Science & Global Security, 1994, Volume 5, pp.37–46
Reprints available directly from the publisher
Photocopying permitted by license only

© 1994 OPA (Overseas Publishers Association)
Amsterdam B.V.
Published under license by
Gordon and Breach Science Publishers SA
Printed in the United States of America

Converting Russian Plutonium-Production Reactors to Civilian Use

Alexander M. Dmitriev[a]

PLUTONIUM-PRODUCTION REACTORS IN RUSSIA

The first Soviet reactor designed to produce weapon-grade began operation in Chelyabinsk in June of 1948. This single-purpose, graphite-moderated, single-pass reactor was a water-cooled reactor. Its cooling water was dumped directly into a lake at roughly 100°C. Several more reactors of this type were subsequently constructed.

In 1958, a reactor of a new type began operation in Tomsk-7. A graphite-moderated production reactor was built to operate in dual-purpose mode, producing both weapons-grade plutonium and heat and electricity for local residents. The primary reactor circuit was closed, and the reactor plant was equipped with heat exchangers, steam generators and turbines to produce electric power. In 1961, 1964 and 1965, four additional dual-purpose reactors began operation: three in Tomsk-7, and one in Krasnoyarsk-26. Shortly after being commissioned, the Krasnoyarsk-26 reactor was fitted with a system to transmit its low-grade heat (i.e., heated water that has passed through steam generators) to meet residential heat demands. (Low-grade heat had already been used for some time to industrial plant buildings at the Tomsk-7 and Krasnoyarsk-26 sites.) Initially, the supply of heat was rather limited, but by 1968 a decision was made to heat the district of the main city of Tomsk with waste heat from the reactor. In 1973, a 17-kilometer heating main was completed. It had four pipelines one meter in diameter, relay pumps, and demineralization equipment. Two direct pipes carried hot water, two others were

---

[a] Department Head, Gosatomnadzor
(Russian State Committee for Radiation Safety), Moscow.

return water mains. The two production reactors at Tomsk-7 (the largest in Russia) shared heat exchanging equipment.

This unique installation has been successfully functioning in Siberia since 1973. Since that time, many residents of Tomsk have had gardens, and there is even a large-scale green-house—all supplied with waste heat. An oil-burning power plant was built as a backup, but it has never been used in emergency mode as there has never been a simultaneous shutdown of both reactors in winter.

In 1963, the first and only U.S. dual-purpose reactor was built in Hanford, Washington. The reactor (called the N-reactor) was shut down for upgrades in January 1987 following the Chernobyl accident. Its operation has never been resumed.

The U.S. N reactor and the Russian dual-purpose reactors were similar in that both U.S. and Russian reactors were graphite-moderated channel-type pressurized-water-cooled reactors designed to manufacture weapons-grade plutonium. In both, waste heat was used to generate electric energy. (As noted, the Russian reactor plants also supply domestic hot water for central heating.)

There are major differences between U.S. and Russian dual-purpose reactors. Russian reactors had aluminum alloy fuel channels and fuel cladding. These components maintain strength up to 300°C, and melt at 650°C.The fuel channels and fuel cladding of the N reactor were made of zirconium alloys, which melt at 1,700°C. Another difference was the N reactor graphite stack design provided for special channels to release water and steam in the event of fuel channel leakages or ruptures, and, in this way, prevented pressure build-up in the reactor graphite stack. Russian reactors lack effective means to remove steam and water from the graphite stack. Thus, Russian production reactors are poorly equipped to deal with coolant leakage from channels. The danger is compounded by the fact that the fuel channels are manufactured from a very weak material which loses strength even at minimal overheating. The reactor cavity lid, which covers the graphite stack could be dislodged if the pressure rises above 2.5 kilograms per square centimeter, even though the gross weight of the top exceeds 2,000 tons. If the lid were dislodged, fission products could escape into the atmosphere. During the Chernobyl accident, the lid of Unit 4 at the Chernobyl nuclear power plant was dislodged by pressure arising from ruptured fuel channels, and vast amounts of uranium, plutonium and fission products were released into the atmosphere.

Whereas the N reactor had a negative coolant void coefficient of reactivity without the use of burnable poisons in its metallic uranium fuel, by contrast the reactivity coefficient for the Russian production reactors becomes positive in the event of loss of coolant. If a large crack or hole appears in the cooling system, reactivity and power increase as water boils, fuel overheats, and pressure in the reactor cavity builds up rapidly. However, the rate of such a power surge would be significantly less than that during the Chernobyl disaster because the value of the void coefficient of reactivity is three to five times less than the value for an RBMK reactor at the time of the Chernobyl disaster.

Also, comparing favorably to the RBMK, the production reactors were originally designed to be shut down much faster. The insertion time for scram rods in the production reactors was 4.5 to 5 seconds, compared to 15 to 18 seconds in the Chernobyl reactor. The scram system was further enhanced between 1990 and 1991 when 30 scram rods in each reactor were equipped with special modified servodrives. The insertion time for absorber rods of this group was decreased to 2.2 to 2.5 seconds.

In the worst case scenario—a sudden rupture of the entire coolant pipeline—a short, minor power surge would occur. In this case, the emergency backup system would activate quickly to suppress the chain reaction in the core. Nuclear specialists state that reactors with positive reactivity must have two independent emergency shut-down systems. Preference is given to automatic systems, which do not require intermediate measurement or trip-point reference systems and are independent of external instrumentation and power systems.

Between 1989 and 1991, the author designed and supervised the testing and installation of such an automatic emergency system at the production reactors in Tomsk. Theoretically, the system makes an abrupt power surge impossible even in a severe accident, such as a coolant header rupture. By the loading of passive reactivity-protection blocks of boron compounds into fuel channels it is possible to prevent power surges. In the event of an accident, boron compounds are transported into the core by steam and water and suppress the neutron chain reaction. Improving reactivity control by substituting new control rods for fuel rods would be very difficult because it would require major changes in the control rod power and cooling systems. Alternatively, the problem of reactivity control might be solved by suitable choices of fuel enrichment, erbium content, fuel lifetime and refueling patterns.

In order to prevent power surges, an automatic response safety system was installed to trigger the separate fast-response group of 30 scram rods. Even so, if a loss of coolant accident does happen, its consequences might be very severe. If a primary circuit were to rupture badly, cooling water would boil and escape from the core. Because there is no emergency high-pressure water-injection system, water from emergency water-supply tanks would not reach the central section of the reactor core which would be blanketed by steam. The operating temperature of graphite is near the melting point of aluminum alloys, and thus the following sequence of events could occur:

1. a coolant loss due to fuel channel rupture,
2. influx of the remaining coolant into the incandescent graphite stack
3. increased pressure in the reactor vessel,
4. dislocation of the reactor lid,
5. fuel melt-down at a later stage, and
6. discharge of radioactive material into the atmosphere.

These events could occur not only after the rupture of a pressure header, but also as a result of less severe accidents, such as rupture of an auxiliary header or a large break in any section of a primary circuit. In these cases, it may take longer for these events to occur, but the end result could be similar.

Because of the potential for disaster, the Russian nuclear regulatory authority—State Committee for Radiation Safety, or Gosatomnadzor—cannot permit long-term operation of these reactors without extensive upgrading and modifications. Even though there has been a great effort over the last five to six years to prevent power surges in the event of serious ruptures of a reactor primary circuit, the reactors still have unresolved safety issues.

Nevertheless, Russian experts have concluded that the reactor's key structures—instrumentation, electrical equipment, heat exchangers, steam generators, turbines, and cooling towers—could easily operate for another 10 to 15 years. The graphite stack in the core region, where the fluence of damaging neutrons is high, has experienced the most damage. The graphite stack has warped, making removal and insertion of fuel channels problematic. This problem has been addressed by securing graphite bricks in the columns. The graphite stack is straightened with channel stretching and special bars.There is no evidence of secondary graphite swelling. Thus, Russian experts maintain, the probability of a failure of internal reactor components that could lead to catastrophic consequences is small. Gosatomnadzor agrees with this conclusion.

Therefore, it is possible that the reactors will continue to provide heat and hot water to Tomsk city. Indeed, the construction of a conventional heat supply system—heating plant No.3—has been very slow. Furthermore, the people of Tomsk may prefer a reactor-based heat supply system, which replaced over 200 small-scale coal-fired boiler-houses in the residential districts of Tomsk. Not many in Tomsk want to live near a large heating plant burning low-grade coals and fitted with inadequate gas filtering devices.

Unfortunately, the performance of the heating main supply system has recently changed for the worse. Because the demineralization facility has not been able to produce enough water for heating to meet city's demand, some of water has not been purified. As a result, a thick layer of mineral sediments has formed on the internal surfaces of the system's pipelines. The hydraulic resistance in the pipelines has increased drastically, and water flow has dropped sharply, as has the amount of heat supplied.

CONVERSION OF PLUTONIUM-PRODUCTION REACTORS

Efforts have been made since 1988 to achieve two goals: to halt the production of weapons-grade plutonium without disturbing the supply of heat and electricity to dependent cities, and to develop a capability to use fissile materials recovered from weapons as fuel for the production reactors.

The following guidelines should be used for converting the reactors:

1. In the event of a loss of coolant accident, the void coefficient of reactivity should remain sufficiently negative to cover all practical uncertainties.

2. Only those fuels which have already been tested in the graphite-moderated production reactors should be used. The manufacture of fuel should be well-established and should be at a level of production capacity to ensure that fuel is always available.

3. Major upgrades of reactor structural elements, control and safety systems, should be avoided. (For example, because control rod channels are cooled by a separate cooling system, introduction of new control rods would result in upgrades of the cooling system and would be expensive, complex and time-consuming.)

4. Additional protection systems should be simple and include both passive and automatic devices, if possible.

5. Power density distribution throughout the core should always be set so that the bulk coolant leaving the reactor is hot enough to satisfy the heat and electricity supply demands. Refueling operations, conducted over the reactor lifetime, should not result in changes of these operating parameters.

6. Testing the new mode of operation should not require large-scale,

expensive or time-consuming experiments.

7. Experimental sections could be set up in the core, and the transition to a new core arrangement and new operation mode should be gradual without long outages.

8. Emergency reactor systems should mitigate the consequences if a severe accident were to occur.

9. The reprocessing of irradiated fuel rods should be carried out at the existing production facility, and should be based on proven technologies. If reprocessing is not planned, storage requirements should be minimized and inexpensive methods should be employed.

Technical aspects of reactor conversion have been discussed with Pacific Northwest Laboratory (PNL). One option PNL evaluated uses a variation on N reactor fuel elements. The N-reactor was fueled with LEU metal with alloying additives and was clad with zirconium alloy. The fuel was designed for long-term wet storage without reprocessing. Many tons of such spent fuel are currently stored in ponds in the U.S.

Experts on both sides believe that if a neutron absorber with a large resonance below one electron-volt such as erbium could be introduced into the fuel of a Russian production reactor, a negative coolant void coefficient of reactivity could be maintained. The N-reactor metallic fuel has a demonstrated capability to operate in a stable manner up to a fuel burn-up of 10,000 MW-days per ton of fuel, i.e., at burn-up levels that are at least 10 times higher than those of the Russian production reactors. Use of erbium in the fuel offers a solution to one of the most difficult problem of converting the production reactors in Russia—reactivity compensation.

Russian experts gradually came to believe that highly enriched uranium in the form of oxide distributed in an aluminum matrix should be employed as reactor fuel. Such fuel withstands fairly high burn-ups without any pronounced shape distortions. There is extensive experience with this fuel in many different reactors. After a cooling period, reprocessing presents no problems, except that of storing high-activity reactor-grade plutonium. The amount of plutonium accumulated during irradiation within the uranium fuel (with enrichment in the range of 20 to 90 percent) is rather modest.

One weakness of this fuel is its very low melting point, which is near that of aluminum. However, if certain core structural components are modified the fuel could be better than fuel fabricated from metallic uranium. Moreover, these adjustments could mitigate accident consequences.

Use of highly enriched fuels would have significant advantages. It would reduce additional processing of fissile materials from weapons during fabrication of fuel. Also, it would minimize production of plutonium in the reactors and produce plutonium with a higher fraction of Pu-240.

To assure negative values of the reactivity coefficient, the use of highly enriched fuels has to be compensated by the use of strong absorbers. Unlike the U.S. approach for erbium utilization which requires homogeneous mixing with fuel materials, heterogeneous absorber accommodation is possible. Boron, in the form of steel and structural elements, could be such an absorber. The simplest solution is to form boron compounds into blocks shaped similar to cylindrical fuel rods. Some of these blocks could be loaded in special channels and removed as necessary to compensate for reactivity loss due to fuel burn-out. Others could be placed in the core to assure negative values of reactivity in the event of a loss of coolant accident.

Such an arrangement of absorber elements and fuel poses a number of problems. Use of separate channels for absorber blocks to compensate for insufficient control and safety system performance causes a loss of overall reactor power and, more important, a drop in the temperature of the outlet coolant. (Power production in an absorber block is much smaller than in fuel.) A 30 to 40°C drop in temperature reduces electricity production and domestic heat output dramatically, so that limiting the number of channels charged with absorbers is a critical issue.

Improving heat utilization allows for an acceptable fuel-element operation period of two to three years. When enrichment is high, the problem of high fuel burn-out in the central part of the core arises. It results in heavy flattening of the axial power distribution, creating an inward flux sag in the center of the core. In this case, xenon stability, the coolant boiling point margin at the outlet of channels, and proper control of the power distribution with regard to the small number of neutron distribution control points all become complex problems.

Although several ideas for conversion exist, much remains to be done. The first step would be to replace fuel channel aluminum alloy tubes with zircalloy tubes. This should significantly mitigate potential accident consequences. Zircalloy fuel channels have been used in graphite-moderated production reactors on a limited scale, and there are enough experts and facilities to fabricate such channels in Russia. Replacement could be done gradually, without lengthy reactor outages. The tubes should last until the final reactor shutdown in 10 to 15 years.

Design of fuel elements presents another practical problem. Highly enriched uranium fuel in the form of uranium oxide in an aluminum matrix seems best at this point. Fuel design should allow simultaneous charging of the neutron absorber in the fuel so that absorber and fuel are placed in the same fuel channel and are close to each other. This would have several benefits. Use of absorber elements for flattening neutron multiplication would allow more extensive use of the control and safety system for accident control and emergency reactor shutdown. It would avoid reductions of coolant temperatures at the reactor outlet (important in view of the deterioration of the pipeline from the reactors to the city).

Finally, the described fuel design would allow use of plutonium, and, in this way, reductions in the plutonium stockpile. Fabrication of plutonium-oxide based fuel would not require any complicated metallurgical processing and could be carried out quickly at facilities at Tomsk-7. (There are probably no alternatives to the Tomsk-7 facilities. At present, fuel for production reactors is produced in Novosibirsk. Environmental regulations and common sense would make it difficult to produce plutonium fuel in Novosibirsk.) Although the use of plutonium based fuels is difficult, the production reactors might be well suited for this mission, and the process of burning up plutonium could be perfected within two to three years. This is the only method available in Russia to burn plutonium in the near future.

On the whole, converting Russian dual-purpose reactors is primarily a social, rather than a technical problem. Although experts, including the author, have been studying this problem since 1989, there has been very little actual progress because Minatom of Russia has not committed itself to investigating and solving the conversion problem. Fortunately, recent political developments could facilitate the resolution of this situation. There are plenty of technical solutions in Russia, but assistance and support from the U.S. would also be most welcome.

Editor's Note:

We asked Darrell Newman of Battelle Pacific Northwest Laboratories to comment on Dmitriev's article. The following is excerpted, with the author's permission, from that comment.

Dmitriev provides a timely and authoritative view of the safety of Russian plutonium-production reactors. The recent upgrade of the protection system described in Dmitriev's article doesn't give complete assurance of safety. True, a power surge will not lift the lid, but a supply pipe or header rupture will still melt fuel in the core. Although there is a low-pressure backup coolant source (emergency supply tanks, and the control rods have a separate coolant circuit from the fuel channels) which may be adequate for removal of decay heat, either accident (lifting the lid or melting the core) could have severe consequences.

The nine conversion goals give a true impression of the practical aspects of conversion. The reactor and processing equipment are all they have to work with; no expensive upgrades to the core or support facilities are possible. The equipment and instrumentation are not subject to major changes, and I agree with seven of the nine goals.

Goal number 5 is: "Power density distribution throughout the core should always be set so that the bulk coolant leaving the reactor is hot enough to satisfy the heat and electricity supply demands. Refueling operations, conducted over the reactor lifetime, should not result in changes of these operating parameters." Dmitriev recommends that the coolant leaving the core should stay at the existing level. However, it may turn out that the final solution results in a net decrease in power due to the power distribution at the end of life of a particular fuel load. Domestic heating could still be realized with the installation of a parallel supply pipe to the city. (This violates the "no expensive upgrade" rule, but it is a low-tech solution that should not be ruled out.)

It is not clear how the Russians will achieve goal number 8: "Emergency reactor systems should mitigate the consequences if a severe accident were to occur." The fuel channels and the fuel must be considerably more robust than the present design. I have to make some assumptions:

- The aluminum channels have to go—I agree with the author, zirconium is the way to go and it should last the rest of the reactor life.
- The fuel must be capable of withstanding a severe transient—blowdown then reflood with a low-pressure source without sustaining substantial damage. This may impose some operational restrictions in the form of thermal limits.

Dmitriev does not address any thermal limits with the exception of prevention of boiling at the outlet. As a minimum, the new fuel should not be any less resistant to accidents than the current fuel.

Dmitriev's comparison of the types of fuel proposed all have the characteristic of eliminating the positive void coefficient and halting the production of weapons-grade plutonium. After all of the descriptions of heterogeneous and homogeneous absorbers, his fuel choice seems to be highly enriched uranium in an aluminum matrix. The burnable absorber concept is the same as the concept from Pacific Northwest Laboratory. PNL has done calculations and has determined the optimum fuel/absorber ratio.

In reference to the drawbacks of the PNL fuel, Dmitriev states the major concern is the reduction of the strength of the control rod system. This problem could be resolved as he states, "by suitable choices of fuel enrichment, erbium content, fuel lifetime and refueling patterns." The PNL analysis indicates that there is still enough rod strength and this is not a problem.

Stopping the plutonium production does not seem to be the overriding question; the safety of the modification has to be as important, if not more important. After any conversion the fuel exposure is increased by a factor of 10 or more. This means that the fission product inventory is also increased by a factor of 10. Fission gases will be at an equilibrium for any exposure. Any fuel melting accident would be more severe, potentially releasing a factor of 10 more fission products.

If one considers that there could be an accident at one of these reactors during their remaining life, fuel which releases the least volatile fission products may be the best even though it doesn't significantly reduce plutonium production.

With respect to the selection of a replacement fuel, the aluminum matrix fuel may be worse under accident conditions than the metallic uranium fuel. The metallic uranium fuel has good heat transfer characteristics and a higher melting point. When I look at this from the practical aspect of reactor operation the LOCA accident must be considered. Operating the reactor at a reduced specific power may be a solution to reduction of risk. The concomitant result is that there may have to be some concessions on total power because of thermal limits that will allow the fuel to survive a LOCA.

Darrell F. Newman