to start at 14:00 on 25 Friday April 1986. Over the previous twelve hours, the reactor power had been slowly reduced. At the last minute, the controller of the electricity grid refused to allow the plant to reduce power further due to a generation problem elsewhere. All the senior managers went home and the reactor remained at 50% power for another nine hours. At 23:10 the electrical grid controller called to say that the supply/demand balance was back to normal.

At midnight, the new shift took over.

Although there are many alternative versions, the description of events that follows is largely as described by Grigori Medvedev's book (Reference 3) and dramatised in an excellent BBC documentary[9].

Deputy chief engineer Anatoly Dyatalov, a physicist by training, came with them. According to colleagues, he was a difficult man to get along with and had little respect for his subordinates.

Yuri Tregub from the previous shift remained on site, handing over to shift supervisor Aleksandr Akimov and reactor operator, Leonid Tuptunov (26 years old and 3 years out of college). All had the necessary training in nuclear reactors, but were repeatedly overruled and threatened by their superior, Dyatalov.

The reactor was not designed to run at low power, and the operator overshot the test target, the reactor power plummeting to 30MW thermal at 00.28. Akimov and Toptunov wanted to abort the test but were overridden by Dyatalov who forced them to continue, threatening to have Tregub take over.

Toptunov began to withdraw the control rods as instructed, and was able to raise the power to 200 MW thermal at around 1:00 am.

With only a few control rods in the core, the reactor's capacity for excursion now exceeded the ability of the remaining safety systems to shut it down (Reference 3).

At 01:19 alarms showed that the water level was too low. Toptunov tried to increase the water flow manually, by now all eight recirculation pumps were running, but with small temperature changes causing large power fluctuations the reactor was increasingly unstable.

By 01:21, the caps on the fuel channels were reported to be jumping in their sockets. The control room printout of core reactivity showed the excess reactivity required immediate shutdown — the warning was ignored and the test initiated.

At 01:23:04 the experiment began by closing the steam to the turbine. As the momentum of the turbine generator decreased, so did the power it produced for the pumps. The water flow rate decreased, leading to increased formation of steam voids (bubbles) in the core.

The reactor power increased. Toptunov reported a power excursion to Akimov.

At 01:23:40 Akimov decided to ignore Dyatalov and abort the test. He pressed the AZ-5 emergency button to insert the control rods and shut down the reactor.

As the graphite tips descended, the rate of fission increased, the reactor power surged. The control rods stopped one third of the way down. In desperation, Akimov disconnected the motor clutches in the hope that the rods would descend into the core under their own weight, but the rods did not move. The intense heat had ruptured the fuel channels. The rising pressure from the excess steam broke every one of the pressure tubes.

The first explosion at 01:23:44 ruptured the reactor vessel,

[9] *BBC Drama Documentary "Surviving Disaster" (https://www.youtube.com/watch?v=njTQaUCk4KY)*

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lifted the 1000 tonne upper reactor shielding slab and rotated it by about 90°. This was followed by a second, more powerful explosion. Lumps of fuel and graphite were ejected from the core catching fire as they hit the air.

Thirty one people died as a direct result of the accident: reactor operators, fire fighters and emergency responders. One man died immediately, killed by the explosion and forever buried in the rubble, one of a heart attack, the others suffered unimaginable pain as they succumbed to acute radiation exposure over the following days and weeks.

The total number of causal deaths (premature deaths due to radiation exposure) and injury is hotly contested and will not be covered here.[10]

The blame game

A first report[11] into the accident blamed the night shift operators.

> *"...the primary cause of the accident was the extremely improbable combination of rule infringement ... (intentional disabling of the emergency protection equipment) ... plus the operational routine allowed by the power station staff."*

Many disagreed.

> *"In the process of operating nuclear power plants... (operators)...have to make a large number of independent and responsible decisions... Unfortunately you will never have instructions and regulations that envisage the entire diversity of every possible combination of states and maladjustments."* (G. Medvedev Reference 3)

> *"The operator activated...the reactor emergency shutdown system...but...(it)...thrust the reactor into a prompt critical state."* (Minenergo expert Gennaddi Shasharin as reported in Reference 4)

And even if his actions had contributed to the accident.

> *"Human error can never be fully eliminated, even among highly qualified specialists. If one operator's mistake could lead to a reactor explosion... then nuclear power should be abandoned."* (Reference 4)

A later report into the accident[12] took account of the design flaws and misguided planning of the test and absolved the hapless operators Toptunov and Akimov who, through acts of extraordinary selflessness and bravery, helped to prevent the disaster spreading and paid with their lives.

So what of the designers? They knew about the flaws. Were they responsible?

> *"Complex technological systems usually have innumerable problems ... We all operate and use imperfect systems on a daily basis. We know about flaws and how to work around them... but it does require knowledgeable, skilled operators who understand how to compensate for the flaw, know their limitations and are committed to safety above everything else, including plant targets, bonuses and yes, orders."* (Reference 4)

Mushroom management: Keep 'em in the dark...

Accidents in Soviet nuclear power plants were kept secret from the public in the USSR. Worse, they were kept secret from the designers, engineers and operators of nuclear power plants.

Even the widely publicised details of the Three Mile Island Accident in the USA on 28 March 1979 (core melt after loss of cooling water to the reactor) were not made available to scientists and engineers inside the former Soviet Union (Reference 3).

If the management and operators of the plant had known about the power surge in Igualina and the partial core meltdowns in other RBMK units, would they have allowed the unsafe-safety test to proceed?

We will never know.

The people of Pripyat were not evacuated on the morning of Saturday 26 April because senior managers could not believe what had happened. Eye witness accounts of an exposed, burning core were ridiculed. Dosimeters that read off-scale for radioactivity were declared faulty. The nuclear power complex had been producing energy for ten years without a major offsite incident. It was all perfectly safe.

The evacuation of Pripyat took place on Sunday 27 April. On Monday 28 April 1986, after radiation levels set off alarms at the Forsmark Nuclear Power Plant in Sweden, hundreds of miles from the Chernobyl Plant, the Soviet Union finally admitted publicly that a serious accident had occurred[13].

But could such secrecy happen now?

Over my working life, I have seen a shift away from sharing process safety stories, not only outside but also inside companies. The short term fear of litigation outweighs the moral duty of disclosure. Company lawyers are increasingly forbidding technical staff to share detailed information, even internally. While most major accidents involving fatalities are independently investigated (what went wrong) sharing near misses (what nearly went wrong) is every bit as important.

As chemical plants become safer, do we forget just how dangerous they can be? Are we sometimes guilty of a willing suspension of disbelief when things are going well? Do we listen to those willing to speak truth to power?

"A leader who ... doesn't welcome bad news will get told everything is ok even when it isn't... We need leaders who can live with a chronic sense of unease and who can spot the warning signs of complacency creeping in." Judith Hackett[14]

If the Chernobyl accident reminds us of nothing else, it is the danger of complacency.

Conclusion

The 1986 Chernobyl accident has lessons that extend beyond the nuclear industry and the former Soviet Union. These lessons are directly applicable to today's international chemical industry.

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[10] http://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_D.pdf

[11] IAEA Report INSAG-A 1986

[12] IAEA Report INSAG-7 1993

[13] Wikipedia Accessed 29th Jan 2016 (wikipedia.org/wiki/Chernobyl_disaster#Announcement_and_evacuation)

[14] http://www.hse.gov.uk/aboutus/speeches/transcripts/hackitt221013.htm

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- artificially imposed deadlines lead to shortcuts;
- simplified targets in complex environments will lead to perverse incentives and unintended consequences;
- real experts tell leaders things they don't want to hear;
- good leaders listen;
- you don't get safety by rules and regulation, it starts with the design and evolves with experience;
- good design is iterative — it takes time, expertise and feedback;
- things happen differently on night shift;
- whatever the designers intended, sooner or later the operator will do something unimaginable — often on night shift;
- sharing process safety information means sharing what went right (near misses) as well as what went wrong (accidents);
- sharing process safety stories widely and acting on the lessons they teach us is the way we shore up our defences faster than the changes can overwhelm us;
- management of change, and a sense of chronic unease, stops only when the field is green again.

References

1. *Voices from Chernobyl – The oral history of a nuclear disaster – Svetlana Alexievivich*
2. *Testament - Valery Legasov, leader of the Soviet delegation to the IAEA Post-Accident Review Meeting*
3. *G. Medvedev, Chernobyl Notebook.*
4. *Producing Power: The Pre-Chernobyl History of the Soviet Nuclear Industry By Sonja D. Schmid*
5. *http://users.owt.com/smsrpm/Chernobyl/RBMKvsLWR.html*
6. *William J. Kelly , Hugh L. Shaffer & J. Kenneth Thompson (1982) The economics of nuclear power in the Soviet Union, Soviet Studies, 34:1, 43-68, DOI: 10.1080/09668138208411395 To link to this article: http://dx.doi.org/10.1080/09668138208411395*
7. *Nuclear Power in the Soviet Union. BA Semenov https://www.iaea.org/sites/default/files/25204744759.pdf*
8. *Nuclear Power Generation: Incorporating Modern Power System Practice edited by P.B. Myerscough*
9. *BBC Drama Documentary "Surviving Disaster" (https://www.youtube.com/watch?v=njTQaUCk4KY*
10. *http://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_D.pdf*
11. *IAEA Report INSAG-1 (International Nuclear Safety Advisory Group). Summary Report on the Post-Accident Review on the Chernobyl Accident. Safety Series No. 75-INSAG-1.IAEA, Vienna, 1986*
12. *"INSAG-7 The Chernobyl Accident: Updating of INSAG-1" (PDF). Retrieved2013-09-12.*
13. *Wikipedia Accessed 29th Jan 2016 (wikipedia.org/wiki/Chernobyl_disaster#Announcement_and_evacuation)*
14. *http://www.hse.gov.uk/aboutus/speeches/transcripts/hackitt221013.htm*
15. *Reactor Accidents 2nd edition David Mosey. ISBN 1-903077-45-1*
16. *Visiting Chernobyl – Bill Murray*
17. *http://chemwiki.ucdavis.edu/Physical_Chemistry/Nuclear_Chemistry/Applications_of_Nuclear_Chemistry/Chernobyl*

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