Nano-to-Macro Scale Engineering Applications of Nuclear Technology-An Overview

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ABSTRACT

Nuclear science and technology offers the capability for radical industrial innovations from the nano-to-macro scales and is a field that already impacts over $600B in annual worldwide activity. Areas impacted are as diverse as medicine, industrial process control, energy, explosives, materials processing, agriculture, food preservation, sterilization, non-destructive interrogation for the molecular structure of compounds to use as tracers for transport and the tracking of fluids. This paper focuses on novel nano-macro scale peaceful applications for the oil-gas industry, for the metals industries, for enabling fundamental advances in boiling heat transfer, for induction of super compression in imploding bubbles to then lead to thermonuclear fusion and energy amplifications of over x 10^6 compared to chemical sources, to generation of nanopores in materials that may see applications such as for high-efficiency membranes for use in batteries and for dialysis, to the development of a novel class of low cost, multidisciplinary, fundamental particle detection systems.

1. INTRODUCTION

Nuclear science based technologies affect virtually all aspects of daily life. Figure 1 depicts the multitude of areas which one normally takes for granted. As noted from Fig. 1, not only does nuclear sciences impact the field of power and energy but also a vast range of areas one encounters in day-to-day activities. With the exception of nuclear explosives, the vast majority of all applications are for peaceful purposes and it is estimated to have a very significant financial footprint to the tune of ~$500B in the USA alone (Waltar, 2004). Nuclear power reactors worldwide produce about 15% of worldwide electricity, and ~20% of electricity consumed in the USA; higher in countries such as France (Nuclear Energy Institute, 2008). Nuclear power produces no greenhouse gases, and indeed, in the USA alone, contributes to over 70% of the non-greenhouse emitting source of energy with the rest taken up by other sources such as wind, hydro, solar, geothermal, etc. The vast majority of impacts from nuclear technology are related to non-power arenas such as for agriculture, propulsion, industrial process control, medicine and health, food preservation, sterilization, artifact preservations, and deep space power sources.

This paper provides a broad overview of nuclear technology applications based on over 30y research by the author, and covers areas of impact from the nano-to-macro scales; areas covered range from applications to industrial safety with possible applications also to the oil-gas industrial enterprises, to fundamental boiling heat transfer enhancements (an area of immense worldwide impact), to production of nano-to-micro pores in films, to development of long-life (10+y) batteries, to developing novel, low-cost ultrasensitive fundamental particle detection systems, and finally to induce super compression of imploding bubbles to produce ultra-high temperatures and pressures – an area of immense promise for tapping thermonuclear fusion energy, the "holy-grail" of energy independence.

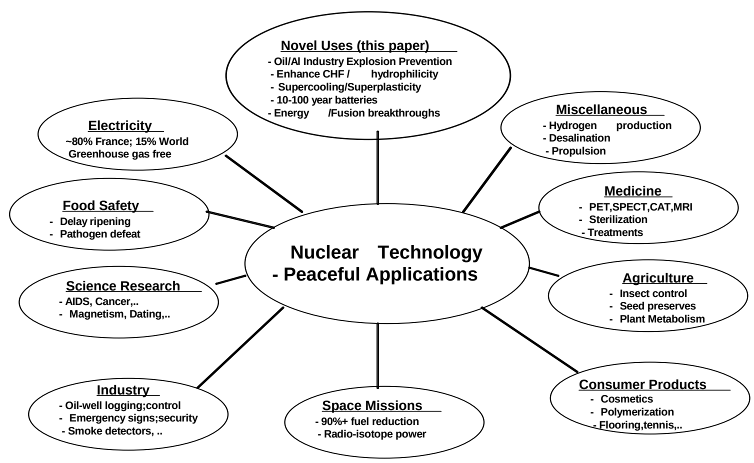


Figure 1: Wide world of peaceful applications of nuclear technology

2. NUCLEAR SCIENCES & FRONTIER ADVANCES IN NON-NUCLEAR AREAS

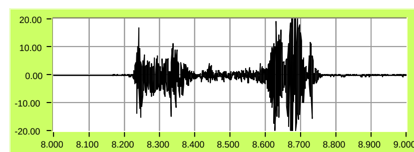
This section focuses on selected applications of nuclear technology for peaceful applications.

2.1 From Nuclear Safety Technology to Safety of Metals Casting and Natural Gas Industries

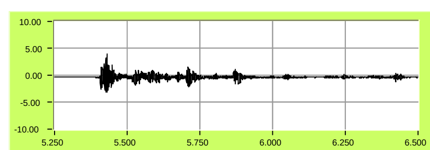
The foremost thought that arises when nuclear technology is mentioned concerns "safety." Since the 1930's, the dawn of the modern nuclear age, the nuclear industry has vigorously addressed safety with a "defense-in-depth" philosophy. As a consequence, after more than 60 years, it is with pride that one can highlight the fact that the nuclear power industry employing (non-Soviet bloc designed) reactor standards has not experienced a single fatality. This industrial safety record is un-paralled considering the world employs around 440 nuclear power reactors. This has been achieved from decades of research into risk-dominant phenomena such as energetic vapor (steam) explosions. It was a vapor explosion which led to the infamous "Chernobyl" disaster in which molten metal (fuel) explosively vaporized water leading to destructive pressure loads and dispersion of fission products to the environment. A not so well-known fact is that several such vapor explosions have occurred (Miller, 1964) in non power research and test reactors employing aluminium as a principle structural material. These events (mainly in the 1960s) gave rise to intense efforts for understanding the causes and phenomena involving molten metal interactions with water. The knowledge base was successfully developed further and applied (Taleyarkhan et al., 1994) for assessing the safety of the 85 MW High Flux Isotope Reactor, the world's most powerful reactor with a thermal power density of ~2 MW/L. The framework provides a practical platform for addressing overall system risk from vapor explosions and include aspects of fuel-water mixing, triggering, propagation, probabilistic fracture machanics, multi-material structural failure, rupture, fragmentation, shock transport and missile structure interactions and their consequences to the environment. It used sophisticated shock transport-related wave codes like CTH (McGlaun, 1990), which are now used for solving "grand-challenge" problems such as meteorite strikes on to earth or even the impact of comets on to other planets such as Jupiter.

<u>Nuclear reactor safety insights applied to solve metal-water explosions in Aluminium industry</u>

The insights drawn from research into vapor explosions for nuclear systems were called upon to resolve a major operational-safety issue facing the aluminium industry (the world's largest industrial consumer of electricity). Despite over 100 years of aluminium casting and decades of empirical-based approaches devastating metal-water vapor explosions continued (Epstein, 1995); this is especially significant when casting ~10,000 kg of aluminium in the so-called direct chill (DC) casting process. Al-Water ignition is highly energetic (~ 18 MJ/kg versus only ~ 4 MJ/kg for TNT) and therefore, 10,000 kg of molten aluminium comprises a potentially devastating explosive energy equivalent of ~ 100 T of TNT. To avoid continued injuries, along with loss of lives and infrastructure, a comprehensive multi-year cooperative research program was undertaken which included ~80% of worldwide aluminium vendors and the Oak Ridge National Laboratory (ORNL) team led by Taleyarkhan (2005) to draw insights from nuclear safety technology for deriving a fundamental understanding on what leads to onset (triggering) of energetic explosions and to evaluate the possibility of a simple, physics-based prevention method that stabilizes the interfacial vapor layer barrier which forms between the hot (molten metal) fluid and water (the cold vaporizing fluid). For studying the fundamentals governing triggering of large-scale molten Al-water vapor explosions in the laboratory, the Steam Explosion Triggering Studies (SETS) facility was set up (Taleyarkhan et al., 2005, 1997). A steam explosion event in general involves various distinct stages: mixing of hot and cold fluids during which a metastable combination of hot fluid-cold fluid is formed with an interfacial vapor layer in between, triggering of an instability that leads to hot fluid-cold fluid contact and the onset of explosive heat transfer, propagation of hot fluid disintegration, and expansion of the pressurized contents which may then lead to damaging shock waves and missiles. If triggering of the explosive heat transfer process can be prevented, then an explosion will not occur. The SETS facility allows separating of the crucial phase of triggering from the following destructive phases. This multi-year industry-laboratory collaboration gave rise to several findings, but also confirmed an important revelation from nuclear safety-based studies with molten metal drops (Taleyarkhan, 2005) that non-condensable gases (NCGs) such as air, when judiciously introduced into the interfacial vapor regions of the hot fluid-cold fluid interfaces results in sufficiently enhanced system stability for explosion prevention. Figure 2 presents evidence of representative shock traces for the cases with and without NCGs; the ameliorating effect is pronounced and obvious. Whereas, without NCGs the explosive entrapment boiling shock loads are in the range of +/- 40 *g*'s, with NCGs the shock loads are lowered by over 1000% to those for normal quench-based boiling. This simple insight was engineered into a patented method for use in worldwide aluminium DC casting sites (Taleyarkhan, 1996).



(No NCGs)



(with NCGs)

Figure 2: Shock traces without NCGs and with NCGs in SETS facility– vertical scale represents accelerometer readings in # *g*'s; horizontal scale is in seconds (Taleyarkhan, 2005)

<u>Nuclear safety insights for the Liquid Natural Gas (LNG) industry</u>

Similar to the nuclear and worldwide metal casting industries, vapor explosions are also of concern in the LNG industry where they are referred to as rapid phase transitions (RPTs). Interestingly, (for LNG-water) RPTs ordinary water even at only ~ 300 K is the "hot" fluid which transfers energy to the relatively cold ~ 111 K LNG. LNG RPT events may pose undesirable consequences such as damage to the thin storage tank walls, fires and the potential for causing injuries (Hightower et al., 2004). The RPT work potential is only ~ 50 kJ/kg (Melham, 2006) but since LNG is transported in ~25,000 m^3 tanks, the total available (non-chemical) energy per tank is high (~ 10^6 MJ); like the Al industry, over several decades the LNG industry has also conducted small scale (Enger, 1972) and large scale tests (e.g., Morgan et al., 1984). Unfortunately, just as was the case for the Al-industry, the LNG industry has largely relied on heuristics or empiricism with no mechanistic framework available for understanding the various stages of RPTs. Applying insights and findings from studies in the nuclear technology field, it is shown (Taleyarkhan, 2009) that the puzzling features observed in small scale and large scale tests in the LNG field can be convincingly explained. Applying methodologies developed for nuclear reactor safety [Taleyarkhan and Lahey, 1985; Matsumura et al., 1996] a mechanistic framework is readily developed for LNG-water RPT triggering studies which results in a multi-parameter stability map as seen from Fig. 3. Fig. 3 reveals that the non-explosive hot fluid-cold fluid temperature regime can be significantly enhanced by varying the value of interfacial vapor layer's condensation heat transfer coefficient (h), which furthermore, is strongly influenced by the concentration of NCGs. This potentially offers the oil-gas industry with a physics-based, simple, prevention methodology – similar to that done for the Al industry.

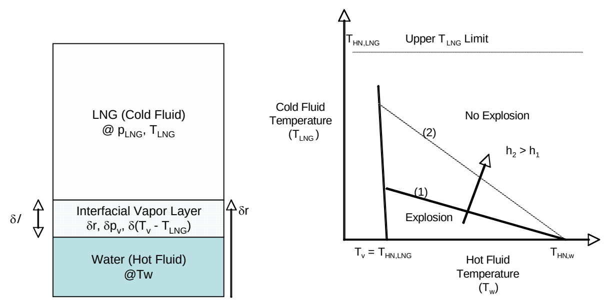


Figure 3: Mechanistic RPT model and stability map for explosion triggering.

2.2 Supercooled (> 10^4 K/s) nano-micron scale powder production

A unique spinoff of nuclear safety technology involving vapor explosions between molten materials and water involves supercooling. In retrospect, it is obvious that the end product of a molten metal-water vapor explosion includes fragmented metallic debris. High speed imaging has provided evidence of breakup to cooldown of molten metals within the ms range, which implies supercooling and nano-micron size particulates, essentially supercooled nanometer range powders. Supercooling provides for an amorphous like body which leads to enhanced ductility and superplasticity (Patankar, 1998) allowing >100 % structural strain-something of immense value in demanding industries such as aerospace. Ordinarily, supercooled powder production is a highly expensive, laborious process. Fig. 5 depicts the overall ease and simplicity with which one may induce spontaneous vapor explosions by choosing hot and cold fluid operation to remain within the "naturally" explosion onset regime of Fig. 4 – thereby, resulting in supercooled powders. This technique appears to embody good potential for impacting the world of materials sciences – *a vivid example of transforming what is a severe danger for nuclear, metals, and gas industries, to opportunity elsewhere*.

2.3 Enhancement of boiling heat transfer and hydrophilicity via irradiation

Some of the most wide-ranging phenomena utilized in every-day life involves hydrophilicity and the boiling of water at hot surfaces. This aspect governs the safety limits and consequently, the power output of water-cooled nuclear reactors; for a 1,000 MWe plant, even 1% enhancement implies power generation availability for an additional 10,000 homes (based on per capita electricity consumption in the USA). Enhancement of boiling heat flux for a given system has enormous significance and implications on economics and safety of operations (including that of nuclear reactors). Radiation treatment of solid surfaces appears to provide such a means as has been noted lately in several nuclear safety-motivated studies (Honjo, 2008) wherein gamma radiation has been shown to improve surface hydrophilicity and enhancement of critical heat flux (CHF) by an impressive ~ 10%, as well as delaying the onset of the well-known Leidenfrost point of the boiling curve – thereby, fundamentally impacting quenching characteristics of hot metals. This field is rapidly evolving with significant potential for application elsewhere. The presentation will cover recent results of examinations by various investigators including frontier studies conducted by the author's group at Purdue university involving irradiations with not only gamma photons but with other fundamental particles.

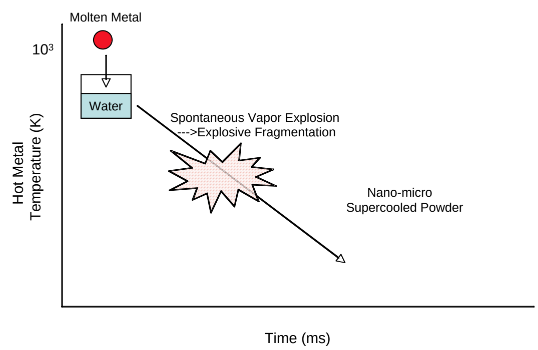


Figure 4. Nano-micron scale supercooled powder production using spontaneous molten metal-water explosions (e.g., 10g Sn at ~1100 K dropped into water bath at ~310 K); Cooling rates estimated to be in range of ~10^5 K/s to 10^6 K/s.

2.4 Nuclear technology for femto-to-macro pore production

Many everyday situations require generation of pores in structures, e.g., for membranes used for kidney dialysis or in common batteries. A fundamental property of nuclear particles involves ionization which may be gainfully employed for pore production. For example, neutron impingment on to a plastic film will give rise to recoil charged protons. Proton tracks lead to pits in the plastic. The wavelength of a fast (MeV) neutron and proton is in the femtometer (10^{-15} m) range and the track length of the recoil ion can range to the several tens of microns. The same film after radiation treatment may now be chemically etched to produce a pattern of pits (holes). Depending on the initial thickness, and composition of the film in combination with the intensity, energy and type of the incident radiation source, one may now tailor the depth, size and degree of porosity of the film – thereby, presenting the practioner with immense flexibility for production of femto-pore to mili-pore films. The track length (the distance over which ions deposit their energy) is readily estimated from the well-known *Bethe-Bloche* formulation.

2.5 Real-time, Non-Destructive Examination and Ultra-Precision Tracking

While active (e.g., offline sampling) investigation of systems (e.g., baggage at airports, or an LNG tank for it's constituents such as CH_4, or C_2H_6 and other contaminants) can be conducted, it is far more desirable to have a sensor that can perform the task in a non-intrusive manner. It is furthermore, useful if the sensor system can perform online, real-time interrogation and evaluate not merely the overall presence, but also to identify the specific molecular species which determines a specific compound (e.g., methane versus hexane; alternately, TNT versus polysterene). Pulsed Fast Neutron Activation Analysis (PFNAA) offers such a unique capability in which neutrons interacting with the nuclei (not electrons) of individual atoms of elements give rise to signature pulses of photons (i.e., gamma rays – which are like X-rays) as shown in Table 1.

Table 3. Key elemental signatures & features for different applications of PFNAA

Material	Key elemental features	Usable neutron-based reactions	Available gamma photon signatures
LNG, Oil, Drugs (e.g., Cocaine/ Heroin)	Relatively high C Relatively high H Relatively low O Low-medium Cl	(n,n') (n_{th},γ) (n,n') (n_{th},γ) & (n,n')	4.43 MeV 2.223 MeV 6.13 MeV 6.11 MeV and other strong Cl lines
Minerals Cement	Ca, Si, Fe, Al, Mg	(n_{th},γ)	Capture gamma photons (e.g., 6.42 MeV for Ca, 4.934 MeV for Si, 7.63/46 MeV for Fe)
Explosives/ Contraband	Relatively high O Relatively high N Relatively low C Relatively low H	(n,n') (n_{th},γ) & (n,n') (n,n') (n_{th},γ)	6.13 MeV 10.8, 5.11, 2.31, 1.64 MeV 4.43 MeV 2.223 MeV

This makes a neutron-based interrogation technique unique when compared for example with use of X-rays, gamma rays or electron beam guns which only provide density-based images. PNFAA is used widely [Sanchez et al (2005); Taleyarkhan (2004); Miller (1998), Womble et al (1995)] and with 90%+ intrinsically efficient tension metastable fluid based detection systems discussed later in this paper [Lapinskas et al. (2008), Smagacz et al. (2006), Taleyarkhan et al. (2008);] promise to permit frontier interrogation systems for various industries, including that for the Oil and LNG industry.

<u>Ultra-Sensitive tracking/tracing systems:</u> LNG and oil are mainly composed of C and H atoms, and as a consequence appear uniquely suited for tracking with chemically similar radionuclides ^{14}C and tritium (^{3}H), both isotopes of carbon and hydrogen, respectively. Specifically, ^{3}H (chemically similar to ^{1}H) with a half-life of ~12 y appears uniquely suited for the task of tracking in real time the progression of LNG streams, as well as for uniquely tagging various inventories from source to destination in a safe, economical and cost-effective manner with unparalled accuracy. As an example, liquid-scintillation spectroscopy can be readily utilized to monitor tritium (the lowest energy beta emitter, E_{avg} ~ 6 keV) to < 1 disintegration per minute per gram of liquid. To put this in perspective, to tag and monitor 1g of LNG in close to real time, would theoretically require the use of only ~ 10^{-17}g of ^{3}H. A 100 Ton load would need ~ 10^{-9} g (or nanogram quantities) of ^{3}H at a cost of ~ $50 for ^{3}H. The ^{3}H quantities are far below amounts used widely in industry (e.g., for airport runway lights or emergency lights in airplanes); radiological levels are millions of times lower than that already received to individuals each year from natural causes alone. ^{3}H appears better suited for LNG applications versus use of ^{14}C from cost, ease of use and other physical considerations. The accuracy for on-line detection appears unparalleled compared with other tagging-tracking methods. Simple adaptations tailored specifically to decipher trace levels of ^{3}H appear feasible to implement for portable use.

2.6 "Life-long" batteries – powered by beta voltaic technology

The need for reliable, safe, economic power sources of various scales of power and size with continuous service lives of over 10-100 years has a multitude of applications (e.g., life support systems like pace-makers, hearing aids, deep space missions). Among the various options that are viable, the option based on beta-alpha-gamma (radioisotope) voltaic cells offers key benefits as depicted graphically in Figure 7. As seen therein, compared with other available options, for long-life, high specific power, mission critical performance, the radioisotope based battery technologies offer unmatched performance potential with several orders of magnitude improved capabilities.

Conventional batteries are dramatically affected by environmental conditions, chiefly temperature. However, due to the early-stage of development there are certain research and development (R&D) remaining to be addressed mainly in relation to optimal configurations, optimal conversion efficiency of beta ray energy from isotopes with chosen semi-conductor types, safety, isotope availability and longevity of materials in radioactive environment. Although promising, beta-alpha-gamma voltaic direct conversion technology is relatively young and mission-based needs must be accounted for in terms of optimal combination of parameters related to mission duration, longevity, performance degradation, safety during all stages of the product life-cycle, reliability, production / availability of needed isotopes for mission-specific applications, efficiency based on choice of the precise isotope or isotopes in combination with selected semi-conductors, etc. Beta-voltaic technology is not mature and still needs R&D for arriving at targeted prototype development for field trials. However, the promise potential is immense, primarily due to recent advances in a combination of areas related to: (1) isotope production and potential availability at reasonable cost; (2) significant advances in novel radiation-hard semi-conductor chips that can be micro-to-nano-fabricated; and, (3) leap-ahead advances in intrinsic conversion efficiencies; as also from significant advances in photo-voltaic technology.

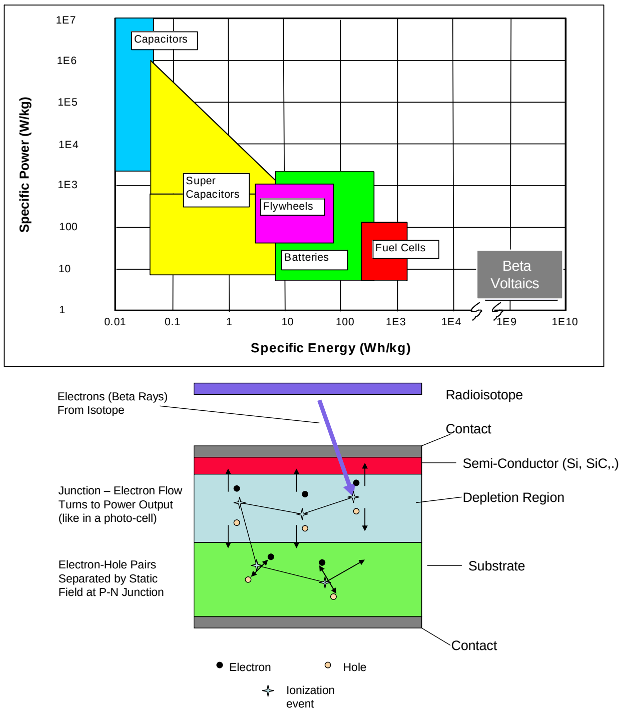


Figure 5.Comparison of various power sources and beta voltaic operational principles.

A betavoltaic power cell is a essentially semiconductor p-n junction diode analogous in principle to a photovoltaic or solar cell. In a photovoltaic cell electrons are produced indirectly via the photoelectric effect when photons interact with targeted atoms. In an enclosed (e.g., pacemaker) environments the photocell does not work. However, the betavoltaic is specifically designed to convert energy directly from beta particles from the included nuclide material rather than photons. Beta particles are electrons that result from the nuclear decay of certain radioisotopes which provide the means to produce electricity in the convertor. Also, unlike the ~ 1 eV energy level of visible photons used for photovoltaic cells, beta energies from isotopes are in the 10^5 – 10^6 eV range, and thus can provide unsurpassed higher-energy densities for application in confined quarters. The principle of operation of the beta-voltaic converter is illustrated in Figure 7. Beta particles that impinge upon the betavoltaic converter travel through the device, constantly losing energy. A portion of each beta particle's kinetic energy is lost to the lattice, but a portion is also used to create electron-hole pairs (EHPs) all along its path. A very high percentage of EHPs created in or near the depletion region of the p-n junction will be collected as generation current at the contact terminals of the device. This current is the manifestation of the energy conversion process. The voltage of the device is a function of this generation current and other parameters which are related to the semiconductor bandgap and the p & n doping levels. Power delivered by the device is current times voltage and varies as a function of load resistance. The theoretical conversion efficiency of a betavoltaic increases sub-linearly with increasing semiconductor bandgap. The direct-conversion technology results in a number of advantages over conventional power sources: Long-lived power: Continuous current is produced during the entire decay period of the radioisotope source. The use of isotope sources with half-lives that range from years to decades allows continuous power production for similar periods. Examples include ^{204}Tl ,^{85}Kr , ^{90}Sr, ^{147}Pm and 3h with half-lives of 3.8y, 10.8y, 28.8y, 2.6y and 12.3y, respectively. Recent advances in efficiency of conversion to > 10% as well as materials degradation with ^{247}Pm type isotopes and related studies using ^{3}H at Purdue University will be discussed at the conference.

2.7 Novel, ultra-sensitive tension metastable fluid nuclear particle detection systems

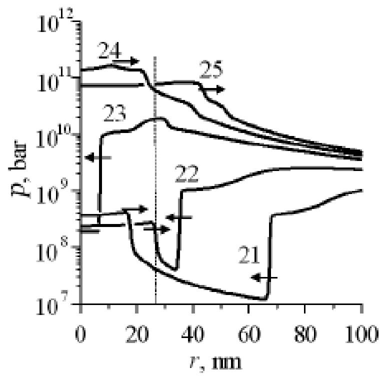
Nuclear particle detection impacts medicine to food preservation to space travel. The field detection of nuclear particles (neutrons, alphas, gamma photons) has remain largely unchanged for over 60 years. Although quite impressive, the systems developed to date have relied mainly on detection either via charge collection from ionization in gases or solids, or monitoring of light pulses from ion interactions with scintillating materials, and to a limited extent from direct ion tracks in solids. However, present day systems have evolved to be situation-specific (e.g., one would use He-filled detectors for thermal neutrons and liquid scintillation systems for fast neutrons – during which the issue of gamma interference becomes important and can significantly reduce the net intrinsic detection efficiency). Recently, Taleyarkhan et a. (2008), Lapinskas et al. (2008), Smagacz et al. (2006), have utilized liquids in tensioned (sub-zero liquid) pressures to develop and qualify a new class of ultra-high efficiency, tension metastable fluid detection (TMFD) systems which encompass unique characteristics as tabulated in Table 2, one of which is the unique ability to physically “see” and “hear” the manifestations that produce audible sounds in liquids when from visibly imploding bubbles.

2.8 Advances in thermonuclear fusion – the ultimate energy frontier

For over 60 years mankind has strived to harness the potential of thermonuclear fusion, the process considered widely to be the “holy grail” of all energy; even solar energy and wind are a result of fusion in stars like our Sun. Fusion of D atoms (virtually infinite in the world’s water supplies) produces energy levels that are x 10^6 of that possible from fossil fuel combustion, and hence could result in a paradigm shift for mankind if possible to tap technologically and cost-effectively. The two traditional approaches (Gross, 1984) involve either rarefied plasma confinement in Tokamaks or laser-based heating of tiny pellets. While considerable progress has been made, a novel approach that is economically feasible and overcomes many of the fundamental first-wall type issues has long been desired.

Table 2. State-of-Art Nuclear Detector Systems versus Novel TMFD Systems

Parameter	Present Systems	Proposed TMFD System
Size, standoff	Limited (e.g., large numbers needed for solid angle coverage)	Can be tailored to situation (single large system)
Intrinsic Efficiency	~30% (MeV); 90% (thermal)	90%+ (eV and MeV) in same system (with borated liquid)
On-Off Times	Seconds to minutes	Microseconds to seconds
Scalability	Low (costs increase non-linearly with size)	High – same drive trains but larger volume and piezo element.
Gamma blind?	Not usually – can become saturated in high photon fields	Yes (needs qualification for photofission systems)
Monitoring (recording)	Remote /electronic circuitry based	Multi-mode; Remote / electronic per acoustic-light pulse signals and also direct visual-audio bubble signals → Transformational.
Can same system detect n, g, α?	Not usual; need different systems for individual particle determination	Yes. Can be tuned to detect individual particles with specificity in same system.
Spectroscopy?	Yes. Demonstrated.	Appears feasible from crude scale experiments and theory



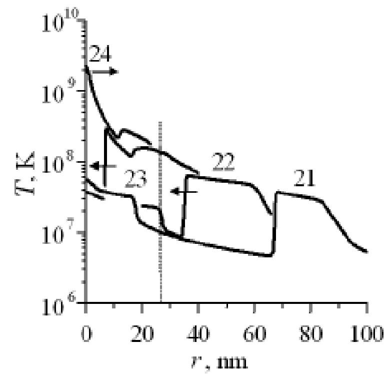


Figure 6. AICF pressure & temperatures within imploding (C_3D_6O) bubbles (Nigmatulin et al., 2005)

In 2002 and 2006 the Taleyarkhan et al. group announced their seminal discoveries supported by a rigorous theoretical foundation (Nigmatulin et al., 2005; Lahey et al., 2007). This discovery describes the acoustic inertial confinement fusion (AICF) methodology for deriving small-to-large scale thermonuclear fusion using acoustically assisted imploding bubbles of deuterated liquids. The discovery has been successfully confirmed and replicated (Xu et al., 2005; Forringer et al., 2006, Bugg, 2006). In this process deuterated acetone (C_3D_6O) vapor bubbles are supercompressed to high pressures and temperatures (10^{11} bar, 10^{8} K) to lead to thermonuclear fusion of D atoms as noted from Fig. 6. The process produces at present neutrons and tritium in the range of $10^5 – 10^6$ n-T/s. The process of supercompression also lends itself to cost-effectively conduct materials synthesis (e.g., convert carbon to diamond states). Ironically, deuterated LNG (mainly CD_4) appears as a superior fuel compared with C_3D_6O for the AICF process since, paradoxically, the implosion intensity is inversely dependent on the temperature of the host working fluid (Nigmatulin et al., 2005). Studies have shown that reducing the temperature from ~300 K to ~273 K initiated faster and more intensified shock-based heating of D-bearing vapors, and increased fusion output by over 10,000. Deuterated LNG, with it's nominal working temperature of ~ 111 K , and with a high proportion of D atoms appears promising for attaining breakeven ignition, an aspect which will be discussed during the presentation – if successful, it would represent a fitting tribute to the Gulf Countries and their principal energy resource to the world at present, to then effectively act to expand the world's energy supply by factors of up to 10^6.

3. REFERENCES

[1] BUGG, W., (2006), “Report onActivities on June Visit Report,” Univ. Tenn., to Purdue University, USA.

[2] ENGER T., (1972.), *Proc. Conf. on LNG Import and Terminal Safety*, Boston, MA.

[3] EPSTEIN, S., (1995), Summary of Ten Years of Molten Aluminum Incident Reporting, *Light Metals*.

[4] FLEISCHER, et al., (1975), *Nuclear Tracks in Solids*, Mc Graw-Hill.

[5] FORRINGER, E., et. al., (2006), Transac. Amer. Nucl. Soc., New Mexico, USA.

[6] FORRINGER, E., et al. (2006), Proc. Int. Conf. on Fusion Energy, New Mexico, USA.

[7] GROSS, R.A., (1984), *Fusion Energy*, John Wiley and Sons.

[8] HIGHTOWER M., et al., (2004), Sandia National Laboratory Report SAND 2004-6258.

[9] HONJO, Y, et al., (2008), *Proc. 16th Int. Conf. Nucl. Engr., ICONE-16,* Orlando, Florida, USA.

[10] KOOPMAN, R. P. et al., (1982), Lawrence Livermore National Laboratory Report UCID-19075.

[11] LAHEY ,R.T., R. P. TALEYARKHAN, and R. NIGMATULIN, (2007), *Nucl. Engr. Design*, **237**, 1571-1585.

[12] LAPINSKAS, J. et al., (2008),. *Proc. 16th Int. Conf. Nucl. Energy (ICONE-16), Orlando, FL, USA.*

[13] MATSUMARA, K., and NARAI, H., (1996.), *J. Nucl. Sci. Technology*, .**33**,No.4,298-306.

[14] McGLAUN J., (1990), CTH – A Three Dimensional Shock Physics Code, *Int. J of Impact Engr*, Vol. 10.

[15] MELHAM, G. A., et al., (2006), IoMosaic Corporation White Paper, Houston, Texas, USA.

[16] MiILLER, T.G., (1994), *Proc. of the SPIE*, Vol. **2093**, pp. 204-217, 1994.

[17] MILLER R. W., et al., (1964), Idaho National Laboratory Report IDO-16883.

[18] PATANKAR, S.N., et al. (1998), *Scripta Materialia*, Vol.38 (1) pp 145-148.

[19] NIGMATULIN et al., (2005), *Phys. Of Fluids*, **17**, 107106, 17-31.

[20] NUCLEAR ENERGY INSTITUTE, (2008), www.nei.org.

[21] SANCHEZ,J, et al. (2005), *SURF Fellowship Report* (internal), Purdue University, USA.

[22] SMAGACZ, P. et al., (2006), *Transac. Amer. Nucl. Soc*., Reno, Nevada, USA.

[23] TALEYARKHAN, R.P., R. T. Lahey,Jr. and M.Z.Podowski, (1985), *J. Heat Transfer*, **107**, No. 1

[24] TALEYARKHAN, R. P. et al., (1994), *Nuclear Safety*, **35**,1:58-73.

[25] TALEYARKHAN R. P., (1996), United States Patent No: 5,586,597.

[26] TALEYARKHAN, R. P., et al. (1997), *Light Metal Age*, pp. 26-35.

[27] TALEYARKHAN, R. P., et al., (2002), *Science*, **295**, 1868.

[28] TALEYARKHAN, R. P., (2004), United States Patent No: 6,603,122.

[29] TALEYARKHAN, R. P., (2005), *Nucl. Engr. Design***, 235**, 1061-1077.

[30] TALEYARKHAN, R.P., (2006), *Phys. Rev. Letters*, PRL 96, 034301.

[31] TALEYARKHAN, R. P., et al., (2008), *Nucl. Engr. Design***, 238**, 1820-1827.

[32] TALEYARKHAN, R. P., (2009), 1st Annual Gas Processing Symposium, Qatar,(Alfadala et al., ed., Elsevier).

[33] WALTAR, A., (2004.),*“Radiation and Modern Life,”* Prometheus Books..

[34] WOMBLE,P.C, et al., (1995), *Nucl. Instr. Methods in Physics Research* **B 99**.

[35] XU, Y., et al., (2005), *Nucl. Engr. And Design*, **253-3**, 1317-1324.