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Research Article

Space Application of the GeNIE Hybrid^{TM} Fusion–Fission Generator

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Abstract

JWK Corporation and Global Energy Corporation (GEC) have spent the past two decades understanding and applying nuclear reactions in condensed matter with the US Navy and NASA. The Navy cooperation resulted in US Patent, 8,419,919, System and Method for Generating Particles. The use of this patent to fission uranium is described in a companion paper, Uranium Fission Using Pd/D Co-deposition. GEC is applying this technology as a non-fissile reactor core suitable for deep-space power under its second NASA Space Act Agreement. This paper discusses the need for space-based nuclear power, the alternatives, the hybrid fusion-fast-reactor and the spaceflight readiness testing facilities.

Keywords: Fast fission, Fusion, LANR, NASA, Space power

1. Overview

NASA has used solar power for 50 years and nuclear power beginning three years later. Solar powered spacecraft are generally limited to the inner Solar System out to Mars, with the exception of the 60 foot solar panel span of the JUNO Jupiter orbiter. Other than the US SNAP-10 fission reactor, each of nearly 40 missions, including New Horizons to Pluto, were powered by plutonium (^{238}Pu) radioactive thermoelectric generators (RTG). Although run for decades as seen with the now 41 years extended missions of the two Voyager spacecraft, RTGs provide less than 1 kW of electrical power (kWe). Meanwhile the Soviets flew 31 fission reactors in low-earth orbit (LEO) each producing up to 10 kWe. Unfortunately, the Kosmos-954 satellite came down over Northern Canada in 1978 and contaminated 124,000 km^2 of territory. Hence, there's reluctance to fly fissile material and non-fissile RTGs as used on the Jupiter Galileo, Saturn Cassini, Pluto New Horizons and Mars Curiosity spacecraft as well as the earlier Voyager and Pioneer Missions

Another need is to develop high Specific Impulse (Isp) propulsion exceeding chemical rocket efficiencies. Various Hall Effect and Ion Drive systems have flown using solar power. Rather than expel oxidized propellant like a chemical rocket, these systems ionize and exhaust heavy ions, like xenon. The ions can exit at 40 km/s vs. a chemical rocket maximum exhaust of 7 km/s. However, it has long been recognized that neither solar nor RTGs can provide sufficient

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power for driving larger ion engines for propelling voyages past the asteroid belt. Consequently, NASA has considered higher power fission reactors for decades including the cancelled 500 kWt (>100 kWe) Project Prometheus [1] during the mid-2000s and the current 43 kWt (10 kWe) Kilopower Program. The goal is to produce long duration, multi-kW to multi-MW reactors for planetary probes, planetary surface power and manned nuclear electric propulsion as in the movie, *The Martian* [4]. High power space nuclear reactors for thermal nuclear propulsion have also been tested but not launched.

GEC has had two Space Act Agreements with NASA. The first was a prelude to the NASA Advanced Energy Conversion Project (AEC) [2,3] under the Radioisotope Power System Program (RPS). The second GEC Space Act Agreement is to develop a space-ready, non-fissile nuclear generator using thorium. Both Space Acts have been conducted at NASA Glenn Research Center (GRC), near Cleveland, OH, and at the Plum Brook Station, 45 miles away outside Sandusky, Ohio with related work at JWK facilities in San Diego, CA and at the University of Texas, Austin, Nuclear Engineering Teaching Laboratory. GRC developed ion engines, heat pipe thermal transport, advanced Sterling Engines for power conversion and the KRUSTY fission reactor. Plum Brook provides space flight qualification facilities for both launch and space conditions. Each of these facilities provides staff, equipment and facilities for GEC to develop and test a non-fissile, deep space power generator suitable for long duration power and nuclear electric propulsion.

2. Nuclear Deep Space Power Needs

There are a mix of US RTGs (e.g. Viking, Curiosity) and solar powered (e.g. Phoenix, Spirit, Opportunity) spacecraft on the Martian surface. As has been found several times, and most recently in 2018, Martian dust reduces solar insolation and consequently solar cell output. While solar powered Opportunity eventually succumbed to a planet wide dust storm the nuclear powered Curiosity mission continued. RTG's provide both electricity and warmth through electric heaters and radioactive decay. Another consideration on Mars and our Moon is the length of night. The Martian day is 24 h and 37 min requiring batteries to cover half that time at the equator and longer at higher latitudes, as on Earth. Polar regions are particularly problematic. Worse, our Moon has a 14 day-night, negating chemical battery backup. Consequently, the Apollo lunar missions left RTG powered instruments on its surface.

But the RTG limit of <1 kWe is barely sufficient for planetary probes far from the sun. Planetary probe science packages including communications would prefer 10 kWe. Planetary power for humans requires at least 40 kWe. A nuclear electric ion drive for the Hermes (Fig. 1) requires on the order of 2–5 MWe.

Human travel beyond the Earth-Moon system will require nuclear electric propulsion if astronauts are to arrive healthy. For example, astronauts on the International Space Station in Low Earth Orbit (LEO) are subject to cosmic rays averaging 300 MeV, with GeV and TeV protons and higher Z nuclei up to iron. Solar MeV protons, spallation neutrons and nuclear fragments from interactions with the Space Station complete the dosimetry problem. Some of these particles are identified in Fig. 2 of an etched CR-39 microphotograph [5]. If sufficient power were available, nuclear electric propulsion could reduce the one way Mars trip time to 2 months [6] from several months.

3. Proposed Space-based Fission Systems

Recognizing both the need for more power for space probes and either nuclear thermal or electric propulsion, especially for manned crews, NASA began the short lived Prometheus Project in 2003. The goal was a 200+ kWe fission reactor for a proposed, unmanned, Jovian three moon encounter[a]. Rather than nuclear thermal propulsion, like the Nuclear Engine for Rocket Vehicle Application (NERVA) [7], whereby hydrogen or other gas is heated by passing

[a]Unlike the movie, *2001: A Space Odyssey,* which had a crew.

Figure 1. Hermes spacecraft [4].

through a fission core and expelled as exhaust [8], Nuclear Electric Propulsion (NEP) expels a highly ionized gas, like xenon. Most geosynchronous satellites [9] use related Hall effect thrusters for station-keeping (staying in orbit) and the asteroid encountering Deep Space 1 probe uses an ion engine [10]. All of these are solar powered.

Figure 3 shows an equivalent sized 300 kWe Nuclear Electric Power system (NEP) as compared to scale with a similar powered Solar Electric Power system (SEP) [11].The large, wing-like, solar panels are far larger than the heat dissipation panels of the NEP where both mass and volume drive launch costs. NASA revisited space nuclear

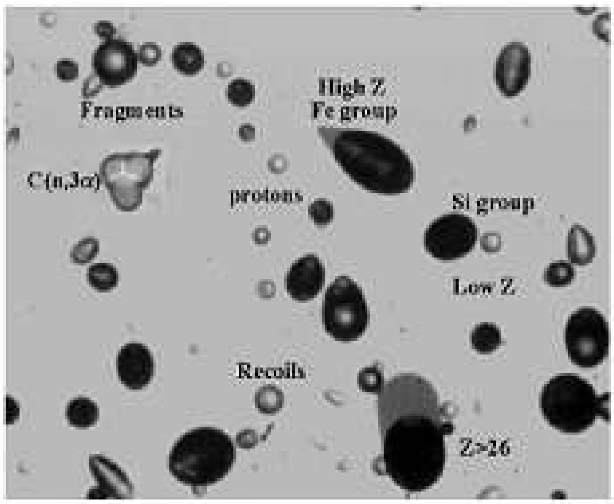


Figure 2. CR-39 particle detector .

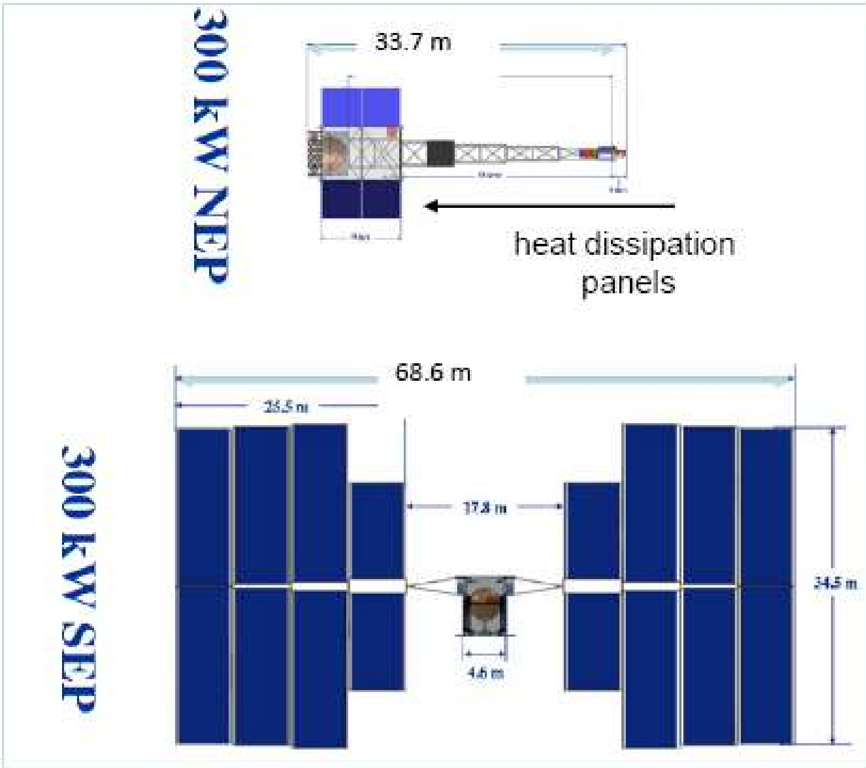


Figure 3. Size comparison.

fission reactors after completing successful tests of the Kilopower KRUSTY 93% ^{235}U reactor with heat pipes and an advanced Stirling Engine for power conversion. This was presented at the American Nuclear Society, *Nuclear Emerging Technologies for Space* conference held in Las Vegas in February, 2018 [12]. The meeting was within driving distance of the DoE NNSA site as the KRUSTY test was conducted.

The goal is to develop a 10 kWe, space-qualified system to run for a decade on our moon, or, with four units, support human activity on Mars.

GEC is able to build upon the power conversion technologies, like the Advanced Stirling Engine, and the various subsystems developed for the Kilopower Program at NASA GRC [13]. For example, Mason [11] has calculated the mass budget of a 2.5 MWe nuclear reactor shown in Table 1. The reactor occupies a small mass percentage, 13%, whereas radiation shielding, heat rejection, power conversion and power management use 87%. This is due to three factors: thermal to electric conversion efficiency, reactor radiation shielding and heat dissipation. Running at higher temperature with more efficient power conversion reduces the amount of waste heat. Direct conversion of charged particles to electricity, not easily realized with a fission reactor, would also increase efficiency.

Table 1. 2.5 MWe nuclear reactor mass budget.

Sub-system	Mass (kg)	Percent (%)
Reactor	3499	13.0
Radiation shield	6734	25.0
Power conversion	2713	10.0
Heat rejection	7930	29.4
Power management	6080	22.6
Total	2695	100.0

4. Proposed Space-based Fusion Systems

Fusion reactors on the ground or in space have problems. A 10^8°C plasma requires multi-tesla magnetic fields while an Inertial Confinement Fusion (ICF) plasma disassembles in nanoseconds. Magnetic tokamaks and Mirror Fusion reactors have been built, some with superconducting magnets, but as yet with no net power production on the ground, *let alone in space*. Furthermore, the size, operating power and mass requirements for both magnetically and inertially confined systems preclude them from being considered for space power. One of the largest fusion spacecraft, employing multiple laser "cannons" and an inertial confinement target delivery system was proposed by Orth in 2000 [14] in Fig. 4. Neither system provides sufficient thrust to launch to orbit, but would need to be ferried up piecemeal by chemical rockets.

Whereas a Mirror Fusion reactor is a solenoid holding a fusion plasma with electrostatic and magnetic mirrors on each end to contain the plasma, Chang-Diaz omitted a "mirror" *allowing the plasma to escape at high velocity.* This high current, ion propulsion system is the VASIMR, or Variable Specific Impulse (Isp) Magnetoplasma Rocket (Fig. 5) [15]. A variable Isp allows a tradeoff between delta-V and thrust. However, using VASIMR for the International Space Station (ISS) to maintain orbit requires 250 kWe. Far higher power is required for trans-lunar propulsion. Yet, this is one of the most efficient rocket engines available with a variable ion exit velocity from 3 to 120 km/s.

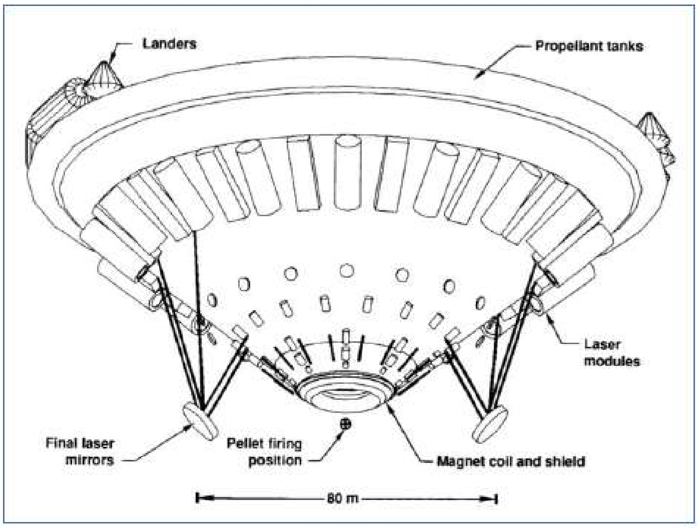


Figure 4. Laser fusion propulsion.

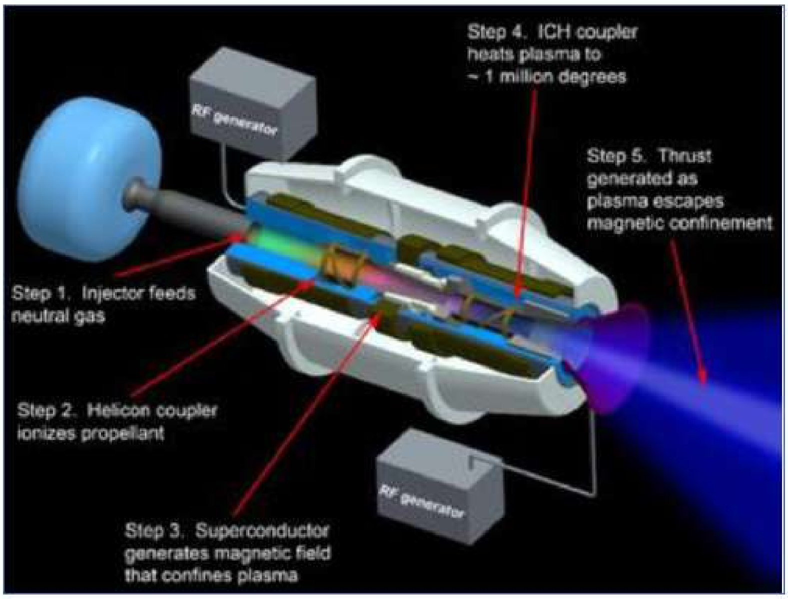


Figure 5. VASIMR propulsion.

5. Proposed Space-based Hybrid Fusion–Fission System

Hybrid Fusion–Fission systems have been considered for decades, largely because 2/3 of the deuteron-deuteron (DD) and deuteron-triton (DT) fusion energy leaves as energetic neutrons. Bethe [16] suggested a fusion hybrid in 1979 as a means to make use of the 2.5 and 14.1 MeV neutrons from the most easily ignited DT plasma. These neutrons would convert fertile isotopes to fissile, fission them, and breed additional tritium from lithium.

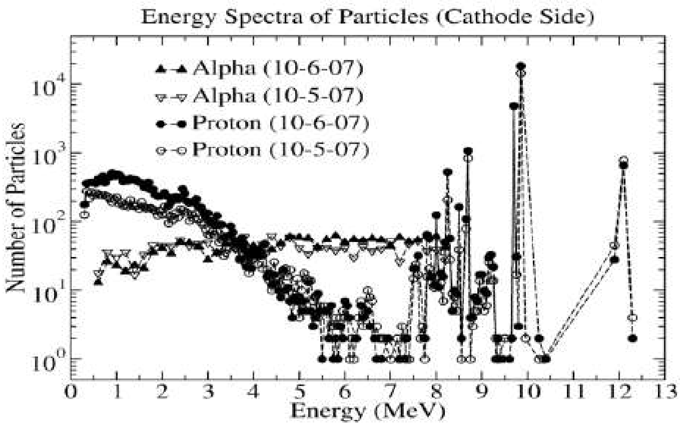


Figure 6. Pd/D Charged particle spectra 1–13 MeV [17].

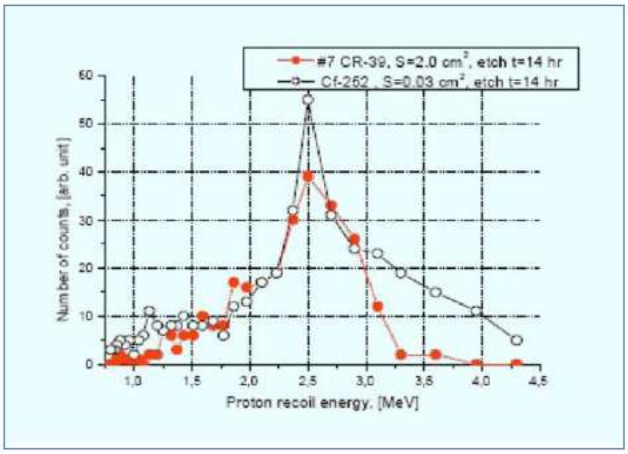


Figure 7. Pd/D Neutron spectra 1–4.5 MeV [18].

Alternatively, the patented (US 8,419,919) Pd/D co-deposition system generates a variety of fast protons, tritons, alphas (^{4}He), helion (^{3}He) [17] (Fig. 6) 2.5 MeV DD (Fig. 7) [18] and 14.1 MeV fusion neutrons [19] These energetic particles fission both natural uranium and thorium with an average neutron energy of $\approx$6.4 MeV [19]. We refer to this as the GeNIE (Green Nuclear Interstitial Energy) Hybrid$^{\mathrm{TM}}$. Given the costly safety and security restrictions on launching either a fissile uranium reactor, or an RTG running on plutonium or americium, a hybrid fusion-fast fission reactor using either natural uranium or thorium has significant advantages. However, present UN treaties [20] for space-based fission reactors specify highly enriched ^{235}U. This requirement has been under UN discussion for years.

5.1. Hybrid reactor

GEC is developing a space-rated, hybrid, fusion-fast-fission, thorium reactor. This has different, and in some ways more stringent, requirements than a terrestrial reactor. For example, it needs a mean-time-to failure exceeding 50,000 h (5.7 years), to enable most missions of interest, as repair is usually impossible [21]. Initially, it will be mated to the NASA Glenn Advanced Stirling Engine that is used with the KRUSTY reactor. This sets specific mass, volume and temperature requirements.

Like KRUSTY, the goal has been to move in steps from tens of watts to tens of kilowatts. The first Kilopower Program demonstration, DUFF, produced 24 We using a Stirling Engine with a heat pipe. These Stirling engines have a conversion efficiency of 10–30% thermal to electric depending upon the temperature difference, ΔT, between the operating temperature and the heat dump. Despite space being cold it is also a well-insulating vacuum.

The Hybrid Reactor upper temperature limit is controlled by materials. But, this has an upside. For example, the hydrided enriched uranium metal fuel rods used in General Atomic TRIGA thermal fission reactors are self-moderating with a rapid, negative temperature co-efficient. *TRIGA reactors are considered inherently safe.*

5.2. ^{238}U and ^{232}Th fission cross-sections

The following figures show the neutron [22] and proton [23] actinide fission cross-sections in barns (1 b=10^{-24} cm^2) and incident particle kinetic energy in meV (10^{-3} eV) to MeV (10^6 eV) units. Colored arrows indicate neutron and proton kinetic energies observed in condensed matter reactions estimating scattering losses through both the co-

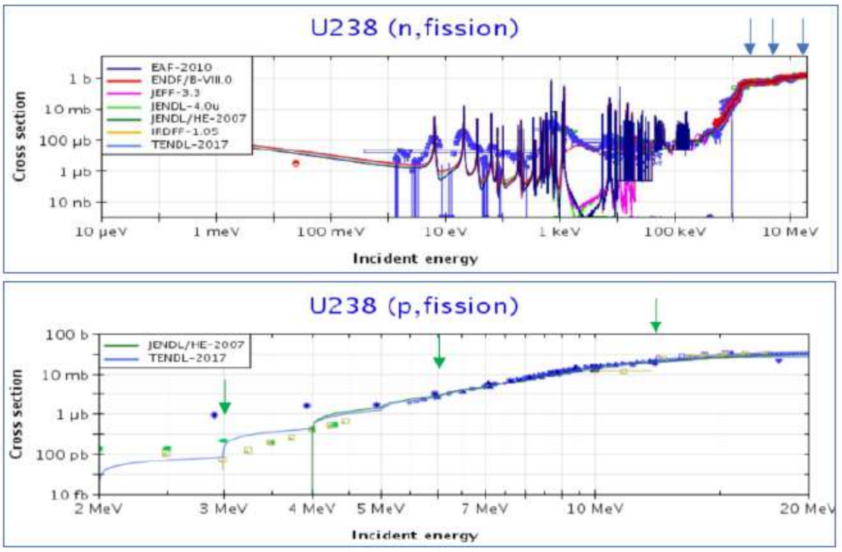


Figure 8. ^{238}U Neutron and proton fission cross-sections.

deposition layer and electrolyte between the active surface and the CR-39. Note that both the log energy and cross-section scales vary by figure. Neutral neutron interactions have a higher cross-section than charged protons due to the lack of a Coulomb Barrier. But, fast protons *will* fission actinides. What is not shown are competing reactions like capture and spallation reactions (n,n′), (n,2n), (n,p), (p,n), etc. These reactions create excited nuclei that do not directly fission.

Sustained thermal neutron fission requires >3%[b] of odd-numbered actinides, like ^{233}U, ^{235}U, and ^{239}Pu that have high thermal neutron (0.025 eV) fission cross-sections, σ_t, of 500–600 b. Most fission reactors use water or graphite to moderate, or thermalize and slow, the 1+ MeV fission neutrons to thermal energy. A fast fission reactor uses unmoderated neutrons but requires nearly 20% enrichment of the odd-numbered, fissile nuclei since the fast neutron fission cross-section, σ_f drops to ≈1 b. Fast and thermal reactors can convert, or breed, even numbered (fertile) nuclei into odd-numbered (fissile) nuclei by neutron capture. Both reactors depend upon a neutron chain reaction producing >2 neutrons/fission. Reactor criticality is maintained by a neutron economy controlling how many neutrons escape (geometry) are captured (fission poisons, control rods and breeding fissile fuel) or are delayed (fission product neutron decay).

5.3. Fusion fast fission reactions

By comparison, our Hybrid reactor is sub-critical relying upon neither fissile fuel nor a fissile chain reaction. It is a fast reactor, fissioning both fissile and fertile nuclei. The fusion-fast-fission reactor is based upon previous work described in "Investigation of Nano-nuclear Reactions in Condensed Matter: Final Report" [24] and discussed in, "Uranium Fission Using Pd/D Co-deposition" [25]. As noted, fast neutron energies of 6.3–6.83 MeV have been measured with average fluxes exceeding 10^6 n/s. The instantaneous flux exceeded this rate.

[b]CANDU reactors can use natural uranium with D_2O which has a reduced n capture cross-section compared to H_2O.

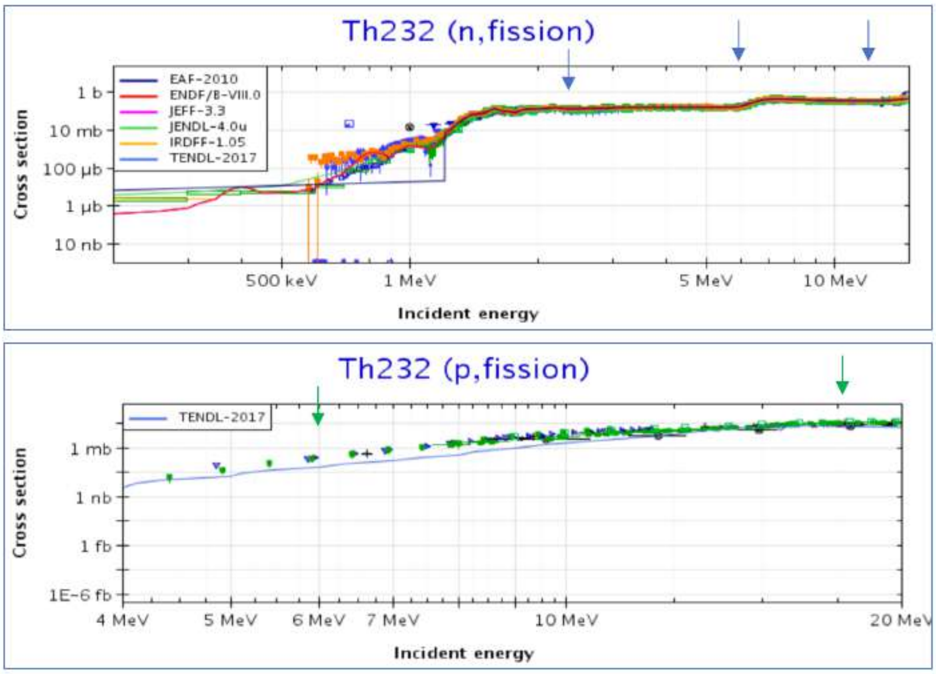
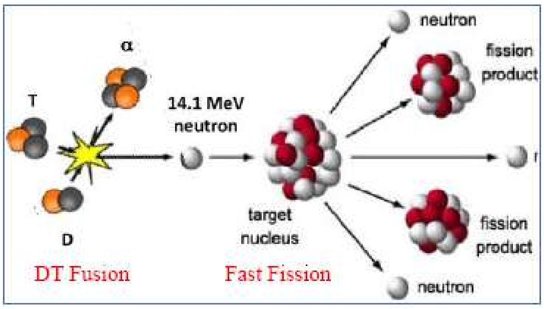


Figure 9. ^{232}Th Neutron and proton fission cross-sections.

Figures 6 and 7 show the measured charged particle and neutron energies and we have observed DT fusion 14.1 MeV neutrons [19]. Figures 8 and 9 indicate these energetic particles will fission both fertile actinides, ^{232}Th and ^{238}U with $\sigma_f \approx 100\ \mu$b - 1 b [22,23]. The higher cross-sections are comparable to the fast fission cross-sections of fissile actinides.

Conventional hot deuteron fusion reaction channels where "D" and "d" are deuterons, "n" neutron, "p" proton, "T" and "t" triton, ^{3}He or helion and α is an alpha particle, ^{4}He or helium ion:

Figure 10 shows the DT Fusion-Fast-Fission reaction. DD fusion-fast-fission is similar. *Both primary and sec-*



Reaction	Energy (MeV)	Occurrence
D(d,n)^{3}He	4.07	Primary $\approx$50%
D(d,p)T	3.25	Primary $\approx$50%
D(^{3}He,p)α	18.3	Secondary
D(t,n)α	17.6	Secondary
T(t,α)2n	11.3	Low probability
^{3}He(^{3}He,α)2p	12.86	Low probability

Figure 10. DT Fusion-fast-fission reaction.

Figure 11. NASA Calorimeter.

ondary fusion and induced fast fission reactions were generated using the patented protocol [24].

Combining the most probable primary and secondary fusion reactions result in ≈8 MeV kinetic energy in fast proton, helium and alpha particles with ≈16 MeV as neutron kinetic energy. By comparison, actinide fission produces ≈170 MeV in charged fission fragments and ≈30 MeV in gamma and neutron kinetic energies with $\approx 3 \times 10^{10}$ fissions/watt-thermal Although the fusion neutron energy drives the fission reactions the overriding thermal power is from fission products.

The NASA version of the Hybrid fusion-fast-fission reactor will be tested in a series of stages analyzing neutron flux, stability and pressurized gain with high temperature aqueous operation at <150°C and <4 bar pressure. Low energy X-ray, γ and visible light diagnostics require a 250 ml glass pressure vessel (Fig. 12). Higher temperatures, pressures and volumes require Hastelloy and stainless steel vessels. The reactor is housed in a calorimeter (Fig. 11) that was recently calibrated to 200 mW or better sensitivity with an ≈ 40 W upper limit. All of the materials, containment vessels and previous operating procedures have been subject to NASA GRC and Plum Brook Health Physics and Safety reviews as will modified experiment protocols.

5.4. Hybrid fuel rod

Our earliest hybrid fuel rod was a natural uranium wire, (99.3% ^{238}U, 0.7% ^{235}U) 0.05 cm diameter ×1 cm long, with a volume of 1.95×10^{-3} cm^3 and a mass of 38 mg. Uranium density is 19.1 g/cm^3. Our previous co-deposition research indicates nuclear reactions occur within a few microns of the surface rather than in the bulk. Consequently, the active region is <1% of the volume and mass, with a 2 μm deep surface. The active cylindrical volume is 3 ×

Figure 12. Pressure vessel.

10^{-5} cm^3 with 0.38 mg of natural uranium.

5.5. Hybrid vs. KRUSTY fission power density

Both the Hybrid and the Kilopower KRUSTY are fast fission reactors. The first Hybrid used 38 mg of 99.3% ^{238}U (0.7% ^{235}U) whereas KRUSTY used 28 kg of 93% enriched ^{235}U. KRUSTY ran 28 h and the Hybrid for 33.5 h. One thermal watt requires 3×10^{10} fissions/s. KRUSTY was producing 3 W/cm^3 or 9×10^{10} fissions/cm^3/s. The *unoptimized* Hybrid reactor produced 10^6 n/s from a volume of 3×10^{-5}cm^3 or the rough equivalent of 3.4×10^{10} fissions/cm^3/s: *or 38% of the KRUSTY power density*.

5.6. Modelling

We have experimentally measured and modeled various neutron reflector and moderator materials at the University of Texas, Austin, Nuclear Engineering Teaching Laboratory (NETL) [26], with the review of the health physicist. The experiments were conducted using electrolytic co-deposition and a Thermo-Fisher DT fusion neutron generator within a graphite neutron moderator/reflector (Fig. 14).

Both the DT fusion generator and graphite reflector were modeled using the Los Alamos Monte-Carlo N Particle (MCNP) code [27].

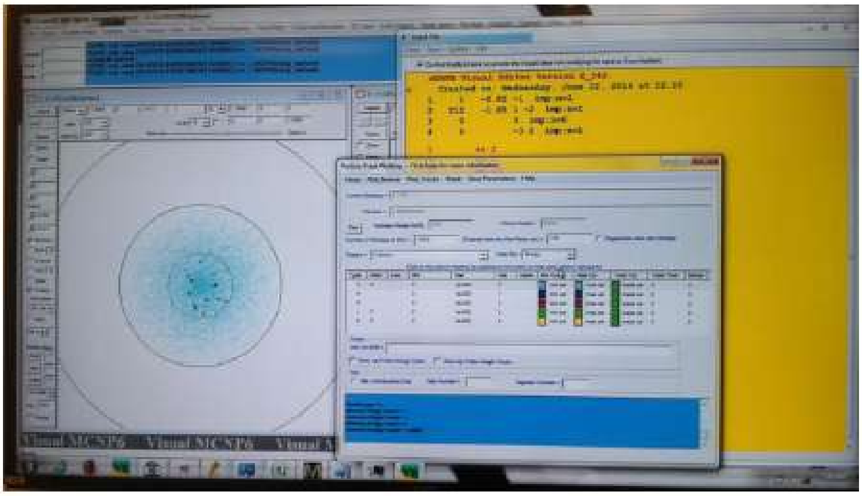


Figure 13. MCNP-6.1 Modeling with Vised Visual Editor.

Although nuclear reactions in condensed matter may appear to side step conventional physics[c] the reaction products follow the Standard Model for particle physics. Consequently, we have modeled the elastic and inelastic nuclear interaction of both neutrons and charged particles as a function of density, nuclear charge, cross-section and the resulting particle mean-free paths.

The Monte-Carlo code, MCNP-6.1 and the University of Michigan developed PoliMi code used with MCNP-2.27 have been used for neutron spectroscopy scintillator response functions. MCNP-6.1 with the visual editor, Vised, [28] was used to model bremsstrahlung triggering of deuterated materials (Fig. 13). Charged particle scattering has been modeled using SRIM/TRIM [29]. Unfortunately, SRIM/TRIM does not handle nuclear interactions and neither MCNP nor the CERN GEANT-4 [30] codes properly model low Z, low energy interactions. Hence, neither code properly models multi-keV energy hydrogen isotope fusion or its products. Previously, we used the known DD and DT fusion neutron energies to model shielding. But, MCNP-6 can be modified to incorporate a subroutine [31] developed in Italy and the UK for DD and DT fusion generators. This code handles deuteron energies between 10 and 50 keV by incorporating SRIM/TRIM scattering tables. With the addition of a screening electron shifted Gamow factor the code may model low energy nuclear reactions in condensed matter.

Nonetheless, both MCNP and GEANT4 have been used to simulate complex reactor configurations, housings, neutron shielding, detector response, as well as neutron moderation, reflection and synthetic HPGe spectra from uranium fission neutron activation and spallation products (Fig. 15). These modeling codes have been instrumental in developing the hybrid fusion-fast-fission reactor.

5.7. Diagnostics

In order to optimize hybrid reactor operation, real-time and post-run diagnostics have been used. The NASA GRC Advanced Energy Conversion Project replicated diagnostics used in JWK and GEC laboratories and developed additional

[c]Nuclear reactions in condensed matter are conventional nuclear reactions in an unconventional place assisted by electron screening and other factors.

Figure 14. Graphite neutron reflector.

ones to study LENR triggering for the NASA GRC Advanced Energy Conversion Project. The nuclear diagnostics include gamma ray, neutron, and charged particle detection as well as witness materials that can be observed via gamma rays *in situ* or counted afterwards. Gamma ray detectors include NaI(Tl), $LaBr_3$, and HPGe, one with a Be window to observe X-rays. Charged particles have been identified afterwords via alpha/beta spectroscopy or can be monitored in real-time with *in situ* fluorescers. CR-39 Solid State Nuclear Track Detectors have been used for both charged particle [32] and neutron spectroscopy [33], and scanned with a TASL 3D scanner [34]. Neutron Time-of-Flight (TOF) is conducted with EJ-200 panels and a CAEN nanosecond timing system (Fig. 16) Real-time neutron spectroscopy uses EJ-309 (Fig. 17), Bicron 501A and Stilbene proton-recoil scintillators with pulse shape discrimination (PSD) [35] These two complimentary techniques give accurate neutron energies from 400 keV to $>$15 MeV. The CERN ROOT [36] system is used for acquisition and data analysis.

6. NASA GRC Plum Brook Station

The NASA Glen Research Center, GRC, includes the Plum Brook Station located 45 miles west of Lewis Field and south of the city of Sandusky, OH, near Lake Erie (Fig. 18) The facility [37] is relatively isolated and built on land reclaimed from a World War II munitions facility. That isolation allowed over 100 live rocket engine tests with many supporting the Apollo moon program. Plum Brook Station was instrumental in developing space nuclear propulsion. The Hydrogen Heat Transfer Facility (HTTF) was built to test NERVA hydrogen exhaust nozzles at high temperature

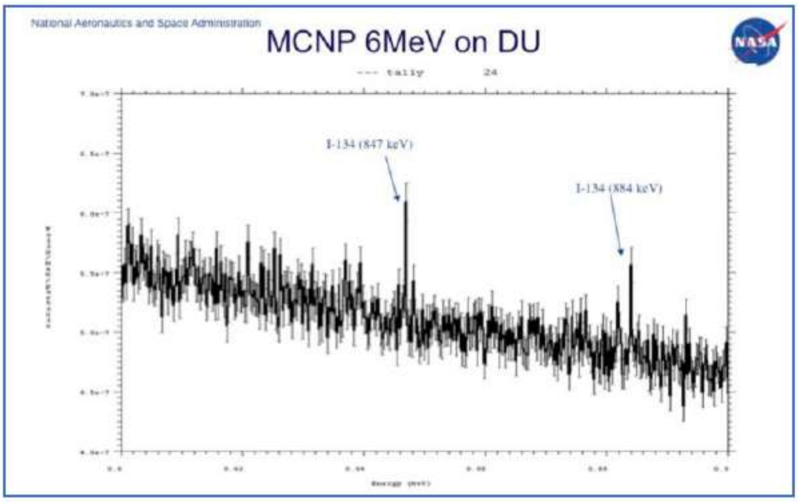


Figure 15. MCNP ^{134}I synthetic HPGe spectra from ^{238}U(γ,f).

and pressure. Later, it became the Hypersonic Test Facility, and housed the Advanced Energy Conversion Project laboratory facilities until the Chemistry/Nuclear Laboratory was setup.

A 60 MWt research reactor was built on site and operated from 1961 to 1973 to test components then fully decom-

Figure 16. AmBe neutron TOF calibration in Igloo.

Figure 17. Shielded scintillators.

missioned in the mid-2000s. Although these activities ceased by the 1970s, NASA's need for nuclear power in space, beyond RTG capabilities, for propulsion and planetary power never ceased. This was noted in a 2005 space power review [38] during Project Prometheus and again in a 2015 Johns Hopkins Applied Physics Laboratory (APL) review [39].

As Fig. 19 shows Plum Brook consists of several facilities. The Chemistry/Nuclear Laboratory (Fig. 20) has been used for test sample/vessel construction, post-operation materials assay and will be used for remote reactor operation.

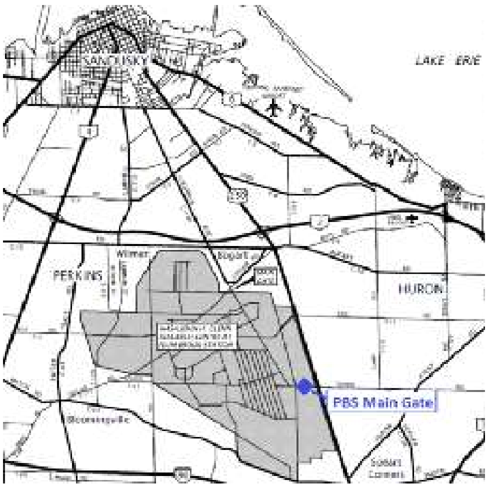


Figure 18. Plum Brook station map.

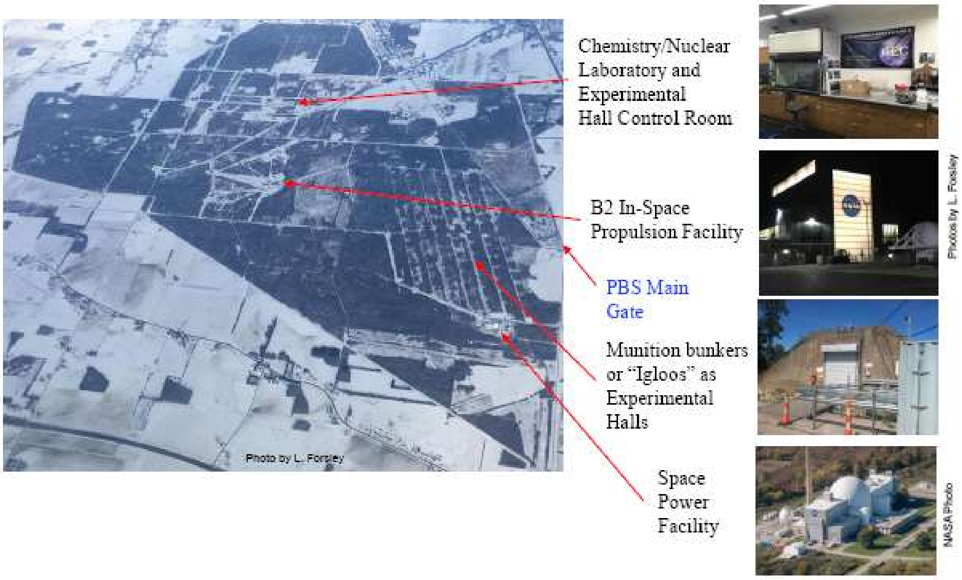


Figure 19. Plum Brook station (PBS) facilities.

Tests have been conducted in the igloos, or experimental halls. The one shown in Fig. 21 has HVAC equipment to dissipate up to 100 kW thermal heat from reactor operation. There are several other igloos available.

The B2 facility is designed for rocket launches and large scale testing under space vacuum at cryogenic temperatures with simulated full spectrum solar irradiation. Complete second stage Centaur rockets were test fired *indoors at altitude* at B2 with the exhaust plume removed. Previous rocket test stands, B1, for testing high energy rockets, and B3, for NERVA nuclear rocket components, predated the Apollo program and were decommissioned.

Figure 20. Chemistry/nuclear laboratory.

Figure 21. Igloo TOF run.

Figure 22. SPF vacuum.

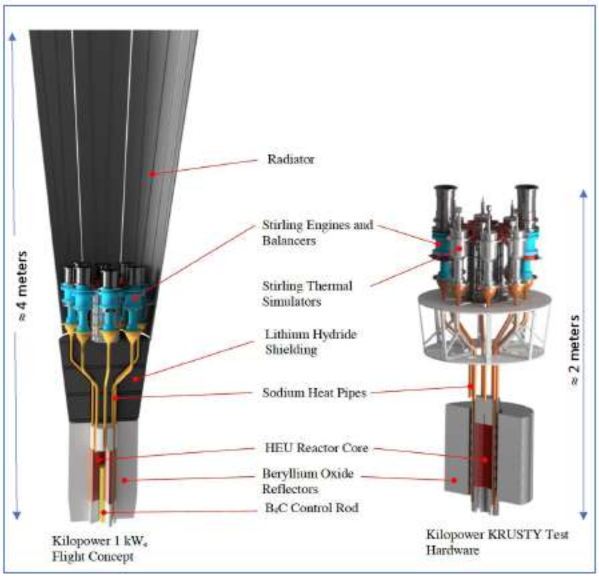


Figure 23. 1 kWe fission reactor flight concept [40]. 1 kWe hybrid generator replaces only the 93% ^{235}U HEU core and B_4C control rod.

The experimental halls, or igloos are used for scale-up and long duration testing. They are operated from a control room adjacent to the igloo or from the Chemistry/Nuclear Laboratory. Figure 21 shows borated polyethylene shielded neutron TOF panels and a lead shielded gamma ray diagnostic with fast timing data collection operating in the igloo. Video, data and control are remotely accessible over a fiber optic network to both the Chemistry/Nuclear Laboratory and the B2 Control Room.

The Space Power Facility (SPF) has the world's largest space vacuum chamber (Fig. 22) along with a shaker table and an acoustic chamber for simulating launch vibration and acoustics. SPF has been used for a variety of US and foreign spacecraft readiness testing including Space-X and ESA modules. The air bag systems used to deliver various Mars rovers were tested under Martian atmospheric pressure. Originally, the facility was designed for, but never used with, nuclear propulsion testing. B2 has a smaller, high vacuum facility, but can simulate long duration, Low Earth Orbit or Martian surface conditions including solar irradiation from UV through Infrared. Smaller space vacuum chambers are available.

7. Hybrid Space Flight Configuration

The goal of the Space Act is to develop a 1 kWe flight ready power system using Hybrid Fusion-Fast-Fission as an alternative to the highly enriched uranium core used in the KRUSTY demonstration [40]. During that test the Stirling engines' efficiency was 30–34% at 50% of Carnot at 800°C. The Hybrid reactor would use all of the power conversion, heat dissipation, and shielding sub-systems developed for the Kilopower Program with a similar form factor, mass and volume as the HEU Reactor Core shown in Fig. 23, replacing only the fissile core. Previously, the non-optimized Hybrid maintained an average nuclear fusion–fission rate/cm^3 that was 38% of the KRUSTY rate. However, since the fusion-fast-fission reactions occur near surface the power scales by surface area, not by mass. The Hybrid reactor components can be folded to occupy less volume to increase the overall fusion-fission-rate and the power output.

8. Conclusion

GEC is developing a high power space-rated generator in conjunction with NASA under an Umbrella Space Act Agreement [42]. Demonstrating a space-flight ready, 1 kWe, (5 kWt) hybrid fusion-fast-fission reactor would meet several existing NASA needs. Scaled up, it would allow deep space nuclear ion propulsion and meet manned planetary power requirements. It is fitting that the GEC Hybrid Reactor technology is being adapted for deep space power missions at Plum Brook Station given two decades of nuclear power in space research there.

The successful KRUSTY Kilopower Program demonstration [40] using highly enriched uranium showed that space-based nuclear fission power needn't be a billion dollar program as KRUSTY was built and tested for $20M. But, by removing the need to launch fissile material or plutonium heat sources, the concerns and costs for production, safety and security are drastically reduced using the GEC Hybrid Reactor. Both the KRUSTY demonstration [41] and the GEC Hybrid Reactor [13] pave the way for high power nuclear reactors in space.

If it is safe enough to launch from Florida, it is safe enough to use in Florida.

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- Dr. Kevin Wolf, *US*

Losses by Country	
Austria	1
Bahamas	1
Canada	1
France	2
India	1
Italy	8
Japan	4
Netherlands	1
Russia	9
Sweden	1
United Kingdom	2
United States	26

I have added two of the more vociferous voices who have left the playing field: Huizenga and Morrison, both of whom

I knew personally. Huizenga shut down my AMS analysis of a Pd cathode while Morrison and I discussed the wisdom of eating Wimpy hamburgers in the UK in light of Creutzfeldt-Jakob disease.

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The NASA Kilopower Program 2012 NASALANL/NNSA Demonstration Using Flattop Fission, (DUFF), experiment had *Homer Simpson's favorite beer…*

From NETS 2013 presentation, McClure LANL

…GeNIE Hybrid^{TM} has *Kilowatt*!