

Final Report for the
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“ENHANCING THE US
POWER INFRASTRUCTURE”



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¹ ProSkills is a system of teaching appropriate educational modules in normal engineering courses. As an example, students complete modules designed to develop and enhance their reading, writing, listening, and speaking skills.

1. Introduction

The primary motivation for this set of research activities was to develop a foundation in several aspects of power in order to position Cleveland State University to lead a multi-university effort to secure funding for enhanced power system projects and to be able to eventually secure a NASA Space Power Systems Center status through the competitive bidding process. This was accomplished by focusing on these major project areas, 1) the design of the next generation nuclear-electric power generation system, 2) the design of a distributed, fault-tolerant, and modular power system, and 3) the development of the dynamics and control of active magnetic bearings for flywheel energy storage without using conventional sensors.

1.1. History

The abstract from the original proposal reads:

“Cleveland State University (CSU) through the Center for Research in Electronics and Aerospace Technology (CREATE) proposes to investigate the use of novel space power systems, currently envisioned for satellites, space power stations, manned missions to the moon and Mars, etc., for their possible utilization to improve or replace existing energy systems that operate our manufacturing and aeronautics industries, and with potential application to the utility power grid as well. These technologies which have been previously investigated through the NASA-Glenn Research Center have the potential to replace the physical, and traditionally energy dependent activities with electric systems that could improve the effectiveness of our manufacturing and power delivery infrastructure.

The underlying technology is also the foundation for advancements in the fields of instruments, controls, and electronics. This inter-related field benefits from the electric research specifically in the areas of sensors and actuators; advanced motion control and robotics; and networked distributed control systems, have the potential to benefit many manufacturing and related industries.

Specifically, CSU is proposing to conduct their efforts towards the utilization of the two (2) following research concepts for use in US industries and electrical distribution systems:

- 1. Design of a distributed, fault-tolerant, and modular power system;
and**
- 2. Develop the dynamics and control of active magnetic bearings for
flywheel energy storage without using conventional sensors.**

The overriding goal of the proposed work being performed through two (2) distinct areas is to increase the reliability and efficiency of electricity generation, delivery, and use in various industries across the United States. In addition,

educational modules and processes will be developed to help train engineers to be able to work with these technologies.”

As our work progresses, we expanded activities to include three major areas instead of just the two original ones. The decision to expand grew out of successful efforts to fully understand the potential that liquid fluoride thorium reactors (LFTRs) have for US energy independence and as well as impacting US balance of payments worldwide in a very substantial manner.

1.2. The design of the next generation nuclear-electric power generation system.

The need for energy independence and economical stability can be met by the development of the next generation of nuclear power plants capable of achieving it. Molten salt thorium reactors (aka Liquid-Fluoride Thorium Reactors or LFTRs) represent one of the most promising means to this end and have the potential of doing so quickly, safely, economically, and with little environmental impact:

1. For all practical purposes, thorium is a renewable energy source since it is so abundant.
2. Nuclear reactors do not generate greenhouse gases, do not require the damming of rivers, do not cover vast areas of land with windmills, do not require dedicating vast agricultural areas to biofuel crops, do not require covering vast land areas with solar panels, and are able to provide power when it is needed.
3. LFTRs do not require any conceptual “breakthroughs” because the Oak Ridge National Laboratory demonstrated the operation of this type of reactor more than four decades ago.
4. Thorium is abundant in the earth’s crust, and the United States has enough readily available thorium to supply 100 percent of its energy needs for many millennia.
5. Many thorium deposits also contain valuable minerals, such as rare-earth elements, used in high-tech industrial processes.
6. The thorium-based fuel cycle has nuclear proliferation advantages resulting from its strong gamma emissions. This facilitates detection of stolen material and causes health problems to personnel near this material for prolonged times so that “would-be” nuclear states are less likely to use this material for weapons. Uranium-233 is equal to or superior to plutonium in some cases, therefore keeping weapons useable material out

of the hands of terrorists and rogue states would remain a concern that requires safeguards.

7. The temperature of a LFTR is self-regulating, so these reactors cannot “melt down” and are intrinsically safe.
8. LFTRs operate at a much higher temperature than conventional reactors, and therefore produce electricity more efficiently and can be used for high temperature industrial processes such as large-scale desalinization and hydrogen fuel production for fuel cells and electric vehicles.
9. The high temperature operation of LFTRs, coupled to closed Brayton cycle turbines, permit the use of much smaller turbines and heat exchangers, significantly reducing the overall physical size and construction cost of the plant compared to a conventional nuclear plant.
10. LFTRs operate at a pressure a hundred times lower than that of conventional light water reactors and are therefore safer and do not require extremely expensive concrete containment domes typically associated with nuclear plants.
11. The thorium isotope used to fuel a LFTR is hundreds of times more abundant than is the uranium isotope comprising most of the fuel used in conventional reactors. This means that fueling a LFTR would be orders of magnitude less expensive and would have much less environmental impact from mining operations.
12. The chemical reprocessing required for waste management of the liquid fuel in a LFTR is much less challenging and expensive than for solid fuels, significantly reducing the demand for long-term storage repositories such as Yucca Mountain.
13. The chemical reprocessing step also provides the opportunity to extract valuable isotopes for medical and industrial use.
14. LFTR plants can be used to convert existing nuclear waste into usable energy.

A renaissance in the nuclear power industry implemented with LFTRs will provide safe, clean, and cost-efficient power for the United States while providing energy-independence. In order to meet its future energy requirements, the USA must increase its nuclear generating capacity by a factor of sixteen. The successful development of the technology required for LFTRs will provide significant economic growth and a multitude of high tech employment opportunities in manufacturing, research, and development in the USA.

1.3. Design of a distributed, fault-tolerant, and modular power system.

The need to design reliable space power systems cannot be overemphasized. The classical approach to increase reliability by simply adding redundancy can actually result in a real decrease in reliability, as our research on power system protection has clearly shown. The components' dominant mode of failure, the power systems network architecture, and the number and location of redundant components, must be carefully considered in the early design stages. Automated failure effect analyses that provide both transient and steady-state solutions, for both repairable and non-repairable networks, yielding information on the probability, frequency, and mean duration of network failure, are essential.

Similar studies are also vital to terrestrial power networks, as they have experienced protection failures with expensive consequences to the economy. The potential for terrorist acts against this infrastructure should also be considered in these studies.

For space applications, the use of modular and distributed power systems is a natural one. However, their automatic control must also be considered for its impact on the overall system reliability.

Although terrestrial power systems due to their evolution in time do not exhibit a modular design, the interest in the incorporation of distributed energy sources to feed the power system network, also present challenges that need to be addressed.

In both instances, the proper operation of such systems will require the inclusion of intelligent, autonomous, distributed, and digitally controlled devices. We focused primarily on bringing the experience gained with space power systems to focus on power related problems in manufacturing, the aerospace industry, and the power grid in the US.

We also focused on the development of a workforce that will be able to use these new technologies. In the area of power, our workforce is aging and shrinking at an alarming rate. If a new, highly educated workforce is not developed to fill this need, both our economy and our national security will be at risk.

1.4. Development of the dynamics and control of active magnetic bearings for flywheel energy storage without using conventional sensors.

A flywheel is an ideal electromechanical energy storage device for its fast charging and discharging capabilities, high energy efficiencies, and relatively long life span. The key component of the flywheel system is a high-speed rotor which can transfer energy to and from an energy source (such as solar array). The energy content of a flywheel increases dramatically with its rotational speed. As a result, most flywheel systems are operating at high speeds (such as 60,000 rpm). The objectives of the research were to understand the operating principles of the

flywheel system, to model the flywheel system mathematically, to find the control problems associated with the system, and to obtain the control solutions to the problems in order to obtain much higher rotational speeds.

2. Design of the Next Generation Nuclear-Electrical Power Generating System

It is fairly clear that if the United States is to ever become energy independent, it must find a source of power that will meet all of its needs for the foreseeable future. A review of all the possible sources reveals that only fusion or Thorium can meet those needs. Fusion, although very promising, still looks to be not possible in the near future. Thorium, as a nuclear source, has already been demonstrated as a viable source of nuclear power able to generate electrical power easily and reliably. In addition, it is estimated that the world has enough supplies to meet all the world's energy needs for about 30,000 years. More importantly, for the US, it has the world's fourth largest supply of Thorium.

Since it is based on proven technology, then it is ready to go and the remaining problems are mostly engineering which should be able to be completed within a reasonable period of time. In addition to its many desirable attributes is the low amount of radioactive material that needs to be handled as waste byproducts and these byproducts have short half-lives as compared with today's conventional nuclear power plants. This means we will not need Yucca Mountain sized storage facilities. The temperature of the resulting nuclear reaction is also self limiting meaning that there is no likelihood of a nuclear meltdown. Finally, the most attractive feature of this source of power is that it is almost impossible to create "nuclear bombs" from it.

The task was broken into these activities:

2.1. Design of a Liquid Fluoride Nuclear Reactor (LFTR) driven electrical power system.

2.1.1. Liquid fluoride thermal loop. The molten fluoride reactor received its name because of the specific character of its fuel – a liquid constituted by molten fluoride salt mixture circulating between a reactor core and a heat exchanger. The fission material is dissolved in a molten fluoride carrier, which is both a moderator and a heat-transferring agent. The fact that the fuel is in a liquid environment allows special, highly efficient reprocessing of the fuel.

Molten fluoride reactors are a special case of molten salt reactors, which were researched beginning with the 2.5 MW(th) thermal nuclear reactor designated as the Aircraft Reactor Experiment (ARE). The research for this project was begun in the 1940s and the reactor was completed and operated for 536 hours in 1954. It demonstrated high-temperature operation (1130 K)

and established benchmarks in performance for a circulating fluoride molten salt (NaF-ZrF₄) system with the uranium dissolved in the salt (NaF-ZrF₄-UF₄) (53-41-6 mole %) moderated by beryllium oxide (BeO). The ARE was abandoned when ICBMs made it obsolete.

After this, there followed the very successful 8 MW(th) thermal nuclear reactor designated as the Molten Salt Reactor Experiment (MSRE). The fuel salt was loaded in 1965 and the reactor ran for 9,000 hours under full power before it was shut down to change to a different fuel. With the new fuel, the reactor ran over 4100 hours under full power. The fuel salt was LiF-BeF₂-ThF₄-UF₄ (64-30-5-1 mole %) moderated with graphite, and the reactor ran at 925 K.

The MSRE provided an effective demonstration of many aspects of the reactor technology. In particular, the experiment verified many of the advantages of a liquid fuel. The preliminary design of this part of the system is complete.

2.1.2. Secondary liquid fluoride thermal loop for powering gas turbines.

Although it is possible to use the above as the primary thermal source for heating the gas for the gas turbines, it is proposed to add a secondary loop with a liquid to liquid heat exchanger and to use the secondary fluoride loop to act as the primary source of thermal energy to power the gas turbines. Later experiments may prove that the secondary loop is not necessary.

2.1.3. Brayton cycle gas turbines for driving the AC generators. The choice of the power cycle to which the nuclear core is coupled to determines the efficiency, size and many other properties of the overall plant. The Brayton cycle was chosen due to its particular suitability for heat transfer mediated through the molten fluoride.

The modern Brayton helium cycle has several advantages over the Rankine steam cycle: *efficiency, freeze protection, tritium control, and chemical reactivity*. a) Efficiency is improved because the cycle can be run at a higher temperature than steam without the corrosive properties of high temperature steam. b) With a steam cycle and the lower temperatures, special design features must be used so that that feed water does not freeze the molten salt. c) Tritium is produced as a fission product that diffuses into the steam and is difficult and expensive to remove. Adoption of a Brayton cycle provides an option where the tritium is removed from the helium in a high-performance, low-cost process. d) Molten salts do not chemically react with helium.

2.2. Design of a submersible, off the shelf, LFTR driven electrical power system.

2.2.1. Construction in a vessel that can be position in the water near large population centers. Everything discussed can be applied to a conventional nuclear power plant. One of the major problems with construction in the US is that every nuclear power plant is a custom design with a hefty price tag to go along with it. It is clear that building nuclear power plants as an off the shelf item will lead to safer, more reliable, and more economical power plants. The fact that these power plants can operate at a much higher temperatures will allow smaller designs. In fact, these would be small enough at they could be constructed in submersible vessels. Since most of the population centers of the world are located with reach of different bodies of water, it makes sense that they could be built and then floated to almost anywhere they are needed. A design for this has been proposed.

2.2.2. Conversion of the AC to DC in order to distribute the power. Delivering power from a submersed power plant cannot be done using AC. Transmission and distribution need to be done with DC do to conductor spacing in the underwater cable. This problem has been thoroughly researched and a design has been prepared.

3. Design of a Distributed, Fault-Tolerant, and Modular Power System

The need to design reliable space power systems cannot be overemphasized. The classical approach to increase reliability by simply adding redundancy can actually result in a real decrease in reliability, as our research on power system protection has clearly shown. The components' dominant mode of failure, the power systems network architecture, and the number and location of redundant components, must be carefully considered in the early design stages. Automated failure effect analyses that provide both transient and steady-state solutions, for both repairable and non-repairable networks, yielding information on the probability, frequency, and mean duration of network failure, are essential.

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Although terrestrial power systems due to their evolution in time do not exhibit a modular design, the interest in the incorporation of distributed energy sources to feed the power system network, also present challenges that need to be addressed.

In both instances, the proper operation of such systems will require the inclusion of intelligent, autonomous, distributed, and digitally controlled devices. It is proposed to

bring the experience gained with space power systems to focus on power related problems in manufacturing, the aerospace industry, and the power grid in the US.

It was also proposed to focus on the development of a workforce that will be able to use these new technologies. In the area of power, our workforce is aging and shrinking at an alarming rate. If a new, highly educated workforce is not developed to fill this need, both our economy and our national security will be at risk.

This task was broken into these activities:

3.1. Knowledge capture for the design and operation of distributed, fault-tolerant, and modular power systems.

3.1.1. Knowledge Capture of Design Strategies for a DC to DC Converter, lead, Jack Redilla. At this point in time, the original objectives of this project have almost been studied and it was determined that we needed to develop an RFP to more fully complete this task. It is clear from our studies at this is very important to the future of NASA as well as electrical power generation in the US.

3.1.2. Knowledge Capturing Integrated Design Environment (KCIDE), lead, Yongjian Fu. At this point in time, the original objectives of this project have been completed.

3.2. Develop the Linking Between Terrestrial systems (US industries and electrical distribution systems) and Their Space Counterparts

3.2.1 Instrumenting the Grid – Wireless Sensor Networks, Lead Ye Zhu. At this point in time, the original objectives of this project have been completed.

3.2.2. Dynamic Allocation of Network Resources, lead, Vincenzo Liberatore. At this point in time, the original objectives of this project have been completed.

3.2.3. Graceful Degradation of Real-Time Communication, lead, Vincenzo Liberatore. At this point in time, the original objectives of this project have been completed.

3.2.4. Co-Simulation Framework, lead, Vincenzo Liberatore. At this point in time, the original objectives of this project have been completed. An exploratory simulation of distributed control of energy grid was completed along with the following: a review of the state-of-the-art in the simulation of power transmission systems (e.g., Agent/Plant, Oak Ridge approach, other), a choice of simulator (ns, modelica, ptolomy, or other), an investigation of the contents and potential usage of the trace data

collected on the Western Grid, a formulation of a co-simulation concept, possibly involving dynamic components such as monitors, a simulation and refinement of the example set-up, and a final report formulation. The simulation, simulation results, and technical documentation were delivered.

3.2.5. Instrumenting the Grid - Real Time Data Acquisition and Control, lead, George Kusic. At this point in time, the original objectives of this project have been completed.

3.2.6. Wright Center for Sensor Systems Engineering (WCSSE), lead, Charles Alexander. This center is important to the objectives of this proposal and will continue to contribute to those objectives in the future.

3.2.7. Comparison of the Fundamentals of Space and Terrestrial Power, lead, Eugenio Villaseca. At this point in time, the original objectives of this project have been completed.

3.2.8. The Status of Graduate Power Systems Education in the USA, lead, Eugenio Villaseca. At this point in time, the original objectives of this project have been completed.

3.2.9. Graduate Level Courses – Advanced Energy Conversion Systems Design I and II, lead, Charles Alexander. At this point in time, the original objectives of this project have been completed.

3.2.10. ProSkills Modules – Development, lead, James Watson. At this point in time, the original objectives of this project have been completed.

3.2.11. ProSkills Modules – Implementation, lead, James Watson. At this point in time, the original objectives of this project have been completed.

4. Develop the Dynamics and Control of Active Magnetic Bearings for Flywheel Energy Storage Without Using Conventional Sensors

A flywheel is an ideal electromechanical energy storage device for its fast charging and discharging capabilities, high energy efficiencies, and relatively long life span. The key component of the flywheel system is a high-speed rotor which can transfer energy to and from an energy source (such as solar array). The energy content of a flywheel increases dramatically with its rotational speed. As a result, most flywheel systems are operating at high speeds (such as 60,000 rpm). The objectives of the research were to understand the operating principles of the flywheel system, to model the flywheel system mathematically, to find the control problems associated with the system, and to obtain the control solutions to the problems in order to obtain much higher rotational speeds.

4.1. Dynamics and Control of Active Magnetic Bearings, lead, Lili Dong. At this point in time, the original objectives of this project have been completed.

An extensive literature review on the operating principles of the flywheel system and the control problems associated with the system has been completed. We have also completed some preliminary system modeling, and the controller designs for the rotors with time-invariant rotation speeds. The results from preliminary system modeling and controller designs are summarized in the reports, **“Dynamics and Control of Flywheel Energy Storage Systems; a Status Report,” “Report On Research for a Magnetically Levitated Energy Storage Flywheel,”** and **“Rotor Position and Vibration Control for Aerospace Flywheel Energy Storage Devices.”**

4.2. Rotor Stabilization by Application of a Three-Phase Rotating Magnetic Field, lead, Baixi Su-Alexander. At this point in time, the original objectives of this project have been completed.

5. A list of the reports which are available.

“A Report on The NEPTUNE Power System”	Rajmohan Rangarajan and Bharat Vyakaranam	8/16/2007
“Data Processing in Wireless Sensor Networks: Capabilities Assessment and White Paper for Planned Activities”	Ye Zhu	4/12/2007
“DC-DC Converter Thought Process and Design Analysis”	Jack Redilla	1/10/2008
“Design and Prototyping of High Performance Control Systems for MEMS Gyroscopes; Annual Report”	Lili Dong	11/27/2006
“Design Considerations for a 100 MWe Thorium Based Nuclear Power Plant”	Rick Rarick, Swetha Kusuru, Bharat Vyakaranam, Rajmohan Rangarajan, Edward Hilton, Baixi Su- Alexander	5/15/2007
“Engineering Specifications for Core Technology Converter”	Jack Redilla	8/13/2007
“Final Programs for Task 1 – Fast Sampling and Diagnosis”	George Kusic	8/10/2006
“Initial Programs for Task 2 – Rule-Based Self Diagnosis for Electronics Units”	George Kusic	9/8/2006
“Modular Communication Units”	Vincenzo Liberatore	4/20/2007
NSF EFRI Response, “Providing Energy From Thorium”	Charles Alexander	9/30/2010
Proposed “IEEE-USA Energy Policy Committee Position Statement on Liquid Fluoride Thorium Reactors”	Charles Alexander	9/20/2010

“Report On Research for a Magnetically Levitated Energy Storage Flywheel”	Lili Dong and Richard Rarick	8/31/2007
“Rotor Position and Vibration Control for Aerospace Flywheel Energy Storage Devices”	Baixi Su-Alexander	6/21/2007
“Rotor Stabilization by Application of a Three-Phase Rotating Magnetic Field”	William Witt	1/24/2008
“Space Power System Options and Selection Constraints”	Bharat Vyakaranam and Rajmohan Rangarajan	7/31/2007
“Space Power Systems Requirements and Issues: the Next Decade”	Bharat Vyakaranam and Rajmohan Rangarajan	8/27/2007
“Summary: An Advanced Molten Salt Reactor Using High-Temperature Reactor Technology”	Richard Rarick	4/30/2007
“Summary: Molten Salt Reactor Technology Gaps”	Richard Rarick	5/1/2007
“Summary: Preliminary Results of a Dynamic System For a Closed-Loop Brayton Cycle Coupled to a Nuclear Reactor”	Richard Rarick	4/30/2007
“The Status of Graduate Power Systems Education in the USA”	Eugenio Villaseca	12/19/2007

6. A list of the proposals which are available.

“Instrumentation and Control Development and Testing for Coupled End-to-End Reprocessing Demonstration at Oak Ridge National Laboratory,” Tom Blue, Ohio State, is the PI. DOE Idaho Operations Office submitted on 5/22/2007. Status, not funded.

“Design and Prototyping of High Performance Control Systems for MEMS Gyroscopes,” Lili Dong, Gao, Lin, and Young, funded for \$50,000 by Ohio ICE. Awarded, 1/31/2006.

“The Wright Center for Sensor Systems Engineering: Using Innovations in Instruments, Controls, and Electronics to Enhance a Sensor’s Utility,” Charles Alexander, funded by the Ohio Department of Development, on 12/15/2006, for \$73 million.