Forestry in the Chornobyl Exclusion Zone: Wrestling with an Invisible Rival

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ABSTRACT

After the Chornobyl (Chernobyl) accident, surrounding forests have served as a sink and long-term accumulator for radionuclides, preventing them from further migration. Never before has the challenge of forestry management under massive radiation impacts existed. The objectives of "Chornobyl Forest," an enterprise responsible for forestry management within the most contaminated Exclusion Zone, not only prioritize the stabilization of radionuclides but also include the resumption of a forest-products industry. Besides the lack of scientific knowledge, the situation is aggravated by harsh budget constraints. Chornobyl Forest managed to tackle the most urgent problems and accumulate valuable experience.

Keywords: Chornobyl; radioactive contamination; exclusion zone; forestry management; reforestation

The world's worst nuclear accident occurred at the Chornobyl Nuclear Power Plant, located 80 miles north of Kyiv (Kiev) on Apr. 26, 1986. About 100–200 million curies (Ki) of fission products, roughly equal to one hundred bombs dropped on Hiroshima and Nagasaki, were released in the environment from the ruined Reactor 4 (Stone 2001). The effects were felt across the Northern hemisphere. The long-term impacts of Chornobyl extend far beyond environmental harm to an extensive collection of social, economic, medical, ethical, and cultural problems. In some years, for instance, Chornobyl-related expenditures reached 12% of the state budget of Ukraine. This article is an attempt to generalize and analyze information on radioactivity effects on forests, their role in binding radioactive materials, and managing those forests.

Never before was mankind faced with the challenge of large-scale radioactive contamination of forests. Twelve of Ukraine's oblasts (provinces), southern Belarus, and the Bryansk region of Russia suffered from this disaster. In Ukraine alone, 39% of all forests were exposed to the effects of serious radiation (with the level of soil contamination by cesium-137 (^{137}Cs) amounting to more than 1 curie per square kilometer (Ki/km^2)) (Nadtochiy 2003). The so-called "Red Forest", a 3,700-ac stand of Scotch pine (*Pinus sylvestris*) that died out because of high direct doses of radiation, is one of the most contaminated terrestrial ecosystems on Earth. The disaster caused a 530 million cubic foot loss in standing timber (Landin 2001). These forests are also lost for the purposes of gathering of mushrooms, berries, nuts, and medicinal plants. Radiation seriously disrupted the gene pools of some species.

Exclusion Zone

Large-scale evacuation, deactivation, and rehabilitation were carried out since 1986. As part of these measures, the Exclusion Zone and Zone of Mandatory Resettlement (EZ), a territory surrounding the nuclear power plant roughly within a radius of 18.5 mi (totally 504,200 ac), was depopulated. This state-owned land was transferred for permanent use and management to the Exclusion Zone Administration, a structure under the Ministry of Emergencies. Administratively, the EZ is situated in the territory of modern Ivankiv and Poliske raions (counties), at the northern part of Kyev oblast neighboring with Chernihiv oblast and Belarus. The area features several tributaries of the Dnipro (Dnieper) River, notably the Prypiat (Pripyat) and the Uzh.

The main changes undertaken within the EZ after the accident are connected with the relief activities at the nuclear plant, the burial of exposed equipment, the evacuation of the towns of Chornobyl and Prypiat and all rural settlements, and the construction of new dams, roads, and waterways. After the last working reactor closed on Dec. 15, 2000, efforts were refocused on minimizing the accident's consequences and maintenance of the EZ. About 120 research, design, and production units employing about 15,000 people are involved in these activities under the Administration's authority. The State Specialized Production Complex Forestry Enterprise of Chornobyl Forest is one of them.

Natural Conditions

The climate of the region is temperate continental. Peat bog with a substantial por-

Figure 1. Exposed machinery and equipment was buried and abandoned on the Exclusion Zone's territory. In the background, Chornobyl Nuclear Power Plant. Copyright 1996, Svit u Doloniakh. Reprinted with permission.

tion of marshland abounded before the total drainage campaign in the 1950–70s. Soddy and soddy-podzolic soils on sand–clay strata with mainly light texture, low humus content, and increased acidity dominate here. In terms of vegetation zoning, it is a part of the mixed-forest zone (Ukrainian Polissya). Scotch pine and common oak (*Quercus robur*) with some silver birch (*Betula pendula* and *B. pubescens*), aspen (*Populus tremula*), and alder (*Alnus glutinosa* and *A. incana*) originally formed mixed stands.

Forests originally covered almost all the territory of the modern EZ. There was a devastating exploitative process during the 19th century. As a result of the clearing of land for agriculture and timber harvesting, the forest cover rate dropped to only 11–12% in the early 1900s. However, dramatically decreased land fertility served as an impetus for reforestation. These activities reached their climax in the 1950–60s, leading to an increase in forest cover rate of up to 50%. Although forest acreage grew significantly, reforestation generally focused on an effort to stock devastated areas with productive stands as quickly as possible. Therefore, monoculture plantations of Scotch pine replaced former mixed old-growth stands (Ukranian State Design 1998).

Forests in the Accident and Aftermath

After the explosion, forests performed a unique role that could be compared with a vacuum cleaner. Dense forest vegetation almost completely prevented further aerial dispersal of radionuclides (excluding those transported in the air from fires) (Nadtochiy 2003). Components of forest ecosystems absorbed the biggest portion of the radioactive fallout, much more than farmlands more easily purified by rains. Most of the absorbed radionuclides are stored in trees' leaves and needles (where assimilation is the most intensive), and in bark. For example, needles and leaves contain 4–12 times more and bark 20–30 times more ^{137}Cs than timber (that is why debarking is an important component of contaminated trunks processing) (Nadtochiy 2003).

Radionuclides migrated to the ground with the fall of dead leaves and needles, where they were originally stored. As a result, the forest floor is still severely contaminated even in areas with a low degree of contamination (1 to 2 Ci/km^2) (Chernobyl.info 2003). The highest degree of contamination by ^{137}Cs (much more severe than that of trees) is observed in mushrooms, and among vascular plants: in bilberry (*Vaccinium myrtillus*), lingonberry (*V. vitis-idaea*), cranberry (*V. oxycoccus*), and heather (*Calluna vulgaris*) (Nadtochiy 2003).

Cesium will persist for a long time in the soil layers where plants have their roots. Strontium is more mobile and soluble in water. More than 80% of it is already involved in natural cycles. The degree of contamination for different plants depends on their variety, type of roots, and soil characteristics. Shallow-rooted plants suffer from radiation more than those with taproots reaching nutrients at deeper layers. In soils lacking in minerals, cesium, chemically similar to potassium, is absorbed by plants in larger amounts (Chernobyl.info 2003).

Forests serve as a sink and long-term accumulator for most of the radionuclides, preventing them from further dispersion, but they are not a panacea per se for the radioactive contamination problem. In the coming decades, the decay of timber in the natural cycle will threaten radionuclide leakage into the environment. However, timing is crucial in this case. Considering that most of the EZ forests are middle-aged or young growth, proper forestry management can prevent the effective release of radionuclides for three to seven decades. This time is sufficient for self-inactivation and transformation into stable nonradioactive isotopes for most of the trapped radionuclides. Additionally, some undergrowth species such as raspberry (*Rubus daeus*) and hazel (*Corylus avellana*) are able to remove radionuclides from the soil, reducing contamination in the trees as well. Unfortunately, these observations have not yet translated into any practical applications (Stone 2001). Therefore, although not a panacea per se, the forests are a key natural factor in stabilizing radioecological conditions.

Chornobyl Forest

Generally, forests could thrive without any human interference. However, this result is not so obvious in a case of forest ecosystems exposed to a millennium-long anthropogenic pressure like those in the Chornobyl region. Even before the explosion, artificial Scotch pine plantations amounting to about half of all EZ's forests; despite good growth, exhibited serious problems such as damage from wildfire, windstorms, fungi, and insect pests (Ukrainian State Design 1998). The accident added a strong limiting factor—radiation. There is no doubt that, without human intervention, some stable plant communities would still develop in the EZ. However, it is also clear that this scenario would mean an inevitable degradation of existing forests. In this case, transportation of radionuclides to new territories because of fires and timber decay most likely would be equal to a series of new explosions. The only way to prevent such developments was to provide adequate management to these forests.

At the time of the explosion, there was no clear experience regarding the sort of forestry management that would be adequate in a case like the Chornobyl accident. Scientists had limited information on dispersion of radionuclides in forest ecosystems based on experimental data and on experience from a nuclear accident in the Ural region

Figure 2. Logo of Chornobyl Forest Copyright 1996, Svit u Doloniakh. Reprinted with permission.

(Russia) in 1950s. However, there was no knowledge of concrete forestry measures (Nadtochiy 2003) or on the broad range of related questions, such as whether the exposure of forestry workers to unhealthy conditions could be justified.

After the accident, conventional forestry management was stopped in this territory. Serious, mainly negative, changes occurred. The infrastructure of forest enterprises was ruined. From 1986 to 1992, the acreage of forests experiencing fire grew eightfold; the share of dead trees in the total stock increased by 5.5 times; and the level of debris increased 10 times. Many delimiting cuts and forest roads became covered with young growth or were turned into swamps (Ukrainian State Design 1998). However, some salvaging of burned areas and debris and replanting was conducted under the Ministry of Forestry Management. Most of the debris in the Red Forest was buried in trenches. Tree-planting was carried out on 1,100 ac of this terrain to prevent dispersion of radioactive particles (Landin 2001).

Starting in Dec. 1992, Chornobyl Forest was responsible for forestry management within the EZ. Its area, amounting to 460,700 ac, encompasses forests and abandoned farmland. Inevitably, the newly-organized enterprise confronted serious difficulties. Never before were forest specialists challenged to manage forests under a massive radioactive contamination. Though such problems are not limited to the EZ in Ukraine, they are the most acute in this region. Besides the lack of scientific knowledge, the situation is aggravated by harsh budget constraints reflecting the country's economic transition.

First of all, identification of priorities was needed: zoning the territory and organizing the enterprise's managerial structure; recruiting personnel and creating relatively safe work conditions; constructing housing, office, and production facilities; and obtaining relevant machinery and equipment. The following priorities were identified:

- forest inventory;
- salvaging cuttings at burned areas and their reforestation;
- development of a fire-prevention system;
- cutting of border openings and maintenance of forest roads (about 808 miles, mostly in unsatisfactory condition);
- afforestation of at least a part of abandoned farmland; and
- conservation of wildlife (Ukrainian State Design 1998).

Stabilization of radionuclides is unambiguously prioritized within the objectives of Chornobyl Forest. However, rehabilitation of contaminated territories, an ultimate goal of human activities within the EZ, also implies the resumption of a forest-products industry. In terms of the EZ, forestry management encompasses a broad array of activities, from preservation to harvesting of forest products, but prevention of further radionuclides dispersal is a principal goal.

Zoning of the Territory

During 1993–1998 the forest's inventory was conducted. All forestland (both land with forest vegetation and land designated for reforestation), amounting to 409,200 ac, was classified as Group I forests, which perform primarily protective functions. But additional zoning differs radically from traditional methods. It is based on radiological criteria. The following subcategories were identified:

- *Section of moderate forestry management* (about 39% of the total acreage). Here, the degree of contamination by ^{137}Cs is <40 Ki/km^2, by strontium-90 (^{90}Sr), <3 Ki/km^2, and by plutonium-239 (^{239}Pu), <0.1–0.3 Ki/km^2. The ultimate objective in this section is to gradually restore the normal regime of forestry management.
- *Section of limited forestry management* (about 27% of acreage). Here, the degree of contamination by ^{137}Cs is 40–100 Ki/km^2, by ^{90}Sr, 3–10 Ki/km^2, and by ^{239}Pu, 0.1–0.3 Ki/km^2. To sustain the viability of these forests and return them to normal status in long-term prospective is the final goal.

Section of strict reserve regime (34% of the total area). Here, the degree of contamination by ^{137}Cs is >100 Ki/km^2, by ^{90}Sr, >10 Ki/km^2, and by ^{239}Pu, >0.3 Ki/km^2. Efforts are focused on fire, pest, and disease control. Some measures for sustaining the forests could be carried out on limited areas (Ukrainian State Design 1998).

The degree of contamination by ^{90}Sr served as a key indicator for this zoning. In the future, ^{239}Pu will become the most important, because its half-life is up to 24,000 years compared to 30 of ^{137}Cs and 90 of ^{90}Sr. Therefore, new zonings will be needed. Additional complexities are associated with the irregular spread of radionuclides. Because of natural factors (wind, rain, relief, etc.), harshly contaminated "hot spots" adjoin mildly contaminated areas. This is why the precise delimitation of the Zone's borders is doubted by many practitioners. Based on above-mentioned criteria, an additional 440,000 ac could be included in the EZ (Atlas of Chornobyl Exclusion Zone 1996).

Managerial Structure

The specific conditions of this territory required unique approaches to the managerial structure of the enterprise. Its land is distributed across 12 forest divisions (17–47,000 ac) incorporated in three forest bases (143–166,000 ac). Generally, the new structure does not coincide with that of former forestry enterprises on this territory, because thousands of acres of former farmland were added. In most cases, buildings and other facilities of these enterprises were also abandoned because their locations were not convenient under the new conditions. According to radiological safety requirements, all housing, office, and production facilities are concentrated in forest bases and at the enterprise's central compound in the town of Chornobyl. As a result, some crews must travel up to 20 miles to their working places (Ukrainian State Design 1998).

Foresters are exposed to a serious health hazard. The dose of their exposure to highly penetrating gamma radiation is 1.5 times higher than that of an average EZ inhabitant (Nadtochiy 2003). Minimizing the collective radiation dose, i.e., both the number of people exposed to ionizing radiation and time of work performance, is the foremost matter for personnel management. Consequently, the administrative staff works four days per week, whereas the personnel of forest bases have 15-day shifts alternating with 15-day breaks. Unlike other Ukrainian for-

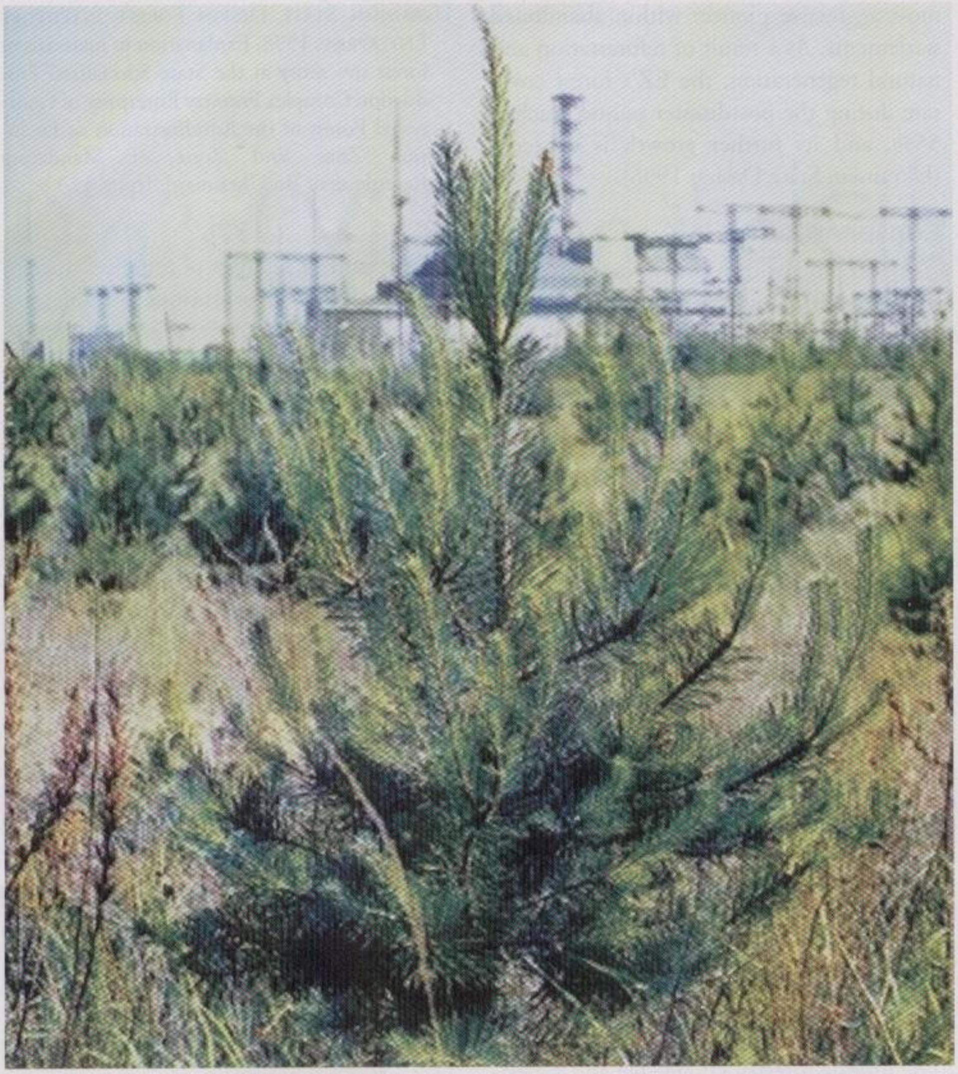

Figure 3. Young Scotch pine stands planted after Chornobyl disaster. Copyright 1996, Svit u Doloniakh. Reprinted with permission.

estry enterprises, Chornobyl Forest cannot rely on part-time workers from the local population. All these factors, as well as the lack of financial motivation for staff, are serious but unavoidable obstacles for the efficiency of this enterprise (Ukrainian State Design 1998).

Forestry Measures

Specific radiological conditions of these territories require special approaches for forestry management that drastically differ from traditional ones. The very idea of sustainable forestry is transformed under the pressure of radiation. In these circumstances, its central point is to prevent the migration of radionuclides outside EZ borders via the conservation and reproduction of forests. Though an extensive program of combating the disaster's negative effects is elaborated, a shortage of funding (about 25% of the amount needed is actually provided) allows Chornobyl Forest to carry out only very basic forestry activities (Landin 2001).

Every forest or grassland fire in the contaminated areas poses a threat. It can raise the radiation level through the secondary release of radioactive substances. Wind can carry them distances of 25–30 miles. Moreover, the losses entailed by fires in the Zone's forests total 42,000 ac. Fire control is among the top priorities of Chornobyl Forest, and it has managed to prevent large-scale wildfires since 1992 (Balashov 1996).

Fire damage and accumulation of weakened trees because of the lack of thinning in monoculture pine plantations promote an intensive growth of populations of insect pests such as pine lappet (*Dendrolimus pini*), pine beauty (*Panolis flammea*), and bordered white (*Bupalus piniaria*). In 1995, aerial insecticide treatment was applied to combat the vast expansion of black arches (*Lymantria monacha*). An extensive system of beaver (*Castor fiber*) dams because of the abrupt growth of their population prolongs the period of spring floods. As a result, about 5,000 ac of aged stands are lost in riparian areas (Balashov 1996).

Forest products (timber, hay, berries, medicinal herbs, etc.) may be harvested in the EZ and used outside the zone. However, such activities are subject to licensing and certification based on radiation control that is established to prevent the proliferation of contaminated forest products. The level of contamination by radionuclides is the standard to determine whether such products meet radiological requirements. Detailed regulations concerning acceptable levels of stored radionuclides in different types of products are already elaborated and implemented. Undoubtedly, a network of radioactive control is necessary, but it imposes additional barriers to the sale of products from the EZ.

Zoning of the territory is another limitation. Only the section of moderate forestry management (39% of the EZ's overall area) could undergo main timber harvesting. Lack of material resources is another reason why the intensity of forestry management will be far lower than before 1986. Therefore, only 347,000 ft^3 of timber annually is planned to be logged as the main harvest in the EZ, compared to ~2,990,000 ft^3 that was logged in the same territory before 1986. Sanitation cutting and thinning are limited only to stands damaged by fire. Planned owned timber-processing facilities were not set-up because of the lack of funding. Nevertheless, Chornobyl Forest is perhaps the only unit within the EZ that could generate some revenue and at least partially cover expenditures (Ukrainian State Design 1998).

Planting versus Natural Regeneration

Based on the knowledge that the dense vegetation cover would prevent further dispersal of radionuclides and bind them, a strategy for replacing the affected forests and abandoned farmland with vigorous forests was chosen. Although securing the forest's role as a biochemical barrier for radiation is prioritized, future harvesting of forest products is also taken into consideration (Nadtochiy 2003). Natural regeneration was considered too slow to meet defined goals.

Therefore, tree-planting was emphasized (Atlas of Chornobyl Exclusion Zone 1996).

To create new stands that are resistant against fire and pests is a primary objective of tree-planting in the EZ. Large-scale planting of forests has been undertaken since 1986. During the first decade, 21,500 ac have undergone planting (Ukrainian State Design 1998). Because of radiation safety requirements and limited resources of Chornobyl Forest, a special planting technology with minimal participation of people was introduced. In particular, the density and species composition of new stands are designed to allow tending and thinning no earlier than in 15–20 years (Savych and Popkov 2001). Based on experience, birch is considered the most preferred species for silviculture because of its viability, whereas young pines require intensive tending (Savych and Pokov 2001). During the last years, planting activities within the EZ were essentially decreased because of lack of funding and good natural regeneration.

Generally, changes in the EZ's ecosystem are compatible with the strategy to increase the EZ's forest cover rate. Thus, one observes a rapid (better than expected) natural afforestation of nonforested lands. At least 15–20% of them can already be considered forests, and, in 20–30 years, almost all of them will be covered with trees (Savych and Popkov 2001). The Red Forest is recovering gradually, with more radiation-resistant aspen and birch replacing pine (Atlas of Chornobyl Exclusion Zone 1996). Dried pine monocultures, and aged pine stands devastated by fire, are succeeded by mixed pine–birch saplings. As a result, such ecosystems become enriched in terms of biodiversity, though the quality of new stands differs strongly depending on site. In many cases, low-density coppice is formed. Debris is a promoting factor rather than the obstacle for regeneration. It enriches the forest ecosystem and protects young trees against damage by rodents and hoofed animals. Riparian high forests, having died from flooding, are succeeded by young growth and shrubs. It provides not only more food for beavers, but, interestingly enough, also more effective water protection. Therefore, in many cases, nature is correcting humans' mistakes. However, there are no reasons to expect natural restoration of stand composition typical of primeval forests with an essential portion of oak and other broadleaved trees (Savych and Popkov 2001). Northern American species inland boxelder (*Acer negundo*) is the most aggressive pioneer within abandoned settlements. As a result of reforestation and natural regeneration, the EZ's forest cover rate during the postdisaster period reached 55%, and its further growth is expected (Ukrainian State Design 1998).

Conservation

Ten plots within the modern EZ have the status of natural reserves since preaccident times. Now, all Chornobyl forests are intensively transforming with only minimal human interference. Hence, they represent a unique pattern for comparison with radiation-free areas undergoing conventional forestry. The Zone has also become a wildlife refuge, where undisturbed fauna is flourishing despite the radiation impacts. Chornobyl Forest is responsible for conservation activities on this land. As in Belarus, it supports the expansion of reserved territories to an essential part of the EZ area, and participates in preparatory works. Although such an idea is controversial, some specialists believe that passive preservation is not an optimal way for restoring viable indigenous stands (Savych and Popkov 2001). The final decision, however, will be made by the central government.

Therefore, Ukrainian forestry, and the country as a whole, continues to struggle with the unprecedented national and global impacts created by the Chornobyl disaster. The unique forestry knowledge and experience accumulated in the Exclusion Zone makes a significant contribution to the world's environmental protection practices and science.

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As a result of the split of uranium nuclei in a nuclear reactor, various unstable radioactive elements arise. These radionuclides or radioisotopes continue to decay, releasing energy as radiation until a stable element is reached. The rate of radioactive decay is measured in curies.

Half-life shows how long a radionuclide is a source of problems for the environment. For instance, the half-life of ^{137}Cs ~30 years. This means that after 30 years, half of the atoms in a given quantity of cesium will remain radioactive. In terms of Chornobyl's harmful impact, the most relevant of these radionuclides are iodine-131 (with a half-life of 8 days, posed the greatest immediate risk but decayed almost completely after a few months), ^{137}Cs the most widely distributed), ^{90}Sr (half-life of up to 90 years), and ^{239}Pu (half-life of up to 24 thousand years). These elements were spread via dust particles in the air and were inhaled, deposited in the earth by rainfall and water, or entered the food chain via plants.

Exposure to radiation has detrimental effects on human health. Damage to DNA causes cancer and other genetic abnormalities. Radiation also provokes leukemia, car-diovascular diseases, and inflammation of the digestive tract. About 25,000 firefighters and soldiers involved in the Chornobyl cleanup operations have already died (Chernobyl.info 2003).

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