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Mu*STAR: A NEW PARADIGM FOR NUCLEAR REACTORS

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Abstract

Commercial Nuclear Reactors have been licensed for construction and operation by the US Nuclear Regulatory Commission based on ensuring that criticality accidents and accidental releases of radioactive isotopes are acceptably unlikely. The process to get these licenses is long and expensive, involving extensive calculations and demonstrations, with explicit requirements on all reactor components that cannot be changed for the several decades that the reactor operates. The process can be replaced by 1) using accelerator-driven subcritical reactors that never contain a critical mass and 2) continuously removing volatile fission products from the molten salt reactors so that any accidental releases are insignificant. Mu*STAR Nuclear Power Plants (NPP), composed of upgradable modular accelerators and reactors, can then be continuously improved using Deming's principles of Total Quality Management.

BACKGROUND

W. Edwards Deming (1900-1993) was an engineer and statistician who is often credited with turning the Japanese economy around after the second world war by providing his 14 principles [1] to companies that became global giants of technology development like Toyota and Sony. Seventy years later we see that new companies like Tesla embrace the same principles as essential to success, especially those based on technology. One of the principles, "Improve constantly and forever the system of production and service, to improve quality and productivity, and thus constantly decrease costs.…" is practically impossible to follow in the case of the nuclear energy sector that has a licensing paradigm that effectively prohibits changing anything without going back to the drawing board to redo the fundamental modelling.

The most obvious difficulties with conventional nuclear power plants (NPP) are that they are too expensive to build and to operate. Economy of scale arguments have been used to make the NPP designs larger, to reduce the licensing, operations and support personnel, and general infrastructure costs per GW-h. In this paper, we argue that a NPP based on smaller replaceable factory-built modules that operate subcritically with online fission product (FP) removal will allow Deming's "Improve constantly..." principle to be used to make the lowest possible cost of nuclear energy.

NUCLEAR ENERGY IS NEEDED NOW

The need for nuclear energy has become increasingly obvious as shown in Fig. 1, where the misperceptions of the safety of nuclear energy are explicitly confronted and the benefits for climate change made clear. Projections for new reactors to be built in the world by year 2050 are uncertain since there are many variables and even the goals are not clearly defined. However, it is likely that 200 GW of new nuclear capacity will be needed to stabilize the global temperature increase.

As described below, there is sufficient time to make tremendous advances in the technology of nuclear reactors if the development paradigm forced on the nuclear energy industry by strict regulations is changed. Starting with a relatively small modular reactor driven by modular proton accelerator and an enthused team of physicists, chemists, and engineers, the development of rapidly deployed, subcritical reactors will proceed in good time according to Deming's principles.

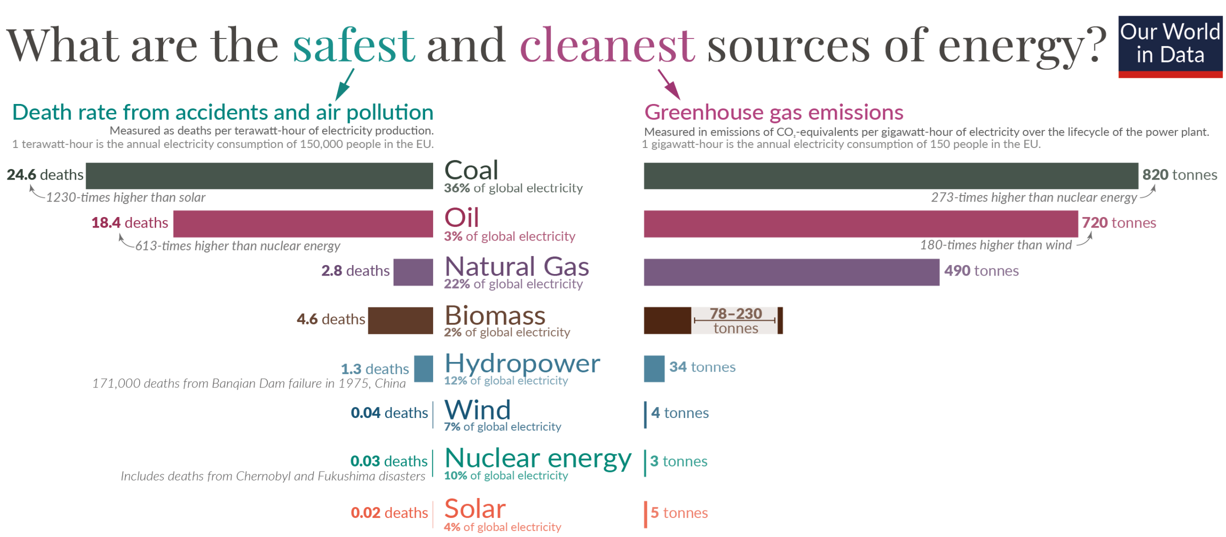

Figure 1: Comparison of safety and GHG emission for all sources of electrical energy. This Figure is taken from OurWorldInData.Org by authors Hannah Ritchie and Max Roser.

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THE NRC AND DEMING'S PRINCIPLES

In the current regulatory scheme, decades are required to certify reactor designs and components. The regulatory process is time-consuming and expensive (e. g. ~$1B for Nuscale). Furthermore, designs are cast in concrete with little ability to accommodate technological breakthroughs and innovations. Operation of a nuclear plant is expected to follow the same procedures for the succeeding 4-8 decades. This is driven by the current regulatory demands to prevent criticality accidents and accidental releasee of radioactive isotopes.

Mu*STAR with its accelerator-driven subcritical design and molten salt fuel with continuous removal of volatile radioactive isotopes addresses these accidents because:

- There is never a critical mass in the reactor.
- Volatile isotopes in the core are less than allowed by regulations for accidental releases per day.

Code of Federal Regulations part 10: a nuclear reactor is defined as "any apparatus or device in which a nuclear chain reaction can be sustained and controlled in a self-supporting or neutron multiplying medium, and which is designed or used to produce heat, power, or any other form of radiation." CFR10 Part 50, Appendix A: nuclear power plants must limit the release of radioactive materials into the environment following an accident. The limit for the release of iodine-131 is 5 curies per day. The limit for the release of cesium-137 is 15 curies per day. Online monitoring of criticality and internal isotope inventory adds robustness to the concept.

TWO EXAMPLES OF PRINCIPLE 5

Figure 2: View of Tevatron site at Fermilab showing what was effectively the world's largest microscope, able to see the smallest and most elusive objects in the universe.

In 1984, we started to develop the design of the Fermilab Tevatron superconducting magnet proton-antiproton collider (Fig. 2) and struggled very hard to find a way to get to a luminosity of 10^{30} $cm^{-2}s^{-1}$ using the most optimistic values of cross-sections and efficiencies. However, once we started to operate the equipment during commissioning, we started to see where innovations could be made. Then the improvements kept coming such that the luminosity, which is effectively the power of the microscope, increased over time to increase by a factor of over 350 (Fig. 3). This allowed the discovery of the Top Quark, which was announced in 2005. If the rules for development for the Tevatron were the same as for nuclear reactors, the improvement would have been only about 25% judging by how well reactors are able to be improved.

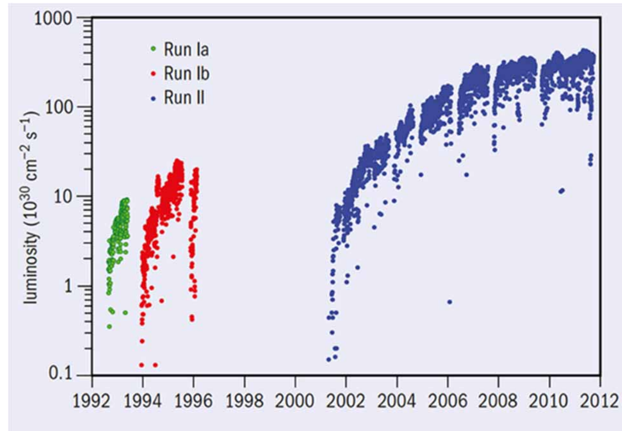

Figure 3: Tevatron 35,000% luminosity improvement in 20 years - top quark discovery/mass measurement.

Most modern technology is developed using Deming's 5th Principle. A famous example is that of Moore's law. Fig. 4, also shown as a semi log plot as on the previous figure, shows the increase of the density of circuits on a semiconductor chip. Over a remarkable span of 50 years this measure of human ingenuity increases with a doubling period of 24 months.

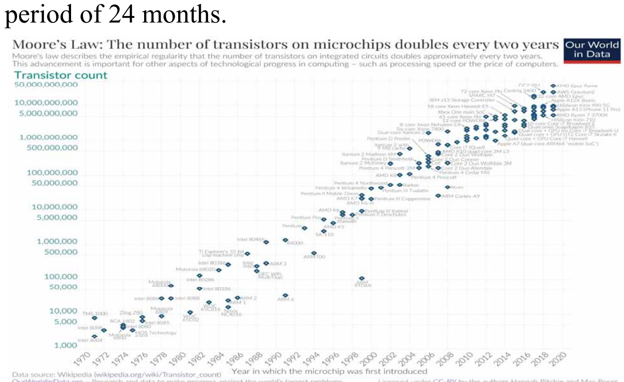

Figure 4: Moore's law showing 24 month doubling time of density of circuits on a chip – over 50 years.

MU*STAR MODULAR REACTOR UNITS

Mu*STAR (Muons Subcritical Technology Advanced Reactor) is an Accelerator Driven Molten Salt Reactor with an internal spallation target and continuous removal of fission products to consume spent nuclear fuel from past, present, and future reactors. A Mu*STAR Nuclear Power Plant (NPP) uses a superconducting (SC) proton accelerator, derived from the technology of the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) Linac, to drive several subcritical small modular reactors (SMRs). Each SMR is a graphite moderated molten salt (MS) fueled reactor, like the one studied in the Molten Salt Reactor Experiment (MSRE) [2], but with an internal

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spallation target to generate source neutrons. These source neutrons initiate fission chains that die out, producing energy in the subcritical core. The MS core remains below criticality (which depends on materials and geometry but not the beam), is always incapable of self-generated operation, and is immune to criticality accidents. The MS fuel in the core is continuously purged of volatile fission products (FPs) such that the offsite doses associated with the core volatile source term can be reduced by orders of magnitude. We believe the combination of subcriticality and the small source term will deliver deployment flexibility and regulatory simplification to enable the US nuclear energy enterprise to have a real impact on greenhouse gas (GHG) emissions.

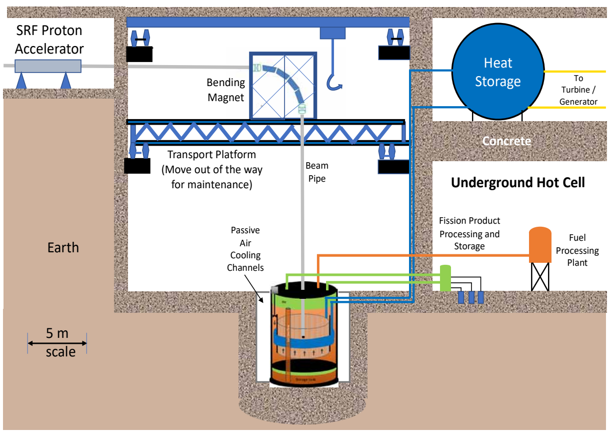

Figure 5: The underground placement of a Mu*STAR SMR, showing the proton accelerator, and hot cell for SNF oxide to fluoride conversion and fission product removal.

Muons Inc is designing a 2 GWe Nuclear Power Plant to contribute to reaching the zero carbon goals of many US states in the next two decades based on subcritical power generation. Up to 10 Mu*STAR modules would share a common accelerator source. Reliability of the single factory-built Linac is addressed by its modularity, internal redundancy, and an intermediate thermal energy storage system to cover downtimes for module repairs or replacement. The levelized cost of electricity is reduced by staged next-of-a-kind SMR factory construction and secure underground economy-of-scale-operation.

The first Mu*STAR NPP would start with a single SC Linac driving a single factory built SMR as a pilot plant on the site of an existing nuclear installation. With operational experience, SMR modules will be added along with Linac upgrades to split the beam to each SMR, on an RF bunch-by-bunch basis. This accelerator-driven, high-temperature Mu*STAR NPP design can be deployed for diverse missions including electric generation, used fuel disposition, process heat generation, hydrogen production, tritium production in support of future fusion systems, or any combination of these. The initial pilot plant is a natural place to develop these various applications and explore upgrade paths for subsequent plants. However, Muons, Inc. is focused on consuming SNF and has received a GAIN voucher grant with ORNL, SRNL, and INL to convert SNF from oxides to fluorides as used by the MSRE and Mu*STAR [3]. Figure 5 shows a conceptual illustration of a Mu*STAR system placed on location of an existing light-water reactor site. The system includes a hot cell for conversion of stored spent fuel rods into molten uranium tetrachloride salts.

REMOVING FP FROM THE MS

Side stream extraction of FP from the MS fuel, as shown in Fig. 6, will allow the actinides to remain in the fuel while many neutron poisons are continuously removed. The efficiency and speed of the extraction can be improved using centrifugal contactor/separators that were developed for PUREX.

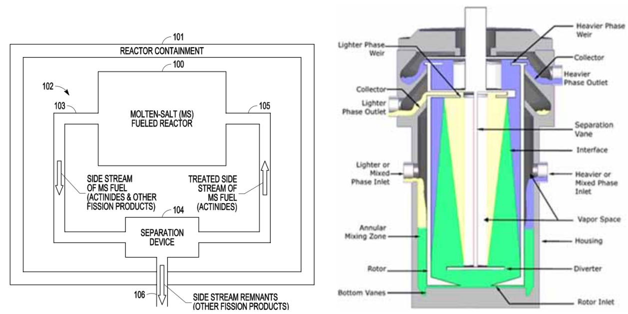

Figure 6. Concept of side stream separation of FPs (left) and Centrifugal Contactor/Separator (right).

SUMMARY/CONCLUSIONS

Summary of features of the proposed Mu*STAR NPP:

- Nuclear Energy developed using Deming's Ideas
  1) Subcritical - No Criticality Accidents
  2) Accidental Radioactive Releases - Mitigated by sparging and side stream removal.
- Decouples nuclear energy from nuclear weapons:
  1) No Uranium enrichment needed.
  2) No dedicated reprocessing facility with Pu stream.
  3) Fissile U and Pu - consumed in the reactor.
- Inexpensive Nuclear Energy - High burnup of SNF.
- Online neutron poison removal improves efficiency.
- Consumes SNF to enable other reactors - SNF becomes a valuable commodity.

REFERENCES

[1] W. Edwards Deming's 14 key principles, `https://deming.org/explore/fourteen-points/`

[2] Paul N. Haubenreich and J. R. Engel, "Experience with the Molten-Salt Reactor Experiment", *Nucl. Appl. & Tech.*, vol. 8, no. 2, pp. 118-136, Feb. 1970. `doi:10.13182/NT8-2-118`

[3] Paul Taylor *et al.*, "Mu*STAR ADSR Fuel Conversion Facility Evaluation and Cost Analysis", ORNL, Oak Ridge, United States, Rep. ORNL/TM-2018/989, Feb. 2019. `doi:10.2172/1493997`