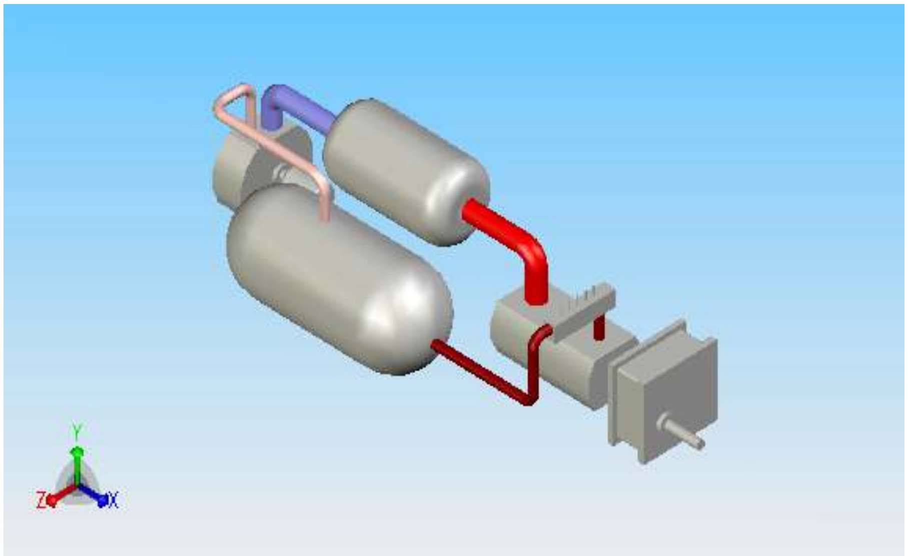
Introduction



Adams Engines™ have been designed with a single guiding principle: Nuclear power plants do not have to be large to be economical.

Small nuclear engines built in a factory using series production techniques can be competitive power sources for a variety of applications. These small engines have the potential to solve difficult problems for a large number of potential customers

The First Atomic Age began with hope, enthusiasm and an inventive spirit. Visionaries imagined ships crossing the ocean using mere bucket loads of fuel, long range aircraft ferrying passengers across Siberia, and atomic trains that did not pollute urban areas with diesel smoke. There were serious projects begun to build nuclear powered merchant ships, to operate nuclear power plants in remote locations and to design submarine tankers for under ice operations. These programs were eventually abandoned; casualties of the idea that bigger nuclear power plants were better than small ones.

In order to regain the hope and make better use of the potential energy stored in uranium and thorium it is useful to move beyond the limitations imposed by focusing on large power reactors. Adams Engines has developed a reasonable and practical way to produce nuclear engines with power outputs of between 1 and 100 MWe.

Our engines will be closed cycle gas turbines using nitrogen heated in a graphite moderated nuclear reactor. These engines have the potential to make heavy metals (uranium, thorium and plutonium) viable fuel options for a wide variety of applications including transportation and independent power projects. The plan is to use series production techniques and the economy of unit volume instead of the economy of scale as the basis for allowing nuclear power to successfully compete with other fuel alternatives.

History of Nuclear Gas Turbines

The idea of nuclear gas turbines is not new; it dates back to the mid 1940s. The main early commercial supporter was Esher Wyss Ltd. of Zurich. The first U.S. plant using the concept was the Army's ML-1 demonstration reactor, a 300 kWe nuclear heated, nitrogen cooled machine designed to be truck transportable. That machine was the first closed cycle gas turbine of any kind built in the U.S. and it operated for several years in the early 1960s before losing its funding as the Vietnam War intensified.

In Holmes F. Crouch's *Nuclear Ship Propulsion*, (Cornell Maritime Press 1960), direct cycle gas turbines were described as the "ultimate nuclear plant for merchant ship propulsion." [page 140]. [Note: This book was still available from the publisher in March 1994.]

Giving a European view, Rowland F. Pocock described the closed-cycle gas turbine as being "particularly suitable for further development as it makes use of currently fashionable techniques in both marine engineering and nuclear power." (*Nuclear Ship Propulsion*, Ian Allan, London, 1968)

The PBMR (Pebble Bed Modular Reactor) was an international endeavor led by PBMR (Pty) Ltd. of South Africa, with the active participation of Westinghouse (then a subsidiary of BNFL) and Eskom, the giant South African electric utility company. The design would have produced approximately 165 MWe per unit. A primary obstacle for the project was the cost and long lead time associated with developing the turbomachinery. After several iterations that included a complete rethinking of the machine and its orientation, the project was cancelled.

With the exception of engines for aircraft carriers and submarines, there has been little recent interest in using nuclear power for propulsion applications. The potential propulsion market is large; in 2019 the global shipping fleet burned about 4 million barrels of residual fuel oil every day. International Maritime Organization rules that came into effect in 2020 dramatically lower the allowed sulfur content from 3.5% to 0.5%. This shifts most of the demand to distillate fuels, which carry a several hundred dollar per ton cost premium over residual fuel oil.

Current Situation

Advances in technology, changes in the world's economy, and a revolution in the world's political situation have made a reevaluation of small closed cycle gas turbines a worthwhile endeavor.

Gas turbines are mature power sources. Gas cooled reactors have been designed and tested through full scale operating programs. The operating temperature available from the gas cooled reactors matches well with simple cycle gas turbines using uncooled blades.

The current power system of choice in our target market is a large diesel engine. Approximately 75-85% of the cost of power from diesel engines is the cost of fuel. Oil is priced at approximately $50.00 per barrel - about 18 times the price that existed when the N.S. Savannah, the only nuclear-powered commercial ship built in the U.S., was determined to be not cost effective.

At $35.00 per pound uranium costs about as much as it did in 1976.

Design Concept Discussion

Adams Engines™ are closed Brayton cycle machines. They combine proven compressor and turbine designs with fully tested gas cooled reactor concepts. They use the inherent stability of a core with a negative temperature coefficient combined with several means of controlling coolant flow. With carefully selected fuels, core materials and core geometry, fuel melting is not credible even in the event of complete loss of coolant flow at full power. The engines use inert gas coolant at a maximum pressure on the order of ~10-30 bar, allowing savings in pressure vessel and containment construction. The ultimate capital cost of the machine should be competitive with combustion gas turbines.

Simple Closed Brayton Cycle for Early Versions

The Brayton cycle is one of the simplest heat cycles available. In its most basic form, it includes a compressor, a heat source, a turbine, and a heat sink.

When an engine is used to propel a vehicle, space and weight play a large part in the overall economy of the system. Energy has to be expended to carry the engine and its fuel source in addition to the energy involved in moving the vehicle and its cargo. Normally, vehicles with Brayton cycle engines use simple cycle machines.

Propulsion engines must also meet strict reliability standards, particularly in aircraft. Engine failures can directly cause human fatalities. Gas turbines have proven themselves capable of meeting the stringent requirements of the commercial aircraft industry.

For terrestrial applications, heat recovery steam generators can be added to Adams Engines™, creating combined cycle gas turbines (CCGT) to increase total cycle efficiency. Alternatively, the exhaust heat can be used for district heating, industrial process heat or desalination. The high temperature gas could even be used as the heat source for a thermoelectric device that directly converts heat into electricity. These improvements may be pursued after the basic system is installed and fully proven.

Though aero-derivative Brayton cycle machines often use a mechanical shaft to drive compressors from the turbine, Adams Engines will normally use mechanically separate turbines and compressors. This decision enables compressor and turbine speed to be independently controlled.

Coolant Gas and Operating Pressure Considerations

Most closed cycle gas turbine designers have assumed that there would be a benefit from pressurizing the coolant circuit to allow smaller diameter machines to move a larger mass of fluid. This concept ignores some potential operational and manufacturing advantages of using low pressure working fluids.

The ability of small gas turbines to produce large amounts of power using a low pressure working fluid is well known. The General Electric LM2500, for example, is a 22,000 kWe machine that fits in a box 26 feet long, 9 feet wide, and 8 feet high weighing about 20,000 kg. Its working fluid is air with a pressure ratio of 18:1. The highest pressure in the system is just 18 bar.

Nitrogen is a gas with aerodynamic and thermodynamic properties that are very similar to those of air. Turbomachinery designed to work with air functions well with nitrogen as the working fluid. Nitrogen is chemically stable at the temperatures used in Adams Engines. Nitrogen is a single-phase fluid over the temperature range of interest so there is no need to raise system pressure in order to keep thermodynamic characteristics predictable.

Atmospheric nitrogen is 99.7% N14 and 0.3% N15. In a neutron flux, there is a significant probability that N14 will undergo an (n,p) reaction to become C14. The rate of production is predictable and can be addressed. In contrast, N15 is not changed when exposed to neutrons. A modest industrial capability exists to separate the two isotopes, it can be expanded if there is a credible demand signal. Both atmospheric nitrogen and enriched heavy nitrogen can be used; the choice may vary based on situational specifics.

One company with the capability of separating N15 from atmospheric air has provided an estimated cost of $15 /gram for N15 when purchased in 1,000 kg quantities.

Adams Engines will operate with the compressor suction at approximately one atmosphere (one bar). The operating pressure ratio will depend on the limiting temperature of the reactor. For the first system, it is likely to be approximately 10:1. Figure 1 is a process diagram of an Adams Engine using moderate temperature limits. Projected thermodynamic efficiency is approximately 35%.

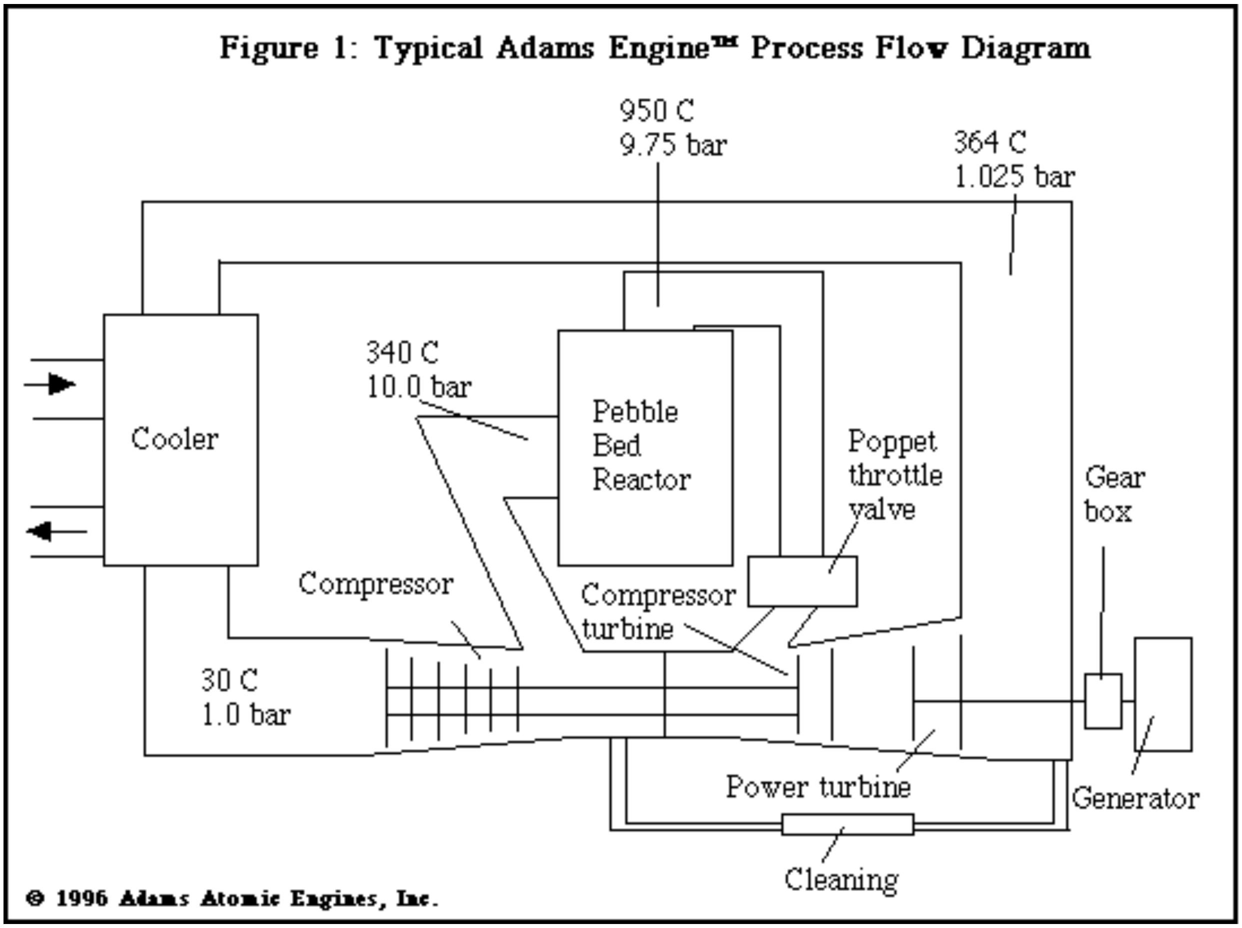


Figure 1: Adams Engine™ process diagram

One potential improvement path includes gradually increasing system pressures to increase power capacity. Each incremental increase will require detailed analysis and potential equipment redesign.

Throttle Control

Throttles have not normally been considered for gas turbine power control. Part of the reason might be explained by the following quote. "The simplest and most obvious method of output variation is the introduction of a throttling valve at some point in the system as is done in some steam apparatus and in the spark-ignition I.C. engine. But we have seen the extremely adverse effects of even the unavoidable pressure drops in the gas turbine cycle; throttling cannot therefore be considered where economy is an object." (Dusinberre and Lester, 1958)

It is possible, however, to design a throttling system where the pressure losses are small and do not substantially lower the system efficiency. With nuclear systems, fuel costs are a small percentage of output costs and a small reduction in thermodynamic efficiency may be acceptable if it can reduce capital, operations, and maintenance costs. When throttle valves are used to adjust system mass flow rates, system temperatures and pressures remain relatively constant. Well-designed throttle valves give a simple means of varying the mass flow in a system without causing a significant pressure loss. Throttle valves control power in steam turbine propulsion plants with little effect on efficiency. They follow the first law of thermodynamics and the principle of continuity.

U. S. Patent number 5,309,492 (expired) describes the use of a throttle valve to control the power level of closed cycle gas turbine machines.

Compressor

The machines selected to serve as compressors for Adams Engines will be able to operate with a wide variety of system flow rates. They might be centrifugal compressors or machines with combinations of axial stages and centrifugal stages. There is an adequate selection of such machines available that are currently in service in industrial, aircraft or marine power applications. Variable speed compressors and multiple parallel compressors are two additional means of varying coolant flow to control reactor power output.

Turbine

The turbine will be a multi-stage axial flow turbine. It will use conventional gas turbine design principles. Using power turbines that are independent of compressors allows each machine to operate at optimal speeds that vary with variable outputs. It might be useful to combine the output of several pebble bed reactors to supply a single turbine. Alternatively, it might be useful to supply more than one turbine from a single reactor.

The turbines in combustion engines operate in a high temperature, corrosive exhaust stream that can include sand, soot or salt. "Even under normal engine operating conditions, with a good inlet filtration system, and using a clean fuel, the engine flow path components will become fouled, eroded, corroded, covered with rust scale, damaged, etc." (Diakunchak p. 161) In contrast Adams Engine turbines will operate in an inert environment that can use a purification system to eliminate even very small particulate matter. This choice should increase the life of the turbine by reducing corrosion, erosion, and the formation of deposits on turbine blades.

Bearings

Reliable operation of high-speed machines like compressors and turbines requires good bearing design. While oil lubricated bearings can be designed to minimize the potential of oil entering into the coolant circuit, they may not be the best choice for refined versions of the Adams Engine. Magnetic levitation bearings offer excellent capabilities and improved performance levels.

A magnetic bearing uses a magnetic coil surrounding the rotating shaft to lift the shaft up and allow it to rotate without physical contact. Magnetic bearings are provided with sensors to determine shaft location and redundant microprocessors to adjust current flow to the electromagnetic coils. These bearings have proven their reliability in some difficult service conditions including compressors for natural gas pipelines. They are more expensive than conventional bearings, but the benefits of reduced maintenance, eliminated mechanical lubrication system and eliminated contamination risk may outweigh the initial cost.

Negative Temperature Coefficient of Reactivity

Most materials expand when they heat up. The probability of neutron interaction is reduced when the materials involved are less dense. These two principles allow reactors to be designed with an inherent negative feedback characteristic.

If fission, scattering, and leakage are relatively more important interactions than parasitic absorptions, then the core will have a negative temperature coefficient of reactivity. With this characteristic, if the core begins to heat up, the fission process will naturally slow down due to the increased possibility of neutrons leaking out of the core without causing fissions. As the power level goes down, the rate at which the core heats up decreases. It is desirable to ensure that this characteristic is available throughout core life and regardless of power level or history.

Fuel Element Considerations

Several different geometries have been used for reactor fuel elements. In the German gas cooled reactor programs, the fuel elements were 6 cm diameter spheres – approximately the same size as billiard balls. In a densely packed bed of spherical elements, approximately 39% of the total volume of the bed is empty space that can be used for coolant flow. The total surface area for heat transfer can be varied by altering the diameter of the fuel elements. Some pebble bed reactor designs use moving beds with on line refueling systems while others use stationary beds. A stationary bed is simpler and represents a reduced capital investment at the possible cost of less efficient fuel use. Some pebble bed designers (notably Aliki van Heek) have suggested using stationary beds that have a means of adding (but not removing) new fuel elements to make up for actinide depletion. Paper referenced in list as [Tavron…] is a useful reference discussing alternative fueling schemes.

Pebble bed reactors have excellent flow and heat transfer characteristics. There is a potential for a large surface to volume ratio by using relatively small fuel elements, there are large flow channels, and the constant changes in direction of the coolant gas around the spheres leads to turbulent flow and good mixing. Since the fuel elements are in contact with the surrounding elements, there is good conduction heat transfer even if all gas flow is stopped. With pebble bed designs, there is no such thing as a "hot channel" where all the worst case conditions must be assumed to take place.

Core Geometry

The core can be designed in an annular fashion with a hollow center. The coolant gas enters the core through a perforated shell at the outer circumference and flows inward to the perforated center annulus. The radial flow increases the flow cross section and reduces the length of travel for the coolant. Figure 2 is a simplified vessel cross section to illustrate the flow path.

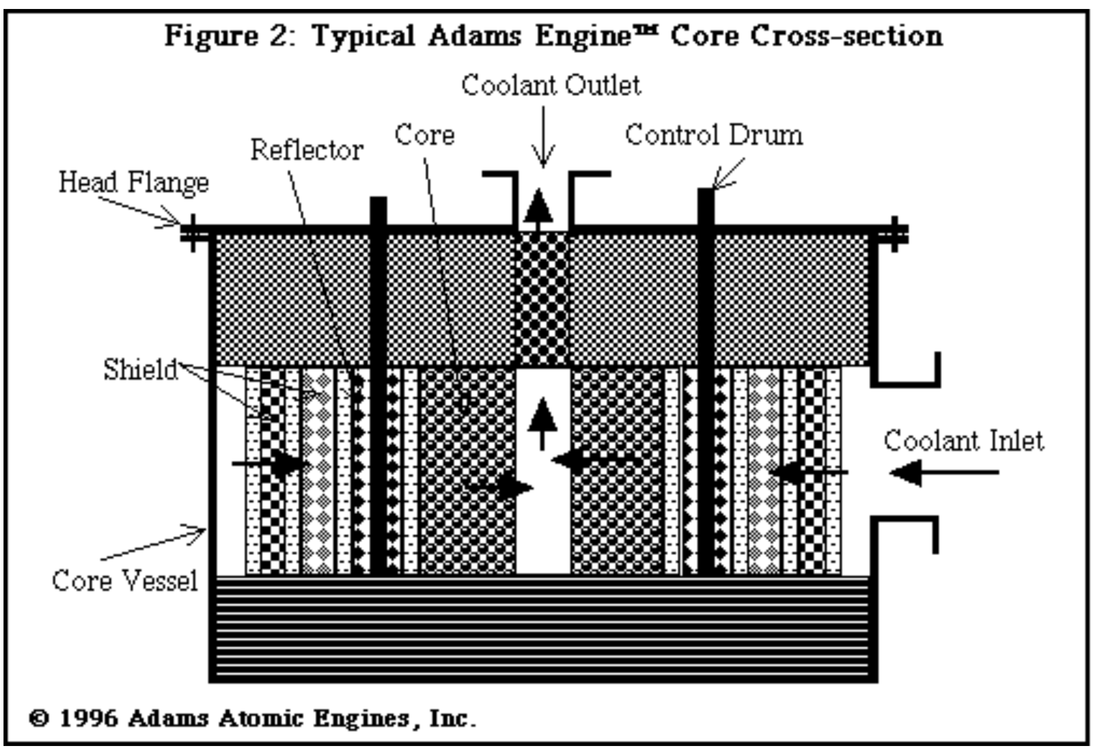


Figure 2. Vessel cross-section

With the flow from the outer boundary to the inner, there is an increase in the mass flow rate per unit area as the area decreases. Power produced in a specific core region is equal to the heat transfer coefficient times the heat transfer area times the difference in temperature between the surface of the fuel element and the coolant temperature. The heat transfer coefficient is a function of the coolant velocity such that an increase in coolant velocity corresponds to an increase in the heat transfer coefficient. At the outer edge of the core, where the coolant gas enters the core, there is a big temperature difference and low coolant velocity past each fuel element. Nearer the center of the core, after the coolant gas has gotten hotter, there is a smaller temperature difference and a faster coolant velocity. This design helps to level power and fuel element temperatures throughout the core.

The core would be provided with neutron absorbing drums located in the reflector region to control reactor temperature and to provide a means to keep the reactor shut down even when temperature is reduced. Because of the peak in the thermal neutron flux in the reflector, these drums will have a relatively high reactivity effect. These drums would have a portion of the drum made of a neutron absorbing material like hafnium or boronated graphite and the other portion of the drum made of a low absorbing moderator material like graphite.

The core reactivity can be controlled by rotating the drums to move the absorbing material into or out of the reflector, thus increasing or decreasing the absorption of neutrons. The drums' principal advantage over control rods is that their effect is felt along the entire height of the core. This provides a more even axial neutron flux distribution than is common for cores with partially inserted control rods. If required to account for reactivity changes due to temperature, fission product poisons and fuel use, it is possible to put control rod channels into tubes that penetrate the active core region. This would eliminate the need to push control rods through the pebble bed itself. If these rods were used, they might be used in a mode where they are either fully inserted or fully removed.

Shielding

The shield is constructed of a variety of materials formed into spherical elements that are placed into concentric cylinders around the reactive portion of the core. Immediately outside the reflector region is the neutron absorption portion of the shield. It is made of boron carbide. Outside the neutron absorber is a gamma shield of dense material like lead, steel or depleted uranium.

Putting the gamma shield outside the neutron shield reduces the effects of capture gammas in the dense material. Putting the entire shield inside the pressure vessel minimizes the possibility of neutron irradiation damage to the vessel. The layers of the shield are separated by perforated silicon carbide cylinders. These provide structural support. The radiation shielding also provides physical protection for the active region of the core from damage in the rare event of a turbine or compressor blade failure. Figure 3 shows cross section of the core and shield arrangement. (It is what one would see by slicing the core (figure 2) horizontally at the level of the coolant inlet.)

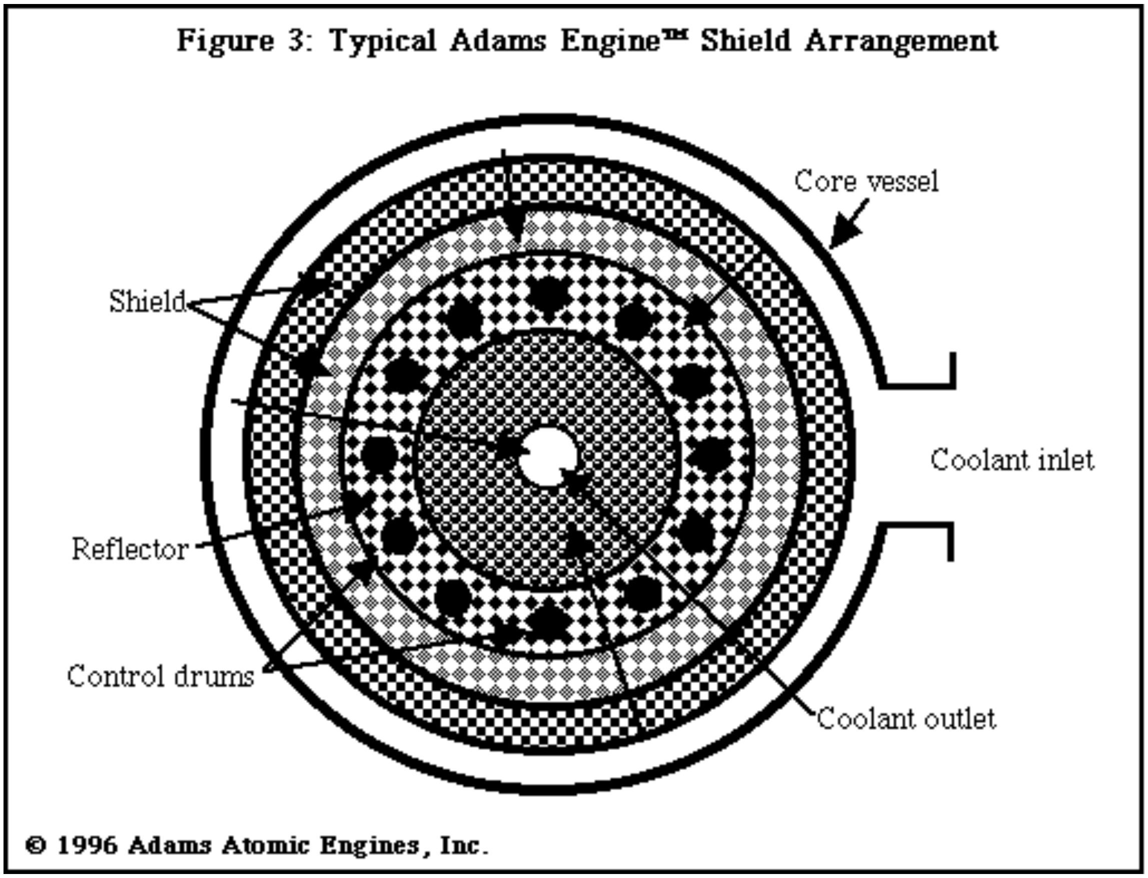


Figure 3. Shield Concept

The porous nature of the shield eliminates the need for conduits through the shield by allowing flow through a tortuous path. Whatever heat is generated in the shield by radiation reactions is used to add heat to the coolant. The shield materials also provide a large heat storage capacity that can help minimize core temperature increase on a loss of coolant flow.

At the bottom of the core, a layered solid shield is used with the same materials as the porous side shields. The top of the core is a large outlet plenum shielded with the same spherical shield elements as the side shields. The hot gas stored in the outlet plenum and in the piping leading to the throttle valve help damp any pressure changes caused by rapid throttle movement.

Fuel Element Construction

The TRISO pellet is the basic building block for modern gas cooled reactors. These pellets consist of a small particle of reactor fuel (there are several different combinations of uranium, plutonium and thorium that are suitable and have been tested) which is coated with four layers of carbon-based materials. The innermost layer is porous pyrolytic graphite which is designed to provide an expansion volume for the gases that are released as the heavy metals fission. The next layer is dense pyrolytic graphite whose purpose is to seal in the gases. The third layer is silicon carbide (SiC) whose purpose is to seal in certain fission products that are capable of diffusing through the pyrolytic graphite. The last layer is an outer coating of pyrolytic graphite. Figure 4 is a drawing of a pellet.

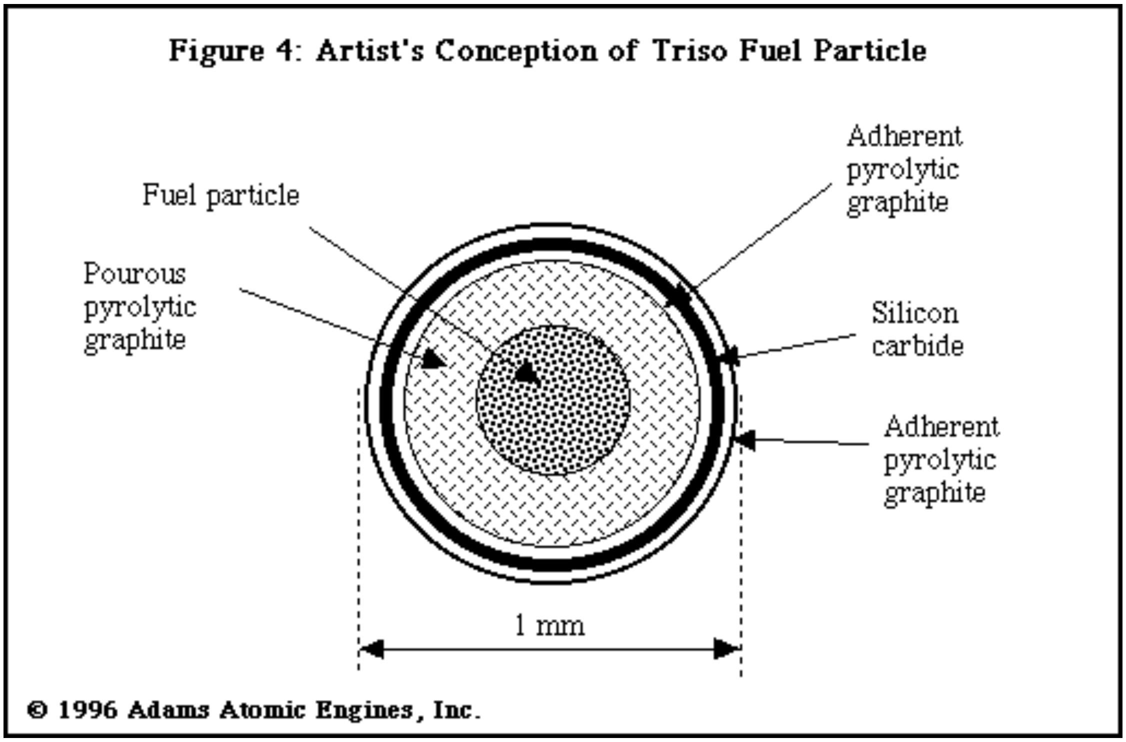


Figure 4. Artist's conception of a TRISO type particle

The governing principle behind the design of these particles is to keep fission products from being released into the coolant circuit. The operating experience at the German AVR and at Ft. St. Vrain validates the idea that fission products are retained with a high degree of certainty. The US Department of Energy's NGNP program produced improved fuel manufacturing processes and validated the design through an extensive irradiation and testing program.

This leads to a relatively clean primary circuit and allows relatively straightforward compressor and turbine maintenance. At Ft. St. Vrain, the coolant activity was less than 2% of the design limit and contributed to a typical yearly dose at the plant of less than 3 man-Rem. (Simon et. al. 1992)

The fuel particles have a long operating history, having been used since the mid 1960s. Irradiated particles have been tested at temperatures up to 2500°C. At temperatures of 1600°C and below, there is essentially no diffusion of fission products through the coating. (Schenk and Heinz 1991) At somewhat higher temperatures there are some fission products that begin to diffuse through the coatings. Accident analysis for pebble bed type reactors less than 250 MWth predicts that the cores will reach 1550°C, below the temperature of any fission product release and well below the melting point of the fuel. Melt downs are not a credible accident scenario.

The next level of assembly in pebble bed reactors is the fuel element. In the German AVR and Thorium High Temperature Reactor these elements were spheres approximately 60 mm (2.5 inches) in diameter. They were made by packing together about 30,000 TRISO particles in a graphite matrix and then surrounding them by a layer of pyrolytic graphite. The matrix and the particle free coating provided an additional barrier to prevent fission product release. (Ziermann 1986) Figure 5 is a diagram of a fuel element.

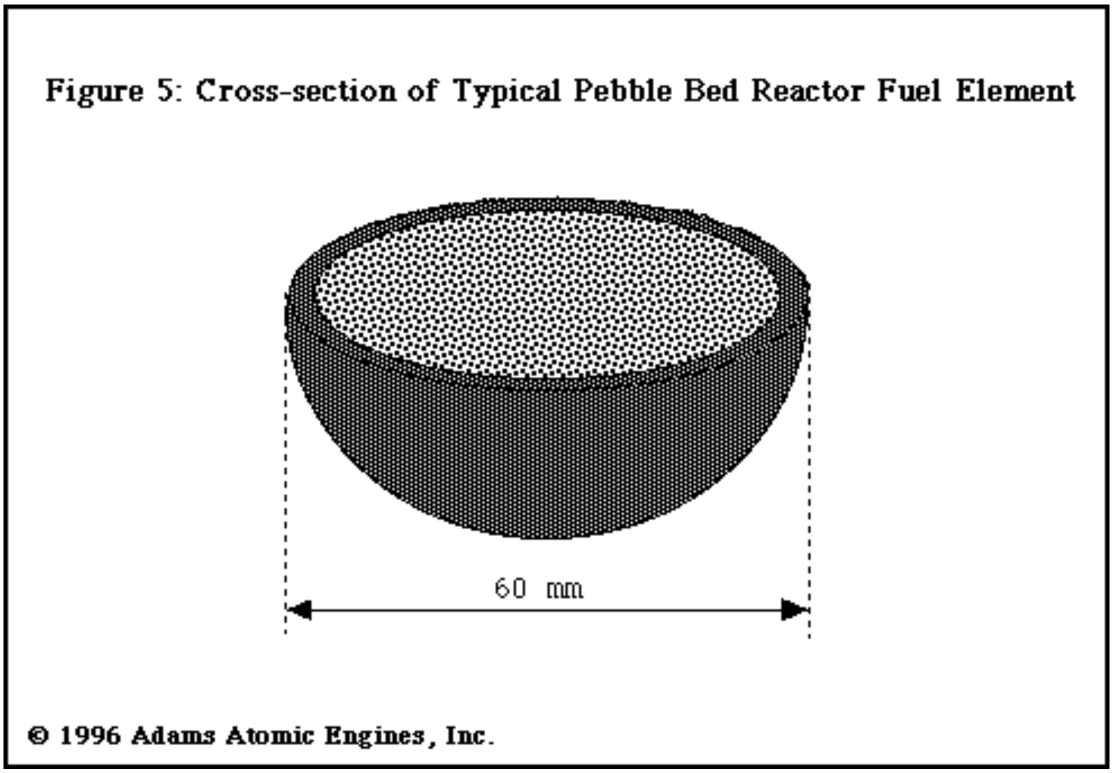


Figure 5. Artist's conception of a fuel element

The fuel elements can be made smaller to provide additional surface area for heat transfer. This will have the effect of lowering the peak temperature within each element since there will be a smaller distance between the center of the element and the heat transfer surface.

An additional advantage to the pebble bed designs is the ease with which the reactor can be scaled up or down without changing the fuel element manufacturing process or equipment. Engines can be sized to fit different markets without having to redesign the fuel or start up an entirely new production line.

Indications and Alarms

While a detailed description of the indication and alarm system is beyond the scope of this paper, it is worth noting that there are some advantages in closed cycle gas turbines over steam plants in terms of the number of different indications that are required to give a complete picture of the plant's condition. There is no need for the liquid level indicators that have caused so much consternation in conventional nuclear plants. Many post TMI regulations are not applicable to direct cycle gas turbine systems. The numbers of different components that must be monitored is vastly reduced. If a means is provided to measure the flow of the coolant, the temperatures and pressures can readily be converted to output power level in order to back up the neutron power level detectors.

Decay Heat Control

When the fission process stops in a reactor, fission product decay continues adding heat to the core region. At the instant of shutdown, the power produced in this manner is approximately 6% of the pre-shutdown power level. Because much of this heat is produced by short lived fission products, it rapidly declines to approximately 1% of the pre-shutdown power level. At this level, much of the heat is produced by longer lived isotopes.

If this heat were produced without any means of allowing it to dissipate, the temperature inside the core would continue to increase until it reached a point where the core material would melt. Most reactor concepts require some kind of convection flow to ensure that the heat is adequately dissipated. This need has added cost and complexity to existing systems.

Small pebble bed reactors have proven that they can be safely withstand the loss of all convection flow by using the heat transport mechanisms of thermal radiation and conduction. These mechanisms continue indefinitely with no operator action.

If all flow is stopped, even at 100% power, the following effects have been observed. The core temperature initially rises since the core is still producing heat while no heat is being removed. The negative temperature coefficient of reactivity shuts down the fission process. The heat production of the core drops to the decay heat power level. The core continues to heat up at a slower rate. The materials in the reflector and shield absorb some of the heat increase. At the vessel boundary, heat is radiated to the surrounding environment. As the temperature of the core boundary increases because of heating, the rate of this radiation heat loss increases. (Radiation heat loss is proportional to the difference between the fourth power of the absolute temperature of the radiating body and the fourth power of the absolute temperature of surrounding environment.)

Eventually, the rate of heat loss equals the rate of heat production and the temperature increase in the core stops. Experiments at the German AVR, the Chinese HTR-10 and computer simulations indicate that for core power levels of less than 250 MWth with power densities of about 4-6 MW/ cubic meter, the final temperature of the hottest part of the core is less than the 1600°C where the fuel particles start to show some loss in their ability to retain fission products.

The method of long term decay heat removal is to allow the core to heat up to its equilibrium temperature. Even if the core is hot, it will be possible to perform routine maintenance on the rest of the system.

Containment

Preventing fission product release is one of the basic principles of safe reactor plant operation. Defense in depth is an important design strategy. This philosophy has proven its worth and it is part of this design concept. As already described, however, the containment boundaries for this concept are less costly because they are under less severe conditions with the low pressure inert gas coolant than they would be with a high pressure water coolant.

There are several boundaries that act to prevent radioactive material release. The first boundary is the fuel particle coating. The distributed nature of these particle coatings also limits the amount of fission products that can be released if a failure in the coatings does occur.

The second boundary is the fuel-free coating surrounding each pebble. This coating is made of the same pyrolytic graphite as the coatings on the individual fuel particles and provides an additional boundary to fission product transport. Testing has shown that the graphite matrix that is used to support the particles within the fuel elements helps to reduce fission product transport since some of the fission products are absorbed by it if a particle fails. (Nabielek et al, 1990.)

The Ultra-Safe Nuclear Corporation has developed an improved fuel matrix called Fully Ceramic Microencapsulated (FCM™) that uses SiC and offers the potential of even higher gas temperatures.

The third boundary that prevents fission products from reaching the environment is the coolant piping. Even if there is a failure in the core that results in a release of fission products, unless there is a concurrent failure in the coolant piping there will be no release to the environment.

The final containment boundary is the container that excludes personnel access to the reactor equipment during operation. This boundary is a vapor barrier and it is a strong container, but it is not the large, reinforced concrete structure normally associated with reactor containments.

The structure walls might be just as thick for radiation shielding and for resistance to external influences, but it will require less expansion volume than that needed in water cooled reactors. Unlike a water reactor, there is not a large mass of high temperature liquid which can expand into a gas if it leaks out of the system. Since the nitrogen is kept at low pressures inside the coolant piping, the total mass of nitrogen that can leak out of the coolant system is small relative to the available expansion volume in the containment.

Heat Sink

The nature of the heat sink will depend on the application where the engine is used. Marine power plants will probably want to take advantage of the ocean to provide cooling. The cooler in this case will resemble a conventional condenser, probably using double tube-sheet design to prevent salt water from entering into the primary coolant system. It may be advantageous to provide an intermediate heat transfer loop between the sea and the primary system, this would also allow the use of the waste heat for space heating.

For a terrestrial power plant, water cooling may be a luxury. Since the exit temperature of the turbine is on the order of several hundred degrees Celsius, a reasonably sized air cooler can provide the necessary heat sink.

There are also the previously mentioned options of using the waste heat for area space heating, desalination, or industrial process heat.

Power Transient Description

The negative temperature coefficient allows power demand to control power output. In response to the transients imposed by altering the throttle position or varying the compressor flow rate, the reactor core responds to maintain a constant average temperature.

When increased power is required, the throttle is opened. This reduces the system's resistance to flow and allows the compressor to push more coolant through the core. The increased flow of coolant immediately increases the power that is removed from the reactor core region.

Initially, this increased power is not produced by the nuclear reaction, it is provided by the energy stored in the hot materials in the core. As the core materials give up their stored thermal energy, the core cools down. This causes the core reactivity to increase. The increased reactivity causes power to increase. When the power level that is being produced by the fission equals that being demanded by the turbine, the average temperature of the core is again stable and the reactivity is again zero.

A reduction in power is similar. The throttle is shut, the power being removed from the core is reduced. The power taken out of the core is initially less than that being produced by the nuclear reaction so the core heats up. This makes the reactivity of the core negative and slows down the reaction until the power again equals that being withdrawn from the core. Power follows gas demand. With the relatively large core mass, these temperature changes are small and gradual thus minimizing thermal stresses and leading to long component life.

These power level changes will have an effect on the reactivity caused by xenon, a neutron absorbing fission product. The xenon reactivity changes take place over a period of hours and will require some movement of the control drums to maintain temperature within the desired range. Using a wide range of operating temperatures enables response to xenon variation with minimal control drum movements.

The ability to rapidly respond to changes in power level are important in an engine designed for use as a ship power plant, but it can also be advantageous in an electric power plant designed for load following. In any electrical network, there must be some plants that are not limited to constant, baseload operation. In the past, this requirement has limited the total nuclear capacity of a system since there are few commercial designs that can be operated effectively in a load following mode.

Waste Strategy

The irradiated fuel that is removed from the reactors after a long operating time will be a complex mixture of fission products and transuranic isotopes. The same fuel element coatings that provide excellent retention of these materials in the high temperature, high radiation environment of an operating core will also retain the materials indefinitely when the fuel is removed. The volume of the materials will be extremely small in relation to the energy that they have produced. A core that can propel a tanker for 8-10 years might require 20 cubic meters of storage space.

These fuel elements should not be viewed as waste, but as valuable raw materials that can be recycled to help improve the living conditions of future generations. As such they should be carefully monitored and stored.

The core elements will be packed into an engineered, dry storage system. The fully licensed Modular Vault Dry Store built for the spent fuel from the Ft. St. Vrain High Temperature Gas Cooled Reactor might be a good choice of systems. The storage systems will be built at convenient locations close to existing transportation and emergency response resources. A port facility, perhaps in or near a city that has been involved in nuclear ship operation and maintenance, is an example of a good location.

Waste storage for a whole series of mobile reactors can be consolidated into a small number of distributed locations. The vehicle will be sent to the refueling and storage site when its core is nearly spent. The distributed sites will be able to generate some scale economies by performing the same tasks for a number of vehicle reactors with a highly trained and experienced work force.

For stationary plants, the irradiated fuel would be unloaded from the reactor, packaged into a transport container and shipped to the same storage location as used by mobile reactors.

At a later date, when the short lived fission products have decayed, the valuable transuranic elements can be recovered for use in other reactors. Creative thinkers will work to develop markets for valuable isotopes like Cs-137 and Sr-90.

Licensing Strategy

The engines will be licensed to be manufactured under 10 CFR 50 appendix M Standardization of Design: Manufacture of Nuclear Power Reactors; Construction and Operation of Nuclear Power Reactors Manufactured Pursuant to Commission License, and under 10 CFR 52 Subpart B Standard Design Certifications.

Although these two rules were put into place in part to encourage new reactor developments, regulators have paradoxically discouraged revolutionary designs and disallowed some of the safety assumptions, instead preferring to work with more conventional systems. A full scale prototype is mentioned in the regulations as a way to test the assumptions and prove their safety margins, but developers have been reluctant to take this approach. With the smallest reactor design being on the order of several hundred megawatts, prototyping and acceptance testing involves a major risk.

With a small, revolutionary engine designed to eliminate the possibility of some conventional failure modes, a prototype is a viable alternative. The small size limits the potential consequences of a test failure while the careful design limits the probability of the failure occurring. With identified markets for engines the same size as the prototype, the costs and risks of later scaling the design are eliminated.

The prototype will be a valuable demonstration and research tool. The investment in the prototype will be recovered with interest in the form of training, public confidence, innovative testing, and product marketing.

Conclusion

Adams Engines™ build on the strengths of well tested and developed technologies. They use a defense in depth strategy to ensure public protection.

The fuel designed for gas cooled reactors has been fully tested and shown to keep the coolant circuit essentially free from fission product contamination. Radiation levels in gas cooled reactors are typically lower than the levels found in water cooled reactors because of the clean coolant circuit and the lack of corrosion products.

The clean coolant circuit also reduces a major cost item and political hurdle to nuclear power acceptance by reducing the need for disposal of low level waste. Any waste generated will be dry, rather than liquid, which tends to be more difficult to handle.

The high temperature capability of the core and its ability to withstand accidents without operator action or automated safety systems make the engines well suited for operation as distributed power systems and merchant ship propulsion. The public will be protected even if the engines are operated in densely populated areas.

The reduced need for engineered safety systems allows plant construction to be simple and focused on maintaining high quality for those few components that remain. Because the plants are smaller and less complex, operators will be able to know their plant in a way that is difficult in large scale steam plants. The knowledgeable operators will be able to deliberately react to any problem based on clear, easily understood indications.

Heavy metals (uranium, plutonium, and thorium) are compact primary energy sources available in almost unlimited quantities here on earth. They offer an energy choice that eliminates much of the environmental damage done by burning fossil fuel without requiring the sacrifices that would be required in order to abandon a high energy economy. Unlike other "alternative" energy sources heavy metal fueled engines can be used where and when needed; they are not subject to the whims of weather variation.

Fuel costs for a given amount of heat have always been lower in nuclear plants than in fossil fuel plants. This was true even in the 1960s when oil cost $3.00 per barrel. The engines described above will retain the fuel cost advantage of nuclear fuel while attacking capital, operations, and maintenance costs in a way that actually improves safety margins. In summary, Adams Engines:

- Use a low pressure, single phase, chemically non active coolant.
- Use a direct heat transfer cycle that eliminates steam generators.
- Use a high temperature fuel design that eliminates the need for forced convection decay heat removal systems.
- Use a fuel design that is ready for long term dry storage.
- Use an internal shield to protect the pressure vessel from neutron damage.
- Use compressor and turbine designs that can be mass produced.
- Can be sized to fit a variety of applications.

- Can be sized to allow economical prototyping.
- Are small enough to decommission without dismantling.
- Are small enough to be produced in a factory and delivered tested and ready for power production.

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