



Emerging Technology

Novel Means of

Radioisotope Production

October, 2010

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The Problem

- **Approximately 16 million procedures involving Molybdenum-99 (Technetium-99m) (^{99}Mo ($^{99\text{m}}\text{Tc}$)) alone per year in the U.S.**
- **There is an acute shortage of fission produced medical radioisotopes in the U.S.**

The Problem (cont.)

- **The shortage is due to unreliable operation of the two reactors that produce nearly all of the U.S. supply**
 - **NRU reactor in Canada**
 - **HFR reactor in the Netherlands**
- **These reactors are very old and unreliable, and require HEU as feedstock to produce medical isotopes**

Stating the Obvious

- **Presently the U.S. has no capability to produce these radioisotopes**
- **A domestic solution is desperately needed**
- **Most proposed solutions use either old existing reactors or reactor concepts**
 - **Research reactors are all ~50 years old and not designed for isotope production**
 - **Aqueous reactors must resolve power instabilities demonstrated previously, NRC must determine licensing strategy for liquid core reactors**

Brief History of Nuclear Medicine

- **All medical radioisotopes were originally manufactured by other mechanisms**
- **By bombarding an aluminum sheet with particles emitted by polonium the Joliot-Curies created the first artificially produced radioactive element, which they called radio-phosphorus: $^{27}\text{Al}(\alpha,\text{n})^{30}\text{P}$**
- **Enrico Fermi produced a whole range of radioisotopes, including phosphorus-32 (^{32}P)**
- **Soon ^{32}P was used to treat a patient with leukemia**

Brief History of Nuclear Medicine

- In contrast to carbon-11 which has a 20 min half-life, ^{14}C has a long half-life (5770 y) thereby allowing practical exploration of metabolism with radiolabeled carbon**
- In 1940, bombardment of carbon-13 with deuterons led to discovery of carbon-14:**
 - $^{13}\text{C}(\text{d},\text{p})^{14}\text{C}$**

Brief History of Nuclear Medicine

- **Ernest O. Lawrence used his cyclotron to bombard molybdenum-98 with deuterons possibly creating element 42 (which at that time was a gap in the Periodic Table)**
- **1937 - Emilio Segrè (who later won the 1959 Nobel Prize for the discovery of the antiproton) studied a sample of Lawrence's product and confirmed it was a new element not existing in nature**
- **Because it was the result of man-made nuclear reactions he dubbed it “technetium”**
 - Doesn't exist in nature

Brief History of Nuclear Medicine

- **John Lawrence (brother of Ernest O.) developed and administered the therapeutic procedures**
- **In 1936 he treated a 28-year old leukemia patient using ^{32}P produced in one of his brother's cyclotrons**
- **It was the first time a radioisotope was used in the treatment of a disease, marking the birth of nuclear medicine.**

Brief History of Nuclear Medicine

- **It was soon discovered that the thyroid accumulated radioiodine (^{131}I)**
- **^{131}I could be used to study abnormal thyroid metabolism in patients with goiter and hyperthyroidism**
- **In patients with thyroid cancer, distant metastases were identified by scanning the whole body with the Geiger counter**

Brief History of Nuclear Medicine

- The names “radioisotope scanning” and “atomic medicine” were introduced
- All of these radioisotopes are now considered as ‘reactor-produced isotopes’
 - But none were reactor-produced at that time...

Brief History of Nuclear Medicine

- **The first commercial medical cyclotron was installed in 1941 at Washington University, St. Louis**
- **Soon there wasn't enough cyclotron capacity to meet the rising demand for isotopes**
- **Civilian use of a military nuclear reactor provided relief**
- **The Manhattan Project resulted in an unprecedented expansion of radiation research and expertise, as well as its diagnostic and therapeutic application in the new field of nuclear medicine**
- **Radioisotopes became abundant - most medical radioisotopes began to be produced in nuclear reactors during World War II**

Brief History of Nuclear Medicine

- **This was all under the secrecy of the Manhattan Project**
- **To protect this secrecy, the ^{32}P produced by the reactor had to appear as if it had been produced by a cyclotron**
- **Thus, ^{32}P was sent from Oak Ridge to the cyclotron group at the University of California at Berkeley, from where it was distributed to the medical centers(!)**

Brief History of Nuclear Medicine

- **The shortage of radioisotopes ended in 1945, when isotopes became widely available, including reactor-produced ^{131}I from Oak Ridge**
- **Globally, particle accelerators produced the vast majority of radioisotopes with medical applications until the 1950s when other countries followed the US by generating isotopes in reactors**

Means of making isotopes

- The predominant method of ^{99}Mo production (and the only method used for North American ^{99}Mo) is through fission of uranium-235
 - $^{235}\text{U}(\text{n},\text{f})^{99}\text{Mo}$
- Fission of HEU by thermal neutrons in a reactor
- The HEU is generally weapons-grade (about 95% ^{235}U) in the form of a uranium-aluminum (U-Al) alloy
 - Roughly 6% of the total fission yield is ^{99}Mo
- Few other Mo isotopes are produced, resulting in a “carrier-free,” high specific activity product
 - The specific activity is about 5000 Curies/gram (Ci/g).

Means of Making Isotopes

- **It is possible to use LEU in a reactor**
- **But requires about 5x increased neutron flux to produce the same amount due to the 5x lower abundance of ^{235}U**
- **It is hoped that this can be partially offset by development of denser U-foil targets**
- **The proportion of undesirable fission products will increase**
 - **may require modifications to the present chemical purification process and will require new FDA regulatory approvals.**

Means of Making Isotopes

- Babcock & Wilcox and others are investigating novel reactor concepts, such as liquid LEU solutions for both fuel and target
- Some have argued LEU is not a practical solution to the ^{99}Mo shortage due to the expense and political difficulty of building new reactors

Alternatives to Conventional Methods

- **A photofission process can be used with either of two reactions**
 - $^{235}\text{U}(\gamma,\text{f})\ ^{99}\text{Mo}$
 - $^{238}\text{U}(\gamma,\text{f})\ ^{99}\text{Mo}$
- **About 50% higher yield is obtained with ^{235}U**
- **For either reaction, roughly 6% of the total photofission yield is ^{99}Mo**
- **The cross section is relatively low**
- **A high electron beam power is required to make significant amounts of ^{99}Mo through these reactions**

Alternatives to Conventional Methods

- An accelerator-driven neutron source could be used for
 - $^{235}\text{U} (\text{n},\text{f}) ^{99}\text{Mo}$ or
 - $^{98}\text{Mo}(\text{n},\gamma) ^{99}\text{Mo}$

Means of Making ^{99}Mo from Non-uranium Targets

- **Neutron capture by enriched ^{98}Mo (natural molybdenum is ~24% ^{98}Mo) is the most commonly used alternative to ^{235}U fission for production of ^{99}Mo , eliminating the need for uranium targets**
 - $^{98}\text{Mo}(\text{n},\gamma) ^{99}\text{Mo}$
- **Other non-uranium approaches exist:**
- **A photoneutron (γ,n) reaction has been proposed targeting ^{100}Mo with a photon beam from a linac**
 - $^{100}\text{Mo}(\gamma,\text{n}) ^{99}\text{Mo}$

Means of Making ^{99}Mo from Non-uranium Targets

- **Another possible neutron reaction is**
 - $^{100}\text{Mo}(\text{n},2\text{n})^{99}\text{Mo}$
- **Using 14MeV neutrons on an enriched ^{100}Mo target**
- **This reaction has an order of magnitude larger cross-section than the $^{98}\text{Mo}(\text{n},\gamma)^{99}\text{Mo}$ thermal neutron capture reaction, but yields a similar low specific activity product**

Alternatives to Neutrons

- The $^{100}\text{Mo}(\text{p},\text{pn})^{99}\text{Mo}$ proton-driven reaction has been investigated by a number of researchers
 - but it (maybe) has a relatively low cross section and
 - would produce a low specific activity product
- The deuteron reaction
 - $^{100}\text{Mo}(\text{d},\text{p}2\text{n})^{99}\text{Mo}$
 - has twice the cross-section of $^{100}\text{Mo}(\text{p},\text{pn})^{99}\text{Mo}$, but requires higher energy beams

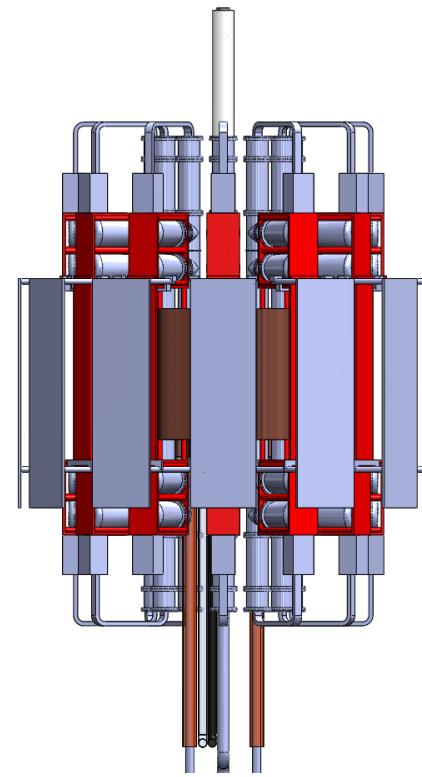
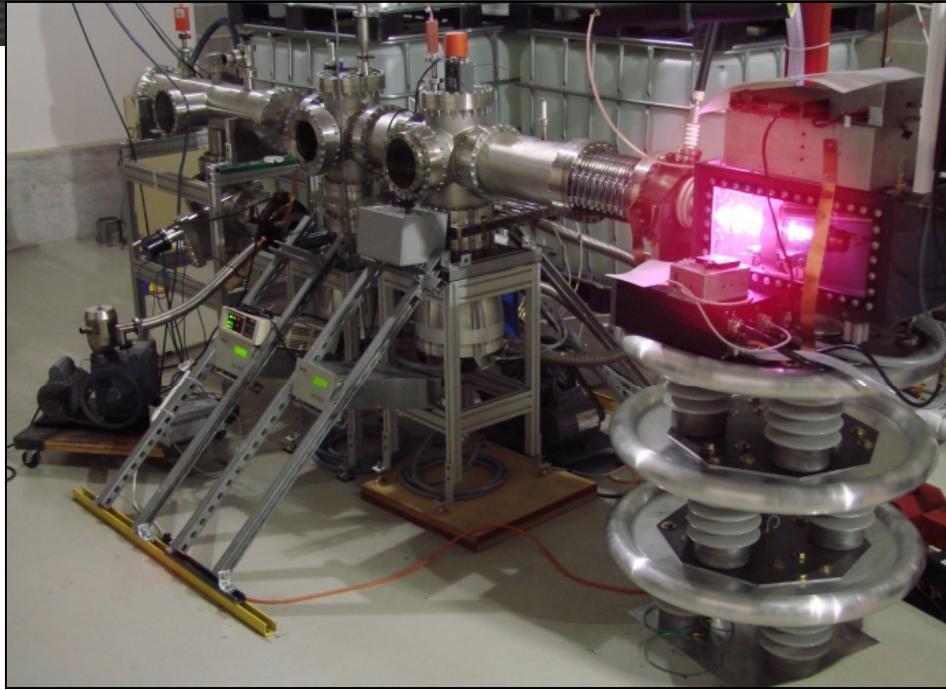
Alternatives to Neutrons

- Bombarding enriched ^{100}Mo targets with protons from a cyclotron to directly produce $^{99\text{m}}\text{Tc}$
 - $^{100}\text{Mo}(\text{p},2\text{n})^{99\text{m}}\text{Tc}$
- This direct production has a relatively large cross section in the region of 20 MeV
- This approach could possibly use regional cyclotrons to provide a local source of $^{99\text{m}}\text{Tc}$ for large metropolitan areas
- But of course is not a global or national solution



PHOENIX NUCLEAR LABS

PROVIDING NUCLEAR TECHNOLOGY FOR THE BETTERMENT OF HUMANITY



**Prepared for James Welsh and the NRC ACMUI on
September 23rd, 2010 by Dr. Gregory Piefer**

- **The Morgridge Institute for Research and Phoenix Nuclear Labs are developing a system to produce reactor grade medical isotopes without a reactor**
- **Two key aspects:**
 - **Primary neutrons created by high output deuterium-tritium (D-T) source**
 - **Neutrons enter aqueous LEU solution where they multiply subcritically and create medical isotopes**
- **This single device could possibly produce nationally relevant quantities of ^{99}Mo and other medical isotopes**

SHINE Overview

- **SHINE: Subcritical Hybrid Intense Neutron Emitter**
- **Based on smaller FLAME™ (Fusion Linear Accelerator for Medicine) technology**
 - **Creates up to 10^{15} neutrons/second (n/s) through fusion by colliding deuteron beams with a tritium gas target**
 - **Neutrons are multiplied and moderated with a combination of beryllium and water**
- **Neutrons strike uranium targets dissolved in solution**
- **Uranium targets provide further multiplication of the neutron flux, but system is operated below criticality**
- **Isotope separation made simpler by aqueous technology**

SHINE Overview

- **Deuterium gas flows into ion source, is ionized by RF or microwaves**
- **Simple DC accelerator pushes ions toward target chamber (300 keV)**
- **Accelerated deuterons strike tritium gas in target chamber, creating neutrons**
 - **Neutrons are made by reactions between deuterium and tritium atoms**
- **Proof of high efficiency and yield already demonstrated ($> 2 \times 10^9$ n/s per watt)**
- **High energy neutrons allow for (n,2n) multiplication on beryllium**
- **Only reaction products from this process are neutrons and helium-4 (${}^4\text{He}$)**

SHINE Driver Specifications

- **Physical**
 - **Consists of two ion injector / accelerator pairs discharging into a common target chamber**
 - **Structure held together with aluminum frame**
 - **Integrated beryllium multiplier ~ 1000 lbs**
 - **Total driver weight ~ 2000 lbs**
 - **Ion source, pumping power supplies, cooling systems fully integrated**
 - **High voltage delivered externally**

SHINE Driver Specifications

- **Operational**
 - **Deuteron / triton current: 100 mA**
(50 mA per injector)
 - **Beam energy: 350 keV**
 - **Beam power: 35 kW**
 - **Neutron output: 5*10¹³ n/s (14.1 MeV)**
 - **Tritium inventory: 0.015 grams (< 150 Ci)**
 - **Tritium consumption (per year): 0.007 grams**
(~ 60 Ci)
 - **Wall power (with pumping): 50 kW**

Subcritical Hybrid Intense Neutron Emitter

- **SHINE (Subcritical Hybrid Intense Neutron Emitter)**
 - **Consists of an aqueous pool of uranium nitrate or sulfate**
- **Pool driven by 12 D-T drivers**
- **Beryllium surrounding pool provides neutron reflection and multiplication**
- **Isotopes made from fission of uranium in solution**
- **Uranium concentration controlled to keep pool subcritical**
- **Solution chamber partitioned so sections may be drained on different days**

Specifications

- **Physical**
 - **Size: 7 meters long by 3.5 meter diameter**
 - **Weight: 20 tons**
 - **Materials: primarily Zircalloy, aluminum, beryllium**
- **Safety**
 - **Subcritical, criticality monitored by in-core neutron detectors**
 - **Large negative power coefficient caused by radiolysis**
 - **Neutron poisons to be added if criticality exceeds operational limits**
 - **Dump tank if reactivity exceeds safety thresholds with passive and active valves**

Specifications

- **Key parameters**
 - **Fission power: ~ 250 kW**
 - **^{99}Mo production rate: 2500 6-day kCi/week**
 - **Driver neutron production: 6×10^{14} n/s @ 14.1 MeV**
 - **Driver power consumption: 600 kW**
 - **Multiplication factor from Be: 2-3**
 - **Maximum Keff : ~ 0.95**
 - **Neutron flux: ~ 10^{13} n/cm²/s average flux in solution**

Specifications

- **Key Benefits**
 - **No criticality**
 - **No instability as demonstrated with all previous aqueous reactor systems**
 - **Inherent safety-needs to be driven to operate**
 - **Greatly reduced nuclear waste (no reactor needed)**
 - **Utilizes low enriched uranium (19.5%)**
 - **Aqueous process improves chemical extraction efficiency**
 - **Simplified regulatory approval process**

Present Status (Summer 2010)

- **Phoenix Nuclear (and the Morgridge Institutes for Research and University of Wisconsin-Madison) is seeking a DOE grant to assist with construction of SHINE production facility**
- **Several key partners secured or in negotiation**
 - **Los Alamos National Laboratory**
 - **Lawrence Berkeley National Laboratory**
 - **TechSource**
 - **MDS-Nordion**
 - **GE**
 - **Lantheus Medical Imaging**
 - **INVAP-Argentina**
- **Goal is to commercialize SHINE by Jan. 1, 2014**

Acronyms

DC – direct current

DOE – Department of Energy

HEU – Highly-enriched Uranium

HFR – High Flux Reactor

keV – kiloelectron volt

kW - kilowatt

Acronyms

Ibs - pounds

LEU – Low Enriched Uranium

mA - milliamp

MeV – megaelectron volt

NRU – National Research Universal

RF – radio frequency