CLIMATE CHANGE MITIGATION   Revised January 23, 2022

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In order to prevent human extinction by the rising lower atmospheric temperatures associated with CO_2 driven climate change it is necessary to fully displace the amounts of energy and dependable power presently provided by combustion of fossil fuels with equal amounts of clean (non-fossil) energy and clean dependable power.

However, this fossil fuel displacement problem is further aggravated by the expectations of tropical countries that expect to more than double their average annual power use during the coming few decades.

A blunt reality which the public must face is that renewable energy alone cannot provide sufficient clean energy or sufficient dependable clean power for fossil fuel displacement, particularly at higher latitudes.

Xylene Power Ltd. is focused on mitigation of CO_2 driven climate change by application of advanced nuclear power reactors and related nuclear fuel recycling technologies.

However, in implementation of this change in energy and dependable power sources, it is essential to avoid depletion of the supply of fissile isotopes and to avoid environmental degradation by nuclear waste.

This document identifies the physical measures which are required to accomplish this goal.

1) Carbon dioxide (CO_2) formed by combustion of fossil fuels is steadily accumulating in the atmosphere and oceans. Excess CO_2 in the atmosphere is causing global warming.
2) The time frame for natural processes to cause the carbon contained in this excess CO_2 to revert into a fossil fuel or carbonate rock is many millions of years. These reversion processes rely on cumulative sunlight to provide the required energy.
3) Our descendants will have to live with the excess CO_2 that has already been produced plus the excess fossil CO_2 that will be produced until there is sufficient clean (non-fossil) power and energy transmission to fully displace fossil fuels.
4) Global warming is melting near polar permafrost, which is releasing large quantities of the green house gas methane, which is causing further global warming.
5) Global warming is reducing the average annual circumpolar snow and ice cover which in turn is reducing the fraction of incident solar radiation reflected back into space (planetary albedo).
6) The consequent increase in absorption of solar energy is causing further global warming which is causing an ongoing increase in sea level.
7) The ocean surface temperature is rising which is raising the average wet bulb temperature in tropical countries and is increasing the frequency and intensity of violent storms.
8) Excess CO_2 dissolved in the ocean is reducing the ocean surface pH which is causing destruction of CO_3^{--} ion dependent plankton and hence most of the marine food chain.

9) The best that we can reasonably do to mitigate these problems is to leave fossil carbon in the ground.

10) Energy conservation in the circumpolar countries will not arrest global warming. World wide consumption of fossil fuels will continue increasing due the increasing air conditioning load caused by the rising wet bulb temperature in the tropics..

11) Even if we could completely stop burning fossil fuels today global warming would continue to increase due to progressive near polar snow and ice melting, which is further reducing the planetary albedo (Earth's solar reflectivity).

12) It is essential to recognize that fossil fuels presently supply over 80% of human world energy requirements.

13) In order to fully displace fossil fuels we need to continuously supply an even greater amount of clean energy from new sources.

14) Due to lack of suitable geography for seasonal energy storage and due to energy transmission and electricity grid stability issues unconstrained wind and solar electricity generation can supply at most about 20% of the required clean energy. The balance of the new clean energy requirement must be met with nuclear reactors operating with sustainable fuel cycles.

15) In order to displace present fossil fuel consumption today we require about 20,000 GWt of new non-fossil thermal power, which is about 50X the present total world wide installed nuclear power capacity. By the year 2050 the projected total power demand will likely be about 50,000 GWt of which over 37,500 GWt must be supplied via nuclear power.

16) This new reactor power capacity requirement can be reduced by about 50% if the new reactors are sited in major urban areas, so that nuclear heat can be delivered directly to thermal loads by piped fluids.

17) There is complete failure by western politicians and their advisers to face the extent of this required nuclear new build, the rate at which these new reactors must be built to arrest climate change, the future reactor fuel requirements and the related energy storage, power transmission and power distribution infrastructure requirements.

18) The potential for sustainable CO2 capture and long term storage as a compressed liquid is orders of magnitude too small to significantly reduce the excess atmospheric CO2 concentration.

19) To be effective the climate change mitigation technologies must be suitable for world wide deployment.

20) The nuclear reactor technologies used for fossil fuel displacement must be conceptually simple and reliable, must not rely on scarce resources and must not require large numbers of highly educated personnel for deployment and ongoing future support.

21) The major raw materials used must be abundant, low in cost and readily available world wide.

22) Nuclear fission reactors are of two types, fast neutron reactors and thermal neutron reactors. As compared to existing thermal neutron reactors fast neutron reactors are potentially about 100X more fuel efficient and potentially produce about 1000X less long lived nuclear waste per unit of energy output.

23) Fast neutron reactors have the disadvantage that in order to operate they require a larger initial fissile fuel inventory than do thermal neutron reactors. However, from the perspectives

of fuel sustainability and nuclear waste disposal fast neutron reactors are the only practical choice.

24) Over time high energy fast neutrons will damage almost any solid material that they impinge upon. Hence for a fast neutron reactor to be durable its replaceable fuel assembly needs to be immersed in a liquid coolant pool that can safely and continuously absorb the fast neutrons that escape from the fuel assembly. The linear dimensions and weight of the required coolant pool enclosure are too large for road truck or rail transport of the pool in its fully assembled state. Thus the primary coolant pool should be assembled on the reactor site.

25) Concrete is not a suitable material for a Fast Neutron Reactor (FNR) primary pool enclosure wall. The contained liquid metal coolant temperatures are typically in the range 410 degrees C to 460 degrees C, which temperatures cause rapid cement deterioration. Cement is chemically bound by metal oxides that absorb water of hydration. At FNR operating temperatures the metal oxides give up their absorbed water of hydration causing gradual cement structural failure. Hence a FNR enclosure inner wall must be field assembled from prefabricated steel sections. These sections should be interconnected by deep penetration welds. The concrete is protected from high temperatures by fiber ceramic insulation.

26) Nuclear reactors must be fabricated from materials and material combinations that are well understood and characterized from chemical, physical and nuclear engineering perspectives.

27) Fabrication of key reactor components must not require large capital equipment that is only available in a few countries.

28) For public safety reasons urban sited nuclear reactors should have low pressure primary coolant and heat transport fluids.

29) Water cooled and moderated nuclear power reactors are unsuitable for large scale fossil fuel displacement from public safety, nuclear fuel sustainability and nuclear waste perspectives.

30) Liquid sodium cooled nuclear reactors and molten salt cooled nuclear reactors both feature low pressure primary coolants.

31) In principle liquid sodium cooled reactors and molten salt cooled reactors can both be designed to enable fuel sustainability.

32) Liquid sodium cooled nuclear reactors running a sustainable U-238 – Pu-239 fuel cycle are presently favored over molten salt cooled nuclear reactors running a sustainable Th-232 – U-233 fuel cycle due to much greater technology maturity.

33) In a liquid sodium cooled FNR (Fast Neutron Reactor) Pu is a much safer fissile fuel than U-235 due to the higher TCE (Thermal Coefficient of Expansion) of Pu and the lower melting point of Pu.

34) Molten salt reactors require both isotope separations and high temperature rated materials which make molten salt reactors inherently expensive. Molten salt reactors with sustainable fuel cycles also require ongoing sophisticated radio chemistry. However, liquid sodium cooled reactors have extra costs related to sodium-water incompatibility and fire prevention.

35) At present the corrosion control and radio chemistry issues in molten salt reactors that can support sustainable fuel cycles are: unproven, too immature and too complex for large scale deployment.

36) In present molten salt thermal neutron reactors there are problems with rapid graphite moderator deterioration, with fuel tube deterioration at high temperatures and with the liquid

fuel residency time in the moderator required for reactor power stability.

37) Some of the excess neutrons generated by the U-238 - Pu-239 fuel cycle used in fuel sustainable liquid sodium cooled reactors will likely be required to provide Th-232 - U-233 molten salt reactor fuel sustainability.

38) A fast neutron nuclear fuel cycle that maximizes energy recovery from the available nuclear fuel inherently minimizes the long term nuclear waste disposal issues.

39) There should be isolated safe dry storage of used nuclear fuel fission products for three centuries to allow the short lived fission products to naturally decay into stable isotopes.

40) After some time in dry storage it is anticipated that it will be economic to extract critically needed platinum and iridium from the fission products.

41) There will likely still need to be a comparatively small amount of isolated long term dry storage for permanent disposal of long lived low atomic weight radio isotopes such as C-14, Cl-36, Ca-41 and Ni-59.

42) Any clean electricity system with sufficient capacity to dependably meet the annual peak electricity load has surplus electricity generation and transmission capacity at other times.

43) In order for the surplus intermittently available clean electrical energy to be sold for fossil fuel displacement there must be peak demand based retail electricity pricing for dependable power. The marginal cost to an end user of a unit of surplus electrical energy, when it is available, must be lower than the marginal cost of the same amount of heat provided by a fossil fuel.

44) Surplus clean electricity will remain economically unavailable to most consumers for fossil fuel displacement until politicians approve appropriate restructure of retail electricity rates and impose a sufficient tax on fossil carbon emissions.

45) In urban areas the least expensive clean heat source will be nuclear heat produced by distributed Small Modular Reactors (SMRs) that is delivered to consumers via a district heating system. Presently in North America almost all waste heat from nuclear reactors is discarded.

46) Liquid sodium cooled pool type reactors with sodium bonded solid metallic plutonium alloy core fuel are favored over other reactor types for urban installation due to ease of fuel recycling and the rapid suppression of prompt neutron criticality provided by thermal expansion and core fuel disassembly within the reactor's sealed metal fuel tubes.

47) Provincial energy regulators must enable municipal district heating utilities. These district heating utilities must be approved to supply both electricity and heat.

48) Municipal planners and building code regulators must do all necessary to enable retrofitting of district heating systems, including provision of energy transmission corridors, pipe easements and terminal space suitable for heat pumps and related equipment.

49) The choice of reactor locations available to municipal planners is constrained by the reactors' elevation requirements with respect to both the local water table and the district heating system's pipe network.

50) To achieve economy a SMR at an urban site should be assembled from standardized truck portable modules.

51) Nuclear power plant modules must be truck transportable along existing city streets and must

comply with applicable truck load dimension and weight constraints.

52) With ongoing module replacement urban nuclear power plants should have an almost unlimited operating life.

53) Siting nuclear reactors in cities requires a different perspective on public safety than is currently the norm in power reactor design.

54) The urban nuclear power plants must have no requirement for a perimeter exclusion zone for public safety.

55) The nuclear reactors must be capable of safe autonomous operation.

56) Anything that can go wrong sooner or later will go wrong. When a technical problem occurs a reactor or its affected heat transport system(s) must safely shut down with no credible threat to public safety.

57) There should be sufficient equipment redundancy that a single unit failure does not impact end users.

58) Every reactor must be walk-away safe.

59) In order to realize a sustainable fuel cycle and to not produce decommissioning waste the reactors must be physically large enough for the reactor blanket and the primary coolant to absorb the entire radial neutron flux.

60) To enable eventual safe repair or removal of the primary coolant enclosure and the intermediate heat exchange bundles these components must always be outside the neutron flux. The metal in these components will likely have a substantial nickel fraction for high temperature strength. However, when Ni-58 absorbs neutrons it becomes Ni-59 which has a large neutron absorption cross section and after subsequent neutron absorption Ni-60 alpha decays. The resulting He-4 collects in metal grain boundaries causing the metal to become brittle. Thus alloys containing Ni must not be exposed to free neutrons.

61) The need for 100% neutron capture within the primary coolant pool effectively sets linear size minimums on both the diameter and height of the reactor primary coolant enclosure.

62) The reactors and accompanying power plant components should be easy to maintain and should have a minimum number of moving parts.

63) To minimize fuel reprocessing costs the cycle time for each fuel bundle should be 30 years. Scheduled reactor shutdowns for fuel bundle repositioning and partial refueling should occur at six year intervals.

64) To minimize fuel reprocessing costs fuel bundles should be truck and/or railway transported back and forth between the reactor site and a remote fuel reprocessing facility.

65) A local fuel bundle warehouse should be intermittently used to minimize the reactor refueling shutdown time.

66) During truck or rail transport each fuel bundle must be surrounded by a neutron absorbing material such as a gadolinium powder or solution sufficient to ensure that the fuel bundle will remain sub-critical if its transport container is accidentally immersed in water.

67) The fuel bundle transportation container must be sufficiently robust that it will remain intact and the contained fuel bundle will remain sub-critical after it is involved in a maximum speed transportation crash.

68) All radioactive fuel and fission products should be contained in sealed metal fuel tubes.

69) The reactor must be able to safely withstand a horizontal earthquake induced acceleration of 0.5 g without sustaining major damage and must tolerate a 3 g earthquake induced acceleration without becoming a hazard to the public.

SUMMARY:

The primary means of displacing energy presently obtained by combustion of fossil fuels with clean energy must be widespread deployment of fast neutron reactors that consist of an atmospheric pressure pool of primary liquid sodium which contains a central assembly of vertical fuel tubes. Heat moves by thermal conduction from the solid fuel to the primary liquid sodium coolant. Heat is removed from the primary liquid sodium by intermediate heat exchange bundles that are immersed in the upper perimeter of the liquid sodium pool. Each reactor must have a liquid sodium guard band surrounding the fuel tube assembly sufficient in thickness to prevent neutrons that escape from the fuel tube assembly from impinging on the intermediate heat exchange tube bundles, the sodium pool structure and overhead equipment. The top of pool temperature will typically be about 460 degrees C.

This type of reactor is intrinsically safe because it acts as a nearly constant temperature heat source. During normal operation the reactor thermal power output is controlled by adjusting the pumped secondary sodium coolant flow rate. After the nuclear reaction is shut down natural circulation of both the primary and secondary sodium coolants is sufficient to remove fission product decay heat.

To achieve the neutron conservation necessary for fuel sustainability the reactor does not use neutron absorbing control rods. Instead the reactor operating temperature set point is adjusted by using hydraulic piston lifters to change the vertical insertion of movable active fuel bundles in the matrix of fixed active fuel bundles. The vertical position, temperature and gamma ray emissions of each movable active fuel bundle are continuously monitored. On loss of control power the hydraulic lifters lose pressure and gravity causes movable fuel bundle withdrawal and hence a reactor cold shutdown.

For a 1000 MWt FNR with natural primary coolant circulation the primary sodium coolant pool size is 20 m diameter X 15 m deep.

After 30 years of fuel bundle operation and 6 years of fuel bundle cooling near the perimeter of the sodium pool the core fuel is reprocessed to extract fission product atoms. These atoms are replaced by new fissile atoms obtained from the reactor blanket fuel. An equal weight of new depleted uranium is then added to the reactor blanket.

In order to arrest climate change the fleet of nuclear reactors must displace at least 80% of the thermal power previously provided by fossil fuels.

IMPLEMENTATION:

1) Retail electricity rates must be restructured and a substantial fossil carbon tax must be imposed to enable private capital to economically address the CO2 problem.

2) Large liquid sodium cooled fast neutron power reactors have been built and operated for many years. The relevant material and safety issues are well understood.

3) In fast neutron reactor power plant design sodium related fire safety issues take precedence over

almost all other considerations. It is important to locate the reactor primary sodium pool above the highest possible elevation of the local water table.

4) There are presently numerous unrealistic claims related to molten salt cooled reactors. The reality is that there is little practical experience with molten salt cooled reactors, and even with an unlimited budget likely 20 years of additional development will be required before a credible fuel sustainable molten salt power reactor design can be considered for prototyping. The major problems with molten salt reactor technology include corrosion control, isotope separations of Li-7 and Cl-37, Mo-95 isotope rejection, moderator durability, moderator residence time and radio-chemical process control. There are also many practical issues related to the high melting points of the salts and maintenance of salt purity.

5) The continuous radio chemistry required for autonomous operation of a molten salt reactor running a sustainable Th-232 – U-233 fuel cycle has never been demonstrated. Making molten salt reactors operate with a sustainable Th-232 – U-233 fuel cycle will likely require more billions of R & D dollars and decades of effort before this technology can significantly mitigate climate change. There are too many difficult material issues and there is presently an unwillingness of electricity utilities to invest in the expensive and protracted R & D necessary to address these issues.

6) If we are serious about mitigation of climate change, we should now be deploying liquid sodium cooled power reactors with a sustainable U-238 – Pu-239 fuel cycle, as are the Russians and Chinese. The primary sodium pools of these reactors should be protected from fire by pyramids or equivalent structures.

7) The climate change situation is too urgent for further delay. Molten salt cooled power reactors fueled by thorium can be deployed in the future when they are ready.

8) Converting existing North American cities to district heating will be a massive task requiring 50 to 100 year future municipal planning. The present practice of municipal infrastructure planning only to the next political election must change.

9) Major political issues are district heating pipe easements, right-of-way for future electricity transmission and public transit corridors. A related issue is land expropriation for nuclear power plant sites and cooling tower sites within existing cities. There will have to be major changes in municipal utility related legislation.

10) Another related issue is modification of building codes and condominium related legislation to enable practical connection of existing condominium buildings to district heating systems.

11) Politicians, green energy proponents and city planners have not put sufficient thought into these practical matters. There is reluctance by these parties to learn from others who do have relevant practical experience. The Russians have extensive practical experience with both large sodium cooled power reactors and with district heating systems but in North America there is reluctance to acknowledge that expertise. There is a "not invented here" mentality.

THE WAY FORWARD

Mitigation of climate change requires displacement of fossil fuels that are presently used to provide heat, Nuclear heat is only directly available from reactors that are sited close to their loads. In terms of directly heating an urban area, nuclear reactors sited 200 km away are useless. The only way to transmit energy that distance is to convert the nuclear heat into electricity or hydrogen, transmit the electric or chemical energy and then at the load convert the electric or chemical energy back into heat. The efficiency of this process is at best 30%. It is far more energy efficient to site the reactors close to the thermal load,

However, siting nuclear reactors in a city imposes numerous reactor and power plant design constraints which do not apply at a rural site. These constraints include:

a) A high cost of real estate that usually must be acquired by expropriation;

b) A practical site area upper limit of about one square city block;

c) No public safety exclusion zone;

d) Heat dissipation related limits on dry air cooling, evaporation and water cooling;

e) Limits on power connections to the city electricity distribution;

f) Limits on the size and weight of individual reactor modules that can be delivered by truck into the center of the city;

g) A requirement for power plant zoning.

h) A minimum reactor physical size to achieve fuel sustainability and to prevent formation of decommissioning waste.

There is little merit in building a prototype reactor at a rural location such as Chalk River. Sodium cooled reactor technology has been extensively demonstrated at rural sites. A rural site does not have the physical and political constraints imposed by a city. A reactor built, operated and maintained at Chalk River will not convince potential investors that it can be successfully built, operated and maintained in downtown Toronto. It may be difficult to obtain zoning for an urban nuclear power plant without a major political campaign that private investors are unwilling to fund. Equally important is relevant legislation with respect to district heating. These matters need serious political leadership. The voters must reject present politicians who discount the importance of climate change.

Thus Xylene Power Ltd. sees the way forward as:

a) Design a fuel sustainable small modular reactor (SMR) that is practical to install, operate and maintain within cities;

b) Identify the SMR application constraints in terms of required: site size per reactor, heat output, site location with respect to the thermal load, site elevation, district heating pipe network, distributed cooling towers, electricity output, local cooling requirement, potable water, natural gas and sewer services;

c) Identify for the public the long term energy and transmission cost savings available from urban SMR siting as compared to rural reactor siting;

d) Let the municipal voters choose whether they prefer to live with very much higher future energy costs related to rural reactor siting or whether they prefer the lower future energy costs available from urban SMR siting.

As a comparison, gasoline is inherently dangerous, but between 1910 and 1920 people learned to live with it because when properly handled its advantages far outweighed its disadvantages. Today urban nuclear power has the same status in the public mind as did gasoline in 1910. Radioactive materials are safe when properly handled, but require the same public respect as does gasoline.