



# Small Scale Modular Nuclear Power: *an option for Alaska?*

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# Small-Scale Modular Nuclear Power: An Option for Alaska?

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**Prepared for:**

The Alaska Energy Authority  
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of ALASKA  
*Many Traditions One Alaska*

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Front Cover: Image of Denali, Jim Norman, ABS Alaskan; Image of TRIGA Research Reactor, courtesy of General Atomics; Artist Rendition of Toshiba 4S Reactor courtesy of Toshiba and Marvin Yoder, MY:T Solutions.

## Executive Summary

The purpose of this report is to explore the viability of a new generation of nuclear power plants, small modular reactors (SMR), for meeting Alaska’s energy needs in the near to intermediate future. This study was conducted at the request of the Alaska Legislature, managed through the Alaska Energy Authority (AEA), and prepared by the Alaska Center for Energy and Power (University of Alaska Fairbanks) in partnership with the Institute of Social and Economic Research (University of Alaska Anchorage).

Why discuss the nuclear power option? With Alaska’s abundant energy resources, this form of energy may seem unnecessary. However, the supply of reliable, affordable energy to small, often-isolated communities remains a challenge. Most of these communities do not have access to developable local resources that can reduce their dependence on high-priced diesel fuel, delivered by barge once or twice each year. Other communities are located near conventional energy sources, such as the gas fields of Cook Inlet that supply energy for Southcentral Alaska, or the coal fields near Healy that supply fuel for coal-fired power plants in the Interior. In these areas, however, as much as 48% of the generating infrastructure will approach the end of its design life within the next 15 years, and decisions have to be made regarding its replacement or refurbishment.<sup>1</sup>

The scope of this report includes identification and evaluation of currently known existing or proposed small-scale nuclear power technologies worldwide. Information contained in this report was obtained through web-based and library research, interviews with technology experts worldwide, and attendance at conferences focused on SMR technology. This report frames and begins to address key questions surrounding SMR technology: Does the technology exist to build these small reactors? Is the technology safe? How will the fuel cycle for SMRs be managed? Are suppliers willing to sell small-scale nuclear reactors in Alaska? Who would own a project? Would this technology be cost-effective? What skills are needed in communities if Alaskans choose to adopt SMR technology as part of their energy portfolio? Should Alaska be an early adopter of this technology?

The nation’s existing commercial nuclear industry is primarily comprised of reactors 1000 MWe (megawatts electric) in size, which is too large for application in Alaska. However, as part of a new generation of nuclear power plants worldwide, SMRs are being developed that range in size from 10 MWe to 300 MWe. These SMRs will be manufactured in factories, allowing standardized design and fabrication, high quality control, shorter power-facility construction times, and lower financing costs during construction. For larger applications, multiple SMR modules could be combined to form a larger power plant complex, which would have several advantages over a single large reactor, including reduced downtime for maintenance and enhanced safety characteristics. Single SMRs could also be developed that are appropriately sized for use in Alaska, making nuclear energy an option for consideration. In addition to providing energy (heat and power) for rural

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<sup>1</sup> “Alaska Railbelt Electrical Grid Authority (REGA) Study—Final Report”, Sept 12, 2008, [http://www.aidea.org/aea/REGAFiles/9-12-08\\_AlaskaRailbeltREGAStudy\\_MasterFinalReport.pdf](http://www.aidea.org/aea/REGAFiles/9-12-08_AlaskaRailbeltREGAStudy_MasterFinalReport.pdf)

communities and/or the Railbelt, other potential applications include providing energy to military bases, remote mining operations, and other industrial users.

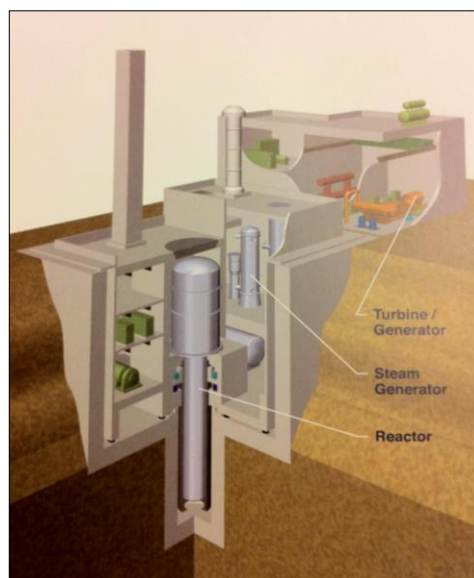
The Toshiba 4S nuclear power plant proposed for Galena in 2003 is familiar to many Alaskans. This project initiated a serious conversation about nuclear energy throughout the state when it was initially reported that Toshiba was willing to “give” a 10 MWe prototype reactor to the community of Galena. Though this project did not advance past the early conceptual phase, it influenced the national conversation about nuclear energy and brought the needs of small, remote communities to the attention of lawmakers and regulators in Washington, D.C. That conversation both identified market opportunities for SMR technology and highlighted regulatory barriers to such installations.

We found that no small-scale nuclear reactor technology is approved for commercial use in the U.S., including Alaska. In fact, no SMR manufacturers have submitted a request for design review and certification to the Nuclear Regulatory Commission (NRC), a critical step toward development of a pilot project and a process that is expected to take several years to complete. Therefore, at least with regard to any SMR that could be installed in the U.S., this technology is still in a pre-commercial phase of development.

During the course of completing this report, a major earthquake and tsunami struck Japan, damaging a nuclear reactor complex in the town of Fukushima. This damage resulted in a significant release of radioactive material into the environment. Although the most serious contamination appears to be limited to a relatively small geographic area surrounding the reactor site, the environmental cleanup after this accident will likely take years. At this time, the full extent of the long-term deleterious impact of this disaster on the nuclear power industry is unknown. However, the immediate impact to the nuclear power industry as a whole is likely to include re-examination of the safety of existing reactors worldwide and the development of the SMR industry specifically.

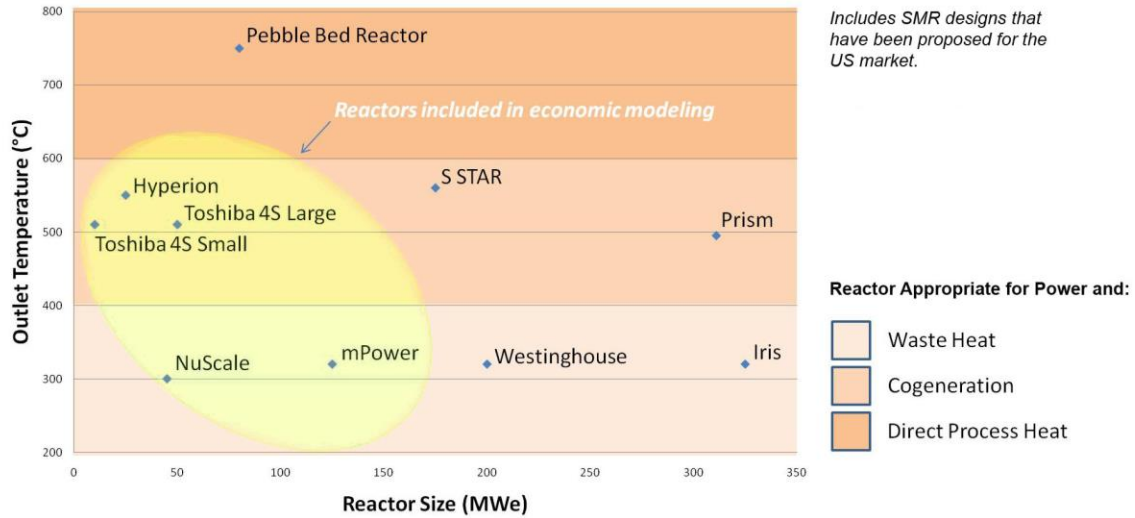
The Fukushima incident is discussed in several places within the body of this report. For now, public support of nuclear power has eroded, thus inhibiting new projects of any size. The Fukushima event has had a negative effect on the potential for implementing the recommendations drawn in this report because of heightened public attention to perceived risks, despite the fact that the event happened at a power plant that was based on 1950s light water reactor technology very different from the SMRs considered here.

The results of our study of current SMR technologies include the following observations:



Artist's rendition of the proposed Toshiba 4S 10 MW reactor proposed for Galena.

- More than 50 nuclear reactor technologies have been proposed worldwide that are classified as small. These nuclear reactors vary in size from 10 MWe to 300 MWe.
- Several of the newer designs for SMRs are based on fast reactor technology, as opposed to light water reactor technology currently used in large commercial reactors. Finding a viable source for fuel is one of the critical steps in the development of this fast-reactor class of technology.
- No SMR systems are expected to be in service before 2020. The first systems approved by the NRC will likely be smaller-scale versions of existing light water reactor technology, such as those proposed by NuScale and Babcock & Wilcox.
- The NRC has not yet reviewed any small reactor designs, although several companies have stated their intention to submit designs for review in the next year or two. Those designs are 10 MWe or larger, a size too large for most rural communities in Alaska. They may be more appropriate for a Railbelt installation or for powering a remote mine.
- Radioisotope thermal generators (RTGs), used for long-term space missions by NASA and for powering critical remote communications sites on Earth, are small enough for use in rural areas or other situations with relatively low power demand. Currently, however, there is little prospect that the special nuclear materials used as fuel for RTGs will be available. Even if the fuel were available, RTGs would probably be unsuitable for village-scale power due to the high cost of the fuel.
- Mini nuclear reactor systems used in mobile applications, such as nuclear submarines or nuclear ships, might be suitable for small communities, but have not been considered seriously for public use. Reactors on U.S. Navy vessels use weapons-grade enriched uranium, which is unavailable to the civilian market because of potential proliferation concerns.
- In addition to the reactor design review, the NRC requires a thorough review of any proposed site for a nuclear power plant. Such a review considers emergency planning, emergency zones surrounding the plant, and appropriate seismic qualification. Currently, there are no permitted, or even seriously contemplated, sites for commercial nuclear power plants in Alaska.
- The NRC evaluates the technical and financial capabilities of the plant owners, including the ability of the owners to finance construction of the plant; to attract, train, and retain a workforce with appropriate skills; and to construct and operate a plant that meets appropriate standards. For this reason, development of a nuclear power plant in Alaska may require partnership with a company from a location outside Alaska that has expertise in nuclear energy, especially when building and commissioning the first plant.
- The Galena Toshiba 4S project is not moving forward at this point, and no formal license application for this project has been submitted to the NRC for review. Some of the designs identified in this study are under construction in other parts of the world—for example, a Russian design for a barge-mounted power plant—but cannot be permitted in the U.S. unless NRC approval is sought and given. The Russian developer, Rosenergoatom, is not considering applying for NRC approval.



Representative small-reactor designs and relative operating temperatures. Reactors with high and medium outlet temperatures are generally fast-reactor technology, while designs based on more traditional light water reactor technology have lower outlet temperatures.

### Economics of Small Modular Reactors in Alaska

As part of this project, we developed an economic model to serve as an initial screening tool for determining if and where SMR technologies could be economically deployed in Alaska when the technology becomes available. Since SMR technology has not been commercialized anywhere in the U.S., our analysis is subject to significant cost uncertainties. Additional analyses can easily be conducted in the future because the screening model was designed to be readily adaptable as new information becomes available.

For our economic analysis, we identified SMR technologies currently under development that could potentially be used in Alaska based on the capacity of the units and the anticipated date of availability. Thus, five manufacturer designs were selected for economic viability screening: mPower, NuScale, Hyperion, Toshiba 4S large (50 MWe), and Toshiba 4S small (10 MWe). Capital costs per installed kWe (kilowatts electric) are estimated to range from \$4,500 to \$8,000. The combined construction and operating license (site and technology) is estimated to cost an additional \$50 to \$70 million regardless of plant size, thus adding \$400 to \$7,000 per installed kWe.

| Capital Cost and Combined Operating License (COL) Costs |                          |                                |                    |                                |                    |                                 |                |
|---|--------------------------|--------------------------------|--------------------|--------------------------------|--------------------|---------------------------------|----------------|
| Technology  | Installed Capacity (MWe) | Capital Cost low (\$ Millions) | COL \$/inst kW Low | Capital Cost med (\$ Millions) | COL \$/inst kW med | Capital Cost High (\$ Millions) | COL \$/inst kW |
| mPower  | 125                      | \$560                          | \$400              | \$750                          | \$480              | \$1,000                         | \$560          |
| Toshiba 4S Large  | 50                       | \$220                          | \$1,000            | \$300                          | \$1,200            | \$400                           | \$1,400        |
| NuScale   | 45                       | \$200                          | \$1,110            | \$270                          | \$1,330            | \$360                           | \$1,560        |
| Hyperion  | 25                       | \$110                          | \$2,000            | \$150                          | \$2,400            | \$200                           | \$2,800        |
| Toshiba 4S Small  | 10                       | \$45                           | \$5,000            | \$60                           | \$6,000            | \$80                            | \$7,000        |

Capital costs include all costs for the SMR project “power island,” which includes costs associated with buying, transporting, and installing the reactor, as well as power-generation equipment, condensers, and construction of the reactor facility. It excludes costs of transmission, distribution, roads, and fuel. The combined construction and operating license includes both the NRC construction and operating license.

Communities that have at least an average annual power load close to, or larger than, 10 MWe were considered in this analysis. Eliminated from consideration were communities that meet the majority of their electrical power requirements with installed hydroelectric capacity. In addition, our analysis was limited to assessing community-based applications rather than large industrial loads, although the screening model could be applied to other possible users. Based on matching community electric loads with SMR unit capacity, potential economic viability was analyzed for rural hubs, including Bethel (4.5 MWe average annual load), Dillingham (2.3 MWe), Galena (1 MWe), Kotzebue (2.4 MWe), Naknek (2.2 MWe), Nome (3.3 MWe), and Unalaska (3.8 MWe). Galena was included in this group despite its smaller electric load for comparison with an analysis conducted in 2004.



Communities analyzed for potential economic viability of SMR technology.

The other area with sufficient load to justify considering SMRs is the Railbelt, which includes Anchorage (652 MWe) and Fairbanks (223 MWe), and Tok (2 MWe), because of its relatively high load use of electrical power and its location on a major road system.

Economic scenarios involving assumptions of low- to high-price forecasts for crude oil, natural gas, and carbon, coupled with low to high costs for SMR power plant construction, fueling, and licensing, comprise 36 unique variations. We present the results of five scenarios that bracket economic viability of the alternatives based on the U.S. Energy Information Administration (EIA) crude oil and natural gas price forecasts and the Massachusetts Institute of Technology (MIT) carbon price forecasts. In addition to EIA forecast-based scenarios, we conducted a Railbelt scenario using the natural gas price forecast of the Regional Integrated Resources Plan (RIRP).

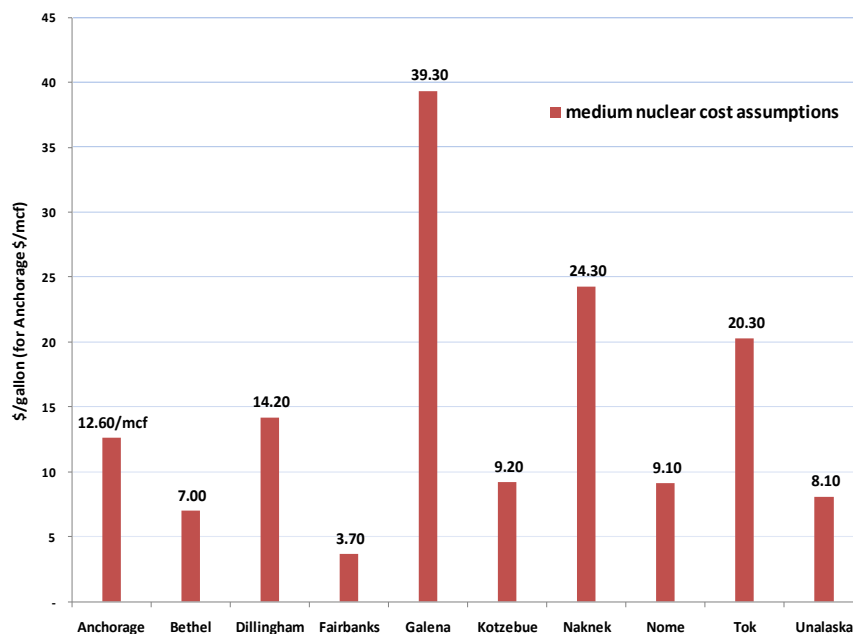
Based on our analysis, small modular reactor technology is not economically feasible anywhere in Alaska under the current EIA low crude oil price forecast, even for the low-cost case of SMR construction and licensing. However, under the medium EIA crude oil price forecast of between \$80 and \$100 per barrel over the next 20 years, SMRs become an economically viable alternative for the Railbelt, regardless of the assumed SMR cost range used in this analysis. As would be expected, the same is true for the scenario that involves high crude oil prices projected at \$130 to \$200 per barrel over the next two decades.



The economic modeling suggests that four out of the five SMR power plants could lower the projected cost of electrical power in Fairbanks as soon as, or soon after, the nuclear technologies are expected to be deployed (2020 or 2025). Most promising was a hypothetical Fairbanks–Eielson Air Force Base scenario that utilizes excess heat from the power plant for the existing Eielson district heating system and delivers power to the Fairbanks market. It should be noted that our analysis was based on a comparison with current generation sources only and did not take into consideration possible changes from this baseline that would occur if a large hydroelectric or gas pipeline project were developed to serve the Fairbanks market. The analysis also did not compare the relative costs of SMR technology against a natural gas pipeline or new hydroelectric project.

Using EIA natural gas price forecasts, SMR technology did not lower the cost of energy in the Railbelt south of the Alaska Range. However, under the RIRP natural gas price forecast, the larger light water reactor designs—NuScale and mPower—could potentially provide savings for Anchorage households shortly after deployment, assumed to be 2020 in the model.

Despite higher energy costs than in the Railbelt, the rural communities considered as part of our economic model were at a disadvantage because most SMRs are oversized for the community load, even when heating is included in the analysis. For this reason, the only rural community where SMRs would potentially lower projected future energy costs is Bethel. For Bethel, the local diesel-fuel price threshold for SMR economic feasibility is \$7 per gallon (2010 dollars). More communities might benefit from nuclear energy if smaller reactors more appropriately sized for typical village-scale loads were to become available, but such reactors are not currently being considered in the U.S.

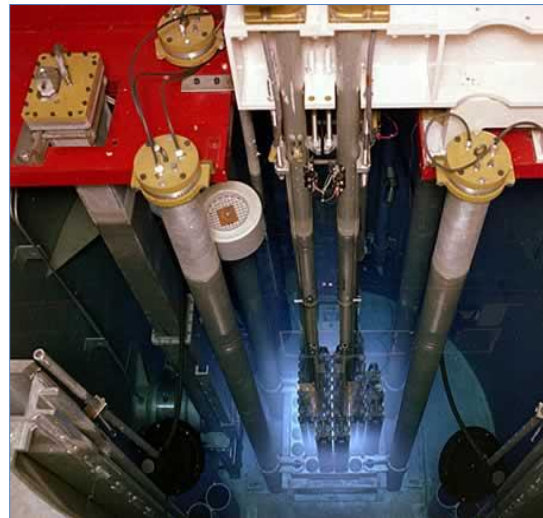


Approximate local fuel price thresholds for SMR economic feasibility (2010\$, per gallon of diesel or mcf)

## Potential State Actions

While small modular nuclear reactors are not available for the Alaska market today, our findings do not preclude opportunities for SMRs to meet the energy needs of Alaska's communities and industries in the future. Our economic screening analysis indicates that if the technology were available today, there would be sites in Alaska where development of a small nuclear reactor for heat and power should reduce energy costs. Barring any unforeseen developments, we believe the chances are high that SMR technology will become commercially available sometime in the next two decades. Therefore, the State of Alaska could take the following prudent actions to safeguard its interests as further advancements of this technology evolve:

- 1) ***Continue explore options for smaller scale (<10 MWe) reactor technology.*** There is virtually no market niche for mini nuclear power reactor technology in the contiguous U.S., and therefore, little effort has been made to commercialize a product in this size range. However, research in this area has not been exhausted. There is no question that several small-power reactors have been developed in the U.S. and other countries. For example, General Atomics has a standard design for a research reactor installed in dozens of locations around the country; it is a nearly fail-safe design with minimal NRC permitting and licensing requirements. This TRIGA reactor could be converted to a power reactor, something that was explored by the manufacturer twenty years ago, but was discontinued due to lack of apparent market potential. Alaska could seek a partnership with other groups interested in pursuing mini nuclear power, such as the U.S. Department of Defense (DoD).

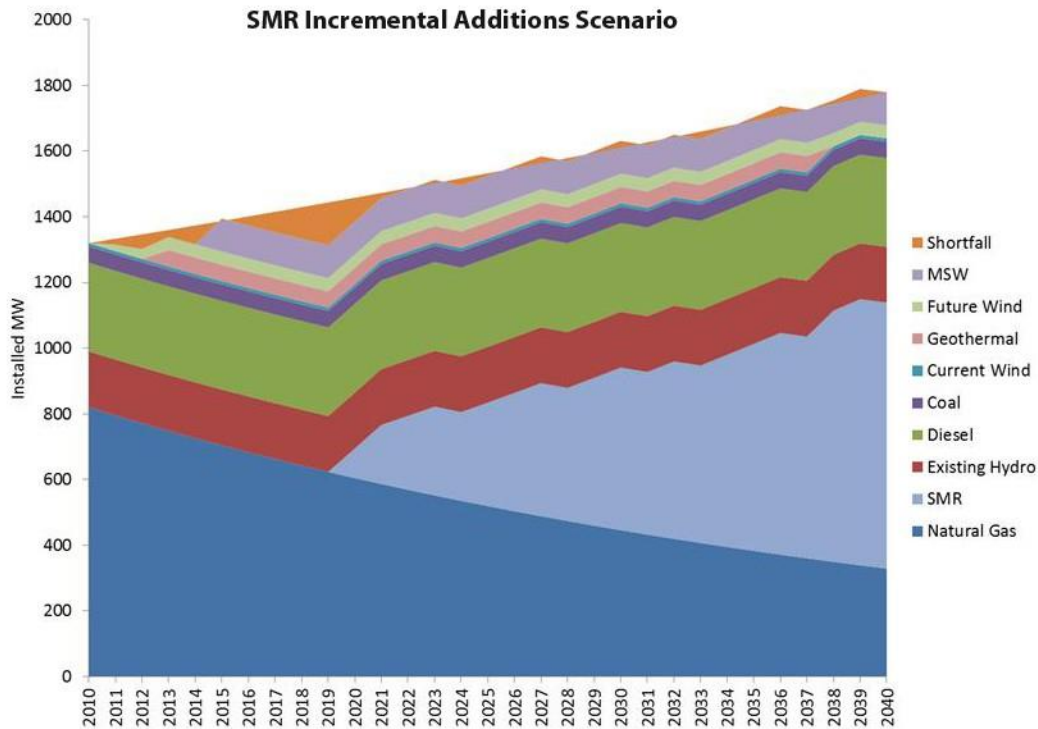


Core of a TRIGA research reactor, designed and constructed by General Atomics.

- 2) ***Continue studies of SMR economics and technology development.*** Collaboration with the U.S. Department of Energy in reviewing their forthcoming economic analysis of SMR technologies for power plant applications in the U.S. would provide Alaska with more data for the model developed as part of this study, as well as technology and permitting insights for the most advantageous applications for Alaska.
- 3) ***Identify a state technology lead.*** The potential for SMR technology in the U.S. has been recognized nationally and in Alaska. Federal licensing and permitting processes are being developed to meet the growing interest in SMR technology as a way to meet energy demands of the future. To stay abreast of these developments, the State of Alaska could identify a lead entity to follow developments by industry and federal agencies that are relevant for Alaska. Specifically, the AEA could designate a Program Manager for Nuclear Energy, who could represent a portion of the duties of an existing staff member. The AEA

could also contract with the University of Alaska to follow developments and report at regular intervals. However, there should be a central point of contact for the State of Alaska, and AEA is the logical choice.

- 4) **Consider SMR technology as one of several alternative scenarios.** While SMR technology is not available commercially today, it may become available in the future and, as such, would be worth comparing with other alternatives now and in the future as a replacement for aging generation capability (such as coal plants) in the Railbelt. The RIRP process did consider a single Hyperion SMR module in the first stage of its screening analysis, but did not consider an array of SMRs added in increments over time to meet expected load growth. A scenario where individual modules were added over time could have the benefit of more closely matching loads and distributing costs over a longer time horizon. In the figure below, we illustrate how this replacement with 45 MW units added incrementally could provide increased total capacity for Alaska beginning in 2020.



Conceptual chart of future generation sources to the Railbelt region, based on a RIRP model and assuming a 3% decline in natural gas supply per year (Cook Inlet), a 1% growth in electrical demand per year, and incremental additions of multiple 45 MW SMRs beginning in 2020.

- 5) **Begin a site feasibility study for two locations in Alaska.** While much of the national focus is on technology design licensing, the site selection and permitting process will be as challenging and involves significant uncertainty. The state could fund preliminary site selection and permitting activities for two locations based on the outcome of the economic screening analysis. Leading contenders include Fairbanks and Bethel, but a final determination should be made with local community input. Moving forward to achieve a

better understanding of the permitting process does not commit Alaska to installation of a SMR, or to becoming a first mover in this technology area. Instead, it provides flexibility and the ability to be an early adopter, while gaining a better understanding of the potential environmental issues associated with deployment in Alaska.

## **Conclusion**

In conclusion, no immediate, large-scale actions need to be considered at this time. Instead, the options as drawn from this study suggest smaller, strategic actions that keep this technology option on the table and allow Alaska to provide some small influence over the development of SMR technology for applications appropriately sized for Alaska's markets and economic sustainability.

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## Acronyms and Abbreviations

|         |  |
|---------|--|
| ACEP    | Alaska Center for Energy and Power                             |
| AEA     | Alaska Energy Authority  |
| AEC     | Atomic Energy Commission                                       |
| AFB     | Air Force Base   |
| AHTR    | Advanced High Temperature Reactor                              |
| ARCTEC  | Alaska Railbelt Cooperative Transmission and Electric Company  |
| BOM     | Beginning of Mission   |
| B&W     | Babcock & Wilcox Company                                       |
| CFR     | Code of Federal Regulations                                    |
| CHP     | Combined Heat and Power  |
| COL     | Construction and Operating License                             |
| DoD     | Department of Defense (U.S.)                                   |
| DOE     | Department of Energy (U.S.)                                    |
| EIA     | Energy Information Administration                              |
| EM2     | Energy Multiplier Module                                       |
| ENHS    | Encapsulated Nuclear Heat-Source                               |
| ESP     | Early Site Permit  |
| FERC    | Federal Energy Regulatory Commission                           |
| FOAK    | First of a Kind  |
| FSAR    | Final Safety Analysis Report                                   |
| GE      | General Electric Company                                       |
| GPHS    | General Purpose Heat Source                                    |
| GT-MHR  | Gas Turbine – Modular Helium Reactor                           |
| GVEA    | Golden Valley Electric Association                             |
| HPM     | Hyperion Power Module  |
| INEEL   | Idaho National Environmental and Engineering Laboratory        |
| INET    | Institute of Nuclear and New Energy Technology, China          |
| INL     | Idaho National Laboratory                                      |
| IPP     | Independent Power Producer                                     |
| ISER    | Institute of Social and Economic Research                      |
| ITAAC   | Inspection, Testing, Analysis, and Acceptance Criteria         |
| JAERI   | Japan Atomic Energy Research Institute,                        |
| KFRD    | Korean Fast Reactor Design                                     |
| kWe     | Kilowatt Electric  |
| kWh     | Kilowatt-Hour  |
| LANL    | Los Alamos National Laboratory                                 |
| LBE     | Lead-Bismuth Eutectic  |
| LFTR    | Liquid Fluoride Thorium Reactor                                |
| LLC     | Limited Liability Company                                      |
| LSPR    | Long-Life Safe Simple Portable Proliferation-Resistant Reactor |
| LWR     | Light Water Reactor  |
| LWR SMR | Light Water Reactor Small Modular Reactor                      |

|                 |   |
|-----------------|---|
| mcf             | Thousand Cubic Feet                                 |
| MIPS            | Medical Isotope Production System                   |
| MIT             | Massachusetts Institute of Technology               |
| MMBtu           | Million British Thermal Units                       |
| MMRTG           | Multi-Mission Radioisotope Thermoelectric Generator |
| MSR             | Molten Salt Reactor                                 |
| MTSPNR          | Modular Transportable Small Power Nuclear Reactor   |
| MW              | Megawatt  |
| MWe             | Megawatt Electric                                   |
| MWt             | Megawatt Thermal                                    |
| NASA            | National Aeronautic and Space Administration        |
| NPP             | Nuclear Power Plant                                 |
| NRC             | Nuclear Regulatory Commission                       |
| NSSS            | Nuclear Steam Supply System                         |
| O&M             | Operations and Maintenance                          |
| OSU             | Oregon State University                             |
| PBMR            | Pebble Bed Modular Reactor                          |
| PBMR (Pty) Ltd. | Pebble Bed Modular Reactor Limited                  |
| PHWR            | Pressurized Heavy Water Reactor                     |
| PRISM           | Power Reactor Innovative Small Module               |
| PSI             | Pounds Per Square Inch                              |
| PWR             | Pressurized Water Reactor                           |
| R&D             | Research and Development                            |
| RIRP            | Regional Integrated Resources Plan                  |
| RRC KI          | Russian Research Center Kurchatov Institute         |
| RTG             | Radioisotope Thermoelectric Generator               |
| SMART           | System-Integrated Modular Advanced Reactor          |
| SMR             | Small Modular Reactor                               |
| SRG             | Stirling Radioisotope Generator                     |
| SSTAR           | Small Sealed Transportable Autonomous Reactor       |
| STAR            | Secure Transportable Autonomous Reactor             |
| TAPS            | Trans Alaska Pipeline System                        |
| TMI             | Three Mile Island                                   |
| TRIGA           | Training, Research, Isotopes, General Atomics       |
| TWR             | Travelling Wave Reactor                             |
| U-235           | Uranium-235   |
| UAF             | University of Alaska Fairbanks                      |
| U.S.            | United States                                       |
| USA             | United States of America                            |
| USACE           | U.S. Army Corps of Engineers                        |
| WNA             | World Nuclear Association                           |

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## Report Overview

The goal of this report is to assess the possible use of nuclear power to meet the energy needs of Alaska. Of particular interest are small modular reactors (SMRs) that are under development by several manufacturers and recently have been proposed for Alaska communities. However, in order to understand whether SMRs present a viable option for Alaska, a thorough understanding of the technical, permitting, environmental, and economic constraints is required. The intent of this report is to provide the reader with a basic working knowledge of the technology and the conditions under which the technology could be applied in Alaska. That information is divided into five basic areas:

- Section 1: The history of the nuclear power industry worldwide and the basic science of nuclear reactions
- Section 2: The history of nuclear energy in Alaska
- Section 3: Brief technical descriptions of proposed SMRs
- Section 4: Siting, permitting, and licensing issues
- Section 5: Economics of SMRs for Alaska applications

The history of the nuclear power industry is complex and includes numerous successes, as well as high-profile failures. The harnessing of the energy of atoms for large-scale production of electricity is arguably one of the greatest technological achievements of the twentieth century. Based on knowledge gained from the basic physics of an atom, chain reactions are created that release energy millions of times greater than the energy available from chemical reactions. However, the continued viability of the nuclear energy industry has been strained by a series of issues, including the accidents at Three Mile Island, Chernobyl, and Fukushima, the political repercussions of aboveground testing, and the issue of how to dispose of spent fuel. Within the U.S. electric utility industry, nuclear power has proved to be a difficult technology to adopt, as major delays and cost overruns during construction have led to the cancelation of many projects and no new developments since 1973. Nevertheless, interest in nuclear power has risen recently, due to rising fossil fuel prices and concerns over global climate change.

In order to understand the differences between the new proposed SMRs and existing technology, some understanding of the basics of nuclear science is required. In Section 1, we provide the reader with basic nuclear definitions and an overview of the history of the nuclear power industry to put discussions of the proposed reactor designs into context. In particular, there is a major difference between the light water reactor (LWR) designs used now, future fast reactors, and SMRs in terms of their fuel fabrication requirements, reactor designs, and waste products.

Historical context helps provide a basis for understanding future nuclear energy projects in Alaska. Therefore, Section 2 includes an overview of non-medical applications of nuclear science that have occurred or been proposed in Alaska. These include the proposed Project Chariot effort to build a harbor in northwest Alaska in the late 1950s, the small nuclear reactor operated at Fort Greely between 1962 and 1972, the underground weapons testing conducted on Amchitka between 1965 and 1973, and the proposed Toshiba 4S project in Galena, Alaska. Because the history of these projects is of interest, we have located as many sources as possible for these projects and summarized the impacts they have had on the state, both environmentally and politically.

Many SMRs have been proposed by developers all around the world. In Section 3, we identify as many of these reactors as possible. In total, about 60 designs have been cataloged in a database created to track these reactors. Web searches were conducted on each design to assess the current state of development of each reactor. The resulting reports are briefly summarized in the database output in Appendix F (SMR Document Database Report). Many of the reactor designs have proved to be “paper reactors,” that is, conceptual designs that have not progressed beyond a handful of articles written largely by laboratory scientists.

A screening study was conducted to identify reactors of potential interest in Alaska in the immediate future. A handful of those reactor designs were identified to be of immediate interest, as commitments have been made to complete designs, seek regulatory approval, build prototypes, and seek commercial customers. A brief summary of each of these reactor designs is included in Section 3.4 of this report. Perhaps the most important barrier to the deployment of any of the designs is the need to obtain approval for the reactor system design by the Nuclear Regulatory Commission (NRC). Note that the reactor designs considered in greater depth in this report only represent the current front-runners. No developers have even started the NRC licensing process. In all likelihood, many or all of these designs will never reach full commercialization. We expect that new designs will be proposed over the next few years. For example, recently, Westinghouse unveiled a plan to develop a new 200 MWe (megawatt electric) design.

Some of the new SMR designs are based on smaller and safer versions of current LWRs, including NuScale and the Babcock & Wilcox mPower. Still, NRC review and approval for these designs is expected to require several years. Since these systems use fuel designs, materials, and heat removal designs similar to, but smaller, less complicated, and therefore safer than larger existing reactors, no major barriers to approval are expected.

Other more-advanced reactor designs diverge significantly from current LWRs and are sometimes referred to as “fast reactors,” “next generation reactors,” “Generation IV reactors,” or “breeder reactors.” All these designs use a fluid other than water as a coolant, since water slows or moderates the speed of neutrons. The Toshiba 4S, Hyperion, Pebble Bed, and Terrapower reactors fall into this category. Many of these reactor designs are based on successful laboratory prototypes developed in the 1950s through the 1980s, but the NRC has never reviewed or approved any of these commercial power reactor designs. Therefore, it is expected that these designs will require significantly more time to complete the NRC licensing process.

Section 4 focuses on the regulatory role of local, state, and federal agencies in permitting and licensing a commercial nuclear power plant. The NRC is the lead agency in any application for the construction and operation of a nuclear power plant, and requires review of both the reactor design and the plant site. Currently, no sites are approved for nuclear power plants in Alaska. The early site permitting (ESP) process could be used to obtain a site permit before design approval of any of the SMRs, but there are no compelling reasons to complete this process early.

Section 5 considers the economics of deploying SMRs in Alaska. Achieving a clear understanding of the costs associated with licensing, permitting, constructing, operating, maintaining, and ultimately decommissioning a nuclear power plant has been challenging. Without information from existing

projects to use as a starting point, many variables are difficult to quantify. Nonetheless, an attempt was made to estimate the economics for an SMR project in Alaska, given a range of deployment scenarios.

Discussion of the results and action items drawn from this study are presented in Section 6. Given a relatively long timeline for development and licensing of small modular nuclear reactor technology at any site, the uncertainty of the costs associated with deployment of known technology, today's unaddressed issues of nuclear waste disposal, and the generally large size of even a SMR for application in Alaska (in the Railbelt, for example), a careful course of action is suggested.



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## 1.0 History of Nuclear Power and General Principles that Apply to the Industry

The energy of nuclear reactors comes from nuclear fission, which is the splitting of heavy nuclei with the release of large amounts of energy. Uranium is the only naturally abundant element that can be used for sustained nuclear chain reactions, specifically the uranium-235 (U-235) isotope, which occurs in natural concentrations of 0.7%, the balance being the nonfissionable U-238. Natural uranium can be used as fuel for a reactor as long as a suitable moderator, namely heavy water (deuterium oxide), is used to provide sufficient density of neutrons of the right energy for sustaining the chain reaction. However, most commercial reactors in the U.S. use uranium enriched 4–6%, with ordinary water as the moderator.

The earliest discussions of commercial nuclear power included a wide variety of reactor designs, as discussed in 1944 by the New Piles Committee. A major concern was the perceived lack of U-235, and the need to breed more fuel. Using a liquid metal such as sodium as a coolant allows neutrons to retain most of their kinetic energy, so these reactors are called “fast reactors.” These fast neutrons are able to transmute nonfissionable materials to fissionable materials, such as U-238 transmuted to plutonium-239 (Pu-239), or thorium-234 (Th-234) converted to U-235. This ability also allows for additional conversion of mass to energy, as well as conversion of highly radioactive substances into more benign forms.

The first commercial nuclear power plant in the U.S. was at Shippingport, PA, a light-water breeder reactor that produced 60 MWe of power for the grid. Promotion and regulation of nuclear power was under the auspices of the Atomic Energy Commission (AEC). In the 1960s, AEC director Glen Seaborg strongly advocated for the building of larger power plants, and hundreds of reactors were ordered by utilities in the U.S.

The accident at Three Mile Island (TMI) precipitated a crisis in the industry that resulted in cancellation of ongoing construction of many reactors. The TMI accident resulted in melting of the fuel and substantial contamination inside the reactor containment, but very limited release of radioactive materials into the environment. The AEC was disbanded in 1974, with the safety and security issues assigned to the new Nuclear Regulatory Commission (NRC) and the research and development functions assigned to the U.S. Department of Energy (DOE). The boom in orders from the 1960s was followed by construction delays and cost overruns in the 1970s, caused partly by retrofits required by the NRC, partly by the lack of standardized plant design, and partly by the increasing cost of borrowed money.

The 1986 accident at Chernobyl further eroded public confidence in nuclear power. This accident was far worse than TMI, due mostly to the lack of a containment system for the reactor, which allowed the release of significant amounts of radioactive material into the atmosphere, comparable to fallout from an aboveground testing event.<sup>2</sup> A brief history of commercial nuclear power from the World Nuclear Association (WNA) can be found at the International Atomic Energy Agency.<sup>3</sup>

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<sup>2</sup> It is difficult to quantify the level of danger from any particular release, as the mix of components and the danger they present over time varies. However, the TMI releases were difficult to detect compared to background radiation, while the Chernobyl accident fallout was measured around the world.

<sup>3</sup> “gc48inf-4\_ftn3.pdf,” n.d., [http://www.iaea.org/About/Policy/GC/GC48/Documents/gc48inf-4\\_ftn3.pdf](http://www.iaea.org/About/Policy/GC/GC48/Documents/gc48inf-4_ftn3.pdf).

In 2003, the Massachusetts Institute of Technology (MIT) published a study on the Future of Nuclear Power,<sup>4</sup> which was updated in 2009.<sup>5</sup> Four issues are identified: cost, safety, waste management, and proliferation risk. Much discussion centers on the availability of uranium, with the authors concluding that there are sufficient known uranium reserves for 1,000 reactors for the next 50 years. The report suggests that the economics of nuclear power look moderately favorable, especially if natural gas prices rise and a global tax on carbon is imposed.

Today, large-scale commercial reactors in the U.S. are light water reactors (LWRs), with 69 pressurized water reactors and 35 boiling water reactors,<sup>6</sup> for a total of 104 operating reactors. These reactors produce approximately 20% of the total electrical power in the U.S.<sup>7</sup> An excellent review of the current state of the nuclear power industry is in a Congressional Research Service Report to Congress: Outlook for New U.S. Reactors, published in 2007.<sup>8</sup> This paper has an excellent discussion of industry retrenchment in the 1980s and the economic losses suffered by utilities. Considerable discussion is on the uncertainty of the licensing process, and the uncertainty about greenhouse gas legislation.

Reactors other than LWRs are now referred to as “advanced reactors” or “Generation IV reactors.”<sup>9</sup> Of these reactors, there are six designs, including sodium fast reactors (such as the Toshiba 4S), lead-cooled fast reactors (such as Hyperion), gas-cooled fast reactors, molten salt reactors, supercritical water-cooled reactors, and very high temperature gas-cooled reactors (such as the Pebble Bed reactor). With the exception of the supercritical water-cooled reactor, all these reactors are designed to use fuels of higher enrichment and different composition than current commercial fuels. It is expected that these new fuels will be obtained largely from the recycling of existing spent fuels from commercial reactors. Unfortunately, the development of reprocessing facilities for these spent fuels is politically difficult for environmental, nonproliferation, and economic reasons. Currently, reprocessing facility development has been curtailed by the federal government.

## **1.1 Elements of the Nuclear Industry**

### **1.1.1 Mining of Uranium**

Uranium is a naturally occurring mineral that is more common than gold or silver.<sup>10</sup> Uranium mines operate in over twenty countries, with the top three producers being Kazakhstan, Canada, and Australia. Most uranium mines have average grades of 0.10% uranium oxide. Improved technology since the first uranium boom of the 1960s has allowed for successful mining operations at as low as 0.02% average grade.

The most popular ways to mine uranium are open-pit mining, underground mining, in situ leaching, and heap leaching. Methods used in open-pit and underground uranium mining are very similar to

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<sup>4</sup> “nuclearpower-summary.pdf,” n.d., <http://web.mit.edu/nuclearpower/pdf/nuclearpower-summary.pdf>.

<sup>5</sup> “nuclearpower-update2009.pdf,” n.d., <http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf>.

<sup>6</sup> “Nuclear Power in the USA,” n.d., <http://www.world-nuclear.org/info/inf41.html>.

<sup>7</sup> “Fundamentals of Nuclear Physics and Reactor Theory,” n.d., <http://www.hss.energy.gov/nuclearsafety/ns/techstds/standard/hdbk1019/h1019v1.pdf>.

<sup>8</sup> “RL33442.pdf,” n.d., <http://www.fas.org/sgp/crs/misc/RL33442.pdf>.

<sup>9</sup> “GEN IV Reactors,” n.d., <http://www.usnuclearenergy.org/GEN%20IV%20Reactors.htm>.

<sup>10</sup> “Uranium Mining,” 2010, April. Retrieved 1/31/2011 from World Nuclear Association: <http://www.world-nuclear.org/education/mining.htm>.

the methods employed in mining other minerals. In situ leaching recovers uranium in groundwater, underground sand, or porous rock by oxygenating the water and pumping a slightly acidic solution into a borehole. The uranium, which dissolves into the solution, is then recovered on the surface.<sup>11</sup> In situ leach mining is also a common method of mining copper. With heap leaching, uranium ore is piled (in a heap) and then irrigated with a solution to dissolve the uranium for recovery, like in situ leaching.<sup>12</sup>

The main difference between mining for uranium and mining for other types of ore is the monitoring and mitigating of radon gas. A natural byproduct of uranium nuclear decay, radon gas is dangerous to living tissue. Radon is common all over the world, since trace amounts of uranium occur worldwide, and is reported as the number-two cause of lung cancer after cigarette smoke.<sup>13</sup>

Another safety concern involves storage of leftover rock called “tailings.” Tailings are covered in water to keep radioactive dust from forming, but the tailing ponds must be maintained to avoid spillage. The NRC found ten cases of water contamination in major waterways by tailings solutions between 1959 and 1977.<sup>14</sup> Abandoned mining and milling sites are found in Utah, Colorado, and New Mexico. Poor mining procedures from the 1940s to the 1960s still trouble these regions.<sup>15</sup> However, modern practices have made uranium mining much safer. Canada has some of the most advanced mines in the world. When Saskatchewan considered ending uranium mining in the early 1990s, a joint study of the Canadian federal government and the province of Saskatchewan determined that modern safe-mining procedures provide benefits that outweigh the risks involved.<sup>16</sup>

### **1.1.2 Nuclear Waste**

The operation of a nuclear reactor produces “spent fuel,” bundles of fuel rods that are no longer capable of producing energy in light water nuclear reactors, but which contain highly radioactive isotopes (including plutonium) that present a human health and proliferation risk. According to federal law, utilities operating commercial nuclear power plants are required to pay a \$0.001 per kWh fee for disposal of this waste, and ownership of the fuel reverts to the federal government once it is removed from the reactor. The long-term plan is for a federal repository for storage of this high-level nuclear waste, but recent termination of work on the proposed Yucca Mountain site in Nevada has apparently prevented the federal government from meeting its contractual obligation to the nuclear industry.

Most experts in the nuclear industry view spent fuel as a resource, not hazardous waste, because spent nuclear fuel can be reprocessed to form fuels for fast reactors. However, this fuel

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<sup>11</sup> “Uranium Mining,” 2010, April. Retrieved 1/31/2011 from World Nuclear Association: <http://www.world-nuclear.org/education/mining.htm>.

<sup>12</sup> “Uranium Mining,” 2010, April. Retrieved 1/31/2011 from World Nuclear Association: <http://www.world-nuclear.org/education/mining.htm>.

<sup>13</sup> “A Citizen’s Guide to Radon,” n.d. Retrieved 2/2/2011 from United States Environmental Protection Agency: <http://www.epa.gov/radon/pubs/citguide.html>.

<sup>14</sup> Quartaroli, M.L., n.d. “The History of North America Colorado Plateau.” Retrieved 2/3/2011 from “Leetso,” The Yellow Monster: Uranium Mining on the Colorado Plateau: <http://cpluhna.nau.edu/Change/uranium.htm>.

<sup>15</sup> “Uranium Impact Assessment Program,” n.d. Retrieved 2/3/2011 from Southwest Research and Information Center: <http://www.sric.org/uranium/index.html>.

<sup>16</sup> “Uranium Mining,” 2010, April. Retrieved 1/31/2011 from World Nuclear Association: <http://www.world-nuclear.org/education/mining.htm>

reprocessing is expensive and involves the handling of plutonium.<sup>17</sup> During the Carter administration, and again recently, the U.S. elected not to build this kind of reprocessing facility, perhaps based on concern that the technology would make plutonium more accessible for weapons. However, given the fact that most industry experts expect that uranium mining will deplete economically available uranium sources (though not for at least several decades), eventually reprocessing facilities will prove economical. A recent study published by the Idaho National Laboratory (INL) surveys the possible technologies that might be used for reprocessing plants, and their associated costs.

Perhaps worth noting is that some have suggested innovative permanent disposal methods for nuclear wastes, such as simply dropping them into mid-ocean trenches, where the natural movement of the tectonic plates would carry these materials into the core of the earth—preventing future uses of these materials, however. Most of these ideas have attracted little enthusiasm in the industry.

### **1.1.3 Proliferation**

Proliferation refers to the expanding availability of nuclear weapons, especially by “rogue states” such as Iran and North Korea, or by terrorist organizations. Most countries (especially those that already possess nuclear weapons) believe the world is a safer place if proliferation does not occur, and therefore support “non-proliferation.”

The most difficult step in producing nuclear weapons is the enrichment of a material sufficiently to use in a bomb. Only some isotopes have unstable nuclei necessary for a chain reaction, but all isotopes have the same chemistry, so chemical processes cannot be used to concentrate the desired materials. Thus, physical properties, depending on the mass of the atom, must be used to separate the isotopes (the speed of a gas molecule in diffusion, the path of an atom in a cyclotron). These processes require large industrial facilities and significant amounts of energy. Very high levels of enrichment are needed (above 90%) for making weapons.

If enriched materials should be stolen or purchased, weapons could be produced without the need for large industrial facilities for enrichment, and once these materials were obtained, it would be difficult to regain control of them. Significant effort is expended, therefore, to protect these materials from theft, or from falling into the hands of people willing to sell them to others with mal-intent.

The development of fast reactors for commercial power is of concern to those involved in nonproliferation, as these reactors, by design, transmute fertile materials into fissile materials that can be removed from the reactor and fabricated into weapons. Much effort is spent by designers of these reactors to engineer safety systems into the power plants to prevent this misuse from happening. Such safety systems include using “low enrichment” materials (less than 20% enrichment), sealing fuel bundles inside the reactors and entombing them in massive underground

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<sup>17</sup> Shropshire, D.E., 2009, “Advanced Fuel Cycle Cost Basis,” published by Idaho National Laboratory, <http://www.inl.gov/technicalpublications/Documents/4536700.pdf>.

concrete structures for their operating life, and fabricating fuel in chemical forms that would make it difficult to separate elements.

#### **1.1.4 Public Safety**

The operation of commercial nuclear power plants for the past 50 years has proved that while most of these facilities have operated for decades without incident, several notable exceptions to this rule have occurred. The most extreme of these events was the explosion of the Chernobyl reactor in the former Soviet Union, resulting in the immediate death of 44 people (mostly workers at the plant who were heavily exposed while trying to control the fires and the reactor), and the exposure of millions of others to varying levels of radioactive fallout. More recently, the Fukushima Daiichi accident in Japan after a 9.0 earthquake (larger than what the reactor design was rated for) and a 20-foot tsunami, which inundated the site, created new concerns about the safety of nuclear energy.

Nuclear power plants are fundamentally different from other power systems in two important ways: (1) Nuclear reactors continue to produce significant amounts of energy even after they are shut down (by inserting the control rods), unlike conventional combustion plants, where the reactions stop once fuel is removed. (2) Nuclear power plants can release radioactive debris that can affect people located far from the plant site.<sup>18</sup> For these reasons, the additional attention paid to safety of design and construction of these plants is appropriate.

In the U.S., the licensing of commercial uses of nuclear materials is under the regulatory authority of the NRC. Applications for the construction and operation of a commercial power plant are reviewed by the NRC in a process that includes public participation.

Nuclear power plants are extremely complex installations, and operate under a variety of conditions, not all of which can be anticipated in advance. The NRC review process requires applicants to assume that severe accident events can occur (the “loss of coolant accident” is a major one) and to prove that the plant design is sufficient to protect the public even under severe conditions. It can be argued that the Three Mile Island event proved the worth of this strategy, in that even though the reactor core was significantly damaged and radioactive materials were released inside the plant, public safety was maintained.

Getting NRC approval for a new plant design is neither easy nor quick. The Pebble Bed reactor is the most recent example of a design that stalled in the middle of the review process. In that case, questions were raised about high fuel surface temperatures and resulting degradation of the fuel pellets that would lead to dust formation, which might be released to the environment if a leak developed in the pressurized helium coolant. This concern resulted in the withdrawal of the application pending further experimental results. While new reactor developers emphasize the safety and simplicity of their designs, none has begun the formal review process required to license these systems in the U.S.

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<sup>18</sup> Note that the release of radioactive materials from ash in coal plants is far greater than that from well-regulated nuclear power plants. “Coal Combustion,” ORNL Review Vol. 26, No. 3&4, 1993, <http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html>.

## 1.2 General Principles of Nuclear Reactors

Nuclear reactors generate power by controlling a sustained nuclear reaction. The nuclear fuel contains some percentage of a fissile material, usually uranium-235. These fissile nuclei absorb neutrons and then emit thermal energy, radiation, and more neutrons to be absorbed by other fissile nuclei. The reaction is controlled by moderators and control rods. Moderators such as water (light or heavy) slow down the neutrons through collisions, which make them more likely to be absorbed by another nucleus. Control rods also absorb neutrons to slow down the reaction. The steady release of energy from the sustained reaction creates heat, which is then used to generate steam. The steam is used to spin turbines that power electrical generators.

### 1.2.1 Terms and Definitions

Several terms are important to understand as they relate to small modular reactors, including:

- Nuclear Fission – The splitting of a heavy nucleus to form lighter elements, along with the release of energy and high-speed neutrons (Figure 1).

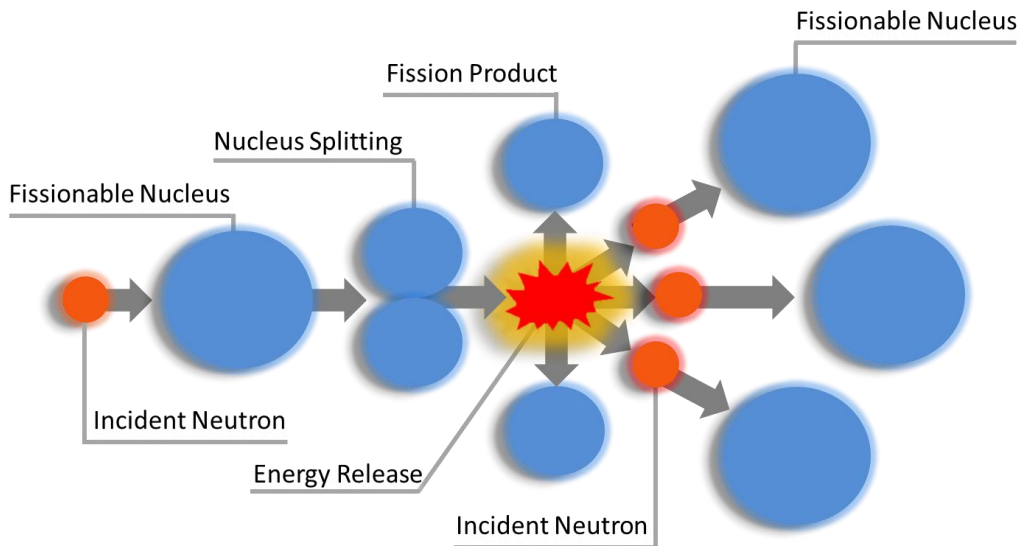


Figure 1. The fission of heavy nuclei to form lighter elements, followed by a chain reaction.

- Enrichment – The process of increasing the amount of fissionable material in nuclear fuel, usually uranium. Naturally occurring uranium contains 0.7% fissionable U-235, which can be used as fuel in heavy water reactors, but commercial light water reactors use fuel enriched 4–6%. In contrast, fuels used for military applications, such as for nuclear-powered submarines, have enrichment levels up to 96%.
- Fuel Fabrication – The process of converting fissile materials such as U-235 into forms suitable for use as fuel in a nuclear reactor. In most commercial reactors, this process involves combining enriched uranium with fluorine or oxygen, which is then sintered into ceramic pellets, sealed into zircalloy tubes to form fuel rods, and arranged in bundles for placement into the reactor core. Other fuel forms include metallic and nitride fuels. The

design of the fuel is one of the most basic aspects of reactor design, as it defines the maximum temperature limit that the system can tolerate. If the fuel is damaged or there is loss of control over the geometry of the reactor, uncontrollable reactions and thermal hot regions could catastrophically damage the reactor.

- Fuel Cycle – The complete management of nuclear fuel from initial uranium mining, to concentration, enrichment, fuel fabrication, use in a nuclear reactor, waste storage, reprocessing and re-use, and ultimate disposal of waste products ( Figure 2). Light water reactors currently used in most commercial nuclear power plants consume only about 1% of the total energy available in the fuel, but reprocessing this fuel for future use is more expensive than mining and enriching additional uranium. Many in the industry, however, consider the spent fuel a resource, not a waste.

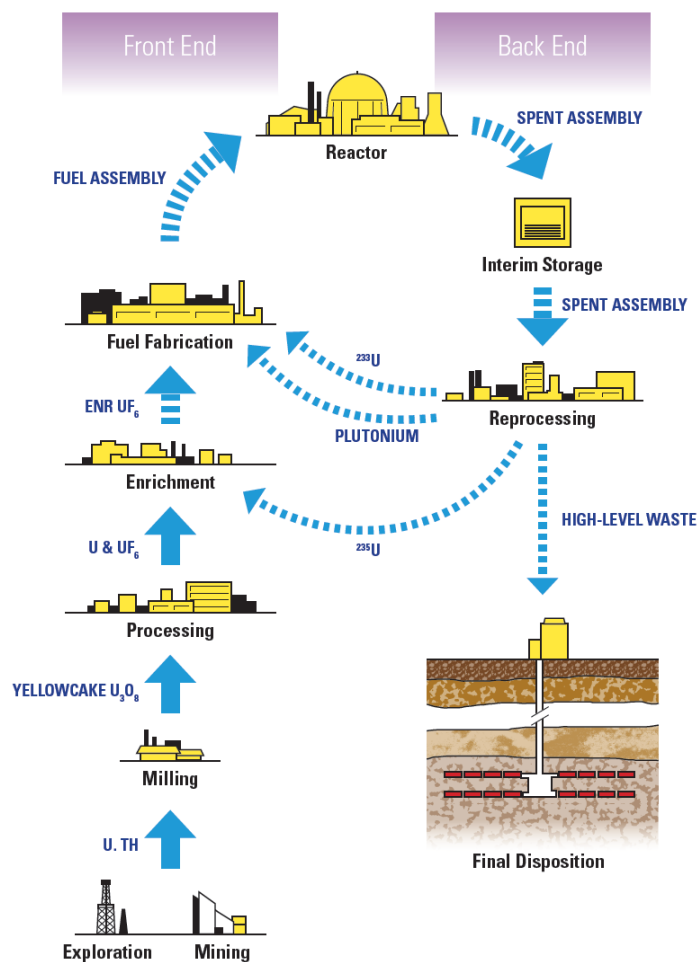
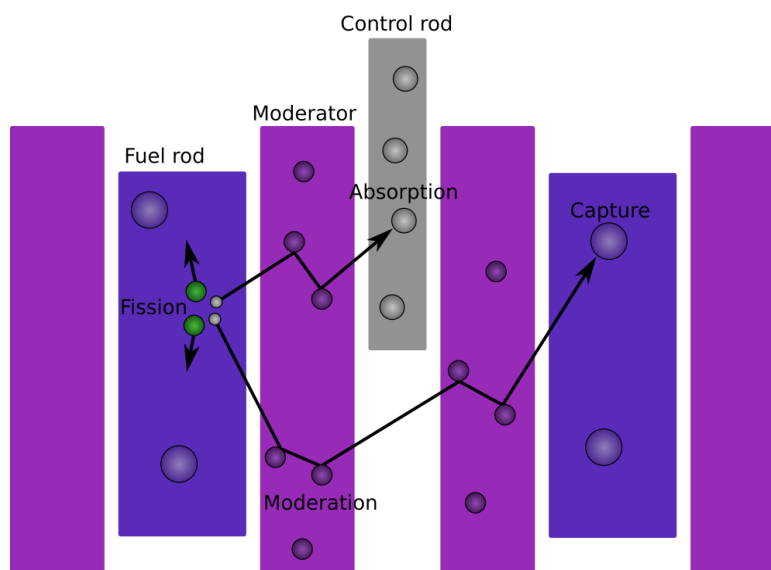




Figure 2. The nuclear fuel cycle. Current LWR practice in the U.S. does not involve reprocessing, but many in the industry expect this step to occur in the future.<sup>19</sup>

- Nuclear Waste – Also known as radioactive waste, a waste product with radioactive material in it. The radioactive waste associated with nuclear power plants is in the form of spent fuel. Spent fuel contains fission by-products (radioactive elements produced by a nuclear reaction) that cannot be used in the reactor. Spent fuel can be reprocessed for use in a different type of reactor. The French have been reprocessing spent fuel since the 1970s, but the practice is not currently allowed in the U.S.
- Fast Reactor – A reactor designed to use neutrons without thermal moderation, capable of transmutation of nuclear waste and production of much higher energy from fuels. These reactors require much higher fuel enrichments and much more attention to design, as changes occur in reactor criticality without the nuclear, mechanical, or thermal properties of a moderator to control reactor behavior. “Breeder reactors” are fast reactors designed to produce more fuel than they consume. Liquid metal reactors (sodium- or lead-cooled), high-temperature gas reactors, and molten salt reactors are forms of fast reactors.
- Light Water Reactor (LWR) – Light water reactors use ordinary water (H<sub>2</sub>O) as opposed to heavy water (deuterium oxide) as the thermal moderator for neutrons. The LWR (Figure 3) is the most common form of commercial nuclear power reactor. While transmutation of heavy nuclei occurs and converts some U-238 to Pu-239 (which accounts for much of the concern with the storage and disposal of spent fuel), this transmutation occurs at a much slower rate than in fast reactors, because the energy of most of the neutrons is reduced below the level where these reactions can occur.



<sup>19</sup> This figure was adapted from <http://nuclearstreet.com/images/img/nuclear-fuel-cycle.gif> by Dixon Jones, Rasmuson Library Graphics, University of Alaska Fairbanks, 2011.

Figure 3. Basic reactor physics in a light water reactor. High-energy neutrons are moderated by the water before reacting with another nucleus, or absorbed by a control rod inserted to control the reaction.<sup>20</sup>

- Heavy Water Reactor (HWR) – Heavy water reactors use “heavy water,” an ordinary water molecule, except each of the hydrogen nuclei have an extra neutron, making the molecule heavier and a better neutron moderator than ordinary water. These reactors can use uranium at its natural enrichment of 0.7%, but require large volumes of relatively rare, but naturally occurring heavy water.

## 2.0 Nuclear Power (and Other Nuclear Projects) in Alaska

Alaska has a history of projects and proposed projects involving nuclear energy. These projects run the full spectrum of the uses for nuclear energy, from power generation to testing of nuclear weapons, to uranium mining. This section of the report is organized chronologically, from the most recent project or proposal, back in time to Alaska’s first experiences with nuclear phenomena in the late 1950s and early 1960s. The section concludes with a discussion of uranium mining in Alaska.

### 2.1 Galena Toshiba 4S Project

The proposed development of a 10 MWe<sup>21</sup> nuclear power plant in Galena, Alaska, in recent years, incurred substantial criticism from groups concerned with potential environmental contamination resulting from an accident. At the time of writing this report, it appears that the Galena Toshiba 4S project is not moving forward. However, it should be noted that the Galena project has had a profound effect on the nuclear industry, by making both reactor designers and nuclear regulators more aware of the needs of small communities. While large reactors providing energy to major grids may be able to justify the permitting costs associated with conventional nuclear power, smaller customers such as remote communities or mine sites cannot afford fees of tens of millions of dollars to obtain a license to operate a system. The NRC has indicated its willingness to consider issues such as the number of personnel needed for security and operation of these small systems as well as the size of security zones.<sup>22</sup> Resolution of these issues will make the permitting of any SMR in Alaska much easier in the future.

The city of Galena has approximately 700 residents and is located along the Yukon River, about 250 miles west of Fairbanks. Galena is an “islanded” community, meaning it is not connected by road or electric grid to other parts of the state. Most of the energy used in the village, for both space heat and electrical power, comes from diesel fuel, which has been rising sharply in price over the past decade.

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<sup>20</sup> Thermal Reactor Diagram, n.d., Wiki Commons,

[http://upload.wikimedia.org/wikipedia/commons/7/72/Thermal\\_reactor\\_diagram.png](http://upload.wikimedia.org/wikipedia/commons/7/72/Thermal_reactor_diagram.png).

<sup>21</sup> It is important to distinguish between electrical and thermal power when discussing nuclear power generation. Throughout this report, the letters “We” will represent electrical power and “Wt” will represent thermal power.

<sup>22</sup> “NRC: SECY-10-0034 – Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs,” n.d., <http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2010/secy2010-0034/2010-0034scy.html>.

Former City Manager Marvin Yoder began seeking ways to lower the cost of power in Galena in 1996. He examined various energy options, including coal bed methane, solar, and conventional coal. However, for a variety of reasons, all of these options appeared nonviable. In May 2003, Mr. Yoder was informed of the 4S (“Super-Safe, Small, and Simple,” as referred to by the designer) reactor, a liquid-sodium-cooled reactor design developed in Japan. Mr. Yoder was put in touch with representatives from Shaw Pittman (a law firm specializing in nuclear power plants) and Toshiba, and a meeting was held in Galena to discuss the reactor.

After the meeting, the *Anchorage Daily News*<sup>23</sup> published an article on the potential siting of the 4S reactor in Galena. The article indicated that Toshiba was willing to donate a 10 MWe generating plant for the village, but that getting NRC approval for the plant would likely take six to eight years and cost \$600 million. The reactor would require no operator, and would run for 30 years with no refueling. Power could be provided to the village for about \$0.10 per kWh (kilowatt-hour), considerably less than the cost of diesel-generated power at about \$0.30 per kWh in Galena. The article also indicated that subsequent plants could be built for \$20 million each. Former U.S. Senator Ted Stevens was quoted as saying that public acceptance would be a big issue, and he noted that ten small radioactive generators had to be removed from Burnt Mountain in 2001 (see Section 2.3) after residents in the Interior learned of their use.

In late April 2004, Toshiba Corporation gave a presentation at the Alaska Rural Energy Conference,<sup>24</sup> outlining the design of the 4S reactor. The system featured a sodium-cooled reactor, with heat transfer to a steam loop for power generation. The entire reactor assembly would be buried, and no access to the fuel assembly would be possible.

In the summer and fall of 2004, a DOE-funded study conducted through the Arctic Energy Office drafted a report, never formally released, that intended to assess the economics of the Toshiba 4S reactor as compared with other options for the village, including small-scale coal and diesel power. (Other options such as coal bed methane, biomass, wind, hydrokinetics, solar, and fuel cells were mentioned, but not included in the economic analysis.<sup>25</sup>) The study used the assumption that the 4S reactor would be installed in the village at no cost, but analyzed an alternative scenario with a capital cost of \$25 million for the installation. The results of this study indicated, not surprisingly, that the no-cost installation would be more favorable economically. If a \$25 million installation cost were applied, the nuclear reactor would not be the preferred option. However, this outcome is strongly dependent on the required staffing levels at the facility, which are unknown. In addition, the report made it explicit that all or most of the permitting costs would need to be borne by Toshiba for the 4S reactor to be economically attractive. On February 2, 2005, a pre-application meeting was held between Galena city officials and the NRC in Washington, D.C.<sup>26</sup> At this meeting, Galena expressed its interest in the Toshiba 4S reactor, and the NRC presented information on the

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<sup>23</sup> “Toshiba’s new nuclear reactor for small villages,” n.d., <http://hyvin.nukku.net/no/toshiba.html>.

<sup>24</sup> “Alaska Center for Energy and Power | Details,” n.d., <http://www.uaf.edu/acep/publications/detail/index.xml>.

<sup>25</sup> “Galena Electric Power—A Situational Analysis,” R. Cheny, S. Colt, R. Johnson, R. Wies, and G. White, September 15, 2004. Report remains in draft form, electronic copy available from ACEP on request.

<sup>26</sup> Documents from this meeting and subsequent meetings with the NRC are documented on the NRC web site, and can be found on the ADAMS web site. Documents referenced below were found by searching on “Galena” and “Toshiba 4S” in the “Simple Search” tabs. Documents need to be downloaded from the site so that they can be read on a local computer, and multiple documents (up to 25 documents, or up to 25 MB) can be downloaded at once.

licensing process. There are two paths to a license: either through an Early Site Permit (ESP) and design certification leading to a combined construction and operating license (COL) (see the licensing section below) or through direct application for a COL. However, the NRC costs for reviewing the applications must be borne by the applicant, and the cost is many millions of dollars. Galena indicated that it intended to begin the site permitting process by preparing a series of white papers that discussed the various issues associated with the plant. The meeting reports make it clear that not everyone at the meeting was supportive of the project, and that the permitting process would need to address a variety of issues.

In discussions with Marvin Yoder during preparation of this report,<sup>27</sup> he recalled that during the meeting, the NRC stated that the typical review cost for an Early Site Permit by the NRC could be as high as \$20 million and that this amount would render the entire project uneconomical. It was hoped that congressional support could be obtained to cover the NRC costs associated with the permit review so that these costs would not be borne by the City of Galena.

The white papers referenced in the NRC meeting were prepared by the consulting firm Burns and Roe<sup>28</sup> and paid for through a \$500,000 appropriation from the Alaska State Legislature. These papers address some of the standard issues the NRC reviews when considering an application for a nuclear power plant license. The white papers make it clear that several issues associated with the small plant size and remote location will be difficult to resolve unless exemptions are granted. These issues include emergency planning (there are no roads out of Galena, so it is difficult to meet the NRC's multiple evacuation route criteria), and the requirement for a large number of security guards (minimum of five per shift, requiring a staff of approximately 34 to cover the plant full time).

There is also the issue of plant ownership. The NRC requires proof that the plant owner has sufficient capital reserves to cover the cost of building and operating the plant, including the ability to maintain staffing through extended shutdowns. The owner is also responsible for maintaining records, training operators, and obtaining insurance for the plant. It is not clear that the existing utility in Galena could meet these requirements, so the white papers propose the creation of an independent power producer (IPP) as a necessary step for obtaining a license for the plant, which is common practice in the nuclear utility industry. The IPP would be organized as a limited liability company (LLC) and hold the title to the power plant.

The City of Galena sent the white papers to the NRC, followed by several letters requesting a meeting with the NRC to discuss the contents of the papers. To date, this meeting has not occurred, and a letter from the NRC to the City of Galena dated September 19, 2008, made it clear that the NRC had no plans to schedule such a meeting.<sup>29</sup>

Toshiba Corporation managed to schedule several pre-application meetings with the NRC, independently from the proposed Galena project, to discuss the technical aspects of the 4S design. These meetings were held on October 23, 2007, February 21, 2008, May 21, 2008, and August 8, 2008, and are well documented on the Agencywide Documents Access and Management System

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<sup>27</sup> Marvin Yoder, personal communication, November 19, 2010.

<sup>28</sup> "Burns and Roe - Technical Publications," 2007, [http://www.roe.com/about\\_techGalena.htm](http://www.roe.com/about_techGalena.htm).

<sup>29</sup> NRC Adams Document ML08260008.

(ADAMS) site.<sup>30</sup> A complete transcript of the proceedings for the first of these meetings is available; the last three meetings were video-recorded. Review of the transcripts of the first meeting reveal some rather pointed questions from the NRC about the methodology used by Toshiba in the safety review, as well as some concern about the safety of the sodium coolant.

One thing of note in each of the Toshiba presentations to the NRC is the inclusion of a statement that “it expects that a U.S. customer will submit a COL application.” In discussions with Marvin Yoder (personal communication, November 19, 2010), it was verified that this “customer” was the City of Galena, and to his knowledge no other U.S. customers have been identified.

A letter from Toshiba dated March 13, 2009, indicates that Toshiba intended to file a Design Approval Application for the 4S design in October 2010. However, at the Small Modular Reactor workshop held in Washington, D.C. on October 19, 2010, Mr. Stewart Magruder, Chief of the Advanced Reactors Division of the NRC, indicated that the NRC was not expecting an application from Toshiba at that time.

In discussing the history of this project with Marvin Yoder (October and November 2010), it became apparent that the business arrangements between Toshiba and the City of Galena have been evolving over time. The “free” power plant offered in 2003 was replaced in 2005 with an offer of a system for \$25 million, a price which rose to \$200 million “about the time Toshiba went to the NRC” in 2008. While the \$25 million price might be reasonable today, in light of recent increases in the cost of diesel fuel, the \$200 million price would push the project into an uneconomical proposition for the residents of Galena, given their current energy needs (see the discussion about project economics in Section 5 of this report).

As part of this study, further efforts were made to assess the economics of the Toshiba 4S reactor for use in Galena or other Alaska communities. In interviews conducted for this report in December 2010, Philip Moor (the prime author of the Galena “white papers”) indicated that current site permitting costs were likely to be \$50–\$70 million (including both NRC fees and the cost of preparing the documents for submittal), but also commented that the initial fuel cost for the reactor would be \$100 million. If this fuel were sufficient to power the plant for 30 years at 10 MWe, the fuel costs would be about \$0.0423 per kWh (simple payback), significantly higher than the current industry average fuel cost of \$0.0067 per kWh for light water reactors. Installed capital costs were quoted at \$50–\$70 million in this same conversation. These numbers add up to the \$200 million that Marvin Yoder mentioned.

These high fuel prices are of special interest, especially since they are considerably higher than industry averages, and represent about half the total cost of the plant. Since the fuel would be loaded for a 30-year run, it should be amortized like capital, so the real cost would be considerably higher than the simple payback calculated above. Why is this fuel cost so high?

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<sup>30</sup> “NRC: Agencywide Documents Access and Management System (ADAMS).” Search on “Toshiba 4S” for documents, available for download.

At least part of the answer is found in the report “Advanced Fuel Cycle Cost Basis,” published by the Idaho National Laboratory in 2009.<sup>31</sup> On page 257 of this report is a discussion on the cost of metallic fuel, the configuration proposed by the developers of the Toshiba 4S. The report states that no cost information was found on these fuels, except in facilities associated with the reprocessing of light-water reactor fuels, and gives no cost estimate for these fuels. Additionally, the report notes that the fuel supplied to the Hanford Fast Fuel Test Facility for testing was plutonium-based and provided by the DOE, and that no cost information could be found with regard to the fabrication of that fuel.

Toshiba Corporation released a 2008 study titled “Long Life Metallic Fuel for the Super-Safe, Small and Simple (4S) Reactor,”<sup>32</sup> which indicates that the processes for making the metallic fuel are well understood.<sup>33</sup> However, a check of the references cited for this claim shows that the information dates back to 1980 and is associated with the breeder reactor program, then still active. It appears that the fuel needed for the Toshiba 4S reactor is probably not available from a commercial vendor at this time and, therefore, would likely need to be produced in a small batch by an undefined vendor.

Based on this discussion, it appears that the Toshiba 4S reactor project in Galena is not currently moving forward and that at least significant technical and economic issues exist that will likely prevent a demonstration project in the near future.

## 2.2 Fort Greely Reactor

Nuclear power was used in Alaska at the Fort Greely Army Base as part of the Army Reactor Program, active in the 1960s and 1970s. The Fort Greely SM-1A Reactor (Figure 4) was installed and operated near Delta, Alaska, from March 13, 1962, until sometime in 1972. At least eight reactors were constructed as part of the Army Nuclear Power Program. The reactors used highly enriched uranium (93% U-235), which is not available for use in civilian reactors due to safety and nonproliferation concerns.

The fact that this reactor operated for only ten years as compared with the thirty-year operation expected from naval propulsion reactors raises the question, What happened? One problem that appears to have occurred is cracking, associated with “stress corrosion” of the stainless steels used in construction of the reactor. The fuel was “clad in stainless steel” (from the Environmental Plan for the SM-1A Reactor).<sup>34</sup> Given this material selection for construction of the reactor, cracking and subsequent failure (either catastrophic or noncatastrophic) would be expected. A solution to the problem would have been to replace all chromium-containing alloys in the plant with other alloys, which most likely would have required repairs so extensive and costly that the only sensible course of action was to terminate the operation of the reactor. Industry practice after that time was to use high zirconium alloys (zircalloy) for these applications, an alloy much more expensive than

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<sup>31</sup> Shropshire, D.E., 2009, “Advanced Fuel Cycle Cost Basis,” published by Idaho National Laboratory, “4536700.pdf.”

<sup>32</sup> Yacout, A. (2008, June), “Long Life Metallic Fuel for the Super-Safe, Small and Simple (4S) Reactor,” available for download from the NRC Adams web site.

<sup>33</sup> Ibid., page 32 of the PDF.

<sup>34</sup> Environmental Plan for the SM-1A, “GetTRDoc,” June 1971, <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=AD726323&Location=U2&doc=GetTRDoc.pdf>.

stainless steel, but much more stable with respect to both neutron bombardment and corrosion. In addition, the nickel content in austenitic stainless steels is considered a problem, because nickel transmutes to other elements under neutron bombardment.

A web page from Fort Belvoir lists several reports that are not publically available.<sup>35</sup> Several of these reports indicate that the fourth and last cores used in the Fort Greely reactor were somehow different from the ones that came before, as some reports include physical measurements made on the cores. One abstract refers to “In-place Annealing” of the reactor pressure vessel. Another source reports that in-place annealing was completed on the reactor to relieve stress caused by neutron-induced embrittlement, indicating that materials susceptible to this form of damage were used in the reactor construction.

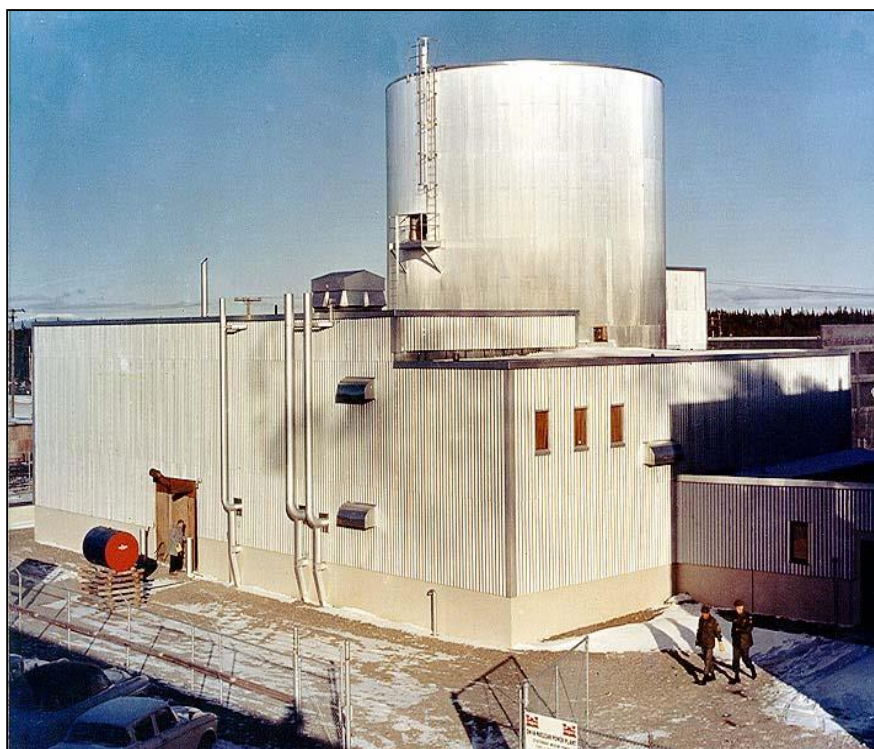


Figure 4. Fort Greely primary reactor facility. Commissioned in 1962 and decommissioned 10 years later in 1972.

All these reports indicate that, while the reactor was intended to provide power to Fort Greely, it also was being used to assess new materials and techniques for use in nuclear power generation systems. The near-simultaneous decommissioning of the SM-1A at Fort Greely and the PM-3A reactor at McMurdo Station in Antarctica may indicate some common issues with materials used in these reactors, given that both reactors were managed by the same Army Nuclear Power Program.

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<sup>35</sup> Army Engineer Reactors Group Fort Belvoir, VA, Engineering Division, Storming Media, n.d., [http://www.stormingmedia.us/corpaauthors/ARMY\\_ENGINEER\\_REACTORS\\_GROUP\\_FORT\\_BELVOIR\\_VA\\_ENGINEERING\\_DIV.html](http://www.stormingmedia.us/corpaauthors/ARMY_ENGINEER_REACTORS_GROUP_FORT_BELVOIR_VA_ENGINEERING_DIV.html).

An issue raised by some environmental groups is the large amount of water removed and reinjected by the operation of the reactor. According to the Environmental Plan mentioned earlier, a total of 1,440,000 gallons of water were pulled from a well, used as cooling for the condenser, and reinjected at a flow of approximately 1,000 gallons per minute. If we assume that the 2 MWe steam plant operated at 33% efficiency, this means that 4 MWt (megawatts thermal) needed to be rejected, which would result in an expected rise in temperature of about 28°F for the water prior to reinjection.

While there is limited public information about the Fort Greely reactor, more-extensive information is available to the public about the PM-3A reactor built by the same Army Nuclear Power Program for use at McMurdo Station. A web source titled “The Antarctic Environmental Awareness Pages,” which is attached to a site dedicated to the South Pole station, was found. There is no author listed, but the narrative appears to be a first-person account by an individual who traveled to McMurdo in the 1970s. It contains the following paragraph:

This plant [the PM-3A] was shut down in September, 1972, three months before my visit, after wet insulation was observed around the reactor pressure vessel, presumably due to leakage in the shield coolant water piping. A team from the Navy nuclear power unit came down on my flight to evaluate the repair needs; at the time everyone assumed it would be back on line quickly. Meanwhile, McM was rather short on power, because the normal summer demand was 1,000-1,200 KWe, and the “standby” power plant (Penguin Power and Light) had 450 KWe diesel generators of which only 2 were operational. Ah yes. As we now know, the plant was never operated again. Since chloride stress corrosion cracking was suspected, it would have been necessary to disassemble everything to inspect for cracks, and that was not practical.

This paragraph is very interesting, in that it indicates that the reason the McMurdo reactor was not restarted was because “chloride stress corrosion cracking” was suspected. This issue had been well established as a problem in nuclear power plants, where stainless steels containing chromium (typically alloys 304, 304L, and 316 contain chromium), subjected to long-term exposure of moderate stress levels in the presence of chlorine ions, experience the migration of these ions down grain boundaries, leading to the formation of a chromium-chloride phase and a chromium-depleted zone next to the grain boundary susceptible to corrosion crack formation. This problem was studied extensively by Charles McMahan, a professor at the University of Pennsylvania Materials Science Department. The solution to the issue is to use alloys with high nickel content rather than stainless steels in the reactor design, and zircalloy cladding for the fuel. In commercial nuclear power plants, this problem required the replacement of various components from the reactor pressure vessel. If plants were operational, the replacement required an extensive shutdown of several months.

Another report titled “Final Operating Report for the PM-3A Nuclear Power Station, McMurdo Station, Antarctica,” was apparently written and released shortly after the reactor was shut down on October 26, 1972.<sup>36</sup> This report lists every start-up and shutdown by the reactor, and there were

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<sup>36</sup> “Final Operating Report.pdf,” n.d., <http://foia.navy.mil/FINAL%20OPERATING%20REPORT.pdf>.



a lot of them. The availability of this reactor was given as 72%, which indicates that the plant was not highly reliable (current nuclear plants operate at 96% availability). The reactor was removed from McMurdo Station several years later.

Returning to the installation at Fort Greely, there remains the issue of persistent rumors in Alaska that the SM-1A reactor ended its useful lifetime in some kind of accident. The most extensive attempt to document radiation release from an event of this type is in a report by the Alaska Community Action on Toxins Report on Fort Greely.<sup>37</sup> While this report stridently claims that a significant event occurred at the SM-1A reactor that affects the health of local residents, the accompanying data are less convincing. The report implies that significant radiation was released during an event with the steam turbine on March 23, 1972, but the U.S. Army Corps of Engineers (USACE) report does not support this conclusion.<sup>38</sup> This report, written in 1992 when the reactor was decommissioned, summarizes the operating records of the SM-1A reactor by including “nuclear incident reports” (without sequencing numbers) and “malfunction reports” (sequentially numbered by year, indicating that these are associated only with the SM-1A reactor, and most likely complete). This report does not describe any incident that resulted from overheating of the fuel, or any major release of radioactive materials to the environment. Malfunction report 67-5 (page 56 of PDF) describes a steam generator leak, allowing water from the primary loop to leak into the secondary loop, but such an occurrence would result only in cross-contamination of the secondary loop, and is a relatively common incident in nuclear power plants.

### **2.3 Burnt Mountain Site**

The Burnt Mountain site, located about fifty miles north of Fort Yukon, Alaska, was a remote seismic station built in the 1970s to monitor Russian underground nuclear testing. Power for this site was provided by ten radioisotope thermoelectric generators (RTGs), and operated without public concern until a wildfire in 1992 damaged some data wires. In 1994, a study was undertaken to evaluate the use of these devices at this site.<sup>39</sup> In 2002, the units were removed and replaced with propane-powered thermoelectric generators (basically the same technology, except that the heat used to generate the electricity is from burning fuel instead of from radioactive decay).

### **2.4 Amchitka**

Amchitka, an island in the Aleutian Chain, was the site of three underground nuclear tests in the 1960s and 1970s, including the largest underground test conducted in the U.S. Protests against the largest of these tests resulted in the formation of Greenpeace, which at that time was concerned that detonating such a large bomb might cause major earthquakes. Some venting of gasses occurred during the testing, and some environmental organizations claimed that radioisotopes might be leaching from the underground test cavities. However, studies by the DOE have not indicated that any such contamination is occurring, at least not associated with the Amchitka testing.

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<sup>37</sup> “Fort\_Greely\_report\_May\_2000.pdf,” n.d., [http://www.akaction.org/Publications/Military\\_Waste\\_in\\_Alaska/Fort\\_Greely\\_report\\_May\\_2000.pdf](http://www.akaction.org/Publications/Military_Waste_in_Alaska/Fort_Greely_report_May_2000.pdf).

<sup>38</sup> “ar008\_sm1a\_summary\_dec1992.pdf,” n.d., [http://www.smdcen.us/rabfga/docs/adminrecord/ar008\\_sm1a\\_summary\\_dec1992.pdf](http://www.smdcen.us/rabfga/docs/adminrecord/ar008_sm1a_summary_dec1992.pdf).

<sup>39</sup> U.S. Congress, Office of Technology Assessment, Power Sources for Remote Arctic Applications, OTA-BP-ETI 129 (Washington, DC, June 1994), <http://www.fas.org/ota/reports/9423.pdf>.

## 2.5 Project Chariot

Project Chariot was an attempt to demonstrate the use of nuclear explosions for major construction projects as a way of showing peaceful uses of nuclear energy, and was active between 1958 and 1962. The plan proposed under Project Chariot was to use four large bombs to excavate a harbor in northwest Alaska. The project would have resulted in radioactive fallout, which has been shown to enter the human food chain in the Arctic through the consumption of caribou that, in turn, consume lichens, which concentrate strontium-90 from fallout.<sup>40</sup> The experiment, which was cancelled, has been well documented in *The Firecracker Boys*, a book by Dan O'Neill. However, the political repercussions from Project Chariot continue to affect Alaska, especially in the form of distrust of anything nuclear.

## 2.6 Uranium Mining in Alaska

A uranium mine site is currently being explored on the Seward Peninsula near Elim.<sup>41</sup> The proposed mining operation would use in situ leaching rather than open-pit mining. This proposal is causing concern among local residents.

A second proposed uranium mine is being explored at Bokan Mountain,<sup>42</sup> a site located on the south end of Prince of Wales Island, very close to the Canadian border. This site includes the Ross Adams mine site, which operated as a uranium mine between 1957 and 1971, with 1.3 million pounds of uranium ore extracted. The Ross Adams mine operation is the only uranium mining that has taken place in Alaska to date.

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<sup>40</sup> "Strontium-90 and Cesium-137 Levels in the Milks of Some Arctic Species," 1979. Retrieved from [http://www.journalofdairyscience.org/article/S0022-0302\(68\)87223-6/abstract](http://www.journalofdairyscience.org/article/S0022-0302(68)87223-6/abstract).

<sup>41</sup> "Uranium mining proposal for Elim area drawing concerns | APRN," n.d., <http://aprn.org/2007/07/31/uranium-mining-proposal-for-elim-area-drawing-concerns/>.

<sup>42</sup> "Ucore Rare Metals | Bokan Mountain, Alaska," n.d., <http://www.ucoreraremetals.com/bokan.asp>.

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### 3.0 Small Modular Reactors (SMRs)

The World Nuclear Association defines a small reactor as being any reactor that produces less than 300 MWe. This size reactor is still a large power plant, especially by Alaska standards. Modular reactors are systems built to a standard design at a factory, as opposed to a unit fabricated on site. All small modular reactors (SMRs) are nuclear reactors, meaning that the energy comes from a controlled, sustained nuclear chain reaction, as opposed to much smaller radioisotope thermoelectric generators that depend only on heat from natural radioactive decay (see Section 3.1.1 and Appendix D).

From the point of view of the nuclear industry, the advantages of SMRs include:

- Greater control over the manufacturing process, leading to higher-quality construction at lower costs.
- Standardization of construction, leading to efficiencies in operator training and maintenance of the units.
- Shorter, better-defined construction times, allowing owners to reduce construction costs.
- The ability to manage power output in smaller units, as planned outages for refueling or other maintenance can be staggered between units.
- The ability to add power to the grid in smaller increments.
- Higher intrinsic safety from smaller reactor sizes, since less nuclear material is located in any single reactor.

Note that the focus of much of the SMR community is on meeting the needs of large grid utilities, and that the installation of multiple units on a single permitted site is planned. For example, the NuScale system envisions grouping twelve 45 MWe modules to form a total plant size of 540 MWe, and the Babcock & Wilcox mPower 125 MWe unit is designed for a plant with four units totaling 500 MWe. With some systems, such as the Toshiba 4S, the modular nature of the system is less well defined.

From the Alaska Railbelt perspective, the smaller units are attractive, as they are comparable in size to existing power plants. Of particular interest may be the ability to replace small coal-fired plants in combined heat and power (CHP) configurations, such as the four systems currently operating near Fairbanks (University of Alaska Fairbanks, Aurora Energy, Fort Wainwright, and Eielson Air Force Base).

Small modular reactors have been proposed by many developers, and the technical literature describing these units is extensive. Appendix F contains brief descriptions of SMRs, and provides links to the web sites of many of these systems, where additional information can be found. In this section, we briefly describe the units of most interest to Alaska, including units that might be appropriate for rural village use, as well as units that might be appropriate for the Railbelt. We have limited this discussion to designs whose developers have indicated an intention to seek NRC approval in the near future (within the next 5 years).

### 3.1 Very Small-Scale Units

#### 3.1.1 Radioisotope Thermoelectric Generator (RTG) Units

The smallest of all nuclear electrical sources is the radioisotope thermoelectric generator (RTG), which is currently used to power spacecraft and remote seismic installations, although power levels in these applications are limited to less than 1 kW. Russian literature, however, indicates that systems as large as 1 MW (megawatt) have been built and successfully operated for extended periods of time.<sup>43</sup> The most common RTG has no moving parts and therefore requires no maintenance for the life of the system. This characteristic and a long operational lifetime (on the order of decades) have made RTG technology the backbone of space exploration.<sup>44</sup> Radioisotope thermoelectric generators have several major drawbacks, however, when considered for use in remote power applications in Alaska. These drawbacks center on the large volume of nuclear material needed, and therefore licensed, along with associated costs that impact the cost of power produced. As recently as 2000, the reported fuel cost for an RTG was at least \$4 per kWh,<sup>45</sup> which is not competitive with existing diesel-power generation systems. A more complete discussion of these systems is included in Appendix D of this report.

#### 3.1.2 NASA Lunar Base Power Program

The National Aeronautic and Space Administration (NASA), which needs power for many applications, used RTGs for a number of missions. However, larger amounts of power will be needed for future missions, such as the proposed operation of manned bases on the moon or on Mars.<sup>46</sup> A small nuclear-powered Sterling engine is being developed for this purpose. This system is expected to generate approximately 40 kWe, a size appropriate for small remote villages. However, neither detail about the nature of the nuclear reactor nor cost estimates are publically available. No indication has been given that these units might be available for commercial use.

### 3.2 Research Reactors

Research and test reactors—also called “non-power” reactors because they generate heat but typically no power—are nuclear reactors primarily used for research, education, and training. According to the NRC,<sup>47</sup> forty-one such reactors are currently regulated in the U.S., located primarily on university campuses, although nine of these are in the process of being decommissioned. In addition to these reactors, the DOE also regulates its own research and test reactors. The licensing process for the most common version of these reactors is extremely simplified compared with the SMR licensing process; however, the operator is still required to have trained personnel and inspections by the NRC at regular intervals, and follow standard security protocols.

As in the case of power reactors, a number of different reactor types have seen service as research reactors. Many are still in operation. The variety and designs are even more variable than power reactors due to the wide spectrum of special research needs to which these reactors are adapted.

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<sup>43</sup> Velikhov, E. (2010, September 24). Personal Interview (D. Witmer, Interviewer).

<sup>44</sup> Sutliff, G.S. (2008). Radioisotope Power: A Key Technology for Deep Space Exploration. *IAC*.

<sup>45</sup> Kulcinski, G. (2000). NEEP 602 Course Notes (Spring 2000): Nuclear Power in Space. Retrieved December 6, 2010, from <http://fti.neep.wisc.edu/neep602/SPRING00/neep602.html>

<sup>46</sup> “NASA Planning to Use Nuclear Powered Stirling Engine for Moon Base | Nuclear Power,” n.d., <http://www.greenoptimistic.com/2009/10/27/nasa-nuclear-stirling-engine-moon/>.

<sup>47</sup> <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/research-reactors-bg.htm>.

Most reactors in service today are water-cooled, reactors that operate over a wide range of thermal power levels, from a few kilowatts to hundreds of megawatts, using enriched uranium fuel in plate assemblies. A common form of this sort of reactor is the pool reactor, in which the reactor core is situated at the bottom of a large, deep pool of water (20 feet is common) that provides both cooling and radiation shielding. Another version of this concept is a tank-type reactor that has a core in a tank with water, sealed at the top. At low thermal power outputs, natural convection of the water is adequate for cooling the reactor and no pumping is required, with heat extracted from the system via a heat exchanger located toward the top of the pool where the hotter (lower density) water circulates. At higher operating power levels, pumping becomes necessary to augment this natural circulation. These reactors either use the water in the pool as a reflector, or employ blocks of a solid moderator such as graphite or beryllium positioned strategically around the core.

A common tank-type water-cooled system is a TRIGA (training, research, isotopes, General Atomics) research reactor (Figure 5). These reactors, built by General Atomics, are becoming increasingly popular in the U.S. and around the world. The NRC had licensed over 60 of these reactors as of 2008,<sup>48</sup> and 35 have been installed in other countries, most recently including Morocco, Thailand, and Romania. TRIGA reactors use a unique fuel that consists of zirconium-clad rods of mixed uranium and zirconium hydrides. The benefit of this fuel is that it has a large negative power-reactivity coefficient, which means that it can go strongly supercritical for a very short period, either intentionally as part of an experiment or due to an accident such as an unintentional dewatering of the pool. The total energy released is not considered a problem, since automatic shutdown occurs quickly and the energy released is a function of the peak power of the reactor and the duration of the event, or “pulse.” This ability makes these reactors inherently foolproof to operate, since an explosive accident involving release of nuclear materials would be highly unlikely.

Several low-power electrical generator systems, designed around use of a modified TRIGA reactor and fuel, have been proposed. Radix has announced their plan to develop a small, portable reactor system designed around the fuel manufactured for the TRIGA system, including one smaller than 10 MWe, employing a steam generator for the power cycle. Other ideas for power generation are currently being investigated by university researchers. This strategy is of interest to the authors of this report, who recommend further exploration of both the technical and economic feasibility of this approach.

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<sup>48</sup> "Interview with John Deal, Hyperion Power Generation." Techrockies.com. September 22, 2008. <http://www.techrockies.com/story/0017490.html>. Retrieved May 22, 2009.

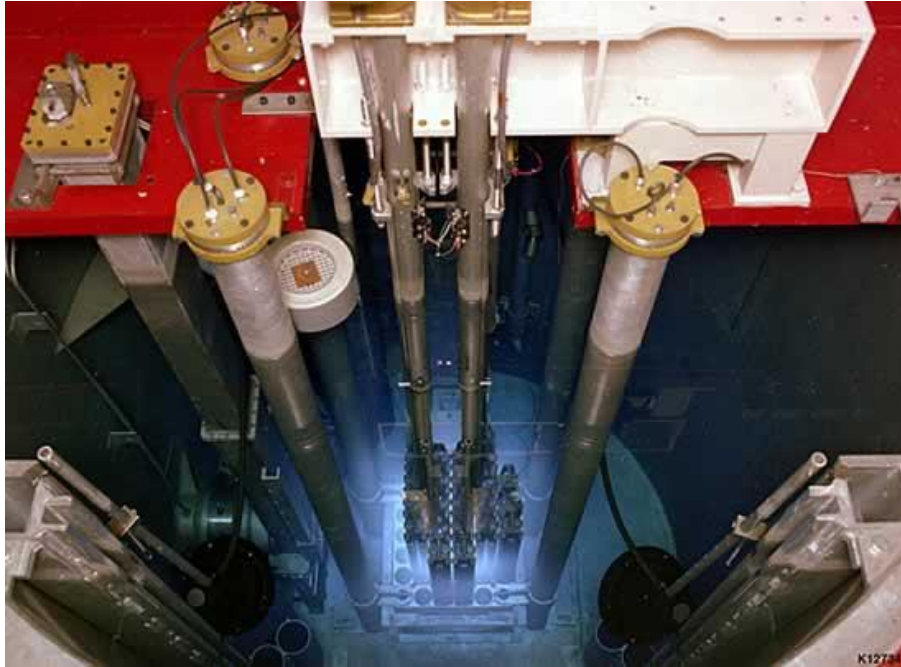


Figure 5. Image of a TRIGA reactor core.<sup>49</sup>

### 3.3 The Russian Barge-Mounted Power System

Russian developers are currently constructing the first of several proposed barge-mounted nuclear power plants (Figure 6) intended for use in the Arctic, named Academician Lomonosov.<sup>50</sup> This barge is powered by two 35 MWe KLT-40S reactors, the same reactor used in Russian icebreakers. In a meeting in Anchorage in September 2010, Evgeny Velikhov, Director of Russia's Kurchatov Institute, indicated interest in entering into contracts with Alaska to provide power to remote communities or mines, "in applications where the value of electricity is between \$0.25 and \$1 per kilowatt hour." However, he also indicated that there were no plans to seek NRC approval for use of this unit in the U.S. Based on this conversation, it does not appear that this system would be permitted for use in Alaska, as Alaska is subject to NRC licensing and permitting restrictions.

The concept of using a reactor from a nuclear submarine or icebreaker has been proposed on several occasions. It has even been rumored (apparently falsely) that a nuclear submarine once temporarily powered the island of Oahu in Hawaii during a power outage. However, nuclear reactors operated by the U.S. Navy use highly enriched (weapons grade) uranium necessitated by the small space available on submarines. For this reason, these reactors are inappropriate for commercial use due to safety and security concerns. Even if it were possible to license such a reactor through the NRC process, the costs for operating the reactor securely would render it uneconomic.

<sup>49</sup> From [http://en.wikipedia.org/wiki/TRIGA#cite\\_note-tr20080922-2](http://en.wikipedia.org/wiki/TRIGA#cite_note-tr20080922-2).

<sup>50</sup> "Nuclear Power in Russia | Russian Nuclear Energy," n.d., <http://www.world-nuclear.org/info/inf45.html>.



Figure 6. An artist's rendition of the Russian floating-barge nuclear power station. The unit can carry two KLT-50S icebreaker-type reactors, for 70 MWe, to a remote site.<sup>51</sup>

### 3.4 Technology Being Developed for Licensing in the U.S.

#### 3.4.1 Village-Scale Unit

Most rural communities in Alaska are not connected to either roads or larger electrical grids, and generate electrical energy from diesel electric generators. Loads on these systems vary from a few tens of kilowatts to a few megawatts. For this reason, only the smallest SMRs could potentially be appropriate for rural Alaska applications.

##### 3.4.1.1 Toshiba 4S Unit (10 MWe)

The Toshiba 4S (Super-Safe, Small and Simple) is a sodium-cooled liquid-metal fast-neutron reactor that was proposed for demonstration in Galena, Alaska. Toshiba teamed up with Central Research Institute of Electric Power Industry in Japan to test materials used in the design of the module.<sup>52</sup> The reactor, which has a capacity of 10 MWe or 30 MWt, is designed for use in remote locations.

In this design (Figure 7), the reactor and steam generator are located below grade. The reactor is fueled by a uranium zirconium alloy enriched to 19.9% U-235.<sup>53</sup> Eighteen hexagonal fuel assemblies

<sup>51</sup> <http://en.wikipedia.org/wiki/File:FNPSAcademicLomonosov.jpg>

<sup>52</sup> Williams, D., 2010a. *Under the hood with Duncan Williams: The Toshiba 4S*. Retrieved from [http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2010/01/27/under-the-hood-with-duncan-williams-toshiba-4s-01272.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2010/01/27/under-the-hood-with-duncan-williams-toshiba-4s-01272.aspx).

<sup>53</sup> NRC, 2010c. *Super-Safe, Small and Simple (4S)*. Retrieved from <http://www.nrc.gov/reactors/advanced/4s.html>.



are contained within the core of the reactor.<sup>54</sup> Each subassembly contains 271 fuel pins<sup>55</sup> that are clad in HT9 steel. Each pin is 5 meters long,<sup>56</sup> with only half the pin filled with fuel pellets. The top half of the pin is left empty to allow space for the buildup of gas from the fission process over the life of the module. A hexagonal cavity in the center of the fuel assemblies is used for insertion of a shutdown rod. Six control devices made of laminated chromium-molybdenum steel, nickel steel, and inconel on the bottom half, and cylindrical hermetically sealed vessels that may be filled with either helium or argon gas on the top half, are inserted or removed from the core to moderate the reactor.<sup>57</sup> A fixed neutron shield made of boron carbide is imbedded in the walls of the reactor vessel to absorb neutrons that would otherwise leak out of the reactor.

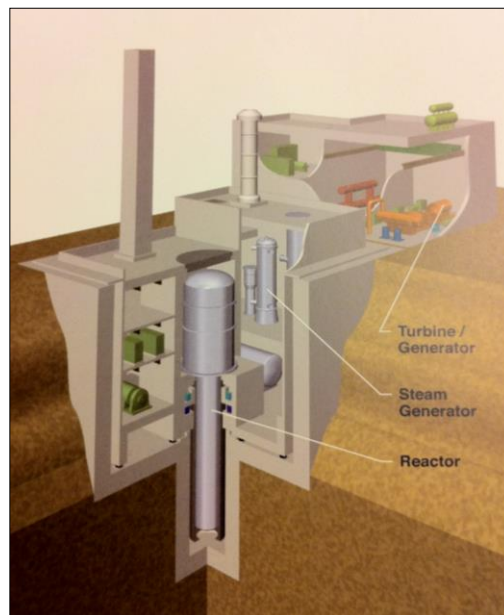


Figure 7. A schematic of the Toshiba 4S reactor design. This reactor is sodium-cooled, and can use natural convective circulation of the liquid metal for emergency cooling.<sup>58</sup>

Reflectors move up around the outside of the fuel assemblies at a rate of 1 millimeter per week for 30 years.<sup>59</sup> The reflectors are moved by electromagnetic impulse force drive. Should the reactor overheat and power cut off, the reflectors would fall to the bottom of the reactor, making the core subcritical. The primary liquid-sodium coolant loop removes heat from the reactor and is circulated throughout the reactor vessel by electromagnetic pumps. The core transfers heat to the primary liquid-sodium loop as it flows upward over the fuel pins. The primary liquid-sodium loop then transfers its heat to an intermediate heat exchanger located at the top of the reactor vessel. A secondary liquid-sodium loop is located on the other side of the intermediate heat exchanger. This

<sup>54</sup> NRC, 2010c. *Super-Safe, Small and Simple (4S)*. Retrieved from <http://www.nrc.gov/reactors/advanced/4s.html>.

<sup>55</sup> Toshiba, 2004, April 27–29. *4S Current Status*. PowerPoint presented at the Alaska Rural Energy Conference, Talkeetna, AK.

<sup>56</sup> Williams, D., 2010a. *Under the hood with Duncan Williams: The Toshiba 4S*. Retrieved from [http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2010/01/27/under-the-hood-with-duncan-williams-toshiba-4s-01272.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2010/01/27/under-the-hood-with-duncan-williams-toshiba-4s-01272.aspx).

<sup>57</sup> Ibid.

<sup>58</sup> Picture from <http://upload.wikimedia.org/wikipedia/en/thumb/3/34/Llnl4s.svg/1000px-Llnl4s.svg.png>

<sup>59</sup> Toshiba, 2004, April 27–29. *4S Current Status*. PowerPoint presented at the Alaska Rural Energy Conference, Talkeetna, AK.

secondary liquid-sodium loop is connected to a steam generator, where it transfers its heat to water, which generates steam and spins a turbine to generate electricity. The secondary liquid-sodium loop then circulates back to the reactor vessel to absorb additional heat from the intermediate heat exchanger.

After the liquid sodium transfers its heat, an electromagnetic pump at the top of the vessel pumps the liquid sodium downward through an annular cavity between the pressure wall and the reactor vessel. The liquid sodium then begins the cycle again as it is drawn into the bottom of the reactor core and flows over the fuel pins. The air flowing around the outside of the reactor vessel removes decay heat.

In 2007, Toshiba began working with the City of Galena as a possible site for a 4S reactor.<sup>60</sup> Toshiba submitted a pre-application for design approval to the NRC the same year. Toshiba is currently expected to submit a Design Approval Application to the NRC in 2012,<sup>61</sup> but this step has been delayed several times in the past.

### **3.4.2 Railbelt-Scale Units**

Most proposed SMRs are sized from a few tens of megawatts to a few hundred megawatts, and thus are too large for rural communities. However, these units may be appropriately sized for use in Railbelt communities, especially if they can be located near sites that could also utilize the excess heat.

#### **3.4.2.1 Hyperion**

The Hyperion Power Module (HPM) is a liquid-metal fast reactor with a lead-bismuth eutectic (LBE) coolant that operates at ambient pressure (Figure 8). The HPM was developed at the Los Alamos National Laboratory (LANL). Hyperion Power Generation, Inc. was given exclusive rights to commercialize the design through a technology-transfer agreement. The HPM is designed to produce a thermal output of 70 MWt, or an electrical output of 25 MWe.<sup>62</sup>

The reactor is fueled by solid-ceramic uranium nitride pellet-filled sealed HT-9 stainless steel clad tubes called fuel pins.<sup>63</sup> The reactor core is made up of 24 fuel pin bundles.<sup>64</sup> The uranium used in the reactor is enriched to no more than 19.75% U-235.<sup>65</sup> The LBE primary coolant loop is pumped upward over the fuel pins extracting thermal power. Larger diameter boron carbide control and safety rods are spread between the fuel bundles. The safety rods can shut down the reactor if necessary. The control rods are used to maintain proper temperature and power production. In the center of the reactor is a drywell that can be filled with boron carbide marbles as an added safety measure to shut down the reactor in case of an emergency. The fuel bundles, safety rods, control rods, and dry well make up the inner vessel. The outer annulus contains tubes for the intermediate loop, which also uses pumped LBE to extract power from the primary cooling loop and transfers

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<sup>60</sup> Williams, D., 2010a. Under the hood with Duncan Williams: The Toshiba 4S. Retrieved from [http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2010/01/27/under-the-hood-with-duncan-williams-toshiba-4s-01272.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2010/01/27/under-the-hood-with-duncan-williams-toshiba-4s-01272.aspx).

<sup>61</sup> NRC, 2010c. *Super-Safe, Small and Simple (4S)*. Retrieved from <http://www.nrc.gov/reactors/advanced/4s.html>.

<sup>62</sup> Hyperion Power Generation, Inc., 2010, August. *Hyperion Power Module* [Brochure]. Denver, CO.

<sup>63</sup> Ibid.

<sup>64</sup> Ibid.

<sup>65</sup> Ibid.

heat to the steam generator. Quartz pellet radial reflectors surround the outer annulus. The reactor is encased in a containment vessel. The HPM is roughly 8 feet long by 5 feet wide,<sup>66</sup> resulting in its nickname, the “hot tub” sized reactor. Similar to the Toshiba 4S, the HPM is sealed in a concrete reactor vault below grade, separate from the electricity generating equipment. The steam generator is connected to the HPM by pipes that circulate the intermediate LBE coolant. The steam generator uses LBE to generate steam, which is used in a steam turbine to produce power.

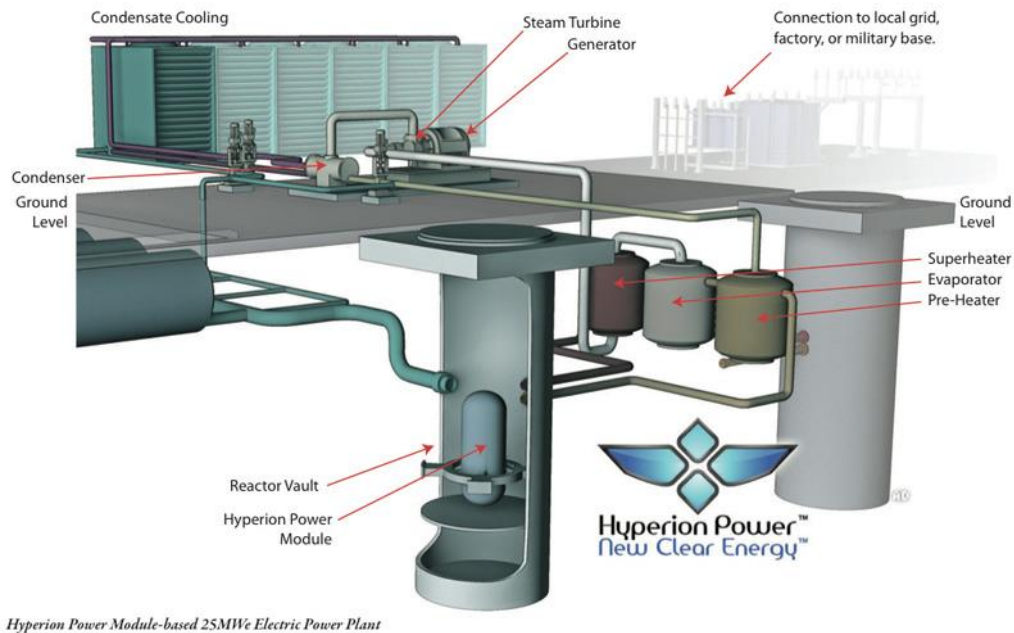


Figure 8. Illustration of the Hyperion Power Module, from promotional material made available by Hyperion Power Generation, Inc.<sup>67</sup>

As proposed, the HPM is sealed at the factory and transported to the site as a single unit. The reactor core has an estimated life of eight to ten years, after which the sealed module is transported back to the factory.<sup>68</sup> According to their representatives, Hyperion Power Generation, Inc. intends to submit a Design Certification Application to the NRC in 2012.<sup>69</sup> In September 2010, the company signed an agreement with Savannah River Nuclear Solutions to build a demonstration unit at their site.<sup>70</sup> The stated intent is for this demonstration unit to be operational in 2017.

### 3.4.2.2 NuScale Power

NuScale Power’s small modular pressurized light-water reactor design is based on existing light-water reactor technology. One unit is designed to generate 45 MWe of electricity or 160 MWt.<sup>71</sup> As proposed; a single site could have up to 12 units operating.<sup>72</sup> The unit, which is designed

<sup>66</sup> Hyperion Power Generation, Inc., 2010, August. *Hyperion Power Module* [Brochure]. Denver, CO.

<sup>67</sup> <http://www.hyperionpowergeneration.com/product.html>

<sup>68</sup> Ibid.

<sup>69</sup> World Nuclear Association, 2011.

<sup>70</sup> (World Nuclear Association, 2011).

<sup>71</sup> NuScale Power, 2008. Retrieved from <http://www.nuscalepower.com/index.php>.

<sup>72</sup> Ibid.

to have a capacity factor greater than 90%,<sup>73</sup> is prefabricated at domestic factories before installation at the power plant site. Both the reactor and the steam-generator tube bundles are contained within the reactor vessel. The unit's reactor and containment vessel is 60 feet in length by 14 feet in diameter.<sup>74</sup> The containment vessel sits within a water-filled pool below grade. The fuel assembly is 6 feet long.<sup>75</sup> The fuel is less than 5% enriched,<sup>76</sup> and the reactor requires refueling every 24 months,<sup>77</sup> typical of existing LWR plants.

The reactor is designed to be cooled passively by a natural circulation cooling system that uses no pumps or mechanical systems to circulate the water, and thus is intrinsically safer than existing larger designs, which require pumps to force cooling water past the core. As the water is heated by the fuel, it rises and transfers its heat to the steam-generator tube bundles at the top of the reactor vessel. The now cooler (and denser) water sinks to the bottom of the vessel by gravity. The natural convective cell that forms in this process enables the cooled water to be circulated upward to extract additional heat from the reactor core. The unit's coolant and steam operating pressures are half that typically found in existing pressurized water reactors (PWRs). The water within the reactor and the water within the steam generator system are separated. Similar to other designs, the steam is used to generate power using a conventional steam turbine and generator. The turbine is located above grade and, as such, is physically separated from the nuclear reactor.

The NuScale reactor design was developed jointly between the Idaho National Environmental and Engineering Laboratory (INEEL) and Oregon State University (OSU), receiving funding from the Department of Energy for early development between 2000 and 2003.<sup>78</sup> Oregon State University continued development of the reactor after this period, and built a one-third-scale test facility that is electrically heated to test the operation of the natural circulation cooling system. In 2007, through a technology transfer agreement, OSU granted NuScale Power exclusive rights to the reactor design.<sup>79</sup> NuScale Power partnered with Kiewit Power Constructors Co. in 2008 to develop plans for manufacturing and constructing the modules.<sup>80</sup> Also in 2008, NuScale Power notified the NRC that the company intended to pursue Design Certification for the new reactor design.<sup>81</sup> Because the design is based on existing LWR technology, the Design Certification process is expected to take less time than the Hyperion and Toshiba designs. According to reports from the company, NuScale Power plans to file for Design Certification in 2012<sup>82</sup> and predicts its first facility will begin operation as early as 2018.<sup>83</sup> However, some industry insiders expressed skepticism about these claims, believing NuScale is further from commercialization than is being reported.<sup>84</sup>

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<sup>73</sup> NuScale Power, 2008. Retrieved from <http://www.nuscalepower.com/index.php>.

<sup>74</sup> Ibid.

<sup>75</sup> Ibid.

<sup>76</sup> Ibid.

<sup>77</sup> Ibid.

<sup>78</sup> NuScale Power, 2008. Retrieved from <http://www.nuscalepower.com/index.php>.

<sup>79</sup> Ibid.

<sup>80</sup> Ibid.

<sup>81</sup> NRC, 2010a. NuScale. Retrieved from <http://www.nrc.gov/reactors/advanced/nuscale.html>.

<sup>82</sup> Ibid.

<sup>83</sup> NuScale Power, 2008. Retrieved from <http://www.nuscalepower.com/index.php>.

<sup>84</sup> Personal communication with authors from unanimous industry source

### **3.4.2.3 Babcock & Wilcox mPower**

The mPower by Babcock & Wilcox (B&W) is a 125 MWe modular advanced light water reactor.<sup>85</sup> The modular design is intended to allow ten or more units to operate at one site.<sup>86</sup> The reactor is fueled by uranium enriched to less than 5% U-235,<sup>87</sup> with an operating life cycle of 4.5 years.<sup>88</sup> Spent fuel is stored onsite in a spent fuel pool for the 60-year life of the reactor.<sup>89</sup> The reactor vessel is roughly 12 feet wide and 72 feet tall.<sup>90</sup> Babcock & Wilcox proposes to produce and supply its system, called the Nuclear Steam Supply System (NSSS) within North America. All components of the NSSS, including the steam generator and nuclear core, will be contained within a single module that is small enough to ship by rail. No primary cooling pipes enter or exit the reactor vessel, so there cannot be a large loss-of-coolant accident. The unit uses 69 fuel pins arranged in a 17-by-17 array. These assemblies are half the length of the fuel rods typically used in large PWRs.<sup>91</sup> The balance of plant components are intended to be off-the-shelf technologies.

The Tennessee Valley Authority has expressed interest in partnering with B&W to install several mPower units near Oak Ridge, Tennessee.<sup>92</sup> In addition, B&W and Bechtel have formed an alliance called Generation mPower to promote the design.<sup>93</sup> Babcock & Wilcox is expected to submit a Design Certification Application to the NRC at the end of 2012.<sup>94</sup>

### **3.4.2.4 GE-Hitachi Nuclear Energy Power Reactor Innovative Small Module (PRISM)**

The Power Reactor Innovative Small Module (PRISM) reactor was designed at the Argonne National Laboratory during the 1980s and 1990s.<sup>95</sup> A Preapplication Safety Evaluation was submitted to the NRC for the PRISM design in 1994.<sup>96</sup> The reactor is fueled by recycled uranium, plutonium, and zirconium.<sup>97</sup> The reprocessing uses a metallurgical process to separate uranium from the spent fuel. Similar to the Toshiba 4S design, PRISM is a liquid-sodium-cooled fast reactor. Control rods with an absorber bundle are designed to shut down the reactor core in a fifth of a second. As an added safety measure, boron carbide balls can be dropped into an open cavity to absorb neutrons to shut down the reactor.

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<sup>85</sup> The Babcock & Wilcox Company. (2011). *Modular nuclear reactors*. Retrieved from [http://www.babcock.com/products/modular\\_nuclear/](http://www.babcock.com/products/modular_nuclear/).

<sup>86</sup> Ibid.

<sup>87</sup> Spring, N., 2010, January. *The mPower modular reactor*. Power-Gen Worldwide. Retrieved from [http://www.powergenworldwide.com/index/display/articledisplay/4286077939/articles/nuclear-power-international/volume-3/issue-1/nucleus/The\\_mPower\\_Modular\\_Reactor.html](http://www.powergenworldwide.com/index/display/articledisplay/4286077939/articles/nuclear-power-international/volume-3/issue-1/nucleus/The_mPower_Modular_Reactor.html).

<sup>88</sup> The Babcock & Wilcox Company. (2011). *Modular nuclear reactors*. Retrieved from [http://www.babcock.com/products/modular\\_nuclear/](http://www.babcock.com/products/modular_nuclear/).

<sup>89</sup> Ibid.

<sup>90</sup> Ibid.

<sup>91</sup> Spring, N., 2010, January. *The mPower modular reactor*. Power-Gen Worldwide. Retrieved from [http://www.powergenworldwide.com/index/display/articledisplay/4286077939/articles/nuclear-power-international/volume-3/issue-1/nucleus/The\\_mPower\\_Modular\\_Reactor.html](http://www.powergenworldwide.com/index/display/articledisplay/4286077939/articles/nuclear-power-international/volume-3/issue-1/nucleus/The_mPower_Modular_Reactor.html).

<sup>92</sup> World Nuclear Association, 2011.

<sup>93</sup> The Babcock & Wilcox Company. (2011). *Modular nuclear reactors*. Retrieved from [http://www.babcock.com/products/modular\\_nuclear/](http://www.babcock.com/products/modular_nuclear/).

<sup>94</sup> NRC, 2010d. B&W mPower. Retrieved from <http://www.nrc.gov/reactors/advanced/mpower.html>

<sup>95</sup> Williams, D., 2010b. *Under the hood with Duncan Williams: GE Hitachi Prism Reactor*. Retrieved from [http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2010/01/20/under-the-hood-with-duncan-williams-ge-hitachi-prism-reactor-01201.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2010/01/20/under-the-hood-with-duncan-williams-ge-hitachi-prism-reactor-01201.aspx).

<sup>96</sup> Ibid.

<sup>97</sup> Ibid.

The primary loop of liquid sodium, which is contained within the reactor vessel, is circulated throughout the vessel by four electromagnetic pumps suspended from the top of the vessel. The electromagnetic pumps have no moving parts. Heat is transferred to the liquid sodium as it flows over the core. The heated liquid sodium then transfers its heat to two intermediate heat exchangers installed at the top of the containment vessel. The heat is subsequently transferred to an intermediate sodium loop, and from there, to water in a steam generator. The steam is used to turn a turbine to generate electricity.

The reactor vessel is designed to be located below grade, within a containment vessel atop seismic isolators. The seismic isolators are designed to protect the reactor vessel in the event of an earthquake. The containment vessel is capped with a carbon steel containment dome. General Electric (GE) Hitachi, which has licensed the rights to the PRISM design, sent the NRC a Letter of Intent in March 2010 for the submittal of a Design Certification Application in mid-2011. To date, however, no submission has occurred.<sup>98</sup>

#### **3.4.2.5 Pebble Bed Modular Reactor**

The Pebble Bed Modular Reactor (PBMR) was developed in Centurion, South Africa, in 1999. The PBMR is a high-temperature graphite-moderated, helium-cooled modular reactor. This reactor is sized to produce 80 MWe.<sup>99</sup> The manufacturer's plan is for the reactor to be fueled by enriched uranium dioxide particles coated in silicon carbide and pyrolytic carbon, all of which is then encased in graphite.<sup>100</sup> The uranium would be enriched to 9.6%.<sup>101</sup> The final fuel "pebble" would be roughly the size of a billiard ball. There would be 360,000 of these fuel pebbles within the reactor core.<sup>102</sup> When operated as designed, new and recycled fuel pebbles continually replenish the reactor from the top, while spent fuel is removed through the bottom of the reactor. The pebbles take three months to cycle through the reactor, and each pebble is recycled through the reactor about ten times before it is spent.<sup>103</sup> A 165 MWe reactor would produce 32 tons of fuel pebble waste per year, which would be stored on the plant site in tanks for the 40-year operational life of the plant.<sup>104</sup> As proposed, the fuel pebbles would be manufactured in South Africa.

The cylindrical reactor core is designed for containment within a metallic core barrel inside of a vertical steel reactor pressure vessel. As designed, the core is surrounded on all sides by reflectors and cooled with helium circulated by a blower. The helium transfers heat from the core to a steam generator through a secondary loop, which generates steam to drive a steam turbine. The steam turbine generates electricity and/or process heat. The plant is intended to be set up in two "islands." The nuclear island houses the reactor, steam generator, and spent fuel. The conventional island houses the non-nuclear components connected to the secondary side of the steam generator.

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<sup>98</sup> Williams, D., 2010b. *Under the hood with Duncan Williams: GE Hitachi Prism Reactor*. Retrieved from [http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2010/01/20/under-the-hood-with-duncan-williams-ge-hitachi-prism-reactor-01201.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2010/01/20/under-the-hood-with-duncan-williams-ge-hitachi-prism-reactor-01201.aspx).

<sup>99</sup> World Nuclear Association, 2011. Small nuclear power reactors. Retrieved from <http://www.world-nuclear.org/info/inf33.html>.

<sup>100</sup> PBMR, n.d. Retrieved from <http://www.pbmr.co.za/>.

<sup>101</sup> Ibid.

<sup>102</sup> Ibid.

<sup>103</sup> Ibid.

<sup>104</sup> PBMR, n.d. Retrieved from <http://www.pbmr.co.za/>.

PBMR Pty, the company developing the reactor, plans to build a test module near Cape Town at Koeberg, South Africa, to demonstrate the technology. A critical need is to improve the high-temperature performance of the coatings on the fuel pellets, as earlier coatings were shown to degrade under the surface temperatures expected in the reactor core. Should the demonstration prove successful, PBMR Pty plans to commercialize the technology. PBMR Pty received funding from the government of South Africa until September 2010, when the government announced that it would no longer fund the project due to delays for the demonstration plant.<sup>105</sup> PBMR Pty is a member of a consortium led by Westinghouse, which has been awarded a DOE contract to develop a heat source to produce hydrogen without the use of fossil fuels.<sup>106</sup> PBMR Pty is expected to submit a Design Certification Application to the NRC in 2013.<sup>107</sup>

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<sup>105</sup> World Nuclear Association, 2011.

<sup>106</sup> PBMR, n.d. Retrieved from <http://www.pbmr.co.za/>.

<sup>107</sup> NRC, 2010b. Pebble Bed Modular Reactor (PBMR). Retrieved from <http://www.nrc.gov/reactors/advanced/pbmr.html>.

## 4.0 Siting, Permitting, and Licensing Issues

In the U.S., the Nuclear Regulatory Commission (NRC) controls all commercial uses of nuclear materials. The rules governing the NRC are published in the Code of Federal Regulations (CFR), a section of Title 10, Energy. As part of its responsibilities, the NRC is the primary permitting agency for all commercial nuclear power plants.

Alaska state law (AS 18.45.20) requires that any nuclear facility in Alaska be licensed by the NRC. In addition, the site used for the facility must be approved by the state legislature, must comply with all state environmental rules, and must be approved by the local municipal government that has authority over the site.<sup>108</sup>

### 4.1 NRC Permitting Process

The current NRC licensing process for commercial power reactors is designed for large-scale commercial reactors constructed in the 1970s. During that time, there were several standard reactor designs, but no attempt was made to standardize other parts of the plant, so completing a safety review required treating each plant as an independent design. The cost of licensing each plant often ran into the hundreds of millions of dollars.

Other countries, most notably France, have worked at standardizing the entire plant design, which allows for faster safety reviews and shorter construction times. Based on this experience, the U.S. is now encouraging the use of standardized designs for new nuclear power plant (NPP) construction, and has created a new (and, as of yet, untried) process for using standardized designs. The interest in small modular reactor (SMR) technology is driven in large part by the economies of standardization that might be possible by building multiple identical systems. Under this model, the initial single standard design will be the only one required by the NRC for approval.

To date, no suppliers for SMR technology have built any plants, demonstrations, or prototype units. The process of obtaining a license for these first units will likely be difficult, much like the process in the 1970s. One step that can be taken fairly early is the reactor “design certification” process, which allows the NRC to review and approve a reactor design, independent of a specific power plant project application. This design certification process typically takes several years, and may cost hundreds of millions of dollars. The process is likely to be even more difficult for the new fast-reactor technologies including the Toshiba 4S and Hyperion designs, since the NRC has never certified a reactor of this type and will need to develop the staff expertise necessary to conduct the design reviews.<sup>109</sup> Any SMR project undertaken at this time would be a first-of-a-kind (FOAK) design, with the plant owner taking a large amount of risk associated with the unknown cost and time required for reactor design certification.

Once a reactor design is certified, the process for completion of the licensing for a proposed project is simpler, as the NRC reviews the specifics of the power plant, including the local environmental impacts and emergency plans, through the Early Site Permit process. The design certification

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<sup>108</sup> “Bill Text 26th Legislature,” n.d., [http://www.legis.state.ak.us/basis/get\\_bill\\_text.asp?hsid=SB0220Z&session=26](http://www.legis.state.ak.us/basis/get_bill_text.asp?hsid=SB0220Z&session=26).

<sup>109</sup> Stewart Magruder, Chief of New Reactors, at the SMR Workshop, October 19, 2010, Washington, DC.



assures the basic safety of the plant, so long as it is constructed and operated to the previously approved specifications. Hopefully, the licensing process can be streamlined to allow for faster and less costly approval for subsequently ordered plants.

### **Specific Rules**

The specific rules pertaining to the licensing of nuclear power plants are 10 CFR Part 50, *Domestic Licensing of Utilization and Production Facilities*,<sup>110</sup> and 10 CFR Part 52, *Licenses, Certifications and Approvals for Nuclear Power Plants*.<sup>111</sup> Either of these two processes can be followed to obtain a license for constructing and operating a nuclear power plant. Part 50 describes a process by which construction can begin on a plant before final designs have been approved,<sup>112</sup> which allows an earlier start to construction, especially for unique designs and FOAK installations. In the past, part 50 created a situation where changing regulations required significant retrofits and rebuilding, which led to difficulty maintaining schedules or budgets.

Part 52 was developed specifically to separate the design certification process of the nuclear reactor from site permitting; it is intended to simplify the process of obtaining a license for a plant where a standardized design is used. This simplification occurs by allowing the plant owner to obtain an Early Site Permit (ESP), which does not require any detail about the specifics of the reactor design, only that design and operational parameters are defined. The ESP allows the owner flexibility in selecting a vendor. The reactor developer obtains a standardized design certification that can then be incorporated into the license application by reference, thus streamlining the approval process. A standardized design certification will be especially useful for SMR designs, where many identical units will be placed at one or multiple locations, but a single design review and approval process can be used for all units.

It would seem that from the view of current SMR developers, the Part 50 process would be the preferred route at this time, since it allows construction of a FOAK unit to begin before the design has been finalized. However, the owner takes on considerable risk in this process, since the lack of an approved design has proved in the past to result in considerable financial cost. It is expected that, after the initial handful of systems has been built, a certified design will be approved by the NRC, and licensing will be done through the Part 52 process.

In a Part 52 process, the reactor supplier provides a standard design certification or a manufacturing license for the reactor. The owner would apply for and obtain an ESP, which could then incorporate by reference the design previously approved by the NRC to form a complete license application. All this could be done before the beginning of construction. As construction progresses, inspection, testing, analysis, and acceptance criteria (ITAAC) protocols would be followed to assure that the plant is built as designed. The results of the ITAAC process would be submitted to the NRC for review before issuance of an operating license. We estimate that the cost of obtaining an ESP would be \$50–\$70 million for NRC fees and application preparation.<sup>113</sup> This cost

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<sup>110</sup> “10 CFR Part 50 – Domestic Licensing of Production and Utilization Facilities,” n.d., <http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/>.

<sup>111</sup> “10 CFR Part 52 – Licenses, Certifications, and Approvals for Nuclear Power Plants,” n.d., <http://www.nrc.gov/reading-rm/doc-collections/cfr/part052/>.

<sup>112</sup> The process by which all of the nuclear power plants were built in the 1960s and 70s.

<sup>113</sup> Personal communication, Philip Moor and Vince Gilbert, in conversation with Ginny Fay, December 2010.

is a relative bargain compared with the Construction and Operating License (COL) fees experienced by plants in the 1970s under a Part 50 application. The NRC anticipates that after multiple units are placed in service, this process might be further streamlined. At the Alaska SMR Workshop held in Anchorage in December 2010, William Reckley from the NRC indicated that permitting fees of \$12 million might be expected after several plants are operating successfully.

Worth noting is that Toshiba was open about the process it expected to follow with the 4S project in Galena. The City of Galena was expected to be the applicant for a combined COL, which indicates that they intended to follow a Part 50 licensing procedure, as they stated in their first pre-application meeting with the NRC.<sup>114</sup> Additionally, in their initial discussions with the press, Toshiba indicated that they would need approximately \$600 million—and six to eight years to get NRC approval.<sup>115</sup> Other SMR developers have indicated similar expectations for the cost and time associated with the design approval process, and they have expressed similar hopes for U.S. federal investment in their projects.

It no longer seems reasonable to expect large amounts of federal support for a FOAK demonstration project like that proposed for Galena. A more appropriate strategy for Alaska would be to allow SMR developers to complete their designs, have them approved by the NRC, and build a demonstration or prototype plant before a contract to purchase such a unit is considered. It is only reasonable to expect that SMR developers will recoup their development costs by including them in the price of initial units sold (as drug manufacturers recoup their research and development [R&D] investments through high drug prices in the first few years after approval). However, the cost of the unit would be better defined, allowing Alaska users to determine if this technology meets their needs.

Figure 9 shows the outline of a license application under Part 52. A license application is a very complex document that can result in tens of thousands of pages. The final safety analysis report (FSAR) is the heart of the application, because it describes the reactor operation and safety systems. However, in a Part 52 application, this section would be completed by the reactor supplier, so the owner would be responsible for only the balance of items in the left-hand column.

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<sup>114</sup> NRC Document #ML073050078, Official Transcripts of the NRC-Toshiba meeting, October 23, 2007, p. 105, Downloaded from the NRC ADAMS site.

<sup>115</sup> "Toshiba's new nuclear reactor for small villages," n.d., <http://hyvin.nukku.net/no/toshiba.html>.

## Combined License Application

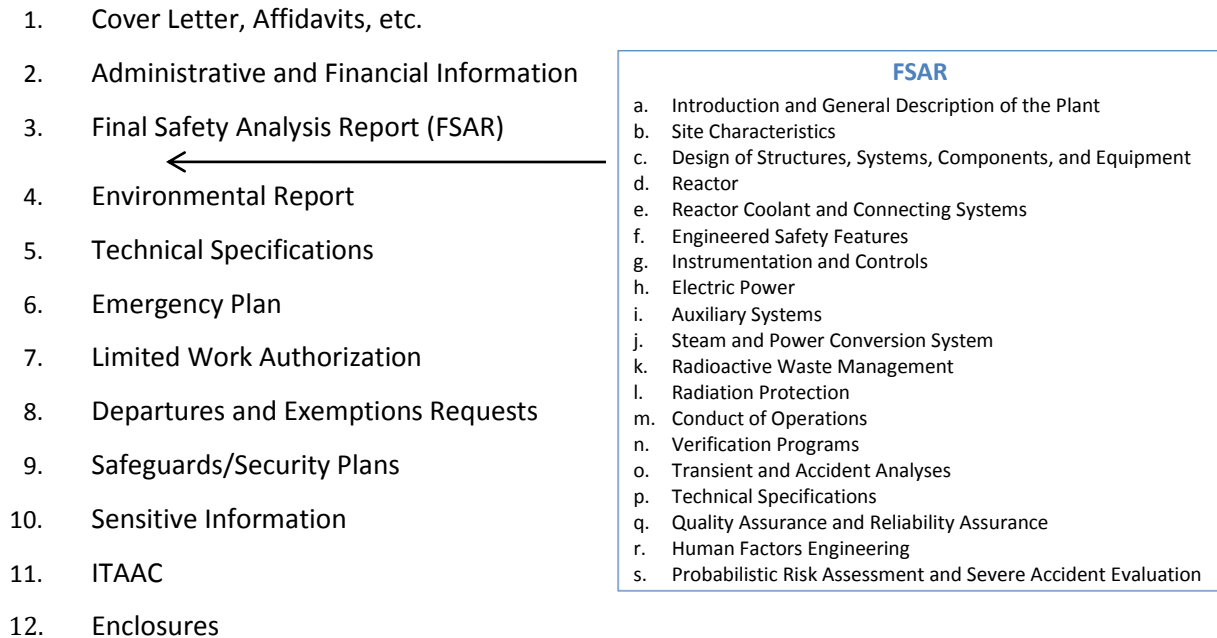


Figure 9. NRC Part 52 License Application. For SMRs, the FSAR would be based on the design certification obtained by the reactor developer, and incorporated by reference.

At the SMR workshop in Anchorage, Vince Gilbert from Excel Services Corporation provided a plan for bringing SMRs to market. At this point in time, Alaska is still working on the first step of the multi-stepped plan, “Determine market needs.”

As noted earlier, existing rules published by the NRC for the operation of commercial nuclear power plants were written for the current fleet of large-scale LWRs. Some of these rules, such as operator-staffing levels (four operators per reactor at all times) would likely make small reactors uneconomical. The proposal for a Toshiba 4S unit in Galena boasted that the reactor could operate with “no operator or maintenance personnel,” and that the steam generator would need about the same number of workers as the community’s present diesel plant.<sup>116</sup> Hyperion has stated that their unit needs “a computer, a man and a dog—the computer runs the reactor, the dog keeps the man away from the computer.” Additional discussion centers on the number of security guards needed at the plant. Conventional LWRs store spent fuel on-site, outside the reactor, while some of the new designs would not require on-site storage of spent fuel. These issues, which were discussed in the Burns and Roe white papers prepared for the City of Galena,<sup>117</sup> are being considered by the NRC, as indicated by the release of SECY-10-0034, “Potential Policy, Licensing, and Key Technical Issues for

<sup>116</sup> “Toshiba’s new nuclear reactor for small villages,” n.d., <http://hyvin.nukku.net/no/toshiba.html>.

<sup>117</sup> “Burns and Roe – Technical Publications,” n.d., [http://www.roe.com/about\\_techGalena.htm](http://www.roe.com/about_techGalena.htm).

Small Modular Nuclear Reactor Designs.”<sup>118</sup> Review of this document reveals that, while the NRC is aware of the perception by SMR developers that staffing levels for these small reactors could be safely reduced, compared with staffing levels for large reactors, the NRC has not yet made that determination. Until appropriate staffing levels are set by the NRC, applications will need to request exemptions from current rules.

The NRC has proved willing to reduce staffing levels when designs can be proved sufficiently safe, as shown by the reduced level of staff required to operate the university research TRIGA reactors. TRIGA reactors, which are frequently left unmanned between experiments, operate under much lower levels of security. However, these reactors have been used since 1956; they were in operation for 18 years before the NRC came into existence. The SMR reactors proposed for development are larger than the TRIGA research reactors, but far smaller than the current commercial reactors. Eventually, if SMR reactors can be safely operated for long periods, the permitting process for these systems may be allowed under a system that would be less onerous than the current process used for larger systems. It is unlikely that the NRC would or should do this before these systems have proved their claims of simple and safe operation.

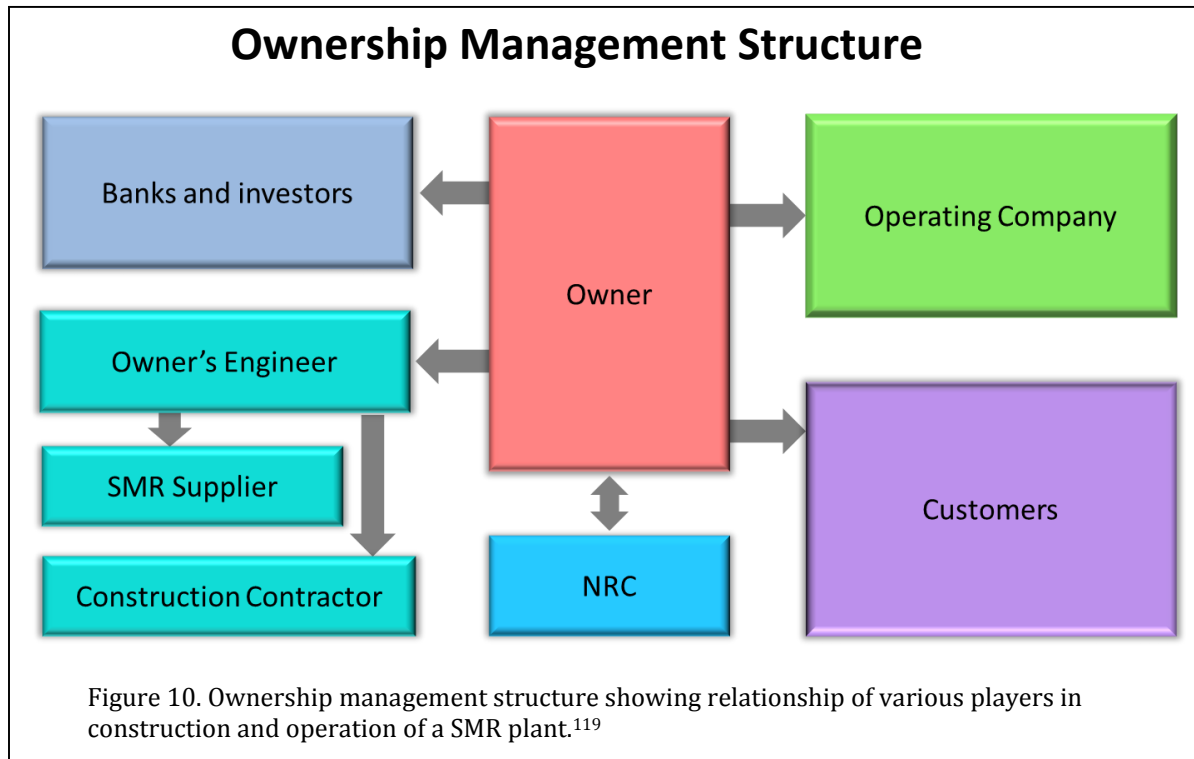
Given that the NRC design review process is likely to take several years, followed by several more years to build a demonstration plant, and potentially followed by multiple commercial installations with declining costs, there is no need to rush into a decision about which specific SMR technology, if any, is most viable for Alaska. Meanwhile, the Early Site Permit process could allow Alaskans to identify possible sites where a SMR might be located and begin the process of obtaining the necessary permits. Fairbanks appears to be a likely site, given the proposed SMR sizes, the current high cost of power in the Interior, and the possible use of heat from the SMR plant for one or more of the combined heat and power plants in the region. A site of special interest might be one of the local military bases, which are federal property, are already guarded, have some experience with the protection and handling of nuclear materials, and have combined heat and power loops.

## **4.2 Ownership Issues**

Figure 10 shows that the construction and operation of a nuclear power plant involves the efforts and skills of a variety of organizations. The owner holds licenses for specific plants located at a permitted site, and has financial responsibility for the operation. For most commercial nuclear power plants in the Lower 48, the owner is either a large electrical utility or a limited liability corporation comprised of several utilities, each with partial ownership. During the construction phase, an engineering firm and a construction contractor are typically hired to build the plant, installing the equipment provided by the reactor supplier. Many owners have discovered that it is best to turn the day-to-day operation of their plants over to operating companies that specialize in these operations. However, the NRC continues to hold the owner responsible for all aspects of the plant design and operation.

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<sup>118</sup> SECY-10-0034, “Potential Policy, Licensing, And Key Technical Issues for Small Modular Nuclear Reactor Designs,” March 2010, available on the NRC ADAMS document site.



Note that in this scenario, the design and construction of the plant are undertaken through the services of the “owner’s engineer,” typically an international construction company, and that the reactor manufacturer is a different entity.

The NRC evaluates the credentials of the owner as part of the license application. The owner is expected to demonstrate the financial ability to construct and operate the plant, even through extended shutdowns, to train operators, and to maintain adequate records to document the safe construction and operation of the plant.

So who would own a SMR plant in Alaska? Most small rural utilities are far too small to undertake the complicated interactions with the NRC and large contractors associated with the nuclear industry. The formation of a corporation to undertake this role seems logical. A partnership with some entity that has previous NRC experience would also seem desirable.

One model suggested is to have a corporation own and operate the power plant as an independent power producer, which sells power to a regulated utility. However, corporations could not be expected to invest in SMRs unless they were convinced of the long-term viability of the projects. Operating a newly designed nuclear power plant in rural Alaska seems an enterprise fraught with peril. Alaska Native corporations might elect to enter this business to provide lower-cost power in remote rural areas while developing a long-term potentially profitable business. If SMRs are considered for the Railbelt region, some might be small enough for individual utilities to own and manage. A consortium of Railbelt utilities, such as ARCTEC, might be a possible owner also.

<sup>119</sup> Figure from Philip Moor, presented at SMR workshop, Anchorage, December 10, 2010.

## 5.0 Economics

Economic modeling of the small modular reactor (SMR) was used as a screening assessment to determine if and where in Alaska SMR technologies could provide potential economically viable energy options. Since SMR technology has not reached commercialization, this analysis is subject to significant cost uncertainties. All of the modeled SMR technologies have estimated deployment scenarios that begin in year 2020 or afterward. Additional analyses should be conducted as costs become more certain. The screening model was designed to be readily adaptable once additional information becomes available.

The primary sources of economic uncertainties are as follows:

- Final capital costs of SMR units are uncertain because of their early development stage. One of the major contributors to cost uncertainties is the scalability of manufacturing for each of the designs. The costs per unit will decline as a larger number of standardized units are manufactured successfully for all customers of the technology and placed into service.
- Nuclear fuel prices are uncertain for the newer advanced reactor designs such as the liquid metal-cooled fast reactors, because none of the more highly enriched fuel has been manufactured for commercial use.
- Licensing-related costs could escalate significantly for these new technologies.
  - Design certification by the NRC for the technology developers has not been completed for any of the technologies.
  - Similarly, no combined construction and operating licenses (COLs) for applicants (that is, owners/operators) have been issued.
- The thirty-year natural gas and crude oil price forecasts are variable and uncertain.
- The application of thirty-year carbon price forecasts are speculative and influenced by political considerations.

We conducted sensitivity analyses that bracket the likely range of these uncertainties, providing reasonable best- and worst-case scenarios. No other similar economic analyses are publicly available with which to compare our results, but the U.S. Department of Energy (DOE) is currently conducting a comprehensive economic analysis.

The first step in this modeling process was to identify which of the technologies and units currently under development could potentially be utilized in Alaska settings. Identification of potential units selected for the economic analysis was primarily driven by the capacity of the units and the anticipated date of availability—2020 for light-water technology and 2025 for advanced technologies.

The analysis was technology-neutral, not favoring or selecting for any particular technology type or developer. That said, the selection of units we analyzed was driven by what technologies are currently being developed in the market. The manufacturers of the anticipated units and their generation capacities identified in that process are shown in Table 1 and discussed in Section 3.4.

Table 1. Potential Small Modular Reactor Sizes and Costs

| Estimated/assumed costs and parameters     | Toshiba 4S |           |           |           |         |
|--|------------|-----------|-----------|-----------|---------|
|  | mPower     | NuScale   | Hyperion  | Large     | Small   |
| Year expected available                    | 2020       | 2020      | 2025      | 2025      | 2025    |
| Electric capacity [MW]                     | 125        | 45        | 25        | 50        | 10      |
| Thermal capacity [MW]                      | 375        | 160       | 70        | 150       | 30      |
| Power facility (\$million)                 |            |           |           |           |         |
| low  | 562.5      | 202.5     | 112.5     | 225.0     | 45.0    |
| med  | 750.0      | 270.0     | 150.0     | 300.0     | 60.0    |
| high                                       | 1,000.0    | 360.0     | 200.0     | 400.0     | 80.0    |
| Years per fuel cycle                       | 4          | 2         | 9         | 15        | 30      |
| Levelized/annualized fuel cost (\$million) |            |           |           |           |         |
| low  | 5.3        | 2.5       | 1.1       | 13.1      | 4.4     |
| med  | 7.8        | 3.7       | 1.7       | 19.6      | 6.6     |
| high                                       | 9.9        | 4.9       | 2.2       | 29.0      | 9.9     |
| Fuel cost per kWh (\$)                     |            |           |           |           |         |
| low  | 0.005      | 0.007     | 0.005     | 0.031     | 0.051   |
| med  | 0.008      | 0.010     | 0.008     | 0.046     | 0.077   |
| high                                       | 0.010      | 0.013     | 0.011     | 0.069     | 0.115   |
| Combined operating license (\$/kW)         |            |           |           |           |         |
| low  | 400        | 1,110     | 2,000     | 1,000     | 5,000   |
| med  | 480        | 1,330     | 2,400     | 1,200     | 6,000   |
| high                                       | 560        | 1,560     | 2,800     | 1,400     | 7,000   |
| Annualized mobilization/demob/overhaul     | 1,839,000  | 2,584,900 | 1,050,400 | 1,022,100 | 350,800 |
| Mob/demob/overhaul [\$/kWh]                | 0.002      | 0.007     | 0.005     | 0.002     | 0.004   |

Sources: Shropshire et al., 2009; Chaney et al., 2004; Hyperion presentation to GVEA, August 2010; NuScale from www.nuscale.com; Philip O. Moor, P.E., Vice President, High Bridge Associates, December 2010, for estimates for mPower and Toshiba fuel costs.

All SMR units are still in the design and development phase, and none has completed the NRC design-review permitting process. The earliest, and probably most optimistic, expectation for completion of a NRC design review of a light water reactor (LWR) SMR is 2020. The smaller, liquid-metal-cooled fast reactor that may be more appropriately sized for Alaska installations is likely to take longer to license because new regulatory guides and requirements are needed. Prior to achieving a COL, these designs require extensive testing to validate their safety. The NRC is currently planning to augment their staff to enable review of these new technologies, but this is a lower-tier priority than reviewing submitted applications for LWR SMRs.<sup>120</sup>

The NRC fee for processing a SMR design license is estimated at \$40 million per developer license, and the process takes three and a half years.<sup>121</sup> The total cost to a developer to complete the design certification and COL process is in the range of \$300–\$800 million.<sup>122</sup> While these costs are borne by technology developers, they will ultimately be reflected in the purchase price of units and shouldered by the purchasers of these systems. Much of the cost uncertainty relates to the still incomplete NRC design-review process and the fact that no SMRs have yet been licensed or

<sup>120</sup> Welling, Craig, Deputy for Advanced Reactor Concepts, Office of Nuclear Energy, Department of Energy, personal communication, January 21, 2011.

<sup>121</sup> Reckley, William, *NRC Licensing Overview*, Advanced Reactor Program, Office of New Reactors, Nuclear Regulatory Commission, Alaska SMR Workshop, Anchorage, December 9, 2010.

<sup>122</sup> Yoder, Marvin, 2010, Galena city manager during Toshiba-Galena SMR analyses in 2004, based on conversation with Toshiba representatives, personal communication, October 2010.  
Goldberg, Stephen, Special Assistant to the Director, Argonne National Laboratory, January 20, 2011.

constructed. The cost picture will become more certain after multiple units are licensed and installed.<sup>123</sup>

One of the key SMR cost factors is whether units can be standardized and manufactured at scale. Currently operating large LWRs produce relatively low-cost energy despite the high regulatory review and licensing costs, because they produce megawatt-hours of energy over a 60-year time horizon that can absorb these high regulatory fixed costs. For the smaller SMRs to absorb these fixed costs and remain economical requires that a sufficient number of standardized units be manufactured at scale. The DOE estimates that a manufacturing facility is likely a \$300 million investment, which makes the manufacturing piece a significant challenge to resolve.<sup>124</sup> There are also industry expectations that regulatory costs can be decreased for SMR technologies via the same standardization principals of multiple similar high-quality units that allow streamlining of the regulatory review process.

The smallest currently anticipated capacity of SMR units available over the next decade is 10 MWe. However, smaller units may be available when the technology reaches mature development—well over a decade away. The load-following capability of LWRs is technologically limited, so it is expected that LWR SMRs currently under development will operate near rated capacity, similar to large light-water nuclear facilities that provide base-load power generation. Advanced reactor technologies may be able to do more load following, which would improve their applicability to rural Alaska's smaller loads. The currently anticipated 10 MWe capacity unit is still much larger than electric loads in most rural Alaska communities, and especially in those with the highest diesel fuel prices. Economic viability increases with the load factor and requires that the reactor be utilized to its maximum capacity in order to cover the large fixed costs. As a result, community loads need to match the capacity of the reactor. This necessity may change if a market develops for a large number of SMRs under 10 MWe capacity that can be manufactured economically.

The potential communities considered in this screening analysis were those that have at least average annual electric loads close to or larger than 10 MWe. Eliminated from our analysis were communities that meet the majority of their loads with installed hydroelectric capacity (Cordova, Juneau, Ketchikan, Kodiak, Petersburg, Sitka, Valdez, and Wrangell). These communities are primarily located in Southeast and Southcentral Alaska.

Applying these considerations, potential economic viability was analyzed for all the largest electric load rural hubs, including Bethel (4.5 MWe average annual load), Dillingham (2.3 MWe), Galena (1 MWe), Kotzebue (2.4 MWe), Naknek (2.2 MWe), Nome (3.3 MWe), and Unalaska (3.8 MWe) (see map in the Executive Summary). Galena was included in this group, despite its 1 MWe load, for the purpose of comparison with an analysis conducted in 2003.<sup>125</sup> The other areas with sufficient load

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<sup>123</sup> Alaska would not be the first deployment of any of the SMR technologies. The Tennessee Valley Authority (TVA) is the announced first U.S. mover with mPower at the Clinch River, Tennessee, site. The TVA already operates a large LWR at this location.

<sup>124</sup> Goldberg, Stephen, Special Assistant to the Director, Argonne National Laboratory, January 20, 2011.

<sup>125</sup> Chaney, Robert E., Stephen G. Colt, Ronald A. Johnson, Richard W. Wies, Gregory J. White, 2004, Galena Electric Power – a Situational Analysis, DRAFT Final Report, December 15, 2004, prepared for the U.S. Department of Energy, National Energy Technology Laboratory, Arctic Energy Office Contract, DE-AM26-99FT40575.



to potentially optimize SMR capacity are the Railbelt, which includes Anchorage and Fairbanks, and Tok, because of its relatively high use of electrical power and its location on a major road system.

In addition to these communities, the Trans-Alaska Pipeline System (TAPS) pump stations, North Slope oil and gas fields, military installations, and large mines are potential SMR installation sites. The TAPS pump stations are similar to mines, in that they need energy at remote locations. The value of stranded natural gas on the North Slope may be too low to make SMR technology sufficiently competitive to displace North Slope oil field natural gas use.<sup>126</sup>

Discussions with large-mine permitting experts indicate that mine developers might be reluctant to utilize SMR technology because of the potential additional public-perception burden to an already challenging mine-permitting process.<sup>127</sup> However, it is likely that SMR technology could be well suited for large, isolated mine sites in Alaska currently under development, such as the Donlin Creek mine, which is in the pre-permitting phase of development.<sup>128</sup> This mine site is located in an isolated area and will have a large electric and thermal load because of the ore-processing method that will be utilized. Small modular reactor technology would avoid the potential environmental impacts of constructing a pipeline to the site or barging millions of gallons of fuel up the Kuskokwim River.<sup>129</sup> While no analyses were done on any specific mine sites or TAPS pump stations, the model can be readily adapted to do so, given electric and thermal load and alternative-generation cost information.

Military installations were also considered. We specifically analyzed a preliminary screening scenario including SMR installation at Eielson Air Force Base (AFB), where nuclear power would supply electricity and district heat to the military base. In this scenario, excess power is sold to Golden Valley Electric Association (GVEA) for the Fairbanks market. This scenario offers a number of potentially beneficial characteristics including the existing security of a military installation, which would possibly lower security personnel costs. Eielson AFB has an extensive district heating system in place that could use the excess heat from SMR electricity generation. In this analysis, however, security costs for Eielson AFB were not lowered; instead, we use labor assumptions consistent with other locations.

Another potential scenario similar to Eielson AFB is the University of Alaska Fairbanks campus, which offers a good match of electric and thermal district heating loads to the smaller SMRs. Similar to the Eielson AFB scenario, excess power could be sold to GVEA, and the university's district heating system could utilize excess heat. However, challenges that affect all SMRs would exist. For example, at this time the NRC requires a ten-mile-radius emergency planning zone around a large nuclear reactor. Siting an SMR within this assumed ten-mile radius to provide heat for space

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<sup>126</sup> Burden, P., M. Hartley, and J. King, 2010. *In-State Gas Demand Study*, Prepared for Trans Canada Alaska Company, LLC, Northern Economics.

<sup>127</sup> Robert Loeffler, University of Alaska Anchorage, Assistant Professor of Natural Resources and former director, Division of Mining, Alaska Department of Natural Resources, December 7, 2010.

<sup>128</sup> Donlin Creek, LLC, website, /www.donlincreek.com/ accessed January 4, 2011; Alaska Department of Natural Resources, Division of Mining, Land and Water, Large Mine Permit Review, Donlin Creek, website accessed January 4, 2011: [dnr.alaska.gov/mlw/mining/largemine/donlin/index.htm](http://dnr.alaska.gov/mlw/mining/largemine/donlin/index.htm) The Donlin Creek project is a large, undeveloped refractory gold deposit located 19 km north of the Kuskokwim River, about 450 km northwest of Anchorage. The deposit is situated on Native lands owned by The Kuskokwim Corporation (surface estate) and Calista Corporation (subsurface estate).

<sup>129</sup> Robert Loeffler, personal communication, December 14, 2010.

heating via the existing steam district heating system could be difficult to implement, given the impacts of this ten-mile emergency-planning area requirement. It is anticipated that the NRC will reduce this emergency planning zone for SMRs, but exact constraints are unknown, as no site licenses have been issued for SMRs.<sup>130</sup>

## 5.1 Methods

Our economic analysis is based on a calculated total energy requirement for the community. The total energy requirement consists of annual kWh sold, plus a distribution loss of 10%. Additional energy requirements for electric heat are calculated based on heating-degree-day (HDD) distribution for each location, space-heating requirements, and a location-specific adjustment that is based on total HDD.

We conducted a long-run levelized cost of energy analysis, assuming a 3% discount rate over a 60-year time horizon. Small modular reactor technologies are still under development, so there is a high level of uncertainty regarding costs, particularly for licensing, construction, and nuclear fuel. These costs are likely to become more certain in later stages of commercialization, when construction, licensing, and other processes are more fully developed. We have assumed that an installation in Alaska would be an nth-of-a-kind module, primarily manufactured in a factory. In addition, we have assumed that an Alaska installation would benefit by learning from early installers of the technology elsewhere. We conducted sensitivity analysis to address uncertainties in SMR construction and licensing and fuel costs, including low-, medium-, and high-cost scenarios (see Table 1).<sup>131</sup> Appendix A (Cost Structure of the Modeled SMR Nuclear System) outlines the costs included in the model.

In addition to the uncertainties related to costs, there are other limitations to the model:

- The validity of the analysis depends on the input to the scenarios and the assumptions that are used to generate them.
- The analytical model does not contain internal “feedbacks” such as an explicit link between higher electricity prices and reduced electricity consumption.
- The model was set up to consider only the total energy available from SMRs. It does not consider daily or hourly peak loads that the reactor would have to match.
- We did not attach probabilities to any of the assumptions or scenarios; therefore, the model did not produce estimates of a single “most likely” or “best” estimate for any of the results.
- There is no estimate of the benefits to the community from construction and operating jobs and from having excess heat and electricity.
- Finally, assuming Alaska entities would be off-takers (not owner/operators), no attempt was made to explicitly evaluate the degree to which any of the options may increase or decrease economic and financial risk to Alaskans.

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<sup>130</sup> Welling, Craig, Deputy for Advanced Reactor Concepts, Office of Nuclear Energy, Department of Energy, personal communication, December 9, 2010.

<sup>131</sup> We define project cost as the sum of power island cost and cost of licensing.

### 5.1.1 Nuclear Permitting Costs

The NRC design-review and site-review process is robust and actively used by several large reactor licensees. The NRC has not completed design certifications for any SMR units (discussed above) nor has it received applications for or issued any final documents for an SMR site or COL, which is the second stage of licensing required for specific installation sites. As a result, actual costs can be estimated, but specific costs are unknown.

The reference or first combined license application<sup>132</sup> is estimated to cost \$40 million in NRC fees and take three and a half years.<sup>133</sup> For the larger SMR units, the combined construction and operating-license (COL) costs per installed kilowatt (kWe) potentially decreases, improving the economy of scale for larger units.

Costs for deployments after the first-of-a-kind unit will be limited to the combined COL and site licensing. The combined licensing cost for subsequent units is estimated to include \$12 million for NRC review fees and takes two and a half years.<sup>134</sup>

We estimate the total combined COL costs per applicant at \$50–\$70 million for the nth-of-a-kind unit. If multiple units were permitted for a given site or set of sites, but added incrementally as the load increased, COL costs per unit and per kilowatt-hour would decline with each additional unit. Worldwide, this modularity is potentially one of the most attractive features of SMR technology over conventional nuclear technology. At the same time, it would take a commitment to SMR technology to obtain the economies of scale mass-production offers by modularity that reduces licensing costs per kilowatt-hour.

### 5.1.2 Overnight Costs

The “overnight cost”<sup>135</sup> for the power facility is assumed to range from \$45–\$1,000 million, or \$4,500 and \$8,000 per installed kWe (see Table 1). In comparison, the Energy Information Administration (EIA) estimates the per-installed kWe cost for current designs of light water reactors in the Lower 48 at \$5,339.<sup>136</sup> We have inflated this cost estimate by 30% to reflect construction costs in Alaska, which results in \$6,940 per installed kWe.<sup>137</sup> Even though the EIA estimate relates to custom-designed nuclear power plants and is not strictly comparable with the serial construction of SMRs, it serves as the only benchmark for comparison. Important to note is

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<sup>132</sup> The combined license application includes: Part 0 Cover Letter, Affidavits; Part 1 Administrative and Financial Information; Part 2 Final Safety Analysis Report (FSAR); Part 3 Environmental Report; Part 4 Technical Specifications; Part 5 Emergency Plan; Part 6 Limited Work Authorization; Part 7 Departures and Exemption Requests; Part 8 Safeguards/Security Plans; Part 9 Sensitive Information; Part 10 ITAAC; Part 11 Enclosures. See the licensing section for more details.

<sup>133</sup> Reckley, William, December 9, 2010.

<sup>134</sup> Ibid.

<sup>135</sup> Philip O. Moor, P.E., High Bridge Associates, personal communication, December 1, 2010. Overnight cost is the cost of a construction project if no interest was incurred during construction, as if the project was completed “overnight.” An alternate definition is the present value cost that would have to be paid as a lump sum up front to completely pay for a construction project. This term is commonly used in power plant construction estimates.

<sup>136</sup> EIA, Updated Capital Cost Estimates for Electricity Generation Plants, November 2010. Note, EIA’s estimates include permitting costs as part of overnight costs, whereas we state them separately.

<sup>137</sup> Alaska Department of Labor and Workforce Development, Alaska Economic Trends, May 2011. Note, due to lack of a construction cost differential, we use the ACCRA Cost-of-Living Index for Anchorage, which equals 128.3, and for Fairbanks 137.3. The Military COLA for Anchorage equals 126, and for Fairbanks 128. Thus, we inflate the Lower 48 construction estimates by 30%.

that we assume in these cost scenarios that the SMRs deployed in Alaska would be nth-of-a-kind units that have seen significant “learning-by-doing” from prior installations in other locations.

### 5.1.3 Nuclear Fuel Costs

Due to the early development stage of new technologies, the use of more highly enriched fuels in reactors, and the potential applicability of fuel recycling, there are considerable uncertainties regarding nuclear fuel costs.<sup>138</sup> Other than LWRs, reactors referred to as “advanced reactors” or “Generation IV reactors” are expected to have higher fuel costs. But how much higher is uncertain? Six advanced reactor designs are currently under development, including sodium fast reactors (such as the Toshiba 4S), lead-cooled fast reactors (such as Hyperion), and high-temperature gas-cooled reactors (such as the NNGP Reactor).<sup>139</sup> The high-temperature gas-cooled reactor fuel requires additional fabrication costs because of its low power density and novel fuel design.<sup>140</sup> The sodium- and lead-cooled fast-reactor designs use fuel with higher U-235 enrichment, which is higher in cost than fuel for LWRs.

Only two of the SMR developers, Hyperion and NuScale, have presented information on the expected fuel costs of their units. We based the low-cost scenarios on industry expertise and fuel-cost estimates presented by SMR developers. For the Toshiba and mPower units, we relied on independent industry expertise.<sup>141</sup> For all units, we bracketed nuclear fuel prices into low, medium, and high cost estimates, applying levelized per kilowatt-hour fueling costs. The medium-cost scenario was assumed to be 50% higher than the low-cost scenario, and the high-cost scenario, twice that of the low-cost scenario.

For the Toshiba 4S small and large reactors, the cost of one fueling cycle was estimated at approximately \$65 and \$100 million, respectively (low cost). After outlining the refueling schedule, we calculated the levelized per-kilowatt-hour fueling cost and applied it to the low-cost scenario for the Toshiba reactors. Then we adjusted accordingly to calculate the medium- and high-cost scenarios.

Table 1 shows levelized nuclear fuel cost ranging from \$0.005 to \$0.013 per kWh for light-water SMR units and from \$0.051 to \$0.115 per kWh for advanced reactors. Estimates for light-water SMR reactors are comparable to fuel costs of approximately \$0.005 per kWh for large currently operating LWR power plants in the U.S. and are not a serious discriminator compared with fossil fuel alternatives.

### 5.1.4 Nuclear Operations and Security Staff

A reasonable number of operations personnel are required for efficiency and safety, but it is not known how many security personnel may be required. A detailed assessment of safety and security

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<sup>138</sup> Shropshire, D.E., K.A. Williams, J.D. Smith, B.W. Dixon, M. Dunzik-Gougar, R.D. Adams, D. Gombert, J.T. Carter, E. Schneider, and D. Hebditch, *Advanced Fuel Cycle Cost Basis*, Rev. 2, December 2009, Idaho National Laboratory, Prepared for the U.S. Department of Energy, Office of Nuclear Energy, Contract DE-AC07-05ID14517, INL/EXT-07-12107, 750 pages. [www.inl.gov](http://www.inl.gov).

<sup>139</sup> Thomas, Steve, 2009, PBMR: Hot or not? *Nuclear Engineering International*, 01 April. The analysis does not include the Pebble Bed reactor because it is not considered a viable technology by the DOE.

<sup>140</sup> Ibid.

<sup>141</sup> Hyperion fuel prices are from a presentation by Hyperion representatives to GVEA, August 2010. NuScale fuel prices are from [www.nuscale.com](http://www.nuscale.com). Philip O. Moor, P.E, Vice President, High Bridge Associates, provided the estimate for the mPower and Toshiba reactors.

risk, required by the NRC licensing process, will determine the necessary staffing levels.<sup>142</sup> For our analysis, we assumed 8 security staff and 35 operations staff to cover 5 shifts with 7 operators per shift. Annual salaries per position range from \$60,000 for security staff to \$99,500 for operations staff.<sup>143</sup>

### **5.1.5 Other Nuclear Cost Assumptions**

Small modular reactor units have an estimated availability of over 90%. This availability varies by SMR unit, however, depending on the fuel cycle and how often the unit must be pulled off-line for refueling. In the case of Fairbanks and rural hubs, we include backup diesel; in the case of Anchorage, natural gas generation costs to cover SMR refueling unavailability. A \$0.005 per kWh decommissioning fee is included, based on the industry standard for large nuclear power facilities and on experience with DOE facility decommissioning. An operations and maintenance (O&M) charge of \$0.015 is assumed to cover a SMR staff simulator and other training, parts, and operations costs in addition to labor. These costs are relatively small as compared with the cost of the power station and regulatory review. Utility distribution and administration costs of \$0.04 per kWh for the Railbelt and \$700,000 annually for rural utilities are also added. We have not included load upgrade costs that would be borne by the owner, depending on the state of the electricity load and wiring.<sup>144</sup> We included a 15% return on investment for the developer/owner/operator, who we assumed is an independent power producer that specializes in nuclear development. If the ownership structure or financing were to include state or federal ownership or assistance, this return on investment could decrease accordingly. This information is shown in Table 2. For the medium SMR and fuel cost base-case scenario, we assumed zero population growth.

### **5.1.6 Diesel and Natural Gas Generation Assumptions**

Table 2 shows assumptions for diesel generation, which includes an assumed capital cost of \$2,575 per installed kW<sub>e</sub> in rural Alaska. Diesel generator fuel efficiency is from Alaska Power Cost Equalization data for the specific utility, if applicable. Operations and maintenance costs for rural utilities are assumed to be \$0.02 for fuel and \$0.06 for non-fuel. For the Railbelt, avoided costs for natural gas and diesel generation are assumed to be those used by Chugach Electric Association and Golden Valley Electric Association. Those avoided costs are provided by the Alaska Energy Authority, and are used for economic review of Renewable Energy Fund grant applications.

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<sup>142</sup> <http://www.nrc.gov/reading-rm/doc-collections/commission/speeches/2010/s-10-021.html>.

<sup>143</sup> Bureau of Labor Statistics (2009), Nuclear Plant Operator hourly wage of \$35.95 and Security Level 7 hourly wage of \$21.69. We assumed employee benefits and an Alaska cost premium that amount to 33% total.

<sup>144</sup> Goldberg, Stephen, Special Assistant to the Director, Argonne National Laboratory, January 20, 2011.

Table 2. Additional Nuclear and Diesel Modeling Cost Parameters

| <b>Nuclear</b>  |  |                    |                   |
|---|--|--------------------|-------------------|
| <b>Capacity</b>   |  |                    |                   |
|   | Availability (approx. – varies w/fuel cycle) | <b>90+%</b>        | annually          |
| <b>Decommissioning cost</b>                                       |  | <b>0.005</b>       | per kWh           |
| <b>Labor cost (employee compensation)</b>                         |  |                    |                   |
|   | Security staff (8, annual salary)            | <b>\$60,000</b>    | each, annually    |
|   | Operator staff (35, annual salary)           | <b>\$99,500</b>    | each, annually    |
|   | Total labor cost                             | <b>\$3,960,850</b> | annually          |
| <b>O&amp;M – parts, training, simulator, in addition to labor</b> |  | <b>0.015</b>       | per kWh           |
| <b>Distribution and admin</b>                                     |  |                    |                   |
|   | Railbelt                                     | <b>0.04</b>        | per kWh           |
|   | Village/hub                                  | <b>700,000</b>     | annually          |
| <b>Annual return to owner/operator</b>                            |  | <b>15%</b>         |                   |
| <b>Diesel</b>   |  |                    |                   |
| <b>Fuel efficiency (PCE data)</b>                                 |  |                    | kWh generated/gal |
| <b>Capital cost</b>   |  | <b>\$2,575</b>     | per installed kW  |
| <b>O&amp;M</b>  |  |                    |                   |
|   | Fuel   | <b>0.02</b>        | per kWh           |
|   | Non-fuel                                     | <b>0.06</b>        | per kWh           |
|   | Total  | <b>0.08</b>        | per kWh           |

Sources: Alaska Energy Authority data and David Lockard, AEA, for diesel generation data; Chaney et al., 2004; Phillip Moor, P.E., Vice President, High Bridge Associates, December 2010.

### 5.1.7 Crude Oil, Natural Gas, and Diesel Prices

In rural hubs, the primary fuel displaced was assumed to be diesel. In the Railbelt, the modeled SMR cost comparisons assumed avoided costs of natural gas in the southern Railbelt and of diesel north of the Alaska Range. Table 2 provides information on additional modeling assumptions.

Fuel prices used in the model are based on U.S. Department of Energy, Energy Information Administration (EIA), *Energy Outlook 2010* forecasts for crude oil and natural gas. Sensitivity analysis was conducted for low-, medium-, and high-price forecasts for crude oil and natural gas (Figure 11 and Figure 12). Price forecasts for community fuel were statistically estimated from refinery rack prices and EIA forecasts using Alaska Power Cost Equalization fuel price data.<sup>145</sup> We

<sup>145</sup> Fay, Ginny, Ben Saylor, and Tobias Schwörer, 2011, *Alaska Fuel Price Projections 2011-2030*, University of Alaska Anchorage, Institute of Social and Economic Research, prepared for the Alaska Energy Authority, January 25, 2011, ISER Working Paper 2011.1.

Fay, Ginny, Ben Saylor, and Nick Szymoniak, 2010, *Alaska Fuel Price Projections 2009-2030*, University of Alaska Anchorage, Institute of Social and Economic Research, prepared for the Alaska Energy Authority, November 12, 2009, revised January 13, 2010, ISER Working Paper 2009.3.

Szymoniak, Nick, Ginny Fay, Alejandra Villalobos-Melendez, Justine Charon, and Mark Smith, 2010, *Components of Alaska Fuel Costs: An Analysis of the Market Factors and Characteristics that Influence Rural Fuel Prices*. University of Alaska Anchorage, Institute of Social and Economic Research. Prepared for the Alaska State Legislature, Senate Finance Committee, 78 pages.

Available from: <http://www.iser.uaa.alaska.edu/Home/pubs.html>

addressed variation in diesel fuel prices by applying Monte Carlo simulations around the general trend in the EIA crude oil price-forecast scenarios to test the robustness of our results.<sup>146</sup>

An adjustment was made to previous Cook Inlet natural gas price forecasts made by the Institute of Social and Economic Research (ISER) that assumed a continued relationship with EIA Henry Hub natural gas price forecasts. Natural gas prices in Southcentral Alaska recently tracked 90% of the Henry Hub price. However, given the abundance of natural gas supplies in the Lower 48 markets and limited markets and supplies in Southcentral Alaska, we allowed the gap to close (2015) and then surpass Henry Hub prices by 10% (2021–2030) over the course of the 30-year forecast. This same adjustment was made to the low, mid, and high EIA natural gas forecasts. Compared with the Railbelt natural gas forecast conducted by Black & Veatch for the Alaska Railbelt Integrated Resources Plan (RIRP) study, the ISER estimates are lower (Figure 12).<sup>147</sup> In the sensitivity analysis, we tested both the ISER EIA-derived and the RIRP natural gas forecasts.

### Crude Oil Price Forecasts 2011-2030

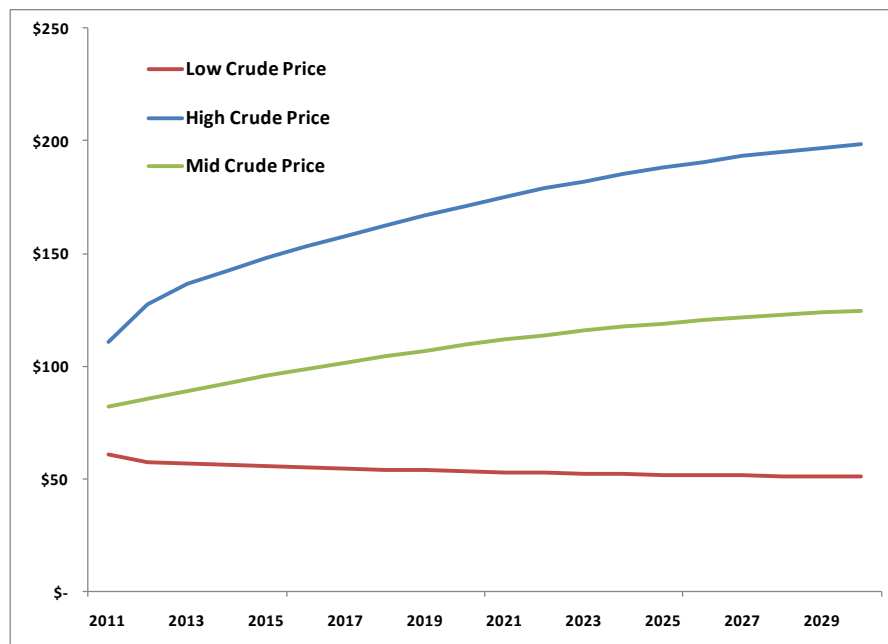


Figure 11. Crude oil price forecasts, 2011–2030 (2010\$ per barrel).<sup>148</sup>

<sup>146</sup> We simulated this variation in oil prices with Palisade Corporation's @Risk software by applying a normal distribution to the general trend in the EIA forecast. This approach tested 100 additional prices for each price given in the EIA forecast.

<sup>147</sup> Black & Veatch, 2010, *Alaska Railbelt Regional Integrated Resource Plan (RIRP) Study*, Part 2, Section 7, Page 9, Table 2.

<sup>148</sup> U.S. Department of Energy, Energy Information Administration, *Energy Outlook 2010*.

## Natural Gas Price Forecasts 2011-2030

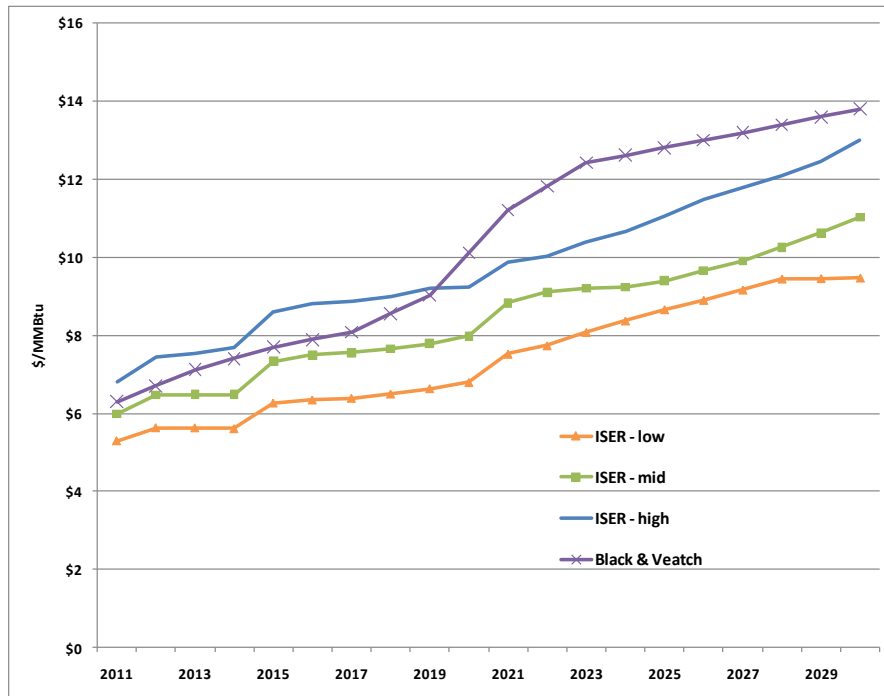


Figure 12. Natural gas price forecasts, 2011–2030 (2010\$ per MMBtu).<sup>149</sup>

### 5.1.8 Carbon Emission Prices

Given that SMR technology will not be available within the next five to ten years, some type of carbon-pricing mechanism is likely to be in place. The ISER developed carbon price forecasts based on estimates by the Massachusetts Institute of Technology (MIT).<sup>150</sup> These carbon prices were not added to the crude oil, natural gas, and diesel fuel prices in the low, medium, and high base cases, but a fourth medium-case sensitivity analysis included a carbon price of \$15.20 per metric ton of carbon dioxide (CO<sub>2</sub>), increasing at 10% annually starting in 2011 (Figure 13, Table 3). The RIRP natural gas price forecast does not include carbon prices. As with all the other parameters, these assumptions can be easily modified. For more details on fuel and carbon price methodologies, see ISER fuel price forecast publications.<sup>151</sup>

<sup>149</sup> ISER estimates based on DOE Energy Information Service, *Energy Outlook 2010*; Black & Veatch for Alaska Energy Authority: RIRP Study, 2010

<sup>150</sup> Massachusetts Institute of Technology, 2007, *Future of Coal: Options in a Carbon-Constrained World*, Summary Report. Massachusetts Institute of Technology, 2009, *Update of the Future of the Nuclear Power*. Intergovernmental Panel on Climate Change. *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3, Pg. 6.28, (Paris France 1997). U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1998*, EPA 236-R-00-001, Washington, DC, April 2000.

<sup>151</sup> Fay, Ginny, Ben Saylor, and Nick Szymoniak, 2010, *Alaska Fuel Price Projections 2009–2030*, University of Alaska Anchorage, Institute of Social and Economic Research, prepared for the Alaska Energy Authority, November 12, 2009, revised January 13, 2010, ISER Working Paper 2009.3.

Szymoniak, Nick, Ginny Fay, Alejandra Villalobos-Melendez, Justine Charon, and Mark Smith, 2010, *Components of Alaska Fuel Costs: An Analysis of the Market Factors and Characteristics that Influence Rural Fuel Prices*. University of Alaska Anchorage, Institute of Social and Economic Research. Prepared for the Alaska State Legislature, Senate Finance Committee, 78 pages. Available from: <http://www.iser.uaa.alaska.edu/Home/pubs.html>



## Carbon Price Forecast 2010

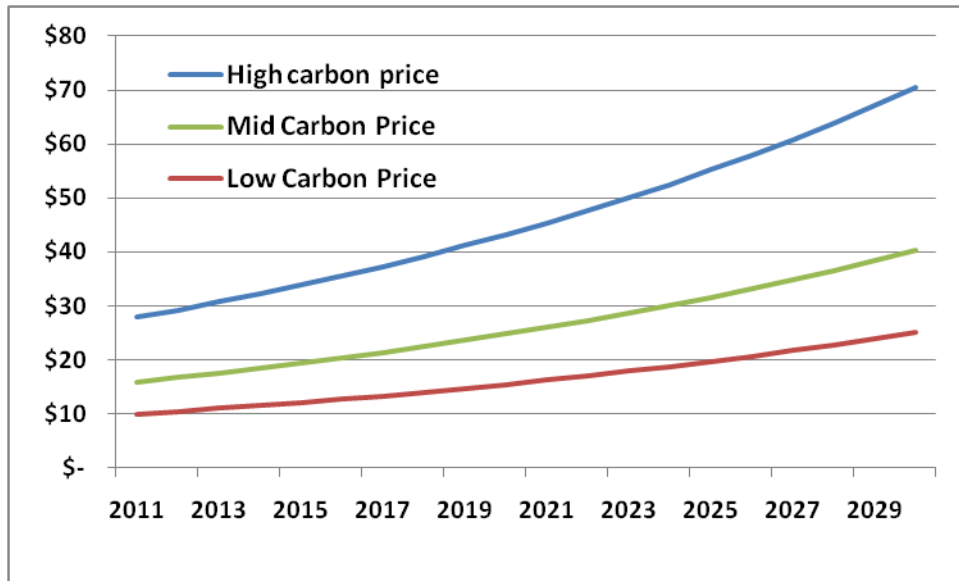


Figure 13. Carbon price forecast (2010\$ per ton).

Table 3. Carbon Dioxide (CO<sub>2</sub>) Price Assumptions

|        |                        | Annual   |            |
|--------|------------------------|----------|------------|
|        | \$/ton CO <sub>2</sub> | Increase | Start Year |
| Low    | \$9.50                 | 5%       | 2010       |
| Medium | \$15.20                | 5%       | 2010       |
| High   | \$33.90                | 5%       | 2010       |

Source: MIT Future of Coal Study and ISER assumptions

### 5.1.9 District and Electric Space Heating

The economic screening model uses thermal output from the reactor for district heat distributed via utilidor and uses excess electric output for residential electric space heating.

The thermal capacity of SMR units is approximately three times that of their electric generation capacity (Table 1).<sup>152</sup> This heat is both a valuable resource and a product that must be dissipated for safety and efficiency. The prospective tariff for district heat is assumed at 75% of the avoided cost, because the utility is unlikely to sell this heat at 100% of its avoided cost, splitting the savings between the utility and the space-heat customer.

For the Railbelt, we assumed that thermal output is used in the Eielson AFB district heating system and has a value of approximately \$5/MMBtu (million British thermal units), based on the cost of

<sup>152</sup> Philip O. Moor, P.E., High Bridge Associates, personal communication, January 21, 2011.

heat in the current Eielson AFB system.<sup>153</sup> District heat at Eielson AFB is distributed via approximately 27 miles of utilidors (steam distribution, condensate return, potable and firefighting water, and sewer piping), utilizing one billion pounds of steam annually from electric generation steam turbines at reduced pressure (100 psi), and input to the steam distribution for heating the base facilities.<sup>154</sup> We assumed no capital costs, because the system is already in place. Due to a lack of existing utilidors in other parts of the Railbelt, our analysis models heat sales predominantly for Eielson AFB.

In village hubs, we assumed a capital cost of \$200 per foot to construct a district heating system that is a minimum of two miles from the village public buildings.<sup>155</sup> Based on fuel oil consumption data recently collected by Schwörer, we assume the annual fuel oil consumption for public buildings to equal about 41,000 gallons/year.<sup>156</sup> This consumption includes heat for a school, city building, fire building, safety building, washeteria, and church, for a village with about 400 inhabitants. Since this consumption rate is applied to the larger hub communities, where more fuel oil would likely be displaced, we find this assumption to be conservative.

Residential electric space heating was assumed to occur once heating costs using conventional technology exceed electric heating costs.<sup>157</sup> Capital costs of residential electric space heating for homes not adjacent to district heating lines include approximately \$3,600 per household for residents and \$947,200 for utilities to upgrade electric distribution lines for electric heat.<sup>158</sup>

## 5.2 Results

The economic screening model calculates outcomes dependent on low, medium, and high parameter values for crude oil, natural gas, SMR overnight capital costs, nuclear fueling cost, and licensing costs. This set of parameter values creates 125 unique variations. In addition, we have included a carbon price scenario based on ISER's mid-range forecast represented by the green curve in Figure 13. Carbon price forecast (2010\$ per ton). and a natural gas price scenario based on a forecast conducted by Black & Veatch for the Railbelt Integrated Resources Plan (RIRP) (see Black & Veatch in Figure 12).

In the following section, we first present results for all study communities and the five selected reactor designs (Table 4 through Table 7). The results include the calculated nuclear electric rate in dollars per kilowatt-hour, potential annual household energy cost savings, and the year in which savings would first occur based on the EIA energy outlook. It is important to note that the nuclear electric rates shown in Tables 4 through 7 are based on assumptions stated in Table 2 and cover the full cost of power. Note also that this calculation does not account for the Power Cost Equalization subsidy to eligible communities. Tables 4 through 7 show the average expected annual energy cost savings, assuming monthly electricity consumption of 700 kWh per household and annual space-

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<sup>153</sup> Joe Weathersby, Chief of Asset Optimization, Eielson AFB, personal communication, January 5, 2011.

<sup>154</sup> Lee, Mike, Deputy Base Civil Engineer, *Eielson Air Force Base Energy Challenges & Energy Opportunities* presentation, no date.

<sup>155</sup> Alaska Energy Engineering, Inc., 2010, *Hoonah diesel heat recovery system*, prepared for the Alaska Energy Authority, November 16, 2010. This estimate is consistent with Chaney et al. (2004) Galena Electric Power: A Situational Analysis.

<sup>156</sup> Schwörer, T., 2010, Norton Sound End Use Data Collection Field Trip. Institute of Social and Economic Research. Note, the average household consumes 900 gallons of fuel oil and four cords of wood per year.

<sup>157</sup> Based on recent end-use data collected by ISER, we assume space-heating requirements of 91 and 221 MMBtu per household annually for rural and Railbelt residents, respectively.

<sup>158</sup> Chaney et al., 2004, Galena Electric Power: A Situational Analysis. Estimate adjusted to 2010\$.

heating needs of 91 MMBtu for rural and 227 MMBtu for Railbelt households.<sup>159</sup> The year in which each unit would begin to show household savings is included.

Due to the large number of possible scenarios, we bracket the sensitivity analysis to include the following five scenarios:

1. BASE CASE: mid-range assumptions for all parameters
2. LOW CASE: low-range assumptions for all parameters
3. HIGH CASE: high-range assumptions for all parameters
4. NUCLEAR CASE: most-favorable assumptions for SMR (high crude oil and natural gas prices, low capital, fueling, and permitting costs)
5. CARBON CASE: mid-range assumptions for all parameters plus mid-range CO<sub>2</sub> prices
6. RIRP CASE: assuming natural gas price forecast for the Railbelt conducted by Black & Veatch

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<sup>159</sup> ENSTAR Natural Gas Company forecast for 2011: 32.7Bcf for 130000 customers equals 251 mcf.  
Schwörer, T., 2010, Norton Sound End Use Data Collection Field Trip. Institute of Social and Economic Research.

Table 4 is our base-case scenario, with medium SMR costs and medium EIA forecasts. Only Fairbanks would realize energy cost savings ranging between \$70 and \$470 per household per year. The mPower and the NuScale units would become feasible as soon as they are expected to be available, in 2020, given that crude prices exceed \$96 per barrel. The Hyperion and Toshiba 4S large reactors would be viable in 2025 and 2027, respectively, at crude prices exceeding \$100 per barrel.

Table 4. Base-Case Results by Community and by Reactor<sup>160</sup>

| Nuclear rates - levelized [\$/kWh] |           |        |            |           |         |          |        |        |        |          |
|------------------------------------|-----------|--------|------------|-----------|---------|----------|--------|--------|--------|----------|
|                                    | Anchorage | Bethel | Dillingham | Fairbanks | Galena  | Kotzebue | Naknek | Nome   | Tok    | Unalaska |
| mPower                             | \$0.13    | \$2.34 | \$5.22     | \$0.13    | \$12.98 | \$4.37   | \$4.65 | \$3.21 | \$8.58 | \$2.74   |
| NuScale                            | \$0.16    | \$1.16 | \$2.46     | \$0.15    | \$6.02  | \$2.09   | \$2.18 | \$1.54 | \$4.01 | \$1.32   |
| Hyperion                           | \$0.17    | \$0.73 | \$1.55     | \$0.15    | \$3.77  | \$1.31   | \$1.37 | \$0.97 | \$2.52 | \$0.83   |
| Toshiba 4S large                   | \$0.19    | \$1.58 | \$3.51     | \$0.18    | \$8.72  | \$2.94   | \$3.13 | \$2.16 | \$5.77 | \$1.85   |
| Toshiba 4S small                   | \$0.31    | \$0.62 | \$1.34     | \$0.26    | \$3.26  | \$1.13   | \$1.19 | \$0.84 | \$2.18 | \$0.72   |

| Annual energy cost savings - levelized [\$/household] |           |        |            |           |        |          |        |      |     |          |
|---|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
|   | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
| mPower  |           |        |            | \$470     |        |          |        |      |     |          |
| NuScale   |           |        |            | \$370     |        |          |        |      |     |          |
| Hyperion  |           |        |            | \$330     |        |          |        |      |     |          |
| Toshiba 4S large                                      |           |        |            | \$70      |        |          |        |      |     |          |
| Toshiba 4S small                                      |           |        |            |           |        |          |        |      |     |          |

| First year in which energy cost savings can be expected |           |        |            |           |        |          |        |      |     |          |
|---|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
|   | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
| mPower  |           |        |            | 2020      |        |          |        |      |     |          |
| NuScale   |           |        |            | 2020      |        |          |        |      |     |          |
| Hyperion  |           |        |            | 2025      |        |          |        |      |     |          |
| Toshiba 4S large  |           |        |            | 2027      |        |          |        |      |     |          |
| Toshiba 4S small  |           |        |            |           |        |          |        |      |     |          |

<sup>160</sup> Assumptions: mid crude, natural gas; medium capital, refueling and licensing costs

Table 5 shows that under low EIA forecasts of crude prices below \$50 per barrel but most-favorable (lowest) assumed SMR costs, SMRs would not result in cost savings for any of the communities analyzed in this study.

Table 5. Low-Case Results by Community and by Reactor<sup>161</sup>

Nuclear rates - levelized [\$/kWh]

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena  | Kotzebue | Naknek | Nome   | Tok    | Unalaska |
|------------------|-----------|--------|------------|-----------|---------|----------|--------|--------|--------|----------|
| mPower           | \$0.12    | \$1.93 | \$4.35     | \$0.12    | \$10.86 | \$3.63   | \$3.89 | \$2.67 | \$7.16 | \$2.27   |
| NuScale          | \$0.14    | \$0.95 | \$2.07     | \$0.13    | \$5.13  | \$1.74   | \$1.85 | \$1.28 | \$3.39 | \$1.10   |
| Hyperion         | \$0.15    | \$0.62 | \$1.33     | \$0.13    | \$3.27  | \$1.12   | \$1.19 | \$0.83 | \$2.17 | \$0.71   |
| Toshiba 4S large | \$0.16    | \$1.25 | \$2.79     | \$0.15    | \$6.92  | \$2.33   | \$2.49 | \$1.71 | \$4.57 | \$1.46   |
| Toshiba 4S small | \$0.26    | \$0.51 | \$1.10     | \$0.21    | \$2.69  | \$0.93   | \$0.98 | \$0.69 | \$1.79 | \$0.59   |

Annual energy cost savings - levelized [\$/household]

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
|------------------|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
| mPower           |           |        |            |           |        |          |        |      |     |          |
| NuScale          |           |        |            |           |        |          |        |      |     |          |
| Hyperion         |           |        |            |           |        |          |        |      |     |          |
| Toshiba 4S large |           |        |            |           |        |          |        |      |     |          |
| Toshiba 4S small |           |        |            |           |        |          |        |      |     |          |

First year in which energy cost savings can be expected

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
|------------------|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
| mPower           |           |        |            |           |        |          |        |      |     |          |
| NuScale          |           |        |            |           |        |          |        |      |     |          |
| Hyperion         |           |        |            |           |        |          |        |      |     |          |
| Toshiba 4S large |           |        |            |           |        |          |        |      |     |          |
| Toshiba 4S small |           |        |            |           |        |          |        |      |     |          |

<sup>161</sup> Assumptions: low crude, natural gas; low capital, refueling and licensing costs

Table 6 illustrates our results under high EIA forecast and least-favorable (highest) SMR costs. We estimate annual energy cost savings per household in Fairbanks, ranging between \$40 and \$1,530. Interesting to note is that, under this scenario, all SMRs modeled except the Toshiba 4S small unit become viable as soon as they are commercially available.

Table 6. High-Case Results by Community and by Reactor<sup>162</sup>

Nuclear rates - levelized [\$/kWh]

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena  | Kotzebue | Naknek | Nome   | Tok     | Unalaska |
|------------------|-----------|--------|------------|-----------|---------|----------|--------|--------|---------|----------|
| mPower           | \$0.15    | \$2.82 | \$6.29     | \$0.15    | \$15.63 | \$5.27   | \$5.60 | \$3.86 | \$10.34 | \$3.30   |
| NuScale          | \$0.18    | \$1.38 | \$2.91     | \$0.17    | \$7.09  | \$2.48   | \$2.57 | \$1.82 | \$4.74  | \$1.56   |
| Hyperion         | \$0.19    | \$0.85 | \$1.80     | \$0.17    | \$4.37  | \$1.52   | \$1.59 | \$1.13 | \$2.92  | \$0.97   |
| Toshiba 4S large | \$0.23    | \$2.04 | \$4.54     | \$0.22    | \$11.27 | \$3.80   | \$4.04 | \$2.79 | \$7.45  | \$2.38   |
| Toshiba 4S smal  | \$0.38    | \$0.76 | \$1.66     | \$0.33    | \$4.06  | \$1.40   | \$1.48 | \$1.04 | \$2.71  | \$0.89   |

Annual energy cost savings - levelized [\$/household]

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
|------------------|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
| mPower           |           |        |            | \$1,530   |        |          |        |      |     |          |
| NuScale          |           |        |            | \$1,410   |        |          |        |      |     |          |
| Hyperion         |           |        |            | \$1,360   |        |          |        |      |     |          |
| Toshiba 4S large |           |        |            | \$910     |        |          |        |      |     |          |
| Toshiba 4S smal  |           |        |            | \$40      |        |          |        |      |     |          |

First year in which energy cost savings can be expected

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
|------------------|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
| mPower           |           |        |            | 2020      |        |          |        |      |     |          |
| NuScale          |           |        |            | 2020      |        |          |        |      |     |          |
| Hyperion         |           |        |            | 2025      |        |          |        |      |     |          |
| Toshiba 4S large |           |        |            | 2025      |        |          |        |      |     |          |
| Toshiba 4S small |           |        |            | 2030      |        |          |        |      |     |          |

<sup>162</sup> Assumptions: high crude, natural gas; high capital, refueling and licensing costs

Table 7 shows the outcome of the most optimistic economic feasibility conditions of high crude oil, natural gas price forecasts, and low SMR construction, fueling, and licensing costs. In this case, annual energy savings in Fairbanks would range between \$1,020 and \$1,850 per household, whereas in Bethel they would reach \$1,780 per household.

Table 7. Nuclear-Case Results by Community and by Reactor<sup>163</sup>

Nuclear rates - levelized [\$/kWh]

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena  | Kotzebue | Naknek | Nome   | Tok    | Unalaska |
|------------------|-----------|--------|------------|-----------|---------|----------|--------|--------|--------|----------|
| mPower           | \$0.12    | \$1.96 | \$4.37     | \$0.11    | \$10.86 | \$3.66   | \$3.90 | \$2.69 | \$7.18 | \$2.30   |
| NuScale          | \$0.14    | \$0.98 | \$2.10     | \$0.13    | \$5.13  | \$1.77   | \$1.86 | \$1.31 | \$3.42 | \$1.12   |
| Hyperion         | \$0.15    | \$0.63 | \$1.35     | \$0.14    | \$3.27  | \$1.14   | \$1.20 | \$0.85 | \$2.18 | \$0.73   |
| Toshiba 4S large | \$0.16    | \$1.27 | \$2.80     | \$0.15    | \$6.92  | \$2.35   | \$2.50 | \$1.73 | \$4.59 | \$1.48   |
| Toshiba 4S small | \$0.26    | \$0.52 | \$1.11     | \$0.21    | \$2.68  | \$0.94   | \$0.99 | \$0.70 | \$1.80 | \$0.61   |

Annual energy cost savings - levelized [\$/household]

|                  | Anchorage | Bethel  | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
|------------------|-----------|---------|------------|-----------|--------|----------|--------|------|-----|----------|
| mPower           |           |         |            | \$1,850   |        |          |        |      |     |          |
| NuScale          |           |         |            | \$1,710   |        |          |        |      |     |          |
| Hyperion         |           | \$1,740 |            | \$1,670   |        |          |        |      |     |          |
| Toshiba 4S large |           |         |            | \$1,540   |        |          |        |      |     |          |
| Toshiba 4S small |           | \$1,780 |            | \$1,020   |        |          |        |      |     |          |

First year in which energy cost savings can be expected

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
|------------------|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
| mPower           |           |        |            | 2020      |        |          |        |      |     |          |
| NuScale          |           |        |            | 2020      |        |          |        |      |     |          |
| Hyperion         |           | 2025   |            | 2025      |        |          |        |      |     |          |
| Toshiba 4S large |           |        |            | 2025      |        |          |        |      |     |          |
| Toshiba 4S small |           | 2025   |            | 2025      |        |          |        |      |     |          |

Table 8 represents the results of the carbon price scenario, with carbon prices starting immediately at \$15.20 per metric ton and increasing 5% annually. All other assumptions are at mid values. Compared with the base case in Table 4, savings to households would increase by \$200 annually per household in Fairbanks. No other communities would realize any savings from switching to SMR technology under this carbon price scenario.

<sup>163</sup> Assumptions: high crude, natural gas; low capital, refueling and licensing costs

Table 8. Carbon-Case Results by Community and by Reactor<sup>164</sup>

Nuclear rates - levelized [\$/kWh]

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena  | Kotzebue | Naknek | Nome   | Tok    | Unalaska |
|------------------|-----------|--------|------------|-----------|---------|----------|--------|--------|--------|----------|
| mPower           | \$0.13    | \$2.34 | \$5.23     | \$0.13    | \$12.98 | \$4.37   | \$4.65 | \$3.21 | \$8.58 | \$2.74   |
| NuScale          | \$0.16    | \$1.17 | \$2.47     | \$0.15    | \$6.02  | \$2.10   | \$2.18 | \$1.55 | \$4.02 | \$1.32   |
| Hyperion         | \$0.17    | \$0.73 | \$1.55     | \$0.15    | \$3.77  | \$1.31   | \$1.38 | \$0.97 | \$2.52 | \$0.83   |
| Toshiba 4S large | \$0.19    | \$1.58 | \$3.52     | \$0.18    | \$8.72  | \$2.94   | \$3.13 | \$2.16 | \$5.77 | \$1.85   |
| Toshiba 4S small | \$0.31    | \$0.62 | \$1.34     | \$0.26    | \$3.26  | \$1.13   | \$1.19 | \$0.84 | \$2.18 | \$0.72   |

Annual energy cost savings - levelized [\$/household]

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
|------------------|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
| mPower           | \$ -      |        |            | \$700     |        |          |        |      |     |          |
| NuScale          |           |        |            | \$590     |        |          |        |      |     |          |
| Hyperion         |           |        |            | \$550     |        |          |        |      |     |          |
| Toshiba 4S large |           |        |            | \$290     |        |          |        |      |     |          |
| Toshiba 4S small |           |        |            |           |        |          |        |      |     |          |

First year in which energy cost savings can be expected

|                  | Anchorage | Bethel | Dillingham | Fairbanks | Galena | Kotzebue | Naknek | Nome | Tok | Unalaska |
|------------------|-----------|--------|------------|-----------|--------|----------|--------|------|-----|----------|
| mPower           |           |        |            | 2020      |        |          |        |      |     |          |
| NuScale          |           |        |            | 2020      |        |          |        |      |     |          |
| Hyperion         |           |        |            | 2025      |        |          |        |      |     |          |
| Toshiba 4S large |           |        |            | 2025      |        |          |        |      |     |          |
| Toshiba 4S small |           |        |            | 2054      |        |          |        |      |     |          |

SMRs are not feasible in any of the selected communities, given low crude oil and natural gas prices even under low SMR capital, fuel, and permitting costs. However, under the most-favorable conditions, SMRs could become economically feasible in Bethel (Table 7) and in Fairbanks (at Eielson AFB), where almost all SMR units were viable. Economic feasibility generally began in the year in which the units were assumed to be commercially available, though fuel and carbon price forecasts and assumptions on construction, fuel, and licensing costs shift the expected kWh rates and, thus, household savings. Figure 14 shows the estimated annual household cost savings for Fairbanks for mid and high crude-price forecasts by SMR unit. Due to its size, a larger-sized reactor, like the mPower, offered better economies of scale for the Railbelt when compared with other SMRs considered in this study and, thus, results in higher household savings.

Figure 15 shows the local wholesale fuel price thresholds for SMR economic feasibility under assumed medium SMR cost scenarios in the communities modeled. For the communities that required the highest fuel prices, the size of the electric load and the ability to spread the costs of the SMR across all kWh generated and sold was a critical factor (Dillingham, Galena, Naknek, and Tok). For Bethel, the threshold price was not considerably higher than current prices, thus the almost immediate economic feasibility. A higher load in Bethel would increase economic feasibility

<sup>164</sup> Assumptions: mid crude, mid natural gas, mid CO<sub>2</sub> starting in 2015; mid capital, refueling and licensing costs



conditions. Bethel, Kotzebue, Nome, and Unalaska fuel price thresholds are conceivable under moderately higher price forecasts.

### Annual Levelized Energy Cost Savings for SMR

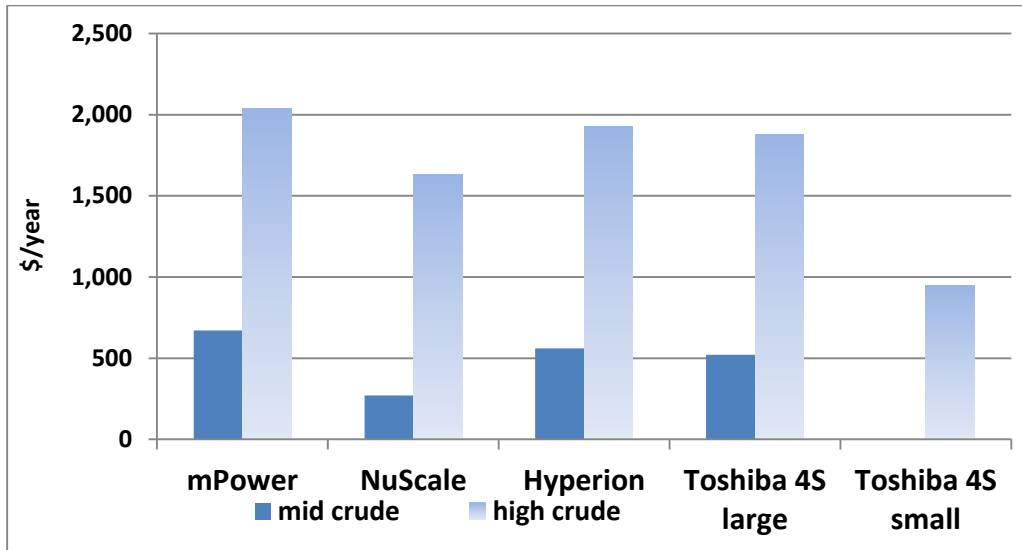


Figure 14. Annual levelized energy cost savings with SMR technology; Fairbanks, \$/household, assumes medium nuclear construction, fuel and licensing costs.

### Local Fuel Price Thresholds for SMR Feasibility

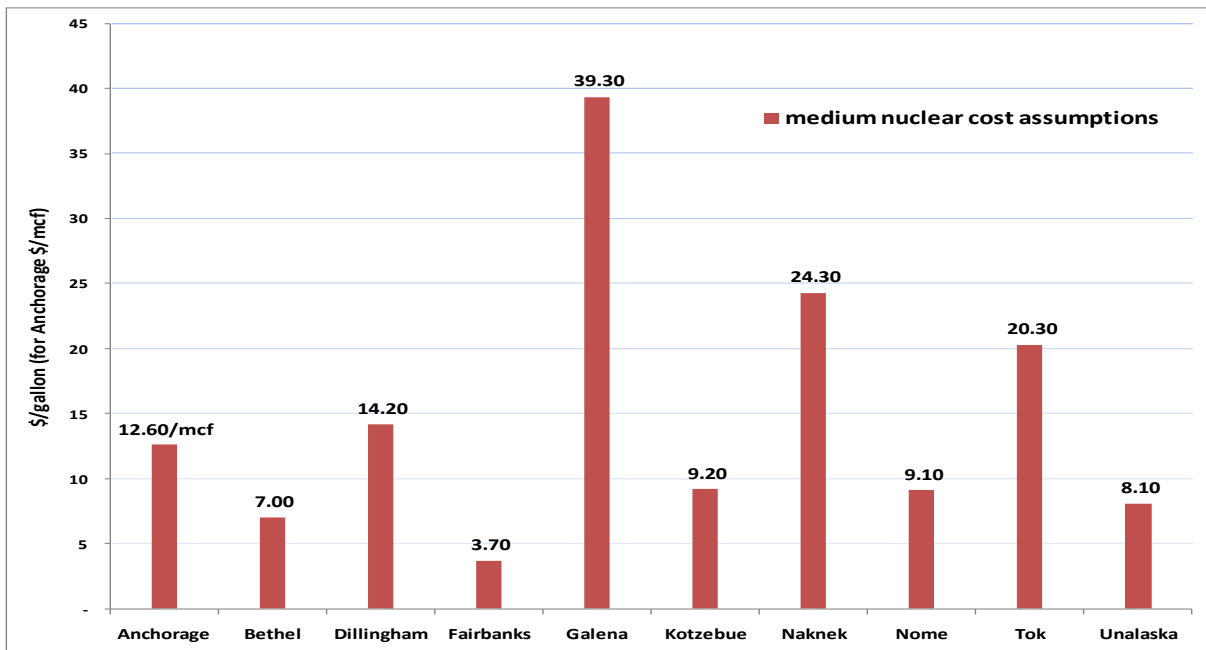


Figure 15. Approximate local fuel price thresholds for SMR economic feasibility (2010\$, per gallon of diesel or mcf).



In Figure 16, we compare current residential electric rates with estimated levelized nuclear residential rates under a medium SMR cost scenario for capital, licensing, and refueling. The only location where nuclear rates would be lower than current rates is Fairbanks, assuming steam sales to Eielson AFB. This finding suggests that in the hypothetical case that SMR technology would be immediately available and manufacturers would have experience installing SMRs in various other locations, SMRs would result in immediate energy cost savings in Fairbanks. Anchorage and Bethel show nuclear rates that are slightly higher than current rates. In all other communities, nuclear rates would be more than double the current rates.

## Comparison between Estimated SMR Rates and Current Rates

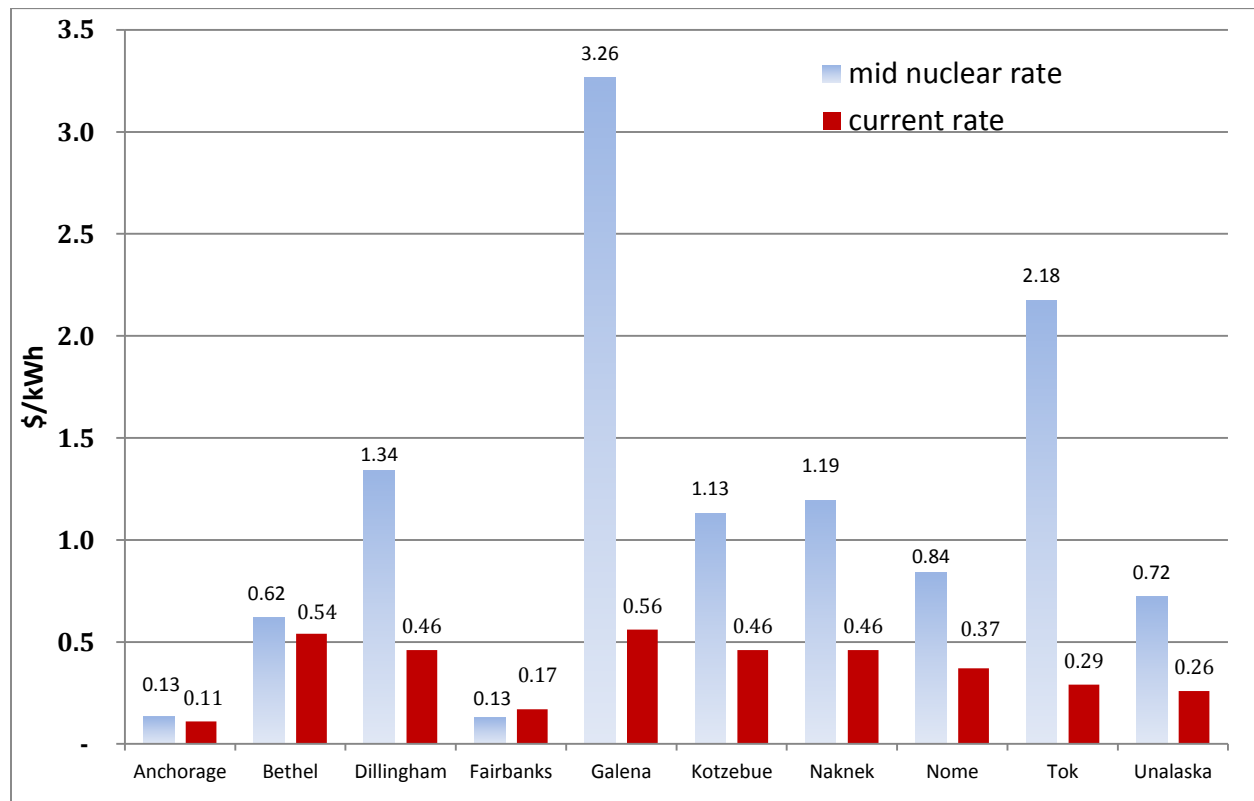


Figure 16. Comparison between SMR estimated residential electric rates and current rates.

As a point of comparison, our analysis of wholesale electric rates in Fairbanks using propane trucked from the North Slope were estimated to be \$0.14 to \$0.15 per kWh depending on the size of the containers used, with 40-foot containers yielding the lower cost as compared with 20-foot containers.<sup>165</sup>

<sup>165</sup> Schwörer, Tobias, and Ginny Fay, 2010, *Economic Feasibility of North Slope Propane Production and Distribution to Select Alaska Communities*, Final Technical Summary, prepared for the Alaska Natural Gas Development Authority June 2010.

Up to this point, we have assumed the ISER-adjusted EIA natural gas price forecast for Anchorage, which did not result in SMRs being economically feasible for displacing electric generation in Anchorage. In addition to using EIA's forecast (see ISER-mid in Figure 12), we conducted a Railbelt scenario using the RIRP natural gas price forecast, which did not include any assumed carbon costs (Black & Veatch in Figure 12). Since Black & Veatch assumed higher natural gas prices for the Railbelt compared to the ISER-adjusted EIA natural gas price forecast, under this scenario, several larger SMRs like the mPower and Hyperion would result in household savings, some of which could occur immediately after commercial release of the technology (Table 9 and Figure17).

Table 9. RIRP-Case Results for Anchorage by Reactor<sup>166, 167</sup>

**Anchorage nuclear rates - levelized [\$/kWh]**

|                         | low cost | mid cost | high cost |
|-------------------------|----------|----------|-----------|
| <b>mPower</b>           | \$ 0.12  | \$ 0.13  | \$ 0.15   |
| <b>NuScale</b>          | \$ 0.14  | \$ 0.16  | \$ 0.18   |
| <b>Hyperion</b>         | \$ 0.15  | \$ 0.17  | \$ 0.19   |
| <b>Toshiba 4S large</b> | \$ 0.16  | \$ 0.19  | \$ 0.23   |
| <b>Toshiba 4S small</b> | \$ 0.27  | \$ 0.32  | \$ 0.38   |

**Anchorage annual energy cost savings - levelized [\$/household]**

|                         | low cost | mid cost | high cost |
|-------------------------|----------|----------|-----------|
| <b>mPower</b>           | \$ 340   | \$ 230   | \$ 70     |
| <b>NuScale</b>          | \$ 160   | \$ 60    | \$ -      |
| <b>Hyperion</b>         | \$ 60    | \$ -     | \$ -      |
| <b>Toshiba 4S large</b> |          | \$ -     |           |
| <b>Toshiba 4S small</b> |          |          |           |

**Anchorage: First year in which energy cost savings can be expected**

|                         | low cost | mid cost | high cost |
|-------------------------|----------|----------|-----------|
| <b>mPower</b>           | 2021     | 2022     | 2023      |
| <b>NuScale</b>          | 2022     | 2024     | 2034      |
| <b>Hyperion</b>         | 2027     | 2033     | 2042      |
| <b>Toshiba 4S large</b> | 2039     | 2039     |           |
| <b>Toshiba 4S small</b> |          |          |           |

<sup>166</sup> Source: RIRP natural gas price forecast, 2010.

<sup>167</sup> Assumptions: Cook Inlet natural gas price forecast, no carbon

## Anchorage SMR Feasibility

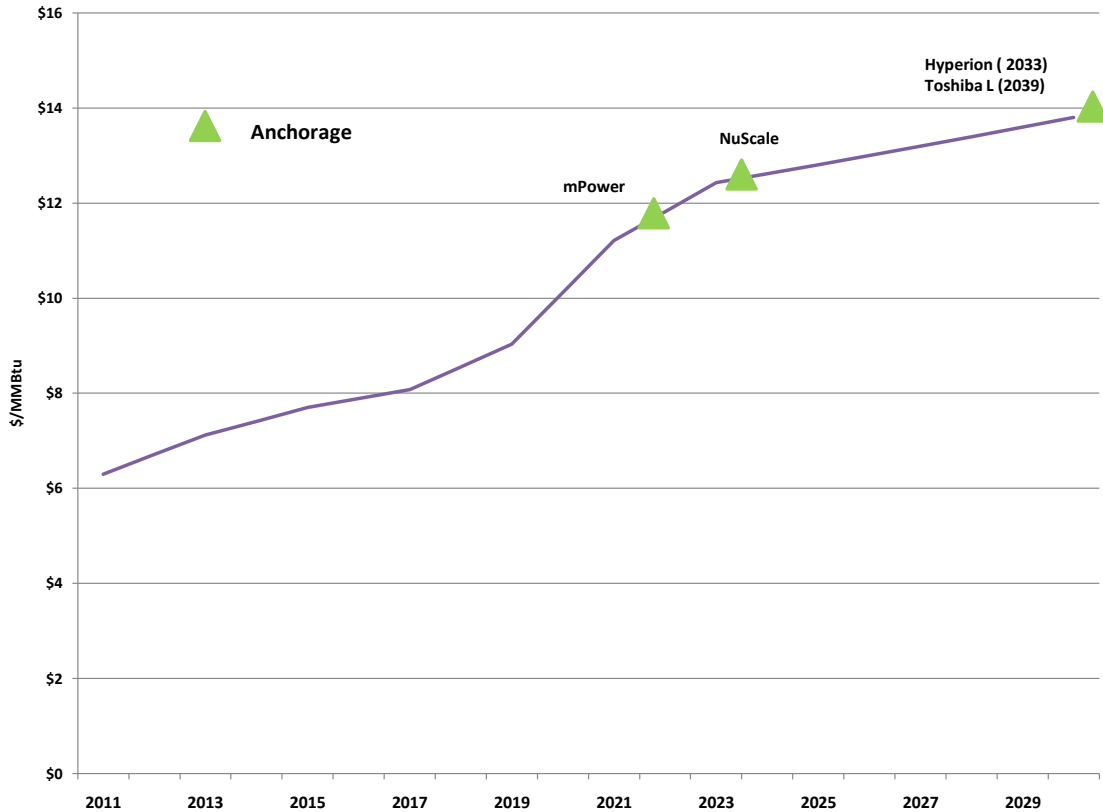


Figure 17. Anchorage SMR economic feasibility under assumptions of medium construction, fueling, and licensing costs and the Railbelt Integrated Resources Plan natural gas price forecast.

In Figure 18 through Figure 20, we take a closer look at how crude oil prices and different levels of overnight, fueling, and permitting costs affect viability of the technology in the Railbelt and in Bethel. For simplicity, we combined overnight, fueling, and permitting costs stated in Table 1 into capital cost. We then solved the model to determine crude oil prices at which SMRs become favorable, dependent on low, medium, and high levels of capital cost.

Overall, Figure 18 through Figure 20 show that higher capital costs require more costly conventional energy prices in order to make SMRs the favorable alternative. For example, in Bethel (see Figure 20), the Hyperion unit at low capital cost would become viable at a crude oil price of \$160 per barrel, whereas at high capital cost crude oil prices would need to exceed \$230 per barrel in order to generate any savings for the community. Load matching is another important factor driving economic viability. For example, the mPower with 125 MWe would already be viable at natural gas prices exceeding \$10/mcf (thousand cubic feet) in Anchorage (Figure 18) and crude oil prices exceeding \$90 per barrel in Fairbanks (Figure 19). In comparison, SMRs with smaller capacity, such as the 10 MW Toshiba unit, do not offer economies of scale for the Railbelt, thus requiring much higher energy prices. The opposite is true for a hub community like Bethel. The largest unit, the mPower, is not viable at crude oil prices below \$300 per barrel; neither are the

NuScale (45 MWe) and the Toshiba L (50 MWe). However, the Hyperion (25 MWe) and the Toshiba 4S (10 MWe) units become viable at crude oil prices exceeding \$150 per barrel with low capital cost and \$190 per barrel with medium capital cost. This result underscores the importance of load matching discussed earlier. The smallest electric capacity of any SMR is 10 MWe, which, assuming limited load-following capacity of current LWR SMR designs, is still too large for most communities in rural Alaska.

Figure 20 shows that fueling costs matter. For the Hyperion reactor, we assume refueling costs between 0.5 cent and 1 cent per kilowatt-hour. The Toshiba 4S is assumed to have fueling costs that are ten times higher than the Hyperion. The much larger range of fueling costs for the Toshiba reflects the large amount of uncertainty in the estimates. As a result, the range of crude oil prices at which the Toshiba unit becomes viable is wider (\$100) than the range for the Hyperion unit (\$60).

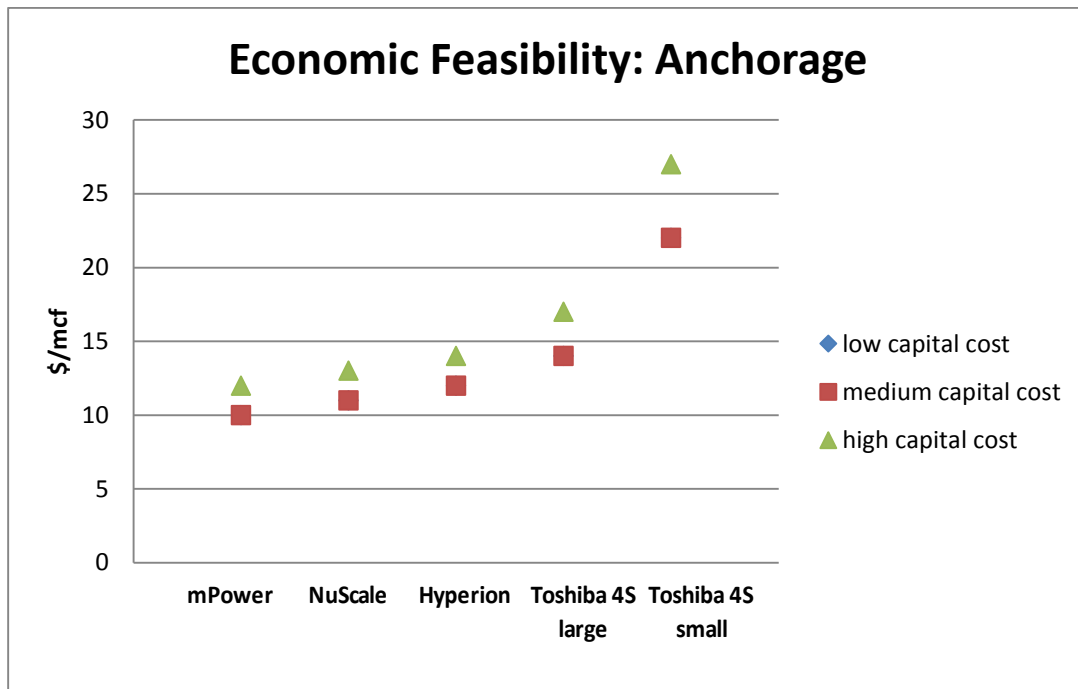


Figure 18. SMR economic feasibility in Anchorage.

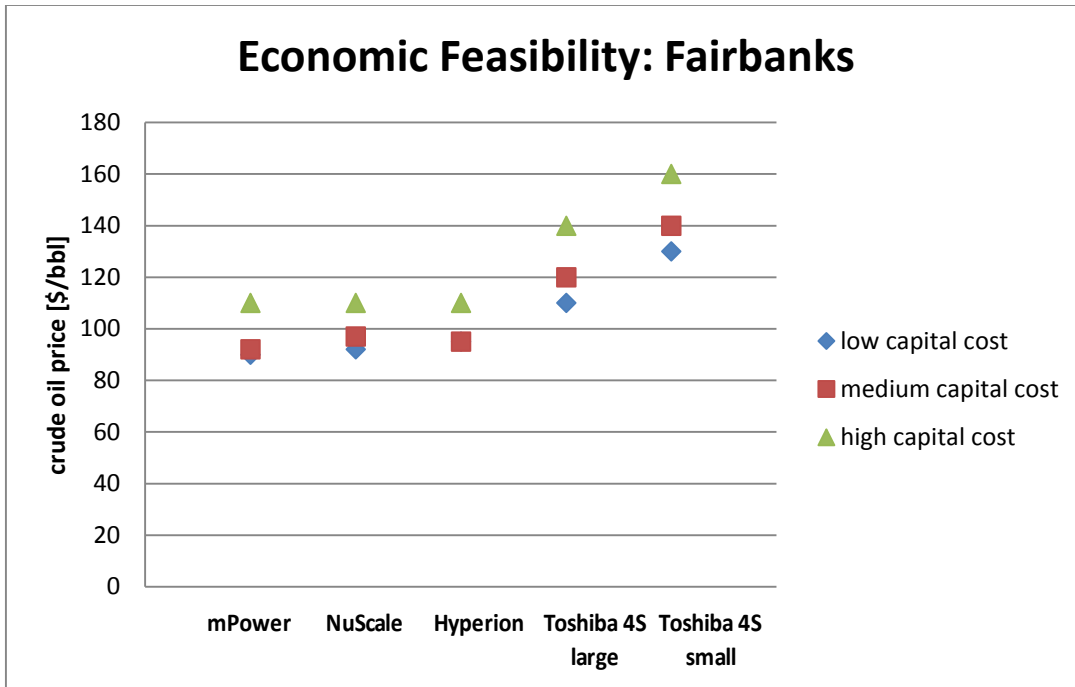


Figure 19. SMR economic feasibility in Fairbanks.

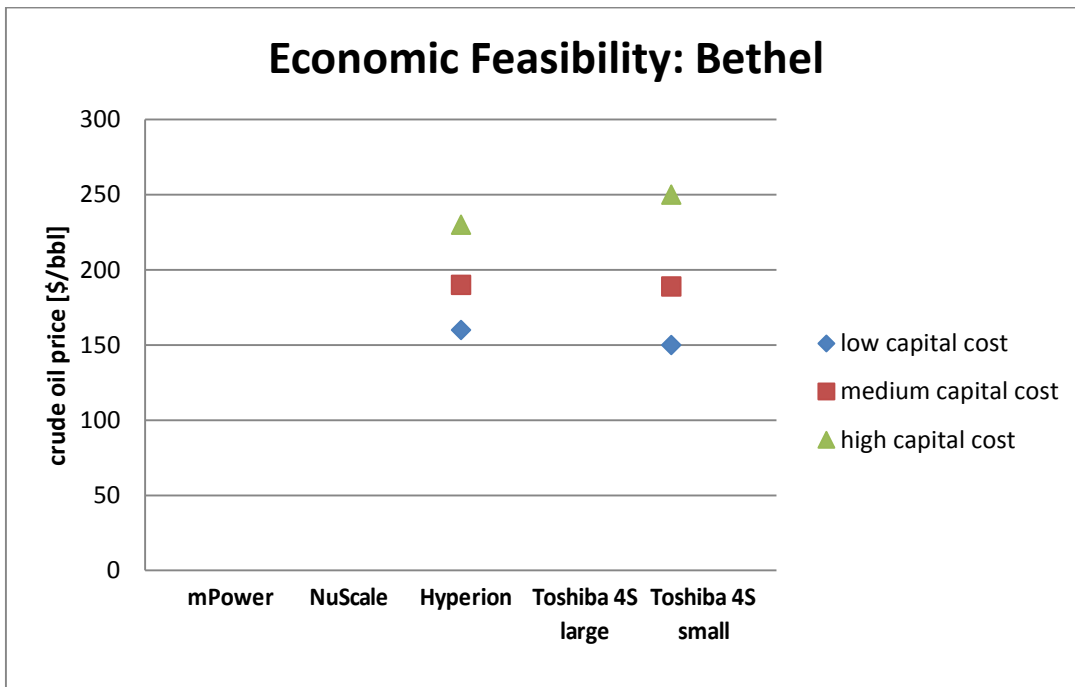


Figure 20. SMR economic feasibility in Bethel.

In summary, only under the most favorable low-cost conditions did SMR technology become a viable energy alternative for Bethel. In no other rural community did we observe favorable conditions for SMRs. Assuming high SMR costs and crude oil prices exceeding \$90 per barrel,

Fairbanks was the only viable location in Alaska for SMR technology (Figure 19). Fairbanks has one of the highest costs of electricity generation in the Railbelt; its load characteristics are favorable for SMRs, as all of the available electric output could be utilized, replacing the highest-cost current generation. One other reason why the model predicted this outcome is the contribution of heat sales at Eielson AFB, which adds to the favorable economics for SMRs at high costs. This result emphasizes the fact that under high SMR costs, it is crucial to utilize fully the electric and thermal capacity of the reactor.

Consistent among all scenarios is that SMR technology is not feasible anywhere in Alaska under the current EIA low crude oil forecast (orange curve in Figure 12), even if SMR construction and licensing costs were the assumed low case. However, under the medium EIA crude forecast, with prices ranging between \$80 and \$100 per barrel (green curve in Figure 11 and Figure 12), SMRs become a viable energy alternative for the Railbelt, regardless of the assumed SMR cost range. As would be expected, the same is true for high crude prices between \$130 and \$200 per barrel (blue curve).



## 6.0 Discussion and Action Items

### 6.1 Discussion

Based on the research given in this report, the following can be summarized:

- Nuclear power is a reality and has been for the past 60 years; it presently produces 20% of U.S. electrical demands at commercially competitive rates with an excellent safety record. Some small-scale reactors were successfully constructed and operated in the 1950s (60 MWe Peach Bottom reactor, for example), but economies of scale drove most utilities to larger 1,000 MWe reactors. Industry has achieved its current level of success after a painful process of rapid growth/cost overrun/retrenchment that resulted in financial setbacks for many utilities that participated in this process.
- The nuclear industry's past focus on large reactors resulted in no commercial nuclear power plants deployed in Alaska, because the power produced by a large reactor is greater than the electrical load in the state. However, the commercial nuclear power industry is currently focused on developing smaller nuclear reactors for safety (smaller reactors are intrinsically safer, because there is less energy in a single reactor), fabrication cost (smaller reactors could be mass-produced using a standardized design built in a factory), and financing costs (construction times would be shorter and more predictable, resulting in reduced costs before plant commissioning). These advantages will be achieved, though, only when the small modular reactor (SMR) industry has reached maturity. The initial cost of designing, constructing, and demonstrating the first-of-a-kind units will be very high. For reactors used in the U.S., obtaining NRC design approval is expected to take several years and require investments of hundreds of millions of dollars.
- Other forces driving the nuclear power industry to new kinds of reactors include the desire to extract more energy from nuclear fuels and eliminate the long-term storage issue with current spent nuclear fuels by reprocessing, to feed fast reactors. (In the U.S., the research for these new reactors is in the Generation IV reactor program.) However, the cost of these reprocessing plants is very high, and currently, no commercial plants fabricate these fuels. Fast reactors will likely be uneconomical to operate until commercial operators are able to supply fuels. The relative abundance of natural uranium and the well-understood process of enrichment and fabrication of commercial fuels for light water reactors (LWRs) mean that fuel-cost factors will not drive the industry to fast-reactor technologies for at least several decades.
- The Fort Greely reactor, which operated between 1962 and 1972, was a small-scale reactor intended to provide both heat and power to a remote military base; it operated with moderate success. The U.S. Army decision to shut down this reactor program appears to have been based on costs—the decision to end the program came several months before the steam turbine was damaged in March 1972. A review of publically available records indicates that the reactor was operated safely, but numerous issues affected the energy

production from the plant. Worth noting is that, at the time the reactor shut down, world oil prices were still only about \$2 per barrel.

- Toshiba's proposal in 2003 to place a 10 MWe sodium-cooled reactor in Galena "for free" garnered much attention in Alaska in the past several years. As generous as this offer appeared at the time, it is now apparent that delivering this reactor would have required overcoming several significant hurdles: (1) obtaining NRC approval for the design of this reactor (a formal NRC application for design review still has not been submitted), made especially difficult because of the lack of NRC experience in reviewing fast-reactor designs; (2) the need to request exemptions from multiple NRC rules regarding operators and security staff, emergency plans, and insurance requirements; (3) the availability of fuel for this reactor; and (4) the uncertainty over who would own and operate the reactor. This study also concluded that the economics of placing a 10 MWe reactor in a community the size of Galena is significantly challenging. There is reason to question the wisdom of placing a first-of-a-kind design in such a remote location, as the engineering support needed for such a unit is likely to be significant.
- Other fast-reactor developers, such as Hyperion, are also contacting potential Alaska users and investors.
- Developers for commercial SMRs include two designs based on current LWR technology, namely the NuScale 45 MWe reactor and the Babcock & Wilcox mPower 125 MWe reactor. The size of these units is interesting, as they might fit well with the existing Railbelt grid. In particular, Fairbanks currently does not have access to natural gas, and has several combined heat and power coal plants, all of which are aging and need either significant retrofits or replacement in the next few years. Preliminary economics indicate that SMR units might provide cost-effective power in this market. However, it does not appear that either of these units will be available for use before 2020. Both of these units are much too large for economical use in smaller remote rural communities.
- Given that a major motivation for development of the SMR industry is the possible reduction in the cost of constructing commercial nuclear power plants for large grids, and that the risk and likely cost of first-of-a-kind units are very high, the possible advantages of deploying the first small nuclear reactor in Alaska do not appear to justify the uncertain risks at this time.
- Once the industry has matured, SMR units may prove to be a cost-effective source of energy for Fairbanks or other communities. Studies to evaluate potential sites are suggested, but application to the NRC for an Early Site Permit at this time appears premature. Further work to scope out potential sites, however, may be of value in preparation for rapidly taking advantage of the technology if it becomes viable.
- Additional research into possible smaller nuclear power plants is suggested. One possible idea is to use the TRIGA reactor design (currently sold as a research reactor for universities) as a heat source for an organic Rankine cycle generator. This system could be designed

much smaller than the SMRs proposed for grid-connected applications. It might be easier to obtain design approval, as the TRIGA design has been shown to be robustly safe.

A number of advancements in the technology need to occur before SMRs can be seriously considered for Alaska. These include factors largely outside the control of the State of Alaska, including technology development (responsibility of manufacturers); safety considerations (purview of the NRC); environmental considerations (NRC and state permitting organizations), and economics (based largely on future world energy markets that are difficult to forecast). Along the way, there are many decision points related to adoption of the technology for Alaska applications. An aggressively optimistic scenario for these interdependent developments is indicated in Figure 21.

## Decision Making Chart and Timeline for SMR Technology for Alaska

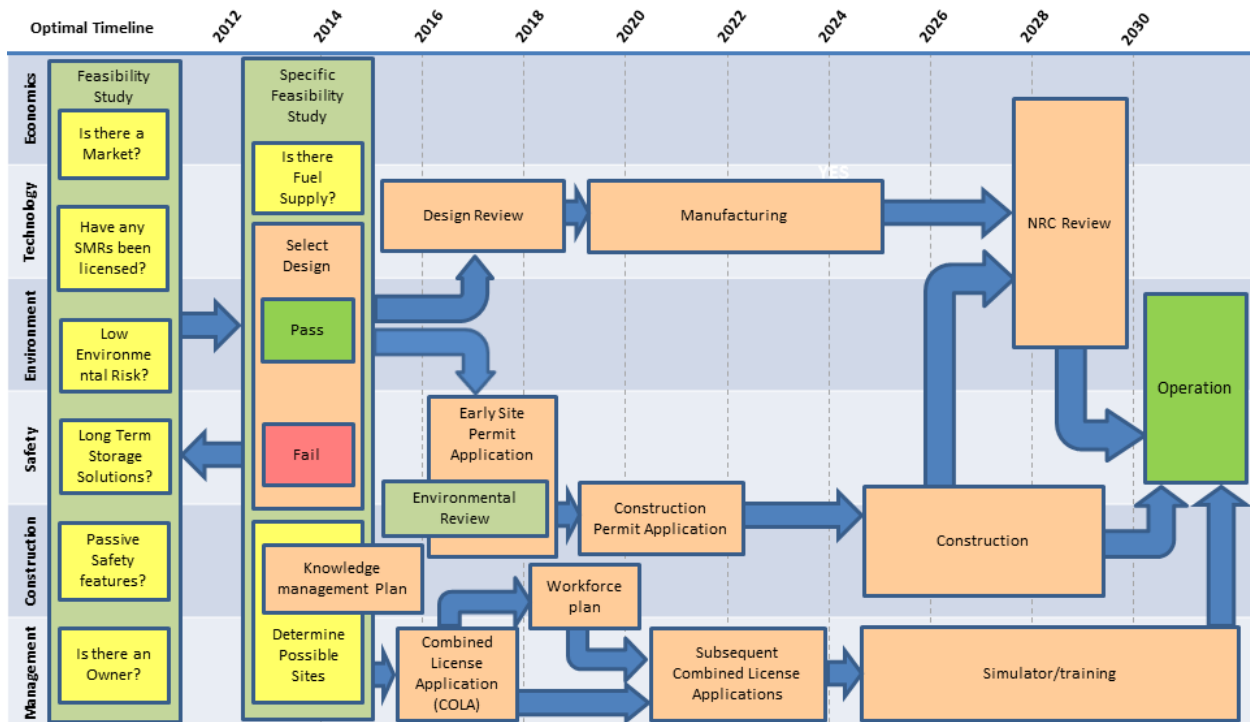


Figure 21. Decision-making chart for SMR deployment in Alaska.

Nevertheless, consideration could be given to steps designed to allow the State of Alaska to “keep the door open” on this technology. If SMRs were readily available today, they would be worth considering seriously for application both on the Railbelt and in rural communities. However, given the uncertainty of SMR commercialization, combined with heightened negative public opinion of

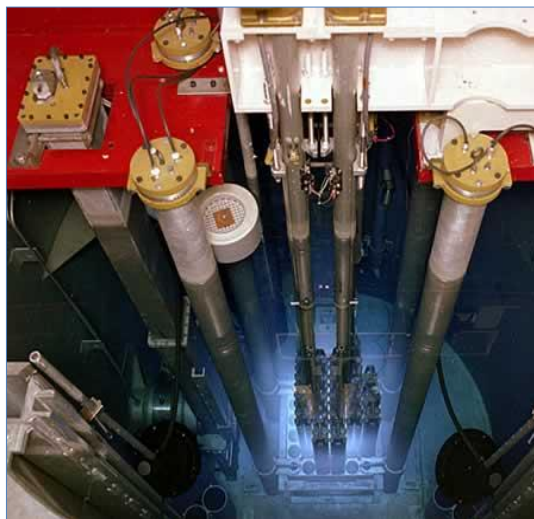
nuclear power in the wake of the Fukushima events, it is not possible today to recommend investment in a SMR-based power plant for Alaska.

## 6.2 Action Items

A number of proactive steps could be taken by the State to protect its interests:

- 1) ***Continue to explore options for smaller scale (<10 MWe) reactor technology.*** There is virtually no market niche for mini nuclear power reactor technology in the contiguous U.S., and therefore, little effort has been made to commercialize a product in this size range.

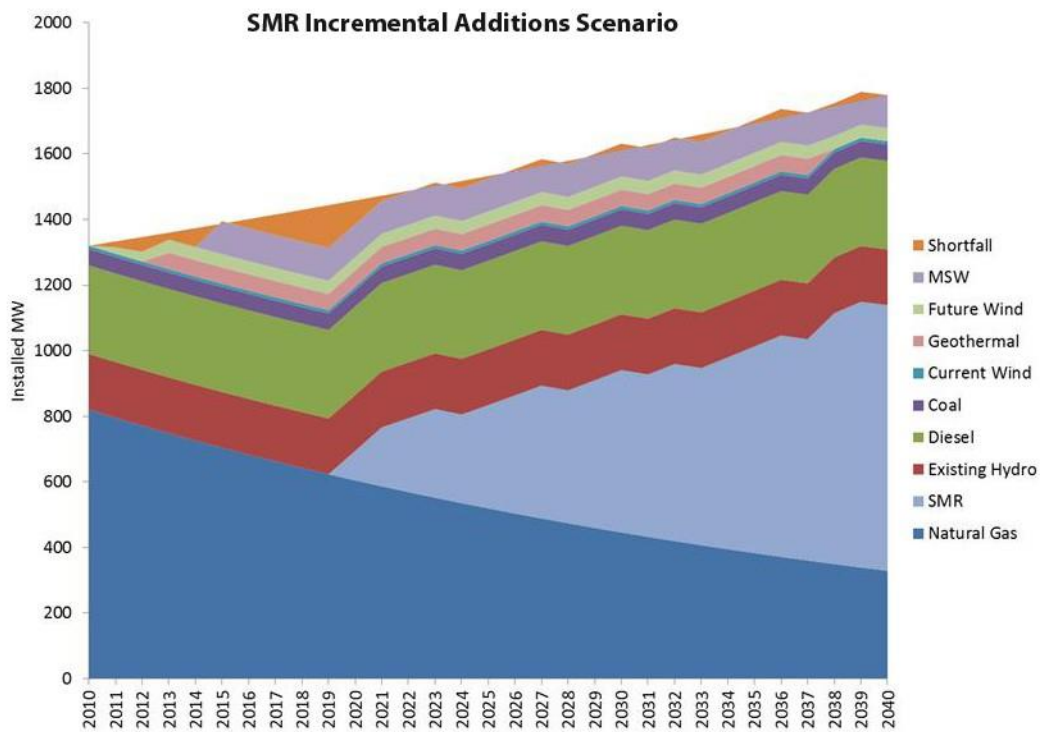
However, research in this area has not been exhausted. There is no question that several small-power reactors have been developed in the U.S. and other countries. For example, General Atomics has a standard design for a research reactor installed in dozens of locations around the country; it is a nearly fail-safe design with minimal NRC permitting and licensing requirements. This TRIGA reactor could be converted to a power reactor, something that was explored by the manufacturer twenty years ago, but was discontinued due to lack of apparent market potential. Alaska could seek a partnership with other groups interested in pursuing mini nuclear power, such as the U.S. Department of Defense (DoD).



Core of a TRIGA research reactor, designed and constructed by General Atomics.

- 2) ***Continue studies of SMR economics and technology development.*** Collaboration with the U.S. Department of Energy in reviewing their forthcoming economic analysis of SMR technologies for power plant applications in the U.S. would provide Alaska with more data for the model developed as part of this study, as well as technology and permitting insights for the most advantageous applications for Alaska.
- 3) ***Identify a state technology lead.*** The potential for SMR technology in the U.S. has been recognized nationally and in Alaska. Federal licensing and permitting processes are being developed to meet the growing interest in SMR technology as a way to meet energy demands of the future. To stay abreast of these developments, the State of Alaska could identify a lead entity to follow developments by industry and federal agencies that are relevant for Alaska. Specifically, the Alaska Energy Authority (AEA) could designate a Program Manager for Nuclear Energy, who could represent a portion of the duties of an existing staff member. The AEA could also contract with the University of Alaska to follow developments and report at regular intervals. However, there should be a central point of contact for the State of Alaska, and AEA is the logical choice.

- 4) **Consider SMR technology as one of several alternative scenarios.** While SMR technology is not available commercially today, it may become available in the future and, as such, would be worth comparing with other alternatives now and in the future as a replacement for aging generation capability (such as coal plants) in the Railbelt. The Regional Integrated Resources Plan (RIRP) process did consider a single Hyperion SMR module in the first stage of its screening analysis, but did not consider an array of SMRs added in increments over time to meet expected load growth. A scenario where individual modules are added over time could have the benefit of more closely matching loads and distributing costs over a longer time horizon. In the figure below, we illustrate how this replacement, with 45 MW units added incrementally, could provide increased total capacity for Alaska beginning in 2020.



Conceptual chart of future generation sources to the Railbelt region based on a RIRP model and assuming a 3% decline in natural gas supply per year (Cook Inlet), a 1% growth in electrical demand per year, and incremental additions of multiple 45 MW SMRs beginning in 2020.

- 5) **Begin a site feasibility study for two locations in Alaska.** While much of the national focus is on technology design licensing, the site selection and permitting process will be as challenging and involves significant uncertainty. The state could fund preliminary site selection and permitting activities for two locations based on the outcome of the economic screening analysis. Leading contenders include Fairbanks and Bethel, but a final determination should be made with local community input. Moving forward to achieve a better understanding of the permitting process does not commit Alaska to installation of a

SMR, or to becoming a first mover in this technology area. Instead, it provides flexibility and the ability to be an early adopter, while gaining a better understanding of the potential environmental issues associated with deployment in Alaska.

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**50 Years of Nuclear Energy (IAEA)** 1/1/2003

[http://www.iaea.org/About/Policy/GC/GC48/Documents/gc48inf-4\\_ftn3.pdf](http://www.iaea.org/About/Policy/GC/GC48/Documents/gc48inf-4_ftn3.pdf)

Discusses the "turnkey" plants built in the 1960s, with significant cost overruns due to changes in regulation, followed by canceled orders and Three Mile Island in the 1970s.

**Nuclear Fuel Reprocessing Costs** 7/1/2003

<http://www.ornl.gov/~webworks/cppr/y2001/pres/116757.pdf>

Summarizes capital costs associated with spent fuel reprocessing facilities. Capital for these plants is given relative to LWR enrichment plants--page 10--shows a factor or 1.5 to 2.5 for Ur-Pu

**The Future of Nuclear Power, 2003 MIT report** 7/1/2003

<http://web.mit.edu/nuclearpower/pdf/nuclearpower-summary.pdf>

Executive summary indicates that nuclear power is not as economical as coal or gas unless a carbon tax is included, that there are significant questions about waste management, concerns about safety and non-proliferation, but that it should remain on the table because it is a greenhouse gas free way of generating electricity.

**Brookings Institute Brief on the Economics of Nuclear Power**

9/1/2004

[http://www.brookings.edu/~media/Files/rc/papers/2004/09environment\\_nivola/pb138.pdf](http://www.brookings.edu/~media/Files/rc/papers/2004/09environment_nivola/pb138.pdf)

Discussion on how the high capital cost of nuclear plants, construction delays, diminishing growth in electrical demand have all contributed to the lack of orders for new nuclear plants in the US and around the world.

**History of the New Piles Committee**

11/1/2004

<http://www.ans.org/pubs/magazines/nn/docs/2004-11-3.pdf>

Breeder reactor discussions in 1944, as well as the history of the light water reactor. Many reactor designs were considered very early on, but safety was not a major concern in early designs.

**US Nuclear Energy Web Page on Gen IV Technology**

7/1/2006

<http://www.usnuclearenergy.org/GEN%20IV%20Reactors.htm>

Toshiba 4S is not mentioned as Gen IV reactor, but technology is similar to Sodium cooled fast reactor.

**CRS Report for Congress: Nuclear Power: Outlook for new US Reactors (2007)**

3/9/2007

<http://www.fas.org/sgp/crs/misc/RL33442.pdf>

Brief discussion on history of nuclear power in US, including reference to 120 canceled reactor orders in 1970s, 12 reactors shut down before their 40 year license expired, and of "unrecovered capital costs" as one factor in the 20 year license extensions granted to some existing plants.

Notes that the cost of the program to cost share the early site permitting process was \$550M over multiple years, for 3 early site permits. Discusses the new licensing process, where standard design certification and early site permitting process are done in parallel, then combined into an operating permit application, to be completed before construction even begins, in the hope this will reduce uncertainty, and therefore plant costs. Economic discussions indicate that high gas prices and carbon taxes of \$30 per ton or more are needed to make nuclear energy viable.

**CBO Testimony: Peter Orszag, Cost of Reprocessing vs. direct disposal of spent nuclear fuel**

11/14/2007

<http://www.cbo.gov/ftpdocs/88xx/doc8808/11-14-NuclearFuel.pdf>

Cost of disposal of spent nuclear fuel is more expensive than direct disposal, but estimates vary between 6% more and 2X. Making FBR fuel requires reprocessing, and could lead to more economical fuel in the future, but this is not evaluated in this paper.

**Early Site Permit Lessons Learned Document--DOE**

3/28/2008

<http://www.nuclear.energy.gov/pdfFiles/FinalReportonESPLessonsLearned.pdf>

Reports on three early site permits reviewed by the NRC, and issues associated with each. Shows flow chart of ESP process, and special notes on the use of Internet references (web sites change, so it's important to get "screen shots" of web sites, and the dates the sites were visited.

**INL cost analysis on cost of reprocessing nuclear fuels**

7/1/2009

<http://www.inl.gov/technicalpublications/Documents/4536700.pdf>

PDF Page 34 has picture showing costs (in arbitrary scale) showing investments required to deploy "Fuel Cycle" plants.

**Update to the 2003 MIT "Future of Nuclear Power" study**

7/1/2009

<http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf>

Nuclear power is a non-greenhouse gas emitting technology, there is a lot of uranium, waste can be handled, but capital costs are high and construction cost overruns are very detrimental. Cost comparisons with gas and coal are included.

**Belfer Center at Harvard Home Page**

10/1/2009

[http://belfercenter.ksg.harvard.edu/publication/19850/nuclear\\_power\\_without\\_nuclear\\_proliferation.html](http://belfercenter.ksg.harvard.edu/publication/19850/nuclear_power_without_nuclear_proliferation.html)

Belfer Center publishes policy papers on Nuclear Energy, including "Promoting Safe, Secure, and Peaceful Growth of Nuclear Energy: Next Steps for Russia and the United States"

**DOE Fact Sheet--Budget Request for SMR program**

2/1/2010

[http://www.nuclear.energy.gov/pdfFiles/factSheets/2011\\_SMR\\_Factsheet.pdf](http://www.nuclear.energy.gov/pdfFiles/factSheets/2011_SMR_Factsheet.pdf)

Indicates a budget request of \$38M in FY 2011 for DOE SMR program, with one objective "Develop recommendations, in collaboration with NRC and industry, for changes in NRC policy, regulations or guidance to license and enable SMRs for deployment in the United States."

**Alaska Legislative language with respect to nuclear power**

4/15/2010

[http://www.legis.state.ak.us/basis/get\\_bill\\_text.asp?hsid=SB0220Z&session=26](http://www.legis.state.ak.us/basis/get_bill_text.asp?hsid=SB0220Z&session=26)

Text of bill that amends Alaska law to allow the deployment of nuclear power plants and other facilities. However, the law states that local municipalities must first allow the facility before the state can issue a permit. It also indicates that the facility must meet NRC regulations.



**Controlling Asia's Nuclear Power Tigers, Forbes Magazine, Charles D. Ferguson,**

5/4/2010

<http://www.forbes.com/2010/05/04/asia-nuclear-power-markets-economy-national-security.html>

Indicates that the only country to keep a fast nuclear reactor operating is Russia, and this has required significant resources. "But fast reactors have a huge price tag. This technology has also suffered technical setbacks. Except for Russia, no country has a commercial fast reactor running.

The Russians have spent considerable financial and technical resources to keep its fast reactor operating. Even so, China, India, France, Japan and South Korea remain committed to a future filled with fast reactors. But most experts agree that the earliest possible time for this to happen is midcentury or later. The proliferation downside to fast reactors is that this technology can also breed lots of weapons plutonium. "

**The nuclear green revolution blog: Seaborg**

5/13/2010

<http://nucleargreen.blogspot.com/2010/05/disasterous-stewardship-3-seaborg.html>

Seaborg was chair of the AEC in the 1960s when the push to commercial light water reactors was made--he apparently did not evaluate the safety issues associated with scaling up experimental reactors, which led to the design changes in the 1970s--also pushed for sodium cooled fast breeder reactors, which have a problem with void reactivity --if a void forms in the sodium, the reaction can run away--and he shut down the ORNL thorium program and the molten salt reactor...

**The Future of the Nuclear Fuel Cycle**

6/1/2010

<http://web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle.pdf>

This report basically says is that the assumption that Uranium supplies are limited and that we have to go to fast sodium cooled breeder reactors is wrong, and that for now it is cheaper to simply use our light water reactors as we have been for the past decades--it even implies that going to sodium reactors isn't really a good idea.

There is no mention specifically of SMRs, but it certainly implies that the Toshiba 4S and the Hyperion designs are not a critical path forward--that development can be done much slower (over decades), and that new forms of LWRs might work...

**"Small Modular Reactors – Challenges and Opportunities": Commissioner William C. Ostendorff, United States Nuclear Regulatory Commission, June 2010**

6/15/2010

<http://www.nrc.gov/reading-rm/doc-collections/commission/speeches/2010/s-10-021.html>

Speech indicates knowledge of SMR issues, including reducing control room personnel and security staffing requirements for small nuclear reactors for rural electrical co-ops and remote mines. However, no resolution of these issues is given.

- NRC Advanced Reactors Web Page** 10/6/2010  
<http://www.nrc.gov/reactors/advanced.html>  
 List of reactors nearing the application phase for NRC approval.
- Small Modular Nuclear Reactors--World Nuclear Association** 10/9/2010  
<http://www.world-nuclear.org/info/inf33.html>  
 Summary of work in small modular nuclear reactors around the world. Source for many of the technical blurbs used in the descriptions in database.
- Nuclear Power in the US--World Nuclear Association** 10/29/2010  
<http://www.world-nuclear.org/info/inf41.html>  
 Summarizes commercial power reactors in US.
- Economics of Nuclear Power--technology review November/December 2010** 11/1/2010  
None  
 Shows Nuclear power as part of the electrical generation mix in many countries. Nuclear is cheaper than most renewables, but still more expensive than coal or gas.
- NUCLEAR AMBITIONS, from Technology Review, Nov/Dec 2010, page 64** 11/1/2010  
 One page summary of world history of nuclear power, showing gap in orders for plants.
- NRC History Page** 11/17/2010  
<http://www.fas.org/sgp/crs/misc/RL33442.pdf>  
 Gives history of NRC, back to AEC formation in 1946, and the creation of the NRC in 1974 due to concerns about AEC regulatory issues.
- New York Times Article on Uranium Prices** 11/18/2010  
[http://www.nytimes.com/2010/11/17/business/energy-environment/17FUND.html?\\_r=1&ref=businessspecial2](http://www.nytimes.com/2010/11/17/business/energy-environment/17FUND.html?_r=1&ref=businessspecial2)  
 Chinese demand is one driving force behind rising Uranium prices--they have no internal sources, and are investing in African mines.
- Comparing the Economics of Nuclear and Renewable Sources of Electricity, Mark Diesendorf** 11/29/2010  
 This article questions the economic assumptions that nuclear advocates have made for new nuclear power plants.

**10 CFR 50.43 (e) Special criteria for non-light water reactors** 12/6/2010

<http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0043.html>

Non-light water reactors will be given extra attention, and need either proof that safety systems will work, or a prototype.

**NRC Enabling Legislation web page** 12/8/2010

<http://www.nrc.gov/about-nrc/governing-laws.html>

Administrative Procedures Act: The Regulatory Flexibility Act requires that agencies consider the special needs and concerns of small entities in conducting rulemaking.

**SRE Fuel Element Damage Interim Report** 11/15/1959

<http://etec.energy.gov/Health-and-Safety/Documents/SSFLPanelFiles/NAA-SR-4488-Interim.pdf>

Report cited by David Lochbaum in his letter about the Galena project.

**"The Forgotten Guinea Pigs" Congressional Committee report, 1980, on Government Liability for nuclear testing fallout** 7/1/1980

[http://www.lib.berkeley.edu/doemoff/govinfo/federal/fdlpexhibit/The\\_Forgotten\\_Guinea\\_Pigs.pdf](http://www.lib.berkeley.edu/doemoff/govinfo/federal/fdlpexhibit/The_Forgotten_Guinea_Pigs.pdf)

Summarizes the effects of fallout on the residents living near the Nevada test site, including the sheep killed.

**The origins of the Nuclear Power Fiasco, by Amory B. Lovins, 1986** 7/1/1986

None

Discusses the really bad economics associated with Nuclear power as seen in 1986, and the politics and the arrogance that led to this situation.

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## Appendices

### Appendix A: Cost Structure of the Modeled SMR Nuclear System

#### Capital cost

power island cost equals the total cost to get the power island in place

The power island includes the cost of buildings necessary to house reactor, condensers, and electricity generating equipment. It is equal to the capital cost required to get the electricity to the transformer.

It does not include the cost of transformation and distribution

It does not include fuel

We assume a low cost scenario of \$4,500/kWh, med cost of \$6,000 /kWh, and high cost scenario of \$8,000/kWh. These cost scenarios were discussed with consultants: Philip Moor High Bridge Associates [Philip.Moor@hba-inc.com](mailto:Philip.Moor@hba-inc.com) and Vince Gilbert Excel Services, <vince.gilbert@excelservices.com

#### Combined license permit

e.g. Federal , local site permitting fees (state, municipal, etc.)

We assume that per reactor independent of its size, the FOAK low cost for this cost item is equal to \$50 million, medium: \$60 million and high \$70 million.

The cost for licensing a site with an SMR than has a certified design that is not the FOAK is estimated at \$20 million

#### Site preparation, roads, transmission line to the reactor

Costs related to the construction of roads, site preparation, and transmission lines to the reactor site were **NOT considered** due to lack of location-specific cost estimates.

#### Total project costs

Sum of capital costs and the cost of a combined license permit. Note, project costs indirectly include costs related to a design review permit. Such costs are believed to be passed on by the owner/developer via capital costs.

#### Fuel costs - specific to selected reactor

We assume reactors DO NOT come with the first fuel load, thus fuel needs to be bought separately (not included in capital cost).

SMR's with longer fuel cycles use highly enriched fuel and thus are much more expensive to refuel than larger units on a per kWh basis. This is especially true for the fast neutron reactors such as the 4S and the Hyperion module.

We include low, medium, and high fuel costs.

#### Overhaul, inspection, mobilization, demobilization cost

Particularly reactors with more frequent fuel cycles incur mobilization and demobilization costs. According to Moor (pers. Communication) these costs associated with preparation for the outage and demobilization afterward range between \$ 3 million (refuel only) to \$10 million (refuel and major overhaul of electricity producing equipment.)

For the longer fuel cycle designs, we assume 10 ( ten ) month overhaul schedule every 15 years and 3 month mobilization/demobilization cost for refueling.

Philip Moor says:

“Each refueling for the frequent refuel cycles carries a mobilization, labor and parts and demobilization cost, which will raise the non-fuel O&M for the shorter fuel cycle designs. The estimated refuel cost for the mobilization, demobilization, inspections and repair could range from \$3 million (refuel only) - \$10 m (refuel + major electricity producing equipment overhaul)”

### **O&M**

In the tradition of the earlier model by Colt (2003), we treat labor costs for operation and security separate from O&M. Colt (2003) observed sensitivity of outcomes to labor costs. Labor: for operation and security, NOT for maintenance and refueling. They are plumbers, electricians, etc.

These are nuclear reactor operators and are not nuclear engineers.

The security personnel is in a separate job category with a lower wage than the operators. SMR are assumed to use less staff but have higher fuel cost due to higher enrichment compared to larger reactors.

O&M of larger scale reactors does include labor and is equal to 0.02/kWh, we use 0.015/kWh which does not include labor.

O&M includes training for operator personnel in simulator, incl. travel to simulator training site

### **Decommissioning cost**

use value similar to current decommissioning costs for larger nuclear power plants and decommissioned DOE facilities

### **Refueling cost**

Capital cost as stated in the model does not include the cost of the fuel.

Mobilization, demobilization cost for refueling and major overhaul costs which includes overhaul of the electricity producing equipment.

### **Rate of Return to operator of power plant**

percentage of nuclear system costs excluding the cost of utility administration, distribution and transmission

### **Distribution and transmission**

this cost is not part of the nuclear power system cost, and thus not subject to return to operator

### **Backup generation for nuclear system**

Diesel Fuel Use

Diesel Fuel Price

Diesel Fuel Cost

Diesel O&M

diesel Cost of capital

Total Identifiable Cost of [backup] Diesel

Total Identifiable Cost of [backup] Railbelt generation

## Appendix B: Small Modular Reactor Technology Screening Report

The following small modular nuclear reactor technologies were considered as part of this study.

***Commercially available, NRC reactor design approved, could be deployed in US with NRC approval of site permit and operating license.***

- No reactors identified in this category

***NRC design review application submitted, design based on previously proven technology, approval expected within 3 years.***

- No reactors identified in this category

***NRC letter of intent submitted, design based on previously proven technology, approval expected within 6 years***

- mPower 125 MWe Reactor, USA, Babcock and Wilcox
- NuScale 45 MWe Light Water Reactor, USA, NuScale Power company

***NRC letter of intent submitted, design includes significant items not previously approved by NRC, approval time unknown***

- Toshiba 4S Reactor, Japan, Toshiba
- Pebble Bed Reactor, South Africa, Pebble Bed Modular Reactor (Pty) Limited and Eskom
- Power Reactor Innovative Small Module (PRISM), USA, GE-Hitachi
- Hyperion Power Module, USA, Hyperion Power Generation Inc.

***New design under consideration by large nuclear development group based on previous experimental reactor experience, but NRC approval process has not begun.***

- 20MWe SMR, Westinghouse
- Secure Transportable Autonomous Reactor (STAR), USA, Argonne National Laboratory
- Small Sealed Transportable Autonomous Reactor (SSTAR), USA, Lawrence Livermore, Argonne and Los Alamos National Laboratories in collaboration with others.

***Proposed design being researched by viable company with sufficient funding, but remains in modeling stage***

- Medical Isotope Production System (MIPS), USA, Babcock and Wilcox
- Encapsulated Nuclear Heat-Source (ENHS), USA, University of California, Berkeley.
- LSPR--LBE-Cooled Long-Life Safe Simple Small Portable Proliferation-Resistant Reactor, Japan
- Liquid Fluoride Thorium Reactor (LFTR), USA, Oak Ridge
- Fuji Molten Salt Reactor (MSR), Japan, Fuji--Russian--USA

- Traveling Wave Reactor (TWR), USA, Terrapower (approaching Toshiba)
- Energy Multiplier Module (EM2), USA, General Atomics
- Advanced High Temperature Reactor (AHTR), USA, Oak Ridge National Laboratory
- Gas Turbine - Modular Helium Reactor (GT-MHR), USA--Russia--Japan, General Atomics in partnership with Russia's OKBM Afrikantov, supported by Fuji (Japan)
- Antares Reactor, International, Areva
- Advanced Reactor Concepts (ACR-100), USA, Advanced Reactor Concepts LLC (ARC)

***International commercial design not seeking NRC approval for licensing in US***

- NP-300, France, Technicatome (Areva TA)
- KLT-40 S Pressurized Water Reactor, Russia, OKBM
- Pressurized Heavy Water Reactors (PHWR-220) (PHWRs), India, Nuclear Fuels Complex, India

***Proposed reactor design appears viable, but not supported by funded research***

- Radix, USA, Radix Power and Energy Corporation
- TRIGA, USA, General Atomics
- Adams Engine, USA, Adams Atomic Engines

***International research design not likely to result in application for NRC license***

- ABV, Russia, OKBM Afrikantov
- Korean Fast-Reactor Design (KFRD), South Korea, Korea Atomic Energy Research Institute
- BREST, Russia, RDIPE
- CAREM Pressurized Water Reactor, Argentina, CNEA & INVAP
- IRIS
- Pebble Bed Commercial Reactor HTR-PM, China, Institute of Nuclear & New Energy Technology (INET) at Tsinghua University north of Beijing
- Pebble Bed Demonstration HTR-10, China, Institute of Nuclear & New Energy Technology (INET) at Tsinghua University north of Beijing
- CNP-300 Pressurized Water Reactor, China,
- ELENA, Russia, Russian Research Centre “Kurchatov Institute” (RRC KI)
- High Temperature Test Reactor (HTTR), Japan, Japan Atomic Energy Research Institute (JAERI)
- System-integrated Modular Advanced Reactor (SMART), South Korea, KAERI
- VKT-12, Russia
- VKR-MT, Russia, Federal State Enterprises NIKIET and VNIAM
- VK-300 Pressurized Water Reactor, Russia, Atomenergoproekt
- VBER-300, Russia, OKBM Afrikantov



- VBER-150, Russia, OKBM Afrikantov
- MRX, Japan, Japan Atomic Energy Research Institute (JAERI)
- SVBR-100, Russia, Rosatom/En+, Hidropress
- MARS, Russia, Russian Research Centre “Kurchatov Institute” (RRC KI)
- SAKHA-92, Russia, OKBM Afrikantov
- RITM-200, Russia, OKBM Afrikantov
- NHR-200, China, Tsingua University's Institute of Nuclear Energy Technology (now the Institute of Nuclear and New Energy Technology)
- Modular Transportable Small Power Nuclear Reactor (MTSPNR), Russia, N.A. Dollezhal
- Research and Development Institute of Power Engineering (NIKIET)
- UNITHERM, Russia, Federal State Enterprise NIKIET

***Obsolete reactor design unsatisfactory for commercial use due to safety, non-proliferation, or other issues,***

- SM-1A Fort Greely Reactor, USA, US Army
- EGP-6 Reactors, Russia,
- Big Rock Point, USA, Army
- PM-3A, USA, US Military
- MH-1A, USA, US Army

***Small-scale designs not suitable for utility power***

- Radioisotope Thermoelectric Generator (RTG), USA, Teledyne Brown
- Rapid-L, Japan, Toshiba
- NASA Nuclear Sterling Engine for Lunar Base, USA, NASA

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## **Appendix C: Conference Summary Review—Attendee List, Power Points**

### **Nuclear Energy Exploratory Workshop Panel Summaries**

The Nuclear Energy Exploratory workshop was hosted by the Alaska Energy Authority and the University of Alaska at the Dena'ina Conference Center in Anchorage, Alaska on December 9 and 10, 2010. The purpose of the workshop was to serve as a forum to discuss the current status of small-scale modular nuclear power technologies including design and permitting considerations, safety and security, economics, ownership structure, nuclear industry resources and environmental issues. The information was presented to help identify the next steps, if any, in considering this technology for Alaska.

### **December 9, 2010**

#### **Technology and Overview Panel**

The technology and overview panel was moderated by Dennis Witmer of Energy Efficiency Evaluations. The first panelist, Vince Gilbert of EXCEL Services Corporation presented an overview of small modular reactor (SMR) technology. Mr. Gilbert's presentation covered SMR technology, definitions, and reactor types. The next panelist, Craig Welling of the U.S. Department of Energy's Office of Nuclear Energy, presented on the DOE experience with small modular reactors and planned feasibility studies to be undertaken by the DOE. The presentation outlined the Department of Energy's Small Modular Reactor program, current SMR technology and economic feasibility studies that have been undertaken by the DOE. The final panelist, Jay Harris of the Canadian Nuclear Society, presented the Canadian nuclear experience and potential opportunities for remote northern communities. Mr. Harris's presentation gave the history of small nuclear reactors throughout the world and discussed the benefits and challenges of SMRs for remote northern communities.

#### **Galena Toshiba 4S Proposed Project and Lessons Learned**

The Galena Toshiba 4S proposed project and lessons learned was moderated by Marvin Yoder, the former city manager of Galena, Alaska. In addition to moderating the panel, Mr. Yoder spoke about the history of the Galena project. Philip Moore of High Bridge Associates presented on the white paper studies on the Galena project. Galena, Alaska was the first town in the U.S. to offer a site for a SMR. Seven white papers covered an overview of the project, insurance, emergency planning, seismic design inputs, decommissioning, containment and physical security. The final panelist, Bill Reckley of the Nuclear Regulatory Commission, spoke about the Nuclear Regulatory Commission's take on the Galena project.

#### **Lunch Presentation**

During lunch, Dennis Beller of the University of Nevada Las Vegas presented on nuclear workforce issues and academic programs. A majority of people working within the nuclear field are nearing retirement age and universities will have to educate a new generation of nuclear engineers to fill opening jobs in the nuclear industry.

### **Potential Economics of Deploying and Operating Small Modular Reactors in Alaska Panel**

The potential economics of deploying and operating small modular reactors in Alaska panel was moderated by Ginny Fay, Assistant Research Professor at University of Alaska Anchorage's Institute of Social and Economic Research (ISER). In addition to moderating the panel, Ms. Fay jointly presented with Tobias Schwörer, also of ISER, about the economic feasibility of an SMR in Alaska. The results of an economic model were presented. The final panelist, Vince Gilbert of EXCEL Services Corporation, presented about operating cost benchmarking used within the nuclear industry.

### **Project Ownership and Financing Panel**

The project ownership and financing panel was moderated by David Lockard of the Alaska Energy Authority. The first panelist, James Hemsath of the Alaska Industrial Development and Export Authority, presented financing options for large energy projects in Alaska. Mr. Hemsath's presentation covered Public-Private Partnerships as an option for financing an SMR. Philip Moor of High Bridge Associates, presented on property ownership structures including an SMR deployment model for Alaska. The final panelist, Craig Welling of the U.S. Department of Energy's Office of Nuclear Energy, presented financing mechanisms for nuclear projects.

## **December 10, 2010**

### **Regulatory and Permitting Requirements Panel**

The regulatory and permitting requirements panel was moderated by Denis Witmer of Energy Efficiency Evaluations. Bill Reckley of the Nuclear Regulatory Commission presented an overview of the federal permitting requirements from Part 50 and Part 52 for a nuclear reactor. Philip Moor of High Bridge Associates presented on American Nuclear Society SMR activities. Tom Crafford of the Alaska Department of Natural Resources' Large Project Permitting Office spoke about Alaska state and local permitting requirements. The final panelist, Vincent Gilbert of EXCEL Services, presented on incorporating state and federal regulatory requirements into a business plan.

### **Legislative Update Panel**

James Hemsath of the Alaska Industrial Development and Export Authority moderated the legislative update panel. Michael Pawlowski, legislative aid to the Alaska State Senate Energy and Resources Committee, presented on changes to Alaska State Statutes related to nuclear development from Senate Bill 220. Isaac Edwards, Senior Council to the U.S. Senate Energy and Natural Resources Committee presented an update on federal legislation relating to nuclear energy.

### **Societal and Environmental Considerations Panel**

The societal and environmental considerations panel was moderated by Bruce Tiedeman of the Alaska Energy Authority. Caitlin Higgins of the Alaska Conservation Alliance spoke about the environmental community perspectives on nuclear energy. Denis Beller of the University of Nevada Las Vegas presented on the public perception of nuclear energy and how acceptance of nuclear energy can be achieved through public outreach and education. Jay Harris of the Canadian Nuclear Society spoke about the use of nuclear energy in remote locations. Bill Reckley of the Nuclear

Regulatory Commission presented on the Nuclear Regulatory Commission's environmental review process for permitting nuclear reactors. Chad Baker of the Chugach Alaska Corporation presented on the Alaska Native perspective on SMRs.

### **Lunch Presentation**

During lunch, Vince Gilbert of EXCEL Services Corporation presented about the existing nuclear industry support system that has been established for large commercial reactors.

### **Notes from Friday Breakout Discussions**

In the afternoon, participants were divided into two groups to allow for more in-depth discussion in particular areas of interest, and to identify next steps (if any) in further considering small modular nuclear reactor technology for Alaska.

#### **Group 1: Economic and Financial Considerations**

The economics and financial considerations group was led by Ginny Fay, Assistant Research Professor at the University of Alaska Anchorage's Institute of Social and Economic Research (ISER) and Vince Gilbert of EXCEL Services Corporation. The following questions were addressed by the group.

#### ***Identification of specific cost questions; did the ISER model adequately address all of the costs?***

It is uncertain whether the \$20 million cost of a training simulator was included in the cost that ISER used in the model. The NRC requires each plant to have simulator on site for operator training. Simulators for large nuclear plants cost \$20 million. Whether simulators for small plants will cost less because of the relatively simplistic design of SMRs compared to traditional large commercial reactors remains unknown.

Permitting costs and decommissioning costs are included in the ISER model.

To assure accuracy, the ISER model cost should be compared to a lifecycle cost analysis for a SMR. Are the plant staffing numbers used in the model correct? A nuclear plant will require an operating crew of 35 people (5 shifts of 7) and a security crew of eight people.

The ISER model uses Henry Hub natural gas prices. The group discussed if this was ideal since Alaska natural gas prices have not always been closely tied to Henry Hub prices. However, since Cook Inlet natural gas production has decreased, Alaska prices have been closer to Henry Hub. There was also discussion of comparing LGN lifecycle cost with the cost of using a nuclear plant for electricity production.

#### ***Should district heating be considered as part of the economics?***

The current ISER model assumes homes convert to electric heating and utilities upgrade to accommodate the switch. The group questioned whether district heating should be used in the model instead. District heating only makes sense when the population is centrally concentrated around the heating source because the cost of the infrastructure is high. If the community is spread out, the capital cost of the system would not be recovered.

***Will there be reactor sizes that make the technology feasible for additional communities, that are not currently being actively considered?***

The current ISER model shows the SMR is only economically feasible in Fairbanks and Bethel because of the high oil prices and those population centers' dependency on oil for electricity generation. The capital cost of the SMR is too high to be economical in areas that cannot use it for base load generation. There was discussion of mini SMRs with capacities of 500 kWe to 1 MWe. A mini SMR could provide base load power for smaller communities, but whether the project would be economically feasible is unknown.

***How could a project potentially be financed in Alaska?***

Alaska would need a "super utility" to fund a SMR. The individual utilities are too small with too few resources to take on projects with high upfront costs such as permitting, licensing, and purchasing an SMR. However, past attempts to create a single Railbelt G&T have not been successful. Few generation units have been built in the Railbelt without utilities teaming up together. Generally, the size of a project is relative to the size of the utility backing the project. Larger utilities can build larger projects.

Some projects, such as large hydro, are subsidized by the state. Will nuclear receive a state subsidy? If not, nuclear will be at a disadvantage.

***What are some potentially appropriate applications of SMR technology in Alaska, and what are the advantages and challenges associated with these?***

SMRs could be used for base load generation in larger communities with high fuel costs. They could also be used at rural mine sites with high fuel costs. Some potential challenges for mining applications include the added stigma of nuclear on top of the stigma of mining. Additionally, the reactor may outlast the mining operation.

SMRs could be used on military bases, but would have to provide both electricity and steam for heating. Military interest in the technology is dependent upon cost.

***Who are the in-state stakeholders that we should continue to engage as part of this discussion?***

The in-state stakeholders include the utilities, military bases, University of Alaska, State Legislature (energy committees), Alaska Energy Authority, Alaska Industrial Development and Export Authority

***Who was missing from this workshop?***

The group would have liked more participants from the different military branches with bases in Alaska.

**Group 2: Barriers to Development**

The barriers to development group was led by Dennis Witmer of Energy Efficiency Evaluations and David Lockard of the Alaska Energy Authority.

The discussion of Group Two was framed by the initial question, "The technology is real and exists. Is this a time for Alaska to pursue?" The response was no, that perhaps now is not the time to pursue by means of commitment to a vendor or manufacturer, or through initial site permitting

work, but rather it is still time for Alaska to closely monitor SMR development, both on the technology front as well as the policy front.

There were a lot of recommended actions that Alaska could take place in the meantime, most importantly being public education (public perception being the major SWOT Threat but also the major SWOT Opportunity). Also important is the gathering and centralization of information and dissemination, and diligent communication and monitoring of technology advancement, through a stakeholders group, a committee, or through a funded position (perhaps at AEA). It was strongly thought that AEA should have a program or project manager with experience/responsibility with nuclear technology.

A first adopter location in Alaska was hard to narrow down. The two driving criteria were size (load) and accessibility. Although the Railbelt meets these two criteria, competing energy sources make it economically questionable, although a DoD angle would be very interesting to pursue (that is, a military base installing an SMR as a means of energy security as well as demonstration). Likely first adopter candidates would be Bethel, mines, North Slope industry, and even perhaps Adak or the Aleutians for industry development.

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## Appendix D: Radioisotope Thermoelectric Generators

### Abstract

The smallest of all nuclear electrical sources is the Radioisotope Thermoelectric Generator (RTG) used to power spacecraft and remote seismic installations. The power delivered for these applications is usually less than one kilowatt. However, Russian literature indicates that systems as large as one megawatt have been built and successfully operated for extended periods of time.<sup>168</sup> The most common RTG has no moving parts and therefore requires no maintenance for the life of the system. This characteristic and a long operational lifetime (on the order of decades) have made RTG technology the backbone of space exploration.<sup>169</sup> However, RTG's have several major drawbacks when considered for use in Alaskan remote power applications, mainly the large volume of nuclear material needed and therefore licensed, along with associated costs. The most immediate drawback to these devices is simply the cost of power produced. An estimate from the year 2000 reported the fuel cost to be at least \$4 per kilowatt-hour.<sup>170</sup> This is not competitive with existing diesel-power generation systems that cost roughly 30 cents per kilowatt-hour in Galena.

### Introduction

The Radioisotope Thermoelectric Generator (RTG), also known as a Radionuclide Thermoelectric Generator, is designed to power remote systems for decades, although their use has been largely limited to power systems of a few tens to a few hundred watts. RTGs take advantage of a temperature difference between hot radioactive material and ambient temperatures. This temperature gradient gives rise to an electrical current in the system through the Seebeck effect, commonly used in thermocouples. RTGs turn heat directly into electricity by using a large number of these junctions to create a usable voltage.<sup>171</sup>

The first RTGs in the United States were developed in the Beneficial Uses of Radioactive Material program in 1959.<sup>172</sup> The Transit 4A spacecraft launched in 1961. Since then there have been 41 RTGs deployed to power 24 space systems including Pioneer, Voyager, Apollo, Viking, Ulysses, Galileo, Cassini, New Horizons, Sojourner, Spirit, and Opportunity.<sup>173</sup> The first Earth-based RTG was constructed in 1966 by the United States Navy at Fairway Rock Island, Alaska.

RTGs are most commonly used in space applications as a power source for satellites and rovers. They have been used previously as power sources for terrestrial applications for weather stations and other instruments as well. The most notable in Alaska was the system of RTGs employed at the Burnt Mountain Air Force installation in Alaska. The first Burnt Mountain RTG went online in 1973. The RTG system received media attention after a forest fire damaged wiring at the facility in 1992.

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<sup>168</sup> Velikhov, E. (2010, September 24). Personal Interview. (D. Witmer, Interviewer)

<sup>169</sup> Sutliff, G. S. (2008). Radioisotope Power: A Key Technology for Deep Space Exploration. *IAC*.

<sup>170</sup> Kulcinski, G. (2000). *NEEP 602 Course Notes (Spring 2000): Nuclear Power in Space*. Retrieved December 6, 2010, from <http://fti.neep.wisc.edu/neep602/SPRING00/neep602.html>

<sup>171</sup> *Seebeck Effect*. (n.d.). Retrieved 1 24, 2011, from Encyclopædia Britannica: <http://www.britannica.com/EBchecked/topic/532358/Seebeck-effect>

<sup>172</sup> U.S. Congress, Office of Technology Assessment. (June 1994). *Power Sources for Remote Arctic Applications, OTA-BP-ETI 129*. Washington, DC.

<sup>173</sup> Bennett, G. L. (2006). Space Nuclear Power: Opening the Final Frontier. *4th International Energy Conversion Engineering Conference and Exhibit*. San Diego, California.

A 1994 report by the Office of Technology Assessment concluded that “continued use of the RTGs at Burnt Mountain entails low risk for the safety of maintenance workers and local populations and for the environment.” Radioisotope Thermoelectric Generators are considered to be a safe and proven technology<sup>174</sup>.

## Technology

The electric current generated by a RTG is produced by a large collection of thermocouples. A thermocouple is a junction of two dissimilar metals that generates an electric voltage when the temperature of each metal is different. Electrons from the hot side diffuse to the cold side giving the cold side a net negative charge and leaving the hot side with a net positive charge. This separation of charge gives rise to the voltage, in a process is known as the thermoelectric effect or the Seebeck effect.<sup>175</sup>

RTGs are passive electric generators, with no moving parts. Only the heat from the radioactive decay is needed for operation, meaning that the reaction is not a chain reaction such as that in larger nuclear reactors or weapons. This provides stable and reliable operation without supervision, albeit at a relatively low conversion efficiency of about 4%. The National Aeronautics and Space Administration (NASA) developed two standard modules for space missions: The General Purpose Heat Source RTG (GPHS-RTG or GPHS) and the Multi-Mission RTG (MMRTG) shown in Figure D1.<sup>176</sup>

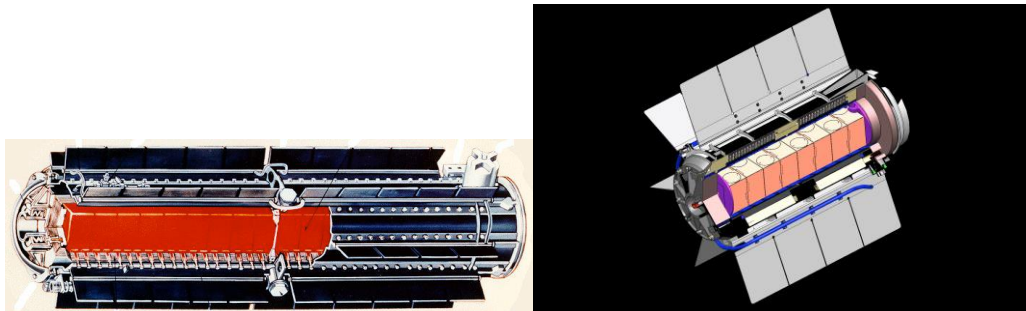


Figure D1: GPHS and MMRTG designs. The heat sources and thermocouples are encased in an aluminum shell with cooling fins to radiate excess heat.<sup>177</sup>

These units have a standard design that allows for quick construction and consistent results. The GPHS has been successfully employed in space missions while the MMRTG has been tested extensively. The GPHS uses Plutonium-238 Oxide ( $\text{PuO}_2$ ) as the heat source and a Silicon-Germanium thermocouple to create 292 We at the beginning of the mission (BOM) in a 56 kg package. The MMRTG uses 4.8 kg of  $\text{PuO}_2$  as the heat source, but uses a lead-tellurium

<sup>174</sup> U.S. Congress, Office of Technology Assessment. (June 1994). *Power Sources for Remote Arctic Applications, OTA-BP-ETI 129*. Washington, DC.

<sup>175</sup> *Seebeck Effect*. (n.d.). Retrieved 1 24, 2011, from Encyclopædia Britannica:

<http://www.britannica.com/EBchecked/topic/532358/Seebeck-effect>

<sup>176</sup> Sutliff, G. S. (2008). Radioisotope Power: A Key Technology for Deep Space Exploration. *IAC*.

<sup>177</sup> Sutliff, G. S. (2008). Radioisotope Power: A Key Technology for Deep Space Exploration. *IAC*.

thermocouple for a system that generates 123 We at BOM.<sup>178</sup> The MMRTG weights 44 kg and has dimensions of 66 cm long by 60 cm across not including the fins.

A similar technology uses a Stirling engine to produce electricity. A Stirling Radioisotope Generator (SRG) is a heat engine that uses a temperature difference to drive a piston (Stirling Radioisotope Generator). This system converts thermal energy into mechanical energy that can then be converted into electricity. While not proven in a space mission, SRGs have shown to produce similar electric power to an RTG with a fourth of the fuel.<sup>179</sup> The advantage of the Sterling engine is that more power can be produced from the heat source since the efficiency is approximately 30% compared to the 4% efficiency of the Seebeck devices.<sup>180</sup> The disadvantage of the Sterling engine is the introduction of moving parts, which introduces the possibility of mechanical failure. Stirling Radioisotope Generators produce four times as much electric power as traditional RTGs, so there could be a real benefit for using SRGs in terrestrial power generation. SRGs are unproven in space partly due to the risk of mechanical failure. In space, a malfunctioning component can never be repaired. On Earth, even in rural locations, maintenance can be performed. As with RTGs, one potential problem for terrestrial uses of SRGs is the warmer ambient temperature on Earth. The reduced temperature difference between the hot and cold side of the Stirling engine will affect the power output.

## Fuel

Many types of radioactive fuel can be used in a RTG. RTGs are not nuclear reactors so they can take advantage of any hot material. There are multiple important differences between fuel sources. Half-life, type of radiation, power density, and cost must all be considered.

Radioactive materials continually radiate energy through a process called radioactive decay.

Radioactive decay is the process where the nucleus of an atom loses energy by emitting a particle or electromagnetic wave. Some isotopes have multiple steps in their decay chain, but the end result is a net loss of energy for the material. Radioactive decay occurs at a predictable rate even though the exact time of a single emission cannot be determined. The accepted way to measure this decay rate is known as the half-life of the material. A half-life is the time half a given number of radioactive nuclei will decay.<sup>181</sup>

The half-life of any RTG fuel is important because it will determine the length of time the generator will be effective. The electrical output of a RTG will decrease with time because the fuel is continually radiating away its energy. Below is a table (Figure D2) of possible RTG fuel half-lives:

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<sup>178</sup> Sutliff, G. S. (2008). Radioisotope Power: A Key Technology for Deep Space Exploration. *IAC*.

<sup>179</sup> Schmidt, G. (2003). Radioisotope Power Systems (RPS) for New Frontiers Applications. *Presentation to New Frontiers Program Pre-Proposal Conference*.

<sup>180</sup> Sutliff, G. S. (2008). Radioisotope Power: A Key Technology for Deep Space Exploration. *IAC*.

<sup>181</sup> Nave, R. (n.d.). *Radioactive Half-life*. Retrieved 1 24, 2011, from Hyperphysics: <http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/halfli.html>

### Half Life of RTG Fuels

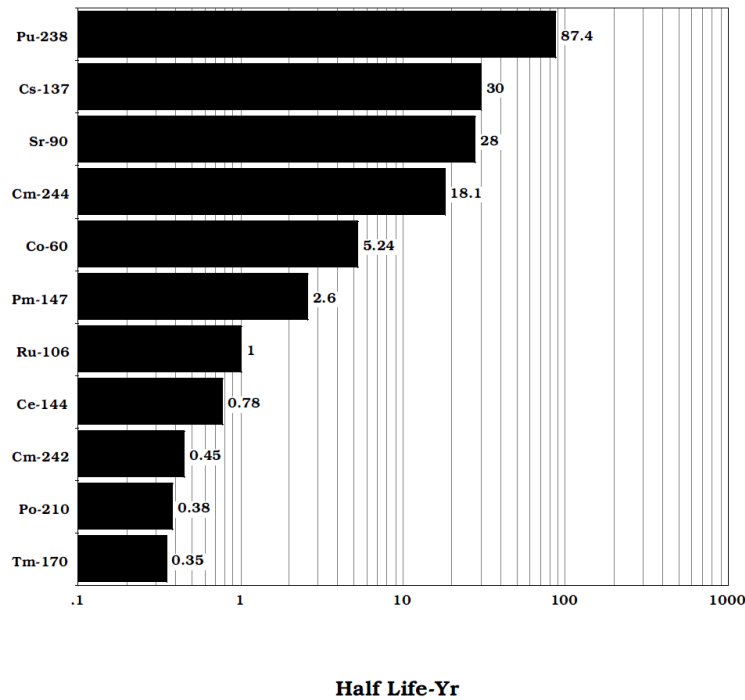


Figure D2: Half Life of RTG Fuels.<sup>182</sup>

NASA used Plutonium-238 successfully in all the space missions listed in the introduction.<sup>183</sup> Therefore, Pu-238 is considered the standard fuel for radioisotope power systems. Strontium-90 was used in approximately 1000 RTGs by the former Soviet Union for remote lighthouses and instruments.<sup>184</sup> Figure D2 shows PU-238 as the longest living RTG fuel. Sr-90 is the third longest lived, but has a half-life 59 years shorter than Pu-238.

Another important aspect of RTG fuel is power density. Power is the rate of using energy and power density is power available per unit volume. This can be turned into power per unit weight as used in Figure D3. According to Figure D3, Pu-238 has a very low power density compared to other options. Sr-90 is slightly better, but still nowhere near the top of the list. However, it must be noted that the higher power density corresponds with rapid decay, a very short half-life, and are very strong radioactive emitters. Since most RTG applications are intended for very long missions, power density is not as important as half-life or safety. Power density is mainly a concern for spaceflight where the power per weight ratio is very important since every kilogram is extremely expensive to launch into space. Power density is a not important for terrestrial RTG applications.

<sup>182</sup> Kulcinski, G. (2000). *NEEP 602 Course Notes (Spring 2000): Nuclear Power in Space*. Retrieved December 6, 2010, from <http://fti.neep.wisc.edu/neep602/SPRING00/neep602.html>

<sup>183</sup> Sutliff, G. S. (2008). Radioisotope Power: A Key Technology for Deep Space Exploration. *IAC*.

<sup>184</sup> Alimov, R. (2005, April). *Radioisotope Thermoelectric Generators*. Retrieved December 9th, 2010, from Bellona: [http://www.bellona.no/bellona.org/english\\_import\\_area/international/russia/navy/northern\\_fleet/incidents/37598](http://www.bellona.no/bellona.org/english_import_area/international/russia/navy/northern_fleet/incidents/37598).

### Power Density in RTG Isotopes

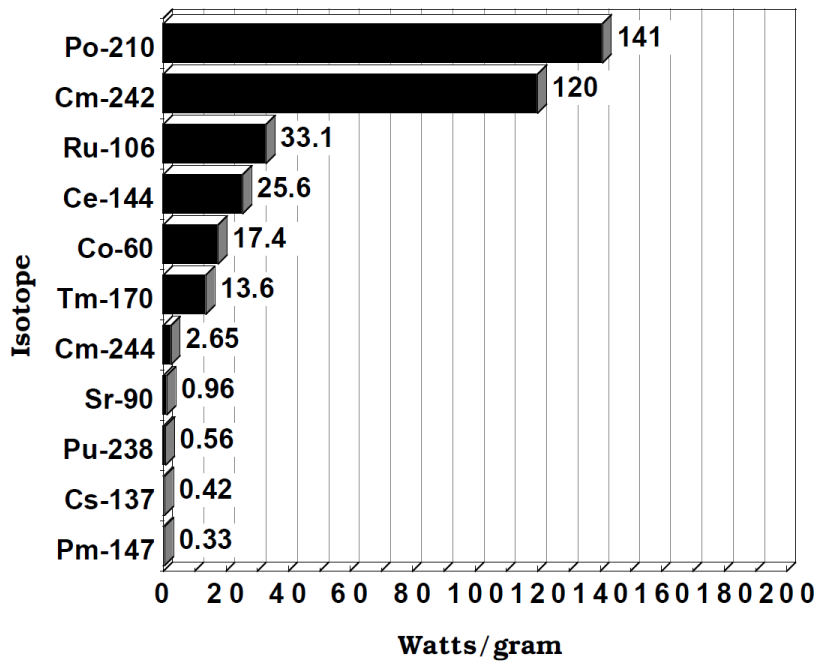


Figure D3: Power densities of various RTG fuel isotopes.<sup>185</sup>

The last consideration for RTG fuel is the decay method of the fuel. There are three types of radioactive decay: alpha, beta, and gamma. While effective shielding exists for alpha, beta, and gamma radiation, alpha radiation is preferred due to its relative safety. Figure D4 shows the decay energy and radiation type of different RTG fuels:

<sup>185</sup> Kulcinski, G. (2000). *NEEP 602 Course Notes (Spring 2000): Nuclear Power in Space*. Retrieved December 6, 2010, from <http://fti.neep.wisc.edu/neep602/SPRING00/neep602.html>

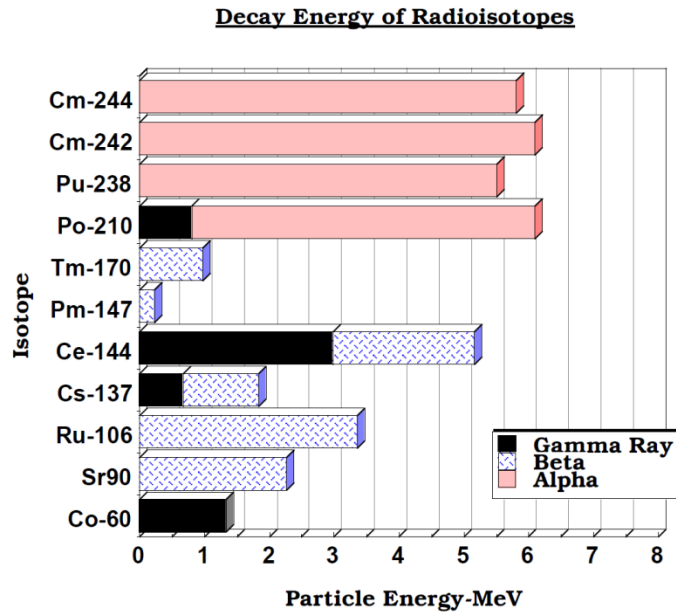


Figure D4: The decay energies and methods of various RTG fuel Isotopes.<sup>186</sup>

The above graph shows Pu-238 is an alpha emitter and is therefore safe with minimal shielding. Sr-90 emits more dangerous beta radiation, but at a low energy.

Each of the above considerations (half-life, power density, and emitted radiation) must be weighed carefully when choosing a radioisotope for power generation. NASA's choice of Pu-238 is a good choice because of its long half-life and relatively safe alpha radiation despite its low power density. The former Soviet Union's preference for Sr-90 is understandable for short missions because of its overall lower energy radiation. Polonium-210 and Curium-242 have the highest power density, but half-lives of less than a year. All of these factors combined with availability produce a cost per kilowatt-hour. Figure D5 displays cost data from the year 2000.

<sup>186</sup> Kulcinski, G. (2000). *NEEP 602 Course Notes (Spring 2000): Nuclear Power in Space*. Retrieved December 6, 2010, from <http://fti.neep.wisc.edu/neep602/SPRING00/neep602.html>

**Energy Cost For Fuel Only For Reasonable Missions**

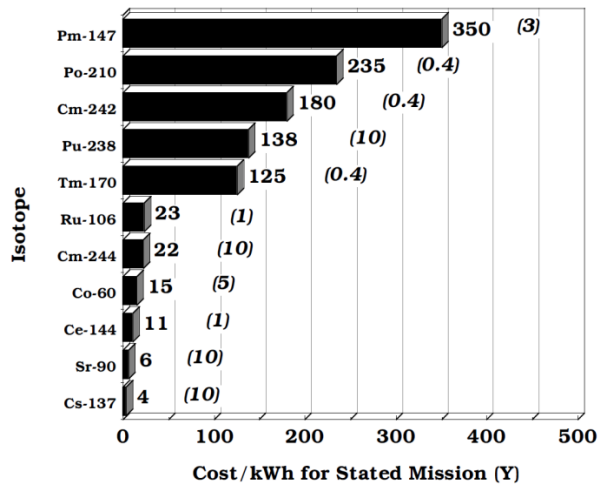


Figure D5: Cost per kilowatt-hour of various RTG fuel isotopes.<sup>187</sup>

**Safety**

Safety is a concern for any method of power generation. Radiation safety requires continuous monitoring since radiation cannot be detected by any of the five senses. Unlike nuclear reactors, RTGs do not employ a nuclear fission or fusion reaction. Therefore, the material cannot undergo a chain reaction leading to an explosion. In fact, none of the potential fuel sources are fissile meaning that they cannot sustain a nuclear chain reaction for power generation or warfare. RTGs generate heat passively which is then converted into electricity. In essence, the RTG fuel is placed in a shielded box and left alone to operate. This means that the safety requirements are the same as storage safety requirements for radioactive material. The US Congress Office of Technology Assessment, with regards to the Burnt Mountain RTGs, states “The probability of any accident –with the exception of dedicated vandalism—causing a release of radioactive material to the environment is very low.”<sup>188</sup> The report goes on to say that no natural disasters pose a risk of releasing radioactive material to the environment. Furthermore, the radionuclides would be contained in a rather inert ceramic material if released into the environment, which is easy to clean up.

The collapse of the former Soviet Union left hundreds of RTGs to the elements.<sup>189</sup> While the generators themselves will operate for decades without maintenance, the enclosures they are contained in may not. There have been a few reports of nuclear contamination at some of the Russian RTG sites.<sup>190</sup> This has led to a poor political climate for the technology. Also, unguarded

<sup>187</sup> Kulcinski, G. (2000). *NEEP 602 Course Notes (Spring 2000): Nuclear Power in Space*. Retrieved December 6, 2010, from <http://fti.neep.wisc.edu/neep602/SPRING00/neep602.html>

<sup>188</sup> U.S. Congress, Office of Technology Assessment. (June 1994). *Power Sources for Remote Arctic Applications, OTA-BP-ETI 129*. Washington, DC.

<sup>189</sup> Alimov, R. (2005, April). *Radioisotope Thermoelectric Generators*. Retrieved December 9th, 2010, from Bellona: [http://www.bellona.no/bellona.org/english\\_import\\_area/international/russia/navy/northern\\_fleet/incidents/37598](http://www.bellona.no/bellona.org/english_import_area/international/russia/navy/northern_fleet/incidents/37598)

<sup>190</sup> Alimov, R. (2005, April). *Radioisotope Thermoelectric Generators*. Retrieved December 9th, 2010, from Bellona: [http://www.bellona.no/bellona.org/english\\_import\\_area/international/russia/navy/northern\\_fleet/incidents/37598](http://www.bellona.no/bellona.org/english_import_area/international/russia/navy/northern_fleet/incidents/37598)

radioactive materials can pose a threat if stolen or tampered with. Autonomy is one of the key benefits of using a radioisotope generator, but it is not autonomous if it must be guarded.

### **Commercial Use**

Radioisotope power generation is a proven technology on earth and in space, but not by civilian entities. Bringing an RTG to market will face many obstacles: the technology must be optimized to run terrestrially, security regulations must be drafted, and licensing regulations must be developed. Licensing regulations exist for research institutions to develop and test radioisotope power-generation technology, but there are no regulations for civilian use. Without regulatory framework many aspects of an economic analysis cannot be performed.

### **Conclusion**

Radioisotope generators have earned a good reputation with the space exploration community for a reason. They have operated consistently for decades with no maintenance. This is a feat rarely achieved by any power source. RTGs can also have a terrestrial niche in remote power generation for power levels of a few tens to a few hundreds of watts. The Air Force pioneered this technology on Fairway Rock Island, but has since shied away from RTGs.

RTGs designed for space must be lightweight, efficient, and physically small. Efficiency is still important on Earth, but size and weight are not limiting factors. A lower density fuel that is cheaper may be more than adequate in large amounts. Larger fuel geometries that maximize surface area may also improve the power output of terrestrial RTGs. The previous terrestrial RTGs were crude experiments done between the 1960s and 1980s. A modern commercial design could be made to effectively meet a wide range of low power needs.



## Appendix E: Fukushima Power Plant Events: March 2011

The recent Fukushima Dai-ichi power plant events have dominated international news, and have sharply [eroded support](#) for nuclear power around the world. At the time of this writing (March 23, 2011), less than two weeks after the 9.0 earthquake and resulting 40 ft. tsunami, it is still not clear that the situation is under control, as reports indicate that [additional radiation](#) is continuing to leak from these plants. However, a preliminary summary of these events is available on [Wikipedia](#), with updates provided as new information is available.

What can be stated with some certainty is as follows:

- The coolant system in Reactor 1 was damaged in the earthquake leading to a partial meltdown, resulting in a declaration of emergency leading to an evacuation near the plant almost immediately after the earthquake.
- Backup diesel generators provided power to the other reactors immediately after the earthquake, but these were rendered inoperable by the tsunami. On-site power from other reactors was not available, as all units shut down during the earthquake, and power lines providing off-site power were destroyed by the tsunami. This left the emergency battery backup as the only source of power for cooling systems in the remaining reactors, but the battery was only rated for 8 hours of operation. The subsequent power blackout was the direct cause of the damage to reactors 2,3 and 4.
- Once the cooling systems failed due to the lack of power, reactors 2 and 3 began overheating due to decay heat, resulting in boiling of the water in the reactor, over pressurization, release of steam to the suppression chamber inside the containment system, and eventually to the need to vent steam to the secondary containment. Eventually, fuel rods were uncovered and the reactor core suffered partial meltdown, with the melting metal from the fuel rod cladding reacting with steam to form hydrogen. When venting occurred, hydrogen formed an explosive mixture with air, resulting in explosions in reactors 1 and 3.
- Spent fuel pools also require cooling during normal operations, and began overheating. The spent fuel pool in reactor 4 contained active fuel (removed from the reactor pressure vessel for maintenance), and was reportedly on fire on March 14. This was of major concern, as these spent fuel pools are located outside the primary containment system, and an explosion or vigorous fire could loft radioactive particles high into the atmosphere and contaminate large areas.
- Efforts to cool reactors using mechanical pumps and seawater began, using a “bleed and feed” cycle—pressure would be released from the system by venting steam (and radioactive gasses), allowing water to be pumped into the reactor. However, the use of corrosive seawater indicated that the power plants would never operate again.
- Radioactive releases from the plant occurred during several discrete events. The predominant source of radioactivity is I-131, which indicates that the majority of the

radiation is from the active reactors rather than the spent fuel pools. Since I-131 has a half-life of 8 days, most of the radioactivity should naturally decay within a few months.

- It does not appear at this time that any of the workers at the plant were exposed to lethal levels of radiation. However, the danger of additional explosions and fires is not yet over, and the clean-up process is not yet begun, so there remains ample opportunity for overexposure to occur.
- It is not expected that any measureable effect on public health will be observed, as evacuation zones removed residents from areas with the highest exposures, and levels at greater distances have been well below thresholds where effects are expected.
- However, the use of seawater to cool the damaged reactor cores, and the subsequent flushing of this water back to the sea, may have resulted in release of radioactive materials.

It is not clear how the events at the Fukushima Dai-ichi Power Plant will play out, or what long-term effect they will have on public opinion for nuclear technology. However, the following points should be noted:

- Existing light water nuclear power plants are critically dependent on the flow of cooling water to maintain safe temperatures both during normal operations, and during a period of several days following reactor shutdown. Either damage to the primary cooling loops (as occurred during the earthquake on Reactor 1), or the absence of power to the cooling pumps (as a result of the loss of all 4 backup power systems) can result in overheating, exposure of fuel to very high temperatures, and reactor core damage resulting in unintended (and somewhat uncontrolled) releases to the surroundings.
- SMR technology addresses the above issue in several ways, including 1) use of technologies that can survive “loss of coolant” type accidents (such as the high temperature gas reactors like the pebble bed technology), 2) use of smaller reactor cores that are easier to cool with appropriately sized passive thermal buffers, and therefore less likely to result in damage to fuel containment systems, and 3) designing the reactors to use passive convective currents to maintain cooling during loss of power incidents (the NuScale reactor and Toshiba 4S designs exhibit this feature).
- The storage of spent fuel is likely to require additional attention.

## Japan Earthquake Nuclear Plant Events

**American Nuclear Society briefing document on Japan Nuclear event,** 3/12/2011

[http://xa.yimg.com/kq/groups/1224833/149161002/name/ANS\\_Japan\\_Background.pdf](http://xa.yimg.com/kq/groups/1224833/149161002/name/ANS_Japan_Background.pdf)

Indicates that off-site power was lost when power lines were "swept away" by Tsunami. Indicates that diesel engine problems were due to contamination of the fuel. Indicates that the zircalloy tubing is oxidizing. Hydrogen is released from this oxidation.

**Radiation exposure from nuclear accident NY Times** 3/13/2011

<http://www.nytimes.com/2011/03/14/world/asia/14health.html?ref=asia&pagewanted=print>

Indicates that several plant workers may be suffering from radiation exposure

**Fukushima Nuclear accident--The Energy Collective** 3/13/2011

<http://theenergycollective.com/barrybrook/53461/fukushima-nuclear-accident-simple-and-accurate-explanation>

Layman's explanation of nuclear accident.

**New York Times article on Japanese Reactor Disaster, March 2011** 3/13/2011

<http://www.nytimes.com/2011/03/14/world/asia/14nuclear.html?hp>

Description of problems with Japanese nuclear power plant--caused by earth quake followed by Tsunami, which flooded back-up diesel generators.

**NY Times--Spent fuel pool fires and potential radiation release** 3/14/2011

<http://www.nytimes.com/2011/03/15/world/asia/15fuel.html?ref=asia&pagewanted=print>

Spent fuel pools require active cooling--if they are not cooled, water might start boiling in a week or so, and eventually start on fire. The fire in the spent fuel pool in reactor 4 is not encouraging.

**Japan faces Nuclear Disaster as Radiation Levels Rise--NY Times** 3/14/2011

<http://www.nytimes.com/2011/03/15/world/asia/15nuclear.html?pagewanted=print>

Potential of containment leak reported

**Spent Fuel Fire on reactor #4--Reuters** 3/14/2011

<http://www.reuters.com/article/2011/03/15/us-japan-nuclear-pools-idUSTRE72E60L20110315?pageNumber=1>

Discussion on the hundreds of tons of material in the spent fuel pool on top of the reactor buildings, and the possibility that if the fuel is uncovered, it may catch on fire and release particles into the atmosphere.

**Radiation could curtail efforts of workers--NY Times** 3/14/2011

<http://www.nytimes.com/2011/03/15/science/15workers.html>

Discusses levels of radiation exposure by plant workers

**IAEA Reports on Japanese Nuclear plant events** 3/14/2011

<http://www.iaea.org/newscenter/news/tsunamiupdate01.html>

Description of venting of gases from nuclear power plant--somewhat contradictory statements...

**Partial Meltdowns presumed at crippled plants--NY Times** 3/14/2011

[http://www.nytimes.com/2011/03/15/world/asia/15nuclear.html?\\_r=1&hp=&pagewanted=print](http://www.nytimes.com/2011/03/15/world/asia/15nuclear.html?_r=1&hp=&pagewanted=print)

Contains reports of releases of radiation and "feed and bleed" pumping of seawater into reactors, followed by allowing steam to vent.

**World Nuclear News article on Loss of Coolant at Daiichi 2** 3/14/2011

[http://www.world-nuclear-news.org/RS\\_Loss\\_of\\_coolant\\_at\\_Fukushima\\_Daiichi\\_2\\_1403113.html](http://www.world-nuclear-news.org/RS_Loss_of_coolant_at_Fukushima_Daiichi_2_1403113.html)

Report indicates that fuel in reactor 2 was exposed to air, and likely resulted in damage to fuel. Radioactive materials in steam released from reactor confirms fuel damage. Attempts to inject water into core area are stymied by high pressure from steam generated.

**Radioactive Releases could last for months** 3/14/2011

<http://www.nytimes.com/2011/03/14/world/asia/japan-fukushima-nuclear-reactor.html?ref=todayspaper&pagewanted=print>

Indicates that there is damage to at least one of the reactor cores. Emergency power needs to be sent through switch gear in the basement of the plant, which is flooded. Gages showing water levels inside the reactor are not working, so they don't know how much water is in the reactors. Attempts to inject seawater mixed with boron are complicated by pressure inside the containment. Explosion of top is intentional--releases pressure without damaging the

**Timeline of the Japanese nuclear events--IEEE** 3/15/2011

<http://spectrum.ieee.org/tech-talk/energy/nuclear/timeline-the-japanese-nuclear-emergency>

Timeline of events at Japanese nuclear power plant.

**Fires Flare up--MSNBC** 3/15/2011

[http://www.msnbc.msn.com/id/42084187/ns/world\\_news-asiapacific/](http://www.msnbc.msn.com/id/42084187/ns/world_news-asiapacific/)

First reports of fuel damage on reactors 1 and 2

**Radiation levels much higher at Japanese plant--NY Times** 3/16/2011

<http://www.nytimes.com/2011/03/17/world/asia/17nuclear.html?pagewanted=3&hp>

US NRC commissioner warned that radiation levels are very high at the plant--"lethal within a short amount of time"--due largely to the fire in the spent fuel pool on reactor 4.

**Status of the Nuclear Reactors at the Fukushima Daiichi Power Plant, NY Times** 3/16/2011

<http://www.nytimes.com/interactive/2011/03/16/world/asia/reactors-status.html?ref=asia>

Shows the status of each of the six reactors as of 3/16/2011

**Japanese workers return to the plant: Associated Press** 3/16/2011

<http://www.clarionledger.com/article/20110316/NEWS02/110316013/1001/news/japan-nuclear-emergency-workers-return-plant>

Workers return to plant after briefly retreating due to high radiation levels. Indicate that 70% of fuel is damaged on reactor 1 and 33% damaged on reactor 2. Discussion about lack of information from utility or government officials.

**Q&A at the NY Times about Japanese Reactor events** 3/16/2011

<http://green.blogs.nytimes.com/2011/03/16/q-and-a-on-the-nuclear-crisis-in-japan/?hp>

Questions and responses on radioactive fallout in US, and on events in Japan.

**Peril and Confusion at Japanese Plant--NY Times** 3/16/2011

[http://www.nytimes.com/2011/03/17/world/asia/17nuclear.html?\\_r=1&hp](http://www.nytimes.com/2011/03/17/world/asia/17nuclear.html?_r=1&hp)

Report indicates concern that the "containment" had cracked on reactor 3, but Japanese officials seem to think this is a less severe problem than previously. Indications that pumping of water into the reactors is continuing even when workers need to pull back due to high radiation levels.

**Radiation levels at Plant** 3/16/2011

<http://www.nytimes.com/interactive/2011/03/16/world/asia/20110316-japan-quake-radiation.html?ref=asia>

Graphic showing radiation levels measured at plant perimeter--showing effects of various explosions and fires. Levels as high as 400 mSV per hour given for one measurement between two reactors.

**Fire and steam explosion--IEEE article** 3/16/2011

<http://spectrum.ieee.org/tech-talk/energy/nuclear/fire-and-steam-at-japans-damaged-nuclear-plant-spread-radiation-worries>

Discussion of cause of fire from spent fuel pool at reactor 4. Could have been caused by water sloshing from pool due to earthquake.

**Japanese engineers strive to restore power to avert catastrophe--Reuters** 3/17/2011

<http://www.reuters.com/article/2011/03/17/us-japan-quake-idUSTRE72A0SS20110317?view=large>

Attempts to restore power to the crippled nuclear power plants are underway, but have not yet been successful. If power can be restored, and pumps can be made operable, water can be pumped in to cover the fuel in the spent fuel ponds. Water levels have been restored in reactors.

**No water in spent nuclear fuel pools--NRC--yahoo news** 3/17/2011

[http://news.yahoo.com/s/ap/20110317/ap\\_on\\_bi\\_ge/us\\_japan\\_quake\\_spent\\_fuel\\_9](http://news.yahoo.com/s/ap/20110317/ap_on_bi_ge/us_japan_quake_spent_fuel_9)

NRC commissioner states that there is no water in the spent fuel pools--but the Japanese disagree, or don't think it matters

**Safety of GE Mark 1 reactors questioned--McClatchy** 3/18/2011

<http://www.mcclatchydc.com/2011/03/17/110648/safety-of-japanese-reactors-questioned.html>

Article cites the GE 3 that questioned the safety of the containment system--concerns that it couldn't take the pressure. But the article quotes Harold Denton indicating that the Fukushima issue is the complete loss of power at the plant

**Boiling Water Reactor--Wikipedia page** 3/18/2011

[http://en.wikipedia.org/wiki/Boiling\\_water\\_reactor](http://en.wikipedia.org/wiki/Boiling_water_reactor)

Wikipedia page for Boiling Water Reactor. Discussion on difficulties associated with 2-phase flow in reactor.

**US Experts believe Japanese spent fuel pool has a breach in the wall of the** 3/18/2011

**Spent fuel pool.**

<http://gazettenet.com/2011/03/18/us-experts-believe-japanese-spent-fuel-pool-has-breach-wall-or-f>

Report that US officials believe that there may be a crack in the spent fuel pool in reactor number

**Japan lays power cable in race to stop radiation** 3/18/2011

<http://www.reuters.com/article/2011/03/18/us-japan-quake-idUSTRE72A0SS20110318>

Utility engineers laid cable to connect grid to Fukushima reactors, but need to string wire between reactor buildings

**Decay Heat--Wikipedia article** 3/18/2011

[http://en.wikipedia.org/wiki/Decay\\_heat](http://en.wikipedia.org/wiki/Decay_heat)

Decay heat curves given--heat rate drops from 6% to 1% in about 2.4 hours--so the diesel generators and the batteries worked during the most critical part of the shutdown.

### **Radiation Spreads--Measured by US Aircraft--NY Times**

3/18/2011

<http://www.nytimes.com/2011/03/18/world/asia/18intel.html?pagewanted=2& r=1&ref=todayspaper>

Radiation measured from a US aircraft--higher levels seen close to plant, but not further out--also discusses the desperate attempts to cool reactors and spent fuel pools.

### **What went wrong at the Fukushima plant?--IEEE**

3/19/2011

<http://www.nytimes.com/2011/03/20/world/asia/20japan.html?pagewanted=1& r=1&hp>

Discussion on the various events at the Fukushima power plants.

### **Executives may have lost time on reactors--NY Times**

3/19/2011

<http://www.nytimes.com/2011/03/20/world/asia/20time.html?pagewanted=2&tntemail1=y& r=1&emc=tnt>

Executives may have delayed on ordering seawater to flood plants--GE reactors have very clear guidelines on temperatures and pressures for flooding, but using seawater ruins the plants-- Executives may have delayed the pumping of seawater for hours to try to save the plants.

### **Deconstructing the Fukushima Plant design**

3/19/2011

<http://www.nytimes.com/2011/03/20/weekinreview/20wald.html?emc=tnt&tntemail1=y>

Discusses why boiling water designs are preferred (allowing steam bubbles to form between fuel rods allows control over the reaction rate and some load following ability for the plant), and why spent fuel ponds are located at the top of the reactor (fuel must be kept underwater when it is moved, so it is easy to do this with a spent fuel storage area at the top).

### **Radioactive Iodine found in food 90 miles from plant--NY Times**

3/19/2011

<http://www.nytimes.com/2011/03/20/world/asia/20japan.html?pagewanted=1& r=1&hp>

Low levels of Iodine 131 were found in milk and spinach near Fukushima, but not in other foods yet.

### **Japanese Reactors More Stable, but Contamination Spreads--NY Times**

3/20/2011

<http://www.nytimes.com/2011/03/21/world/asia/21japan.html?pagewanted=2&tntemail1=y&emc=tnt>

Reactors are being brought under control, but contamination is spreading, with reports of I-131 in spinach and milk. 25 workers are reported to have been exposed to radiation levels above the legal limits. 2 workers are missing, one dead (from a crane accident).

### **Radiation, once free, can follow a tricky path--NY Times**

3/21/2011

<http://www.nytimes.com/2011/03/22/science/earth/22food.html?emc=tnt&tntemail1=y>

Discusses the way radiation is deposited and moves through the food chain. Radioactive Iodine is dangerous because it can accumulate in the thyroid, but it has a very short half-life. Cesium is not as hot, but persists for centuries.

**UN Agency for International Atomic Energy Agency not effective in Japan Crisis** 3/22/2011

[http://www.nytimes.com/2011/03/22/world/asia/22iht-atomic22.html?\\_r=1&emc=tnt&tntemail1=y](http://www.nytimes.com/2011/03/22/world/asia/22iht-atomic22.html?_r=1&emc=tnt&tntemail1=y)

Discusses comments made by the head of the IAEA indicating that the IAEA was not able to effectively communicate to the public about the level of radiation releases from the Fukushima plants.

**IAEA Event Log for Fukushima event** 3/22/2011

<http://www.iaea.org/newscenter/news/tsunamiupdate01.html>

Event log being updated with data including temperatures of spent fuel pools.

**Nuclear Power loses support in new CBS poll** 3/23/2011

<http://www.nytimes.com/2011/03/23/us/23poll.html?emc=tnt&tntemail1=y>

New CBS poll shows that public support for nuclear power in the US has eroded sharply after the events in Fukushima.

**UN Watchdog: Source of Radiation Leaks Unclear: NPR** 3/23/2011

<http://www.npr.org/2011/03/22/134755891/urgent-work-continues-at-japanese-nuclear-plant>

Radiation is continuing to leak from the Fukushima Power Plant site, but the source of this continued leaking is not clear. Article also discusses the evacuees

**Japan Nuclear Crisis revives US fight over spent fuel--NY Times** 3/23/2011

<http://www.nytimes.com/2011/03/24/us/24yucca.html?ref=todayspaper>

Discussion on Yucca Mountain--rock was thought to be impermeable, but has cracks that allow rapid transport of nuclear material. Texas and Washington also have sites, but had powerful political players in the 1980s when decisions were made.

**Radiation with Dots: Randall Munroe** 3/23/2011

<http://hereandnow.wbur.org/2011/03/23/radiation-dots-sound>

Cartoonist illustrated with dots the levels of radiation exposure from various everyday activities and nuclear events, including Fukushima, TMI, and Chernobyl.

**Radiation is a danger only after drinking 58,000 glasses of milk--NPR** 3/23/2011

<http://www.npr.org/blogs/health/2011/03/22/134746912/radioactive-milk-only-a-danger-after-58-000-glasses>

Radiation has been discovered in food and water in Japan, but at levels so low that they are unlikely to have detectable effects on health.



### **Wikipedia page on Fukushima event**

3/23/2011

[http://en.wikipedia.org/wiki/Fukushima\\_I\\_nuclear\\_accidents](http://en.wikipedia.org/wiki/Fukushima_I_nuclear_accidents)

Extensive write up on Fukushima accident, PDF created on 3/23/11.

### **New Problems arise at Fukushima Power Plant**

3/23/2011

[http://www.nytimes.com/2011/03/24/world/asia/24nuclear.html?\\_r=1&emc=tnt&tntemail1=y](http://www.nytimes.com/2011/03/24/world/asia/24nuclear.html?_r=1&emc=tnt&tntemail1=y)

Problems with accumulation of salt from use of seawater to cool reactors is given--if the salt coats the zircalloy tubing, this can prevent cooling water from reaching the tubes, allow melting, and release radioactive Iodine gas. However, at least some of the seawater has been returned to the ocean, meaning that at least some of the salt has been removed from the reactors.

### **Panic may slow development of nuclear power in China--NY Times**

3/23/2011

<http://www.nytimes.com/2011/03/24/world/asia/24iht-letter24.html?pagewanted=2&tntemail1=y&emc=tnt>

Discussion on the panic buying of Iodized salt, regular salt, and soy sauce in China as a response to the Japanese nuclear events. Goes on to discuss the Chinese energy planning process, and the jailing of a corrupt official responsible for nuclear power.

### **It could happen here--Frank Von Hippel**

3/23/2011

<http://www.nytimes.com/2011/03/24/opinion/24Von-Hippel.html?pagewanted=2&tntemail1=y&emc=tnt>

Opinion page piece on the US NRC developing a cozy relationship with the industry it is supposed to regulate, and the problems that creates. Notes that Chernobyl is likely to cause 10,000 cancer deaths, a rate equal to that of the deaths from coal plants in the US alone on an annual basis. Also suggests developing safer reactors less dependent on cooling pumps, such as the pebble bed reactor.

### **Spent fuel hampers efforts at Japanese Nuclear Power plant**

3/23/2011

[http://www.nytimes.com/2011/03/23/world/asia/23japan.html?\\_r=1&emc=tnt&tntemail1=y](http://www.nytimes.com/2011/03/23/world/asia/23japan.html?_r=1&emc=tnt&tntemail1=y)

Workers needed to add water to the spent fuel pool on reactor #2. Article also contains a general update on the condition of the plant, including a discussion about radioactive fallout at various distances from the plant.

### **Radiation data near plant eases concern about health--NPR**

3/23/2011

[http://www.npr.org/blogs/health/2011/03/20/134658088/radiation-data-near-nuclear-plant-offers-little-cause-for-concern?ps=sh\\_stcathdl](http://www.npr.org/blogs/health/2011/03/20/134658088/radiation-data-near-nuclear-plant-offers-little-cause-for-concern?ps=sh_stcathdl)

Readings taken beyond the 12-mile radius from the Fukushima plant indicate levels near background, except in one area 37 miles from the plant. It is not clear if this elevated area is due to the events at the plant, or some other cause, including strip mines or naturally higher levels. However, levels measured so far do not appear to be a cause for concern.

**Two Workers hospitalized after radiation exposure in plant--LA Times**

3/24/2011

<http://www.latimes.com/news/science/la-sci-japan-workers-exposed-20110324.0.5425809.story>

Two workers were hospitalized when radioactive water seeped through their boots while they were trying to lay electrical cables. Their total radiation exposure was about 180 mSv, very close to the 250 mSv annual dose they are permitted. Skin burns are being treated, but it appears the men are expected to recover.

**Conditions of Fukushima Reactors 3\_24\_11**

3/24/2011

<http://www.nisa.meti.go.jp/english/files/en20110324-2-2.pdf>

Power point slides of each of the six reactors showing places where items of concern remain.

**Japan Raises possibility of breach in reactor**

3/24/2011

[http://www.nytimes.com/2011/03/25/world/asia/25japan.html?\\_r=1&emc=tnt&tntemail1=y](http://www.nytimes.com/2011/03/25/world/asia/25japan.html?_r=1&emc=tnt&tntemail1=y)

Workers exposed to radiation when stringing power cables were exposed when they stepped in highly radioactive water, and it went over their boots. The presence of highly radioactive water in the turbine building seems to indicate some kind of major breach in containment on reactor 3, which is fueled with MOX fuel containing plutonium.

## Appendix F: SMR Document Database Report

There are a great many sources available for information regarding the nuclear power industry in general, and specifically about small modular reactors. In order to keep track of sources, a database was created to collect and organize documents reviewed in the course of this study. In addition, notes from meetings (some public gatherings, others smaller gatherings with industry experts) were also included, as these verbal discussions were often more frank than written documents.

The database was created as a Microsoft Access database, and contains PDF copies of all web-retrievable documents as they appeared at the time of retrieval (an issue especially with sites such as Wikipedia, which usually contain excellent summaries, but may be modified by multiple users at any time). The hyperlink to the web source has also been included, where possible. A short summary of the source has also been written, mostly to attempt to allow future readers to quickly identify sources that may be of continuing interest. At the time of this writing, this database contains more than 200 entries on more than 55 reactors, as well as general references on the industry. It is estimated the total information is probably about 10,000 pages.

The following output from this database is given for the convenience of readers unfamiliar with the database environment (which can be intimidating to the inexperienced user). This summary contains some brief information about the general topic (often a reactor design name), the name of a document (sometimes as given by the author, sometimes simply a description of where the information came from), a hyperlink (if available), and a short description of what information this source contains.

The items listed below are notes from presentations given at the Small Modular Reactor workshop held in Washington, DC, October 18-20, 2010. Presentations were given by only some of the participants, and are not available on the web. However, they are included in the full database assembled by ACEP.

### Amchitka Nuclear Test site information

Amchitka Island was used as a test site for three underground nuclear tests between 1965 and 1971.

#### **Nuclear Flashback: Report of a Greenpeace Scientific Expedition to Amchitka Island, Alaska--Pam Miller**

10/30/1996

<http://web.archive.org/web/20060928190111/http://www.greenpeace.org/raw/content/usa/press/reports/nuclear-flashback.pdf>

Claim to have collected samples that show that the largest nuclear test ever conducted is leaking radiation into the environment.

#### **Modeling Groundwater Flow and Transport of Radionuclides at Amchitka Island's Underground Nuclear Tests: Milrow, Long Shot, and Cannikin**

10/15/2002

<http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=9CB565BA5C66DBE34CB77766BE050C18?purl=/806659-8KjQem/native/>

Modeling of possible transport of radionuclides.

**Amchitka DOE Fact Sheet**

1/1/2006

<http://web.archive.org/web/20070630165411/http://www.lm.doe.gov/documents/sites/ak/amchitka/factsheet/amchitka.pdf>

Indicates Tritium detected at "Long Shot" site (the smallest test), but levels peaked in 1966 below EPA drinking water standards.

**Amchitka -- Wikipedia Page**

12/7/2010

<http://en.wikipedia.org/wiki/Amchitka>

History of the island, including three nuclear tests, and the formation of Greenpeace to oppose the testing. Tests were conducted so that US could learn to tell underground testing apart from earthquakes.

**Project Chariot**

Project Chariot was proposed in the late 1950s as a harbor project for Northwest Alaska, intended to demonstrate peaceful uses of nuclear weapons.

**Time Feb 18, 1957 article on Sr 90 in human bone study**

2/18/1957

<http://www.time.com/time/magazine/article/0,9171,809133,00.html>

Sr 90 was measured in the bones of humans (500 samples) from around the world, detected in all places, attributed to above ground testing, at an average level of .12 pico-Ci per gram of body calcium, although one individual from Vancouver had a level 75X the average.

**Potential Effects of Project Chariot on Local Water Supplies in Northwest Alaska, By ARTHUR M. PIPER**

7/1/1966

<http://www.dggs.alaska.gov/webpubs/usgs/p/text/p0539.PDF>

Gives results from the deliberate spiking of Cape Thompson soils with radioactive ions from soils imported from the Nevada test site. Results are based on 6 small plots, approximately 1 meter square, which was the sole source of the radioactive materials cleaned at the Project Chariot site in 1994.

**Strontium-90 and Cesium-137 Levels in the Milks of Some Arctic Species, B. E. BAKER, B. H. LAUER and E. R. SAMUELS**

9/1/1968

<http://www.journalofdairyscience.org/article/S0022-0302%2868%2987223-6/abstract>

Levels of Sr 90 in the human milk of inland Eskimo women were 100 x higher than that of urban women. Attributed to the concentration of Sr 90 in lichens which were eaten by caribou, which in turn were eaten by humans.

**Project Chariot: Nuclear Legacy of Cape Thopson, by Douglas L. Vandegraff, US Fish and Wildlife Service.**

7/1/1992

<http://arcticcircle.uconn.edu/VirtualClassroom/Chariot/vandegraff.html>

Description of the experiment at Project Chariot

**NRC SECY 10-0034 POTENTIAL POLICY, LICENSING, AND KEY TECHNICAL ISSUES FOR SMALL MODULAR NUCLEAR REACTOR DESIGNS** 3/28/2010

<http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2010/secy2010-0034/2010-0034scy.pdf>

NRC paper on issues of concern for SMR

**ANS Small Nuclear Reactor Report July 2010** 7/15/2010

<http://www.ans.org/pi/smr/ans-smr-report.pdf>

Industry written summary of SMRs

**Technical Training on the Operations of Small Modular Nuclear Reactors** 10/18/2010

Vince Gilbert

Afternoon session, Business Cases, James “Vince” Gilbert, Moderator

- To meet NRC regulations for 10 CFR part 52, need Simulator, need to train operators, need prototype, need workforce plan, knowledge sharing
- TerraPower is “a rather large reactor” because of the long term fuel storage

**Nuconomics: Value Drivers for Scalable Power, Workshop B, InfoCast Summit** 10/18/2010

**on Small Modular Reactors, Glenn R. George, PE, PhD, Washington, DC,**

**October 18, 2010**

Glen George

- There are “fundamental disadvantages of scale” on small systems
- If R&D costs are too high, companies fail
- NPV calculations accentuate immediate returns
- Referred to many of the SMRs as “Paper systems”
- Nuclear power is very uncertain in the short term, but has proved to be very cheap and reliable in the long term
- \$10B up-front costs mentioned as the price of developing a new system
- \$8B for a new plant is a large investment, even for large utilities
- 35 GW of small scale plants that need replacement, mostly small coal systems on the east coast, “brownfield” sites—but these sites are contaminated, often with radioactive isotopes from burning coal, and the politics of putting nuke plants on them is unknown.
- If gas is available at \$4-6, nuclear has a very uncertain future.
- Carbon taxes of \$20-30 per ton, but right now the cost is 0, and it appears that there is no will to change that.
- Diversification of generation is important as a hedge in large markets, but only very large players are concerned about this.
- Electric vehicles might create a new problem—everybody plugs their car in at the same time in the evening, creating a surge in demand, and the need for a smart grid
- There are sweet spots for nuclear power, in the southeast, where they depend on gas from Texas, and in Texas, where they would rather sell the gas than burn it.

**Developing & Evaluating Business Cases for Small Modular Reactors, Reiner Kuhr, Senior Executive Consultant, Shaw Consultants International**

10/18/2010

- Who owns the reactor, who owns the site?
- Smaller plants probably don't have a lower per kWe cost
- If licensing costs are as high for larger sites on a per plant basis, the cost per installed kWe is higher
- Oil sands—need to renew permits every six months—are interested in nuclear, but concerned about public opposition
- “First of a Kind” (FOAK) engineering
- State of Indiana has signed a 30 year purchase agreement for syngas—will float a pipeline project—need \$10-12 gas to float the project
- Potential sites for SMRs in US include mines and military bases
- Tritium “tends to go everywhere and get people excited”

**NRC Annual Licensing fees for SMRs, Pareez Goulb**

10/18/2010

Proposed licensing fees for small reactors (has a low fixed fee, and a high fixed fee, cost per kWe in between)

**NRC--Small Modular Reactor Licensing issues--Stewart Magruder**

10/18/2010

- There is some work being done on new fast reactors
- NRC publication SECY 10-3410 (March 2010)
- There are several dozen new reactor designs
- The NRC expects to make rule changes, but wants to see experiments first.
- iPWR (Integral Pressurized Water Reactor) likely to be approved first.
- Trying to streamline the application process
- There will always be a need for emergency planning.
- Physical security—can the security staff be reduced?
- Offshore Power Systems—company obtained a manufacturing license to build large nuclear power plants off the east coast in 1982—company failed.
- NRC might change regulations after some experience
- NRC takes input in the form of white papers, but the decision process is not to be rushed.
- Price Anderson insurance requirements might be excessive—Congress may act.
- NRC is focused on safety, industry needs to be focused on cost.
- NO MENTION of application from Toshiba in presentation, first application expected from NuScale in December 2011
- DOE provides the licensing basis from demonstration plants, but the NRC needs to check QA.
- NRC can license a prototype.
- During Q&A, when asked, stated that “Toshiba asked that their letter to the NRC be held in confidence”, so did not directly state that Toshiba had withdrawn, but also did not indicate

that Toshiba was moving forward in any way. Others noted that Toshiba no longer appears to have a customer.

**Small Scale Modular Reactor Licensing Issues, Bud Haemer**

10/18/2010

Presentation from a legal point of view of licensing issues. There are many, but it appears that congress and the NRC are moving to accommodate these issues, including staffing, emergency protection zones, fees, etc. Slide 12 talks about the staffing of the control room which requires 4 operators per shift, which would mean that the Toshiba 4S reactor would be required to maintain between 40 and 80 trained operators on staff.

Budd Haemer

- “If you have to ask how much it costs, you shouldn’t be in nuclear”. There is always something cheaper and easier than nuclear power.
- Building smaller cheaper reactors with a core life of 30 years.
- Off Shore Power (OPS) didn’t get a license because of SAMDA
- Federal regulations on “Fuel Cycle Activities”

**SMR Licensing issues**

10/18/2010

Tyson Smith

- “Walking across the river one stone at a time.”
- Best case for NRC review is 5 years for a new technology (slide 11)
- NRC will likely not have the resources to review every design, and are focusing on ones where there is a customer.
- Need for applicant to have a “stable application”
- Safety review is much larger than the environmental review.
- TerraPower is going to China.
- Regulatory process is “incompatible with SMR reactor”

**Spent Fuel Issues: Myth and Reality, John H. O’Neill, Jr., A SMR Perspective**

10/18/2010

John H. O’Neill, Jr., Partner, Pillsbury Winthrop Shaw Pittman LLP

- In the US, spent fuel is a government problem—the federal government has agreed to take fuel at end of life, and has been collecting a \$0.001 per kWh fee for disposal of spent fuel—now has accumulated \$25B fund.
- Fuel Storage Solutions—a private company—tried to get a license for fuel storage, but their facility is not operable, and the company is no longer in business
- There are 34 sites in the US with dry cask storage.

- 95% of the fuel value remains in the spent fuel (the reaction products poison the neutrons and must be removed from the fuel—which is why fuel need to be “re-processed”)
- If Yucca Mountain were called a “Strategic fuel storage” facility rather than a nuclear waste dump, it probably wouldn’t incite such strong political opposition.
- Problem—cost of Uranium is less than the cost of reprocessing.
- Waste is a political problem—Yucca mountain is a perfect place to store spent fuel, until it can be reprocessed.
- NRC (1984) “We are confident there is a solution to the waste issue”
- Finland, Sweden, and France are all operating reprocessing facilities.
- Small fast reactors could use reprocessed fuel
- SMRs might be a product of a government program to deal with nuclear waste
- Right now, LWRs (Light Water Reactors) are “licensable” while fast SMRs are not
- Koreans have built more reactors in the last 20 years than anyone else in the world.
- New fuel cycles will need new core designs, require higher levels of enrichment, but cores could last for up to 30 years.
- Reprocessing into fuel cost more than mining Uranium
- Problem with low level waste—there is no approved place to ship it, so every plant license needs to be litigated
- Spent fuel storage is the responsibility of the government, and is currently costing \$500M per year (cannot use the fees collected to date, because they are not providing a storage site as agreed to by contract.

**SMR Licensing Issues, Steve Frantz** 10/18/2010

Summary of several possible paths to license.

- Noted that it takes 13 years to build a plant—5 years for design certification, 4 years for licensing, 4 years for construction
- Building a pilot plant still take 13 years.
- The plant for the Pebble Bed reactor was to do an offshore demonstration in South Africa, but they changed their design and ran out of money.
- You can also get a license followed by certification, but this is very risky.
- For operating plants, there is a \$4M per reactor per year licensing fee to the NRC
- NRC is working at reducing this cost for SMR
- Multiple reactors greater than 100 MWe treated as a single unit.
- “Span of control” issues—new reactor designs, operator is required to do less (many times the best reaction is to do nothing—need to train operators to do nothing)
- Need to identify “Design Basis Accidents”
- Pilot plant may be required for non-light water designs (i.e., Toshiba 4S could not be sited directly in Galena)
- Imports—but you still need a license to possess a reactor.



## Small Modular Reactors of interest to Alaska

### *Toshiba 4S Reactor*

Developer Name: **Toshiba**

Technology: **Liquid Metal Reactor**

Size Thermal (MWt): **30**

Preliminary Design Review Stage

Size Electrical (MWe): **10**

Technology Description (from literature):

The Super-Safe, Small & Simple (4S) 'nuclear battery' system is being developed by Toshiba and the Central Research Institute of Electric Power Industry (CRIEPI) in Japan in collaboration with SSTAR work and Westinghouse (owned by Toshiba) in the USA. It uses sodium as coolant (with electromagnetic pumps) and has passive safety features, notably negative temperature and void reactivity. The whole unit would be factory-built, transported to site, installed below ground level, and would drive a steam cycle via a secondary sodium loop. It is capable of three decades of continuous operation without refueling. Metallic fuel (169 pins 10mm diameter) is uranium-zirconium enriched to less than 20% or U-Pu-Zr alloy with 24% Pu for the 10 MWe version or 11.5% Pu for the 50 MWe version. Steady power output over the core lifetime is achieved by progressively moving upwards an annular reflector around the slender core (0.68m diameter, 2m high in the 10 MWe version; 1.2m diameter and 2.5m high in the 50 MWe version) at about one millimeter per week. After 14 years a neutron absorber at the center of the core is removed and the reflector repeats its slow movement up the core for 16 more years. Burn-up will be 34 GWday/t. In the event of power loss the reflector falls to the bottom of the reactor vessel, slowing the reaction, and external air circulation gives decay heat removal. A further safety device is a neutron absorber rod which can drop into the core. After 30 years the fuel would be allowed to cool for a year, then it would be removed and shipped for storage or disposal.

Both 10 MWe and 50 MWe versions of 4S are designed to automatically maintain an outlet coolant temperature of 550°C – suitable for power generation with high temperature electrolytic hydrogen production. Plant cost is projected at US\$ 2500/kW and power cost 5-7 cents/kWh for the small unit– very competitive with diesel in many locations. The design has gained considerable support in Alaska and toward the end of 2004 the town of Galena granted initial approval for Toshiba to build a 10 MWe (30 MWt) 4S reactor in that remote location. A pre-application Nuclear Regulatory Commission (NRC) review is under way with a view to application for design certification in October 2010 (delayed from 2009 by NRC workload), and combined construction and operating license (COL) application to follow. Its design is sufficiently similar to PRISM – GE's modular 150 MWe liquid metal-cooled inherently-safe reactor which went part-way through the NRC approval process (see section below on PRISM) – for it to have good prospects of licensing. Toshiba plans a worldwide marketing program to sell the units for power generation at remote mines, desalination plants and for making hydrogen. Eventually it expects sales for hydrogen production to outnumber those for power supply.

**The L-4S is a Pb-Bi cooled version of 4S.**

<http://www.toshiba.co.jp/nuclearenergy/english/index.htm>

**Alaska Daily News article, October 21, 2003**

1/21/2003

<http://hyvin.nukku.net/no/toshiba.html>

First news article about Toshiba 4S reactor in Galena. Indicates that the cost of electricity should be about 10 cents per kWh. Also notes that getting NRC approval will take 6-8 years, and cost \$600M. Indicates that the reactor needs no operator or maintenance workers. Gives price of \$20M for additional reactors.

**Galena Fax related to Anchorage Daily News Article about Toshiba in Galena**

12/15/2003

<http://wba.nrc.gov:8080/ves/>

Letter indicates that Toshiba is likely to "invade" Galena, refers to article in Anchorage Daily news on 10/21/2003. Also indicates that Marvin Yoder contacted Toshiba after reading their information on the web.

**4S Current Status, April 2004, Alaska Rural Energy Conference Presentation**

4/27/2004

<http://www.uaf.edu/acep/publications/detail/index.xml>

48 page power point with diagrams of 4S

**Galena Power Study—2004—US DOE Arctic Energy Office**

12/15/2004

[None](#)

This study lists the cost of a 10 MWe reactor as \$25M, based on the Toshiba estimate of a cost of \$2500 per kWe based on the larger 50MWe unit. No estimate of cost from Toshiba exists for the cost of the smaller unit.

**NRC PowerPoint from 2\_2\_05**

2/2/2005

<http://wba.nrc.gov:8080/ves/>

Very short PowerPoint presentation that only gives the briefest of NRC overviews, with tribal contact.

**Galena meeting 2/2/2005 at NRC in DC documents**

2/2/2005

<http://wba.nrc.gov:8080/ves/>

Williams Document outlines NRC 10 CFR Part 52 licensing process, and notes that fees are collected for NRC review, and indicated that these fees would be "millions". Marvin Yoder indicated that the city of Galena was interested in an Early Site Permit, and was preparing "White Papers". Public participation was heavy from the Yukon Tribal Watershed council and the Alaska Committee on Toxics.

**Atomic Insights Nuclear Power for Galena, Alaska**

3/20/2005

[http://www.atomicinsights.com/AI\\_03-20-05.html](http://www.atomicinsights.com/AI_03-20-05.html)

View from a competitor (Adams Atomic Engine) noting likely costs of maintaining plant.

**NRC Memo on meeting with Yukon Inter-Tribal Watershed Council, March 2005**

3/28/2005

<http://wba.nrc.gov:8080/ves/>

Meeting between NRC and YITWC, March 2005, in which the NRC stated that it has no formal government to government relations with tribes but does keep them informed. Also stated that NRC is an "independent agency" and is not bound by executive orders, and that it's job is to protect public health and safety, and if these requirements are met, it is obligated to provide a license to operate.

**Letters from Galena to NRC requesting meeting to discuss Burns and Roe "white papers"**

4/19/2006

<http://wba.nrc.gov:8080/ves/>

Request from the city of Galena to NRC to arrange meeting to discuss Burns and Roe "white papers". First letter dated April 7, 2006 requesting meeting late May, 2006. Reply on 4/19/06 says, we'll get back to you.

**NRC Policy Issue Notation Vote SECY-05-0121, and additional letters about the formation and activities of a TCT (Tribal Consultation Team), with .4 FTE designated for this activity.**

5/22/2006

<http://wba.nrc.gov:8080/ves/>

NRC agreement to "consult" tribes (keep them informed, listen), but document is not clear on how this input will be used in NRC review process.

**Brian Yanity 2 part series on 4S reactor for Galena**

9/22/2006

[http://www.insurgent49.com/yanity\\_nuclear2.html](http://www.insurgent49.com/yanity_nuclear2.html)

Summarize history of the nuclear power industry, including sodium cooled near breeder reactors.

**Letter from Union of Concerned Scientists**

11/27/2006

<http://www.yritwc.org/Portals/0/PDFs/nuclearreactorletterucs.pdf>

Letter outlining technical objections to Toshiba 4S project in Galena. Most of the objections are that the technology remains unproved, and that Sodium cooled reactors have been failures, and that the alleged safety features of the 4S have never been proved. The letter is written by David Lockbaum, who has been involved in writing reports about other sodium reactors,

**Yukon River Drainage Fisherman's Association resolution against Galena, and any other nuclear power station in the Yukon River Drainage area.**

2/28/2007

<http://wba.nrc.gov:8080/ves/>

Resolution by YRDFA against Galena NPS. Effort led by Rob Rosenfeld. Dated February 28, 2007.

**Burns and Roe White Papers for Galena**

3/12/2007

[http://www.roe.com/about\\_techGalena.htm](http://www.roe.com/about_techGalena.htm)

"White Papers" prepared by Burns and Roe for NRC review.

|  |            |
|--|------------|
| <b>Toshiba request for Pre-Application meeting, August 24, 2007</b>  | 8/24/2007  |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| Requests pre-application meeting for September 2007  |            |
| <b>Nome letter of support to NRC with respect to Toshiba 4S project</b>  | 10/1/2007  |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| Letter of support for Toshiba 4S in Galena   |            |
| <b>AEL&amp;P Support letter</b>  | 10/7/2007  |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| Support letter for Toshiba 4S review   |            |
| <b>Transcripts of Toshiba Preliminary meeting with NRC October 23, 2007</b>  | 10/23/2007 |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| Transcripts and presentation from Toshiba to NRC, On page 105, line 5, NRC states that the "applicant", i.e., the city of Galena, will be responsible for the siting licensing costs.                        |            |
| During the NRC questioning part of the meeting, questions were asked about the methodology for estimating risks, and a lot of discussion about "beyond design basis accidents". Some questions on materials. |            |
| <b>NRC Tribal Consultation Team letter</b>   | 12/29/2007 |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| <b>Toshiba-NRC 2nd pre-application meeting February 21, 2008</b>   | 2/21/2008  |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| Documents from second pre-application meeting between Toshiba and NRC. In the Toshiba slides, number 5, Toshiba states that it expects a US customer will submit a COL application.                          |            |
| <b>Toshiba Design Description for 4S</b>   | 5/20/2008  |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| Written description of 4S, submitted just before 3rd preapplication meeting with NRC.  |            |
| <b>Toshiba 4S Third Pre-application meeting with NRC</b>   | 5/21/2008  |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| Presents Toshiba review of NRC review process, indicates strategies for meeting safety concerns. Still indicates that they expect a COL Application from a US client.  |            |
| <b>Toshiba comments to NRC</b>   | 6/23/2008  |
| <a href="http://wba.nrc.gov:8080/ves/">http://wba.nrc.gov:8080/ves/</a>  |            |
| Toshiba comments on Draft policy regarding reviews of new reactor designs  |            |

**Toshiba report to NRC, titled "LONG-LIFE METALLIC FUEL FOR THE SUPER SAFE, SMALL AND SIMPLE (4S) REACTOR"** 6/30/2008  
<http://wba.nrc.gov:8080/ves/>  
 Report to NRC on Fuel design. Does not expect NRC to comment.

**Toshiba-NRC meeting--4th pre-application meeting August 8, 2008** 8/8/2008  
<http://wba.nrc.gov:8080/ves/>  
 Presentation focuses on process used to assess safety issues. The NRC summary document dated 8/22/08 indicates that the COL applicant is expected to be the city of Galena.

**NRC Memorandum about pre-application meeting with Toshiba 5/21/2008** 8/8/2008  
<http://wba.nrc.gov:8080/ves/>

**Toshiba-NRC meeting--4th pre-application meeting August 8, 2008** 8/8/2008  
<http://wba.nrc.gov:8080/ves/>  
 Presentation focuses on process used to assess safety issues. The NRC summary document dated 8/22/08 indicates that the COL applicant is expected to be the city of Galena.

**Letter from NRC to Toshiba regarding review effort** 9/18/2008  
<http://wba.nrc.gov:8080/ves/>  
 Indicates that effort on small reactors will be limited

**NRC letter to Galena Mayor September 19, 2008** 9/18/2008  
<http://wba.nrc.gov:8080/ves/>  
 Indicates that the NRC is not working very hard on the issues raised by the Galena white papers.

**E-mail from Deborah Blackwell to Don Carlson, NRC** 9/28/2008  
<http://wba.nrc.gov:8080/ves/>  
 Deborah Blackwell (Hyperion) states that it appears that "Galena is no longer certain..."

**Toshiba Seismic Isolation design report** 2/27/2009  
<http://wba.nrc.gov:8080/ves/>  
 Report prepared to describe the seismic isolation system for the Toshiba 4S reactor.

**Letter from Toshiba to NRC regarding Design Approval Application** 3/13/2009  
<http://wba.nrc.gov:8080/ves/>  
 Letter states that Toshiba intends to file Design Approval Application in October, 2010.

**Toshiba 4S Safety Analysis Report to NRC** 7/28/2009  
<http://wba.nrc.gov:8080/ves/>

**US DoE Web Site on Sodium Reactor Experiment Incident**

8/29/2009

<http://etec.energy.gov/History/Major-Operations/SRE-Workshop-2009.html>

Web site with presentations given at 2009 workshop on the Sodium Reactor Experiment incident in 1959, including library of documents.

**Blog Post from ANS Meeting Nov 2009 with Info on NRC Review of Small**

11/15/2009

<http://diysrv.blogspot.com/2009/11/will-nuclear-renaissance-start-with.html>

Panel presentation indicates that NRC does not have the skills necessary to review fast neutron reactors (both Toshiba 4S and Hyperion), not clear how long the review will take, but the part 52 review looks doable. Water reactors (NuScale) will have an easier time. The issue of keeping a nuclear engineer in Galena to watch the plant was also raised.

**Under the Hood with Duncan Williams**

1/27/2010

[http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2010/01/27/under-the-hood-with-duncan-williams-toshiba-4s-01272.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2010/01/27/under-the-hood-with-duncan-williams-toshiba-4s-01272.aspx)

Describes patents associated with the 4S technology as well as a congressional bill that would provide funding for half the approval process costs through DOE.

**Berkley Forum 2010 Presentation on 4S reactor for Galena**

3/15/2010

<http://bnrc.berkeley.edu/documents/forum-2010/Presentations->

Indicates construction costs for 4S at "only 30 million", and state that Toshiba will apply for NRC approval in October 2010. Indicates that the plant would need only 4 guards and 8 operators.

**NRC Summary Sheet for Toshiba 4S**

3/23/2010

<http://www.nrc.gov/reactors/advanced/4s.html>

Indicates letter of intent sent to NRC on March 23, 2010, and that Galena is still listed as the site of interest.

**Bill Gates Joins with Toshiba with 4S and Traveling Wave reactor projects**

3/23/2010

<http://www.fastcompany.com/1594671/bill-gates-goes-nuclear-with-toshiba-tie-up>

Announce about Bill Gates investing in Toshiba for both 4S and Traveling Wave Reactor projects.

**Wikipedia Page**

9/21/2010

[http://en.wikipedia.org/wiki/Toshiba\\_4S](http://en.wikipedia.org/wiki/Toshiba_4S)

States that the 4S is in preliminary design review, and expected to be approved by 2014

**Wikipedia Report on Sodium Reactor Experiment incident**

9/21/2010

[http://en.wikipedia.org/wiki/Sodium\\_Reactor\\_Experiment](http://en.wikipedia.org/wiki/Sodium_Reactor_Experiment)

Sodium Reactor incident due to leak from oil driven pumps into liquid sodium created deposits that plugged liquid flow paths and caused overheating and partial melting of fuel rods. There continues to be controversy about how much radiation was leaked from this incident.

## **Hyperion**

Developer Name: **Hyperion Power Generation Inc.**

Technology: **Fast Neutron Reactor**

Size Thermal (MWt): **75**

Design--Submit application to NRC in 2012

Size Electrical (MWe): **25**

Technology Description (from literature):

The Hyperion Power Module is a 70 MWt/25 MWe lead-bismuth cooled reactor concept using 20% enriched uranium nitride fuel. The reactor was originally conceived as a potassium-cooled self-regulating 'nuclear battery' fuelled by uranium hydride. However, in 2009, Hyperion Power changed the design to uranium nitride fuel and lead-bismuth cooling to expedite design certification. This now classes it as a fast neutron reactor, without moderation.

The unit would be installed below ground level. The reactor vessel housing the core and primary heat transfer circuit is about 1.5 meters wide and 2.5 meters high. It is easily portable, sealed and has no moving parts. A secondary cooling circuit transfers heat to an external steam generator. The reactor module is designed to operate for electricity or process heat (or cogeneration) continuously for up to 10 years without refueling. Another reactor module could then take its place in the overall plant. The old module would be put in dry storage at site to cool for up to two years before being returned to the factory.

In March 2010, Hyperion notified the US Nuclear Regulatory Commission that it planned to submit a design certification application in 2012. The company says it has many expressions of interest for ordering units. In

September 2010, the company signed an agreement with Savannah River Nuclear Solutions to possibly build a demonstration unit at the Department of Energy site there. (Over 1953-1991, this was where a number of production reactors for weapons plutonium and tritium were built and run.)

<http://www.hyperionpowergeneration.com/>

### **John Reeves Hyperion module for Ester**

6/21/2009

<http://www.adn.com/2009/06/20/838182/fairbanks-man-pursues-nuclear.html>

John Reeves intends to install Hyperion reactor in Ester on 4 acre lot--idea later abandoned when he discovered that the lead time on the reactor was about 12 years.

### **Alaska Railbelt Integrated Resource Plan Small Nuclear Module**

2/1/2010

<http://www.aidea.org/aea/regionalintegratedresourceplan.html>

RIRP includes a single modular nuclear reactor, 27 MWe, installed at Beluga. Also indicates significant risk for permitting unit, and a \$200M permitting cost.

**Hyperion White paper: Uranium Nitride Fuel / HT-9 Cladding / Liquid Lead-Bismuth Coolant: Maturity of Technology for Use in the Hyperion Power Module by Andrew R. Marchese, Consultant (Chamberlain Group), April 7, 2010**

4/7/2010

[GVEA](#)

Uranium Nitride fuel has been tested in small quantities, but has not been produced or used commercially. Cladding in Nb-Zr alloys has been done, and performance was as expected. Some additional testing may be needed to assess corrosion in LBE reactors at high temperatures and neutron fluxes. Advantages include the ability to almost instantly adjust power levels, good heat transfer, resistance to explosions, and compact size. A number of significant safety issues are raised with respect to the use of sodium, including the propensity of liquid sodium to react with concrete and water. LBE has the disadvantage of Po 210 formation, which is a very nasty radiotoxic material if spilled.

**Hyperion Power Module, Description Brochure, August 2010**

8/1/2010

[GVEA](#)

Brochure given to GVEA October 2010. Page 11 indicates a staff of 6 per shift. Construction times given as 9 months. Claims that NuScale and mPower need a staff of 30+ per shift to operate (page 11), but greater power output per module brings the cost per kWh down to a reasonable (2-6 cents per kWh) rate.

**Nuclear Town hall Blog post on Hyperion reactor--interview with Deborah Deal-Blackwell**

9/29/2010

<http://www.nucleartownhall.com/blog/qa-homegrown-hyperion-power-shaking-up-the-world-of-nuclear-energy/>

Interview outlining the virtues of the Hyperion reactor--price of the reactor is given as \$50-75M, and the balance of plant steam turbine systems is \$25-50M, so the total (excluding permitting and site prep) is \$75-125M for a 25 MWe system.

**Press Release announcing demo for Savannah NL, 2017**

9/30/2010

<http://climateerinvest.blogspot.com/2010/09/hyperion-to-build-demonstration-nuke.html>

Press release indicating that papers have been signed for an off-grid demonstration of the Hyperion reactor. Unit should be constructed by 2017 or 2018.

**Alutiq Corporate discussion of Hyperion**

10/31/2010

[GVEA](#)

Lunch meeting with GVEA 11/12/2010. Present: Kate Lamal and Paul Parks from GVEA, Gwen Holdmann and Frank Williams from UAF, and Dennis Witmer. Topic: Hyperion visit to GVEA, end of October, 2010

GVEA was visited by Dusty Kaiser from Afognak Native Corporation, who is acting as a sales rep for Hyperion, and Griz Deal (from Colorado), the CEO of Hyperion SMR is 10 years away, 25 MWe, 75 MWt, 8-10 year life before refueling (Hyperion recycles fuel) All in costs of 10 cents per kWh Afognak willing to offer sales, or to own unit and sell power. Looking for a non-military site (apparently to prove to the NRC that they have a commercial client) Next step—feasibility study—



need \$800K, could fund half that amount. Hyperion is supposed to be sending a proposal to GVEA. Gwen noted that the DoE is most likely the source of that funding, and they might be willing to fund a technology neutral study. Concern about RUS (Rural Utility Systems) lending requirements with respect to nuclear power. RUS is not lending for new coal plants. This is one of the problems with the Healy Clean Coal plant.

### Hyperion GVEA PowerPoint presentation

10/31/2010

[GVEA](#)

PowerPoint slides for GVEA presentation.

### *mPower 125 MWe Reactor*

Developer Name: **Babcock and Wilcox**

Technology: **Pressurized Water Reactor**  
Design

Size Thermal (MWt):

Size Electrical (MWe): **125**

Technology Description (from literature):

In mid-2009, Babcock & Wilcox (B&W) announced its B&W mPower reactor, a 125 MWe integral PWR designed to be factory-made and railed to site. The reactor pressure vessel containing core of 2x2 meters and steam generator is thus only 3.6 meters diameter and 22 m high, and the whole unit 4.5 m diameter and 23 m high. It would be installed below ground, have an air-cooled condenser giving 31% thermal efficiency, and passive safety systems. With cold water source for condensers the efficiency increases and capacity is up to 136 MWe. The integral steam generator is derived from naval designs, as is the control rod set-up. It has a "conventional core and standard fuel" (< 20 t) enriched to 5%, with burnable poisons, to give a five-year operating cycle between refueling, which will involve replacing the entire core as a single cartridge. Burn-up is less than 40 Gwd/t. (B&W draws upon over 50 years' experience in manufacturing nuclear propulsion systems for the US Navy, involving compact reactors with long core life.) A 60-year service life is envisaged, as sufficient used fuel storage would be built on site for this

The mPower reactor is modular in the sense that several units would be combined into a power station of any size, but most likely 500-750 MWe and using 250 MWe turbine generators (also shipped as complete modules), constructed in three years. B&W's present manufacturing capability in North America can produce these units, and it has set up B&W Modular Nuclear Energy LLC to market the design. The company intends to apply for design certification in mid-2012, with a view to a combined construction and operating license application in 2013, construction start in 2015 and operation of the first unit in 2018.

When B&W announced the launch the mPower design, it said that Tennessee Valley Authority (TVA) would begin the process of evaluating Clinch River at Oak Ridge as a potential lead site for the mPower reactor, and that a Memorandum of Understanding has been signed by B&W, TVA and

a consortium of regional municipal and cooperative utilities to explore the construction of a fleet of mPower reactors. It was later reported that the other signatories of the agreement are First Energy and Oglethorpe Power4.

[http://www.babcock.com/products/modular\\_nuclear/](http://www.babcock.com/products/modular_nuclear/)

**Web page--Nuclear Street--discussion on mPower reactor from 2009, By Stephen Heiser**

6/11/2009

[http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2009/06/11/pictures-of-b-amp-w-s-new-mpower-reactor.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2009/06/11/pictures-of-b-amp-w-s-new-mpower-reactor.aspx)

The mPower reactor is an "Advanced Light Water Reactor" (ALWR) that can be licensed within today's regulatory structure.

**B&W Brochure for mPower Reactor, 2010**

7/1/2010

<http://www.babcock.com/library/pdf/E2011002.pdf>

Very short brochure describing reactor design. Contains no detailed information about reactor design.

**mPower Web page**

7/1/2010

[http://www.babcock.com/products/modular\\_nuclear/](http://www.babcock.com/products/modular_nuclear/)

Basic description of mPower modular reactor

**Bechtel joins effort to build small nuclear reactor**

7/15/2010

<http://www.allbusiness.com/energy-utilities/utilities-industry-electric-power-power/14815736-1.html>

Indicates that small power plants cost just as much to operate as big ones...

**B&W plans reactor prototype for Bedford County research center**

7/27/2010

<http://www2.newsadvance.com/business/2010/jul/27/babcock-wilcoxs-bedford-county-testing-site-featur-ar->

News article announcing a prototype build, July 2010. B&W is building a reactor prototype with electrical heaters in place of fuel rods at their headquarters in Virginia. Link is to a video of company spokesman interview with local news TV.

### *NuScale 45 MWe Light Water Reactor*

Developer Name: **NuScale Power Company**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt): **160**

Plans to file for NRC Design Certification in 2012,

Size Electrical (MWe): **45**

Technology Description (from literature):

A smaller unit is the NuScale multi-application small PWR, a 160 MWt or 45 MWe integral PWR which is apparently similar to IRIS but with natural circulation. It will be factory-built with 3 meter diameter pressure vessel and convection cooling, with the only moving parts being the control rod drives. It uses standard PWR fuel enriched to < 4.95% in normal PWR fuel assemblies (but which are only 1.8 m long), with 24-month refueling cycle. Installed in a water-filled pool below ground, the 4.3 m diameter, 18 m high cylindrical containment vessel module weighs 450 tonnes and contains the reactor and steam generator. A standard power plant would have 12 modules together giving about 500 MWe. An overhead crane would hoist each module from its pool to a separate part of the plant for refueling.

An application for US design certification is expected early in 2012 and there are hopes for a first operating unit in 2018. The NuScale Power company was spun out of Oregon State University in 2007, though the technology originates in the US Department of Energy. The company estimates in 2010 that overnight capital cost for a 12-module, 540 MWe NuScale plant is about \$4000 per kilowatt.

<http://www.nuscalepower.com/>

**NuScale--Under the hood--By Duncan Williams -**

12/30/2009

[http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2009/12/30/Under-The-Hood-With-Duncan-Williams- 2D00 -NuScale-Power-12302.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2009/12/30/Under-The-Hood-With-Duncan-Williams- 2D00 -NuScale-Power-12302.aspx)

Article discusses the design of the NuScale reactor--including discussion about patents indicating the use of natural convection from bubble formation in the reactor core.

**NuScale**

5/11/2010

<http://www.nrc.gov/reactors/advanced/nuscale.html>

NuScale has submitted a letter of intent to the NRC, application expected 2Q FY 2012

**NuScale Suspends Operations due to Financing Problems**

1/20/2011

[http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2011/01/20/nuscale-suspends-operations-due-to-investment-firm\\_1920\\_s-issues-012005.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2011/01/20/nuscale-suspends-operations-due-to-investment-firm_1920_s-issues-012005.aspx)

The investment firm financing NuScale is in trouble with the SEC, forcing NuScale to suspend some operations.

***Pebble Bed Reactor***

Developer Name: **Pebble Bed Modular Reactor (Pty) Limited and Eskom**

Technology:**Pebble Bed**

Size Thermal (MWt): **200**

Size Electrical (MWe): **80**

Technology Description (from literature):

The Pebble Bed Modular Reactor (PBMR) is a particular design of pebble bed reactor under development by South African company PBMR (Pty) Ltd since 1994. The project entails the construction of a demonstration power plant at Koeberg near Cape Town (now postponed indefinitely[1]) and a fuel plant at Pelindaba near Pretoria.

[http://en.wikipedia.org/wiki/Pebble\\_bed\\_modular\\_reactor](http://en.wikipedia.org/wiki/Pebble_bed_modular_reactor)

**Nuclear Engineering International Article on PBMR**

4/1/2009

<http://www.neimagazine.com/story.asp?storyCode=2052590>

Indicates that gas temperatures necessary to operate PBMR reactor lead to the generation of contaminated graphite dust that could be released in a depressurized incident, leading to the abandonment of this reactor design for power generation.

**NRC Summary Sheet**

5/28/2010

<http://www.nrc.gov/reactors/advanced/pbmr.html>

PBMR licensing of demonstration plant in South Africa is on hold, agreement with Chinese for cooperation in development.

***Pebble Bed Commercial Reactor HTR-PM***

Developer Name: **Institute of Nuclear & New Energy Technology (INET) at Tsinghua University north of Beijing**

|                                      |                        |            |
|--------------------------------------|------------------------|------------|
| Technology: <b>Pebble Bed</b>        | Size Thermal (MWt):    | <b>600</b> |
| Construction of Experimental Reactor | Size Electrical (MWe): | <b>200</b> |

Technology Description (from literature):

In February 2006, the State Council announced that the small high-temperature gas-cooled reactor (HTR) was the second of two high priority projects for the next 15 years. The small HTR-PM units with pebble bed fuel were to be 200 MWe reactors, similar to that being developed in South Africa, but plans have evolved to make them twin 105 MWe units driving a single steam turbine. China Huaneng Group is the lead organization in the consortium to build the demonstration Shidaowan HTR-PM with China Nuclear Engineering & Construction Group (CNEC) and Tsinghua University's INET, which is the R&D leader. Chinergy Co. is the main contractor for the nuclear island. The initial HTR-PM will pave the way for 18 (3x6) further 210 MWe units at the same site – total 3800 MWe

**Web article--American observing Chinese PB Reactor China Leaps Forward:  
The People's Republic is embarking on the world's biggest nuclear building**

2/6/2006

<http://www.msnbc.msn.com/id/11080908/site/newsweek/>

2006 article indicates China is operating a prototype of Pebble Bed Reactor.

### *Pebble Bed Demonstration HTR-10*

Developer Name: **Institute of Nuclear & New Energy Technology (INET) at Tsinghua University north of Beijing**

Technology: **Pebble Bed** Size Thermal (MWt): **10**  
Experimental Size Electrical (MWe): **3**

Technology Description (from literature):

China's HTR-10, a 10 MWt high-temperature gas-cooled experimental reactor at the Institute of Nuclear & New Energy Technology (INET) at Tsinghua University north of Beijing started up in 2000 and reached full power in 2003. It has its fuel as a 'pebble bed' (27,000 elements) of oxide fuel with average burn-up of 80 GWday/t U. Each pebble fuel element has 5g of uranium enriched to 17% in around 8300 TRISO-coated particles. The reactor operates at 700°C (potentially 900°C) and has broad research purposes. Eventually it will be coupled to a gas turbine, but meanwhile it has been driving a steam turbine. In 2004, the small HTR-10 reactor was subject to an extreme test of its safety when the helium circulator was deliberately shut off without the reactor being shut down. The temperature increased steadily, but the physics of the fuel meant that the reaction progressively diminished and eventually died away over three hours. At this stage a balance between decay heat in the core and heat dissipation through the steel reactor wall was achieved, the temperature never exceeded a safe 1600°C, and there was no fuel failure. This was one of six safety demonstration tests conducted then. The high surface area relative to volume, and the low power density in the core, will also be features of the full-scale units (which are nevertheless much smaller than most light water types).

**Wikipedia page for Pebble Bed Reactor**

4/26/2010

<http://en.wikipedia.org/wiki/HTR-10>

Brief description of small scale pebble bed reactor based on German design.

### **SMR Reactors by country of origin**

#### *USA*

#### Adams Engine

Developer Name: **Adams Atomic Engines**

Technology: **High Temperature Gas Cooled Reactor** Size Thermal (MWt):  
Design on hold for financial reasons Size Electrical (MWe): **10**

Technology Description (from literature):

A small HTR concept is the Adams Atomic Engines' 10 MWe direct simple Brayton cycle plant with low-pressure nitrogen as the reactor coolant and working fluid, and graphite moderation. The reactor core is a fixed, annular bed with about 80,000 fuel elements each 6 cm diameter and containing approximately 9 grams of heavy metal as TRISO particles, with expected average burn-up of 80 GWd/t. The initial units will provide a reactor core outlet temperature of 800°C and a thermal efficiency near 25%. Power output is controlled by limiting coolant flow. A demonstration plant is proposed for completion after 2018. The Adams Engine is designed to be competitive with combustion gas turbines.

<http://www.atomicengines.com/>

**Adams Engine--Design from web page**

11/15/2008

<http://www.atomicengines.com/engines.html>

Design looks pretty sketchy, not clear if this is anything more than a one person company. Most of the web page was written in 1995.

## Advanced High Temperature Reactor (AHTR)

Developer Name: **Oak Ridge National Laboratory**

Technology: **Molten Salt Reactor**

Size Thermal (MWt): **2400**

Size Electrical (MWe): **1000**

Technology Description (from literature):

The Advanced High-Temperature Reactor (AHTR)<sup>13</sup> is a larger reactor using a coated-particle graphite-matrix fuel like that in the GT-MHR (see above section on the GT-MHR) and with molten fluoride salt as primary coolant. While similar to the gas-cooled HTR it operates at low pressure (less than 1 atmosphere) and higher temperature, and gives better heat transfer than helium. The salt is used solely as coolant, and achieves temperatures of 750-1000°C while at low pressure. This could be used in thermochemical hydrogen manufacture. Reactor sizes of 1000 MWe/2400 MWt are envisaged, with capital costs estimated at less than \$1000/kW.

[http://www.ornl.gov/sci/ees/nstd/research\\_ahtr.shtml](http://www.ornl.gov/sci/ees/nstd/research_ahtr.shtml)

**Modular Pebble-Bed AHTR Design Review, Per F. Peterson, Department of Nuclear Engineering, University of California, Berkeley**

10/7/2009

[http://www.nuc.berkeley.edu/PB-AHTR/PB-AHTR\\_Review\\_Slides\\_10\\_7\\_09.pdf](http://www.nuc.berkeley.edu/PB-AHTR/PB-AHTR_Review_Slides_10_7_09.pdf)

Power point presentation of details of AHTR reactor design--pebble fuel with molten salt cooling.

**Advanced High Temperature Reactor Web page from ANL**

9/20/2010

[http://www.ornl.gov/sci/ees/nstd/research\\_ahtr.shtml](http://www.ornl.gov/sci/ees/nstd/research_ahtr.shtml)

Summary of AHTR reactor

## Wikipedia page on the Advanced High Temperature Reactors

10/8/2010

[http://en.wikipedia.org/wiki/Very\\_high\\_temperature\\_reactor](http://en.wikipedia.org/wiki/Very_high_temperature_reactor)

Similar to Pebble Bed Reactor, except uses molten salt as coolant (reduces the surface temperatures in the reactor). No commercial activity indicated. This page includes general descriptions of high temperature reactors.

## Advanced Reactor Concepts (ARC-100)

Developer Name: **Advanced Reactor Concepts LLC (ARC)**

Technology:**Fast Neutron Reactor**

Size Thermal (MWt):

Design stage--but very new company in 2010

Size Electrical (MWe): **100**

Technology Description (from literature):

Advanced Reactor Concepts LLC (ARC) is commercializing a 100 MWe sodium-cooled fast reactor based on the 62.5 MWt Experimental Breeder Reactor II (EBR-II). The EBR-II was significant fast reactor prototype at Idaho National Laboratory (formerly Argonne National Laboratory - West) which produced 19 MWe over about 30 years. It used the pyro-metallurgically refined used fuel from light water reactors as fuel, including a wide range of actinides. After operating 1963 to 1994 it is being decommissioned. EBR-II was the basis of the US Integral Fast Reactor (IFR) program (originally the Advanced Liquid Metal Reactor program). An EBR-III of 200-300 MWe was proposed but not developed (see also information page on Fast Neutron Reactors).

The ARC-100 system comprises a uranium alloy core submerged in sodium. The liquid sodium is passed through the core where it is heated to 510°C, then passed through a heat exchanger where it heats sodium in an intermediate loop, which in turn heats working fluid for electricity generation. It would have a refueling interval of 20 years. A 50 MWe version of the ARC is also under development.

Uses Metallic fuel, similar to 4S reactor, but enrichment is 10-13%.

<http://www.advancedreactor.net/>

## Brochure for ARC-100

7/1/2010

<http://www.advancedreactor.net/-/product-solutions/4537736534>

Company brochure for ARC-100 reactor. 4 pages. Indicates that the reactor will use U-Zr fuel and Sodium cooling (similar to Toshiba 4S), but enrichment is lower at about 11%.

## Encapsulated Nuclear Heat-Source (ENHS)

Developer Name: **University of California, Berkeley.**

Technology:**Fast Neutron Reactor**

Size Thermal (MWt):

Concept stage, no progress since 2002

Size Electrical (MWe): **50**

Technology Description (from literature):

The Encapsulated Nuclear Heat-Source (ENHS) is a liquid metal-cooled reactor concept of 50 MWe being developed by the University of California, Berkeley. The core is at the bottom of a metal-filled module sitting in a large pool of secondary molten metal coolant which also accommodates the eight separate and unconnected steam generators. There is convection circulation of primary coolant within the module and of secondary coolant outside it. Outside the secondary pool the plant is air cooled. Control rods would need to be adjusted every year or so and load-following would be automatic. The whole reactor sits in a 17 meter deep silo. Fuel is a uranium-zirconium alloy with 13% enrichment (or U-Pu-Zr with 11% Pu) with a 15-20 year life. After this the module is removed, stored on site until the primary lead (or Pb-Bi) coolant solidifies, and it would then be shipped as a self-contained and shielded item. A new fuelled module would be supplied complete with primary coolant. The ENHS is designed for developing countries and is highly proliferation-resistant but is not yet close to commercialization.

<http://www.nuc.berkeley.edu/node/610>

**Novel Nuclear Reactor (Batteries Included) by David Pescovitz**

**9/30/2002**

<http://coe.berkeley.edu/labnotes/1002/reactor.html>

Short press article describing the ENHS reactor design, but dated in 2002.

**Energy Multiplier Module (EM2)**

Developer Name: **General Atomics**

Technology: **High Temperature Gas Cooled Reactor**

Size Thermal (MWt): **500**

Design Announced February 2010

Size Electrical (MWe): **240**

Technology Description (from literature):

In February 2010, General Atomics announced its Energy Multiplier Module (EM2) design, a 500 MWt, 240 MWe helium-cooled fast-neutron HTR operating at 850°C and fuelled with 25 tons of used PWR fuel, leavened with some low-enriched uranium as starter. A 48% thermal efficiency is claimed, using a direct Brayton cycle. It would also be suitable for process heat applications. The main pressure vessel can be trucked or railed to site, and installed below ground level. The company anticipates a 12-year development and licensing period, which is in line with the 80 MWt experimental technology demonstration Gas-cooled Fast Reactor (GFR) in the Generation IV program.

<http://www.ga.com/energy/em2/>

**Wikipedia Page for EM2**

**10/8/2010**

[http://en.wikipedia.org/wiki/Energy\\_Multiplier\\_Module](http://en.wikipedia.org/wiki/Energy_Multiplier_Module)

Fast neutron reactor, sounds much like TVR.

**EM2 Web site**

**10/8/2010**

<http://www.ga.com/energy/em2/>



Fuel cycle looks similar to that of the Traveling Wave Reactor--intention is to use depleted Uranium or used fuel for this reactor.

## Liquid Fluoride Thorium Reactor (LFTR)

Developer Name: **Oak Ridge**

Technology:**Molten Salt Reactor**

Concept

Size Thermal (MWt):

Size Electrical (MWe): **100**

Technology Description (from literature):

The Liquid Fluoride Thorium Reactor (LFTR) is one kind of MSR which breeds its U-233 fuel from a fertile blanket of liquid thorium salts. Some of the neutrons released during fission of the U-233 salt in the reactor core are absorbed by the thorium in the blanket salt. U-233 is thus produced in the blanket and this is then transferred to the fuel salt. LFTRs can rapidly change their power output, and hence be used for load following. Because they are expected to be inexpensive to build and operate, 100 MWe LFTRs could be used as peak and back-up reserve power units.

<http://blogs.howstuffworks.com/2009/12/01/how-a-liquid-fluoride-thorium-reactor-lftr-works/>

### **Wikipedia Page on Molten Salt Reactors**

10/11/2010

[http://en.wikipedia.org/wiki/Molten\\_salt\\_reactor](http://en.wikipedia.org/wiki/Molten_salt_reactor)

Experimental breeder reactor developed at ORNL

### **World Nuclear Association Thorium summary**

10/18/2010

<http://www.world-nuclear.org/info/inf62.html>

Thorium has been used as a fuel in at least a dozen experimental and commercial reactors around the world. There is a major program to use it in India because of the international difficulty in obtaining U, but Thorium is abundant. The major drawback seems to be the high cost of reprocessing radioactive fuel to prepare it for use as compared to the mining and enrichment of U.

### **John Kutsch, Lithium Fluoride Reactor**

10/18/2010

[N/A](#)

Description of LFTR technology, indicates that a successful demonstration of LFTR technology was done in the 1950s. Fails to note that the "Fireball" reactor that flew in a plane at that time was not powering the aircraft, only a check on the configuration.

### **Thorium Reactor Pitch, SMR conference, James Kenedy**

10/18/2010

[N/A](#)

Outlines the strategic advantages of Thorium, but also focuses on the need for US mining for Rare Earth metals.

### **China is developing Thorium Reactor--UK Telegraph**

3/21/2011

[http://www.telegraph.co.uk/finance/comment/ambroseevans\\_pritchard/8393984/Safe-nuclear-does-exist-and-China-is-leading-the-way-with-thorium.html](http://www.telegraph.co.uk/finance/comment/ambroseevans_pritchard/8393984/Safe-nuclear-does-exist-and-China-is-leading-the-way-with-thorium.html)

China has announced a plant to develop a liquid salt thorium reactor, using technology developed at Oak Ridge in the 1960s.

## Medical Isotope Production System (MIPS)

Developer Name: **Babcock and Wilcox**

Technology:**Aqueous Homogenous Reactors**

Size Thermal (MWt): **200**

Concept

Size Electrical (MWe): **100**

Technology Description (from literature):

At the end of 2007, Babcock & Wilcox (B&W) notified the US Nuclear Regulatory Commission that it intended to apply for a license to construct and operate a Medical Isotope Production System (MIPS) – an AHR system with low-enriched uranium in small 100-200 kWe units for Mo-99 production. A single production facility could have four such reactors. B&W expects a five-year lead time to first production. The fuel is brought to criticality in a 200-litre vessel. As fission proceeds, the solution is circulated through an extraction facility to remove the Mo-99 and then back into the reactor vessel, which is at low temperature and pressure. In January 2009, B&W Technical Services Group signed an agreement with radiopharmaceutical and medical device supplier Covidien to develop technology for the MIPS.

<http://www.babcock.com/library/pdf/PS-301-110.pdf>

**Brochure for B&W MIPS system**

7/1/2009

<http://www.babcock.com/library/pdf/PS-301-110.pdf>

Brochure describing reactor.

## PM-3A

Developer Name: **US Military**

Technology:**Light Water Reactor**

Size Thermal (MWt): **11**

Obsolete

Size Electrical (MWe): **2**

Technology Description (from literature):

**Light Water Reactor installed at McMurdo Station, Antarctica.**

[http://en.wikipedia.org/wiki/Army\\_Nuclear\\_Power\\_Program](http://en.wikipedia.org/wiki/Army_Nuclear_Power_Program)

**The Antarctic Environmental Awareness Page**

7/1/2003

<http://www.southpolestation.com/env/env1.html>

Report here based on account from scientist headed to McMurdo 3 months after reactor shut down due to "wet insulation" caused by leaks in reactor shield cooling loop--due to cracking from chlorine--intergranular stress corrosion cracking of stainless steels.

## Power Reactor Innovative Small Module (PRISM)

Developer Name: **GE-Hitachi**

Technology:**Liquid Metal Reactor**

Size Thermal (MWt): **850**

Preliminary Design

Size Electrical (MWe): **311**

Technology Description (from literature):

GE with the US national laboratories had been developing a modular liquid metal-cooled inherently safe reactor – PRISM (Power Reactor Innovative Small Module) – under the Advanced Liquid Metal Reactor/Integral Fast Reactor (ALMR/IFR) program funded by the US Department of Energy. The program was cancelled in 1994 and no US fast neutron reactor has so far been larger than 66 MWe and none has supplied electricity commercially. However, the 1994 pre-application safety evaluation report<sup>10</sup> for the original PRISM design concluded that "no obvious impediments to licensing the PRISM design had been identified."

Today's PRISM is a GE-Hitachi (GEH) design for compact modular pool-type reactors with passive cooling for decay heat removal. After 30 years of development it represents GEH's Generation IV solution to closing the fuel cycle in the USA. Each PRISM power block consists of two modules of solution to closing the fuel cycle in the USA. Each PRISM power block consists of two modules of 311 MWe (840 MWt) each, operating at high temperature – over 500°C. The pool-type modules below ground level contain the complete primary system with sodium coolant. The metal Pu & DU fuel is obtained from used light water reactor fuel. However, all transuranic elements are removed together in the electrometallurgical reprocessing so that fresh fuel has minor actinides with the plutonium. Fuel stays in the reactor about six years, with one-third removed every two years, and breeding ratio is 0.8. Used PRISM fuel is recycled after removal of fission products. The commercial-scale plant concept, part of an 'Advanced Recycling Center', would use three power blocks (six reactor modules) to provide 1866 MWe. An application for design certification is expected to be submitted in 2012, and a decision by GEH on building a demonstration plant is expected soon after then. See also Electrometallurgical 'pyro-processing' section in information page on Processing of Used Nuclear Fuel.

<http://www.nrc.gov/reactors/advanced/prism.html>

**Advancing Technology for Nuclear Fuel Recycling: What Should Our Research, Development and Demonstration Strategy Be? Prepared Congressional Testimony, Lisa Price, GE** **6/15/2009**

[http://democrats.science.house.gov/Media/file/Commdocs/hearings/2009/Full/17jun/Price\\_Testimony.pdf](http://democrats.science.house.gov/Media/file/Commdocs/hearings/2009/Full/17jun/Price_Testimony.pdf)

Congressional testimony presented in June 2009. Outlines the basic technology of fuel recycling, and how PRISM would reduce the waste that needs to be stored.

**Under the hood--The PRISM reactor-- By Duncan Williams -**

**1/20/2010**

[http://nuclearstreet.com/nuclear\\_power\\_industry\\_news/b/nuclear\\_power\\_news/archive/2010/01/20/under-the-hood-with-duncan-williams-ge-hitachi-prism-reactor-01201.aspx](http://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2010/01/20/under-the-hood-with-duncan-williams-ge-hitachi-prism-reactor-01201.aspx)

The PRISM reactor appears to be a system for recycling spent nuclear fuel, locating the reactor with the reprocessing facility. Fuel will be uranium, plutonium, and zirconium in metallic form (not oxides), and coolant will be liquid sodium. The biggest barrier to development seems to be the price tag associated with building the first facility.

**NRC Fact Sheet for PRISM**

6/18/2010

<http://www.nrc.gov/reactors/advanced/prism.html>

GE intends to submit design for NRC review by 2012

**PRISM Wikipedia page**

10/5/2010

<http://en.wikipedia.org/wiki/S-PRISM>

Indicates that PRISM is a descendant from the breeder reactor programs in the US. Breeder program shut down by Congress in 1994.

**GE Hitachi Advanced Recycling Center Solving the Spent Nuclear Fuel Dilemma**

10/5/2010

[http://www.usnuclearenergy.org/PDF\\_Library/\\_GE\\_Hitachi%20advanced\\_Recycling\\_Center\\_GNEP.pdf](http://www.usnuclearenergy.org/PDF_Library/_GE_Hitachi%20advanced_Recycling_Center_GNEP.pdf)

This is a description by GE Hitachi showing how their reprocessing facility would reduce spent fuel waste.

## Secure Transportable Autonomous Reactor (STAR)

Developer Name: **Argonne National Laboratory**

Technology: **Fast Neutron Reactor**

Size Thermal (MWt): **350**

Design

Size Electrical (MWe): **175**

Technology Description (from literature):

The Secure Transportable Autonomous Reactor (STAR) project at Argonne National Laboratory is developing small, multi-purpose systems that operate nearly autonomously for the very long term. The STAR-LM is a factory-fabricated fast neutron modular reactor cooled by lead-bismuth eutectic, with passive safety features. Its 300-400 MWt size means it can be shipped by rail. It uses uranium-transuranic nitride fuel in a 2.5 m diameter cartridge which is replaced every 15 years. Decay heat removal is by external air circulation. The STAR-LM was conceived for power generation with a capacity of about 175 MWe.

<http://www.ne.anl.gov/research/ardt/hlmr/index.html>

**Star-LM Web page: Argonne National Laboratory**

**10/8/2010**

<http://www.ne.anl.gov/research/ardt/hlmr/index.html>

Describes reactor design, including passive safety features.

## SM-1A Fort Greely Reactor

Developer Name: **US Army**

Technology:**Boiling Water Reactor**

Size Thermal (MWt): **20.2**

Obsolete

Size Electrical (MWe): **1.6**

Technology Description (from literature):

The SM-1A is a 20.2 megawatt thermal (MWT) nuclear power plant with a net maximum design capacity of 1,640 kilowatts (kw) of electricity and 37,950 pounds of steam per hour for post heating at Fort Greely. The reactor core consists of 38 parallel plate stationary fuel elements. Fuel is uranium oxide highly enriched in the isotope <sup>235</sup>U, and clad in stainless steel. Water under pressure serves as both a moderator and primary coolant. Heat is transferred to the independent secondary system in a steam generator within the containment vessel. Extraction steam is bled from a low pressure stage of the turbine for post heating.

### Critique of in-place annealing of SM-1A nuclear reactor vessel

[http://www.sciencedirect.com/science?\\_ob=ArticleURL&\\_udi=B6V4D-47XSX4X-5&\\_user=10&\\_coverDate=07%2F31%2F1968&\\_rdoc=1&\\_fmt=high&\\_orig=search&\\_origin=search&\\_sort=d&\\_docanchor=&view=c&\\_searchStrId=1541924648&\\_rerunOrigin=google&\\_acct=C000050221&\\_version=1&\\_u](http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V4D-47XSX4X-5&_user=10&_coverDate=07%2F31%2F1968&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1541924648&_rerunOrigin=google&_acct=C000050221&_version=1&_u)

**Environmental Radiation Monitoring Plan for the SM-1A Reactor at Fort Greely, Alaska**

**5/20/1971**

<http://www.dtic.mil/cgi-bin/GetTRDoc?AD=AD726323&Location=U2&doc=GetTRDoc.pdf>

Plan for monitoring radiation, but description of reactor indicates that the fuel is "clad in stainless steel".

**Storming Media Abstracts from Fort Belvoir**

**5/16/1973**

[http://www.stormingmedia.us/corpauthors/ARMY\\_ENGINEER\\_REACTORS\\_GROUP\\_FORT\\_BELVOIR\\_VA\\_ENGINEERING\\_DIV.htm](http://www.stormingmedia.us/corpauthors/ARMY_ENGINEER_REACTORS_GROUP_FORT_BELVOIR_VA_ENGINEERING_DIV.htm)

Indicates several reports were written about the SM-1A reactor at Fort Greely, and that Core 4, the last core to be installed in the reactor was in some way different from the previous cores. Only the environmental monitoring plan is listed as available in full text.

**Final operating report for the PM-3A reactor in McMurdo**

**10/20/1973**

<http://foia.navy.mil/FINAL%20OPERATING%20REPORT.pdf>

Freedom of Information Act release. Reactor shutdown October 26, 1972.

**SM-1A Nuclear Power Plant Historical Summary, US Army Corps of Engineers**

**12/21/1992**

[http://www.smdcen.us/rabfga/docs/adminrecord/ar008\\_sm1a\\_summary\\_dec1992.pdf](http://www.smdcen.us/rabfga/docs/adminrecord/ar008_sm1a_summary_dec1992.pdf)

On page 48 of this report, the turbine event of March 23, 1972 which ended the useful life of the plant is described. Steam valves to the turbine did not shut as expected on a reactor scram, and the fourth stage of the turbine became "unkeyed" (not connected to the shaft) and three diaphragms were damaged. They elected not to repair the turbine. (the decision to end the program had already been made.) There is no indication of radioactive release from this event.

#### **History of Nuclear Reactors--Military Reactors**

**7/1/1994**

<http://www.fas.org/spp/othergov/doe/heu/appd.pdf>

Source of info on Wikipedia page--

#### **40 Years of Government Sponsored Eco-Terrorism**

**7/15/1994**

<http://gulfwavets.com/greely.htm>

Discussion of Chemical and biological weapons testing at Greely, and possible effects on residents and soldiers.

#### **Alaska Community Action on Toxins Fort Greely**

**5/1/2000**

<http://www.akaction.org/PDFs/FTGreely.pdf>

Alaska Community Action on Toxins reports imply that a significant event occurred at Fort Greely with the SM-1A reactor, and that the military has never released the details of this event.

#### **Alaska Community Action on Toxins Fort Greely**

**5/1/2000**

<http://www.akaction.org/PDFs/FTGreely.pdf>

Alaska Community Action on Toxins reports imply that a significant event occurred at Fort Greely with the SM-1A reactor, and that the military has never released the details of this event.

#### **DEC contaminated site database**

10/21/2009

[http://www.dec.state.ak.us/SPAR/csp/search/IC\\_Tracking/Site\\_Report.aspx?Hazard\\_ID=1706](http://www.dec.state.ak.us/SPAR/csp/search/IC_Tracking/Site_Report.aspx?Hazard_ID=1706)

Discussion about SM-1A reactor site, currently entombed, and a waste pipe to Jarvis Creek.

#### **Agency for Toxic Substances database record for Fort Greely Reactor, Jan 2010**

1/15/2010

<http://www.atsdr.cdc.gov/HAC/pha/pha.asp?docid=904&pg=3>

Indicates that radiation contamination levels at Fort Greely were below federal guidelines in 1972, and should not pose a problem. However, they recommend a single test of the water to verify

#### **Wikipedia page on Army Nuclear Power program**

8/13/2010

[http://en.wikipedia.org/wiki/Army\\_Nuclear\\_Power\\_Program](http://en.wikipedia.org/wiki/Army_Nuclear_Power_Program)

Lists the 8 reactors designed and operated as part of the Army nuclear program.

#### **History of the Army Nuclear program**

11/15/2010

[http://www.absoluteastronomy.com/topics/Army\\_Nuclear\\_Power\\_Program](http://www.absoluteastronomy.com/topics/Army_Nuclear_Power_Program)

Indicates that the SM-1A at Fort Greely used an enrichment of 93% U 235, and operated from 1965 to 1972.

## Small Sealed Transportable Autonomous Reactor (SSTAR)

Developer Name: **Lawrence Livermore, Argonne and Los Alamos National Laboratories in collaboration with others.**

|             |                             |                        |           |
|-------------|-----------------------------|------------------------|-----------|
| Technology: | <b>Fast Neutron Reactor</b> | Size Thermal (MWt)     | <b>45</b> |
|             | Design                      | Size Electrical (MWe): | <b>20</b> |

Technology Description (from literature):

A smaller STAR variant is the Small Sealed Transportable Autonomous Reactor (SSTAR) being developed by Lawrence Livermore, Argonne and Los Alamos National Laboratories in collaboration with others. It has lead or Pb-Bi cooling, 564°C core outlet temperature and has integral steam generator inside the sealed unit, which would be installed below ground level. Conceived in sizes 10-100 MWe, main development is now focused on a 45 MWt/20 MWe version as part of the US Generation IV effort. After a 30-year life without refueling, the whole reactor unit is then returned for recycling the fuel. The reactor vessel is 12 meter high and 3.2 m diameter (20 MWe version). SSTAR will eventually be coupled to a Brayton cycle turbine using supercritical carbon dioxide. A prototype was envisaged for 2015, but this seems unlikely.

<https://www.llnl.gov/str/JulAug04/Smith.html>

**Nuclear Energy to Go: A self-contained, portable reactor. By Gabriele Rennie** **7/1/2004**

<https://www.llnl.gov/str/JulAug04/Smith.html>

Lawrence Livermore description of SSTAR.

**US Plans Portable Reactors--New Scientist web site** **9/3/2004**

<http://www.newscientist.com/article/dn6344-us-plans-portable-nuclear-power-plants.html>

2004 article on SSTAR reactor.

**Status Report on the Small Secure Transportable Autonomous Reactor (SSTAR)/Lead-Cooled Fast Reactor (LFR) and Supporting Research and Development** **9/29/2006**

Technical Report from 2006 on progress of SSTAR reactor, 166 pages

**SSTAR Wikipedia Page** **10/7/2010**

<http://en.wikipedia.org/wiki/SSTAR>

Describes the reactor as a tamper proof breeder reactor.

## Traveling Wave Reactor (TWR)

Developer Name: **Terrapower (approaching Toshiba)**

Technology: **Traveling Wave Reactor**

Concept

Size Thermal (MWt):

Size Electrical (MWe): **500**

Technology Description (from literature):

An old design has resurfaced as the travelling wave reactor (TWR). This has been considered in the past as, generically, a candle reactor, or breed-burn reactor, since it burns slowly from one end of a core to the other, making the actual fuel as it goes. The reactor uses natural or depleted uranium packed inside hundreds of hexagonal pillars. In a 'wave' that moves through the core at only one centimeter per year, the U-238 is bred progressively into Pu-239, which is the actual fuel and undergoes fission. The reaction requires a small amount of enriched uranium to get started and could run for decades without refueling. However, it is a low-density core and needs to be relatively large. The reactor uses liquid sodium as a coolant, and core temperatures are about 550C, giving high thermal efficiency. In 2009 this was selected by MIT Technology Review as one of ten emerging technologies of note<sup>12</sup>. In 2010, the company promoting it, Terrapower, made overtures to Toshiba concerning its development, hoping to have a 500 MWe demonstration reactor operating by 2020. Eventual sizes could range from a few hundred MWe to 1000 MWe.

<http://www.intellectualventures.com/OurInventions/TerraPower.aspx>

**Summary of Traveling Wave Reactor technology**

**4/15/2010**

<http://gigaom.com/cleantech/terrapower-how-the-travelling-wave-nuclear-reactor-works/>

Hyperlinked Technology Brief for ACEP April 2010 on TWR.

**Wikipedia Page for TerraPower**

**10/11/2010**

<http://en.wikipedia.org/wiki/TerraPower>

Basic story of TerraPower, including visit in November 2009 to Toshiba, signed NDA.

## TRIGA

Developer Name: **General Atomics**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt): **64**

Commercial as a research reactor, by design is not

Size Electrical (MWe): **16**

Technology Description (from literature):

The TRIGA Power System is a PWR concept based on General Atomics' well-proven research reactor design. It is conceived as a 64 MWt, 16.4 MWe pool-type system operating at a relatively low temperature. The secondary coolant is perfluorocarbon. The fuel is uranium-zirconium hydride enriched to 20% and with a little burnable poison and requiring refueling every 18 months. Used fuel is stored inside the reactor vessel.

<http://www.ga-esi.com/triga/>



**TRIGA Reactor Utilization at a university in Slovenia, Vicktor Dimik**

**7/1/1999**

[http://www.rcp.ijs.si/ric/pdf/reactor\\_utilization.pdf](http://www.rcp.ijs.si/ric/pdf/reactor_utilization.pdf)

Discusses use of reactor for various experiments needing high and moderate neutron flux.

**General Atomics web page**

**10/8/2010**

<http://www.ga-esi.com/triga/>

Web page indicates that 66 of these reactors have been sold, between 0.1 and 16 MWt, and that the safe fuel configuration has allowed these reactors to be sited more easily.

**Wikipedia Page**

10/8/2010

<http://en.wikipedia.org/wiki/TRIGA>

Indicates that 60 TRIGA reactors have been installed in the US. Most common type of research reactor at universities. Used for medical isotope production.

***USA - Russia - Japan***

**Gas Turbine - Modular Helium Reactor (GT-MHR)**

Developer Name: **General Atomics in partnership with Russia's OKBM Afrikantov, supported by Fuji (Japan)**

|  |                        |           |
|--|------------------------|-----------|
| Technology: <b>High Temperature Gas Cooled Reactor</b> | Size Thermal (MWt):    | <b>60</b> |
|  | Size Electrical (MWe): | <b>25</b> |

Technology Description (from literature):

A larger US design, the Gas Turbine - Modular Helium Reactor (GT-MHR), will be built as modules of up to 600 MWt. In its electrical application each would directly drive a gas turbine at 47% thermal efficiency, giving 285 MWe capacity. It can also be used for hydrogen production (100,000 t/yr claimed) and other high temperature process heat applications. The annular core consists of 102 hexagonal fuel element columns of graphite blocks with channels for helium coolant and control rods. Graphite reflector blocks are both inside and around the core. Half the core is replaced every 18 months. Burn-up is up to 220 GWd/t, and coolant outlet temperature is 850°C with a target of 1000°C.

The GT-MHR is being developed by General Atomics in partnership with Russia's OKBM Afrikantov, supported by Fuji (Japan). Areva was formerly involved. Initially it was to be used to burn pure ex-weapons plutonium at Seversk (Tomsk) in Russia. A burnable poison such as Er-167 is needed for this fuel. The preliminary design stage was completed in 2001, but the program to construct a prototype in Russia has languished since.

General Atomics says that the GT-MHR neutron spectrum is such, and the TRISO fuel is so stable, that the reactor can be powered fully with separated transuranic wastes (neptunium, plutonium, americium and curium) from light water reactor used fuel. The fertile actinides would enable

reactivity control and very high burn-up could be achieved with it – over 500 GWd/t – the 'Deep Burn' concept. Over 95% of the Pu-239 and 60% of other actinides would be destroyed in a single pass.

A smaller version of the GT-MHR, the Remote-Site Modular Helium Reactor (RS-MHR) of 10-25 MWe has been proposed by General Atomics. The fuel would be 20% enriched and refueling interval would be 6-8 years.

**Technology description** **10/8/2010**

<http://gt-mhr.ga.com/description.php>

Diagram of reactor design.

**General Atomics Web Page on GT-MHR** **10/11/2010**

<http://gt-mhr.ga.com/>

Basic PR description of system--reactor cooled by helium, used to operate turbine.

**Web Page--History of Helium cooled reactors** 10/11/2010

<http://gt-mhr.ga.com/history.php>

History includes experimental reactor, and Peach Bottom Reactor, which generated commercial power for 7 years in US, 1967-1974.

## *Russia*

### ABV

Developer Name: **OKBM Afrikantov**

Technology: **Pressurized Water Reactor**

Under Development

Size Thermal (MWt): **18**

Size Electrical (MWe): **4**

Technology Description (from literature):

A smaller Russian OKBM Afrikantov PWR unit under development is the ABV, with a range of sizes from 45 MWt (ABV-6M ) down to 18 MWt (ABV-3), giving 4-18 MWe outputs. The units are compact, with integral steam generator. The whole unit will be factory-produced for ground or barge mounting – the ABV-6M would require a 3500 ton barge; the ABV-3, 1600 tone. The core is similar to that of the KLT-40 except that enrichment is 16.5% and average burn-up 95 GWd/t. Refueling interval is about 8-10 years, and service life about 50 years.

[http://en.wikipedia.org/wiki/Russian\\_floating\\_nuclear\\_power\\_station](http://en.wikipedia.org/wiki/Russian_floating_nuclear_power_station)

## ABV Reactor and Power plants based on the ABV Reactor, 2004 IAEA report

7/1/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Page 103 begins discussion on the ABV reactor--

## BREST

Developer Name: **RDIFE**

Technology: **Liquid Metal Reactor**

Size Thermal (MWt):

Concept stage

Size Electrical (MWe): **300**

Technology Description (from literature):

Russia has experimented with several lead-cooled reactor designs, and has used lead-bismuth cooling for 40 years in its submarine reactors. (Pb-208 – 54% of naturally-occurring lead – is transparent to neutrons.) A significant Russian design from NIKIET is the BREST fast neutron reactor, of 300 MWe or more with lead as the primary coolant, at 540°C, supplying supercritical steam generators. The core sits in a pool of lead at near atmospheric pressure. It is inherently safe and uses a U+Pu nitride fuel. No weapons-grade plutonium can be produced (since there is no uranium blanket), and used fuel can be recycled indefinitely, with on-site facilities. A pilot unit was planned to be built at Beloyarsk, and 1200 MWe units are planned.

<http://www.springerlink.com/content/q8028l2t315l5067/>

## EVOLUTION OF THE TECHNICAL CONCEPT OF FAST REACTORS: THE CONCEPT OF BREST

7/1/2004

[http://www.iaea.org/inisnkm/nkm/aws/fnss/fulltext/tecdoc1348\\_3.pdf](http://www.iaea.org/inisnkm/nkm/aws/fnss/fulltext/tecdoc1348_3.pdf)

Paper summarizing the design concept of the BREST reactor

## FUEL CYCLE OF BREST REACTORS. SOLUTION OF THE RADWASTE AND NONPROLIFERATION PROBLEMS, A.G. Glazov, A.V. Lopatkin, V.V. Orlov a, P.P. Poluektov, V.I. Volkb , V.F. Leontyevc, R.S. Karimovd

7/1/2004

[http://www.nikiet.ru/eng/publications/nfcnp/Lopatkin\\_paper.pdf](http://www.nikiet.ru/eng/publications/nfcnp/Lopatkin_paper.pdf)

Describes fuel cycle for BREST reactor, how it can use spent fuel from traditional NPPs

## KLT-40 S Pressurized Water Reactor

Developer Name: **OKBM**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt): **150**

Commercial

Size Electrical (MWe): **35**

Technology Description (from literature):

Well proven in ice breakers, and now proposed for wider use in desalination and, on barges, for remote area power supply. Here a 150 MWt unit produces 35 MWe (gross) as well as up to 35 MWt

of heat for desalination or district heating (or 38.5 MWe gross if power only). These are designed to run 3-4 years between refueling with on-board refueling capability and used fuel storage. At the end of a 12-year operating cycle the whole plant is taken to a central facility for overhaul and storage of used fuel. Two units will be mounted on a 20,000 ton barge to allow for outages (70% capacity factor). Although the reactor core is normally cooled by forced circulation, the design relies on convection for emergency cooling. Fuel is uranium aluminum silicide with enrichment levels of up to 20%, giving up to four-year refueling intervals.

The first floating nuclear power plant, the Akademik Lomonosov, commenced construction in 2007 and is planned to be located near to Vilyuchinsk. The plant is due to be completed in 2011.

<http://en.wikipedia.org/wiki/KLT-40>

**KLT 40 S Description from IAEA 2004 paper** **7/1/2004**

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Description of reactor design

**Slide from Evgeny Velikhov at Arctic Energy Summit in 2007** **10/18/2007**

<http://www.channels.com/episodes/show/4394597/Arctic-Energy-Summit-Dr-Evgeny-Velikhov>

Indicates that two KLT-40S units will be incorporated into a floating nuclear power plant, with completion expected in 2009.

**BBC web article on Russian Nuclear Barges** **9/22/2010**

<http://www.bbc.co.uk/news/world-11381773>

Video of nuclear barge being built.

**OKBM Home page** 9/27/2010

<http://translate.google.com/translate?hl=en&sl=ru&u=http://www.okbm.nnov.ru/component/content/%3Flang%3Dru-RU&ei=u8KgTOmaOJLEsAO0y-3PCA&sa=X&oi=translate&ct=result&resnum=1&ved=0CBUQ7gEwAA&prev=/search%3Fq%3DOKBM%2BAfrikantov%26hl%3Den%26client%3Dfirefox->

OKBM Home page (Translated into English by web program)

## MARS

Developer Name: **Russian Research Centre “Kurchatov Institute” (RRC KI)**

|  |                        |           |
|--|------------------------|-----------|
| Technology: <b>Molten Salt Reactor</b> | Size Thermal (MWt):    | <b>16</b> |
| Concept                                | Size Electrical (MWe): | <b>6</b>  |

Technology Description (from literature):

**CONCEPT OF MARS REACTOR (REACTOR WITH MICRO FUEL ELEMENTS AND MOLTEN SALT COOLANT) AND POWER PLANTS ON ITS BASIS**

The Russian Research Centre “Kurchatov Institute” (RRC KI) has developed the conceptual design of an integral reactor of 16 MWt with its core consisting of spherical fuel elements similar to those used in high temperature gas cooled reactors but being cooled by molten salt coolant [25-29]. Two variants of the core design for 15 and 60 years of operation without on-site refueling have been developed.

The coolant (a mixture of eutectic compounds) has high boiling temperature (~1300°C) at low pressure and freezes when it gets outside the reactor vessel. For electric power generation, an effective air-turbine cycle is used, making no use of water as heat receiver. Small NPPs with MARS reactor are developed as autonomous sources for electric power co-generation (up to 6 MWe) with high-grade and low-grade heat production (up to 8.5 MWt) and seawater desalination. Different options for nuclear cogeneration plant are considered: floating, ground based, or underground.

**Key data:**

**Overall length, m – 115**  
**Middle width, m – 17**  
**Vessel side height, m - 8**  
**Draught, m – 2.8**  
**Displacement, t – 5500**

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

**MARS reactor description, IAEA 2004 Report**

7/1/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Short description of theoretical reactor

## Modular Transportable Small Power Nuclear Reactor (MTSPNR)

Developer Name: **N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET)**

Technology: **High Temperature Gas Cooled Reactor**

Size Thermal (MWt):

Stalled

Size Electrical (MWe):

**2**

Technology Description (from literature):

A small Russian HTR which was being developed by the N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET) is the modular transportable small power nuclear reactor (MTSPNR) for heat and electricity supply of remote regions. It is described as a single circuit air-cooled HTR with closed cycle gas turbine. It uses 20% enriched fuel and is designed to run for 25 years without refueling. A twin unit plant delivers 2 MWe and/or 8 GJ/hr. No recent information is available.

**Pilot transportable reactor may appear through international cooperation.**

12/3/2009

## Abstract from paper in Russia

[http://www.nuclear.ru/eng/press/nuclear\\_power/2112070/?print\\_version=1](http://www.nuclear.ru/eng/press/nuclear_power/2112070/?print_version=1)

Indicates that there is development activity on this reactor, at a 2 MWe size.

## RITM-200

Developer Name: **OKBM Afrikantov**

Technology: ? Size Thermal (MWt):

**210**

Under Development

Size Electrical (MWe): **55**

Technology Description (from literature):

OKBM Afrikantov is developing a new icebreaker reactor – RITM-200 – to replace the KLT reactors and to serve in floating nuclear power plants. This is an integral 210 MWt, 55 MWe PWR with inherent safety features. A single compact RITM-200 could replace twin KLT-40S (but yielding less total power). A major challenge is the reliability of steam generators and associated equipment which are much less accessible when inside the reactor pressure vessel.

## Construction of new icebreakers

6/26/2009

[http://rusnavy.com/news/navy/index.php?ELEMENT\\_ID=7187](http://rusnavy.com/news/navy/index.php?ELEMENT_ID=7187)

Indicates that new generation Russian Icebreakers currently under construction will use the RITM-200 reactor.

## Summary of Russian nuclear industry, March 2010

3/15/2010

<http://www.powertecrussia.com/blog/technology-developments-russian-nuclear-power/>

Russia is developing a new icebreaker reactor – RITM-200 – to replace the current KLT 40 reactors. This is an integral 210 MWt, 55 MWe PWR with inherent safety features. For floating nuclear power plants a single RITM-200 would replace twin KLT-40S (but yield less power).

## SAKHA-92

Developer Name: **OKBM Afrikantov**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt): **3**

Concept

Size Electrical (MWe): **1**

Technology Description (from literature):

The small nuclear cogeneration plant SAKHA-92 [11] is a small-size power source intended for generation of electric power and district heating. The maximum electric power supplied to the consumer is 1000 kWe. Low-grade heat output falls in the range of 1200 to 3000 kWe at electric load drop. SAKHA-92 is a maintenance-free nuclear power plant of increased safety. Plant design was developed on the basis of PWR technology, but implements integrated steam and gas pressurizer systems and relies on natural circulation of the primary coolant (Fig. 1). The use of such

designs as leak-tight turbine-generator, canned condensate and feed pumps allows to secure the tightness of both primary and secondary circuits, which in turn make it possible to exclude some auxiliary systems.

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

#### **SAKHA-92 Description**

**7/1/2004**

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Description of very small reactor with 25 year fuel supply installed at factory.

#### **Procedures for assessing the profitability of using thermoelectric nuclear power plants and nuclear heating plants under conditions in the Russian far**

7/1/2004

<http://www.springerlink.com/content/g21jrh7t60270260/>

Study about using small scale nuclear power in Siberia.

### **SVBR-100**

Developer Name: **Rosatom/En+, Gidropress**

Technology: **Liquid Metal Reactor**

Size Thermal (MWt):

Size Electrical (MWe): **100**

Technology Description (from literature):

A smaller and newer Russian design is the Lead-Bismuth Fast Reactor (SVBR) of 75-100 MWe, from Gidropress. This is an integral design, with the steam generators sitting in the same Pb-Bi pool at 400-495°C as the reactor core. It is designed to be able to use a wide variety of fuels, though the reference model uses uranium enriched to 16.5%. Uranium-plutonium fuel is also envisaged. Refueling interval is 7-8 years. The SVBR-100 unit would be factory-made and shipped as a 4.5m diameter, 7.5m high module, then installed in a tank of water which gives passive heat removal and shielding. A power station with 16 such modules is expected to supply electricity at lower cost than any other new Russian technology as well as achieving inherent safety and high proliferation resistance. (Russia built seven Alfa-class submarines, each powered by a compact 155 MWt Pb-Bi cooled reactor, essentially an SVBR, and 70 reactor-years operational experience was acquired with these.)

In December 2009, AKME-Engineering, a 50-50 joint venture, was set up by Rosatom and the En+Group (a subsidiary of Basic Element Group) to develop and build a pilot SVBR unit<sup>11</sup>. En+ is an associate of EuroSibEnergo and a 53.8% owner of Rusal, which has been in discussion with Rosatom regarding a Far East nuclear power plant and Phase II of the Balakovo nuclear plant. The plan is to complete the design development by 2017 and put on line a 100 MWe pilot facility by 2020, with total investment by Russkiye Mashiny of RUR16 billion (\$585 million). The site selection process is underway – earlier plans were to put it Obninsk. The SVBR-100 could be the first reactor cooled by heavy metal to be utilized to generate electricity. It is described by Gidropress as a

multifunction reactor. An SVBR-10 is also envisaged, with the same design principles, a 20-year refueling interval and generating capacity of 12 MWe, though it too is a multi-purpose unit.

<http://www.theoil Drum.com/node/5383>

#### SVBR-100 description in 2004 IAEA report

7/1/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Diagram of SVBR-100

#### Oil Drum Blog post on SVBR-100

5/17/2009

<http://www.theoil Drum.com/node/5383>

Pictures of the SVBR-100 reactor

## UNITHERM

Developer Name: **Federal State Enterprise NIKIET**

Technology: ? Size Thermal (MWt):

Concept

Size Electrical (MWe): **1.5**

Technology Description (from literature):

The Federal State Enterprise NIKIET has developed a conceptual design of a cogeneration plant with an integral modular PWR type small reactor UNITHERM. The design assumes that fabrication, assembly and balance and commissioning of certain NPP modules are performed at specialized machine-building Enterprises, with only a small number (10-15 pieces) of large modules (from 100 to 175 tons) being supplied to the site. The principal characteristics are:

**Electric power for consumers 1.5 MWe**

**Thermal power for consumers 4.0 GCal/h**

**Period of operation without on-site refueling 20 years.**

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

#### IAEA 2004 Report

7/1/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Diagram of Reactor Design

## VBER-150

Developer Name: **OKBM Afrikantov**

Technology: **Light Water Reactor**

Size Thermal (MWt): **350**

Size Electrical (MWe): **110**

Technology Description (from literature):



A larger Russian factory-built and barge-mounted unit (requiring a 12,000 ton vessel) is the VBER-150, of 350 MWt, 110 MWe. It has modular construction and is derived by OKBM from naval designs, with two steam generators. Uranium oxide fuel enriched to 4.7% has burnable poison; it has low burn-up (31 GWd/t average, 41.6 GWd/t maximum) and eight-year refueling interval.

**RUSSIAN CONCEPTS OF NUCLEAR POWER PLANTS WITH SMALL REACTORS  
WITHOUT ON-SITE REFUELLING 2004 IAEA**

7/1/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Excerpt describing VBER 150

**RUSSIAN CONCEPTS OF NUCLEAR POWER PLANTS WITH SMALL REACTORS  
WITHOUT ON-SITE REFUELLING**

7/1/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

IAEA report 2004 including VBER 150 and about 10 other barge floating reactor designs

## VBER-300

Developer Name: **OKBM Afrikantov**

Technology: **Light Water Reactor**

Size Thermal (MWt):

Size Electrical (MWe): **295**

Technology Description (from literature):

OKBM Afrikantov's larger VBER-300 PWR is a 295 MWe unit, the first of which is planned to be built in Kazakhstan. It was originally envisaged in pairs as a floating nuclear power plant, displacing 49,000 tons. As a cogeneration plant it is rated at 200 MWe and 1900 GJ/hr. The reactor is designed for 60-year life and 90% capacity factor. It has four steam generators and a cassette core with 85 fuel assemblies enriched to 5% and 48 GWd/tU burn-up. Versions with three and two steam generators are also envisaged, of 230 and 150 MWe respectively. Also, with more sophisticated and higher-enriched (18%) fuel in the core, the refueling interval can be pushed from two years out to 15 years with burn-up to 125 GWd/tU. A 2006 joint venture between Atomstroyexport and Kazatomprom sets this up for development as a basic power source in Kazakhstan, then for export.

**Slides from Evgeny Velikhov at the Arctic Energy Summit, October 2007**

10/18/2007

<http://www.channels.com/episodes/show/4394597/Arctic-Energy-Summit-Dr-Evgeny-Velikhov>

Shows conceptual design of a 600 MWe floating nuclear power plant, but does not indicate time frame for constructing such a unit. Meeting on 9/24/2010 with Evgeny Velikhov indicates that the design is still conceptual.

## VK-300 Pressurized Water Reactor

Developer Name: **Atomenergoproekt**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt):

Size Electrical (MWe): **300**

Technology Description (from literature):

Another larger Russian reactor is the VK-300 boiling water reactor being developed specifically for cogeneration of both power and district heating or heat for desalination (150 MWe plus 1675 GJ/hr) by the N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET). It has evolved from the 50 MWe (net) VK-50 BWR at Dimitrovgrade, but uses standard components wherever possible, and fuel elements similar to the VVER. Cooling is passive, by convection, and all safety systems are passive. Fuel burn-up is 41 GWd/tU. It is capable of producing 250 MWe if solely electrical. In September 2007 it was announced that six would be built at Kola and at Primorskaya in the far east, to start operating 2017-20.

**Nuclear Power Plant with District Heat**

7/1/2004

<http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/29067712.pdf>

Short paper describing use of VK-300 reactor for district heat.

**Nuclear Desalination Complex with VK-300 Boiling-Type Reactor Facility, 2004**

9/8/2004

<http://www.world-nuclear.org/sym/2004/pdf/kuznetsov.pdf>

Describes desalination plant and reactor design.

**NON-ELECTRICITY APPLICATION OF NUCLEAR ENERGY: SOME GENERAL ISSUES AND PROSPECTS Yu.N.Kuznetsov, B.A.Gabaraev**

7/1/2007

<http://www-pub.iaea.org/MTCD/Meetings/PDFplus/2007/cn152/cn152p/Y%20Kuznetsov%20Russia%20Presentation.pdf>

Power point discussing VK-300 use for CHP and desalination, safety features

*Japan*

**Fuji Molten Salt Reactor (MSR)**

Developer Name: **Fuji--Russian--USA**

Technology: **Molten Salt Reactor**

Size Thermal (MWt):

Will build 10 MW prototype as soon as they get

Size Electrical (MWe): **100**

Technology Description (from literature):

The Fuji MSR is a 100 MWe design to operate as a near-breeder and being developed internationally by a Japanese, Russian and US consortium. The attractive features of this MSR fuel cycle include: the high-level waste comprising fission products only, hence shorter-lived radioactivity; small inventory of weapons-fissile material (Pu-242 being the dominant Pu isotope); low fuel use (the French self-breeding variant claims 50kg of thorium and 50kg U-238 per billion kWh); and safety due to passive cooling up to any size.

[http://www.ithems.jp/e\\_index.html](http://www.ithems.jp/e_index.html)

### **Fuji MSR Wikipedia page**

10/8/2010

[http://en.wikipedia.org/wiki/Fuji\\_MSR](http://en.wikipedia.org/wiki/Fuji_MSR)

Molten Salt Reactor based on Oak Ridge experimental reactor.

### **LSPR--LBE-Cooled Long-Life Safe Simple Small Portable Proliferation-Resistant**

Developer Name:

Technology: **Fast Neutron Reactor**

Size Thermal (MWt): **150**

Conceptual

Size Electrical (MWe): **53**

Technology Description (from literature):

A lead-bismuth-eutectic (LBE) cooled fast reactor of 150 MWt /53 MWe, the LSPR (LBE-Cooled Long-Life Safe Simple Small Portable Proliferation-Resistant Reactor), is under development in Japan. Fuelled units would be supplied from a factory and operate for 30 years, then be returned. The concept is intended for developing countries.

<http://www.nr.titech.ac.jp/~hsekimot/HomePageMM060313.pdf>

### **LEAD-BISMUTH EUTECTICS COOLED LONG-LIFE SAFE SIMPLE SMALL PORTABLE PROLIFERATION RESISTANT REACTOR (LSPR)**

7/1/2004

<http://www.nr.titech.ac.jp/~hsekimot/HomePageMM060313.pdf>

Technology similar to that of Sodium cooled reactors, except Lead-Bismuth eutectic used as coolant. There were thought to be some corrosion problems, but these can be minimized by reducing oxygen content.

### **MRX**

Developer Name: **Japan Atomic Energy Research Institute (JAERI)**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt): **50**

Size Electrical (MWe): **30**

Technology Description (from literature):

The Japan Atomic Energy Research Institute (JAERI) designed the MRX, a small (50-300 MWt) integral PWR reactor for marine propulsion or local energy supply (30 MWe). The entire plant would be factory-built. It has conventional 4.3% enriched PWR uranium oxide fuel with a 3.5-year refueling interval and has a water-filled containment to enhance safety. Little has been heard of it since the start of the Millennium.

**Advanced Marine Reactor MRX and its applications for electricity and heat co-generation. T. Ishada, M Ochiai**

7/1/1999

[http://www.iaea.org/inisnkm/nkm/aws/fnss/fulltext/1172\\_8.pdf](http://www.iaea.org/inisnkm/nkm/aws/fnss/fulltext/1172_8.pdf)

Description of MRX reactor for use for ship propulsion, but also describes uses in "distant power". Includes schematic drawings of reactor design.

**The Economic Potential of a Cassette-type-reactor-installed Nuclear Ice-breaking Container Ship. KONDO K(Marine Technical Coll.) TAKAMASA T(Tokyo Univ. Mercantile Marine)**

7/1/2009

<http://scielinks.jp/j-east/article/200004/000020000400A0068255.php>

Description of "cassette" style nuclear reactor to reduce cost of these ships.

## Rapid-L

Developer Name: **Toshiba**

Technology: **Fast Neutron Reactor**

Size Thermal (MWt): **5**

Concept of reactor for lunar mission

Size Electrical (MWe): **0.2**

Technology Description (from literature):

A small-scale design developed by Toshiba Corporation in cooperation with Japan's Central Research Institute of Electric Power Industry (CRIEPI) and funded by the Japan Atomic Energy Research Institute (JAERI) is the 5 MWt, 200 kWe Rapid-L, using lithium-6 (a neutron poison) as control medium. It would have 2700 fuel pins of 40-50% enriched uranium nitride with 2600°C melting point integrated into a disposable cartridge. The reactivity control system is passive, using lithium expansion modules (LEMs) which give burn-up compensation, partial load operation as well as negative reactivity feedback. During normal operation, lithium-6 in the LEM is suspended on an inert gas above the core region. As the reactor temperature rises, the lithium-6 expands, moving the gas/liquid interface down into the core and hence adding negative reactivity. Other kinds of lithium modules, also integrated into the fuel cartridge, shut down and start up the reactor. Cooling is by molten sodium, and with the LEM control system, reactor power is proportional to primary coolant flow rate. Refueling would be every 10 years in an inert gas environment. Operation would require no skill, due to the inherent safety design features. The whole plant would be about 6.5 meters high and 2 meters diameter.

<http://www.jaea.go.jp/jaeri/english/press/2001/010704/index.html>

**Design of a Super Safe Compact Reactor RAPID-L in pursuit of extreme size and weight reduction, JAERI**

7/4/2001

1998 design for small reactor for lunar base

## **Argentina**

### **CAREM Pressurized Water Reactor**

Developer Name: **CNEA & INVAP**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt):

Design stage

Size Electrical (MWe): **27**

Technology Description (from literature):

The CAREM reactor being developed by INVAP in Argentina, under contract to the Argentine National Atomic Energy Commission (CNEA), is a modular 100 MWt (27 MWe) pressurized water reactor with integral steam generators designed to be used for electricity generation or as a research reactor or for water desalination (with 8 MWe in cogeneration configuration). CAREM has its entire primary coolant system within the reactor pressure vessel, self-pressurized and relying entirely on convection. Fuel is standard 3.4% enriched PWR fuel, with burnable poison, and is refueled annually. It is a mature design which could be deployed within a decade, and scaled up to 300 MWe or more. The prototype is to be built in the northwestern Formosa province of Argentina.

#### **CAREM Project description--Main Research and Development for SMRs in Argentina-- D. Delmastro**

7/1/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Describes development of the CAREM reactor, including prototypes and mock-ups.

#### **Preliminary Fueling costs for CAREM**

7/1/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

This paper begins on Page 97 of the document on the web site. Provides cost estimates of Fueling the CAREM reactor.

## **China**

### **NHR-200**

Developer Name: **Tsingua University's Institute of Nuclear Energy Technology (now the Institute of Nuclear and New Energy Technology)**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt): **200**

Size Electrical (MWe): **66**

Technology Description (from literature):

The Chinese NHR-200 (Nuclear Heating Reactor), developed by Tsingua University's Institute of Nuclear Energy Technology (now the Institute of Nuclear and New Energy Technology), is a simple 200 MWt integral PWR design for district heating or desalination. It is based on the NHR-5 which was commissioned in 1989, and runs at lower temperature than the above design. Used fuel is stored around the core in the pressure vessel. In 2008, the Chinese government was reported to

have agreed to build a multi-effect distillation (MED) desalination plant using this on the Shandong peninsula.

<http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/29067732.pdf>

**IAEA 1996 Paper on NHR-200 reactor: Analysis of the nuclear heating reactor and its possible uses in desalination.**

7/1/1996

<http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/29067732.pdf>

Older paper describing NHR reactor, with discussion of district heating and desalination.

**Abstract to 2008 paper**

7/1/2008

<http://inderscience.metapress.com/app/home/contribution.asp?referrer=parent&backto=issue,11,11;journal,5,14;linkingpublicationresults,1:110883,1>

Abstract from 2008 indicates that reactor is still being planned.

## **France**

### **NP-300**

Developer Name: **Technicatome (Areva TA)**

Technology: **Pressurized Water Reactor**

Size Thermal (MWt):

Size Electrical (MWe): **100**

Technology Description (from literature):

Technicatome (Areva TA) in France has developed the NP-300 PWR from submarine power plants and aimed it at export markets for power, heat and desalination. It has passive safety systems and can be built for applications of 100 to 300 MWe or more with up to 500,000 m<sup>3</sup>/day desalination. Areva TA makes the K15 naval reactor of 150 MWe, running on low-enriched fuel, and the land based equivalent: Réacteur d'essais à terre (RES) a test version of which is under construction at Cadarache.

<http://www.areva.com/EN/operations-1556/index.html>

**None**

[None](#)

Brief web search did not identify any useful documents.

## **India**

### Pressurized Heavy Water Reactors (PHWR-220)

Developer Name: **Nuclear Fuels Complex, India**

Technology: **Pressurized Water Reactor**

Commercial, but not intended for import into US.

Technology Description (from literature):

Size Thermal (MWt):

Size Electrical (MWe): **220**

Based on Canadian Technology, India is now focusing on 450 MWe and 700 MWe versions of its PHWR.

<http://www.nfc.gov.in/history.htm>

#### **India All Set To Export 220 MWe PHWRs To Kazakhstan**

7/22/2009

<http://www.asiannuclearenergy.com/News/Latest/india-all-set-to-export-220-mwe-phwrs-to-kazakhstan.html>

Indicates that this reactor is commercial in India, and ready for export to other countries needing small reactors.

## **International**

### International Reactor Innovative and Secure (IRIS)

Developer Name: **Westinghouse**

Technology: **Pressurized Water Reactor**

Technology Description (from literature):

Size Thermal (MWt):

Size Electrical (MWe): **100**

Westinghouse's IRIS (International Reactor Innovative & Secure) is an advanced 3rd generation reactor. A335 MWe capacity is proposed, although it could be scaled down to around 100 MWe. IRIS is a modular pressurized water reactor with integral primary coolant system and circulation by convection. Fuel is similar to present LWRs and (at least for the 335 MWe version) fuel assemblies are identical to those in AP1000, according to Westinghouse. Enrichment is 5% with burnable poison and fuelling interval of four years (or longer with higher enrichment). US design certification is at the pre-application state.

#### **Web page about Estonia planning to install an IRIS plant**

5/20/2009

[http://www.energy-business-review.com/news/eesti\\_energia\\_to\\_install\\_iris\\_nuclear\\_reactor\\_in\\_its\\_planned\\_nuclear\\_plant\\_090520](http://www.energy-business-review.com/news/eesti_energia_to_install_iris_nuclear_reactor_in_its_planned_nuclear_plant_090520)

Estonia wants an IRIS reactor because the small size fits the country, but there are concerns about cost over-runs associated with the first installation.

**NRC Summary Sheet**

5/28/2009

<http://www.nrc.gov/reactors/advanced/iris.html>

Submittal expected to NRC by 3Q FY 2012

**NRC Summary on New Nuclear Power Plant Designs**

8/14/2009

<http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/new-nuc-plant-des-bg.html>

Lists the IRIS reactor design review as "inactive". Only the Pebble Bed reactor and the 4S are listed as in the "pre-application review" stage.

**IRIS Wikipedia Site**

10/5/2010

[http://en.wikipedia.org/wiki/International\\_Reactor\\_Innovative\\_and\\_Secure](http://en.wikipedia.org/wiki/International_Reactor_Innovative_and_Secure)

Discussion of the international consortium working on this project, still not attached to a final design. Economics of 3 reactors for \$300M, cost of power at \$0.04 per kWh.

**South Korea****Korean Fast Reactor Design (KFRD)**Developer Name: **Korea Atomic Energy Research Institute (KAERI)**Technology: **Fast Neutron Reactor**

Size Thermal (MWt):

Size Electrical (MWe): **35**

Technology Description (from literature):

In South Korea, the Korea Atomic Energy Research Institute (KAERI) has been working on sodium cooled fast reactor designs. A second stream of fast reactor development there is via the Nuclear Transmutation Energy Research Centre of Korea (NuTrECK) at Seoul University (SNU). It is working on a lead-bismuth cooled design of 35 MWe which would operate on pyro-processed fuel. It is designed to be leased for 20 years and operated without refueling, then returned to the supplier. It would then be refueled at the pyro-processing plant and have a design life of 60 years. It would operate at atmospheric pressure, eliminating major concern regarding loss of coolant accidents.

**None**

A brief web search did not produce any additional information about this reactor design.

**System-integrated Modular Advanced Reactor (SMART)**Developer Name: **KAERI**Technology: **Pressurized Water Reactor**Size Thermal (MWt): **330**Size Electrical (MWe): **100**

Technology Description (from literature):

South Korea's SMART (System-integrated Modular Advanced Reactor) is a 330 MWt pressurized water reactor with integral steam generators and advanced safety features. It is designed by the



Korea Atomic Energy Research Institute (KAERI) for generating electricity (up to 100 MWe) and/or thermal applications such as seawater desalination. Design life is 60 years, with a three-year refueling cycle. While the basic design is complete, the absence of any orders for an initial reference unit has stalled development. KAERI is now intending to proceed to licensing the design by 2012.

**Nuclear Desalination Technology using SMART**

7/15/2004

[http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1451\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf)

Describes SMART Program, beginning in 1996, start building prototype in 2002.