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Rev. 1

Special Purpose Application Reactors: Systems Integration Decision Support

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Special Purpose Application Reactors: Systems Integration Decision Support

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SUMMARY

Microreactors, also known as very-Small Modular Reactors (vSMRs) or Special Purpose Reactors (SPRs), are being considered for use in unique applications where other methods of megawatt level energy production are uneconomical or unavailable. For the purposes of this report, a microreactor is defined as meeting the following criteria:

- Factory manufacturable
- Easily transportable by truck, plane, train, and/or ship
- Produce no more than 20 megawatt thermal (MWth) energy, in order to qualify as Hazard Category 2 under 10CFR830
- Maintains neutronic simplicity, allowing semi- or fully-autonomous operation

In the United States (U.S.), there are two general types of microreactors under development: high-temperature gas reactors (HTGRs) and heat pipe reactors. These two reactor types may, due to their differences in working fluid temperatures, be more effectively suited to different use cases. Additionally, they will require different interfacing components depending on their intended use.

This report identifies a broad range of use cases for micro-reactors. Additionally, multiple reactor technologies are examined with an emphasis on the reactor sub-systems and interconnections. Using this information, a decision support framework is developed to guide future efforts.

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ACRONYMS

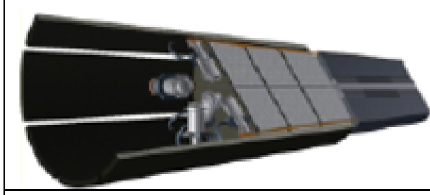
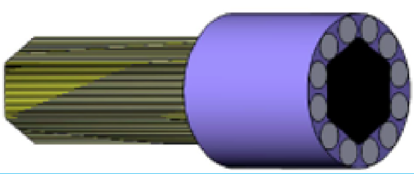
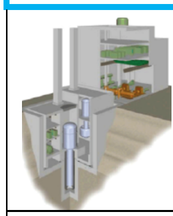
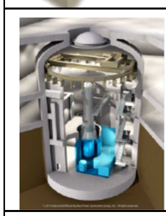
AEMR	Annual Energy Management and Resilience
CNA	Center for Naval Analyses
CO	carbon monoxide
CO_2	carbon dioxide
CONUS	continental United States
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-OE	U.S. Department of Energy–Office of Electricity
DOT	U.S. Department of Transportation
DSB	Defense Science Board
EPZ	emergency planning zone
FBCE	fully burdened cost of energy
FOAK	First of a Kind
FOB	forward operating base
GE	General Electric
GHG	greenhouse gas
GWh	gigawatt hour
HALEU	high-assay, low-enriched uranium
HIP	hot isostatic press
HTGR	high-temperature gas reactor
HTSE	High-Temperature Steam Electrolysis
HVAC	heating, ventilating, and air-conditioning
IED	improvised explosive device
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
IPP	independent power producer
K	Potassium
kWh	kilowatt hour
LANL	Los Alamos National Laboratory
LEU	low-enriched uranium
LFR	lead fast reactor
LOCA	loss of coolant accident
LWR	light-water reactor
MPa	megapascals

MRL	Manufacturing Readiness Level
MSF	multistage flash desalination
MWe	megawatt electric
MWth	megawatt thermal
Na	Sodium
NASA	U.S. National Aeronautics and Space Administration
NHES	Nuclear Hybrid Energy System
NRC	U.S. Nuclear Regulatory Commission
OCONUS	outside the continental United States
OE	Office of Electricity
PCU	power conversion unit
PIRT	Phenomena Identification and Ranking Table
PV	photo voltaic
RO	reverse osmosis
sCO_2	supercritical carbon dioxide
SFR	Sodium Fast Reactor
SMR	Small Modular Reactor
SPR	Special Purpose Reactor
SRL	System Readiness Level
TES	Thermal Energy Storage
TRISO	tristructural isotropic
TRL	technology readiness level
U.S.	United States
vSMR	very Small Modular Reactor

1. INTRODUCTION

A microreactor, also known as a very-Small Modular Reactor (vSMR) or a Special Purpose Reactor (SPR), is designed for use in unique applications where energy generation on the order of mega-watts is needed but otherwise unavailable or prohibitively expensive. Microreactors generally produce less than 20 megawatt thermal (MWth),[a] are factory manufacturable, easily transportable (e.g., truck, train, plane, or ship), and neutronically simple so as to allow for semi- or fully-autonomous operation. The use cases for the generated energy may call for electricity production, direct use of process heat, or both. Table 1.1 shows the electric power production potential of microreactors relative to other types of reactors [1].

Table 1.1. Relative electric power production of microreactors vs. other reactor types [1].

	Electric Power	Type	Application(s)	Power (kW)
	500 W – 10 kW	Non-Light Water Reactor (LWR)	• Deep space power	10^0
	10 kW – 1 MW	Non-LWR	• Space propulsion • Planetary surface power • Military applications	10^1 10^2
	1 MW – 10 MW	Non-LWR	• Military bases • Remote locations • Disaster relief	10^3
	10 MW – 50 MW	Non-LWR	• Power to grid • Military bases • Process heat	10^4
	50 MW – 300 MW	LWR & Non-LWR	• Power to grid • Small cities • Burning of actinides	10^5
	>500 MW - ~1000 MW	Mostly LWR	• Power to grid	10^6

[a] The limit of 20 MW_{th} allows for classification of microreactors as Hazard Category 2 per 10 CFR 830, DOE-STD-1027.

The objectives of this report are as follows:

1. Outline the expected use cases, including the needs and constraints present in each use case. This includes considerations for reactor deployment, geographic factors, and integration with existing infrastructure.
2. Examine the known microreactor technologies currently under development and the associated sub-system technologies, including interfaces.
3. Develop a decision support framework for examining the potential performance of a given microreactor in a defined use case.
4. Discuss the integration of a microreactor with a microgrid.

1.1 Background

There is an increasing need for more reliable and readily available energy in special purpose applications. Possible applications include, but are not necessarily limited to, military installations, remote communities, and industrial processes. Mobile power for emergency response may also be considered among these relatively small, but high consequence, markets. Typical power needs in these use cases range from 1 to 10 megawatt electric (MWe). In many current applications, power generation at this scale is achieved through the use of diesel generators. However, increasing costs and supply chain constraints have prompted a desire to examine other options to ensure energy availability and reliability.

In combat scenarios, the fully burdened cost of energy (FBCE) for truck-delivered fuel is estimated to range from $10 - $50 per gallon [2]. For air-dropped fuel, this cost increases to as much as $400 per gallon [3]. In remote Alaskan villages, fuel costs can rise to as much as $10 per gallon, with electricity costs exceeding 40 cents per kilowatt hour (kWh) [4]. Additionally, there is renewed interest in using nuclear power for certain process heat and industrial applications, such as water desalination [5]. These economic and technical realities have motivated a desire for developing other methods of energy production. Microreactors could be ideal for many of these scenarios due to their potentially long-term reliability, ease of deployment, and relatively abundant energy production. This has led several national laboratories and private companies to explore the development and deployment of microreactor concepts.

While several concepts are under development, none of them have been constructed. There is a desire to begin operation of a First-of-a-Kind (FOAK) demonstration microreactor in the early 2020s. This aggressive goal will require the use of high technology readiness level components, as well as fuels and materials that are already qualified for use in nuclear fission environments. Additional rapid maturation of integration and control technologies will also be required. Later systems may pursue advanced materials, advanced fuels, and novel heat exchangers in order to achieve higher performance, greater efficiency, and lower cost.

2. USE CASES

Microreactors are primarily intended for non-traditional applications of nuclear energy. Specific deployment opportunities may include provision of heat and electrical power to remote commercial and industrial applications, remote civilian municipalities, or remote or islanded military installations. Currently anticipated requirements for each of these use case categories are summarized in the following section.

The specific use cases outlined here can be characterized by three general use scenarios:

1. Remote Sites
    - Meet the needs of remote locations outside the continental United States (OCONUS), and/or fixed Department of Defense (DoD) bases (e.g., Alaska, Guam, Northern Canadian Communities).
    - Provide combined heat and power.
    - Support critical loads (e.g., hospitals and radar stations).
    - Microreactors would displace diesel or JP-8 fueled generators.
2. Mobile Power
    - Mining operations and/or ‘mobile’ DoD bases such as Forward Operating Bases (FOBs).
    - Provide combined heat and power.
    - Reactors design should be mobile rather than just transportable.
    - Microreactors would displace diesel or JP-8 fueled generators.
3. Renewable Microgrids
    - Provide baseload power to stabilize the variability of renewable wind and solar energy.
    - Displace ‘fast-ramp’ open cycle gas turbine generators.
    - Could potentially be used to decrease battery storage needs.

2.1 Military Installations

United States (U.S.) DoD installations are working towards ensuring greater energy security through the addition of on-site renewable energy to reduce reliance on the grid. Given that the average energy use of most DoD installations is less than 20 MWe, microreactors may be an option for future energy production. Figure 2.1 shows the breakdown of average energy demand at DoD installations in 2016. The data is based on the DoD Annual Energy Management and Resilience (AEMR) Report for FY2016 [6]. Additional detail is provided in Appendix A.

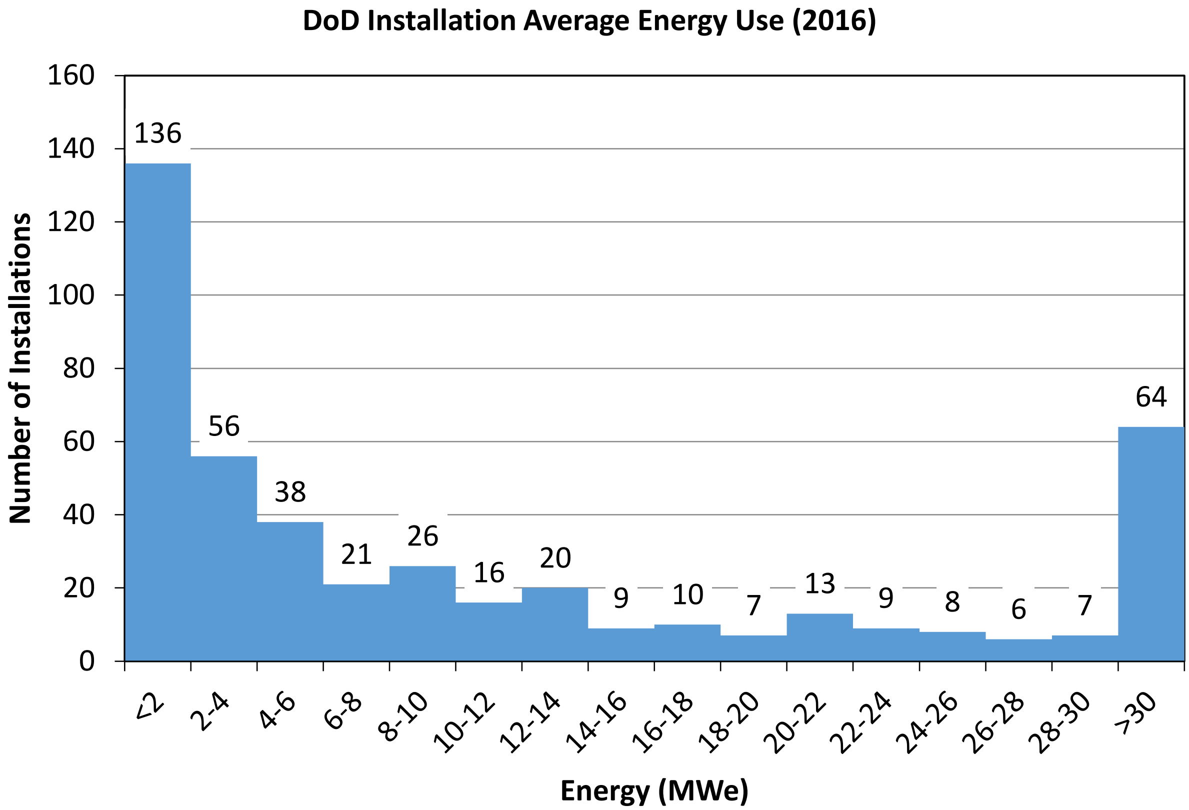


Figure 2.1. Breakdown of average energy demand at DoD installations in FY-2016.

Not all of the DoD installations noted in Figure 2.1 or Appendix A are suitable for a nuclear reactor. The decision matrix determining which facilities may benefit from MW scale, on-site nuclear power will be evaluated in future studies that engage energy planners within DoD. It is worth noting that, in general, the level of energy use at these locations is within the capability range of microreactor systems.

The use of Small Modular Reactors (SMRs) at military installations was examined in a 2011 study by the Center for Naval Analyses (CNA) for the DoD [7]. While the study showed that SMRs can meet DoD targets for energy reliability and clean energy production, several issues were identified. Many of these issues related to the size of the SMR plant, which would be ~50 MWe. This plant size would require extensive effort for siting. Additionally, the cost for a FOAK plant would likely make the plant economically unfeasible.

Microreactors avoid or minimize concerns regarding potential impact to the public due to their much smaller footprint and more simplistic design. As a result of the reduced source term and radionuclide inventory for microreactors relative to large-scale reactors, the associated emergency planning zone (EPZ) could be as close as the containment boundary. The small size of microreactor plants is additionally expected to simplify the siting process. Particularly in the case of a FOAK reactor, licensing and siting could be further simplified with construction at an existing U.S. Department of Energy (DOE) site. Public-private cooperation can help keep FOAK microreactor costs lower than those previously anticipated with SMR plants.

2.1.1 Forward Operating Bases

FOBs require significant fuel supplies to maintain operations. As of 2007, fuel consumption was approximately 22 gallons per soldier per day in Iraq and Afghanistan, a significant increase over past engagements. Figure 2.2 shows the historic trend of military fuel consumption.

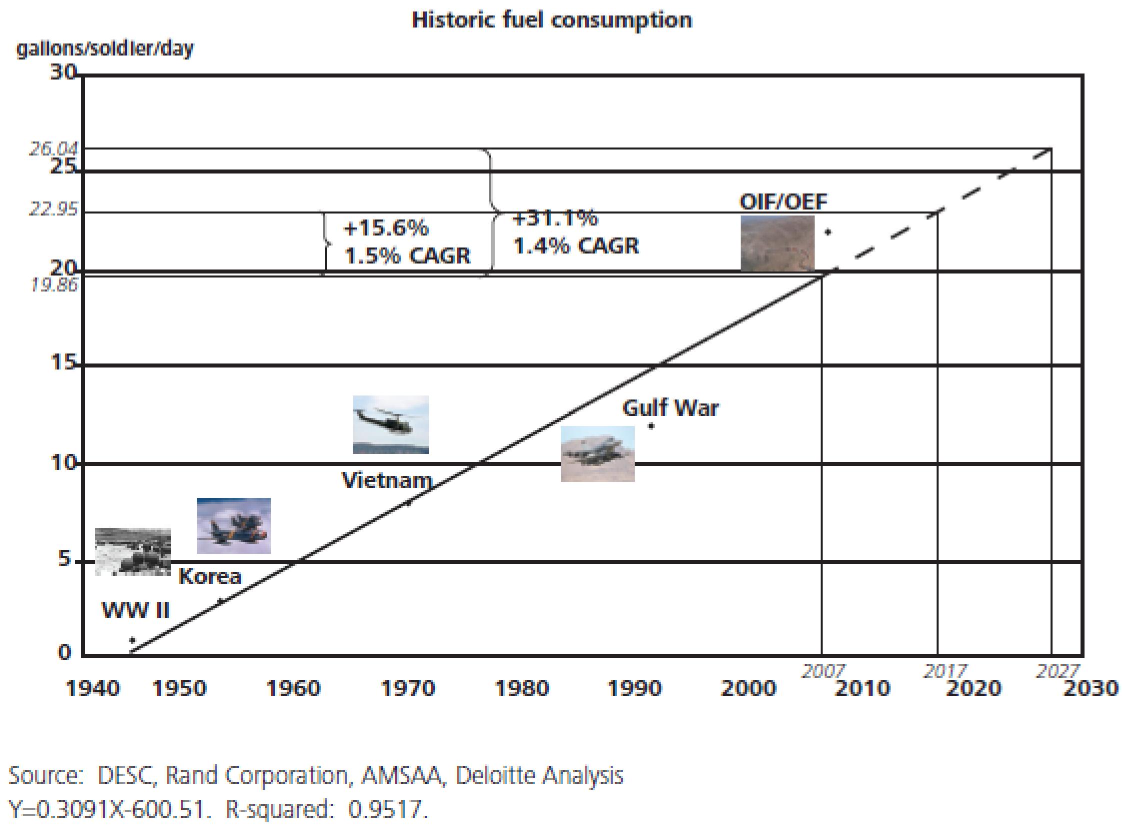


Figure 2.2. Military fuel consumption history and forecast[b] [8].

Diesel fuel is used not only for operating vehicles, but also for electricity generation at FOBs. To transport fuel to a FOB, a fuel convoy is used. These convoys are susceptible to a variety of hazards ranging from weather and traffic accidents to attacks and disruption from roadside improvised explosive devices (IEDs). These logistical hazards have been a significant source of casualties in the recent conflicts in Iraq and Afghanistan. Based on history, the need for energy in future conflicts is only expected to grow [8].

A recent report from the Defense Science Board (DSB) Task Force on Energy Systems for Forward/Remote Operating Bases considered the potential impact of alternative energy on fuel consumption. The use of alternative energy sources for base support would result in a significant reduction, but not an elimination, of fuel demand. The DSB Task Force also found that many renewable energy sources, such as solar and wind, are limited by their variability and the large footprint necessary to produce an adequate amount of electricity [2].

Microreactors tend to address many of the concerns raised by renewable energy sources. Microreactor systems produce a stable, continuous supply of abundant energy in a relatively small footprint. The DSB report noted the potential for microreactors to enable new capabilities, since the bases would switch from a scarce energy supply to an abundant one [2]. An abundance of energy opens up the possibility for using

[b] AMSAA: Army Materiel Systems Analysis Activity; CAGR: Compounded Annual Growth Rate; DESC: Defense Energy Support Center; OEF: Operation Enduring Freedom; OIF: Operation Iraqi Freedom; WW II: World War II

nuclear-generated heat for synthetic fuel production. This would further reduce the reliance on fuel supply convoys and therefore reduce the casualties associated with protecting convoys.

A summary of requirements from the DSB report is reproduced here [2]:

- **Outputs:** Modular and scalable units capable of producing 2-10 MWe and potentially useful heat (which would facilitate water or fuel production)
- **Size and transportability:** 25-40 tons; transportable by truck or C-17 aircraft
- **Ultimate heat sink:** Ambient air (in contrast to conventional water-cooled reactors); capable of passive cooling
- **Time to install:** 12-72 hours
- **Refueling:** Refueling should not be required more than annually; fresh and used fuel should be transportable by air, sea, and ground
- **Time for planned shutdown, cool down, disconnect, and removal:** 6 hours to 7 days
- **Operation:** Autonomous or semiautonomous operations with minimal manning to monitor overall health of the vSMR
- **Response to emergency:** Capable of immediate shutdown and passive cooling
- **Health and safety risks:** No net increase in risk to public, military personnel, environment; no net increase in consequences of adversary attack
- **Proliferation risk:** No net significant increase in proliferation risk

In addition to these requirements, the DSB report also summarizes some key performance parameters from an Idaho National Laboratory (INL) report, which are reproduced in Table 2.1 [2].

Table 2.1. Key performance parameters and challenges [2]

Key Performance Parameter (KPP)	Challenge
Transport fresh and used fuel by air, sea, rail, and highway.	Need a nuclear energy system capable of air transportation, while addressing highly radioactive source terms and large residual heat loads.
No significant increase in FOB threat consequence effects, e.g., avoid unacceptable radiological consequences.	Need a nuclear energy system design that mitigates toxic and radioactive dispersal and related consequences from credible transport or operation accidents or design basis attacks, e.g., ballistic, IED, direct fires that breach the system.
Transportable by C-17 aircraft.	Need a nuclear energy system that can be transported to FOBs worldwide by military transport.
Installed and operating within 72 hours.	Need a nuclear energy system that is agile, quickly set-up and operating.
Shutdown, cool down, disconnect and transport to another location in less than seven days.	Need a nuclear energy system that is agile and able to move with the FOB, i.e., it is not the "long pole in the FOB tent."
Capable of immediate shutdown and passive cooling.	Need a nuclear energy system that is inherently safe, with no negative outcome if all active systems and controls are lost, e.g., due to attack.

Table 2.1 (continued)

No significant increase in risk to the health and safety of the public, military personnel or to the environment.	Need a nuclear energy system that does not result in a significant increase in risk to the health and safety of the public, military personnel nor to the environment, relative to the risk associated with normal human activity.
Greater than one year refueling cycle.	Need a self-contained nuclear energy system that dramatically reduces the number of energy related convoys.
No proliferation risk.	Need a nuclear energy system that is designed to minimize proliferation risk by reducing fuel access opportunity, reducing fuel attractiveness and avoiding production of attractive fuel.
Scalable reactor design; 2–10 MWe	Need to adjust to FOB size and load demand.

2.1.2 Other Military Installations

A recent DoD report (2017) discusses the mandate to increase the use of renewable energy at military installations. While significant progress has been made, current targets for renewable energy utilization are being missed. The report also discusses the potential for SMRs at military installations. The report states that SMRs, which generate at least 50 MWe, are too large for a single military installation and should therefore be considered by regional utility providers. There are additional concerns about financial and technical hurdles to SMR deployment. DoD also doubts the ability to deploy prior to 2025 [6].

A 2011 report by CNA considered nuclear power, and SMRs in particular, for military applications. The report concluded that while nuclear power can assure abundant energy for critical functions, there are several drawbacks. These included siting of reactors, as well as economic viability. In particular, the FOAK expenses were estimated to be in the hundreds of millions of dollars. Additionally, the cost of electricity was estimated to be slightly higher than the projected average retail price for industrial users in the US. Ultimately, the report did consider SMRs feasible, particularly in remote locations for electricity and heat, if the concerns related to licensing and FOAK costs can be addressed [7].

Microreactors can reduce the need for diesel for electricity production at military installations. Additionally, the reactors can be used to supplement other needs, such as district heating and water desalination. In cases where a military installation already has sufficient access to an external power supply, a microreactor could be used for backup power of critical infrastructure. The specific needs of individual military installations will need to be considered on a case-by-case basis. A case study to assess energy system needs at high priority installations will help to define the deployment criteria.

Given their significantly smaller footprint and lower power generation level, microreactors can address many of the concerns DoD raised for SMRs.

- **Simplicity:** Microreactors are designed from the start to be lower cost and simple, with reduced operations and maintenance overhead. Additionally, they are designed to continuously operate for several years without refueling.
- **Power output:** Power output on the order of 10 MWe is in line with the average demand of many military installations. This removes the need for a reactor to be connected to an outside regional grid to distribute excess energy.

- **Technology readiness:** While some development is still needed in microreactor technology, the designs under consideration for initial deployment are largely based on known technologies with high technology readiness level (TRL).
- **Licensing:** The licensing path still needs clarification. The smaller reactor size should simplify siting considerations and simplify some parts of the licensing process. The details of microreactor licensing are currently being defined by the U.S Nuclear Regulatory Commission (NRC) and private sector stakeholders.

2.2 Remote Communities

Remote communities provide unique challenges for reliable energy generation. In rural Alaska, electric power can vary from $0.50 to $1.50 per kWh, and heating fuel can vary from $1.40 to $10.00 per gallon [9], [10]. The harsh climate means that fuel can only be delivered during warmer months of the year, with diesel providing more than 90% of electric power in rural areas. In November of 2011, the town of Nome Alaska was scheduled to receive its final fuel shipment of the year [11]. The shipment of heating fuel, diesel, and gasoline is necessary for the town to survive the harsh winter. When a massive storm hit earlier than expected, the town was iced in prior to arrival of the fuel shipment. Without adequate fuel to survive the winter, there was the potential of evacuating until spring. Luckily, arrangements were made to have the fuel brought in on a double-hulled barge, with the help of a U.S. Coast Guard icebreaker.

In order to diversify and increase the resilience of power generation systems, Alaskan villages are turning to microgrids. In Cordova, Alaska, a microgrid system is being installed which will reroute power to ensure that critical services are always supplied. The system is designed to be make automated decisions about power transmission, allowing it to reconfigure to accommodate changes in the grid [12].

Microreactors have the potential to revolutionize how energy is produced and distributed in remote locations. The communities generally have significant fuel costs and are often isolated from much of the world for long periods each year. Their limited accessibility, infrastructure, and low population density introduce unique requirements for reliable power and heat generation. Due to its current reliance on microgrids which use fossil and renewable energy sources, Alaska is a prime location where microreactors could have a major impact.

Alaska is divided into 12 land-based regional corporations and over 200 village corporations. Figure 2.3 shows the geographic boundaries for the land-based regions and how they overlap with 11 energy planning regions [13]. Data from the Alaska Energy Data Gateway was used to examine total annual energy generation for the years 2008 through 2013 in each of the 11 energy regions. Appendix B summarizes this data, showing the annual average demand when divided by the number of hours in a year (8760 hours). Figure 2.4 and Figure 2.5 show this average energy generation rate for each region in each year.

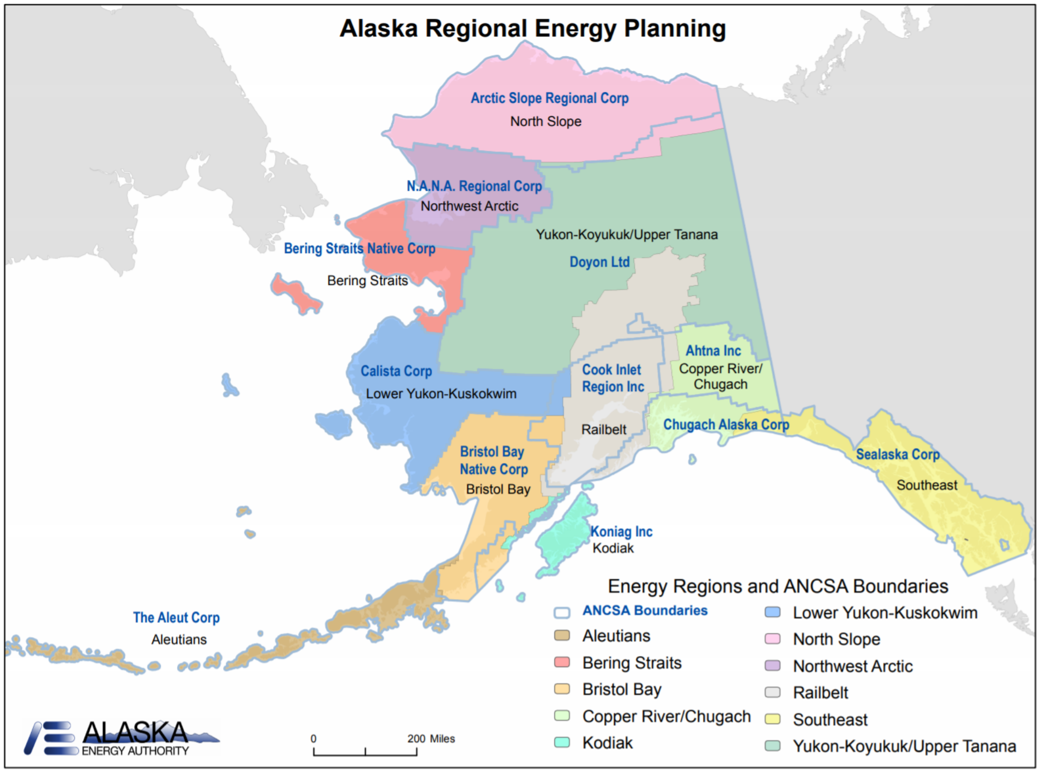


Figure 2.3. Alaska energy regions [13]

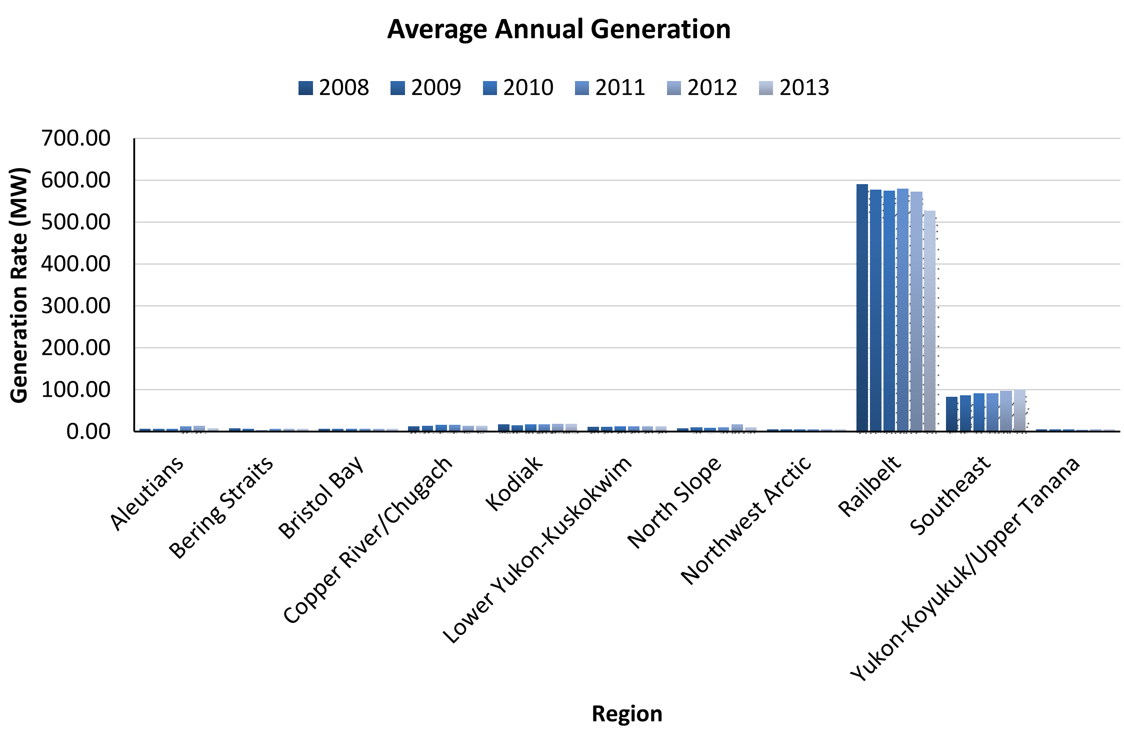


Figure 2.4. Energy generation in Alaska regions averaged over full year [14]

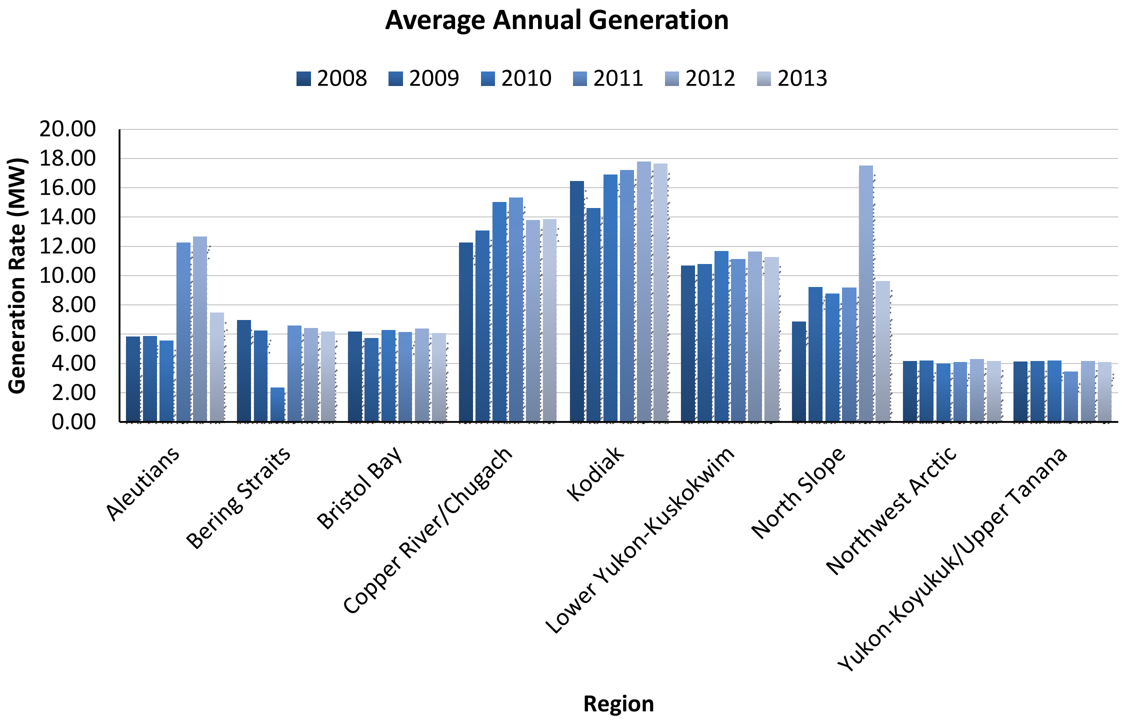


Figure 2.5. Energy generation in Alaska regions averaged over full year (regions with <20 MWe)

The average power demand is less than 18 MWe in all but two of the energy regions. Hourly and seasonal variations in demand mean that actual demand at any given time is likely to be significantly different from these values. However, the data in Figure 2.5 show an opportunity for microreactors to integrate into microgrids. Microreactors that work in concert with other energy sources through a smart microgrid such as the one being deployed in Cordova, have the potential to provide these remote locations with abundant rather than scarce energy supply.

2.3 Desalination of Brackish/Sea Water

A potential alternative energy application is the desalination of sea water. This would be a particularly useful application in areas such as Southern California or the Southwestern U.S., where availability of potable drinking water is an increasing concern. To ensure adequate water supplies, desalination plants such as the Claude "Bud" Lewis plant in Carlsbad are being brought online in Southern California [15], [16].

For desalination plants with a capacity of 4000 m^3 per day or more, the two main technologies available are multistage flash (MSF) desalination and reverse osmosis (RO). As of 2000, MSF accounted for 69% of high capacity plants, while RO accounted for 23% [17]. MSF desalination is based on heating seawater in a brine heater to approximately 100 °C. The hot brine then enters a flash chamber under vacuum. Since the water entering the chamber is above the boiling temperature at vacuum, part of the water flashes to steam. The steam rises to condensing coils where it cools and condenses to fresh water. The process is illustrated in Figure 2.6.

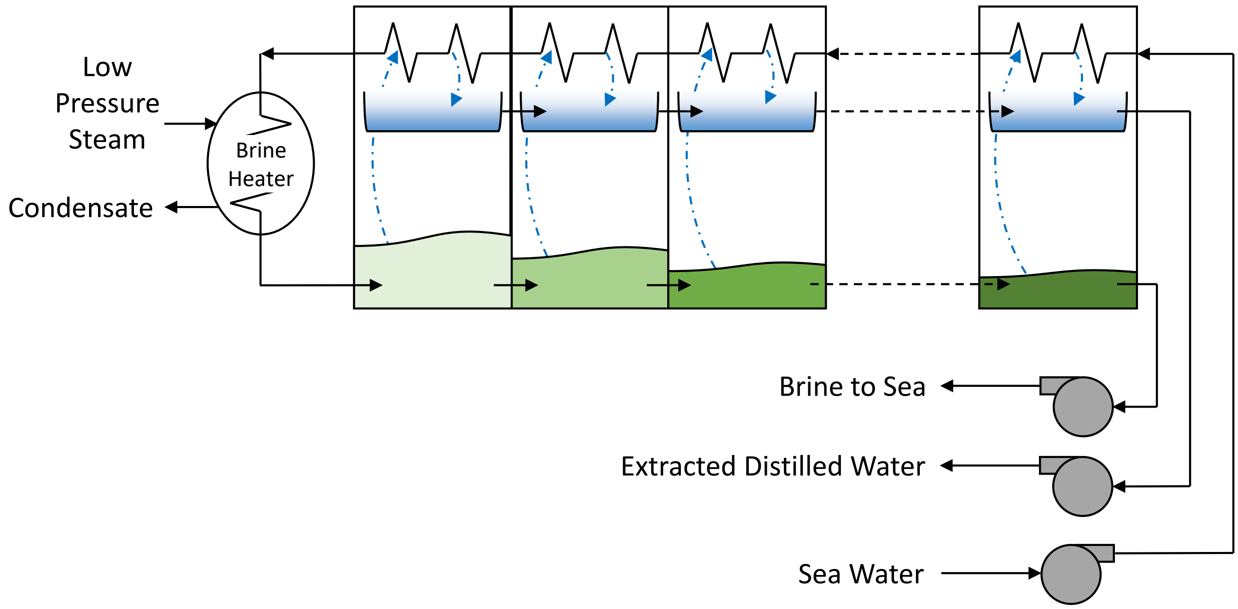


Figure 2.6. Schematic of basic MSF desalination process

RO desalination works by passing water at high pressure through fine membranes which allow only water molecules to pass. A typical RO plant works in two stages, the first being a pretreatment stage where chlorine and other chemical additives are used to remove biological contaminants, as well as control the pH and hardness of the water. The water is then sent to the membrane filtration system where high pressure forces the water molecules through the membranes and into an inner collection tube. The RO desalination process is shown in Figure 2.7.

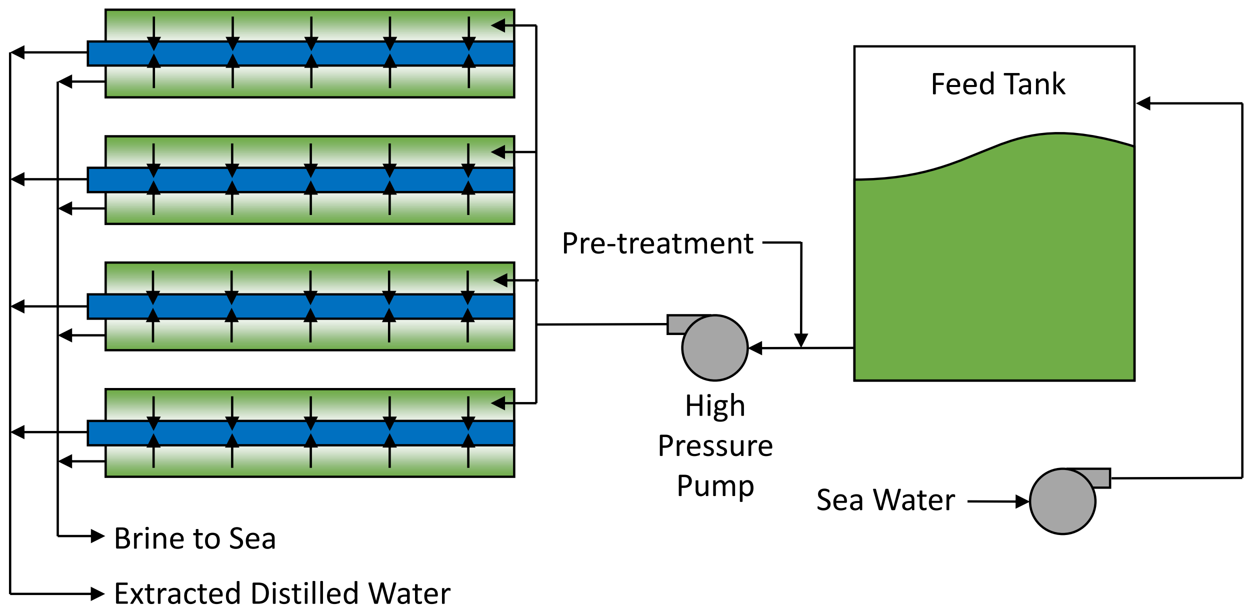


Figure 2.7. Schematic of basic RO desalination process

MSF is a proven technology for water desalination. It is a simple and extremely reliable process that requires no moving parts other than pumps. Unfortunately, MSF is more energy intensive than current RO plants, requires a direct steam connection to the power plant, and typically runs at full capacity to limit potential system instabilities [18]. These challenges limit MSF applications when steam shedding is being used as a load leveling strategy.

RO has the benefit of consuming less energy than MSF. RO also does not need a direct steam connection to the power plant, as it only requires electric energy to run pumps and has simple start/stop operating capability [18]. Since RO is operated in modules, operation can be staged to take advantage of available excess energy instead of the all or nothing operation of MSF. These properties make RO a highly attractive secondary energy application for microreactors in remote locations.

2.4 Hydrogen Production

Excess thermal and electrical energy can be used for hydrogen production. The anticipated development and deployment of fuel cell technology and infrastructure into the transportation sector will create substantial additional demand for hydrogen. One of the motivations to switch to a hydrogen-based infrastructure is to reduce greenhouse gas (GHG) emissions. However, significant GHG reduction will only occur if the hydrogen is produced from carbon-free sources.

Current large-scale hydrogen production is accomplished by stripping hydrocarbon fuel via the steam-methane reforming process shown in Eq. 1 [19]. In steam-methane reforming, methane reacts with steam in the presence of a catalyst to produce hydrogen and carbon monoxide (CO). In a subsequent "water-gas-shift reaction," the CO and steam are reacted using a catalyst to produce carbon dioxide (CO_2) and hydrogen, as shown in Eq. 2.

$$CH_4 + H_2O + (heat) \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 + (small\ amount\ of\ heat) \tag{2}$$

A byproduct of this reaction is CO_2, which does not meet the GHG reduction standards established in the Paris agreement [20]. Fortunately, an alternative clean energy source of hydrogen with zero CO_2 emissions comes from the dissociation of water via conventional (i.e., low temperature) electrolysis and High Temperature Steam Electrolysis (HTSE) [21]. HTSE is ~40% more efficient than conventional electrolysis, but requires temperatures of ~800 °C. HTSE uses approximately 79% electrical energy and 21% thermal energy [22], [23]. While this option's usefulness may be limited in remote locations due to limited hydrogen production needs, this is a viable option for small microgrid deployments. Note that hydrogen may also be used within a number of industrial processes that could be of interest to remote facilities.

2.5 Chilled Water Production

Chilled water is used in large manufacturing facilities, college campuses, and district heating and cooling systems to satisfy cooling demands. During warmer months of the year, a large portion of a facility's electricity demand is generated from heating, ventilation, and air-conditioning (HVAC) equipment. Because building cooling loads regularly peak during the early to late afternoon hours, the HVAC equipment is sized to accommodate these peak loads. At night or during early morning hours when cooling loads are low, excess chiller capacity exists. Moreover, these facility cooling loads often coincide with peak electricity demands, thereby putting further strain on utilities. Thermal Energy Storage (TES), in the form of chilled-water storage, is a way to combat peak cooling loads by shifting them from on-peak to off-peak hours [24].

Stratified chilled-water storage tanks have emerged as an effective option for storing chilled water [25]. In a stratified chilled-water storage tank, warm and cold water are stored in the same vessel with no structural interface. Instead, differences in density between cold and warm water cause a thin thermocline, or sharp temperature gradient, to form. Excess chilled water, produced when facility cooling demands are low, is deposited in the bottom of the tank via diffusers. Because the tank is a constant volume device, charging the tank with cold water means simultaneously removing warm water from the top of the tank to be sent to the chillers. Conversely, discharging the cold water to be used during times of peak facility cooling loads results in warm water being deposited in the top of the tank. Therefore, a fully charged tank implies the tank is full of chilled water, while a fully discharged tank implies the tank is full of warm water.

A previous case study examined using stratified chilled-water storage in conjunction with centrifugal electric chillers to offset cooling loads synonymous with a large office space or college campus in a Nuclear Hybrid Energy System (NHES). Results demonstrated that chilled-water storage can shift cooling loads to off-peak hours and help promote more steady-state reactor operation. Another option for cooling water involves the use of single effect, lithium bromide absorption chillers, which use steam less than 205 kPa (15 psig) or hot water and the affinity between an absorbent and a refrigerant to create a chilling effect [26].

Absorption chillers become particularly attractive when a source of waste heat that would normally be rejected to the environment or some other low-temperature sink is available. In a NHES, low-pressure steam can be diverted from waste heat reservoirs or low-pressure sections of the energy conversion cycle to absorption chillers to make chilled water for facility cooling.

2.6 Disaster Relief

Any power source which is to be used for disaster relief needs to be readily available, portable either by ship or aircraft, be capable of accommodating variable loads, and employ passive safety systems.

Temporary and emergency power generation in areas impacted by natural disasters has historically been met provided by diesel generators. Diesel generators, like most generators, simply require transport to the disaster area and a fuel supply. However, in areas affected by natural disasters, fuel supply can be limited. Natural gas lines tend to break during earthquakes [27], and diesel transport can become limited during major storms due to inundated roadways. A system devoid of refueling or cooling requirements during emergency scenarios is ideal.

Following Hurricane Maria's devastation across the Caribbean, and particularly in Puerto Rico, DOE Secretary Rick Perry stated during a panel discussion at a National Clean Energy Week event in Washington, D.C. that small nuclear power plants are the kind of "innovation" he would like to "expedite" for Puerto Rico's rebuild. He further stated:

> *"Wouldn't it make abundant good sense if we had small modular reactors that literally you could put in the back of a C-17 aircraft, transport it to an area like Puerto Rico, and push it out the back end, crank it up, and plug it in?"*
>
> *"Hopefully we can expedite that." [28]*

For a 5 MWe diesel system to run nonstop for three days, it would require approximately 25,000 gallons of fuel [29]. The typical large tanker truck holds up to 9,100 gallons of fuel, meaning that over those three days, three tanker trucks would be required. Additional challenges are encountered when supplying to remote locations such as Puerto Rico. This requirement further increases shipping and electric supply costs. Microreactor technologies that are "plug and play" could potentially carve out a niche in these challenging situations due to their lack of fuel refueling requirements. While a microreactor would likely not be able to supply power to all of a disaster stricken region, it could provide ample energy for emergency crews and critical infrastructure such as hospitals.

A challenge to be considered for microreactors is removal after normal operations are restored. The reactors will need to remain in a shutdown mode to allow decay heat to dissipate for some period of time prior to transport. Generally, after a period on the order of one week, a decay heat exchanger should be adequate to maintain cooling for transport.

The key performance parameters and challenges for FOBs summarized in Table 2.1 are generally applicable to disaster relief scenarios. These parameters emphasize the need to easily transport a reactor by aircraft and have it operational in a short period of time. Additionally, the capabilities to scale output and ensure passive cooling are critical. Other parameters, such as the requirement to remove a reactor within a week, may be less critical in disaster relief.

3. TECHNOLOGY OPTIONS

Design and construction of microreactors will require the development and interfacing and several technologies. The reactor, heat exchangers, power conversion systems, control systems, and other technologies must be mature and their interactions with each other must be well understood. Starting with a specific technology and working up to the full system, the maturity of various reactor designs can be assessed through the following metrics:

- Technology Readiness Level (TRL)
- Manufacturing Readiness Level (MRL)
- System Readiness Level (SRL)

Each reactor concept and the associated sub-systems will require evaluation in order to determine a path forward to a FOAK microreactor.

3.1 Reactor Types

Microreactors can generally be categorized by their fuel type, neutron spectrum, and heat removal method. In the U.S., two general microreactor types are currently being considered at the MW scale:

- High-Temperature Gas Reactors (HTGRs) using tristructural isotropic (TRISO) fuel and operating in a thermal neutron spectrum. These reactors are typically designed to use forced circulation of helium for the primary coolant through the core.
- Heat Pipe Reactors using metallic, oxide, or nitride fuel and operating in a fast neutron spectrum. These reactors typically use sodium (Na), potassium (K), or NaK heat pipes, which operate at high temperatures around the boiling point of the working fluid contained in the passive, self-pumping heat pipes.

Some reactor developers have historically considered pumped liquid-metal cooled, fast-spectrum reactors that use either sodium or lead coolant for MW-class systems. One European developer is currently considering a lead cooled fast reactor concept, but they have not expressed any interest in the U.S. market and presently there is no evident U.S. developer interest in this technology.

Based on an INL study, the DSB report summarized some generic performance attributes [2]. These attributes, shown in

Table 3.1, cover a generic HTGR concept, the Los Alamos National Laboratory (LANL) heat pipe concept, and a smaller radioisotope power system for comparison. The HTGR and heat pipe concepts use nearly the same amount of U-235, although in different forms for each concept. One significant difference is the operating temperature, with the HTGR nearly 200 °C above that of the heat pipe reactor. This should lead to higher efficiency of the power conversion system of the HTGR relative to the heat pipe reactor. One issue which is common to both concepts is the availability of high-assay, low-enriched uranium (HALEU). HALEU is <20% U-235, and there is currently no well-defined source for this fuel. Down-blending of existing high-enriched uranium supplies or a new enrichment capability will be required for making the fuel for these reactors.

Table 3.1. Performance attributes of microreactor candidates [2]

Performance Attributes	High Temperature Gas- Cooled Reactor	LANL Heat Pipe Reactor
Power output (MW_e)	5	2
Shutdown cooling (MW_t)	<2 (decay heat)	<0.8
Operating temp (°C)	850 (outlet)	675 (outlet)
Fuel type (TRL)	UCO TRISO (TRL 5–6)	UO_2 (TRL 9)
Fuel clad failure temp. (°C)	>1650	~1450
LOCA peak reactor temp. (°C)	~1250	~1200
Emergency cooling	Passive	Passive
Operating pressure (MPa)	7.4	0
Fuel (fissile) quantity	~ 800 kg U-235 (<20% enrichment)	~880 kg U-235 (19.75% enrichment)
Release potential if breached	TRISO should retain fission products	Minimal release (atm press; fuel in SS block)
Cladding/encapsulation	Silicon carbide	SS-316L
Refueling approach and interval	Refuel by replacement of reactor fuel module every 2 yrs	Refuel by replacement of reactor fuel module every 5 yrs

3.1.1 High-Temperature Gas-cooled Reactor

HTGRs operate in a thermal neutron spectrum and typically circulate high-pressure helium gas to extract nuclear heat from the fuel. Helium coolant cannot become radioactive, thereby minimizing any risks associated with a loss of the primary coolant. The use of graphite blocks and TRISO particle fuel with the ability to retain fission products within the multi-layer spherical particles also reduces the risk of radioactivity release to the environment [2]. HTGRs also have strong negative temperature reactivity feedback from the graphite moderator and fuel. By design, these reactors are inherently safe to operate and have reduced probability of a core meltdown [30].

Most of the proposed concepts cycle the primary coolant through a heat exchanger to a secondary circuit, which in turn cycles through a generator (or other process). An alternative concept from HolosGen is derived from a nuclear turbojet concept initially proposed by General Electric (GE) in the 1960s [31]. The HolosGen concept in Figure 3.1 is a compact, closed loop, combined nuclear-turbine which heats helium or CO_2 in a reactor before passing it immediately through a turbine [32].

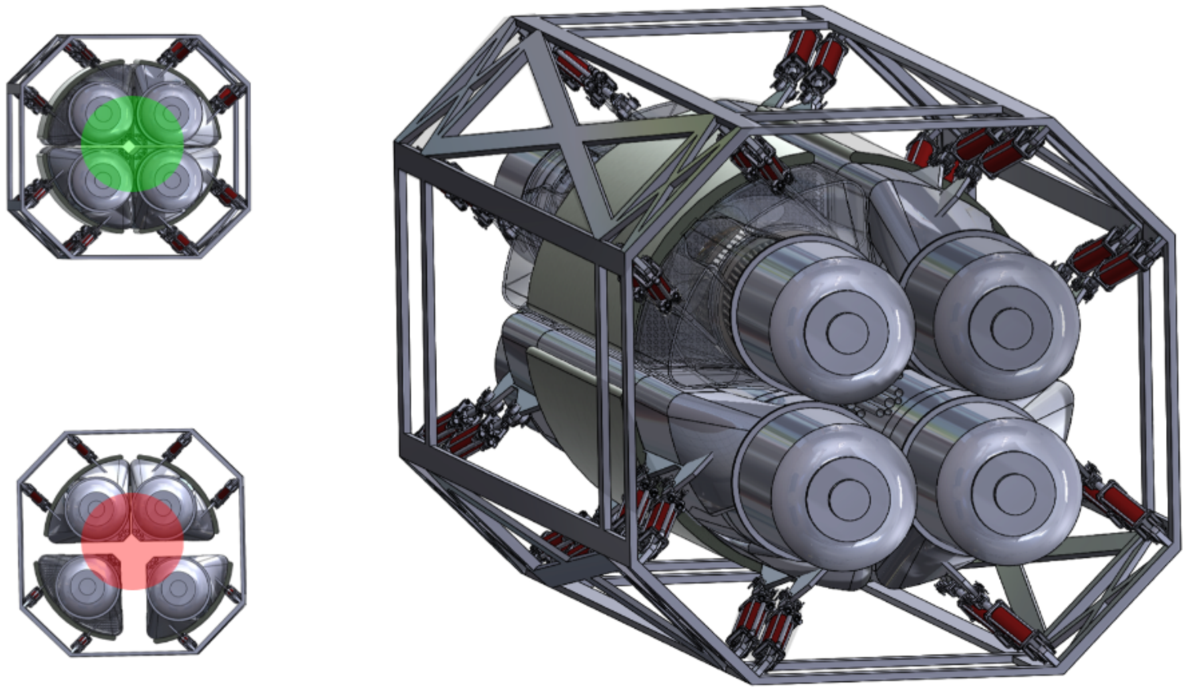


Figure 3.1. HolosQuad reactor [33].

In considering HTGRs for micro-reactor applications, several important factors stand out:

- **Packing fraction of the TRISO particles:** The current limit for TRISO packing fraction is approximately 40% before the particles begin to experience damage during compacting.
- **Reactor shielding:** Potentially several feet of steel shielding will be necessary outside of the container housing the reactor.

Refueling: From

- Table 3.1, fuel modules would be replaced approximately every 2 years, which is significantly more frequent than the 5 year cycle anticipated for a heat pipe reactor.
- **End of life disposition:** While the fuel can be easily removed from the reactor and stored safely, the non-nuclear components will also need to be disposed.
- **Manufacturing of graphite blocks**: The reactor core structure housing the TRISO fuel is likely to be made of graphite blocks. Methods for manufacturing nuclear grade graphite will need to be defined.

3.1.2 Heat Pipe Cooled Reactor

Researchers at LANL and the U.S. National Aeronautics and Space Administration (NASA) have a long history of investigating the use of liquid-metal heat pipes for primary reactor cooling for tens to hundreds of kilowatt scale NASA missions (including use for both power and electric propulsion) [34]. Recently, scaled-up versions which operate at the 5-10 MWe level have been investigated by the national laboratories [1], [35]. These reactors maintain a core structure interspersed with fuel and heat pipes which extend outside the core. The heat pipes typically operate with sodium, potassium, or NaK working fluid at low pressure. Additionally, the heat pipes are passive devices, negating the need for external pumping of coolant. One concept which is being pursued by Westinghouse is the eVinci reactor in Figure 3.2.

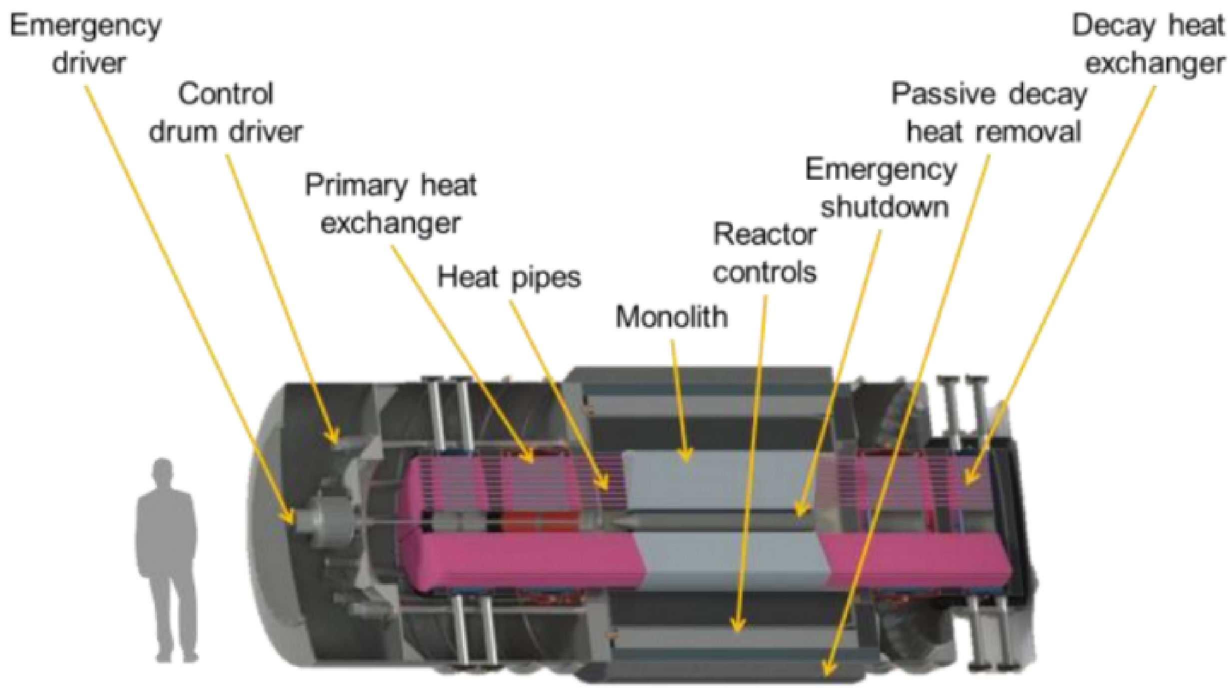


Figure 3.2. Westinghouse eVinci heat pipe cooled reactor concept [36].

Heat pipe reactors tend to operate around the boiling point of the heat pipe working fluid. For potassium heat pipes, the operating temperature is approximately 760°C. For sodium,[c] the operating temperature is approximately 880°C. Depending on how the reactor is designed, these high temperatures

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[c] Sodium heat pipe reactors are occasionally referred to as Sodium Fast Reactors (SFRs). This is a bit of a misnomer. Traditionally, SFRs are sodium-cooled reactors with pumps cycling a large quantity of sodium through the core. Sodium heat pipe reactors operate passively, using the phase change of sodium to transfer heat from the core. Since sodium heat pipe reactors operate around the boiling temperature of sodium, they are operating at higher temperatures than traditional SFRs. Sodium heat pipe reactors also use a much smaller mass of sodium than SFRs. Both reactor types operate in the fast spectrum.

present potential obstacles, particularly in selection of structural and pressure boundary materials for components in the reactor core. Each proposed heat pipe reactor concept will need to be evaluated to determine the applicable engineering standards and whether the desired structural materials are approved for use at the expected operating temperatures. If new materials are proposed, the viability of building a code-case to qualify a material will need to be considered, since the qualification process can be potentially long and costly.

Some considerations when evaluating heat pipe reactors include:

- **Fuel source and manufacturing:** Different microreactor concepts may have different fuel forms in both shape and composition. Two INL concepts considered both cylindrical fuel pins and hexagonal elements [35]. Given the number of fuel pins/elements in a heat pipe reactor, reliable manufacturing processes for both the fuel and the cladding will be critical.
- **Refueling:** In the LANL MegaPower design, both the fuel and heat pipes are housed, un-cladded, inside channels of a stainless steel monolith [1]. This potentially complicates refueling of the reactor.
- **End of Life Disposition:** Similar to the HTGR concepts, methods for disassembly and disposal of the fueled and unfueled components of the reactor need to be defined.
- **Manufacturing of the monolith core:** The LANL MegaPower design calls for a stainless steel monolith to house the heat pipes and fuel. In a 2017 Phenomena Identification and Ranking Table (PIRT) analysis of the MegaPower concept by INL, the manufacturability of the steel monolith was identified as a significant issue [37]. Hot isostatic press (HIP), 3D printing or other advanced manufacturing processes may yield a path forward on monolith manufacturability.

3.1.3 Lead Fast Reactor

Lead Fast Reactors (LFRs) operate in a fast neutron spectrum and circulate molten lead as the primary coolant. The reactor coolant is nominally at low pressure and has a high boiling point. This allows for higher temperature operation, providing higher efficiency in the power conversion system, and eliminating boiling concerns [38].

Presently, LFRs are being pursued primarily outside the U.S. for research reactor applications and limited power applications. The current designs do not appear easily transportable.

3.1.4 Others

Sodium Fast Reactors (SFRs) are fast spectrum reactors with molten sodium coolant. These reactors use an intermediate heat exchanger (IHX) to transfer heat from the molten sodium to water, which is used in a steam turbine system for electrical power generation [39]. Presently, SFRs at the size and power scale of interest for microreactor applications are not being pursued in the U.S.

3.2 Thermal Transport & Heat Exchangers

In order for the thermal energy generated in a nuclear reaction to be useful, it must be transferred out of the reactor to the power conversion system or heat exchanger for process heat end use. Additionally, in order to regulate the fuel temperature during both normal operation and after shutdown, the primary thermal transport system must be able to adequately transfer heat to the environment. Given the small size of microreactors, ambient air can be used as the ultimate heat sink in electricity generating cases. For process heat applications such as desalination, another fluid, such as sea water, may be the ultimate heat sink.

3.2.1 Heat Pipes and Thermosiphons

One option for removing heat from the reactor core is by using heat pipes. Heat pipes are passive devices, requiring no pumps to circulate a coolant. Rather, the coolant circulates within a heat pipe through the evaporation and condensation cycle of a working fluid as illustrated in Figure 3.3. In the reactor core section, heat conducts from the fuel to the heat pipe. Inside the heat pipe, the working fluid is evaporated and the vapor transports to the other end of the pipe. At the condenser end of the pipe, external cooling removes heat and causes the working fluid to condense. The fluid condenses into the wick structure, and moves by capillary motion back to the evaporator end of the pipe. A thermosiphon is similar to a heat pipe, but does not contain a wick. This limits the energy transfer capacity of a thermosiphon relative to a heat pipe.

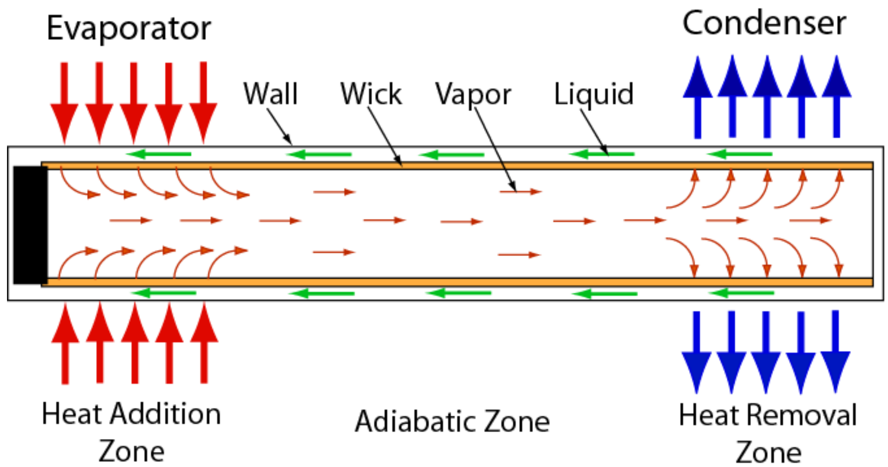

Figure 3.3. Heat pipe operation schematic [40]

Heat pipes have been used extensively in small reactors, such as kilowatt space reactors. Because they operate passively and require few components, they are extremely reliable. They also allow operation at higher temperatures, thereby increasing the efficiency of the power conversion system. Heat pipe operating temperature is essentially determined by the boiling temperature of the working fluid. Table 3.2 shows the boiling temperatures of a few candidate working fluids for microreactor heat pipes.

Table 3.2. Boiling temperature of selected heat pipe working fluids

Working Fluid	Boiling Temperature
Potassium (K)	759 °C
NaK	785 °C
Sodium (Na)	883 °C

3.2.2 Intermediate Heat Exchangers

Most microreactor designs utilize an IHX to transfer heat from the primary reactor coolant to the secondary coolant which interfaces with the power conversion system. This design is typical in nuclear power and has the benefit of keeping the nuclear heated primary coolant separate from the secondary coolant that passes through the power conversion system.

The supercritical carbon dioxide (sCO_2) recompression Brayton cycle is a cycle developed at the Massachusetts Institute of Technology [41]. The sCO_2 coolant is heated by the available heat from the heat pipe reactor and further expanded through the turbine to produce electric power. Using sCO_2 as the power cycle working fluid enables one to achieve much higher thermal efficiencies (~45% and above for recompression cycle at 550ºC) and compact turbomachinery (with few components), which could be modularly constructed and has a much smaller footprint [42]. The existing challenges with SCO_2 are the high turbine inlet pressure and that the cycle is still in small-scale testing, and therefore not available commercially.

The calculated power conversion cycle thermal efficiency (η_{pcs}) could be defined as:

$$\eta_{pcs} = (P_{turbine} - P_{compressors})/P_{reactor} \tag{3}$$

where:

$P_{turbine}$ = Power of the primary side
$P_{compressors}$ = Power of the high and low pressure compressors
$P_{reactor}$ = Reactor heat

The type of power conversion system has not yet been finalized. Once the type of power conversion system is decided, the assumptions, performance and requirements will be narrowed down.

Table 3.3 summarizes general operating conditions and principal features for various heat exchanger types in the current industry [43]. This table summarizes the following:

- **Heat exchanger type:** Fifteen heat exchanger types are listed in this table.
- **Compactness:** Indicates (surface area)/ (heat exchanger core volume). If compactness is high, the heat exchanger can be smaller.
- **System Type:** Indicates what fluid phases are generally used for a certain heat exchanger type in the industry.
- **Material:** Indicates materials which have been used for specific heat exchangers in current industry.
- **Temperature Range:** Indicates the applicable temperature ranges of a certain type of heat exchanger.
- **Maximum Pressure:** Indicates the applicable pressure ranges of a certain type of heat exchanger.
- **Cleaning Method:** Indicates if the heat exchanger can be cleaned physically or chemically.
- **Multistream Capability:** Indicates if it can connect several independent flow loops in a single heat exchanger.
- **Multipass Capability:** Indicates if it can split flow into several paths in the heat exchanger.

Table 3.3. Principal features of several types of heat exchangers [43].

Heat Exchanger Type	Compactness (m^2/m^3)	System Types	Material	Temperature Range (C)[a]	Maximum Pressure (bar)[b]	Cleaning Method	Multistream Capability[c]	Multipass Capability[d]
Shell and Tube	~100	Liquid/Liquid, Gas/Liquid, 2Phase	s/s, Ti, Incoloy, Hastelloy, graphite, polymer	~ +900	~ 300	Mechanical, Chemical	No	Yes
Plate-and-frame (gaskets)	~200	Liquid/Liquid, Gas/Liquid, 2Phase	s/s, Ti, Incoloy, Hastelloy, graphite, polymer	-35 ~ +200	25	Mechanical	Yes	Yes
Partially welded plate	~200	Liquid/Liquid, Gas/Liquid, 2Phase	s/s, Ti, Incoloy, Hastelloy	-35 ~ +200	25	Mechanical, Chemical	No	Yes
Fully welded plate (Alfa Rex)	~200	Liquid/Liquid, Gas/Liquid, 2Phase	s/s, Ti, Ni alloys	-50 ~ + 350	40	Chemical	No	Yes
Brazed plate	~200	Liquid/Liquid, 2Phase	s/s	-195 ~ +220	30	Chemical	No	No
Bavex plate	200 to 300	Gas/Gas, Liquid/Liquid, 2Phase	s/s, Ni, Cu, Ti, special steels	-200 ~ +900	60	Mechanical, Chemical	Yes	Yes
Platular plate	200	Gas/Gas, Liquid/Liquid, 2Phase	s/s, Hastelloy, Ni alloys	~700	40	Mechanical	Yes	Yes
Compabloc plate	~300	Liquid/Liquid	s/s, Ti, Incoloy	~300	32	Mechanical	Not usually	Yes
Packinox plate	~300	Gas/Gas, Liquid/Liquid, 2Phase	s/s, Ti, Hastelloy, Inconel	-200 ~ +700	300	Mechanical	Yes	Yes
Spiral	~200	Liquid/Liquid, 2Phase	s/s, Ti, Incoloy, Hastelloy	~400	25	Mechanical	No	No
Brazed plate fin	800 to 1500	Gas/Gas, Liquid/Liquid, 2Phase	Al, s/s, Ni alloy	~ 650	90	Chemical	Yes	Yes
Diffusion bonded plate fin	700 to 800	Gas/Gas, Liquid/Liquid, 2Phase	Ti, s/s	~ 500	> 200	Chemical	Yes	Yes
Printed circuit	200 to 5000	Gas/Gas, Liquid/Liquid, 2Phase	Ti, s/s	-200 ~ +900	> 400	Chemical	Yes	Yes
Polymer (e.g. channel plate)	450	Gas/Liquid	PVDF, PP	~ 150	6	Water Wash	No	No
Plate and shell	—	Liquid/Liquid	s/s, Ti	~ 350	70	Mechanical, Chemical	Yes	Yes

s/s Stainless steel.

a. Heat exchanger operational temperature ranges.

b. Heat exchanger maximum applicable pressure.

c. Capability to connect several independent flow loops in a single heat exchanger.

d. Capability to split flow into several paths in the heat exchanger.

3.3 Power Conversion System

An integral part in designing a Special Purpose reactor is its power conversion unit (PCU). For military ground operations, the efficiency of the PCU may not be as important as its size and portability. However, for isolated communities where economics is important, the thermal efficiency may have a higher value.

Developing power conversion units that best fit the reactor type is an important part of the reactor development process. A wide variety of power conversion units should be considered. A study at Idaho National Laboratory with respect to small modular reactors showed that the reactor inlet and outlet temperatures had an effect on the performance of a wide variety of power conversion units [44].

3.3.1 Rankine Steam Cycle

The Rankine cycle is the most common power conversion cycle used in the nuclear power industry. Figure 3.4 illustrates a simplified flow diagram for the model used for the Rankine power cycle. The Rankine cycle is typically comprised of high, intermediate, and low-pressure turbines. High-pressure steam is generated by a heat source, such as a nuclear reactor, and then passed through a turbine or set of turbines to generate power. The low-pressure steam/water effluent mixture is condensed and then is pumped back to high pressure before entering the steam generator. To increase the efficiency of the cycle, after the first turbine expansion, the power cycle steam is reheated by the heat source to the same temperature as the steam entering the high-pressure turbine [45].

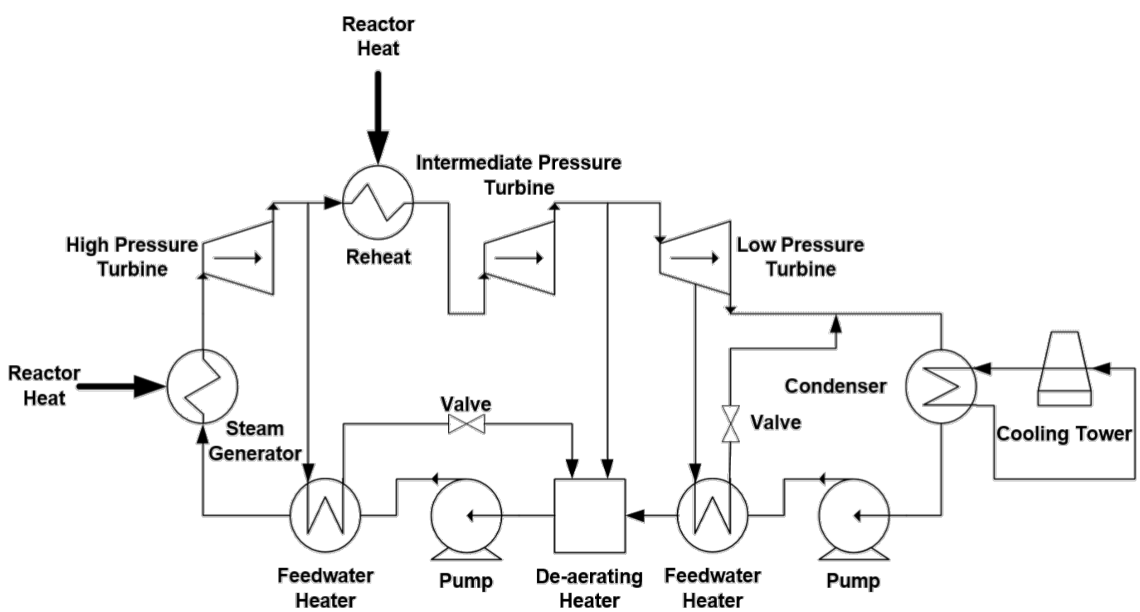

Figure 3.4. Rankine cycle with feed-water heaters and reheat.

Another means to increase the efficiency of the cycle is to add feed-water heaters. Feed-water heaters are recuperating heat exchangers that draw steam from turbines to heat the feed-water that is returning from the condenser to the steam generator, which reduces the amount of heat needed by the steam generator to generate the same power. By balancing the amount of steam and the pressure at which the steam is drawn, the cycle can be optimized for maximum thermal efficiency. The high pressure within the power cycle steam loop is set by the temperature exiting the steam generator and the amount of superheating needed for the system. The low pressure of the system is determined by the condensing temperature, which is a function of the temperature of the cooling water used to cool the condenser. For special purpose reactors, a single turbine should be sufficient. A feed-water heater and reheat could still be applied. With respect to reactor outlet temperatures, the steam Rankine cycle can provide ideal thermal efficiencies, electric power to heat input ratio, up to temperatures of 600ºC [44]. The cycle has decades of development and operational experience.

3.3.2 Closed Brayton Gas Cycle

A closed Brayton gas cycle is shown in Figure 3.5. In this cycle, the hot, high-pressure working gas is expanded in a turbine to produce power. The low-pressure warm gas is further cooled through heat recuperation with the return gas from the compressors. A gas cooler rejects heat to the cooling tower before compression within the low-pressure compressor. The heat generated by the compressor is rejected by an intercooler to a cooling tower or ambient fluid. The gas is further compressed by the high-pressure compressor before entering the recuperating heat exchanger. Finally, heat is added to the gas at the gas heater.

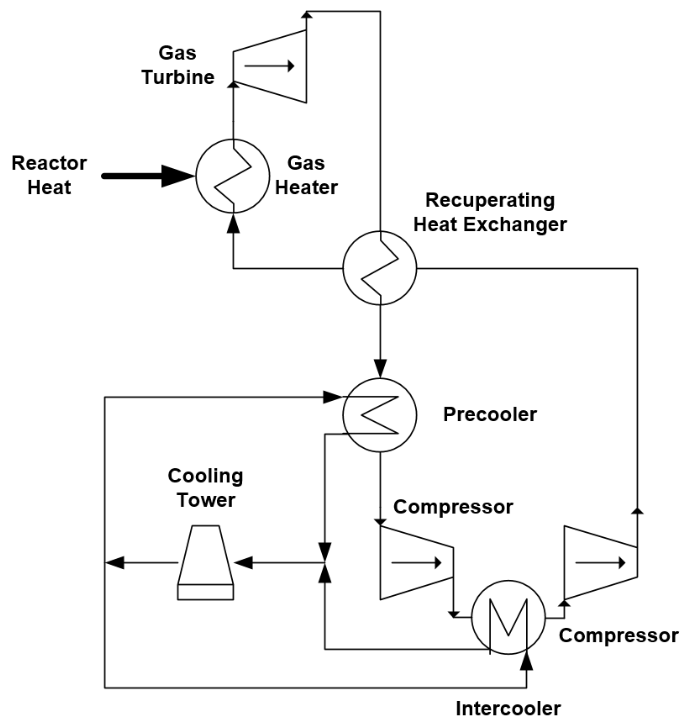

Figure 3.5. Closed Brayton cycle with recuperation and intercooling.

The dual compression with cooling reduces the work of compression, which helps in providing a more efficient cycle. Recuperation reduces the amount of heating needed at the gas heater and the amount of heat rejection at the gas cooler and intercooler, which helps attain higher thermal efficiencies. The pressure ratio across the turbine has a greater effect on thermal efficiency than a given high or low pressure. The Brayton cycle can run at a variety of pressures. For a given low pressure, the high pressure is set by the optimal pressure ratio or a given high pressure ratio. Higher pressures produce high densities throughout the cycle, which in turn could reduce equipment size. However, operation at higher temperature and pressure would require more expensive materials when compared to lower pressure cycles. By the same logic, low pressure systems would require large equipment sizes to account for the larger volumetric flows.

The closed Brayton cycle could be used as the primary loop for a high temperature gas reactor. Power output would be at its greatest for a given reactor outlet temperature, and by generating power, the working fluid is at a much lower temperature during compression, thereby reducing compression costs when compared to a primary loop circulator. For special purpose reactors, having the cycle as the primary coolant loop would reduce the footprint considerably. The disadvantage is the contamination of the power conversion unit. The Brayton cycle alone, however, is not effective at lower reactor temperatures < 500ºC but improves at higher temperatures.

3.3.3 Open Air Brayton Cycle

The open air Brayton cycle shown in Figure 3.6 is a common cycle used in power production and jet aircraft. For power production using only the open air Brayton cycle, recuperation is critical to increase the thermal efficiency of the cycle.

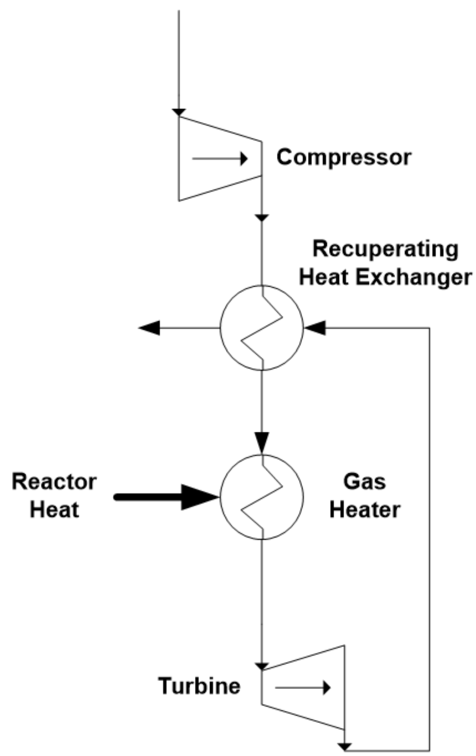

Figure 3.6. Open air Brayton cycle with recuperation.

Ambient air is first compressed to a higher pressure before entering the recuperating heat exchanger. The air is then pre-heated in the recuperating heat exchanger by the hot air returning from the turbine. Heat is added to the air at the heater before the air is expanded through a turbine. Power is generated at the turbine as the air is expanded. The air is further cooled within the recuperating heat exchanger before it is rejected to the atmosphere. The heat rejected by the power cycle is carried by the exiting air.

The low pressure within an open air Brayton cycle is the pressure of the ambient air. The high pressure is set by the optimal thermal performance of the cycle. Air Brayton cycles have small footprints and the least amount of equipment. They also have a long legacy of development and a high technology readiness level. However, they tend to have the lowest thermal efficiencies when considering only the cycle itself.

The INL PIRT analysis conducted for the LANL MegaPower reactor examined the power conversion system in some detail [37]. The report examined an air Brayton cycle due to its wide use in power conversion systems, and therefore the wide availability of components. Depending on factors such as supply temperature and heat-recuperation, thermal efficiencies were calculated to be between 25% and 40%. The analysis also determined that commercial units are available to meet the design requirements.

3.3.4 Supercritical Carbon Dioxide Recompression Brayton Cycle

A process diagram for the supercritical carbon dioxide recompression Brayton cycle, sCO_2, is provided in Figure 3.7. High pressure (~20 MPa) supercritical CO_2 is heated to a high temperature by the gas heater. Power is produced by expanding the gas through the turbine. The low-pressure gas is cooled to a lower temperature within the high temperature recuperating heat exchanger or recuperator (HTR) by the gas returning from the compressors. The gas is further cooled within the low temperature recuperator (LTR) by the gas returning from the main compressor. The gas flow exiting the LTR is split into two unequal streams. The larger fraction of the flow is cooled by the cooling tower before compression at the main compressor. The smaller fraction of the flow is directly compressed without cooling at the recompression compressor. The heat from the recompression compressor is used to raise the temperature of the exiting gas. This higher temperature gas reduces the amount of heat needed at the gas heater for a given power output.

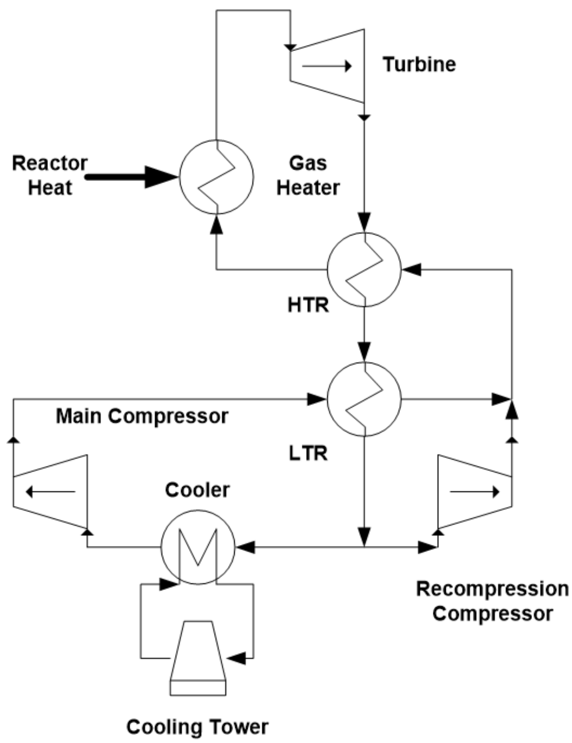

Figure 3.7. Supercritical carbon dioxide recompression Brayton cycle.

The optimal thermal efficiency is achieved by balancing the flow between the main compressor and the recompression compressor. If too much flow goes to the recompression compressor, the power to run the compressor will reduce the thermal efficiency of the cycle. The biggest advantage of the cycle is the high density of the CO_2 at the compression stages. The pressure at this point is just above the critical point of CO_2 (~7.3 MPa). The high density of the CO_2 reduces the work of compression. Due to the high pressures within the cycle, the footprint for this cycle is small. However, the cycle is under development and does not have the legacy of operation that the air Brayton and steam Rankine cycles have.

3.3.5 Organic Rankine Cycle

An Organic Rankine cycle (ORC) is a Rankine cycle which uses a refrigerant instead of steam as the working fluid. The cycle works well with low temperature heat and has the following advantages:

- Evaporation occurs at lower pressures and temperatures
- The condensation pressure is above atmospheric which prevents air intake

- Single stage turbines may be used due to smaller temperature differences between the evaporator and the condenser.

Recent scoping studies by INL and the University of Idaho have shown that for a micro reactor with an outlet temperature of 675 ºC (e.g. heat pipe or molten salt reactor), the thermal efficiency can increase from 35% to 40% with the addition of an ORC to a recuperated air Brayton cycle.

3.3.6 Other Power Conversion Units

Most power conversion units use a simple compressible system in some form or other to provide the power. The previously described PCUs are these type of systems. Other PCUs of this type are Stirling and Ericsson cycles. The Stirling cycle uses a gas, such as air, as a working fluid. Heat is transferred to the cycle during a constant volume process and during isothermal expansion. Heat is rejected during a constant volume and isothermal compression. The Ericsson cycle uses constant pressure processes in place of the constant volume processes of the Stirling cycle. Both use a regenerator which allows the cycles to have potential high efficiencies.

Systems other than simple compressible systems can also provide power. As a potential source of supplemental power to support emergency operations, thermoelectric modules could be added to the reactor. These modules work by using the electric potential generated in a thermoelectric material from a temperature differential. They are highly inefficient but could be useful for providing some small amount of reliable power for ensuring operation of critical equipment.

4. MICROGRID INTEGRATION

The main purpose of microgrids is to provide the means for integration of distributed generation sources into electricity grids and to allow those sources to operate independently in a reliable, secure, and controlled manner. One of the most important characteristics of microgrids is that the distributed power sources are in close proximity to the end users [46]. A smart microgrid will further allow for power and data to flow both ways between the supply and demand ends of the grid, enabling demand response functionality [47]. The communication infrastructure, known as "Advanced Metering Infrastructure," uses smart meters to enable two-way interaction, such that demand and supply are linked and are able to manage peak demands by sending signals to the customers. This in turn allows customers to reduce consumption in response to those signals [47]. Current grids are not considered "smart" mainly because the consumers are not involved and are not given choices or tools to help them manage and control their usage, especially during system peak demand hours or during supply shortages [48].

The motivations for introduction of a microgrid include the following:

- Communities or regions which are too isolated or remote to connect to the main electrical grid.
- Microgrids which can connect to and disconnect from the main grid, as necessary, can have an economic advantage when coupled with modern controls to account for fluctuations in supply and demand. This leads to less wasted energy and greater cost savings [49].
- Microgrids expedite the integration of renewable energy sources, such as solar and wind. The intermittent nature of renewable energy results in variable generation when integrated into the main grid. These variations are easier to predict in microgrids, and could be supplemented by microreactors.
- Since microgrids operate independent of the main grid, they are not impacted by outages in the main grid. There are also fewer voltage sags and frequency interruptions in microgrids [50].

There are currently several operating microgrids. Table 4.1 provides some examples of operating microgrids, including their generating capacity and the technologies they utilize.

Table 4.1. Examples of microgrids [51], [52]

Location	Purpose(s)	Total Generating Capacity	Energy Generation Sources
Bornholm Island, Denmark	• Integrate renewable energy into the grid • Provide a microgrid test bed	127 MW	• Diesel generators • Oil fired boiler • Coal boiler • 35 wind turbines • Biogas turbines
Hartley Bay, Northern British Columbia, Canada	• Provide power to commercial and residential buildings in a remote town	1050 kW	• Diesel generators
Illinois Institute of Technology	• Prevent power outages	9 MW	• Combined cycle gas • Small wind turbine • Rooftop solar PV
Fort Collins, Colorado	• Increase grid efficiency • Integrate renewable energy into the grid • Reduce peak loading	3.5 MW	• Solar PV • Fuel cells • Biogas • Diesel
Isle of Eigg	• Integrate renewable energy into the grid • Reduce individual generator use	166 kW	• Hydro-electric • Solar PV • Wind • Diesel (individual homes)
Santa Rita Jail	• Reduce energy consumption from grid	3.5 MW	• Solar PV • Fuel cell • Diesel (backup)
University of California at San Diego	• Reduce costs • Increase resiliency	31.2 MW	• Solar PV • Gas turbine
University of Alaska-Fairbanks	• Power generation • District heating	17 MW	• Coal

Power generation sources vary depending on the purpose of the microgrid and regional resource availability. Microgrids that are designed for increasing utilization of renewable energy do not prioritize diesel; however, in remote locations such as northern Canada where reliability is important, diesel is a good choice to assure power availability and reliability. Similarly, military bases are more concerned with reliability over efficiency and cost, and therefore tend to opt for diesel generators over variable renewable generators [53]. SMRs, which tend to range from ~50-300 MWe, have been proposed as an option for microgrids. While offering reliability, SMRs tend to be more expensive and less flexible than other generation methods currently adopted within microgrids [54]. Figure 4.1 summarizes the use cases for different generation methods. Combining microgrids with microreactors offers significant flexibility which can support a wide range of applications.

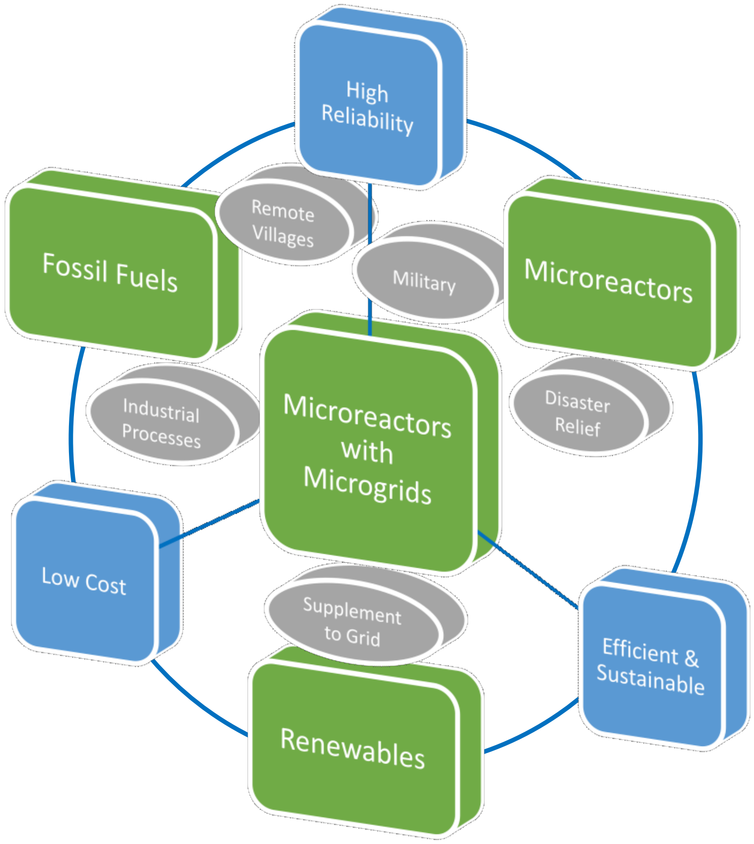

Figure 4.1. Energy generation methods, use cases, and benefits.

Due to their small size and increasing reliance on renewable energy sources, microgrids must be flexible. This results in a need for load-following capabilities and other ancillary services, such as voltage support and frequency control. When connected to a large grid, microgrids can load-follow by either taking energy from the main grid when more power is needed, or injecting power back into the main grid when the microgrid is producing a surplus. When microgrids are separated from the main grid and operating in "island mode," all load-following must be handled internally. This can be accomplished through the use of dispatchable generation from sources such as diesel or natural gas, energy storage (e.g., mechanical, thermal, electrical, or chemical), or variation in how energy is apportioned between heat applications and power generation. On short time scales of seconds or less, ancillary voltage support or frequency control services can balance momentary mismatches in supply and demand. Load-following services are used to balance large mismatches on longer time scales, and therefore are tuned to high energy capacities rather than quick response times. A potential joint energy storage system includes supercapacitors for fast response times, with batteries for high energy capacity. Batteries would have sufficient energy storage capacities since microgrids are typically on the order of tens of megawatts [55]. Batteries, however, still fail to provide long duration, seasonal storage solutions.

4.1 Current Work on Microgrids

The U.S. Department of Energy - Office of Electricity (DOE-OE) is a proponent of microgrid technologies. DOE-OE's goal is to develop commercial microgrids in the tens of megawatt range, which would reduce outage times for essential loads, reduce GHG emissions, and improve energy efficiency. DOE-OE is working with several national laboratories on the design, planning, and architecture of microgrids, as well as their control and operation. Lawrence Berkeley National Laboratory is working on a model that minimizes the cost of micro-generators. The model works to find the optimal combination of energy generators and storage units tailored to a microgrid with a particular load, while reducing energy consumption and shaving the peak demand. Sandia National Laboratories developed the Microgrid Design Toolkit, which allows microgrid designers to search grid designs and identify alternate design decisions for microgrids and assess their impacts [56].

Designing, controlling, and modeling microgrids is an important focus in current work. It is a complex problem due to the nature of microgrids and their distributed generators. Control of microgrids is important for providing voltage and frequency regulation, optimum load-sharing among generators, switching between grid and island modes, optimizing operating cost, and handling transients. There are a number of control methods presented in the literature, each of which are optimized for different scenarios [57]. Design of microgrids is complex and dependent on the goal of the microgrid. Resiliency, cost, and environmental impact are some of the most important aspects considered when designing a system. Accurate modeling of microgrid design and operation is critical to developing an optimal design and operational control [58].

Microgrids have been gaining popularity in residential developments, such as one in Alabama that includes 62 homes powered with solar and natural gas [59]. Rural communities in developing countries, such as India, are another place where microgrid integration is gaining interest [60]. These rural communities are not powered by the main grid and have ample renewable energy resources, such as solar, that can be harvested on a small scale to power them. Research into design and optimization of these grids is ongoing, and they continue to improve in affordability and efficiency.

4.2 Hybrid Energy Systems

Hybrid energy systems use energy generated from various sources to provide electricity at lower costs, with reduced emissions, and with greater reliability than traditional single-source, electricity-only systems. Hybrid energy systems coordinate the use of different technologies to overcome the potential shortcomings of any single generation method. Possible energy sources that could be included in a hybrid system include solar, wind, nuclear, and fossil fuels. The intermittent nature of solar and wind can be accounted for with baseload production of nuclear and fossil fuels, where excess energy produced during times of high renewable availability or low demand can be directed to alternative energy users to produce a saleable commodity other than electricity. Fossil fuels are currently widely preferred in scenarios that call for flexible generation due to their ability to be ramped to meet changing load requirements (e.g., dispatchable), as well as their low operating costs. Dissimilar energy supply and demand in hybrid energy systems can also be accommodated with energy storage. Similar to microgrids, hybrid systems require both fast response and high-capacity energy storage.

The U.S. energy grid is becoming increasingly hybridized. The traditional dependence on fossil fuels such as coal and petroleum is giving way to more renewables, such as solar and wind, along with natural gas. Solar alone has gone from generating 864 gigawatt-hours (GWh) in 2008 to 52,958 GWh in 2017 [61]. Other renewable sources are also seeing increased integration, while the generation by coal is dropping. The rate of hybridization of the energy grid will likely slow due to the intermittent nature of renewable energy sources. Renewables do not provide constant or dispatchable power, are location dependent, and need a large geographic footprint mainly due to lower energy density [62].

Hybrid energy systems can utilize different energy generation technologies depending on their location, regional resource availability, and the load. Most energy generating technologies cannot be built in any location. Solar plants, for example, need high levels of solar irradiation; wind power needs both sustainable winds and a large footprint (on-land or off-shore, depending on the use location). Conventional thermal plants using fossil fuels and nuclear do not have the same geographic restrictions as renewables. Using nuclear as the main energy source in locations where large-scale deployment of renewables isn’t feasible is the best option for an emission-free grid. Traditional, large-scale nuclear plants may be limited in their siting options by the need for cooling water, but microreactors and other advanced reactors that do not require water for primary or secondary heat removal will experience fewer siting limitations. Currently, large scale nuclear plants have difficulty competing against low cost natural gas [61]. However, this is not a significant issue for microreactors since they are intended for deployment in unique environments where natural gas is generally not available.

5. GEOGRAPHIC CONSIDERATIONS

The transportation of microreactors is a non-trivial task. Radioactive material transportation has historically been complicated by difficulties in finding arrangements that are mutually agreeable to stakeholders at the federal, state and community levels. Additionally, deployment to or transportation through non-U.S. territories could lead to further complications.

Compared to the current fleet, microreactors are expected to require more highly enriched, HALEU fuel (5% - 20% enriched) [63]. To date, large-scale shipments of HALEU have not occurred in the public arena. This is because the U.S. Department of Transportation (DOT) has not yet approved commercially viable cylinders or packages for material that is enriched to greater than 5% U-235 [63]. A potentially viable solution for transport of HALEU or of reactor vessels containing HALEU maybe Type B packaging, which is currently used to transport highly radioactive materials such as spent nuclear fuel. Risk assessments conducted by the NRC to ascertain the safety of spent nuclear fuel transport using Type B casks have concluded that advancements in modeling tools have resulted in a reduction in the calculated per-shipment risks over the past 35 years [64]. Hence, Type B packaging is likely the best existing option for microreactor and HALEU transport, but it would still need to be qualified and licensed for such use.

Given the desire to deploy microreactors to remote or potentially hostile locations, proliferation risks need to be considered. These risks are minimized through the use of LEU. Additionally, physical security at the site of deployment will need to be considered for each use case as part of the licensing path, as will cyber security associated with the operation and potential remote monitoring of microreactors. It is important that microreactors be essentially impenetrable or have poisons in the fuel that further reduce proliferation risks. After deployment, a “set it and forget it” mentality would be ideal. To accomplish all these goals, strategies that employ a combination of autonomous control, remote monitoring, proper fuel design, and system encasement (either inherent from the factory or placement within one at the final destination) will likely be required.

An additional challenge with geographic mobility of microreactors to remote destinations is staffing requirements. Typical large-scale reactors require approximately 1,000 staff for 1,000 MWe produced [65]. Of these, approximately 100 staff are required for operations, with the rest being a combination of engineers, maintenance, etc. NuScale is currently working with the NRC to reduce operational staffing requirements for their plants [66]. Through elimination of plant systems, autonomous control, and smart design, NuScale will be able to drastically reduce staffing requirements. This could prove invaluable to microreactor technologies, as this will allow a path forward to acquire licensures to operate in remote locations with minimal staffing.

Further, depending on microreactor technology classification, research reactors across the country have set a precedent to operate facilities of this size with fewer staff. The North Carolina State University Pulstar reactor, for example, has an operational power of 1 MWth, employs a total staff of ten, including five operators [67]. The 6 MWth reactor at the Massachusetts Institute of Technology has 15 operators in a total staff of 36 [67]. Thus, the ability to classify microreactors in the same field as research reactors could potentially further reduce staffing requirements and ultimately their economic viability.

6. DECISION SUPPORT FRAMEWORK

This section summarizes operational factors that motivate the deployment of microreactors and provides a framework for the selection of reactor and balance of plant design, licensing path, and end use considerations that would help guide the development of this technology to its deployment. This framework will evolve as higher readiness levels are achieved and more information becomes available. Table 6.1 summarizes some of the motivating factors for deploying microreactors in certain use cases. Depending on the end user and purpose for a microreactor, various social, economic, environmental, or operational factors will influence the decision to deploy a reactor to support energy needs and, subsequently, what type of reactor and balance of plant system is most appropriate for the planned application.

Table 6.1. Motivating factors for microreactor deployment in certain use cases.

		Social	Economic	Environmental	Operational		
Use Case	Typical Customer (Decision Maker)	Renewable & Desalination integration	Fuel & cost savings	Reduce CO_2 footprint	Fuel independence	Process byproducts	Uninterrupted supply
Rural Islands	• Utility • IPP	XX	XX	XX	XX	x	XX
Remote Civil and DoD	• Utility • IPP • Government • Development institutions • Government Defense	XX	XX		XX	x	
Industrial	• Mining companies • Oil & gas • Paper & industry		XX	x	XX	XX	XX
Defense	• Defense & DOE • CONUS and OCONUS	x	x	x	XX	XX	XX
Urban Communities	• Utility • IPP • Educational institutions • Data centers	XX	XX	XX		x	

XX Primary value proposition
x Secondary value proposition

Legend: **Off-Grid** (Rural Islands); **Off-Grid or Grid-Connected** (Remote Civil and DoD, Industrial, Defense); **Grid-Connected** (Urban Communities)

In order to develop and deploy microreactors, a number of factors must be considered in parallel. When examining end uses, each use case has unique considerations which will help in the selection of a specific reactor system technology. When examining the specific reactor technologies, there are a number of factors that will influence development efforts, as well as the timeframe for deployment. Additionally, licensing considerations are of interest to both end users and reactor designers/developers. Figure 6.1 outlines some of the factors that will enable successful development and deployment of microreactors. These factors span a wide range, and include materials development, reactor and system modeling, and integration with microgrids and hybrid energy systems. As specific reactor designs and use cases are evaluated, a robust decision support framework will help ensure the requirements of the full system are addressed. Figure 6.1 summarizes the key considerations that will support selection of the most applicable technologies and associated licensing path for various use cases. This "framework" is subdivided into three equally important categories: reactor considerations, licensing, and end use considerations.

The deployment and operation of a microreactor needs to follow the guidelines and rules of a regulatory body (such as the NRC, DOE, or DoD), where the appropriate regulating body depends on the application. The "Reactor Considerations" category of Figure 6.1 can further be divided into three branches: materials, thermal-hydraulics, and neutronics, which are intimately coupled. For materials, the primary development efforts necessary to deploy a microreactor include testing, qualification, code case development, and manufacturability of individual components. Additionally, data on thermal stresses which result from transient events such as startup, shut down, and load following must be acquired. Thermal-hydraulics and neutronics analyses are inter-linked with each other due to fuel and coolant thermal response interactions.

Information on various subsystems is required to perform a fully integrated system analysis, and testing is required to perform verification and validation of design and modeling assumptions. The uncertainties in neutronic cross-section libraries need to be examined, and geometry dependence and flux (neutron spectrum) needs to be considered in a detailed neutronic analysis. Thus, in order to perform a detailed system analysis for a microreactor, having information on all three categories is critical. The decision framework proposed will evolve as more information is gathered on microreactors and other integration avenues mature and become available.

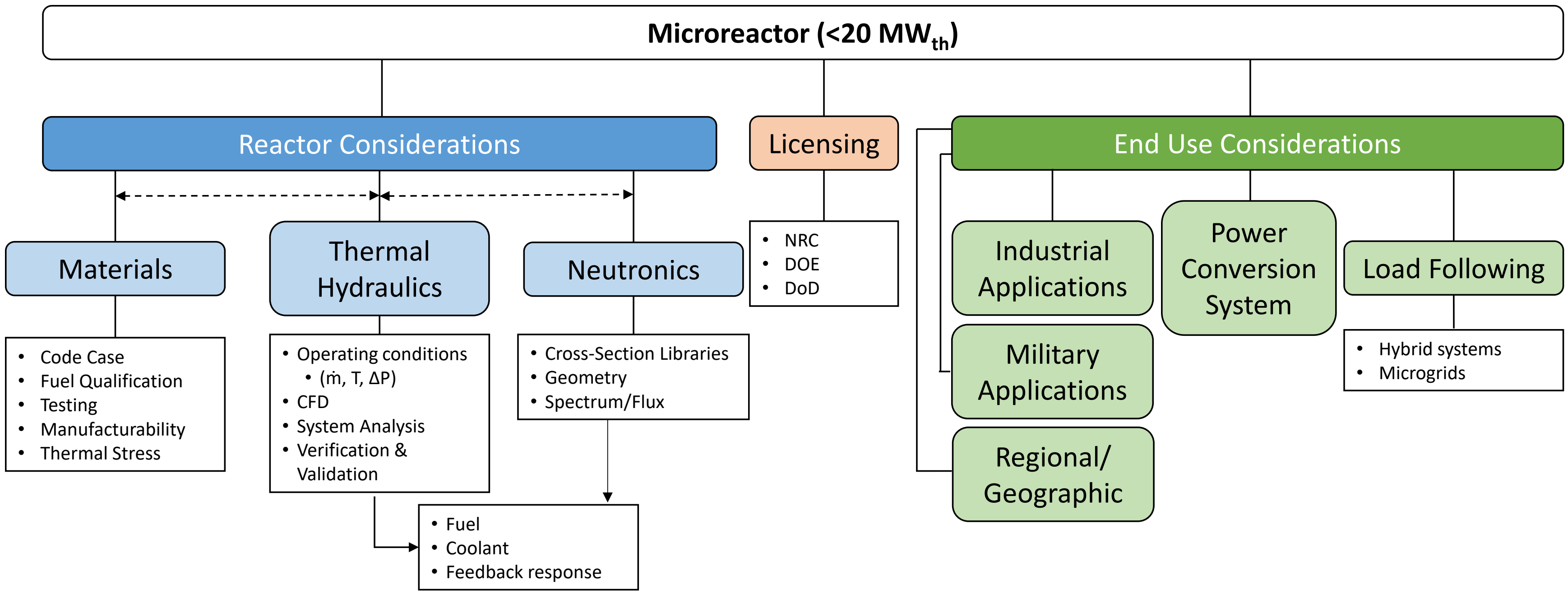

Figure 6.1. Decision support framework for microreactor development and deployment

7. CONCLUSIONS

A microreactor is designed for use in unique applications where energy generation on the order of megawatts is otherwise unavailable or prohibitively expensive. These reactors generally produce less than 20 megawatt thermal (MWth), are factory manufacturable, easily transportable (e.g., truck, train, plane, or ship), and neutronically simple so as to allow for semi- or fully-autonomous operation.

Microreactors are currently being considered for multiple use cases, including:

- Military installations
- Remote community electricity production
- Industrial applications (e.g., desalination, hydrogen production, and chilled water production)
- Integration with hybrid energy systems and microgrids, while providing potential load following capabilities.

The end use applications of microreactors will depend on the regional/geographic location and needs, which will drive the requirements for reactor design. For example, these requirements may include the temperature required for industrial applications, which would further drive the selection of the coolant as well as the power conversion cycle to attain both higher thermal efficiency and maintain economic feasibility.

In the U.S., both HTGR and heat pipe microreactors are being considered at the MW scale. These reactors operate in different thermal regimes, and therefore allow for flexibility when selecting a reactor for a specific use case. Ongoing efforts to investigate materials, manufacturing techniques, and heat exchangers will allow for evaluation of TRLs and SRLs for specific reactor concepts. Those readiness level evaluations can then be used in conjunction with an expanded decision framework to define a path toward FOAK deployment.

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Appendix A
DoD Installation Energy Use

Appendix A
DoD Installation Energy Use

The table below identifies energy use at DoD installations in 2016. Total annual energy use data is taken from the FY2016 DoD Annual Energy Management and Resilience (AEMR) Report [6]. Total energy use in mega-joules is divided by the number of seconds in the year 2016 (366 days * 24 hours/day * 60 minutes/hour * 60 seconds/minute) to give the average energy demand at the site in mega-watts. Note that this data only gives the average energy demand during 2016, and does not reflect the variability in demand or peak demand.

Table A.1. DoD installation energy use 2016.

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	ANDERSEN AIR FORCE BASE	FPO	GUAM	3	0.10
NAVY	NSA SARATOGA SPRINGS NY	SARATOGA SPRINGS	NEW YORK	3	0.10
AIR FORCE	CAMP PENDLETON MILITARY RESERVATION(ANG)	VIRGINIA BEACH	VIRGINIA	4	0.13
AIR FORCE	CAMP PERRY ANG STATION	PORT CLINTON	OHIO	4	0.13
AIR FORCE	NORTH HIGHLANDS ANG STATION	NORTH HIGHLANDS	CALIFORNIA	5	0.17
AIR FORCE	CAMP BLANDING MILITARY RESERVATION (ANG)	STARKE	FLORIDA	6	0.20
ARMY	9TH MISSION SUPPORT COMMAND	HONOLULU	HAWAII	7	0.23
DCMA	DCMA(2)	BRATENAHL	OHIO	8.75	0.29
DCMA	DCMA(1)	CARSON	CALIFORNIA	9.23	0.31
DFAS	DFAS LIMESTONE	LIMESTONE	MAINE	10	0.33
ARMY	GUAM ARNG (MOB)	FPO	GUAM	10	0.33
AIR FORCE	LAMBERT ST LOUIS IAP ANG	ST. LOUIS	MISSOURI	10	0.33
AIR FORCE	CAMP MURRAY ANG STATION	TACOMA	WASHINGTON	11	0.37
ARMY	MILITARY OCEAN TML	CONCORD	CALIFORNIA	11	0.37
AIR FORCE	MOFFETT FLD ANG	MOUNTAIN VIEW	CALIFORNIA	11	0.37
AIR FORCE	FT INDIANTOWN GAP ANG STATION	ANNVILLE	PENNSYLVANIA	12	0.40

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	JEFFERSON BARRACKS ANG STATION	LEMAY	MISSOURI	12	0.40
ARMY	VIRGIN ISLANDS ARNG (MOB)	FPO	VIRGIN ISLANDS	12	0.40
AIR FORCE	NIAGARA FALLS IAP-AIR RESERVE STATION (ANG)	NIAGARA FALLS	NEW YORK	13	0.43
AIR FORCE	CARSWELL AIR RESERVE STATION	FORT WORTH	TEXAS	14	0.47
AIR FORCE	CHANNEL ISLANDS ANG STATION	PORT HUENEME	CALIFORNIA	16	0.53
AIR FORCE	FAIRCHILD AIR FORCE BASE (ANG)	AIRWAY HEIGHTS	WASHINGTON	16	0.53
AIR FORCE	FRESNO YOSEMITE INTERNATIONAL	FRESNO	CALIFORNIA	16	0.53
ARMY	MOT SUNNY POINT	SOUTHPORT	NORTH CAROLINA	16	0.53
NAVY	NAVMAG INDIAN ISLAND WA	PORT HADLOCK	SOUTH CAROLINA	16	0.53
DIA	DLOC WAREHOUSE	LANDOVER	MARYLAND	17	0.57
AIR FORCE	KIRTLAND AIR FORCE BASE	ALBUQUERQUE	NEW MEXICO	18	0.60
AIR FORCE	SKY HARBOR INTERNATIONAL AIRPORT	PHOENIX	ARIZONA	18	0.60
AIR FORCE	LITTLE ROCK AIR FORCE BASE	LITTLE ROCK	ARKANSAS	19	0.63
AIR FORCE	BURLINGTON INTERNATIONAL AIRPORT (ANG)	SOUTH BURLINGTON	VERMONT	20	0.67
ARMY	MILAN AAP (GOCO)	MILAN	TENNESSEE	20	0.67
AIR FORCE	NASHVILLE INTERNATIONAL AIRPORT	NASHVILLE	TENNESSEE	20	0.67
AIR FORCE	RENO TAHOE INTERNATIONAL AIRPORT	RENO	NEVADA	20	0.67
AIR FORCE	ABRAHAM LINCOLN CAPITAL AIRPORT	SPRINGFIELD	ILLINOIS	21	0.70

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	FORT SMITH MUNICIPAL AIRPORT ANG	FORT SMITH	ARKANSAS	21	0.70
AIR FORCE	TOLEDO EXPRESS AIRPORT ANG	SWANTON	OHIO	21	0.70
AIR FORCE	HARRISBURG IAP	MIDDLETOWN	PENNSYLVANIA	22	0.73
AIR FORCE	ROSECRANS MEMORIAL AIRPORT	ST. JOSEPH	MISSOURI	22	0.73
NAVY	NSA ORLANDO FL	ORLANDO	FLORIDA	23	0.77
AIR FORCE	AIR NATIONAL GUARD READINESS CENTER (ANGrc)	ANDREWS AFB	MARYLAND	24	0.80
AIR FORCE	BRADLEY INTERNATIONAL AIRPORT (ANG)	WINDSOR LOCKS	CONNECTICUT	24	0.80
ARMY	HAWAII ARNG	HONOLULU	HAWAII	24	0.80
AIR FORCE	LOUISVILLE INTERNATIONAL AIRPORT - STANDIFORD FIELD	LOUISVILLE	KENTUCKY	24	0.80
AIR FORCE	NEW CASTLE COUNTY AIRPORT	WILMINGTON	DELAWARE	24	0.80
DFAS	DFAS ROME	ROME	NEW YORK	25	0.83
AIR FORCE	MARTIN STATE AIRPORT ANG	MIDDLE RIVER	MARYLAND	25	0.83
AIR FORCE	WILL ROGERS WORLD AIRPORT	OKLAHOMA CITY	OKLAHOMA	25	0.83
AIR FORCE	EIELSON AIR FORCE BASE	MOOSE CREEK	ALASKA	26	0.87
AIR FORCE	JACKSONVILLE IAP ANG	JACKSONVILLE	FLORIDA	26	0.87
NAVY	CFA CHINHAE KOR	FPO	KOREA, REPUBLIC OF	27	0.90
AIR FORCE	KEY FIELD AIR NATIONAL GUARD	MERIDIAN	MISSISSIPPI	27	0.90
AIR FORCE	LUIS MUNOZ MARIN INTERNATIONAL AIRPORT	CAROLINA	PUERTO RICO	27	0.90
AIR FORCE	BIRMINGHAM INTERNATIONAL AIRPORT	BIRMINGHAM	ALABAMA	28	0.93

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	BOISE AIR TERMINAL (ANG)	BOISE	IDAHO	28	0.93
AIR FORCE	GENERAL MITCHELL INTERNATIONAL APT (ANG)	MILWAUKEE	WISCONSIN	28	0.93
USMC	MCB CAMP MUJUK	FPO	SOUTH KOREA	29	0.97
AIR FORCE	CHARLOTTE/DOUGLAS INT AIRPORT (ANG)	CHARLOTTE	NORTH CAROLINA	30	1.00
AIR FORCE	KELLY FIELD ANNEX (LACKLAND AFB)	LACKLAND AFB	TEXAS	30	1.00
AIR FORCE	MORON AIR BASE	FPO	SPAIN	30	1.00
ARMY	NEW HAMPSHIRE ARNG	CONCORD	NEW HAMPSHIRE	30	1.00
NRO	NROV	LOMPOC	CALIFORNIA	30	1.00
AIR FORCE	DANE COUNTY REGIONAL AIRPORT-TRUAX FIELD	MADISON	WISCONSIN	31	1.03
ARMY	DELAWARE ARNG	WILMINGTON	DELAWARE	31	1.03
AIR FORCE	GREAT FALLS IAP ANG	GREAT FALLS	MONTANA	31	1.03
AIR FORCE	LINCOLN MUNICIPAL AIRPORT (ANG)	LINCOLN	NEBRASKA	31	1.03
ARMY	NEVADA ARNG	CARSON CITY	NEVADA	31	1.03
NAVY	SINGAPORE AREA COORDINATOR	FPO	SINGAPORE	31	1.03
AIR FORCE	GENERAL WAYNE A. DOWNING PEORIA INTERNATIONAL AIRPORT (ANG)	PEORIA	ILLINOIS	32	1.07
AIR FORCE	GULFPORT-BILOXI REGIONAL AIRPORT (ANG)	GULFPORT	MISSISSIPPI	32	1.07
AIR FORCE	MONTGOMERY REGIONAL AIRPORT (ANG) BASE	MONTGOMERY	ALABAMA	32	1.07

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	SPRINGFIELD BECKLEY MUNICIPAL AIRPORT	SPRINGFIELD	OHIO	32	1.07
AIR FORCE	BARNES MUNICIPAL AIRPORT ANG	WESTFIELD	MASSACHUSETTS	33	1.10
AIR FORCE	FRANCIS S GABRESKI AIRPORT (ANG)	WESTHAMPTON BEACH	NEW YORK	33	1.10
USMC	MCSF BLOUNT ISLAND FL	JACKSONVILLE	FLORIDA	33	1.10
AIR FORCE	NEW ORLEANS NAS ANG	BELLE CHASSE	LOUISIANA	33	1.10
ARMY	PUEBLO CHEMICAL DEPOT	PUEBLO	COLORADO	33	1.10
AIR FORCE	DES MOINES INTERNATIONAL AIRPORT ANG	DES MOINES	IOWA	34	1.13
AIR FORCE	QUONSET STATE AIRPORT ANG	NORTH KINGSTOWN	RHODE ISLAND	34	1.13
DIA	ROWE BUILDING AND ULC 1/RIVANNA STATION	CHARLOTTESVILLE	VIRGINIA	34	1.13
ARMY	WASHINGTON ARNG	CAMP MURRAY	WASHINGTON	34	1.13
AIR FORCE	HECTOR INTERNATIONAL AIRPORT (ANG)	FARGO	NORTH DAKOTA	35	1.17
AIR FORCE	HICKAM AIR FORCE BASE	HICKAM AF BASE	HAWAII	35	1.17
NAVY	NSA SOUDA BAY GR	FPO	GREECE	35	1.17
AIR FORCE	RAF FAIRFORD	FPO	UNITED KINGDOM	35	1.17
AIR FORCE	SCOTT AIR FORCE BASE (ANG)	BELLEVILLE	ILLINOIS	35	1.17
AIR FORCE	SIOUX GATEWAY AP/COL. BUD DAY FIELD(ANG)	SIOUX CITY	IOWA	35	1.17
AIR FORCE	FORT WAYNE INTERNATIONAL AIRPORT	FORT WAYNE	INDIANA	36	1.20

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	MCENTIRE JOINT NATIONAL GUARD BASE	EASTOVER	SOUTH CAROLINA	36	1.20
AIR FORCE	MINNEAPOLIS-ST PAUL IAP-AIR RESERVE STN (ANG)	MINNEAPOLIS	MINNESOTA	36	1.20
AIR FORCE	SCHENECTADY COUNTY AIRPORT ANG	SCOTIA	NEW YORK	36	1.20
AIR FORCE	FORBES FIELD ANG	TOPEKA	KANSAS	37	1.23
AIR FORCE	MANSFIELD LAHM AIRPORT ANG	MANSFIELD	OHIO	37	1.23
AIR FORCE	TULSA INTERNATIONAL AIRPORT	TULSA	OKLAHOMA	37	1.23
AIR FORCE	W K KELLOGG AIRPORT	BATTLE CREEK	MICHIGAN	37	1.23
AIR FORCE	KLAMATH FALLS AIRPORT-KINGSLEY FIELD	KLAMATH FALLS	OREGON	38	1.27
ARMY	PUERTO RICO ARNG (MOB)	SAN JUAN	PUERTO RICO	38	1.27
AIR FORCE	JOE FOSS FIELD ANG	SIOUX FALLS	SOUTH DAKOTA	39	1.30
AIR FORCE	WILLOW GROVE AIR RESERVE STATION	HORSHAM	PENNSYLVANIA	39	1.30
AIR FORCE	YEAGER AIRPORT ANG	CHARLESTON	WEST VIRGINIA	40	1.33
AIR FORCE	ATLANTIC CITY INTERNATIONAL AIRPORT	EGG HARBOR TOWNSHIP	NEW JERSEY	41	1.37
AIR FORCE	CHEYENNE REGIONAL AIRPORT	CHEYENNE	WYOMING	42	1.40
AIR FORCE	VOLK FIELD	CAMP DOUGLAS	WISCONSIN	42	1.40
AIR FORCE	BANGOR INTERNATIONAL AIRPORT (ANG)	BANGOR	MAINE	43	1.43
AIR FORCE	ELLINGTON FIELD	HOUSTON	TEXAS	43	1.43
USMC	MCAS CAMP PENDLETON CA	CAMP PENDLETON	CALIFORNIA	43	1.43
USMC	NAVAL HOSPITAL 29 PALMS CA	TWENTYNINE PALMS	CALIFORNIA	43	1.43

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	RICKENBACKER INTERNATION AIRPORT (ANG)	COLUMBUS	OHIO	43	1.43
ARMY	PARKS CSTC	DUBLIN	CALIFORNIA	44	1.47
AIR FORCE	PITTSBURGH IAP-AIR RESERVE STN	MOON	PENNSYLVANIA	44	1.47
AIR FORCE	SALT LAKE CITY INTERNATIONAL AIRPORT ANG	SALT LAKE CITY	UTAH	44	1.47
ARMY	DC ARNG (MOB)	WASHINGTON	DISTRICT OF COLUMBIA	45	1.50
NRO	GLEN	SCHRIEVER AFB	COLORADO	45	1.50
AIR FORCE	SAVANNAH/HILTON HEAD INTERNATIONAL AP	GARDEN CITY	GEORGIA	45	1.50
ARMY	FORT HUNTER LIGGETT	FORT HUNTER LIGGETT	CALIFORNIA	46	1.53
USMC	MCMWTC BRIDGEPORT CA	BRIDGEPORT	CALIFORNIA	46	1.53
AIR FORCE	HULMAN REGIONAL AIRPORT	TERRE HAUTE	INDIANA	47	1.57
AIR FORCE	JOINT BASE ANDREWS-NAVAL AIR FACILITY WASHINGTON	ANDREWS AFB	MARYLAND	48	1.60
USMC	MARBKS WASHINGTON DC	WASHINGTON	DISTRICT OF COLUMBIA	48	1.60
AIR FORCE	TUCSON INTERNATIONAL AIRPORT	TUCSON	ARIZONA	48	1.60
AIR FORCE	SYRACUSE HANCOCK FIELD ANG	SYRACUSE	NEW YORK	49	1.63
ARMY	MAINE ARNG	CAMP KEYES	MAINE	50	1.67
AIR FORCE	MCGUIRE AIR FORCE BASE (ANG)	MCGUIRE AFB	NEW JERSEY	50	1.67
AIR FORCE	MARCH AIR RESERVE BASE (ANG)	RIVERSIDE	CALIFORNIA	51	1.70
ARMY	VERMONT ARNG	COLCHESTER	VERMONT	51	1.70

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	DULUTH INTERNATIONAL AIRPORT (ANG)	DULUTH	MINNESOTA	52	1.73
AIR FORCE	JACKSON INTERNATIONAL AIRPORT	FLOWOOD	MISSISSIPPI	52	1.73
NAVY	CFA OKINAWA JA	FPO	JAPAN	54	1.80
AIR FORCE	JOINT BASE ELMENDORF-FT RICHARDSON	ELMENDORF AFB	ALASKA	55	1.84
AIR FORCE	LAJES FIELD	FPO	PORTUGAL	56	1.87
AIR FORCE	PITTSBURGH INTERNATIONAL AIRPORT (ANG)	CORAOPOLIS	PENNSYLVANIA	56	1.87
ARMY	SOUTH DAKOTA ARNG	RAPID CITY	SOUTH DAKOTA	56	1.87
AIR FORCE	ALPENA COUNTY REGIONAL AIRPORT	ALPENA	MICHIGAN	57	1.90
AIR FORCE	OTIS AIR NATIONAL GUARD BASE	OTIS ANGB, MASHPEE	MASSACHUSETTS	57	1.90
ARMY	RHODE ISLAND ARNG	CRANSTON	RHODE ISLAND	57	1.90
NAVY	NAF MISAWA JA	FPO	JAPAN	59	1.97
AIR FORCE	PORTLAND INTERNATIONAL AIRPORT	PORTLAND	OREGON	59	1.97
ARMY	NEW MEXICO ARNG	SANTA FE	NEW MEXICO	60	2.00
USMC	CATC CAMP FUJI JA	FPO	JAPAN	63	2.10
AIR FORCE	HOMESTEAD AIR RESERVE BASE	HOMESTEAD	FLORIDA	63	2.10
ARMY	FORT HAMILTON	NEW YORK CITY	NEW YORK	65	2.17
AIR FORCE	MCCONNELL AIR FORCE BASE (ANG)	WICHITA	KANSAS	65	2.17

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	MEMPHIS INTERNATIONAL AIRPORT	MEMPHIS	TENNESSEE	65	2.17
AIR FORCE	MINNEAPOLIS-ST PAUL IAP-AIR RESERVE STN (AFR)	MINNEAPOLIS	MINNESOTA	66	2.20
ARMY	ALASKA ARNG	FORT RICHARDSON	ALASKA	67	2.24
ARMY	ARIZONA ARNG	PHOENIX	ARIZONA	68	2.27
AIR FORCE	EWVRA SHEPHERD FIELD ANG	MARTINSBURG	WEST VIRGINIA	68	2.27
AIR FORCE	ROBINS AIR FORCE BASE (ANG)	ROBINS AF BASE	GEORGIA	69	2.30
ARMY	KENTUCKY ARNG	FRANKFORT	KENTUCKY	71	2.37
NAVY	PMRF BARKING SANDS HI	KEKAHA	HAWAII	71	2.37
AIR FORCE	YOUNGSTOWN-WARREN REGIONAL AIRPORT ARS	VIENNA	OHIO	71	2.37
NRO	CAPE	PATRICK AFB	FLORIDA	72	2.40
ARMY	FORT A P HILL	BOWLING GREEN	VIRGINIA	72	2.40
NAVY	NAF EL CENTRO CA	EL CENTRO	CALIFORNIA	74	2.47
ARMY	COLORADO ARNG	ENGLEWOOD	COLORADO	75	2.50
AIR FORCE	MCGHEE TYSON AIRPORT	LOUISVILLE	TENNESSEE	75	2.50
ARMY	MONTANA ARNG	HELENA	MONTANA	76	2.54
ARMY	NEBRASKA ARNG	LINCOLN	NEBRASKA	76	2.54
ARMY	FLORIDA ARNG	SAINT AUGUSTINE	FLORIDA	77	2.57
AIR FORCE	NIAGARA FALLS IAP-AIR RESERVE STATION (AFR)	NIAGARA FALLS	NEW YORK	78	2.60
NAVY	NSF BEAUFORT SC	BEAUFORT	SOUTH CAROLINA	78	2.60
ARMY	USAG MIAMI	MIAMI	FLORIDA	80	2.67
ARMY	WYOMING ARNG	CHYENNE	WYOMING	81	2.70
ARMY	CONNECTICUT ARNG	HARTFORD	CONNECTICUT	82	2.74

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
ARMY	MARYLAND ARNG	BALTIMORE	MARYLAND	83	2.77
NRO	ADF - SOUTHWEST	LAS CRUCES	NEW MEXICO	85	2.84
AIR FORCE	GRISSOM AIR RESERVE BASE	KOKOMO	INDIANA	86	2.87
AIR FORCE	DOBBINS AIR RESERVE BASE	MARIETTA	GEORGIA	88	2.94
AIR FORCE	STEWART INTERNATIONAL AIRPORT	NEWBURGH	NEW YORK	88	2.94
ARMY	UTAH ARNG	DRAPER	UTAH	89	2.97
ARMY	DEVENS RFTA	DEVENS	MASSACHUSETTS	91	3.04
ARMY	NEW YORK ARNG	LATHAM	NEW YORK	93	3.10
NAVY	WPNSTA SEAL BEACH CA	SEAL BEACH	CALIFORNIA	93	3.10
AIR FORCE	LOS ANGELES AIR FORCE BASE	EL SEGUNDO	CALIFORNIA	94	3.14
AIR FORCE	RAF CROUGHTON	FPO	UNITED KINGDOM	95	3.17
AIR FORCE	PEASE INTERNATIONAL TRADEPORT	PORTSMOUTH	NEW HAMPSHIRE	96	3.20
NAVY	NAS WHITING FIELD MILTON FL	MILTON	FLORIDA	97	3.24
ARMY	OREGON ARNG	SALEM	OREGON	97	3.24
ARMY	IDAHO ARNG	BOISE	IDAHO	101	3.37
ARMY	SOLDIER SYSTEMS CTR,	NATICK	MASSACHUSETTS	103	3.44
DLA	DEFENSE DISTRIBUTION DEPOT SAN JOAQUIN	TRACY	CALIFORNIA	104	3.47
ARMY	TOOELE ARMY DEPOT	TOOELE	UTAH	105	3.50
NAVY	NAS KINGSVILLE TX	KINGSVILLE	TEXAS	106	3.54
ARMY	BLUE GRASS ARMY DEPOT	RICHMOND	KENTUCKY	107	3.57
WHS	FORT BELVOIR	FORT BELVOIR	VIRGINIA	107	3.57
ARMY	OKLAHOMA ARNG	OKLAHOMA CITY	OKLAHOMA	107	3.57
ARMY	KANSAS ARNG	TOPEKA	KANSAS	108	3.60

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
USMC	FIRST MCD GARDEN CITY LI NY	LONG ISLAND	NEW YORK	113	3.77
ARMY	FORT BUCHANAN	FORT BUCHANAN	PUERTO RICO	113	3.77
ARMY	GEORGIA ARNG	ATLANTA	GEORGIA	115	3.84
USMC	NAVAL HOSPITAL CAMP PENDLETON CA	CAMP PENDLETON	CALIFORNIA	115	3.84
ARMY	NEW JERSEY ARNG	LAWRENCEVILLE	NEW JERSEY	116	3.87
ARMY	SOUTH CAROLINA ARNG	COLUMBIA	SOUTH CAROLINA	117	3.90
AIR FORCE	BUCKLEY AIR FORCE BASE (ANG)	AURORA	COLORADO	120	4.00
AIR FORCE	MARCH AIR RESERVE BASE (AFR)	RIVERSIDE	CALIFORNIA	120	4.00
AIR FORCE	LAUGHLIN AIR FORCE BASE	DEL RIO	TEXAS	122	4.07
AIR FORCE	VANCE AIR FORCE BASE	ENID	OKLAHOMA	123	4.10
ARMY	CARLISLE BARRACKS	CARLISLE	PENNSYLVANIA	124	4.14
ARMY	TENNESSEE ARNG	NASHVILLE	TENNESSEE	125	4.17
USMC	MCAS FUTENMA JA	FPO	JAPAN	126	4.20
ARMY	NORTH DAKOTA ARNG	BISMARK	NORTH DAKOTA	126	4.20
ARMY	USAG BENELUX	FPO	BELGIUM	126	4.20
NAVY	CBC GULFPORT MS	GULFPORT	MISSISSIPPI	130	4.34
USMC	MARFORRES NEW ORLEANS LA	NEW ORLEANS	LOUISIANA	131	4.37
ARMY	MISSOURI ARNG	JEFFERSON CITY	MISSOURI	133	4.44
NAVY	NAVSTA EVERETT WA	EVERETT	WASHINGTON	133	4.44
ARMY	NORTH CAROLINA ARNG	RALEIGH	NORTH CAROLINA	133	4.44
AIR FORCE	COLUMBUS AIR FORCE BASE	COLUMBUS	MISSISSIPPI	135	4.50
NAVY	NSA PANAMA CITY FL	PANAMA CITY BEACH	FLORIDA	136	4.54
USMC	NAVAL HOSPITAL CAMP LEJEUNE NC	CAMP LEJEUNE	NORTH CAROLINA	137	4.57

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
NAVY	WPNSTA EARLE COLTS NECK NJ	COLTS NECK	NEW JERSEY	139	4.64
ARMY	YUMA PROVING GROUND	YUMA	ARIZONA	143	4.77
NAVY	NSA MONTEREY CA	MONTEREY	CALIFORNIA	144	4.80
ARMY	ILLINOIS ARNG	CAMP LINCOLN	ILLINOIS	145	4.84
ARMY	SIERRA ARMY DEPOT	HERLONG	CALIFORNIA	147	4.90
ARMY	IOWA ARNG	JOHNSTON	IOWA	149	4.97
AIR FORCE	RAF ALCONBURY	FPO	UNITED KINGDOM	149	4.97
ARMY	OHIO ARNG	COLUMBUS	OHIO	151	5.04
ARMY	TEXAS ARNG	CAMP MABRY	TEXAS	151	5.04
ARMY	LOUISIANA ARNG	JOHNSON BARRACKS	LOUISIANA	152	5.07
ARMY	MASSACHUSETTS ARNG	MILFORD	MASSACHUSETTS	152	5.07
AIR FORCE	WESTOVER AIR RESERVE BASE	CHICOPEE	MASSACHUSETTS	154	5.14
USMC	NAVAL HOSPITAL OKINAWA JA	FPO	JAPAN	155	5.17
ARMY	HAWTHORNE AAP (GOCO)	HAWTHORNE	NEVADA	158	5.27
NAVY	NAS MERIDIAN MS	MERIDIAN	MISSISSIPPI	158	5.27
AIR FORCE	SELFRIDGE ANG BASE	MOUNT CLEMENS	MICHIGAN	165	5.51
ARMY	ALABAMA ARNG	MONTGOMERY	ALABAMA	166	5.54
NAVY	NAS JRB NEW ORLEANS LA	NEW ORLEANS	LOUISIANA	170	5.67
AIR FORCE	BUCKLEY AIR FORCE BASE (AFSPC)	AURORA	COLORADO	171	5.71
ARMY	VIRGINIA ARNG	FORT PICKETT	VIRGINIA	171	5.71
ARMY	WISCONSIN ARNG	MADISON	WISCONSIN	179	5.97
ARMY	PRESIDIO OF MONTEREY	MONTEREY	CALIFORNIA	180	6.01
NRO	WESTFIELDS	CHANTILLY	VIRGINIA	182	6.07
ARMY	ADELPHI LABORATORY CTR	HYATTSVILLE	MARYLAND	184	6.14

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
USMC	MCAS BEAUFORT SC	BEAUFORT	SOUTH CAROLINA	192	6.41
NAVY	WPNSTA YORKTOWN VA	YORKTOWN	VIRGINIA	194	6.47
ARMY	CALIFORNIA ARNG	SACRAMENTO	CALIFORNIA	195	6.51
ARMY	WEST VIRGINIA ARNG	CHARLESTON	WEST VIRGINIA	197	6.57
NAVY	NAVSTA ROTA SP	FPO	SPAIN	204	6.81
NAVY	NAS FALLON NV	FALLON	NEVADA	207	6.91
USMC	MCAS YUMA AZ	YUMA	ARIZONA	210	7.01
AIR FORCE	MOODY AIR FORCE BASE	MOODY AF BASE	GEORGIA	211	7.04
NAVY	NAVSTA MAYPORT FL	JACKSONVILLE	JAPAN	212	7.07
NAVY	NAS SIGONELLA IT	FPO	ITALY	213	7.11
NAVY	NSA MID SOUTH MILLINGTON TN	MILLINGTON	TENNESSEE	217	7.24
ARMY	ARKANSAS ARNG	CAMP ROBINSON	ARKANSAS	221	7.37
AIR FORCE	GOODFELLOW AIR FORCE BASE	SAN ANGELO	TEXAS	221	7.37
NAVY	NAS CORPUS CHRISTI TX	CORPUS CHRISTI	TEXAS	224	7.47
ARMY	MISSISSIPPI ARNG	JACKSON	MISSISSIPPI	230	7.67
ARMY	63RD REGIONAL SUPPORT COMMAND	MOFFETT FIELD	CALIFORNIA	231	7.71
AIR FORCE	GRAND FORKS AIR FORCE BASE	GRAND FORKS AFB	NORTH DAKOTA	232	7.74
DLA	DEFENSE SUPPLY CENTER RICHMOND	RICHMOND	VIRGINIA	235	7.84
ARMY	MINNESOTA ARNG	CAMP RIPLEY	MINNESOTA	245	8.17
AIR FORCE	RAF MILDENHALL	FPO	UNITED KINGDOM	246	8.21
NAVY	NAS LEMOORE CA	LEMOORE	CALIFORNIA	247	8.24
ARMY	FORT GREELY	DELTA JUNCTION	ALASKA	248	8.27
AIR FORCE	MCCONNELL AIR FORCE BASE (AMC)	WICHITA	KANSAS	250	8.34

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
NAVY	NAS JRB FORT WORTH TX	FORT WORTH	TEXAS	253	8.44
NAVY	NSA BAHRAIN	FPO	BAHRAIN	253	8.44
ARMY	81ST REGIONAL SUPPORT COMMAND	FORT JACKSON	SOUTH CAROLINA	255	8.51
AIR FORCE	ALTUS AIR FORCE BASE	ALTUS	OKLAHOMA	255	8.51
USMC	MCLB BARSTOW CA	BARSTOW	CALIFORNIA	257	8.57
ARMY	DUGWAY PROVING GROUND	DUGWAY	UTAH	262	8.74
USMC	MCAS MIRAMAR CA	SAN DIEGO	CALIFORNIA	263	8.77
ARMY	USAG DETROIT ARSENAL	HARRISON TOWNSHIP	MICHIGAN	264	8.81
ARMY	PINE BLUFF ARSENAL	WHITE HALL	ARKANSAS	266	8.87
USMC	CG MCLB ALBANY GA	ALBANY	GEORGIA	269	8.97
USMC	MARCORCRUITDEP SAN DIEGO CA	SAN DIEGO	CALIFORNIA	269	8.97
ARMY	USAG ANSBACH	FPO	GERMANY	273	9.11
ARMY	SCRANTON AAP	SCRANTON	PENNSYLVANIA	275	9.18
DLA	DLA LAND AND MARITIME	COLUMBUS	OHIO	277	9.24
NAVY	CFA SASEBO JA	FPO	JAPAN	280	9.34
AIR FORCE	LUKE AIR FORCE BASE	GLENDALE	ARIZONA	281	9.38
AIR FORCE	AVIANO AIR BASE	FPO	ITALY	286	9.54
AIR FORCE	SHAW AIR FORCE BASE	SHAW AF BASE	SOUTH CAROLINA	291	9.71
ARMY	WATERVLIET ARSENAL	WATERVLIET	NEW YORK	292	9.74
ARMY	WHITE SANDS MISSILE RANGE	WHITE SANDS	NEW MEXICO	293	9.78
AIR FORCE	SEYMOUR JOHNSON AIR FORCE BASE	SEYMOUR JOHNSON AFB	NORTH CAROLINA	297	9.91
AIR FORCE	DYESS AIR FORCE BASE	ABILENE	TEXAS	300	10.01
AIR FORCE	INCIRLIK AIR BASE ADANA	FPO	TURKEY	305	10.18

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	MOUNTAIN HOME AIR FORCE BASE	ELMORE	IDAHO	305	10.18
ARMY	PENNSYLVANIA ARNG	ANNVILLE	PENNSYLVANIA	306	10.21
USMC	MCB HAWAII KANEOHE BAY HI	KANEOHE BAY	HAWAII	315	10.51
NAVY	NAS KEY WEST FL	KEY WEST	FLORIDA	317	10.58
AIR FORCE	BEALE AIR FORCE BASE	BEALE AFB	CALIFORNIA	318	10.61
ARMY	INDIANA ARNG	INDIANOPOLIS	INDIANA	318	10.61
DLA	DEFENSE DISTRIBUTION CENTER, SUSQUEHANNA	NEW CUMBERLAND	PENNSYLVANIA	323	10.78
AIR FORCE	FRANCIS E WARREN AIR FORCE BASE	CHEYENNE	WYOMING	324	10.81
ARMY	JOINT BASE MYER-HENDERSON	FORT MYER	VIRGINIA	326	10.88
AIR FORCE	KUNSAN AIR BASE	FPO	KOREA, REPUBLIC OF	329	10.98
ARMY	99TH REGIONAL SUPPORT COMMAND	JOINT BASE MDL	NEW JERSEY	331	11.04
ARMY	FORT MCCOY	SPARTA	WISCONSIN	334	11.14
AIR FORCE	DAVIS-MONTHAN AIR FORCE BASE	TUCSON	ARIZONA	342	11.41
ARMY	CORPUS CHRISTI AD	CORPUS CHRISTI	TEXAS	343	11.44
ARMY	MICHIGAN ARNG	LANSING	MICHIGAN	360	12.01
AIR FORCE	TYNDALL AIR FORCE BASE	PANAMA CITY BEACH	FLORIDA	360	12.01
NAVY	NAVBASE VENTURA CTY PT MUGU CA	POINT MUGU	CALIFORNIA	362	12.08
AIR FORCE	CANNON AIR FORCE BASE	CANNON AFB	NEW MEXICO	363	12.11

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
ARMY	FORT LEAVENWORTH	FORT LEAVENWORTH	KANSAS	375	12.51
NAVY	NSA ANDERSEN GUAM	FPO	GUAM	376	12.54
ARMY	FORT IRWIN	FORT IRWIN	CALIFORNIA	379	12.65
AIR FORCE	SPANGDAHLEM AIR BASE	FPO	GERMANY	382	12.75
NAVY	NSA NAPLES IT	FPO	ITALY	386	12.88
NRO	ADF - EAST	FORT BELVIOR	VIRGINIA	391	13.05
AIR FORCE	LITTLE ROCK AIR FORCE BASE	LITTLE ROCK	ARKANSAS	393	13.11
AIR FORCE	FAIRCHILD AIR FORCE BASE (AMC)	AIRWAY HEIGHTS	WASHINGTON	394	13.15
AIR FORCE	MALMSTROM AIR FORCE BASE	MALMSTROM AFB	MONTANA	395	13.18
ARMY	LETTERKENNY ARMY DEPOT	CHAMBERSBURG	PENNSYLVANIA	401	13.38
NAVY	NAS WHIDBEY ISLAND WA	OAK HARBOR	WASHINGTON	401	13.38
AIR FORCE	DOVER AIR FORCE BASE	DOVER	DELAWARE	405	13.51
ARMY	TOBYHANNA ARMY DEPOT	TOBYHANNA	PENNSYLVANIA	409	13.65
NAVY	JBAB WASHINGTON DC	JOINT BASE ANACOSTIA BOLLING	DISTRICT OF COLUMBIA	414	13.81
NAVY	NAVBASE POINT LOMA CA	SAN DIEGO	CALIFORNIA	415	13.85
AIR FORCE	ELLSWORTH AIR FORCE BASE	ELLSWORTH AFB	SOUTH DAKOTA	417	13.91
NAVY	NSS NORFOLK NAVAL SHIPYARD VA	NORFOLK	VIRGINIA	422	14.08
ARMY	LIMA JSMC	LIMA	OHIO	429	14.31
ARMY	USAG DAEGU	FPO	KOREA, REPUBLIC OF	445	14.85
ARMY	FORT HUACHUCA	FORT HUACHUCA	ARIZONA	447	14.91

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	SCHRIEVER AIR FORCE BASE	COLORADO SPRINGS	COLORADO	447	14.91
ARMY	MCALESTER AAP	MCALESTER	OKLAHOMA	451	15.05
AIR FORCE	BARKSDALE AIR FORCE BASE	BARKSDALE AF BASE	LOUISIANA	469	15.65
AIR FORCE	TRAVIS AIR FORCE BASE	FAIRFIELD	CALIFORNIA	477	15.91
USMC	MARCORCRUITDEP PARRIS ISLAND SC	PARRIS ISLAND	SOUTH CAROLINA	479	15.98
AIR FORCE	HANSCOM AIR FORCE BASE	BEDFORD	MASSACHUSETTS	484	16.15
AIR FORCE	WHITEMAN AIR FORCE BASE	KNOB NOSTER	MISSOURI	487	16.25
ARMY	PICATINNY ARSENAL	DOVER	NEW JERSEY	492	16.42
NAVY	NAF ATSUGI JA	FPO	JAPAN	501	16.72
AIR FORCE	HURLBURT FIELD	EGLIN AFB	FLORIDA	509	16.98
ARMY	FORT RUCKER	FORT RUCKER	ALABAMA	513	17.12
ARMY	88TH REGIONAL SUPPORTCOMMAND	FORT MCCOY	WISCONSIN	523	17.45
AIR FORCE	SCOTT AIR FORCE BASE (AMC)	BELLEVILLE	ILLINOIS	531	17.72
NAVY	NAVBASE GUAM	FPO	GUAM	534	17.82
AIR FORCE	MACDILL AIR FORCE BASE	TAMPA	FLORIDA	537	17.92
AIR FORCE	HOLLOMAN AIR FORCE BASE	ALAMOGORDO	NEW MEXICO	545	18.18
ARMY	ROCK ISLAND ARSENAL	ROCK ISLAND	ILLINOIS	545	18.18
AIR FORCE	VANDENBERG AIR FORCE BASE	LOMPOC	CALIFORNIA	554	18.48
AIR FORCE	MINOT AIR FORCE BASE	MINOT AFB	NORTH DAKOTA	578	19.28
AIR FORCE	JOINT BASE ANDREWS-NAVAL AIR FACILITY WASHINGTON	ANDREWS AFB	MARYLAND	580	19.35
NAVY	NSA BETHESDA MD	BETHESDA	MARYLAND	580	19.35

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	RAF LAKENHEATH	FPO	UNITED KINGDOM	582	19.42
AIR FORCE	SHEPPARD AIR FORCE BASE	WICHITA FALLS	TEXAS	603	20.12
NAVY	NAVSTA NEWPORT RI	NEWPORT	RHODE ISLAND	613	20.45
NAVY	NAWS CHINA LAKE CA	CHINA LAKE	CALIFORNIA	613	20.45
ARMY	FORT DRUM	FORT DRUM	NEW YORK	619	20.65
ARMY	FORT GEORGE MEADE	FORT MEADE	MARYLAND	620	20.69
ARMY	USAG VICENZA	FPO	ITALY	629	20.99
NAVY	JEB LITTLE CREEK-FORT STORY VA	VIRGINIA BEACH	VIRGINIA	632	21.09
ARMY	USAG STUTTGART	FPO	GERMANY	632	21.09
AIR FORCE	KEESLER AIR FORCE BASE	BILOXI	MISSISSIPPI	638	21.29
AIR FORCE	MAXWELL AIR FORCE BASE	MONTGOMERY	ALABAMA	643	21.45
AIR FORCE	OSAN AIR BASE	OSAN AFB	KOREA, REPUBLIC OF	646	21.55
ARMY	USAG WIESBADEN	FPO	GERMANY	650	21.69
ARMY	CAMP ZAMA JAPAN	FPO	JAPAN	656	21.89
USMC	MCAS IWAKUNI JA	FPO	JAPAN	670	22.35
NAVY	SUBASE NEW LONDON CT	GROTON	CONNECTICUT	674	22.49
NAVY	NAS OCEANA VA	VIRGINIA BEACH	VIRGINIA	681	22.72
NAVY	SUBASE KINGS BAY GA	KINGS BAY	GEORGIA	685	22.85
USMC	MCAS CHERRY PT NC	CHERRY POINT	NORTH CAROLINA	688	22.95
AIR FORCE	EARECKSON AIR STATION	ADAK STATION	ALASKA	696	23.22
ARMY	IOWA AAP (GOCO)	MIDDLETOWN	IOWA	705	23.52
ARMY	ANNISTON ARMY DEPOT	ANNISTON	ALABAMA	707	23.59
NGA	NGA	SPRINGFIELD	VIRGINIA	717	23.92
NAVY	NSA MECHANICSBURG PA	MECHANICSBURG	PENNSYLVANIA	732	24.42

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
ARMY	FORT POLK	FORT POLK	LOUISIANA	736	24.56
NAVY	NSA ANNAPOLIS MD	ANNAPOLIS	MARYLAND	739	24.66
ARMY	RED RIVER DEPOT	TEXARKANA	TEXAS	744	24.82
AIR FORCE	OFFUTT AIR FORCE BASE	OFFUTT A.F.B.	NEBRASKA	745	24.86
NAVY	FRC EAST CHERRY POINT NC	CHERRY POINT	NORTH CAROLINA	746	24.89
ARMY	FORT LEE	FORT LEE	VIRGINIA	747	24.92
AIR FORCE	CHARLESTON AIR FORCE BASE	CHARLESTON	SOUTH CAROLINA	748	24.96
AIR FORCE	EDWARDS AIR FORCE BASE	LANCASTER	CALIFORNIA	782	26.09
AIR FORCE	PATRICK AIR FORCE BASE	PATRICK AFB	FLORIDA	782	26.09
ARMY	USAG HUMPHREYS	FPO	KOREA, REPUBLIC OF	786	26.22
ARMY	KWAJALEIN ATOLL	FPO	MARSHALL ISLANDS	826	27.56
AIR FORCE	KIRTLAND AIR FORCE BASE	ALBUQUERQUE	NEW MEXICO	827	27.59
ARMY	USAG HAWAII	WAHIAWA	HAWAII	830	27.69
ARMY	FORT GORDON	AUGUSTA	GEORGIA	850	28.36
ARMY	WEST POINT MIL RESERVATION	WEST POINT	NEW YORK	854	28.49
ARMY	FORT DETRICK	FORT DETRICK	MARYLAND	866	28.89
NAVY	CAMP LEMONNIER DJBOUTI	FPO	DJBOUTI	871	29.06
ARMY	FORT JACKSON	COLUMBIA	SOUTH CAROLINA	879	29.33
AIR FORCE	USAF ACADEMY	AIR FORCE ACADEMY	COLORADO	887	29.59
AIR FORCE	NELLIS AIR FORCE BASE	LAS VEGAS	NEVADA	895	29.86
ARMY	USAG YONGSAN	FPO	SOUTH KOREA	901	30.06
USMC	CG MCCDC QUANTICO VA	QUANTICO	VIRGINIA	902	30.09

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
ARMY	USAG RED CLOUD	FPO	KOREA, REPUBLIC OF	916	30.56
NAVY	NAS JACKSONVILLE FL	JACKSONVILLE	FLORIDA	921	30.73
NAVY	NAS PATUXENT RIVER MD	PATUXENT RIVER	MARYLAND	936	31.23
NAVY	NSF DIEGO GARCIA	FPO	INDIAN OCEAN	950	31.70
ARMY	LAKE CITY AAP (GOCO)	INDEPENDENCE	MISSOURI	955	31.86
NAVY	NSA HAMPTON ROADS VA	NORFOLK	VIRGINIA	957	31.93
ARMY	FORT KNOX	FORT KNOX	KENTUCKY	984	32.83
ARMY	FORT STEWART	FORT STEWART	GEORGIA	989	33.00
USMC	CG MCB CAMP BUTLER JA	FPO	JAPAN	1,000	33.36
USMC	CG MCB CAMP PENDLETON CA	CAMP PENDLETON	CALIFORNIA	1,004	33.50
NAVY	NAVSTA GREAT LAKES IL	GREAT LAKES	CALIFORNIA	1,004	33.50
NAVY	NSA CRANE IN	CRANE	INDIANA	1,008	33.63
USMC	CG MCAGCC TWENTYNINE PALMS CA	TWENTYNINE PALMS	CALIFORNIA	1,018	33.96
AIR FORCE	RAMSTEIN AIR BASE	FPO	GERMANY	1,050	35.03
NAVY	NAS PENSACOLA FL	PENSACOLA	FLORIDA	1,056	35.23
ARMY	FORT RILEY	FORT RILEY	KANSAS	1,065	35.53
NAVY	NAVBASE SAN DIEGO CA	SAN DIEGO	CALIFORNIA	1,065	35.53
NAVY	NSY BOS PORTSMOUTH NH	PORTSMOUTH	NEW HAMPSHIRE	1,068	35.63
WHS	WASHINGTON HQS SERVICE	ARLINGTON	VIRGINIA	1,081	36.07
NAVY	NAVSTA GUANTANAMO BAY CU	FPO	CUBA	1,108	36.97
NAVY	JB PEARL HARBOR-HICKAM HI	PEARL HARBOR	HAWAII	1,121	37.40
AIR FORCE	YOKOTA AIR BASE	FPO	JAPAN	1,137	37.94
AIR FORCE	MCGUIRE AIR FORCE BASE (AMC)	MCGUIRE AFB	NEW JERSEY	1,142	38.10
ARMY	FORT BELVOIR	FORT BELVOIR	VIRGINIA	1,153	38.47

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	LANGLEY AIR FORCE BASE	LANGLEY AFB	VIRGINIA	1,168	38.97
ARMY	FORT SILL	FORT SILL	OKLAHOMA	1,186	39.57
AIR FORCE	EGLIN AIR FORCE BASE	EGLIN AFB	FLORIDA	1,203	40.14
AIR FORCE	KADENA AIR BASE	KADENA AIR BASE OKINAWA	JAPAN	1,224	40.84
AIR FORCE	MISAWA AIR BASE	FPO	JAPAN	1,225	40.87
ARMY	USAG RHEINLAND-PFALZ	FPO	GERMANY	1,227	40.94
NAVY	NAVBASE CORONADO SAN DIEGO CA	SAN DIEGO	CALIFORNIA	1,250	41.71
ARMY	FORT CARSON	COLORADO SPGS	COLORADO	1,351	45.08
ARMY	FORT BLISS	EL PASO	TEXAS	1,409	47.01
AIR FORCE	JOINT BASE ELMENDORF-FT RICHARDSON	ELMENDORF AFB	ALASKA	1,440	48.04
ARMY	USAG BAVARIA	FPO	GERMANY	1,475	49.21
ARMY	FORT BENNING	FORT BENNING	GEORGIA	1,477	49.28
ARMY	FORT CAMPBELL	FORT CAMPBELL	KENTUCKY	1,518	50.65
ARMY	FORT LEONARD WOOD	FORT LEONARD WOOD	MISSOURI	1,525	50.88
ARMY	REDSTONE ARSENAL	HUNTSVILLE	ALABAMA	1,557	51.95
NAVY	NSA SOUTH POTOMAC DAHLGREN VA	DAHLGREN	VIR	1,676	55.92
AIR FORCE	ARNOLD AIR STATION	ARNOLD A F STATION	TENNESSEE	1,695	56.55
NAVY	NSA WASHINGTON DC	WASHINGTON NAVY YARD	DISTRICT OF COLUMBIA	1,710	57.05
ARMY	FORT WAINWRIGHT	FORT WAINWRIGHT	ALASKA	1,724	57.52

Table A.1 (continued)

Component	Installation Name	City	State / Country	Total Site Delivered Energy (BBTU) Goal Subject	Annual Average Site Energy (MWe)
AIR FORCE	PETERSON AIR FORCE BASE	COLORADO SPRINGS	COLORADO	1,811	60.42
NAVY	NAVSTA NORFOLK VA	NORFOLK	VIRGINIA	1,827	60.96
AIR FORCE	ROBINS AIR FORCE BASE (AFMC)	ROBINS AF BASE	GEORGIA	1,837	61.29
ARMY	FORT HOOD	KILLEEN	TEXAS	1,875	62.56
AIR FORCE	EIELSON AIR FORCE BASE	MOOSE CREEK	ALASKA	2,004	66.86
DIA	JOINT BASE ANACOSTIA-BOLLING	WASHINGTON	DISTRICT OF COLUMBIA	2,036	67.93
ARMY	JOINT BASE LEWIS MCCHORD	TACOMA	WASHINGTON	2,078	69.33
NAVY	NAVBASE KITSAP BREMERTON WA	BREMERTON	WASHINGTON	2,120	70.73
AIR FORCE	HILL AIR FORCE BASE	OGDEN	UTAH	2,256	75.27
NSA	FORT GEORGE G MEADE	FORT MEADE	MARYLAND	2,534	84.54
ARMY	HOLSTON AAP (GOCO)	KINGSPORT	TENNESSEE	2,568	85.68
AIR FORCE	TINKER AIR FORCE BASE	OKLAHOMA CITY	OKLAHOMA	2,703	90.18
NAVY	CFA YOKOSUKA JA	FPO	JAPAN	2,729	91.05
ARMY	ABERDEEN PG	ABERDEEN	MARYLAND	2,734	91.22
AIR FORCE	WRIGHT PATTERSON AIR FORCE BASE	WRIGHT-PATTERSON AFB	OHIO	2,828	94.35
ARMY	RADFORD AAP (GOCO)	RADFORD	VIRGINIA	2,949	98.39
USMC	CG MCB CAMP LEJEUNE NC	CAMP LEJEUNE	NORTH CAROLINA	3,161	105.46
ARMY	FORT BRAGG	FORT BRAGG	NORTH CAROLINA	3,504	116.91
AIR FORCE	JOINT BASE SAN ANTONIO (JBSA)	SAN ANTONIO	TEXAS	3,726	124.31

Appendix B
Alaska Energy Generation Statistics

Appendix B
Alaska Energy Generation Statistics

Table B.1. Alaska total annual energy generation (MWh) [14].

Year	Aleutians	Bering Straits	Bristol Bay	Copper River/Chugach	Kodiak	Lower Yukon-Kuskokwim	North Slope	Northwest Arctic	Railbelt	Southeast	Yukon-Koyukuk/Upper Tanana
2008	50962	60801	54037	107259	144021	93591	60018	36180	5171486	723465	36130
2009	51387	54659	50115	114405	127748	94184	80467	36546	5057740	749035	36183
2010	48649	20522	54704	131406	147925	102246	76570	34779	5029282	791596	36526
2011	107218	57691	53622	134245	150564	97469	80336	35823	5076251	792046	30187
2012	110899	55971	55918	120639	155892	101939	153397	37664	5010178	843141	36370
2013	65266	54071	53046	121301	154367	98609	84382	36335	4623852	880133	35839

Table B.2. Alaska average energy demand (MW). The annual total values in the table above have been divided by the number of hours in a year (8760 hours).

Year	Aleutians	Bering Straits	Bristol Bay	Copper River/Chugach	Kodiak	Lower Yukon-Kuskokwim	North Slope	Northwest Arctic	Railbelt	Southeast	Yukon-Koyukuk/Upper Tanana
2008	5.82	6.94	6.17	12.24	16.44	10.68	6.85	4.13	590.35	82.59	4.12
2009	5.87	6.24	5.72	13.06	14.58	10.75	9.19	4.17	577.37	85.51	4.13
2010	5.55	2.34	6.24	15.00	16.89	11.67	8.74	3.97	574.12	90.36	4.17
2011	12.24	6.59	6.12	15.32	17.19	11.13	9.17	4.09	579.48	90.42	3.45
2012	12.66	6.39	6.38	13.77	17.80	11.64	17.51	4.30	571.94	96.25	4.15
2013	7.45	6.17	6.06	13.85	17.62	11.26	9.63	4.15	527.84	100.47	4.09