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A Look Back at the Portable Nuclear Reactor that Sat on Top of the World

Hylko, James M.

Hylko Nuclear, LLC

*Corresponding author: *JHylko1@msn.com*

I. INTRODUCTION

Small Modular Reactors (SMRs) – a term used to differentiate them from larger nuclear reactors – are a newer generation understood to be smaller than 300 MW(e) per reactor in output. The SMR design concepts can be deployed in multiple module configurations within a single power plant providing flexible power generation for a wider range of users and applications, such as remote areas, district heating, desalination systems and even conventional electrolysis to support hydrogen gas production. Furthermore, these concepts provide an alternative to importing fossil fuels [1].

These ideas antedate to the 1940s, when the U.S. Air Force, Army, and Navy each initiated small-reactor research and development projects. Today's modular field concepts are most comparable to the U.S. Army Nuclear Power Program (ANPP). Its mission was to develop small, pressurized water reactors (PWRs) and boiling water reactors (BWRs) to generate electrical and space heating energy at remote, relatively inaccessible sites.

For example, electrical and heat analyses, and fuel requirements at remote installations, such as the Greenland Ice Cap, indicted nuclear power could overcome supply and transportation issues providing an overall savings compared to using conventional fuels. A conventional diesel engine plant supplying electrical energy for a remote site would require ~8,500 barrels of diesel fuel, costing ~1,510,000 zł (32,5000 €) and weighing ~1,700 metric tonnes. Transportation and deliveries would require 15 451-km round trips across the Ice Cap by six D9-type tractors having 1.4-metre tracks giving them low ground pressure over the soft snow, each pulling two tankers. The tractors delivering this fuel would consume ~852,00 litres of fuel, while a single aircraft could transport and deliver a nuclear power plant with enough fuel to operate for one to two years [2].

Of the 6 PWRs and one BWR developed and operated by the ANPP, this paper reviews the Portable Medium Power Plant (PM-2A) as part of the extensive history of portable nuclear reactors, equivalent to today's small modular reactors. The PM-2A was the first field reactor to demonstrate the feasibility to assemble and then disassemble a prefabricated nuclear plant in ice tunnels at Camp Century - referred to as the "Arctic City Under the Ice" - located 222 km inland from Thule Air Force Base on the Greenland Ice Cap, and less than 1,450 km from the North Pole [3], [4], [5].

II. CONSTRUCTING CAMP CENTURY

Camp Century was built by the U.S. Army Polar Research and Development Center (PRDC) in 1960 to learn how to construct military facilities on the Greenland Ice Cap using snow as a construction material, including prefabricated Arctic housing; power sources; steam to melt sub-surface snow as a water supply; and waste disposal, while providing a year-round habitable Arctic laboratory. The PRDC was headquartered at Camp Tuto ("Thule Take-Off") located at the foot of the Greenland Ice Cap, 29 km East of Thule Air Base, and one of the best locations to access the ice cap, and jumping off point for Camp Century.

At the time, Greenland, Northern Canada, and Alaska had become strategic military locations having the shortest air routes between the major land masses of the Northern Hemisphere. The scientific developments at Camp Century were for a defense-related operation, codenamed Project Iceworm, seeking to deploy ballistic missiles under the Greenland ice sheet. Since the ice sheet was too unstable, Project Iceworm was officially canceled in 1963 and remained a closely guarded secret until 1997 [6].

Camp Century construction materials consisted of 363 metric tonnes of pipes, machinery, and components in 27 packages, and was assembled in a series of subsurface, cut-and-cover tunnels to provide protection against the severe polar climate, since severe storms, drifting snow, and extremely low temperatures were serious disadvantages to above-surface facilities. For example, the winter season lasted from October to February, and surface temperatures were reported to reach -57 °C and wind velocities ≥200 km per hour. Each tunnel was constructed by cutting deep trenches with a rotary snow plow. The tunnels ranged from 46 to 335 metres long, 5.5 to 8 metres wide, and 6 to 12 metres deep. The reactor trench measured 54 metres long, 9 metres wide and 18 metres deep. The trench walls were cut to maximize tunnel floor width, and to accommodate semicircular corrugated steel roof arches. The reactor tunnel arches were 12 metres in diameter (Figure 1).

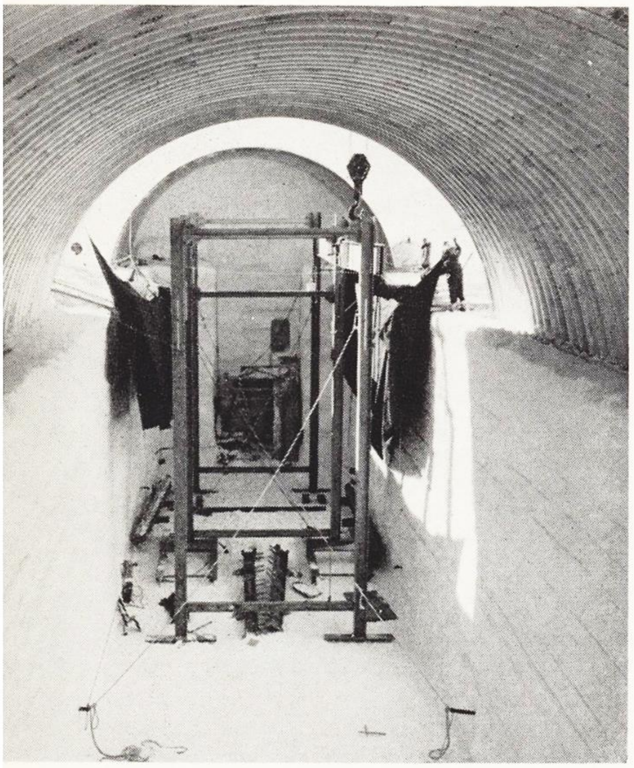

Figure 1. Reactor Cut-and-Cover Tunnel Bridged by Metallic Arches [7]

Light, insulated buildings were constructed inside tunnels housing the PM-2A nuclear reactor and all camp facilities. Annual snow tunnel temperatures were expected to stay between -32 °C and -7 °C even with building interiors maintaining temperatures between 16 °C and 21 °C. The tunnel ventilation system prevented heat losses keeping tunnel temperatures below -7 °C upholding snow wall and roofing structural integrities (Figure 2).

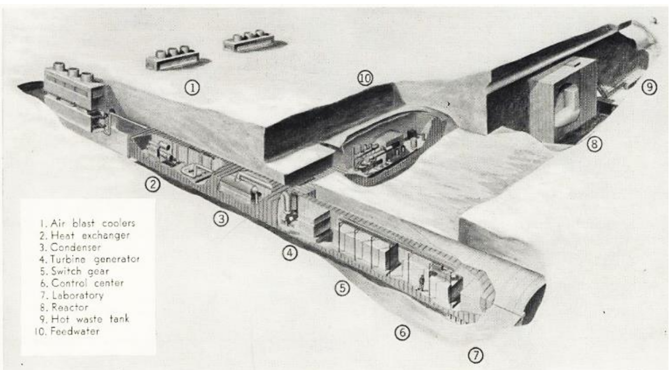

Figure 2. Sketch of PM-2A Nuclear Power Plant Installation at Camp Century [8]

Snow was then blown over the arches using the snow plow, where it would harden, permitting light traffic to cross the tunnels safely. "Timber" roadways prevented tunnel floor damage from vehicles. This enabled 105 civilian scientists and military personnel to work and live comfortably in one of the earth's most forbidding climates [2], [5], [7], [8], [9].

III. PM-2A - THE FIRST FIELD REACTOR (1960 - 1963)

A. Design, Environmental and Shipping Specifications

The PM-2A design contract was awarded January 23, 1959 to the American Locomotive Company to demonstrate the ability to assemble a nuclear power plant from prefabricated components in a remote, Arctic location. Another design feature is that the plant may be disassembled and relocated to another station extending its useful life.

The PM-2A equipment was mounted on ten skids to meet air transport weight and size restrictions. The package size limit was 2.7 metres wide, 2.7 metres high, and 9 metres long, and weight limit of ~13,600 kg. All system piping and wiring was terminated at the skid boundaries in flanged and bolted pipe connections and pin-type electrical connections. Interconnecting piping between skids were prefabricated in 9.1-metre lengths having flanged and bolted connections at each end. Interconnecting wire was contained in multiconductor cables terminating at each end in quick connectors mating with the terminals on the skids. Piping, wiring, pipe supports, cable trays, and maintenance equipment were packaged for shipment in eighteen additional crates of varying sizes below the maximum weight limits. Transporting equipment and supplies were accomplished by the D8 / D9 tractors, each pulling six or seven sleds carrying 9 and 18 metric tonnes of supplies.

B. The PM-2A Nuclear Reactor

The PM-2A nuclear reactor was a prefabricated, pressurized light-water-cooled and moderated assembly containing 32 fixed fuel elements and 5 control elements each measuring ~6.4 cm by 6.4 cm by 69 cm, and sealed inside a bolted vessel-head cover (Figure 3).

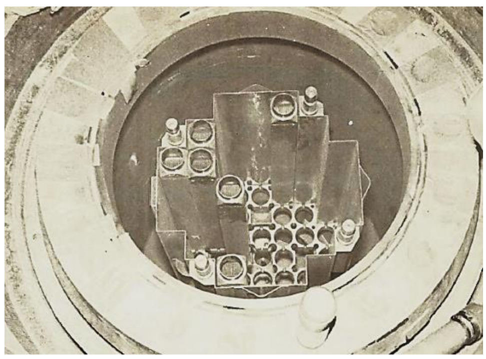

Figure 3. Six training fuel elements loaded into PM-2A reactor during testing at Dunkirk, May 1960 [10]

The fuel elements consisted of uranium dioxide (UO_2) plate assemblies at 93% uranium-235 enrichment in a stainless-steel matrix clad with low-cobalt stainless steel. Europium oxide was the absorber material used in the control rod elements. The design life of the core was 9.2 megawatt-years at an operating power level of 10 thermal megawatts. The primary loop was pressurized to 12,000 kilopascals and the coolant temperature leaving the reactor was 270 °C.

A horizontal, kettle-type heat exchanger (i.e., a horizontal U-tube or floating head bundle placed in an oversized shell; the large empty space above the tube bundle acts as a vapor disengaging space [volume] for the vapor separation of liquid droplets), generated steam in the secondary loop at 3,450 kPa. A 7-stage steam turbine, with two extraction points, drove an AC generator producing 1,980 kw at the generator terminals. Plant auxiliaries required 420 kW, providing a net output of 1,560 kW available to the camp. In addition to the electrical output, a small heat exchanger generated 1,000,000 BTUs/hour of ~1,000 kPa steam for distribution to the camp water supply system where the steam was jetted deep into the snow to melt a subsurface pond and draw water as required. Condenser waste heat was removed using a water and ethylene glycol solution to three air blast coolers ultimately discharging this heat to the atmosphere through ducts penetrating the tunnel roof. Plant instrumentation and controls used only solid- state devices instead of electron tubes to decrease maintenance and improve resistance to damage during shipment.

C. Powered by Nuclear Power

Nineteen plant operators participated in plant assembly and testing at the factory, field installation, and assumed all power plant operational duties, and were specialists in one of four areas: mechanical, electrical, instrumentation, and process control. The training consisted of a one-year program comprised of academic and operational phases gaining hands-on experience with operating the plant's reactor and power generation equipment.

The installation of the plant equipment, buildings, utilities, and preliminary testing to permit limited operation were completed in ten weeks, and at 6:52 a.m. on October 2, 1960, the reactor achieved initial criticality for the first time. At 5:30 a.m. on November 12, 1960 - about 22 months following contract award - the plant began to generate electrical power. A short time later, it was discovered that additional shielding would be required, and a layer of two-inch-thick lead bricks was added to the primary shield tank. Total project cost for fabrication, transportation and installation of the PM-2A power plant was ~24.9 M zł (5.3 M €) [2], [5] through Fiscal Year (FY) 1961, and almost 10 times higher in FY 2022. Upon completion of the acceptance tests, which included a 400-hour run, the plant became Camp Century's primary power source. A standby diesel power plant equivalent to the PM-2A would require >1.5 million litres of fuel annually.

D. Schedule Change

In 1962, it was decided that Camp Century would operate only during the summer Arctic season. The reactor was shut down on July 9, 1963 after thirty-three months of operation for planned maintenance, and later announced the PM-2A would not resume operation. By that time, the reactor core had produced 11,232,400 kilowatt-hours of electricity for Camp Century. This included a record period of more than 2,500 consecutive hours of uninterrupted power production from October 1962 through February 1963. Factors such as: a) only needing 300-500 kW of expected energy needs compared to the original 1,560 kW design; b) prolonged shutdowns resulting from conventional turbine-generator repairs; and c) the standby diesel power plant supplying enough seasonal power, no longer made the PM-2A economically viable to operate [11]. An additional factor in shutting down the reactor was recurring damage to the tunnel support structures due to compacting snow [2].

E. Decommissioning and Relocation

Closing the Camp in the winter of 1963-1964 was contingent upon the successful removal of the nuclear reactor core by the summer of 1964. Removal of the reactor core was necessary to allow the PM-2A to be left unheated and unattended over the winter, and was also a first step in relocating the plant. An 80-day cooling period was required before the PM-2A fuel elements could be transferred to shipping casks. The morning of September 27, 1963 was the earliest date which the core unloading operation could begin. Following fuel removal, all plant systems were shut down, drained, and winterized [11]. Water from the spent fuel tank, primary system, and all shield tanks was circulated through the demineralizer and filters to reduce radioactivity to acceptable levels before being discharged into the hot waste well [3].

F. Fuel Element and Shipping Cask Removal

The process of removing the fuel began with installing a Bailey bridge, with a triple-story center section, across the reactor trench. The hoist, mounted on an overhead crane, was on running rails. The reactor's bolted, vessel-head cover was removed for unloading the fuel elements, allowing direct access with long-handled remote-actuated tools from an upper working platform. The water in the shield tank above the reactor and in the spent fuel tank shielded radioactive plant components and reduced radiation exposure of personnel on the platform. The fuel elements were moved individually from the reactor to a spent fuel tank where they were loaded into a lead-lined shipping cask. The sealed cask was raised to an upper reactor room. Hold-down bolts for the cover were replaced and the cask was washed down with detergent to remove residual radioactive contamination from the spent fuel tank water. Simultaneously, pneumatic pressure was applied to the cask interior through fittings, purging water from the cavity by siphon drain. After the water was removed from the cask, plugs were placed in the drain holes and the cask was hoisted to the snow surface.

Radiation levels and airborne radioactivity were monitored using hand survey instruments and installed instrumentation, respectively. Radiation surveys were also taken over the cask surfaces prior to release. Dose rates at the duct openings were reported as high as 3.5 Roentgens per hour, but were small in area and could be avoided. It was mentioned that all personnel working around the casks were aware of these radiation fields [11]. Thermocouple devices were installed on the casks to monitor interior temperatures after loading. Readings taken every two hours verified the absence of excessive temperature rises.

Seven casks were required to ship one entire core. The total core weight was ~340 kg, and each shipping cask weighed slightly less than 9.1 metric tonnes. The last cask was secured to its trailer by mid-afternoon, September 28, 1963. Winds up to 15 meters/second and temperatures down to -29 °C were experienced during this time [11]. The loaded casks were picked up by a crawler-crane and placed on a trailer. Figure 4 shows the PM-2A core unloading process.

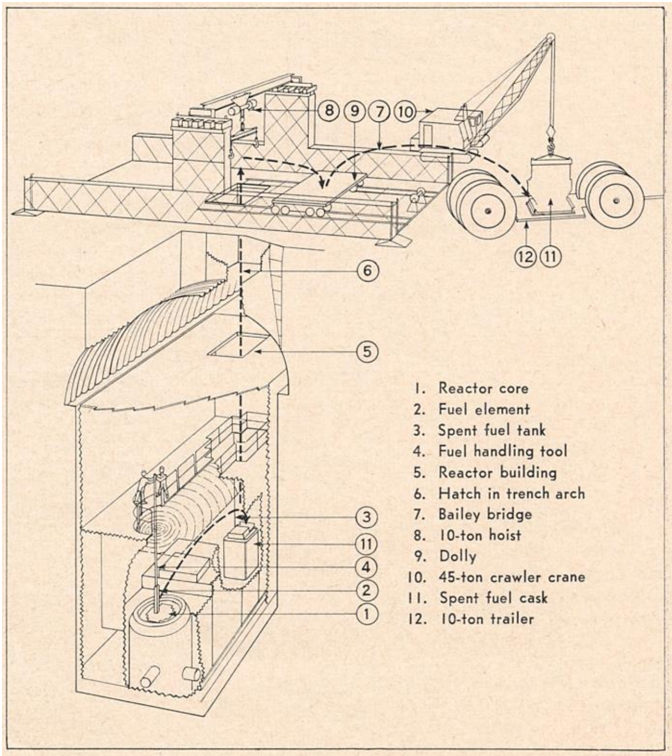

Figure 4. PM-2A Core Unloading Process [11]

After tie-down was completed, the over-snow trailers were connected into trains and pulled by D9 low-ground-pressure tractors to Camp Tuto, Greenland for winter storage until the 1964 shipping season.

G. Disassembly, Packaging, and Component Preservation Phases

The earliest project start date to begin disassembling the PM-2A reactor was April 1, 1964, and the latest delivery date to the Thule port for shipment back to the U.S. was September 1, 1964. This rigid timeline was necessitated by the Arctic construction season and vagaries of the Arctic weather. Recognizing the complexity and vital interrelationship between reopening and operating the Camp, increasing conventional diesel fuel requirements, reactor disassembly and removal, predicted radiation levels, packaging, and cargo movements, the Engineer Reactors Group prepared detailed technical procedures for all disassembly, packaging, and component preservation phases, prompting >800 individual line items. Obviously, the Procurement assignment had key importance. Additional logistical considerations included having only finite numbers of sleds and tractors available for icecap transportation of supplies to the camp and PM-2A cargo from the camp, referred to as “swings”. The first swing of the season left Camp Tuto on March 31, 1964, carrying a crew to reopen Camp Century and begin PM-2A disassembly [12].

H. Final Cargo Removal

The final PM-2A cargo was removed from Camp Century, which left for Camp Tuto on June 30, six weeks ahead of schedule. All items were trucked to Thule for temporary storage. About a third of the sixty-seven packages containing the PM-2A were never lifted until they arrived at Thule. Up until this point, they were winched from floor to sled and sled to trailer to reduce the risk of damaging sensitive components and because of the heavy package weights (up to 52 metric tonnes). The nearest crane with sufficient lifting capacity was over 4,000 km away [12].

The logistical task in Greenland consumed 21,116 person-hours and 21,928 equipment hours. At the stroke of midnight on July 26, 1964, and ahead of schedule, the USNS *Greenville Victory* backed away from the Thule pier with the PM-2A tightly secured in her holds and on deck signaling closure of nuclear power at Camp Century, coordinated with the U.S. Air Force, and dependent upon the U.S. Navy for shipment [12]. The inability to re-site the Camp Century power plant foreshadowed the end of the ANPP.

I. Component Disposal

Since no military service was willing to accept the plant at another location, the radioactive primary system, consisting of fifteen pieces, was loaded on 8 flatcars and shipped to the National Reactor Testing Station in Idaho. The radioactive-free secondary system, consisting of thirty-four pieces, was shipped on fifteen flatcars to the New Cumberland Army Depot, Pennsylvania. The 3 vapor container sections were off-loaded onto a barge and sent to the Savannah River Nuclear Facility via the Intercoastal Waterway [3]. A legacy issue remains about discharging ~47,100 gallons of liquid radioactive waste into the Ice Cap [2]. The PM-2A spent fuel was sent to the Savannah River Site.

J. Afterlife Non-Destructive Testing

The PM-2A reactor vessel, embrittled by in-service irradiation, was subjected to destructive testing by Phillips Petroleum Company in 1966 to study neutron embrittlement in carbon steel. The purpose of the test was to improve the understanding of conditions required to obtain brittle fracture in an operating reactor vessel, and to establish improved criteria for use in reactor vessel design and operation. The test consisted of a prescribed pressure-temperature sequencing procedure with a series of defects of increasing size in the vessel wall to assure fracture at a lower bound condition. After extreme testing, the reactor vessel was found to be much more durable than expected, achieving a brittle fracture which initiated at the defect at ~30,860 kPa and -29 °C [13].

IV. CONCLUSION

The PM-2A nuclear reactor successfully demonstrated this first-of-a-kind demonstration where nuclear-generated electric power and heat could be supplied to isolated remote areas, even under extreme climactic conditions. Skid-mounted, preassembled modules were compatible with all modes of transportation (e.g., ship, aircraft and cargo sleds). Also, installation, operation, disassembly and relocation were performed using standard construction equipment. Once in operation, the PM-2A provided dependable power in a remote area unencumbered by the logistical considerations inherent with conventional power plants. Camp Century would eventually close in 1967.

Unlike the U.S. Navy’s submarine reactors, the U.S. Army reactors were eventually displaced by conventional diesel generators, and eventually cancelled the ANPP in 1976. Nevertheless, the program’s foresight to build and operate small nuclear plants to provide electric power and heat in remote areas showed a vision for a technology that did not yet exist, thus providing a valuable historical perspective to the modern, land-based small modular reactor concepts.

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