CLIMATE CHANGE MITIGATION LOGIC January 28, 2021

By Charles Rhodes, P.Eng., Ph.D.

Xylene Power Ltd. is focused on mitigation of CO_2 driven climate change. There is no benefit in committing public resources to new energy infrastructure that is physically incapable of mitigating climate change. The climate change mitigation logic is summarized below:

1) Carbon dioxide (CO_2) formed by combustion of fossil fuels is accumulating in the atmosphere and oceans.
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.
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 non-fossil power to fully displace fossil fuels.
4) Excess fossil CO_2 in the atmosphere is causing global warming.
5) Global warming is melting near polar permafrost, which is releasing large quantities of the green house gas methane, which is causing further global warming.
6) 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).
7) The consequent increased absorption of solar energy is causing further global warming which is melting land borne glaciers, causing an ongoing increase in sea level.
8) The ocean surface temperature is rising which is increasing the frequency and intensity of violent storms.
9) Excess CO_2 dissolved in the ocean is reducing the ocean surface pH which is causing destruction of plankton and hence the entire marine food chain.
10) The best that we can do to mitigate these problems is to leave fossil carbon in the ground.
11) Simple energy conservation will not arrest global warming. World wide consumption of fossil fuels is increasing in spite of widespread energy conservation efforts.
12) 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).
13) It is essential to recognize that fossil fuels presently supply about 85% of human world energy requirements.
14) In order to fully displace fossil fuels we need to continuously supply an at least equal amount of non-fossil energy from new non-fossil energy sources.
15) Due to lack of suitable geography for seasonal energy storage and to energy transmission constraints renewable energy can supply at most about 30% of the required non-fossil energy. The balance of the non-fossil energy requirement must be met with nuclear reactors operating

with sustainable fuel cycles.

16) In order to displace present fossil fuel consumption today we require about 20,000 GW of new non-fossil thermal power, which is about 50X the present total world wide installed nuclear electric power supply capacity.

17) 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.

18) 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 transmission and distribution infrastructure requirements.

19) The potential for CO2 capture and long term storage by any method is orders of magnitude too small to significantly reduce the excess fossil CO2 accumulation.

20) To be effective at climate change mitigation the technologies for supplying and distributing new non-fossil power must be suitable for world wide deployment.

21) The nuclear reactor technology 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 future support.

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

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

24) Fast neutron reactors have the disadvantage that in order to operate they require a larger initial fissile fuel inventory than thermal neutron reactors. However, from fuel sustainability and waste disposal perspectives fast neutron reactors are the only practical choice.

25) 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 pool of liquid coolant that can safely and continuously absorb the fast neutrons that escape from the fuel assembly. The linear dimensions and weight of this pool are too large for truck or rail transport of the pool in its fully assembled state.

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 and secondary coolants.

29) Water cooled 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) 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 in part due to much greater technology maturity and in part due to much lower educational requirements for field personnel. Molten salt cooled reactors have complex unresolved material problems. Liquid sodium cooled reactors have extra costs related to sodium-water incompatibility and fire prevention.

33) 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. One of the most difficult chemical issues is ongoing extraction of protactinium from the reactor blanket and controlled reinsertion of U-233 into the reactor core.

34) In molten salt thermal neutron reactors there are problems with rapid graphite moderator deterioration and with the liquid fuel residency time in the moderator required for reactor power stability.

35) 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.

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

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

38) There must be a comparatively small amount of isolated long term dry storage for future disposal of long lived low atomic weight radio isotopes.

39) Any non-fossil electricity system with sufficient capacity to dependably meet the annual peak electricity load has surplus electricity generation and delivery capacity at most other times.

40) In order for the surplus intermittently available non-fossil electrical energy to be sold for fossil fuel displacement there must be peak demand based retail electricity pricing. The marginal cost 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.

41) Surplus non-fossil electricity will remain economically unavailable to most consumers for fossil fuel displacement until Canadian and US politicians approve appropriate restructure of retail electricity rates and impose an appropriate price on fossil carbon emissions.

42) In urban areas the least expensive non-fossil heat source will be nuclear heat produced by distributed Small Modular Reactors (SMRs) that is delivered to consumers via a piped fluid district heating system. Presently almost all waste heat from nuclear reactors is discarded.

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

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

45) Provincial energy regulators must enable district heating municipal utilities. These district heating utilities will likely also supply electricity for powering circulation pumps, heat pumps and fan coil heat rejection units located on or adjacent to consumer premises.

46) Municipal planners and building code regulators must do all necessary to enable retrofitting of district heating systems, including provision of energy supply corridors, pipe easements and accessible space for terminal heat exchange units and related pumps.

47) The choice of potential distributed 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.

48) Nuclear power plant modules must be truck transportable along existing city streets and must comply with applicable truck load height, weight and length constraints.

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

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

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

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

53) 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.

54) Every reactor must be walk-away safe.

55) In order to be durable and to realize a sustainable fuel cycle the reactors must be physically large enough for the primary coolant to capture the entire radial neutron flux.

56) To enable eventual safe removal of the primary coolant enclosure and the intermediate heat exchange bundles these components must always be outside the neutron flux.

57) This constraint effectively sets linear size minimums on both the diameter and height of the reactor primary coolant enclosure.

58) Hence a fully assembled reactor primary coolant enclosure is too large for truck or rail transport and must be assembled on the reactor site.

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

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

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

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

63) During truck or rail transport each fuel bundle must be surrounded by a neutron absorbing material such that it will remain sub-critical if its transport container is accidentally immersed in water.

64) The fuel bundle transportation container must remain intact and the contained fuel bundle must remain sub-critical after it is involved in a maximum speed transportation crash.

65) All radioactive fuel should be contained in sealed metal fuel tubes.

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

67) A major advantage of sodium bonded metallic nuclear fuel in fuel tubes is that reactors can be made with two different temperature ratings.

Medium Temperature > 330 C to 480 C at the thermal load, Fe-Cr fuel tubes, stainless steel primary sodium pool enclosure, U-Pu-Zr Na bonded fuel;

or

High Temperature > 600 C to 750 C at the thermal load, Mo fuel tubes depleted in Mo-25, 617 alloy primary sodium pool enclosure, U-Pu Na bonded fuel;

SUMMARY:

The main means of displacing energy obtained from combustion of fossil fuels with non-fossil energy must be widespread deployment of fast neutron reactors that consist of an atmospheric pressure pool of liquid sodium containing a central assembly of vertical fuel tubes. Heat is removed from the primary liquid sodium via immersed intermediate heat exchange bundles that are located around the perimeter of the coolant pool. Each reactor must have a liquid sodium guard band surrounding the fuel tube assembly sufficient to prevent neutrons that escape from the fuel assembly from impinging on the intermediate heat exchange tube bundles, the sodium pool enclosure and overhead equipment. The top of pool temperature will be about 500 degrees C for a medium temperature rated reactor or about 800 degrees C for a high temperature rated reactor.

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

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 set by using hydraulic piston lifters to change the relative vertical positions of mobile core fuel bundles. The vertical position, temperature and gamma ray emissions of each mobile core fuel bundle are continuously monitored. On loss of control power gravity causes a reactor cold shutdown.

For practical reactors rated for 900 MW thermal power with natural primary coolant circulation the primary coolant pool size will likely be about 20 m diameter X 15 m deep.

To arrest climate change the nuclear reactor fleet must displace at least 70% of the thermal power presently provided by fossil fuels.

IMPLEMENTATION:

1) Retail electricity rates must be restructured and substantial 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 maximum 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 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 many 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) Hence, 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. 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.

7) 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.

8) A major political issue is easements and right-of-way for future energy transmission and public transit corridors. A related issue is land expropriation for nuclear power plant sites within existing cities. There will have to be major changes in municipal utility related legislation.

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

10) Neither politicians nor green energy proponents have put sufficient thought into these practical matters. Worse yet, there is reluctance to learn from parties who do have relevant practical experience. The Russians have 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.

11) Why has OPG failed to send a delegation to Russia to learn about these matters? In Toronto there has been a representative of a European district heating equipment supplier for over 35 years. However, that knowledge base has not been utilized by either the City of Toronto or the government of Ontario. 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, transmit the electricity and then at the load convert the electricity back into heat. The efficiency of this process is at best 30%. From both thermal efficiency and an equipment cost perspectives it is far better to site the reactors close to the load,

However, siting nuclear reactors in a city imposes numerous reactor and power plant design constraints that 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 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. 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 a 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 major 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, electricity output, local cooling requirement, potable water and sewer services;

c) Identify for the public the 2X to 3X long term energy and transmission cost savings available from urban SMR siting as compared to rural SMR siting;

d) Let the municipal voters choose whether they prefer to live with very much higher future energy costs related to rural SMR 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 risk. 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 respect as does gasoline.