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Igoe's Notes on Midnight in Chernobyl, by Adam Higginbotham

Below are some thoughts about the book, which I thoroughly enjoyed, as well as a few comments about the state of the nuclear power industry in the US

I. The Book

General. This book presents a detailed, sweeping account of the greatest and most devastating accident involving the global nuclear power industry. Well researched and driven by a narrative that reads like a riveting novel, the work carefully lays the foundation for this catastrophic event through analysis of (1) the Soviet Union's design, testing and development of the relatively small model that became the prototype for the construction of large nuclear reactors, each capable of generating 1000 MW or more, (2) the weaknesses of the authoritarian, top-down culture of the multiple scientific and political organizations that were responsible for oversight of the Soviet Union's civilian nuclear program, (3) the troubled history of the construction of the large reactors, including critical issues associated with unrealistic milestones and timelines, the related challenges associated with maintaining high quality design and construction, and the suppression of information about prior nuclear incidents that would cast doubt upon the safety of the country's overall power plant design, (4) the training, assignment and oversight of personnel who would be responsible for leadership of the program and for managing the operation of the nuclear units, and (5) the political forces within the USSR that constrained the country's ability to complete timely and accurate analyses of the causes and effects of the melt-down of Unit 4 at Chernobyl and the rapid dissemination of practical information and guidance about the emerging risks of the nuclear disaster upon peoples in the surrounding communities, in more distant parts of the USSR and in other European countries where radiation particles and dust were likely to spread.

The author asserts that the evident failure of Soviet leadership in an area where the country had previously boasted, both to its own people and to the world at large, about the overall quality and strength of its nuclear scientific leadership had, by virtue of the dramatic sequence of events that unfolded shortly after midnight on April 26, 1986, unmasked the ugly fact that its civilian nuclear program was riven by serious design flaws, as well as critical leadership, operational and training difficulties and challenges, that collectively threatened the safety and welfare of the public. More importantly, the Soviet leaders' conduct, including their repressive approach to the development and communication of accurate and complete facts surrounding the emerging disaster, and their lack of candor about serious threats posed by dispersal of highly toxic radiation, seriously undermined the credibility of the Communist leadership among the peoples of the Soviet republics and throughout the world and became a major contributing factor to the demise of the Soviet Union which occurred but a few years later.

A few specific comments follow.

The Beginning. In the early 1970s, in a bid to meet its surging need for electricity and to catch up with the West, the USSR embarked upon a crash program of reactor building. In 1954, the Soviets had built the first reactor to generate commercial electricity but, in the ensuing years, the Soviets had fallen far behind the US and other countries. The Soviet minister of energy and electrification called for an aggressive expansion of nuclear construction, setting ambitious targets for a network of new plants across the European part of the USSR, with giant mass-produced reactors.

The initial instructions for the Chernobyl plant, the first to be built in Ukraine, called for the construction of a pair of nuclear reactors – a new model known by the acronym RBMK – or high-power channel-type reactor. In keeping with the Soviet tendencies toward "gigantomania," the RMBK, a graphite-water reactor, was physically larger and more powerful than almost any reactor in the West. The first unit was due to come on line in December 1975 and the second before the end of 1979. Subsequently, additional units were added to the complex such that by 1986, there were four 1000 MW nuclear units in operation, with two additional ones planned to go on line by 1988.

The challenges involved in construction of the units, under unrealistic time constraints, were considerable, particularly in light of the limited availability of high quality mechanical parts and building materials (steel and zirconium, pipework and reinforced concrete) and the inadequate capabilities of the Soviet workforce. The quality of workmanship suffered at all levels of manufacturing during this time, and labor disputes and infighting among construction managers were commonplace.

The Technology. The generation of energy from nuclear fission is a delicate process requiring three components: a moderator, control rods and a coolant. In simple terms, if the right quantity of uranium 235 is gathered in the presence of a neutron moderator – water, for example, or graphite, which slows down the movement of the uranium neutrons so that they can strike one another – a self-sustaining chain reaction will begin (called “criticality”), releasing molecular energy as heat. In a reactor, the behavior of the neutrons must be controlled, to ensure that the chain reaction stays constant and the heat of fission can be harnessed to create electricity. However, only about 1% of the affected neutrons, called “delayed neutrons” which emerge slowly from the fission process, can actually be controlled, thereby enabling operation of the nuclear reactor. But this is a very delicate and challenging task.

By the insertion of electromechanical rods containing neutron-absorbing elements – such as boron and cadmium, which act like atomic sponges, soaking up and trapping these neutrons, preventing them from triggering further fission – the growth of the chain reaction can be controlled incrementally. With the rods inserted all the way into the reactor, the core remains in a “subcritical” state. As they are withdrawn, fission increases slowly until the reactor becomes critical – and can then, with proper controls, be maintained in that state and adjusted as necessary. Withdrawing the control rods farther, or in greater numbers, increases reactivity and thus the amount of heat and power generated, while inserting them farther has the opposite effect.

If the rods are withdrawn too quickly, too far, in too large a number – or any of the myriad safety systems fail – the reactor may be overwhelmed by the fission and become “supercritical.” The result is a reactor runaway, a catastrophic scenario accidentally triggering a similar process to the one designed in the heart of an atomic bomb, creating an uncontrollable surge of power that increases until the reactor core either melts down or explodes.

Serious Design Flaws with the RMBK. With a water-graphite reactor, as the reactor becomes hotter and more water turns to steam, the chain reaction continues to grow, the water heats further and more of it turns to steam, which forms bubbles or “voids”. That steam, in turn, absorbs fewer and fewer neutrons, and the chain reaction accelerates further in a feedback loop of growing power and heat. To stop or slow the effect, the operators must rely on inserting the reactor control rods. If they were to fail for any reason, the reactor could run away, melt down or explode.

This "positive void coefficient" overshadowed the operation of every Soviet water-graphite reactor. And it became apparent that the effects of the positive void coefficient grew worse as more of the fuel was burned; the longer the reactor was in operation, the harder the reactor became to control. By the time it reached the end of its typical three-year operational cycle, the RBMK would be at its most unpredictable, and even though some modifications in design were made to address this concern, instabilities remained. Soviet leaders provided no safety analysis of the void coefficient in the manuals accompanying each reactor. (Reactors designed in the West were not afflicted with the positive void coefficient problem.)

The challenges posed by the positive void coefficient were exacerbated by the colossal size of the reactors, which made control much more difficult, as reactivity in one area of the reactor often had only a loose relationship to that in another (thereby rendering an operator's understanding the actual state of overall reactivity somewhat speculative) and by the fact that the system for using the control rods to implement an emergency shut-down (triggered by pushing the so-called "AZ-5 button") was designed not to bring about an *abrupt* emergency stop but to shut down the reaction in a measured fashion that could take up to 18 seconds, which the author characterized as "an eternity in a nuclear reactor with a high positive void coefficient." Moreover, under certain circumstances, the descending control rods might displace water from the bottom of the core and cause a sudden spike in reactivity, thereby contributing to a runaway situation.

In 1980, one of the Soviet nuclear agencies completed a confidential study that listed major design failings and thermohydraulic instabilities that undermined the safety of the RMBK reactor. The report made it clear that accidents were not merely possible but likely to occur in everyday operation. Yet, nuclear leaders took no action to redesign the reactor or even to warn plant personnel about its potential hazards.

All of these factors, plus others (including critical problems with technical leadership, plant staffing and discipline, and operator ignorance and failings), contributed to the meltdown of Unit 4 at Chernobyl.

The Massive Clean-up Effort and the Enduring Cost. The book provides an extensive history of the clean-up efforts and adverse effects upon the population: (1) the initial evacuation of the nearby town of Pripyat of 50,000 (which had been established for plant operators and their families) and of a 30-kilometer radius area around the plant, (2) the massive efforts to clean up the nuclear site, exposing up to 600,000 people to deadly radiation levels, (3) the adverse and sometimes curious effects upon humans and plants and animals of continued exposure to radiation, (4) the long-term medical treatment of plant operators and those involved in the clean-up efforts, and (5) the building of two enormous structures that covered the highly radioactive Unit 4, including the dilapidated and decaying structures and the highly dangerous remnants of the fuel core that remained at the very bottom of the reactor structure.

One estimate put the cost for all aspects of the disaster at more than $128 billion – equivalent to the total Soviet defense budget for 1989. Beyond the economic cost, the political cost, in terms of damage to the credibility and reputation of Soviet Russia, and its ability, as a Communist state, to continue to assert effective control over the Soviet republics, was extraordinary and devastating.

The impact upon neighboring countries was also severe and lasting. The original 30-kilometer zone around the plant remains deeply contaminated and this exclusion zone was expanded repeatedly. Altogether, by 2005, the contiguous parts of the Belarusian and Ukrainian exclusion zones made up a total area of more than 4,700 square kilometers of northwestern Ukraine and southern Belarus, all of it rendered officially uninhabitable by radiation.

Beyond the borders of the evacuated land, the contamination of other parts of Europe with radionuclides from the explosion proved to be widespread and long-lasting.

II. <u>Observations About the Nuclear Power Sector in the US.</u>

Operating Reactors. Nuclear power in the United States is provided
by 99 commercial reactors with a net capacity of 100,350 MW, 65 pressurized

water reactors and 34 boiling water reactors. In 2016 they produced a total of 805.3 terawatt-hours of electricity, which accounted for 19.7% of the nation's total electric energy generation. In 2016, nuclear energy comprised nearly 60 percent of U.S. emission-free generation.

As of late 2017, there were two new reactors under construction with a gross electrical capacity of 2,500 MW, while 34 reactors have been permanently shut down. The US is the world's largest producer of commercial nuclear power, and in 2013 generated 33% of the world's nuclear electricity.

Over the longer term, in absence of a nuclear renaissance (which appears to be unlikely in light of the public’s enduring concerns over safety and other complex issues – see below), the number of nuclear plants operating in the US is gradually expected to decline as existing plants are retired and decommissioned at the end of their useful lives.

Regulation. The Nuclear Regulatory Commission, an independent agency of the United States government, is tasked with protecting public health and safety related to nuclear energy. Established by the Energy Reorganization Act of 1974, the NRC began operations on January 19, 1975 as one of two successor agencies to the US Atomic Energy Commission. Its functions include overseeing reactor safety and security, administering reactor licensing and renewal, licensing radioactive materials, radionuclide safety, and managing the storage, security, recycling, and disposal of spent fuel. The NRC's regulatory mission covers three main areas:

- *Reactors* – Commercial reactors for generating electric power and research and test reactors used for research, testing, and training
- *Materials* – Uses of nuclear materials in medical, industrial, and academic settings and facilities that produce nuclear fuel
- *Waste* – Transportation, storage, and disposal of nuclear materials and waste, and decommissioning of nuclear facilities from service

Continuing Issues Affecting the US Nuclear Power Industry. The US nuclear industry has been and continues to be plagued by significant concerns over safe operation of nuclear facilities, the challenges associated with the long-term storage of spent fuel, and the substantial costs to be incurred in connection with the retirement and decommissioning of the reactors.

Safety. On March 28, 1979, equipment failures and operator error contributed to loss of coolant and a partial core meltdown at the Three Mile Island Nuclear Power Plant in Pennsylvania. The accident reflected the unanticipated interaction of multiple failures in a complex system; specifically, the mechanical failures were compounded by the initial failure of plant operators to recognize the situation as a loss-of-coolant accident due to inadequate training and human factors, such as human-computer interaction design oversights relating to ambiguous control room indicators in the power plant's user interface. The scope and complexity of the accident became clear over the course of five days, as employees of the utility, Metropolitan Edison, Pennsylvania state officials, and members of the NRC tried to understand the problem, communicate the situation to the press and local community, decide whether the accident required an emergency evacuation, and ultimately end the crisis. The NRC's authorization of the release of 40,000 gallons of radioactive waste water directly in the Susquehanna River led to a loss of credibility with the press and community.

Cleanup of the damaged nuclear reactor system at TMI took nearly 12 years and the reported cost approximated $973 million. In addition, it was estimated that the TMI accident caused a total of $2.4 billion in property damages. The health effects of the Three Mile Island accident are widely, but not universally, agreed to be very low level. The accident nevertheless triggered protests around the world.

Other reported incidents appear to have been less severe. For example, on March 5, 2002, maintenance workers discovered that corrosion had eaten a football-sized hole into the reactor vessel head of the Davis-Besse plant. Although the corrosion did not lead to an accident, this was considered to be a serious nuclear safety incident. The NRC kept Davis-Besse shut down until March 2004, so that the utility, FirstEnergy, was able to perform all the necessary maintenance for safe operations. The NRC imposed its largest fine ever—more than $5 million—against FirstEnergy for the actions that led to the corrosion. The company paid an additional $28 million in fines under a settlement with the US Department of Justice.

These various incidents notwithstanding, overall, the US nuclear industry has maintained one of the best industrial safety records in the world with respect to all kinds of accidents. For 2008, the industry hit a new low of 0.13 industrial accidents per 200,000 worker-hours. This is improved over 0.24 in 2005, which was still a factor of 14.6 less than the 3.5 number for all manufacturing industries. However, more than a quarter of US nuclear plant operators "have failed to properly tell regulators about equipment defects that could imperil reactor safety", according to an NRC report.

And concerns have continued to be expressed about safety issues affecting a large part of the nuclear fleet of reactors. For example, in 2012, the Union of Concerned Scientists, which tracks ongoing safety issues at operating nuclear plants, found that "leakage of radioactive materials is a pervasive problem at almost 90 percent of all reactors, as are issues that pose a risk of nuclear accidents". The NRC has reported that radioactive tritium has leaked from 48 of the 65 nuclear sites in the US.

Beyond the normal operating risks, the US 9/11 Commission stated that nuclear power plants were potential targets originally considered for the September 11, 2001 attacks. If terrorist groups could sufficiently damage safety systems to cause a core meltdown at a nuclear power plant, and/or sufficiently damage spent fuel pools, such an attack could lead to widespread radioactive contamination. Research scientist Harold Feiveson has urged that nuclear facilities should be made extremely safe from attacks that could release massive quantities of radioactivity into the community. The NRC carries out "Force on Force" exercises at all nuclear power plant sites at least once every three years.

Storage of Spent Nuclear Fuel. Spent fuel pools are storage pools for spent fuel from nuclear reactors. They are typically 40 or more feet deep, with the bottom 14 feet equipped with storage racks designed to hold fuel assemblies removed from reactors. A reactor's local pool is specially designed for the reactor in which the fuel was used and is situated at the reactor site. Such pools are used for immediate "cooling" of the fuel rods, which allows short-lived isotopes to decay and thus reduce the ionizing radiation emanating from the rods. The water cools the fuel and provides radiological protection shielding from their radiation. As plants have continued to age, many on-site spent fuel pools have come near capacity, prompting creation of dry cask storage facilities as well. Several lawsuits between utilities and the US government have transpired over the cost of these facilities, because by law the government is required to foot the bill for actions that go beyond the spent fuel pool.

Pools also exist on sites remote from reactors for longer term storage or as a production buffer for 10 to 20 years before being sent for reprocessing or dry cask storage.

There are at least 65,000 tons of nuclear waste now in temporary storage throughout the US. Yucca Mountain, in Nevada, had been the proposed site for the Yucca Mountain nuclear waste repository, but the project was shelved in 2009 following years of controversy and legal wrangling. An alternative plan has not been proffered. In June 2018, the Trump administration and some members of Congress again began proposing using Yucca Mountain, with Nevada Senators raising opposition.

Without a long-term solution to store nuclear waste, a nuclear renaissance in the U.S. seems unlikely. A number of states have explicit moratoria on new nuclear power until a storage solution emerges.

Plant Decommissioning. The price of energy inputs and the environmental costs of every nuclear power plant continue long after the facility has finished generating its last useful electricity. Both nuclear reactors and uranium enrichment facilities must be decommissioned, returning the facility and its parts to a safe enough level to be entrusted for other uses. After a cooling-off period that may last as long as a century, reactors must be dismantled and cut into small pieces to be packed in containers for final disposal. The process is very expensive, time-consuming, dangerous for workers, hazardous to the natural environment, and presents new opportunities for human error, accidents or sabotage.

The total energy required for decommissioning can be as much as 50% more than the energy needed for the original construction. In a number of cases, the estimates of decommissioning costs ranged from $300 million to $5.6 billion. New methods for decommissioning are currently being developed in an effort to minimize the usual high decommissioning costs.

Decommissioning at nuclear sites that have experienced a serious accident are the most expensive and time-consuming. In the U.S. there are 13 reactors that have permanently shut down and are in some phase of decommissioning, but none of them have completed the process.

Personal Footnote. During my professional career, I served as legal counsel for a number of large US investor-owned electric utilities, with the work involving corporate finance, securities and corporate regulation. Much of my time in the 1970s, 1980s and 1990s was spent assisting these companies in raising sufficient capital to fund their construction programs. The largest capital outlays covered the design and construction of various nuclear steam electric generating stations.

The particular nuclear facilities with which I became familiar included:

- The Grand Gulf Nuclear Station, operated by Entergy Corp. It has a GE boiling water reactor, which is the most powerful one in the US, with a core power of 4,408 MW yielding a nominal gross electrical output of 1500 MW
- The Waterford Steam Electric Station, Unit 3, operated by Entergy Corp. The plant has a Combustion Engineering two-loop pressurized water reactor, capable of producing 1240 MW of electricity
- Arkansas Nuclear One Electric Station, a two-unit pressurized water reactor owned and operated by Entergy. Unit 1, which has a generating capacity of 846 MW, was supplied by Babcock & Wilcox, and Unit 2, which has a generating capacity of 930 MW, was supplied by Combustion Engineering
- The Comanche Peak Nuclear Power Station, consisting of two Westinghouse pressurized water reactors, the first unit having a rating of 1084 MW and the second unit a rating of 1124 MW. The plant was originally operated by the Texas Utilities Company system
- The Susquehanna Steam Electric Station, originally operated by Pennsylvania Power & Light. The plant has two GE boiling water reactors, each capable of generating 1350 MW

One of last financing transactions in which I was engaged on behalf of Entergy involved the sale and leaseback of its Waterford 3 nuclear unit. I recall that the deal closed in September 1993. In conjunction with the transaction, I took advantage of an opportunity to visit the plant. Fitted out with my Waterford 3 hard hat, I was escorted around various parts of the facility and allowed into the control room, a cavernous space that included a dizzying array of panels, lights, switches and levers.

Any possible demonic inclination on my part to touch the nearby buttons, switches and levers was blunted by the notable presence of firearms in the room.

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